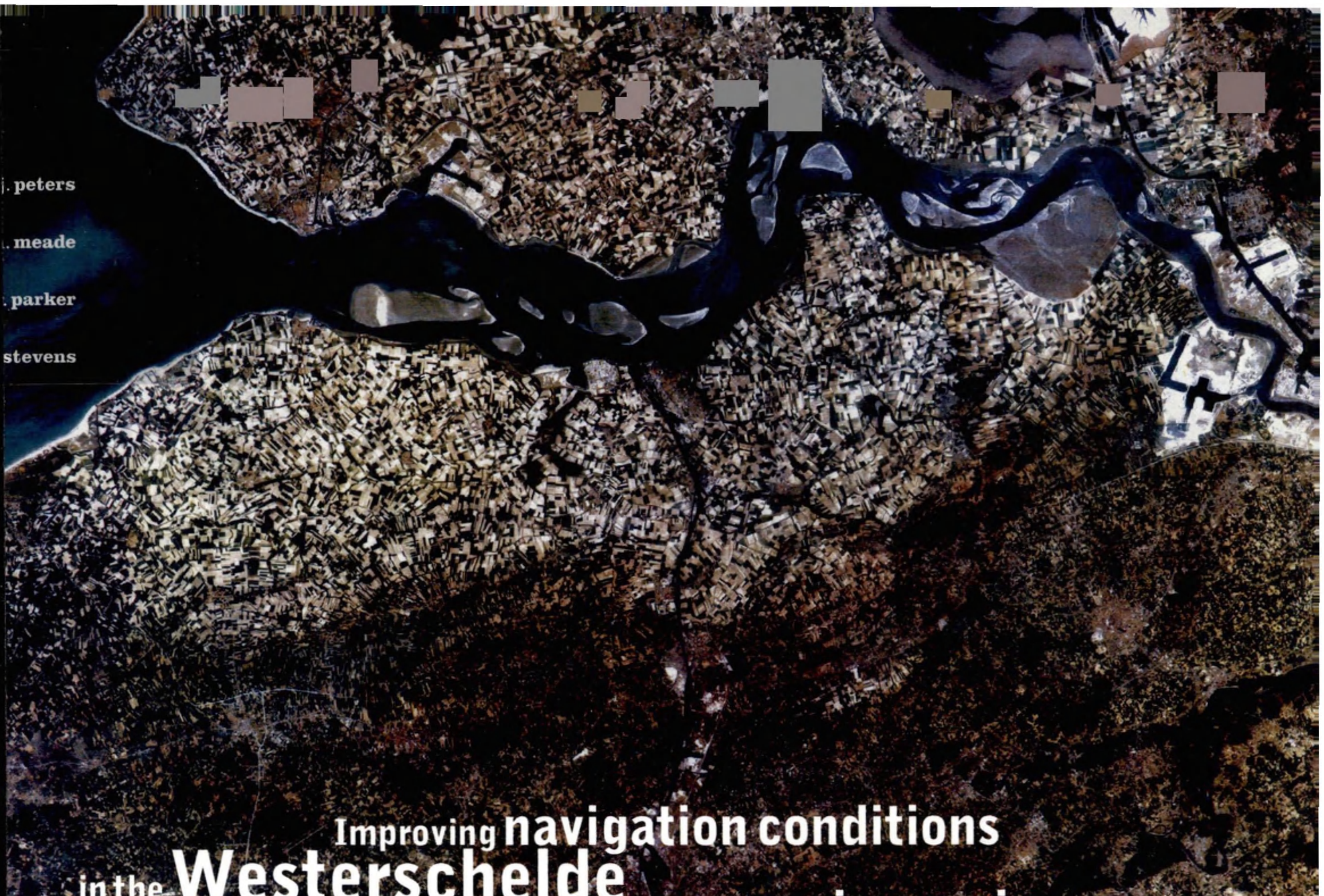

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January **2001**

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How to harmonize accessibility, safetyness and naturalness?

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Foreword

In 1999, the Dutch and Flemish governments decided to conduct a comprehensive, multidisciplinary research project that would result in a long-term vision (LTV) about the further evolution of the Westerschelde. The main issues considered in this project are the improvement of the navigation channels (accessibility), the risk for flooding (safetyness) and the preservation of the estuarine ecology (naturalness). A "cluster morphology" was set up for investigating the morphological aspects, common to all three main LTV issues.

By the end of 1999, the Port of Antwerp called on a team of international experts to provide advice on the feasibility of a further deepening of the navigation route in the Westerschelde between the sea and Antwerp. At the request of the LTV cluster morphology, regular contacts were established and information was exchanged between the teams.

The expert team appointed by the Port of Antwerp issued a first report in July 2000. This "baseline report" places the present Westerschelde in the context of its historical evolution and gives the basis for a discussion about the future changes, both natural and anthropogenic.

The final report presented here contains some original views and ideas about the way to manage the Westerschelde. One of these ideas is an alternative dredging and dumping strategy, combined with possible modifications of the river training works. These aspects are developed in more detail in a technical addendum.

The expert team wants to thank the Port of Antwerp and the members of the LTV cluster morphology for the constructive and collaborative spirit in which they could work. We hope this work has contributed to the further management of this so valuable estuarine environment.

Jean Jacques Peters
Team Leader

CONTENTS

EXECUTIVE SUMMARY

The natural evolution of the morphology of the Westerschelde has continued for several thousand years, following a pattern of growing and coalescing shoals and banks linked with a simplifying and deepening channel network. This has led naturally to increased tidal penetration into the estuary. This natural development path has been perturbed, possibly accelerated or enhanced, by poldering and other reclamation and stabilising activities which started in pre mediaeval times.

These factors have resulted in the present situation in which the continuing evolution of tidal morphology and dynamics leads to higher tidal levels penetrating further up the estuary with attendant risks of flooding and changes in morphology, and leading to reduced morphological diversity and consequent reductions in ecological diversity. Tidal energy is the principal driving force for morphological change. Examination of time-series of tidal parameters and dredging quantities does not reveal any clear and unequivocal effects of the major dredging and deepening campaigns on tidal propagation parameters. Any effects are indistinguishable from changes in tidal parameters which have taken place before started a significant dredging in the Westerschelde, downstream of Bath.

Estuarial morphological management strategies need to have as their target the satisfaction of the requirements for safety, navigation and ecology through the conservation or the redevelopment of morphological diversity. Management strategies should rest upon a thorough understanding of the natural physical processes in the estuary based principally on field observation and experience supported by analyses of historical and geological data and the use of appropriate physical and numerical modelling techniques.

The analysis of existing data shows that a “do nothing” or “leave everything as it is” management strategy is neither a practical nor a sustainable option in the context of either safety, navigation, or environmental quality.

The proposed approach of morphology in the L.T.V. project, which is based largely on model studies and sediment budgets which have great uncertainties. Comparison of results of the LTV study method with specific documented cases of dredging, disposal and morphological development does not support the validity of the LTV approach to defining permissible intra-estuarine disposal quantities. The LTV proposal, which involves the removal of sediment from the estuary, is regarded by the expert team as having great uncertainty and does not provide a secure basis for future management decisions or methods. In particular the removal of sediment from the Westerschelde system is not within the generally accepted meaning of “sustainable” or “reversible”.

The strategy advocated by the expert group recognises the need to meet targets of safety, transport and ecology using an holistic approach to estuarine management based on secure field data and appropriate interpretation of field observations as well as the use of appropriate physical and numerical models. The proposed use of pilot studies of morphological management satisfies the crucial observance of requirements for due prudence in achieving sustainability and reversibility in management strategies.

1 INTRODUCTION

1.1 Initial Terms of Reference and Objectives

The initial Terms of Reference aimed at bringing together a team of international experts, who would review the existing documentation on the Westerschelde and would formulate an independent advice on the technical feasibility of a further deepening of the maritime access to the Port of Antwerp. Three reports would be issued. The first one, called the "baseline report", issued in July 2000, places the present Westerschelde in the context of the long-term trend of the estuary's behaviour. The second report would analyse the dredging works and the relationship with the morphological evolution. The third report would focus on the feasibility of a further deepening of the maritime access to the Port of Antwerp (PA) and formulate recommendations about the future dredging strategy. For reasons explained hereafter, it was decided to merge reports 2 and 3 and to issue them as a single final report. An Addendum of other technical issues has been prepared.

1.2 Linking to LTV

Two months after starting its activities, the expert team was asked to liaise with a working group on "morphology", acting in the Long-Term-Vision (LTV) project launched by the Dutch and Flemish Governments in the binational Technical Schelde Commission. Although this collaboration has slowed down the work rhythm of the PA expert team, it has very much enriched its output. Members of the team participated in LTV meetings in Belgium and in The Netherlands. Advice was given about the work in the LTV Cluster Morphology. The expert's first report - the baseline report - was included in an audit performed on LTV in October 2000.

1.3 Final Report Objectives

The objectives of the final report deviate somehow from the contractual ones. This report merges the proposed reports 2 and 3. It makes an overview of the results obtained by the expert team, taking into account those results of the three components of the LTV working groups related to the dredging works in the Westerschelde and their likely impact on aspects such as accessibility, naturalness and safety. Basic questions addressed in this final report were indicated already in the baseline report, which should also be considered as an annex.

The questions presented in the baseline report were:

- *What could be the future evolution of the estuary under the 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 than the one that existed some fifty or sixty years ago?*

The following may added:

- *On the shorter term, what are the dredging strategies that could serve both purposes: to further improve the navigation conditions and to steer the morphological changes in a direction favourable for the naturalness and safeness of the Westerschelde?*

- *What kinds of works, other than dredging, may contribute to the recovery of the Westerschelde's morphology?*

2 SUMMARY OF KEY POINTS OF THE BASELINE REPORT

2.1 Natural Morphological Evolution

Coastal areas and estuaries were shaped during the Holocene period. Scientists agree about the magnitude of the eustatic sea level rise during the transition from the Pleistocene geological period - the last ice age, about 21 kyr BP[1] - to the Holocene - 10 kyr BP - (Fig. 2.1-01). During this period sea level rose from about -125 m to - 30 m relative to the present level, which was almost reached some 3 kyr ago. The stabilisation of the ocean levels in recent times does not mean that there are no fluctuations anymore. The present rate of mean sea level rise amounts to about a quarter of a metre per century. It is influenced by climate changes, a major concern to environmentalists. This continuing long term trend must be recognised and accounted for when assessing flood risk. Land subsidence may also contribute to the danger for catastrophic flooding of coastal regions, like in some areas bordering the North Sea.

Before the Atlantic Ocean invaded the area between Europe and England, the major European rivers Rhine, Meuse and Schelde discharged somewhere in the middle of what is now the North Sea (Fig. 2.1-02). In a first phase, the sea intruded the river courses, creating estuaries. When ocean levels stabilized, the further morphological evolution of the North Sea coasts depended on the relative magnitude of the hydraulic mechanisms and forces originating from sea and river. Some coasts were eroded by tides and waves, while others were replenished by sediments either originating from the rivers or from coastal erosion. When the channel between England and France was invaded by the Atlantic Ocean, shore erosion yielded large amounts of detrital material. Those eroded from the cliffs along the French coast were transported by the currents in a north-eastern direction, along what became the Belgian, Dutch and part of the German coastline. The path of the sediment is determined by the topography, by the direction of the residual tidal currents, and by the winds coming predominantly from the southwest. All these factors induce the net displacement of water and sediment in north-eastern direction.

Some 5 kyr BP, the sediment transit had created a ridge of sediment, with high shoals. These formed the border of a large lagoon into which Rhine, Meuse and Schelde discharged their freshwater and continental sediment load. The Schelde river supplied a rather limited quantity, compared to the two first ones. Van Veen (1950) presented a sketch of what it must have looked like in Roman times, 2 kyr BP (Fig. 2.1-03). Since then, the larger quantities of sand and gravel transported by Rhine and Meuse rivers partially filled the northern and northeastern part of the lagoon, while marine sediments were moved into it by the sea currents, through breaches created during storms. Around 1 kyr BP, the lagoon had partly silted up in many areas, its southern part mainly with marine sediments. On a document from RIKZ, an extended area of Flanders and Zeeland is composed of schorre and peat (Fig. 2.1-04).

[1]One thousand years is 1 kyr; BP is 'Before Present'

Archeological evidence indicates human settlements from the stone- and bronze age in the area mainly downstream of Hansweert, and from Roman times close to Vlissingen. Some researchers consider that in Roman times, the mainly peat area of the "delta" was invaded by the sea through the river mouths because of the sea level rise (Eck, van, B., 1999). The expert team favours the hypothesis - explained above and as put forward by Van Veen - that the lagoon was first created as a consequence of the emergence of a sand barrier formed by a "litoral" marine sediment transport. This process became possible when the sea level rise slowed down, letting currents and wind work together to build up the islands and dunes. The lagoon must have functioned as an almost closed sea, isolated from the newly created North Sea. The river mouths were at the land borders of the lagoon, to the East, not at the sea border to the West.

Until around a thousand years ago anthropogenic changes in the Westerschelde's morphology were negligible while the morphological changes resulting from the eustatic sea level rise were strong. These made the southern part of the lagoon - in the "Lower Lands" (The Netherlands) - evolve towards an intricate system of islands, shoals and channels. According to Coen (1988), tides reached Antwerp for the first time between 1.4 and 1 kyr BP (Fig. 2.1-05 & 06). The tidal wave could easily dissipate in the lagoon and did not penetrate very far into the river reaches. Subsequently, the more inland propagation of the tide must have been the result of an increased flow conveyance capacity of the main channels in the lagoon, enhanced by the accretion of the shallow areas by siltation, and the scouring of the channels by the tidal flow. At that time, anthropogenic changes were insignificant. The lagoon in the so-called "delta" of Rhine, Meuse and Schelde was progressively evolving towards an area with groups of shoals separated by major channels through which the tide could propagate further inland.

In the absence of any human impact, the system of shoals and active tidal channels would have developed further, with a progressive accretion of higher grounds to slikke, schorre and finally islands, while the secondary channels would continue to decline. The main channels, of which the Honte was one of the deepest, were in fact created by the scouring by the tidal currents through breaches in the littoral sand barrier, during heavy storms. The fate of the Honte sea branch would have been to further silt up, were it not draining the Schelde river basin. Indeed, the river system in this catchment forms the "lung" through which the estuary may respire, as the tidal flows propagate into it. The Zwin, another such sea branch created by the breaching of the coastal sand barrier, did not drain a large river catchment and it silted up naturally, though the process was accelerated by human intervention.

The mouth area of the Honte - the present Westerschelde - underwent, and still undergoes, significant natural changes. The Flemish Banks are a series of large marine sand ridges, deposited by the water and sediment circulation in the Southern Bay of the North Sea. Until about 200 y BP (1800), the ridges penetrated well into the funnel-shaped mouth area of the Honte. The rapid morphological evolution of the mouth area, over at least the last two centuries, is likely to be linked to the changes in the Westerschelde. The recent works along the Belgian coast, including the extension of the

Zeebrugge harbour, will inevitably have had an effect but one which is at present unquantified.

2.2 Anthropogenic Morphological Changes

Sea level reached is present general level about 3 kyr BP after which it has oscillated around its present level, though contemporary knowledge suggests an underlying trend of a rise at about on quarter of a metre per century. Once the sea level had stabilised the fine suspended load carried by the tidal flow deposited marine clay on the shoals which rose high enough to allow new human settlements. The settlers progressively built levees to protect themselves from the highest tide levels. In some cases, levees were erected by consolidating the natural levees that are formed during inundation by the deposition of sand ridges along the most active tidal channels.

The flow of the Schelde river discharged into what is now the Oosterschelde (Eastern Scheldt). The Honte - the present Westerschelde downstream of Bath - was in fact formed by a series of sea branches scoured in the lagoon bottom by the tidal currents during storm events. These sea branches surrounded shoals on which man-made levees reduced progressively the extent of the inundation area. Confining the flow in channels by reducing the inundation area enhances the penetration of the tidal wave. This results in higher peak levels and increased flood risk so that settlers build successively higher levees.

With the higher levees, polders became more vulnerable to catastrophic inundations, during which new, deep channels were scoured by tidal currents through the new breaches. The settlers, reclaiming the inundated land, rebuilt levees not across the newly formed channels, but rather following their banks. As a result, the plan form of the levees makes some sharp changes in direction. The repeated process of land reclamation, levee breaching, inundation, levee building and again land reclamation started in the 11th century. In the 15th and 16th centuries, heavy floods reshaped significantly the morphology of the Westerschelde. In the 17th century the present shape appears, though still with many secondary channels and many flooded shoal areas. Morphologically, the Westerschelde is not a typical meandering coastal plain estuary. This explains why it is still evolving, despite the many civil engineering works undertaken to control the estuary.

Figure 2.2-01 shows the result of successive flooding and land reclamation over the past 800 years. Interpretation is obviously made difficult by the fact that some areas have been reclaimed and flooded several times. Some inundations were man-made, often strategic during war time. This is illustrated by the comparison of the zones poldered before 0.7 kyr BP and never flooded again (in Fig. 2.2-01) with the map of 0.7 kyr BP (Fig. 2.6-01).

With reliable charts becoming available since the beginning of the 19th century, it is possible to assess quantitatively the impact of human interventions (Fig. 2.2-02). From these charts and from the older, more qualitative maps, it may be concluded that poldering and cutting off secondary channels accelerated and modified significantly the natural trend of the morphological changes. The analysis of this impact is not yet sufficient to make a good estimate of its magnitude and further study work is needed.

2.3 Changes in Tidal Regime

The long term morphological trend analysis presented in the baseline report shows evidence of the formation of a limited number of major sea branches. The tidal-water storage area in the Honte - the sea branch in the Rhine-Meuse-Schelde lagoon that captured the Schelde river flow - was progressively reduced by siltation on shoals and scouring of the main sea branches. Before any significant impact of human activities, these natural processes favoured the inland penetration of the tidal wave. Since the Middle Ages, poldering and cutting-off many secondary channels have enhanced significantly the inland intrusion of the tides long before any dredging operations, which started at the end of the nineteenth century.

Appendix 2 of the baseline report presents the results of an evaluation of tidal observations within the Schelde for the period 1880 to 2000, more than 6 nodal cycles. These data were compared with observations outside the estuary (Oostende) and at sites in the southern North Sea. This analysis concluded that changes in tidal parameters within the estuary (high water height, tidal range, high water interval) were far greater than changes in equivalent tidal characteristics in the southern North Sea. The changes are not cyclical but indicate a shift in one direction over the period of 100 or so years data. These data are discussed further in section 3.3. of this document.

Comparative consideration of the temporal changes in tidal characteristics and intertidal area is informative. Between 1800 and 1980, some 58% of the initial (1800) intertidal area has been lost to poldering. It is concluded that this may be the principal anthropogenic factor causing the changes in tidal propagation during the period of observations. It is likely that dredging since 1970 has contributed to the easier penetration of the tidal wave in the estuary. In a recent paper, Arends and Langerak (2000) came to a similar conclusion. However, they do not corroborate with facts their statement that “channel enlarging by dredging dominated (since 1970) the development of the estuary.” The graphs they present (Fig. 2.3-01 & 2.3-02) are in line with the trend over the past millennium and correspond to the changes due to natural factors. This is not to say that dredging has no effect but rather that it is one factor amongst several others and that the relative significance of the different factors is still unknown. Major and continuing changes in channel geometry have been observed in the past decades. A typical example is the change of the Middelgat, between Terneuzen and Hansweert, from a predominantly flood channel in the 1960's to a predominantly ebb channel by the 1970's, the Gat van Ossenisse taking over as the flood channel (see Fig. 2.2-02).

Data with which to evaluate other morphologically relevant changes have not been readily accessible to the Port of Antwerp expert team

2.4 Salinity and Mixing Processes.

The mixing of the freshwater river flow with the salt sea water determines the specific water and salt circulation in estuaries. Salinity data are available only for the past fifty years, or so. Besides exceptions, salinity data were not collected in the Westerschelde in view of analysing in a systematic way the impact the morphological changes could have on the mixing processes. This is unfortunate, because salinity is an excellent parameter to assess the variation in flow conveyance of the estuary.

Several authors have reported results of measurements of the longitudinal, transversal and vertical structure of salinity in the Westerschelde (Fig. 2.4-01)(De Pauw & Peters, 1973; Peters, 1975; Peters & Sterling, 1976; Peters & Wollast, 1976; Peters & Wollast, 1980). These studies showed that the Schelde Estuary may be subdivided in 3 zones, where water and salt circulation have different patterns. They reveal the high mixing potential in the Westerschelde downstream of Hansweert, where the distinctive flood and ebb channels recirculate the water around and over the large shoal areas. Mixing is enhanced by the presence of areas where water can be retained during some time - areas that can be called temporary dead zones - while the rest of the flow continues moving. The mixing power of the flood and ebb channel patterns diminishes progressively upstream of Hansweert, as the morphology changes steadily from the distinct multiple-channel towards a single channel pattern.

The changes in the mixing power and its distribution along the Westerschelde determines the vertical stratification of salinity and velocity, hence the suspended sediment circulation. It explains the presence of the so-called “turbidity maximum”, also the mud deposits observed upstream of the Dutch-Belgian border. Suspended sediment budgets were established on the basis of systematic measurements performed between 1967 and 1976 (Peters & Sterling, 1976; Peters & Wollast, 1976). Although they focussed on the existence of the mud accumulation in the area of the Port of Antwerp, thus on the transport of suspended materials, the data show a significant net transport of marine sediments because of the stratified flow. Bed material transported as pure bed-load was not measured, but there is enough evidence to suggest that the movement of sediment as pure bed-load must be varying all over the Westerschelde, with in some areas net inland oriented movement of bed material, more intense than without the existence of the stratification. How much this affects the natural morphological changes is not known, but one may suppose that the further simplification of the Westerschelde’s morphology - natural and anthropogenic - may modify these patterns of bed sediment movement, as will be discussed further.

2.5 Morphodynamics of the Westerschelde

The morphodynamic behaviour of coastal plain estuaries is in general still poorly understood. Because of their complexity, investigators tend wrongly to favour modelling more than field observations and physical interpretation of the field data. Very interesting study work was made in the past about the morphology of the Westerschelde and the available information is unfortunately not well used in investigations.

The physical processes governing the changes in morphology of an estuary are basically the same as those in rivers. The changing pressure gradients and reversing flows of tidal movement obviously complicates the interpretation. Large efforts have yet to be made in understanding the physical processes governing the movement of channels, shoals and bars, crossings etc. The shape of a shoal or a bar is determined by the flow pattern and the sediment transport, mainly the transport of bed material. Methods were already developed for interpreting the morphological changes in large alluvial rivers (Peters & Sterling, 1975; Coen, Peters & Roovers, 1977; Peters & Wens, 1991). They rely on understanding the morphological processes, using field data together with modelling. Modelling, both physical and mathematical, is used as a tool to assist in the understanding of the processes, not to make predictions. Indeed, in most applications, models for predicting morphological changes are producing poor results because the models can not reproduce correctly some of the basic physical processes. Therefore, "geographical" analysis of past morphodynamic evolutions is essential in addition to the traditional flow-sediment modelling. There is no reason to pretend that the basic processes governing the morphological changes in an estuarial sand bed environment would differ from those in an alluvial river.

The baseline report presents a preliminary analysis of the Westerschelde morphodynamics. Charts of the Westerschelde in 1636, 1800, 1865, 1938 and 1972 served to illustrate the mobility of the morphological features: the shifting and deformation of bar areas, the movement and deformation of channels, changes in the location and elevation of crossings. The baseline report concludes that the long-term trend in morphological change, as a consequence of the post-Pleistocene sea level rise, is still going on. This is now confirmed by a closer analysis of tide data, as presented in this final report. Moreover, the baseline report discusses the anthropogenic change before major dredging started in the Westerschelde. It concludes that poldering and cutting off secondary channels, which started in the Middle Ages, have enhanced and accelerated the natural trend.

The series of more precise charts between 1800 and 1972, presented in Figure 10 of the baseline report, has been completed with the additions of charts for the 17th Century and for 1997 (Fig. 2.2-02). The information presented in this figure provides no indication of any obvious or dramatic changes in the pattern of shoals and channels after the onset of major dredging programmes in 1970. The shapes of bars and channels have continued to evolve as they had done prior to dredging and dumping in the Westerschelde.

2.5.1 Movement of Channels

The morphodynamic behaviour of the Westerschelde upstream Vlissingen is determined by the sediment transport capacity of the channels and their degree of freedom to move laterally. This is best illustrated in Figure 2.5-01. When observing these charts, it should be remembered that the apparently meandering shape of the Westerschelde is accidental, the result of repetitive flooding and land reclamation. The eastern channel (Gat van Ossenisse and Overloop van Hansweert) has been evolving tremendously over the past 200 years, a very short period for such a change. It became a continuous channel after the forties and took over the role of flood channel from Middelgat only in 1969. The morphology of the bar-complex located between the two main channels is still evolving, not only as a result of sediment transport on and along the bars, but also with the shift of the Gat van Ossenisse channel to the east (Fig. 2.5-01). The Platen van Hulst, a slikke and schorre area remnant of the extended marsh land (see Fig. 2.5-02 (17th Century)) - is still eroded by flood and ebb flows. The bank defences - man-made hard points - north and south of the area make the channel bend becoming more pronounced. The middle bar shows a discontinuity in its shape just across the eroding part of the Platen van Hulst.

In all the documents consulted by the expert team, nowhere is this kind of evolution analysed morphologically, i.e. taking into account the sediment transport together with the erosion potential of the channel banks. In the baseline report is mentioned that the shape of the eastern channel (Gat van Ossenisse - Overloop van Hansweert) became tortuous, a morphologically "unhealthy" situation. From the visual analysis of the charts, it seems that this evolution is "natural", influenced by poldering and channel cut-off's. The impact of dredging and dumping is unknown, but is likely to be limited. However, this and similar issues merit more research work, not foreseen in our assignment.

Bank erosion and the accretion of a bar across the bank are linked, but the link is complex. The flow pattern and the sediment movements are continuously changing with the tide, and they depend on the magnitude of the tidal amplitude. Also storms affect the sedimentation mechanisms. Despite the complexity of these processes, the movement of the channels are quite progressive and slow. They move continuously as a result of erosion and deposition processes at a time scale of months and years. The sediment transport is rarely in equilibrium with the sediment transport capacity of the flow. The actual transport depends on the available sources of sediment.

In the overall sediment budget of the Westerschelde, the average input of sediment may be considered as negligible, compared to the actual movement of sediments inside the system. Though there seems to be a consensus about an internal circulation of sediment, there are different opinions about the way it happens. In the cell concept, developed by Delft Hydraulics, the circulation of sediment is estimated from sediment transport formulas. These formulas were established for stationary flow conditions and provide the solid discharges in the hypothesis that the transport capacity is transporting fully available sediment. The models do not consider a sorting of the sediment particles by size, although river bed data show a heterogeneous spatial distribution of the median sediment size and silt content all over the Westerschelde (Fig. 2.5-03 & 04). Sedimentation in quiet flow zones may create consolidated sediment, less easily eroded than the medium size sediment transported and deposited in active flow zones.

A free lateral - and thus also vertical - changes in tidal channel layout are hampered by the presence of man-made hard points, like dykes, groynes, levees, etc. Differences in erosion resistance of the bottom sediments because of the size distribution variation influence these channel movements. However, the channel bottom and banks may be composed of geologically older materials that may have a still stronger resistance to erosion; these are called the geological controls.

2.5.2 Geological Control of Estuarine Morphodynamics

From maps showing the positions of banks and channels during the period 1800 to present it appears that there are areas through which the channels have not migrated. The question arises as to whether these areas have not been "cycled" because of the morphological and positional envelope of channel form or because they are composed of older materials which are resistant to erosion, thereby limiting or inhibiting channel migration. Presence of clay layers in the bottom of the Westerschelde has been reported (Fig. 2.5-05)

It would not be unusual or unexpected for some significant topography to have developed during low or high stands of sea level. It is known (personal communication from dredgers) that in channel reaches such as Borssele, the steep channel walls are formed in cemented materials and that various deposits having significant erosion resistance occur at levels higher than the target channel depth of - 14 m. Geological investigations might give a clue about the age of this bottom material, possibly older deposits from an earlier sea transgression and their surface morphology developed during other sea levels. In these circumstances the morphological evolution may be determined by the "topography" and properties of any erosion resistant sediment as much as, or in some cases possibly more than, hydrodynamic processes and sediment transport.

2.6 Relationship with the Vlakte van de Raan

The Vlakte van de Raan was for long considered as lying outside the Westerschelde; Vlissingen - Breskens was the sea boundary of the estuary. In a study report for the model North Sea - Schelde Estuary (Peters & Sterling, 1976), a first attempt was made to analyse morphologically the interaction between the Vlakte van de Raan and the Westerschelde. Nowadays, this interaction between the two areas is considered as important. However, management of the two areas is not yet well integrated.

Until the early nineteenth century, the area seawards of Vlissingen continued to have a strong marine character, with the Flemish Banks extending from the French border into the mouth of the Honte. Several channels conveyed the tidal flow in and out the estuary. This was the end phase of a long term morphological evolution, during which the Schelde river flow changed its discharge point, first into the Meuse in Roman times (2 kyr BP), then in the Oosterschelde (1.4 kyr BP) and finally in the Honte (1.2 kyr BP) (Coen, 1988). Maps from 0.7 kyr BP (Fig. 2.6-01) reveal the complexity of the channel system - sea branches - in what at that time remained of the lagoon. Until some 1000 years ago, the morphology of the Honte was complex, shallow and presented a high resistance to the tidal flow. The currents entering and leaving the estuary in Vlissingen remained limited, as compared to what occurs today. However, as the tidal range at the mouth of the Honte was larger than the one at the mouth of the Oosterschelde, the scouring enlarged progressively the Honte sea branch. The tidal prism in the Honte was initially small, but increases progressively when tides intruded further in the widening channels. When the Honte became sufficiently enlarged, it took over the Schelde river flow and tides intruded still more easily. This enhanced the exchange of sediment between the Westerschelde and the Vlakte van de Raan, that became the outer estuary. The charts of the Westerschelde (Fig. 2.2-02) show that the entrance of the estuary has evolved significantly. The lay out with the sequence of Flemish Banks penetrating towards the bottleneck Vlissingen - Breskens has been progressively replaced by a complex of banks which now make up the Vlakte van de Raan.

2.7 Dynamic Equilibrium

A central aspect of contemporary morphological study is the concept of "dynamic equilibrium". In this concept a property, condition or variable can fluctuate randomly, or periodically, about a notional mean condition or value such that the average value of the property, condition or variable, taken over an appropriate timescale, does not change. For the Schelde Estuary the minimum appropriate timescale may be the 18.6 years of the nodal cycle or several such cycles (e.g. 37.2 or 55.8 years).

In respect of the morphological development of the Schelde Estuary a number of issues need to be addressed in this context and these can be examined as 2 sets of questions.

Question A. If the morphological equilibrium is the result of hydrodynamic forces and the resulting sediment transport:

- A1. Is the system constrained or free to change?
- A2. Are the various forcing functions in a state of dynamic equilibrium or stationary over a "long period"?
- A3. Is the response of the morphology in equilibrium with the forcing or does its response lag, and does this lag vary with the rate of change of the function?

Question B. If the morphological equilibrium involves the movement of sediment and its redistribution within the system leading to morphological change:

- B1. Is the total quantity of sediment in the system constant?
- B2. Is the redistribution of sediment within the system constant?
- B3. What is the timescale of the redistribution and thus the morphological response? (See A3).

A.1 : The channel/bank systems of the Schelde appear to have permanent components, areas of bank through which the channels have not migrated. Are these hard spots which exercise a deterministic and limiting influence on morphological change? Some channels are now deeper than they have ever been and have shapes and side slopes not consistent with their being formed in erodible sediment. Anecdotal evidence indicates that some channels are formed in cemented sediments.

There is thus a clear possibility that parts of the channels and banks are not free to be changed by hydraulic and hydrodynamic processes and as such do not constitute an “equilibrium” system but are, in part at least, a fixed system. In other places historical records indicate that the geology and bank protection unquestionably form fixed controls.

A.2 : The main forcing function is the tide. Tidal characteristics vary on 18.6 year and shorter cycles. However, the sea level is rising in a non-equilibrium manner. More than this however, observations show gross changes in important tidal variables (range, asymmetry, phase, etc) in a non-cyclical way over time-scales longer than the nodal cycle. On this basis we suggest that the basic dynamic forcing within the system is not in a state of equilibrium and as such we are concerned that any morphological management strategy based on an assumption of dynamic equilibrium may be unsound.

A.3 : The response of any material, or by analogy a system, to a forcing or stress may be characterised by the ratio (D_e) of the relaxation time of the system to the period of the stress.

For example, in the case of simple materials, where $D_e << 1$ the material is a fluid, where $D_e >> 1$ the material is a solid. In the case of estuarial sediments, the individual sediment particles respond instantaneously to the contemporary fluid forcing. However, the residual movements of the sediment leading to erosion or sedimentation respond to the longer scale cycles. The erosion of some sediments may respond only to extreme events. Un-erodible sediment does not respond. There is thus a variable hysteresis in the response of the sediment population to the hydrodynamic forcing and there is, as can be expected, an unknown and unpredictable lag between any changes to the hydrodynamic forcing and the response of the morphology resulting from sediment erosion, transport or deposition. However, this does not invalidate the concept of dynamic equilibrium if the forcing is in dynamic equilibrium. It just means that the prediction of the equilibrium morphology is very difficult. Nevertheless, if, as is shown by observation, the forcing function is not in dynamic equilibrium, then neither will be the morphology. For these reasons we do not consider that the morphology of the Westerschelde should be assumed to be in a state of dynamic equilibrium on any practically relevant timescale.

Turning to the question of sediment budgets posed in Question B:

B.1 and B.2.

The determination of sediment budgets, which may be regarded as the net import or export, gain or loss, of sediment in an area is notoriously difficult, especially in circumstances of reversing flow and lateral differentiation of longitudinal transport. This is exacerbated in regions where the main transport vectors rotate with channel meandering, where lateral transport occurs (as is the case in most three-dimensional flow systems) and where the net transport is estimated as the difference between 2 large quantities determined with only poor precision.

At present we have been unable to identify any observations or computations of net transport of sediment accompanied by estimates of uncertainty. As such we consider that the condition of the system with respect to the increase or decrease of its sediment population is unknown.

B.3. There is yet no systematic, quantitative and audited assessment available of either natural or anthropogenic redistribution of sediment within the system and its associated morphological change. Surveys are infrequent and related to specific locations. System wide charts rely on data collected over several years rather than being reasonably synoptic (e.g. period of 1-3 months). No systematic seasonal comparisons, even of sensitive or dynamic areas, are available.

In considering these 2 groups of questions we conclude that:

1) The assumption of dynamic morphological equilibrium is not justifiable on the basis proposed here, though it may provide a basis for exploring the possible application of one type of management tool.

2) The assumption of dynamic equilibrium cannot be established for the sediment budget which is not adequately documented, either on a system wide basis or for areas within the system. This is a crucial gap in information.

2.8 Summary

As a result of the continuing, fluctuating, rising sea level and the geological, geomorphological and sediment transport processes related to it, the area of what is now the Westerschelde Estuary has experienced, and continues to experience, a continually changing pattern of tidal hydrodynamics and related morphological development. This naturally changing development is still ongoing and in certain facets, such as tidal characteristics, changes are more rapid than outside the estuary system. It is evident that the present morphology of the estuary is not just a product of sediment transport but is influenced by geology and human actions. Although the relative importance of these influences is quantitatively undefined, from first principles the effects of poldering would be expected to produce the observed changes in the tidal regime. It is considered that the morphological evolution of the Westerschelde is also linked to the evolution of coastal areas such as the Vlakte van de Raan. Whatever morphological management strategies are developed will have to take into account the continuing dynamic nature of the system, its links to other coastal systems and its links to the rest of the Schelde catchment. As a consequence of the continuing changes in morphology and tidal dynamics, it is evident that in terms of safety from flooding, the conservation or improvement of navigation and the sustainable management of the environment, a “do nothing” or “keep things as they are” management strategy for morphology and ecology is neither a viable nor a sustainable option.

3 DREDGING AND ITS INFLUENCE ON THE ESTUARIAL DYNAMICS

3.1 General Comments

Information about dredging works in the Westerschelde is available in several documents. The expert team acknowledges the uncertainties in the data found in different reports. These uncertainties have little influence on the assessment to be made of the impact the works have on the estuarial morphology and ecology. However, in view of a the future management of the estuary, the team advises the creation of a unified Belgian-Dutch data base, with thorough data quality control. Nevertheless, it is realised that there will always remain uncertainties, linked to the nature of the dredging activity, either for deepening and widening of the channels, or for sand mining.

The team realises how difficult it is to get a clear picture of the relationship between dredging effort and navigation depth. Many factors intervene in the process, especially the self-scouring capacity of the flow as related to the morphology of the Westerschelde. A section on dredging efficiency in relation to morphology is included in the Addendum.

One of the key questions which has to be addressed is :

> "Is it feasible, with the available information, to draw some conclusions about the impact that dredging and dumping have on the morphological changes of the Westerschelde?"

Another question which the team consider relevant is:

> "Can dredging and dumping be used as a tool to influence morphological evolution with the objective of making the morphology "healthier", i.e. preserving or enhancing the ecological value by increasing morphological diversity, reducing the risk of inundation and optimising the dredging, so that larger depth can be obtained with the smallest possible dredging volumes?"

One poorly understood element is the relationship between morphology (mainly the plan-form), the dredging and the elevation of crossings. During a World Bank funded project on the maritime reach of a large alluvial river, the team leader was asked to establish the requirements of dredging equipment for a given target navigation depth. The study revealed that, for about 90 years of observations, the relationship between the navigation depth achieved for a given dredging effort and the volume of dredged material to be removed was mainly determined by the self scouring (auto-dredging) capacity of the river. The plan-form shape of the channels was a key element. However, sediment over- or under-loading of some reaches played an important role. This kind of analysis was not in the assignment of the expert team, though it would have been very useful and should certainly be a part of any future management plan development.

3.2 History of dredging in the Westerschelde

The dredging activities for improving the navigation conditions in the Westerschelde started at the end of the 19th century (Fig. 3.2-01). Initially, maintenance dredging was mainly needed in Belgium. After 1927, dredge sites were also found in The Netherlands, upstream of Hansweert. Since World War II, the volume of sediment dredged in the Westerschelde (capital and maintenance) increased steadily, from about 2 million cubic metres in 1945 to about 8 million at the end of the sixties. The dredging locations extended progressively seawards, reaching the bottleneck area of the estuary between Vlissingen and Breskens in 1973, with the dredge site of Borssele.

The navigation depths increased progressively with the deepening of the crossings. The percentage figures pre 1920 are based on very small volumes, often zero, and so small changes produce large percentage fluctuations. In 1970, at the start of the first intensive deepening programme, the Port of Antwerp was accessible for ships with a draught of about 13 m. At that time, the volume of material dredged annually in the Westerschelde reached a maximum of more than 16 million cubic metres, about half of it in Belgium. During the 1971-1976 deepening programme, the share in Belgium of this volume decreased to about 20 % (Fig. 3.2-02). Consequently, the volumes dredged between the Dutch-Belgian border and the sea have since become by far the largest. In the period 1971-1976, the crossings downstream of the Zandvlietsluis were deepened by 1.5 to 2 m. It is interesting to note that the steady trend after the deepening programme shows an increase of draught and a decrease of volumes dredged. The dredging efficiency obviously plays an important role in this evolution, but it is worth analysing the role played by the continuing alteration of the Westerschelde's morphology, exemplified by the significant change in the channel configuration between Terneuzen en Hansweert which occurred at the end of the sixties.

The deepening programme performed at the end of the nineties implies a larger dredging effort. It will be interesting to observe the further trend, either a reduction in the dredging effort or an increase of the volumes to be dredged for maintaining the new target depths.

Until 1924 the sediment removed from crossings was initially used as land fill material. After that, the percentage of sediment dumped back in the river increases, mainly in the Dutch part. The strategy adopted until recently was to dispose as much as possible of the dredged soil in secondary channels, mainly in flood channels. The morphological impact of this strategy is stronger in the wide multi-channel system in the Dutch part - the sea branch - than in the much simpler Belgian part.

The modelling performed in LTV with a "cell" model leads to the conclusion that the "overloading" of the flood channels will make them die. The expert team worked out the data about volumes dredged in the various cells. Details are given in the Addendum. The variations of these volumes between 1961 and 1997 shown that before 1970, dumping was negligible downstream of Hansweert (cells 3 and 4). The significant morphological changes were natural. Large volumes were dumped in cell 5 from the end of the sixties, in either flood or ebb channels. This increased with the first deepening programme 1971-1976 and was said to have resulted in over siltation of the flood channels. The expert team believes that the morphological changes were mainly due to natural factors, as explained in the Addendum.

Models were used in LTV for determining the maximum quantities that may be dumped in a given "cell". As is documented in the Addendum, these allowed quantities were exceeded over several years in more places, without resulting in a degradation by siltation. In this context the expert team considers that the models do not provide a secure basis for the development of management strategies. Recommendations based upon these model concepts should not be regarded as dependable.

The team proposes that a comprehensive study of the morphodynamics of this area and the application of alternative dredging strategies for morphological management in this area should be made as explained in Section 4.5.

3.3 Tidal parameters since 1938

Previous analyses of tidal data have examined gross, long term changes over the period 1880 - 1990. It is of interest to examine similar tidal parameters in more detail during the period from 1938 to the present, when more significant dredging was performed for improving the access to the Port of Antwerp, and for sand mining. At this time only tidal data averaged over 10 year intervals is used. These data are not synchronised with particular parts of the nodal cycle and so some process related aspects may be obscured. Further work on this is needed.

Dredging activity comprises:

a) Capital and Maintenance dredging with relocation of material within the system.
b) Capital and Maintenance dredging with removal of material from the system.
c) Sand mining with removal of material from the system.

The rates of change of six tidal parameters, Mean High Water, Mean Low Water, Mean Tidal Range, Mean Duration of Flood, Mean Duration of Ebb and High Water Interval from Vlissingen have been examined using data supplied by Ministerie van de Vlaamse Gemeenschap, Antwerpse Zeehavendienst. For Vlissingen, Terneuzen, Hansweert, Bath, Hedwigpolder-Prosperpolder, Lillo-Liefkenshoek and Antwerpen, for each tidal parameter, the gross mean annual rate of change was estimated by calculating the difference between 10 year data blocks, assuming this change took place over 10 years. Negative values indicate a reversal of trend. The results are shown in Figs 3.3-01. to 3.3-06. Also shown are the actual curves of change. These data should be compared with the curves for dredging, (Figs 3.2-01 to 03 in Section 3.2). The onset of the major dredging campaigns in 1970 is shown by the vertical white line on the graphs.

3.3.1 Mean High Water (Fig. 3.3-01)
In the baseline report it was noted 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 300 m per year. The increasing asymmetry of the mean high water profile is also evident in Fig B.1. of the Baseline Report. However, although the changes are consistent as noted, and for all locations, the height of high water increases steadily, though with small fluctuations, the rate of change is relatively steady throughout the period considered. Some locations appear to show fluctuations around 1970, others show fluctuations throughout the period.

3.3.2 Mean Low Water (Fig. 3.3-01)
The heights of low water were not evaluated in the Baseline Report for the reasons of variability. Trends are both up or down depending on location though there seems to be a sudden but apparently temporary drop in level after 1970, visible on the data for the periods 1970 to 1980 and 1980 to 1990. For most locations the rate of change is variable, but some inflection occurs between the 1960-1970 and 1970-1980 data blocks. These are the effects of single data points and there are some points which may be in error. The 1980-1990 data blocks appear to fall back within the envelope of pre 1960 data. The change in 1970 can have more than one explanation. On the one hand a natural morphological change in the flood and ebb channel system “Middelgat - Gat van Ossenisse”, which resulted in much wider channels and lower crossings, so that the ebb flow was eased. On the other hand, the deepening by dredging of the navigation channel, that made the crossings deeper so that the main channel could easier convey the water at the lowest tide levels. Both modes of change - the natural and the anthropogenic - have happened in the period 1969-1975.

3.3.3 Mean Tidal Range (Fig. 3.3-02)
The studies undertaken for the Baseline Report revealed 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 Amands by 1981/1990, a distance of the order of 44 Km, a mean rate of more than 400 m per year. The studies suggest that the changes are more variable in the short term and that 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. From Prosperpolder the mean tidal range appears to have increased most strongly since the 1950 to 1960 period. In the results of the present study, the curves for each location are different. Terneuzen, Bath, Lillo-Liefkenshoek and Antwerpen, show a peak in the 1970-1980 data block but the 1980-1990 data point returns to the pre 1970 envelope. Vlissingen is quite different showing a peak in the 1950-1960 data block, a trough in 1960-1970 data block and a return to the pre 1950 envelope in 1970-1980 and 1980-1990. Hansweert shows a drop in the 1980-1990 data block compared to the pre 1980 data. Of the long term data sets, Bath, Lillo and Antwerpen show marked increases in tidal range after 1950.

3.3.4 Mean Duration of Flood and Ebb Tide (Fig. 3.3-03)

This parameter was not evaluated in the Baseline Report because of the many factors which can influence it. The various effects which may influence the time of low water and high water lead to greater variability in these data. In the analysis of the rate of change in Flood Tide duration no estuary wide trend is clear. Some locations, Vlissingen, Terneuzen, and Hansweert, show steady or slightly declining trends, others show marked reductions to a minimum in 1960-1970. The rates of change are very variable.

3.3.5 High Water Time Interval (Fig. 3.3-04)

In the baseline study it was shown that the time between high water at Vlissingen and other locations has decreased during the period of the data. The tide propagates at a greater speed. However the annual rate of change is variable throughout the period of data. Small changes in observed interval have a dramatic effect on the graphs. There is some indication that the rate of decrease has slowed but the data needs further quality control.

3.3.6 Discussion.

The onset of major dredging campaigns in 1970 is marked by the white vertical line on the illustrations. In some graphs there is a coincident excursion in the data points. In others there is an excursion prior to the onset of the dredging campaign. In others there is no evident effect. For some parameters the excursion seems to be temporary with recovery by 1980. Comparison of these data with records of dredged volumes (Fig 3.2-01) does not show any clear correlation between the estuary wide trends or rates of dredging and the patterns of changes in tidal propagation parameters relevant either to safety or navigation. Further, more detailed, analysis is needed.

3.4 Summary

Comparison of available dredging data for the period 1895 to 1997 with various tidal propagation parameters for the period 1880 to 1990 does not reveal any significant changes in the trend, or rate of change, in tidal parameters which can reasonably be attributed to the dredging, especially to the dredging campaigns of 1970 and 1995. In that the tidal propagation parameters within the Westerschelde are believed to be linked mainly to morphological changes, in a feed-back type of system, it would appear that the scale of dredging has been such that it has, so far, not perturbed the overall morphological changes, and there-by changed the overall characteristics of tidal propagation, beyond what has occurred “naturally” during the previous 100 years or so. Possible exceptions to this are apparently temporary effects on the rates of change of Low Water levels and apparently temporary effects on the rate of change of High Water time interval although these seem to have returned to pre 1970 levels by 1980/90. More detailed investigation of these issues is needed.

4 FUTURE DEVELOPMENTS

4.1 Objectives

The principle objectives of future development should be to:

- Ensure the safety of the areas surrounding the Schelde Estuary and the safety of users of the estuary.
- Ensure the continued sustainable use of the estuary for navigation and commercial benefit
- Ensure the sustainable management of the environment of the estuary.

4.2 Management Methods and Tools

The present system of management is focussed on navigation. It relies on processes of relocation of sediment within the system by dredging crossings ("drempel") and dumping in a variety of locations. There is no integration with other dredging activities and no coordination of dredging with ecological management goals.

There is a widely held consensus that in the absence of any dredging activity the Westerschelde would evolve to a single channel system. The principal objective of the LTV study is to identify strategies and methods which will allow management of the system to satisfy the requirements for Navigation, Safety and Environment. The consensus mongst technical specialists is that this is best met by a multichannel system.

It is, therefore, necessary to have access to management tools which will allow the prediction of the effects of particular actions in order that management strategies may be designed and specified to achieve sustainable management. It is our view that no single tool can provide all the necessary answers and that the tools used must be based upon a reliable understanding of the system, the way it works and the factors which govern its morphological evolution since morphological diversity is basic to ecological diversity.

Two main groups of management approaches may be identified:

1. Predictive Simulations
These tools include numerical simulation of flows and sediment transport, schematised numerical simulations of the morphological evolution of spatial units and physical simulations of channel or bank sectors. They are based on data analysis and observation, assumption, wide ranging simplifications, other models and experience. In this approach, the essential management tool is the morphological model. However, there are several natural aspects of the system which we believe make complete or even substantial reliance on such tools as inadvisable.

These may be summarised as follows:-

- Morphology and morphological development does not depend solely on hydrodynamic and sediment transport processes but is influenced, possibly in key places, by the geology of the area.
- The morphological boundaries of the Westerschelde system, the dykes, sea walls and training structures, mean that there are non-natural limits and non-natural components in the morphology determining mechanisms.
- Management tools based on assumptions of dynamic equilibrium do not take into account the non-stationarity of hydrodynamic forcing or the long term effects of such processes as poldering or land creation on the tidal dynamics of the system. This is further complicated by the expectable hysteresis in the morphological response of the system to changes in tidal dynamics which makes model calibration and validation extremely difficult.
- The various components of the simulation systems have unknown uncertainty due to uncertainties in sediment transport calculations or observations. In particular it is not known if the system as a whole, and especially the Westerschelde (Breskens/Vlissingen to, say, the Dutch-Belgian border) is gaining or losing sediment. This is a key aspect of the overall system development and in the view of the expert team casts very serious doubts on the LTV proposal that sediment from crossings should be relocated seaward of a Breskens-Vlissingen line rather than within the Westerschelde estuarine system.

2. Field Observation and Experimentation.

Many workers experienced in field observation of fluvial and estuarial phenomena are also users of numerical simulations and so recognise the difficulties faced by simulations due to the complexity of the natural system. They recognise the limitations on the reliability of field observations of sediment transport as much as the uncertainties in simulations. Nevertheless field observations, which include bathymetric data, flow and sediment transport observations, observation of the patterns of bed-forms or the internal structure of sand banks, channel walls, crossings, etc, provide crucial information on what actually occurs as opposed to what would happen according to theory. These types of field observations form the basic platform for any understanding of the mechanistic framework within which morphological development occurs. Direct observation is now possible with a degree of resolution, sophistication, convenience, economy and versatility not imagined 20 years ago. It offers a greatly improved method of understanding morphological processes and checking the validity of simulations.

This surge in observational capability brings into realistic reckoning the use of carefully designed experiments to test essential hypotheses regarding such factors as time-scales, spatial-scales and intensity of sediment transport, dispersal of material dredged, changes in bed morphology on model time-step scales and the monitoring of the local morphological impact of particular relocation methods and programmes. The great advantage of such observations and experiments is that all processes and process scales are included. No variables are omitted or simplified.

For these reasons we believe that management methods need to be evolved using a combination of field observation and field and laboratory experimentation in combination with numerical or physical simulation and morphological analysis and interpretation. These approaches need to be placed in the context of experience in the study of natural systems. Indeed, the difficulties faced by modelling requires the best possible understanding of the morphological changes. Therefore, experts from different disciplines must collaborate. As an example the expert team emphasises that very little has been done in the past with the available historical information to clarify the detail of the evolution of the Westerschelde morphology during historical and archaeological times.

4.3 Management of the Contemporary Situation

The deepening to 14 m completed in 1997 represents the latest in a series of non-natural morphological developments. There is a consensus technical view that the system will evolve towards a single channel system, which, it is believed, will have serious adverse consequences for safety from flooding and ecology and so there is a need to institute an integrated sedimentation management strategy designed to maintain a multichannel system. This requirement exists independently of any proposals to deepen the channels in the Westerschelde. The proposal for adoption of a "do nothing" or "keep things as they are" management strategy is unsustainable in the context of the observed trends in estuarial evolution. The study and other recommendations presented below (Section 5) are necessary whatever the decision regarding deepening.

4.4 Role of Depoldering

Poldering has been progressive. Natural levees were elevated and consolidated by the local people. However, the history of poldering consists in a process of building levees which could be breached during flood or storms. The process of losing land, reclaiming it again and building other levees was repeated many times. Together with the cutting-off of secondary channels, it produced in the Westerschelde a morphology which was a complex series of interconnected sea branches. This evolved towards an estuary whose geometry conveys the tidal flow better than before. However, the natural trend made the shoals and bars silt up and main channels deepen. In the absence of a further increase in tidal amplitude with time, the tidal prism would have decreased. This would have reduced the tidal "pumping", leading the Westerschelde to evolve towards a single channel system. Fortunately, the steadily deeper penetration of tides into the estuary and the increase in tidal amplitude in the Westerschelde, compensated for the loss of storage by siltation. Land reclamation by poldering was reducing the storage area - not the volume - since it enhanced the tidal intrusion.

Some measures were proposed to alleviate the increasing flood risk associated with the stronger penetration of the tidal wave. Depoldering is one of these. Recently, reconnecting the Oosterschelde to the Westerschelde was also considered, but only for the highest flood levels, effective mainly during extreme storms.

Some areas selected for depoldering were secondary channels which had been cut-off (Fig. 4.4-01). This might seem logical, but meanwhile, the active channel lay-out has changed and there is no special reason for not depoldering at other places. Depoldering should be considered not only to increase the flood-water storage area, but also for modifying the lay-out of the levees. Doing so would influence the flow and sediment pattern, correcting in some places the plan-form of the Westerschelde, where it has a negative impact on the development of the channels. This depoldering is to be considered where the Westerschelde has its typical multiple channel system, in Dutch territory. Depoldering in the Belgian territory would have as its objective fluvial flood water storage, rather than changing the way levees guide the flood flow. This measure must be studied in a morphological perspective which is more than just flow and sediment transport.

4.5 Alternative Dredging Strategies

It is the view of the expert team that hitherto dredging in the Westerschelde was organised with no or limited interest for steering the overall estuarine morphology. Dumping sites were selected on the basis of the changes in the local morphology, favouring the disposal of dredge material in secondary channels, mainly the flood channels.

For the reach between Hansweert and the international Dutch-Belgian border, it has been written in the LTV reports that the larger volumes dumped in the flood channels after 1970 resulted in the dying out of these flood channels. In a meeting between LTV Cluster Morphology and the Port of Antwerp the expert team, it was agreed to discuss the evolution of that area. The comments presented hereafter are detailed in the Addendum.

Without challenging the idea that dumping large amounts of sediment in flood channel may have this effect, the team came to the conclusion that one of the likely reasons for these flood channels to become less active was the morphological changes in the reach between Terneuzen and Hansweert. Indeed, by the end of the sixties, the Overloop van Hansweert opened completely, making the Gat van Ossenisse the flood channel instead of the Middelgat. With the fixed points controlling the morphological changes in that region - among which are the protruding jetties of the harbour of Hansweert - this evolution oriented the flood flows more towards the Plaat van Walsoorden. The seaward tip of this bar has regressed progressively, so that, after passing Hansweert, the flood flow enters into a reach where the flow loses its erosive power because of an expansion in the cross section (Fig. 4.5-01).

The alternative relocation strategy would aim at reshaping specific areas in which morphological changes are evolving towards a less favourable lay-out such as, for example, a reduced self scouring of the crossings or the dying out of important secondary channels. In the case of the reduced activity of the Schaar van Waarde and Schaar van Valkenisse, the Plaat van Walsoorden needs to be developed so that it could make a better bifurcation of the flood flow, guiding enough flood-water towards the flood channels. This strategy requires a programme of careful investigation and monitoring, more sophisticated than the present data acquisition programme.

Dredged soils are presently disposed by hopper dredges in deep channels. In the alternative strategy, the sediments would be partly disposed in shallow water, so that other equipment would be needed. The sediment would be removed from the hopper by means of a floating line and brought to the disposal site. The technique is perfectly feasible technically, and would need to be assessed economically. However, the ecological (morphological) benefit needs to be considered when establishing the cost/benefit ratio.

4.6 Reversibility

The new, alternative strategy must be tried out and an obvious question concerns the reversibility of the process, in case the morphological changes would appear to be negative. This issue merits careful consideration. It must be clearly placed in the context of leading the Westerschelde towards a more favourable morphological situation, in terms of safeness and naturalness. The advantage of recurrent measures (soft engineering) versus training works (hard engineering) is that the recurrent measures are adjustable and reversible. Hitherto, morphological management decisions regarding coastal plain estuaries like the Westerschelde have favoured hard engineering solutions like training works whose long-term impact is uncertain. Some groynes or spur dykes were designed on the basis of model tests with the morphological situation of that time. Due to morphological changes they act now in a very different situation. From the analysis made by the expert team, it appears that some of these training structures have today a negative impact on the morphological development but changing or removing them does not appear to be considered. This aspect should be included in future strategic considerations.

A key facet of future management is the initiation of a comprehensive monitoring programme. Comprehensive does not mean expensive, and the data acquisition must be well thought out. The expert team believes that this kind of monitoring is not only needed but is both economically and technically feasible, cost effective and beneficial.

4.7 Possibility for Further Deepening

Due to natural processes, the navigation depths in the Westerschelde have increased over the past millennia, as the tidal wave penetrated further and more easily inland. This trend was enhanced by reducing the lateral mobility of the channels in the estuary by poldering, bank protection and cutting off secondary channels. Due to the lack of reliable historical data, it is not feasible to make an accurate estimate of the evolution with time of the natural depth on the crossings. It would none-the-less be worth making a semi-quantitative analysis of available bathymetric data.

The evolution of the first significant deepening in the early seventies is documented. The available information should be analysed morphologically, i.e. assessing the result of deepening by dredging with the lay-out of the channels and bars. Such an analysis is needed to get more insight in the sediment transport mechanisms and either confirm or negate the opinion shared by many specialists of the Westerschelde that deepening of the crossings as such would not influence negatively the ongoing trend, the one that would occur anyhow, even without any dredging (the so-called "autonomous" evolution). Scientific opinion is divided about the impact of dumping the increasing amounts of dredge material, as would be required with a further deepening.

The studies conducted with models in Delft Hydraulics, discussed in the baseline report, lead to the conclusion that there are limitations on the volume that can be dumped in the secondary channels of the Westerschelde. The expert team expressed its reservations about the use of these models. Nonetheless, one idea put forward in LTV is to export the sediment to the North Sea. This implies a enlargement of the Westerschelde's geometry in the hypothesis that the estuary has very little input of sediment from outside. In the absence of reliable and quality assured evidence to the contrary, the export of dredge material seems dangerous and possibly harming the environment by degradation of the shoals, bars, slikke and schorre.

If export of sediment could lead to unforeseeable morphological evolutions, redistribution of the sediment within the estuary must be continued. Experiments on a new dumping strategy, such as the one proposed for the area between Hansweert and the Dutch-Belgian border, should be tested. If proved to be beneficial for halting or slowing down the ecological and morphological degradation of the Westerschelde, this strategy could then be tested on a larger scale.

A further deepening is feasible, if designed and conducted in the frame of a remodelling of the estuarine morphology. It should be designed with the objective of conserving naturalness, safeness and accessibility.

5 RECOMMENDATIONS

5.1 Data Review

The baseline study sought to identify the general framework within which the proposals for deepening should be examined. This study identified a number of primary issues which are fundamental to morphological management. This study also identified further areas where more extensive and more detailed data assembly, review and analysis is needed. These include:

- The geology of the Schelde Estuary (bottom and sub-bottom) as it may affect the ability of channels to migrate under purely hydrodynamic forces. This is basic to the viability of various approaches to predicting future morphology.

- A detailed analysis of the migration patterns of the channels to identify those areas which may not have been crossed by channel migration. This links with assessment of the geology of the estuary and other man-made hard points.

- An assessment of tidal propagation for the period 1948 to 1958 in an effort to detect any signal from the changes in intertidal volumes and distributions consequent upon the flooding of previously poldered lands in 1953. This exercise will identify the sensitivity of the system to losses in intertidal area and indicate the viability, or otherwise, of possible depoldering projects.

- The topographic evolution of the sea areas in front of the estuary narrows at Vlissingen/Breskens should be analysed. It is now generally accepted that the Schelde Estuary extends well westward from the previously considered limits at Vlissingen. The evolving morphology of this area is relevant to tidal propagation and to the overall sediment supply into the "middle" estuary between Vlissingen and Bath. No systematic and detailed analysis of the available data has been completed

- Sediment Type distributions. The morphological response will be influenced by the nature of sediment types, particularly lightly cemented or over consolidated sediments having resistance to contemporary hydrodynamic conditions.

5.2 Data Collection

A number of aspects of the system which require understanding suffer from the lack of basic data. These include:

- Hydrodynamics
  The degree to which transverse water surface gradients influence energy dissipation and may influence sediment transport is unknown since the patterns of water surface elevation is only known at the estuary margins. Modern survey techniques allow precise and very rapid evaluation of such factors.

- Sediment Budgets
  Some attempt must be made to establish whether or not the “middle” estuary is gaining or losing sediment, or is in balance. A careful programme of analysis and measurement needs to be undertaken to look at this issue which is fundamental to the management philosophy which may be developed.

- Patterns of Sediment Circulation
  There is little doubt that sediment moves around the estuary in a complex manner. The pathways followed by the sediment have been evaluated by a number of qualitative and highly theoretical methods. However, this factor is crucial to the development of management tools and the design of management strategies. This study will require a range of techniques to be deployed in order to first develop a qualitative understanding of the sediment transport pattern and subsequently a quantitative estimate of fluxes along key sectors. Such a study would underpin the whole of any morphological management strategy.

5.3 Monitoring

- Regular monitoring of both dredging areas and disposal sites is a basic input to all aspects of study.

- Annual estuary wide bathymetric surveys should be undertaken and completed within a period of no more than 2 weeks. This is possible using modern Lidar and Swathe Bathymetry techniques.

- Tidal observation and analysis should include Mid-estuary data points.

5.4 Studies

A comprehensive study programme is essential to achieve the best possible understanding of how the Westerschelde's morphology develops. Four approaches are needed:

- detailed analysis of historical records and data
- field investigations and field experimentation
- scale or physical modelling,
- mathematical or numerical modelling

Analysis of historical data should receive a high priority, starting with setting up an international data base, with a Geographic Information System.

The field studies are much more than the data collection for feeding the models, or than the monitoring needed to collect data for assessing the impact of works. They include field investigations for comparison with studies on historical data, acquisition of new data and specific experiments to test understanding of processes as well as check model concepts or results. The study work needs to be assigned to an international (The Netherlands & Flanders), multi-disciplinary team.

Field investigations should be started on areas of direct interest, such as around Vlissingen (for the new Container Terminal project) or Walsoorden - Waarde (for the selection of dumping sites). Modern field data acquisition tools need to be applied, amongst others, to measure data that are nowadays more often produced only by models:

- ADCP or OSCAR for current measurements (quantitative) and suspended particulate matter (qualitative)
- Remote sensing (satellite images, also radar images)
- Special float techniques for measuring surface flow pattern (DGPS positioning)
- DGPS together with tide gauges for longitudinal and transverse water surface slope measurements
- Sediment sampling, both suspended load, bed load and near bed transport, and sediment size analysis
- Sonar and seabed classification systems for description of sediment distributions
  sediment transport zones and relative sediment transport intensities.

This list is not exhaustive and needs to be discussed with the competent authorities.

Scale and numerical models should be used to visualise and analyse the typical three-dimensional flow mechanisms and the way they affect sediment movement. To start with, this can be done on a fixed-bed model, as the one existing in

Flanders Hydraulics. Special techniques may help analysing the distribution of shear stress in relation to the flow pattern. The scale effects induced by the distortion of the models have to be assessed carefully, but distortion as such may be acceptable for semi-quantitative investigations.

Numerical models need to be evaluated thoroughly. It might be useful to have more than one model used to compare results. Several two- and three-dimensional were developed in various European countries.

5.5 Trial of Alternative Strategies

Using appropriate data small scale tests of alternative management strategies for particular crossings should be planned and executed. This would involve both monitoring of the dredging and disposal, the related movements of sediments and changes in morphology.

5.6 Institutional Aspects

It is clear that morphological management has to be approached on an estuary wide basis and needs to integrate an appreciation of all the relevant activities in the system. This will need the full collaboration of all authorities having interests in the Schelde Estuary. An international collaboration between the Netherlands and Belgium must be furthered. The planned reorganisation in the Flemish administration opens new possibilities for improving the internal collaboration, setting up integrated data bases and conducting relevant studies.

6 CONCLUSION

Deepening the channel to Antwerp is feasible. To secure the aims of the LTV project it will require an integrated programme of study and monitoring. There are no technological barriers to monitoring relevant processes but there is a need to place existing or future morphological management strategies on a secure technical and factual base. This base would involve an understanding of the sediment transport in the Westerschelde system as a whole, which includes the Vlakte van de Raan, the integration of all sediment removal and relocation strategies into the morphological and environmental management strategy and the monitoring of existing and future procedures and effects.

Development of the management strategy will require the definition of targets for safety by the reduction in tidal levels, for environment by creation or redistribution of habitat and for navigation by optimisation of channel maintenance and all other dredging procedures and their integration into the morphological and ecological management processes.

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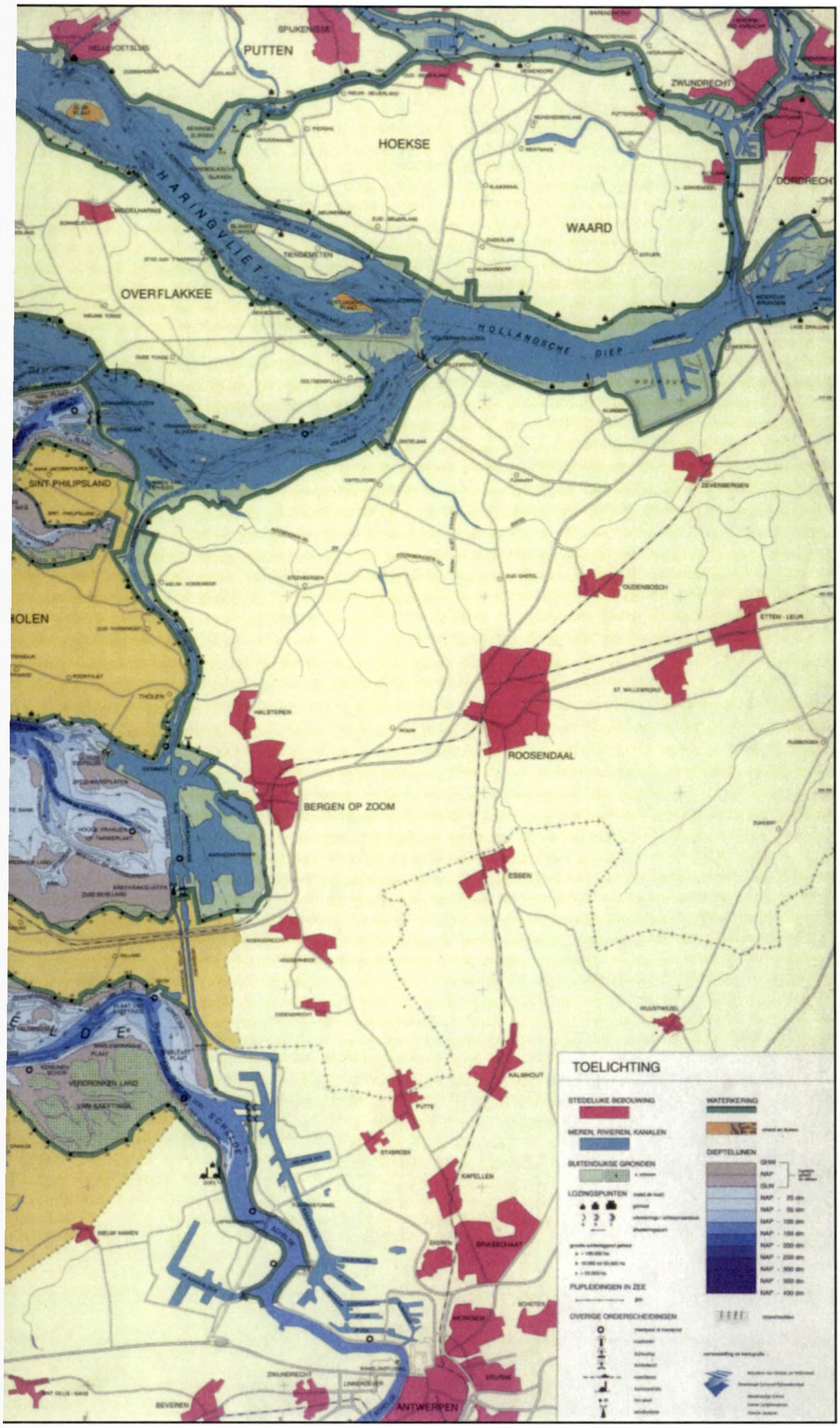
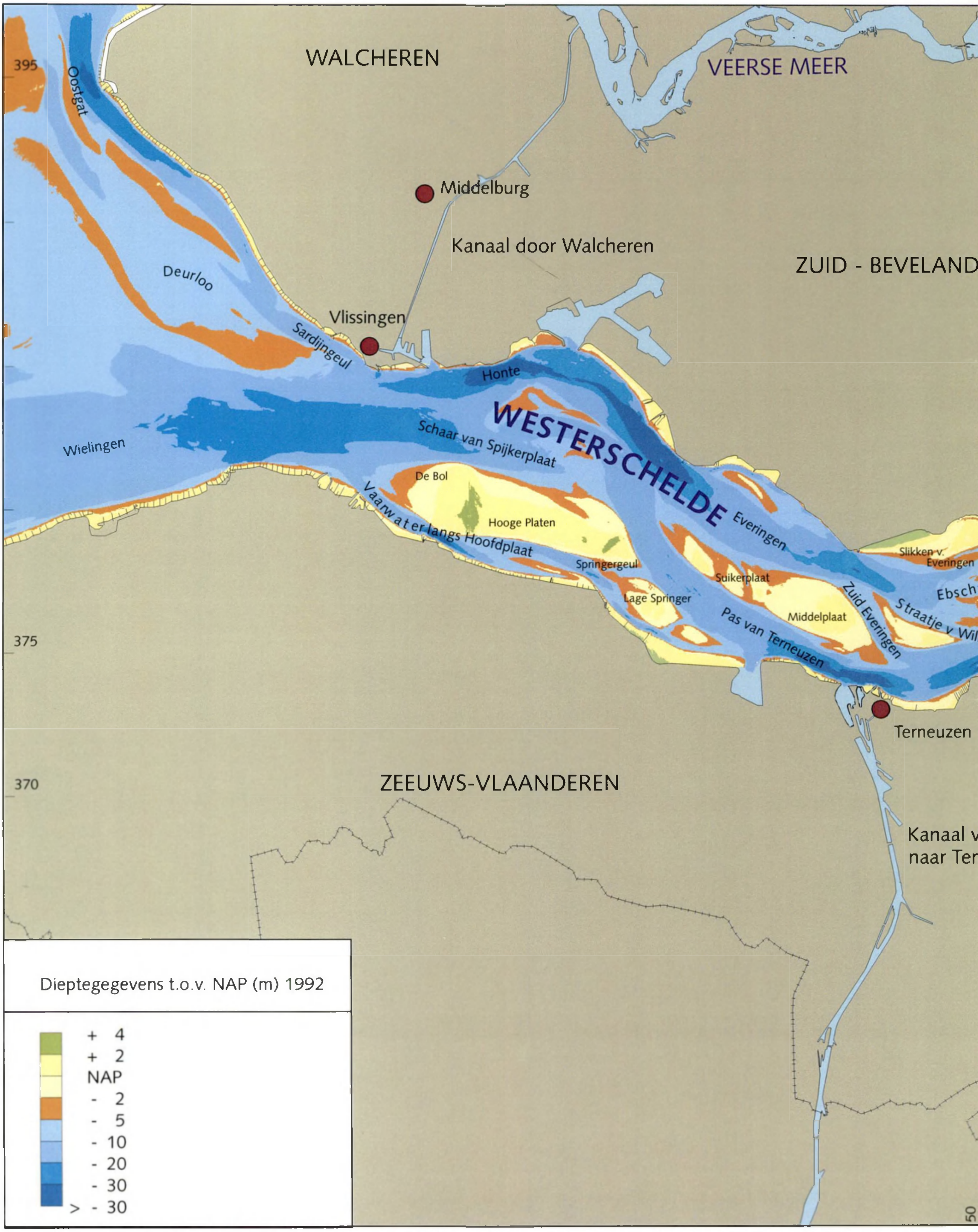


PUTTEN
SPIJKENISSE
HOEKSE
WAARD
ZWIJNDRECHT
DORDRECHT
HARINGVLIET
OVERFLAKKEE
HOLLANDSCHE DIEP
SINT PHILIPSLAND
THOLEN
ZEVENBERGEN
OUDENBOSCH
ETTEN - LEUR
ROOSENDAAL
BERGEN OP ZOOM
ESSEN
KALMTHOUT
KAPELLEN
BRASSCHAAT
SCHELDE
VERDRONKEN LAND
VAN SAEFTINGE
ANTWERPEN
TOELICHTING

0-01 The southern part of the Thine, Meuse and Schelde delta

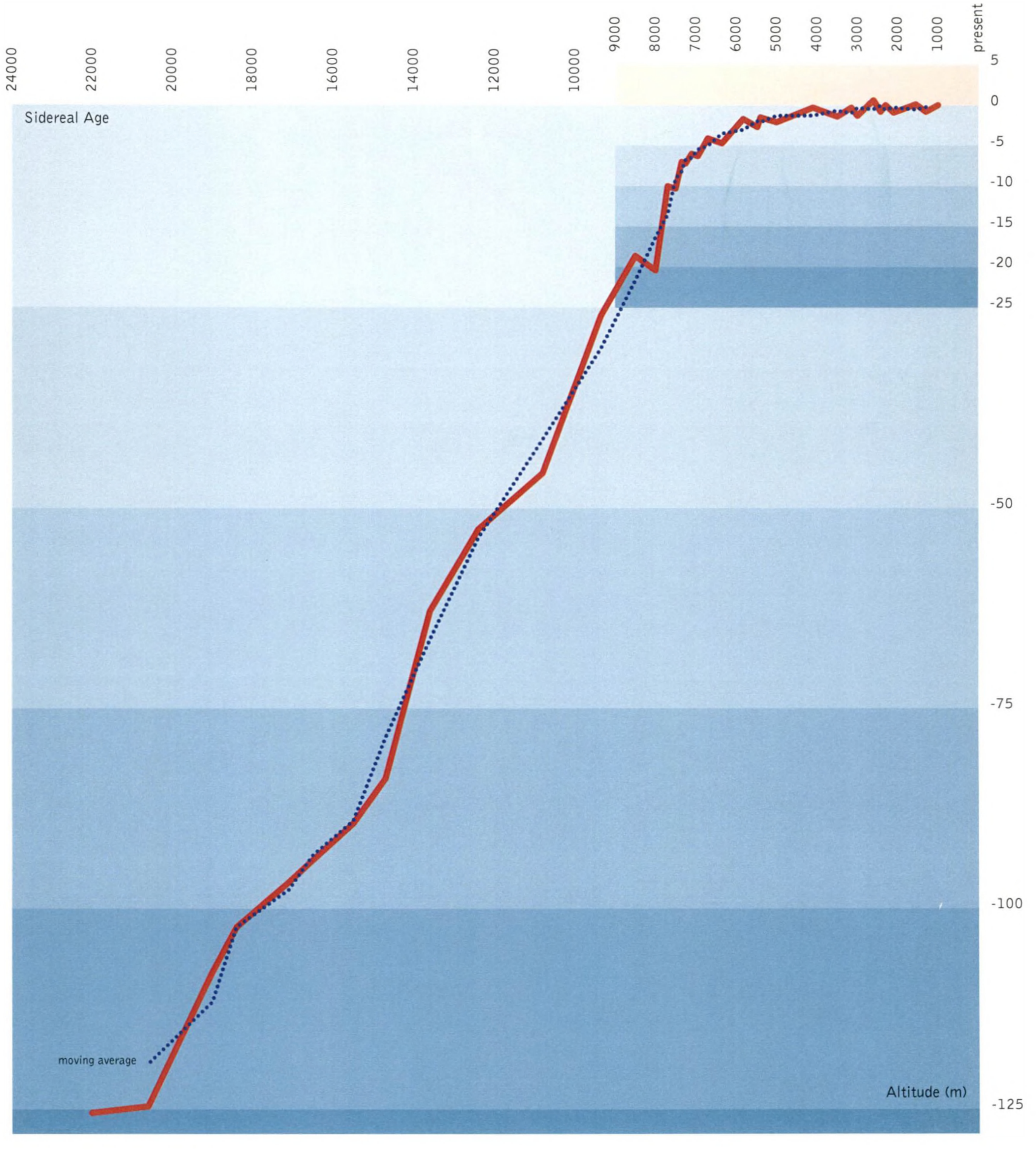
THOLEN
N
OOSTERSCHELDE
Kanaal door
Zuid - Beveland
Molenplaat
Put v Hansweert
Middelgat
Overloop van Hansweert
Platen van
Ossenisse
Schelde-Rijn Kanaal
Rug v Baarland
Schaar v Ossenisse
Schaar v Waarde
Schaar van Valkenisse
Geul Zimmerman
Nauw van Bath
Sch v d Noord
Appelzak
Pas van Rilland
Ballastplaat
Plaat van
Walsoorden
Platen van
Valkenisse
Zuidergat
Overloop van Valkenisse
Schor van
Baalhoek
Konijnenschor
Speelmansgat
Gat van Ossenisse
Platen van Hulst
Verdronken Land van Saeftinge
ZEESCHELDE
NEDERLAND
BELGIE
0
5
10 km
80

0-02 Topo-bathymetry of the Westerschelde, situation 1992



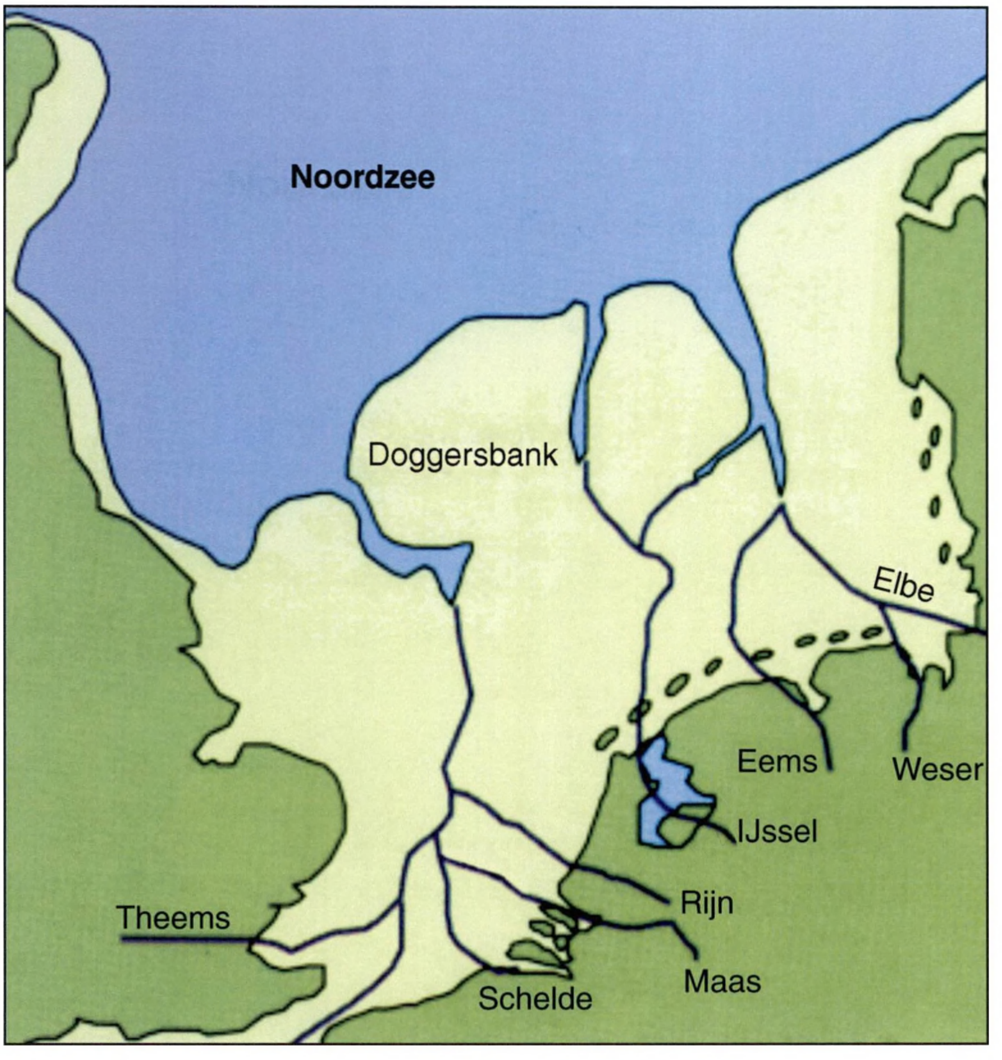
from figure 1A in De ScheldeAtlas, een beeld van een estuarium, 1999, Schelde Informatie Centrum

2.1-01 Eustatic sea level rise since 21 kyr BP



Data between -21 kyr and -9 kyr from SCHNEIDER R.R., E. BARD and A.C. MIX, 2000,
Last Ice Age global ocean and land surface temperatures: The EPILOG initiative, in IGBP Newsletter 43
Data between -8.5 kyr and -1 kyr from SHENNAN I., 1987, Holocene sea-level changes in the North Sea,
in "Sea-level Changes", ed. TOOLEY M.J. & SHENNAN I.

2.1-02 The North Sea at the end of the Pleistocene

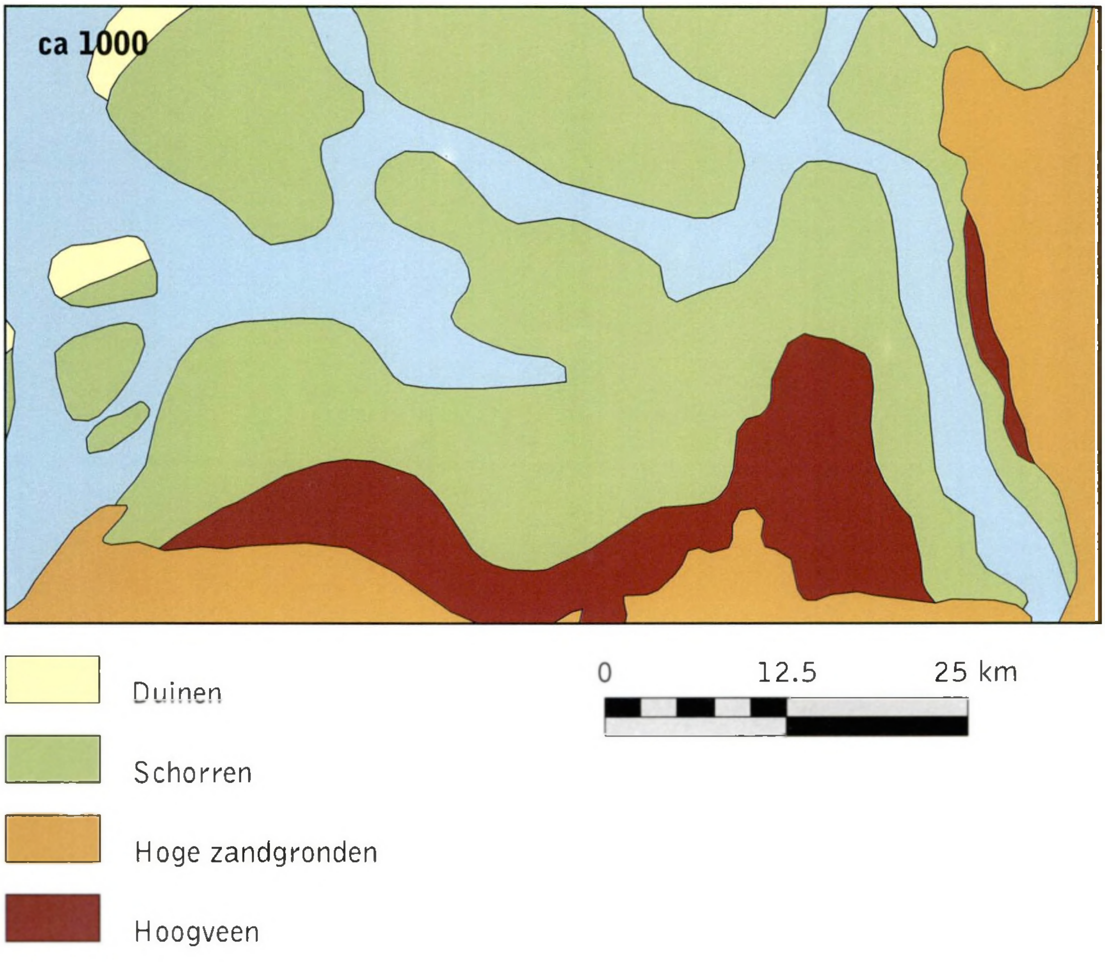


Ref.: De Schelde, een stroom natuurtalent, 1995, published by AMINAL - RIKZ - ZMF

2.1-03 The North Sea and Rhine-Meuse-Schelde "delta" in Roman times

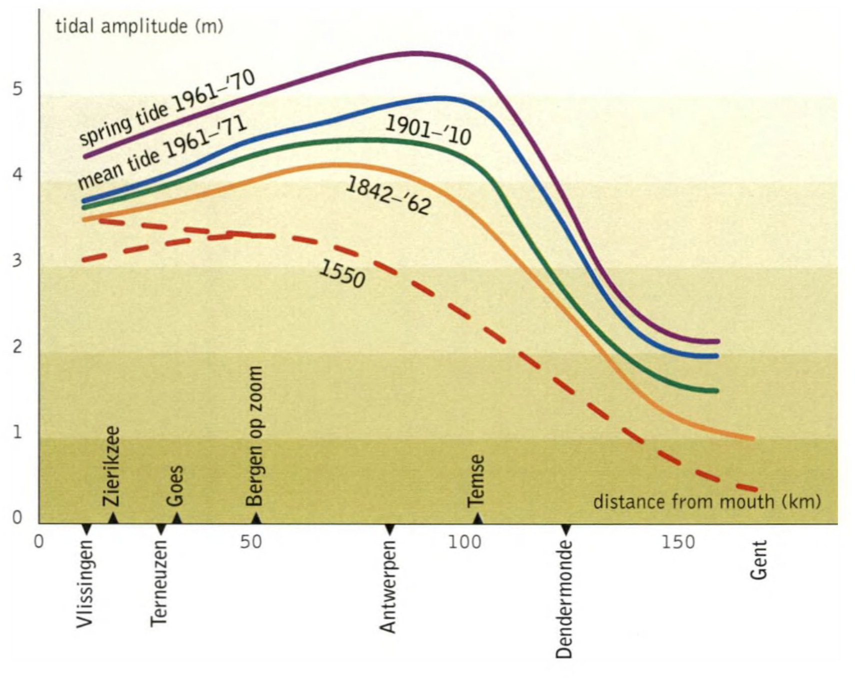
after VAN VEEN, 1950. Eb- en vloedschaar systemen in de Nederlandse getijdwateren, Koninklijk Nederlands Aardrijkskundig Genootschap

2.1-04 The Schelde area around 1 kyr BP



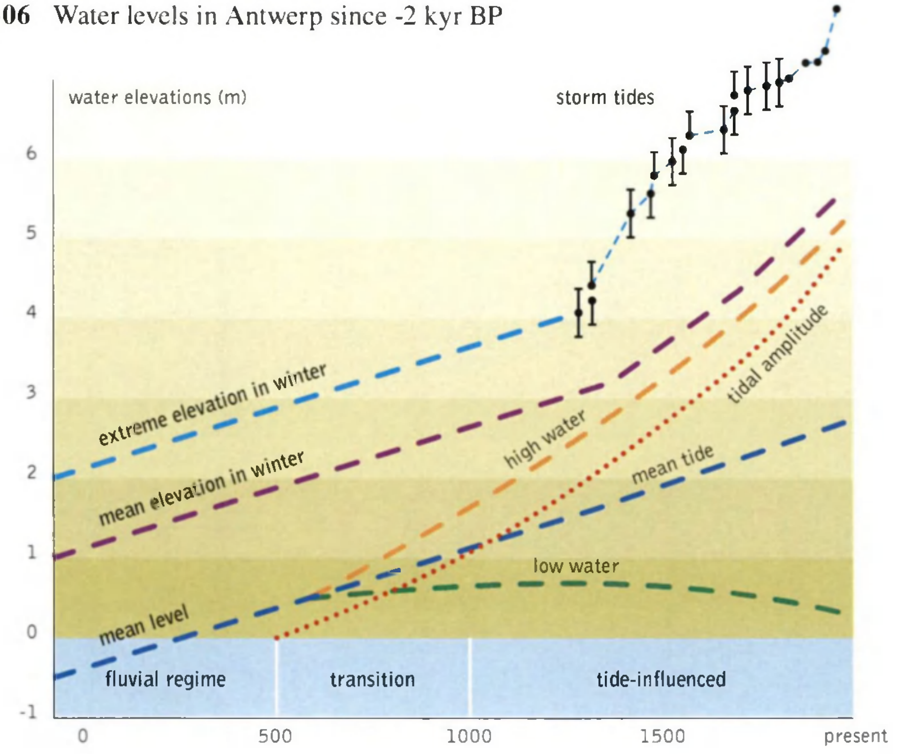
from figure 7 in De ScheldeAtlas, een beeld van een estuarium, 1999, Schelde Informatie Centrum

2.1-05 Evolution of tidal amplitude along the Schelde from 1550 till 1970



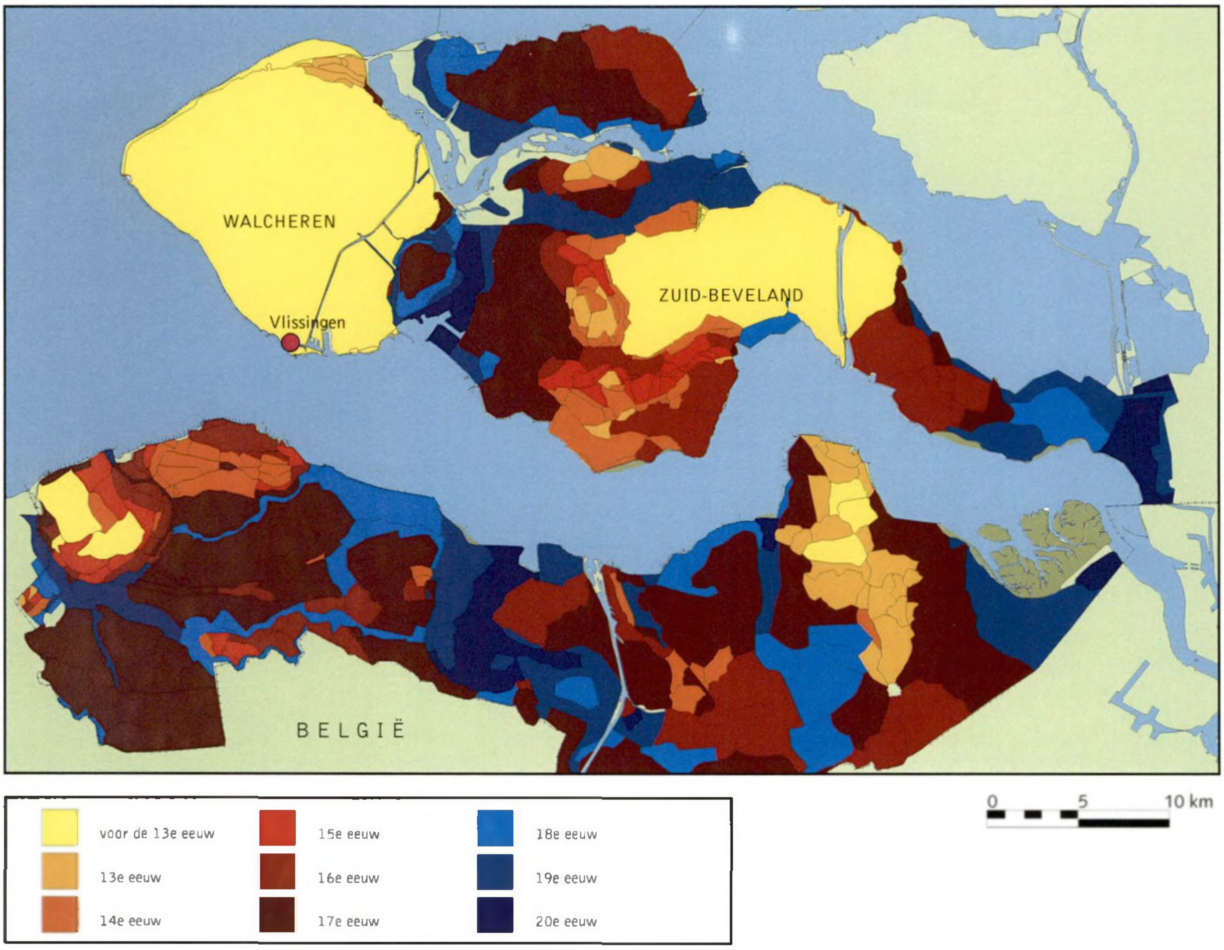
from COEN I., 1988, Ontstaan en ontwikkeling van de Westerschelde, Tijdschrift WATER 43/1

2.1-06 Water levels in Antwerp since -2 kyr BP

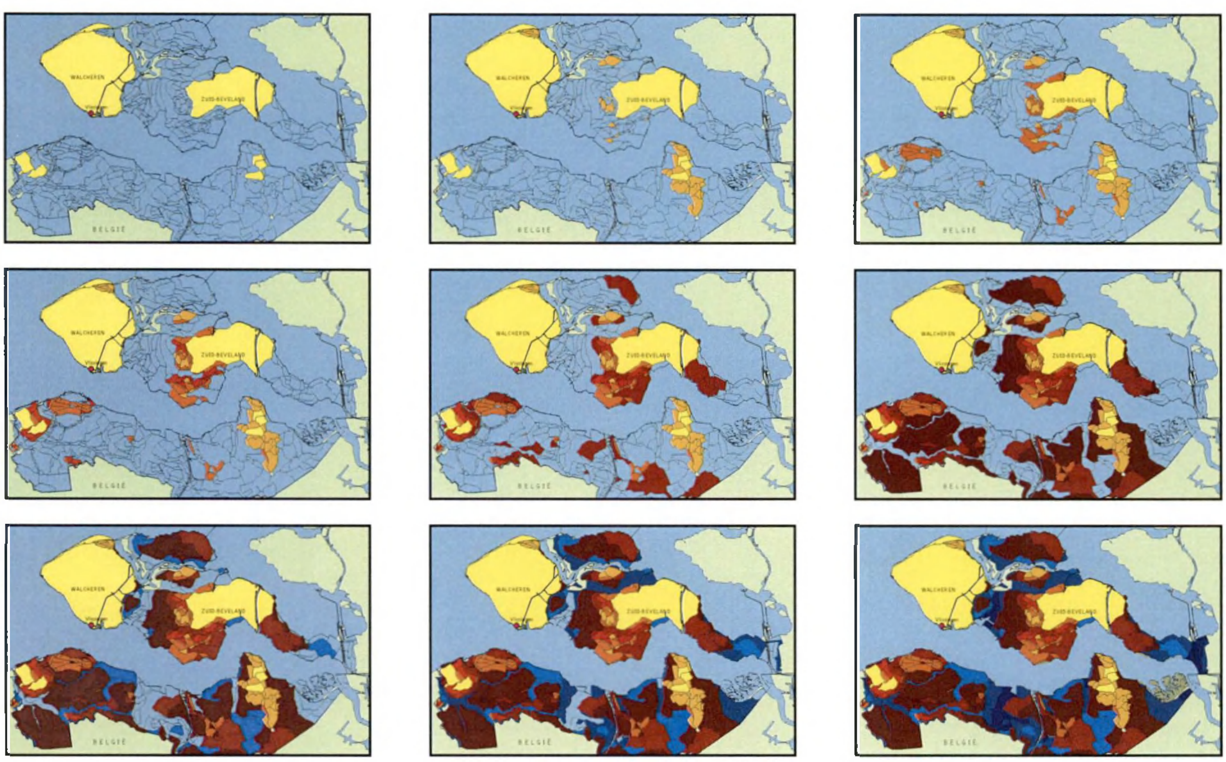


from Fig. 10 in COEN I., 1988, Ontstaan en ontwikkeling van de Westerschelde, Tijdschrift WATER 43/1

2.2-01 Land reclaimed in the Westerschelde at different times since the Middle Ages

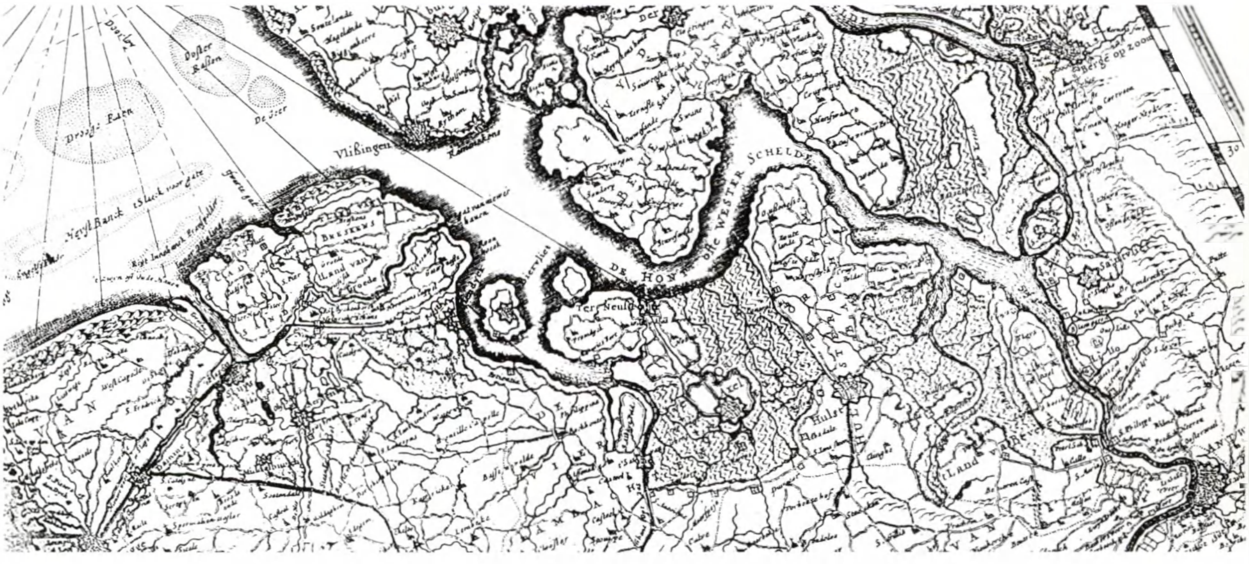


from: De ScheldeAtlas, een beeld van een estuarium, 1999, Schelde Informatie Centrum

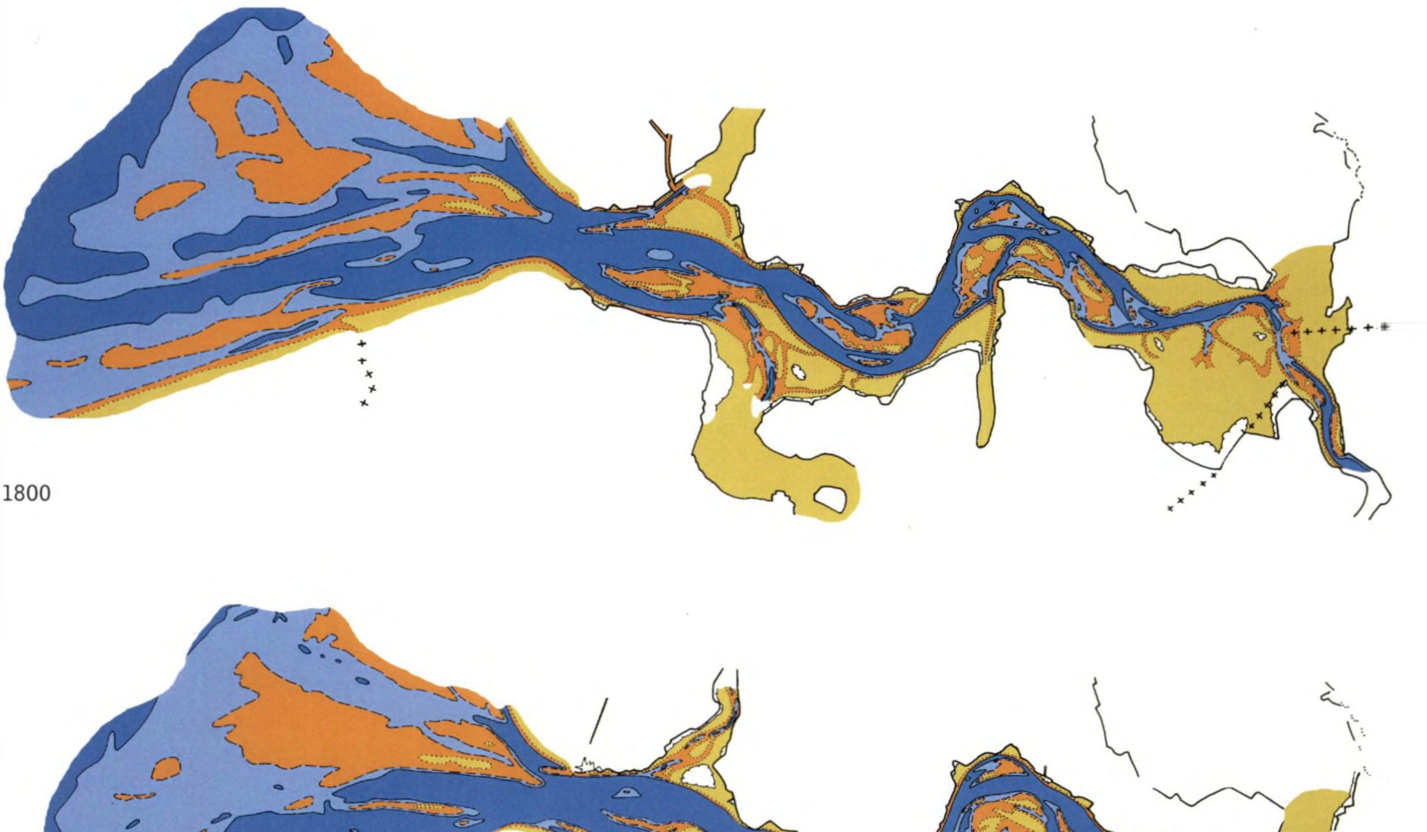


Zones reclaimed before and during the indicated century; the figure does not represent the situation of polders at that moment, because some reclaimed areas were lost later on during storms

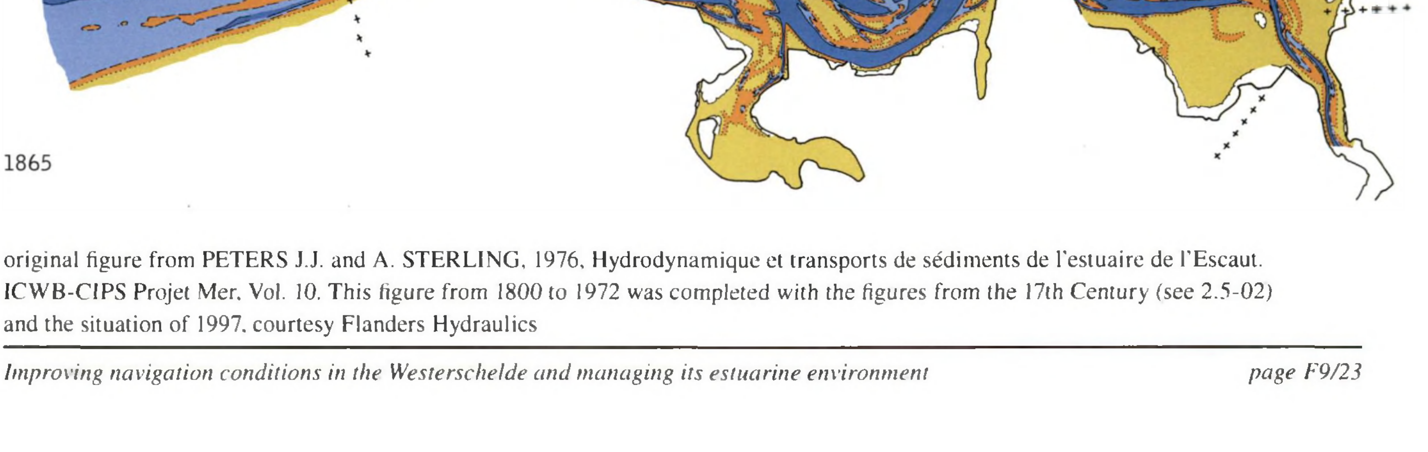
2.2-02 The morphological changes of the Westerschelde from the 17th Century to 1997



1636

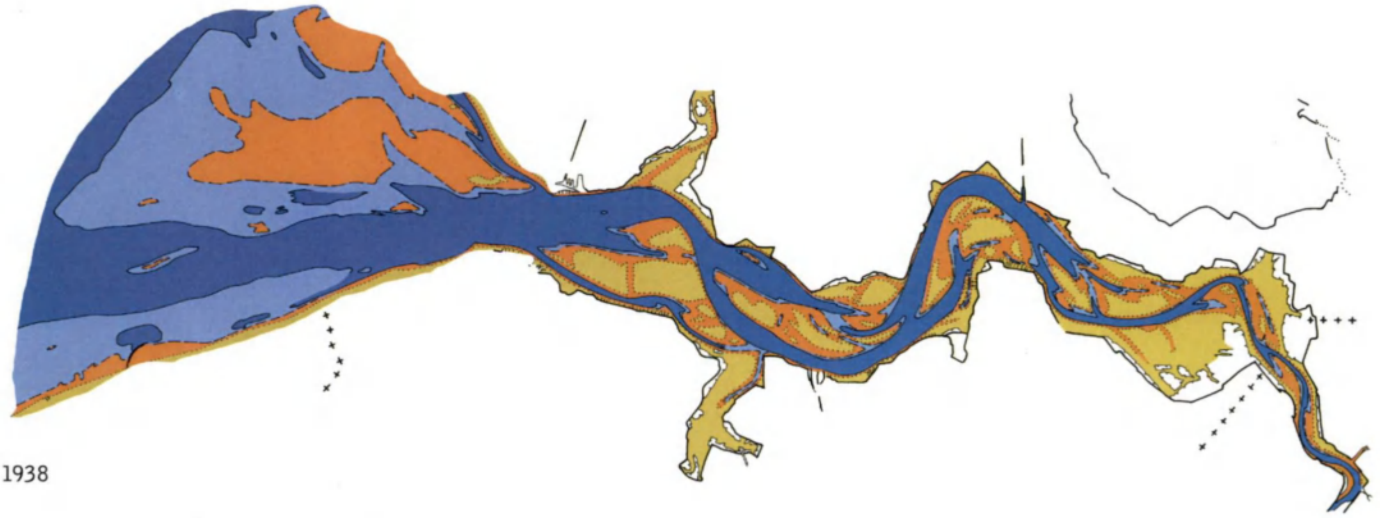


1800

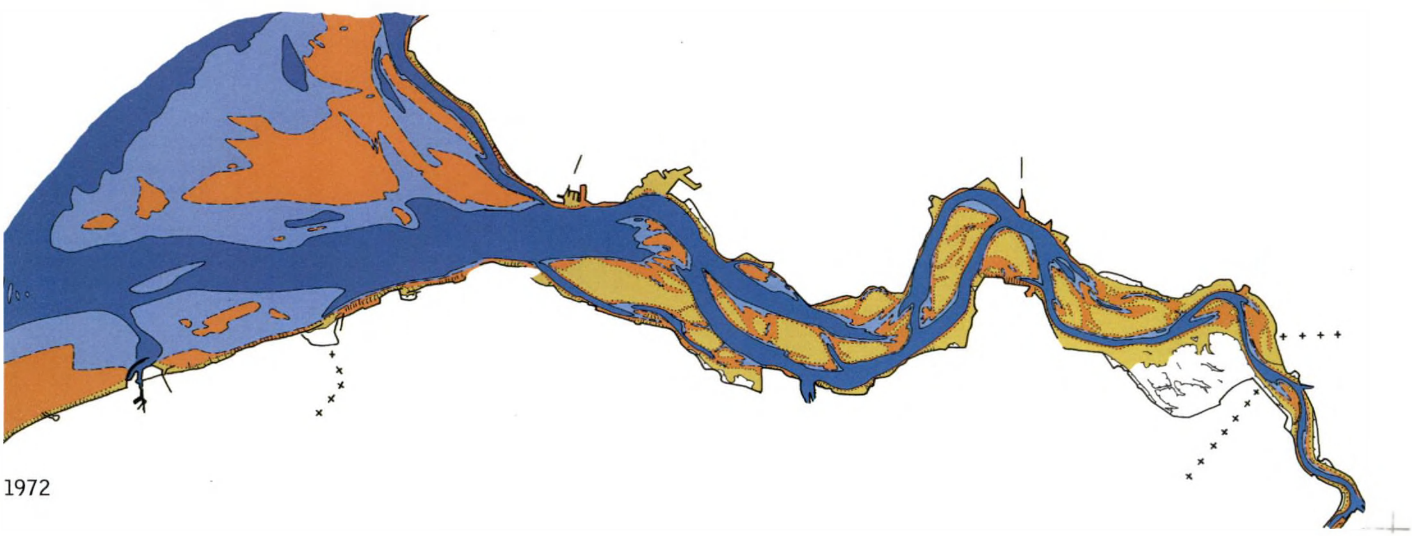


1865

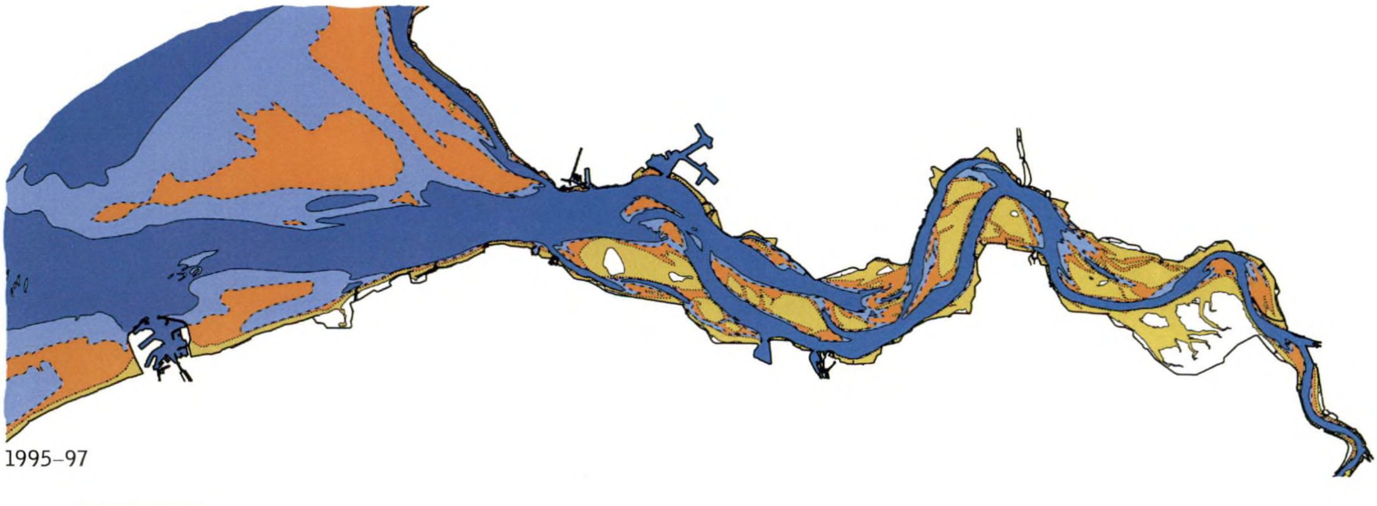
original figure from PETERS J.J. and A. STERLING, 1976, Hydrodynamique et transports de sédiments de l'estuaire de l'Escaut. ICWB-CIPS Projet Mer, Vol. 10. This figure from 1800 to 1972 was completed with the figures from the 17th Century (see 2.5-02) and the situation of 1997, courtesy Flanders Hydraulics



1938

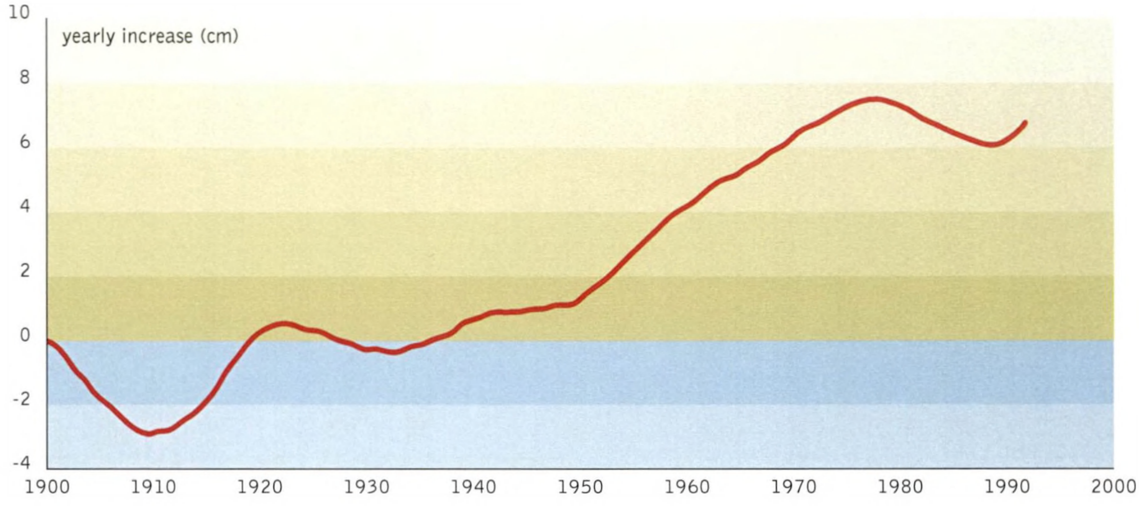


1972

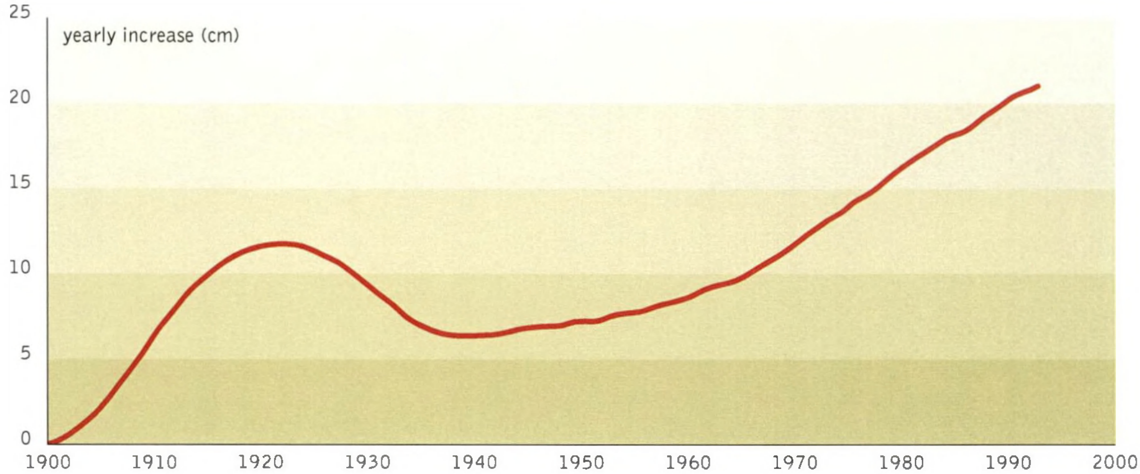


1995–97

2.3-01 Increase of mean high water at Vlissingen relative to the mean sea level

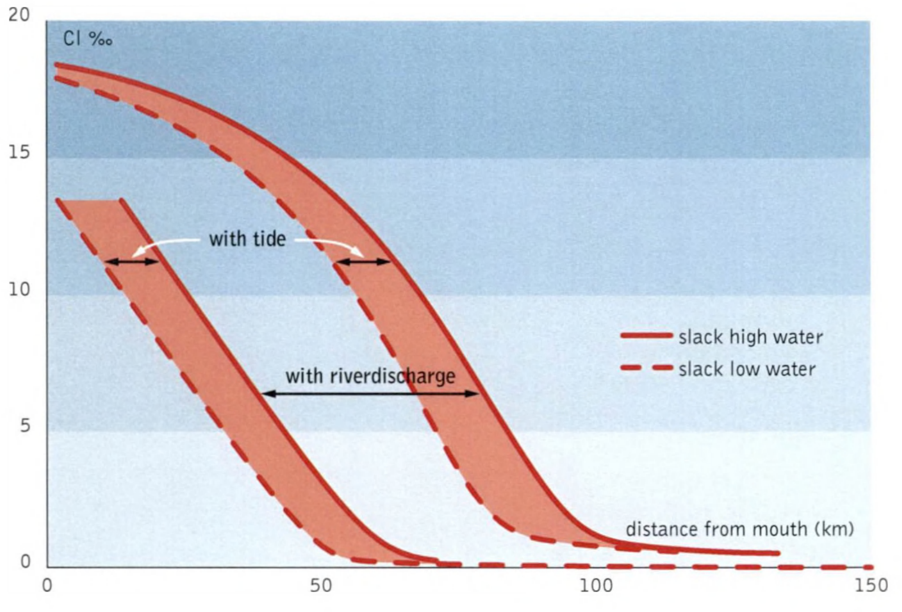


2.3-02 Increase of mean high water at Bath, relative to the mean high water at Vlissingen

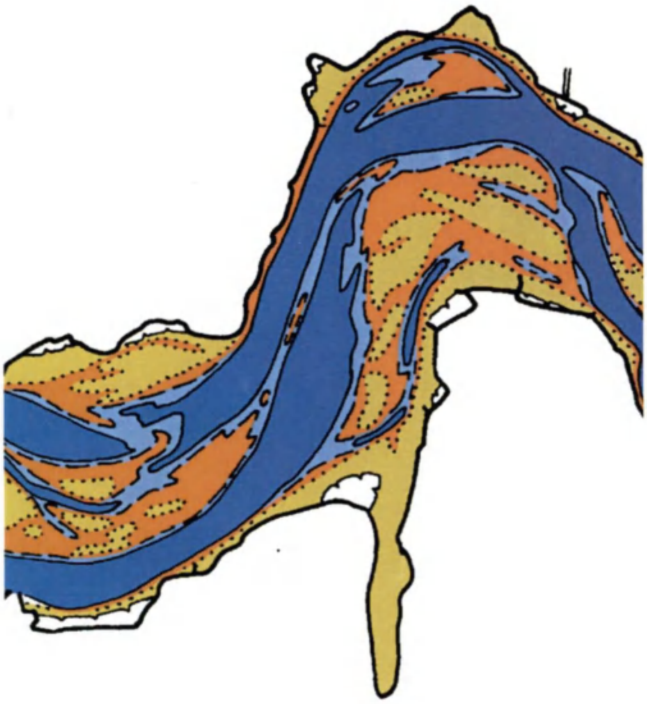


from ARENDS, A., & A. LANGERAK, 2000. Causes and effects of high water rise in the Western Scheldt estuary; paper presented in 1999 on the MAFF (UK) conference for coastal and river engineers

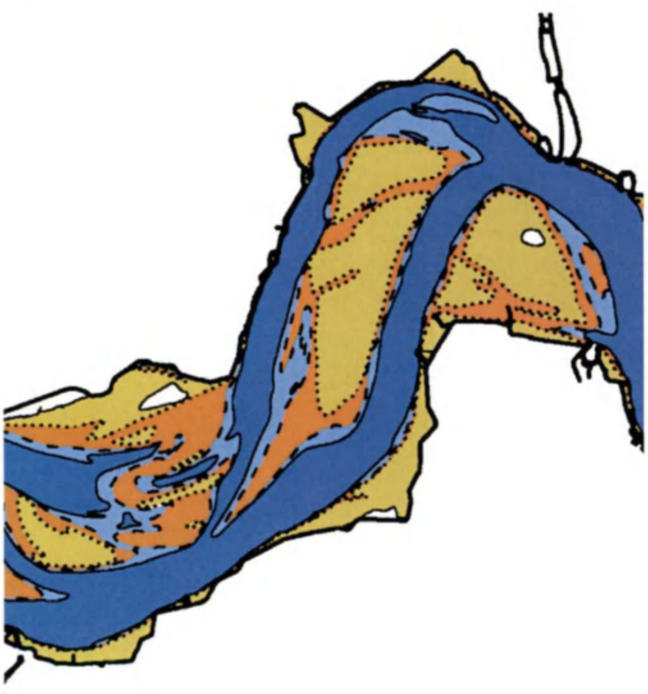
2.4-01 Longitudinal salinity profile and its shift with tide and river discharge



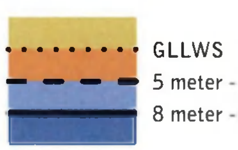
from Fig. 7. in PETERS J.J. and A. STERLING, Hydrodynamique et transports de sédiments de l'estuaire de l'Escaut. ICWB-CIPS Projet Mer, Vol. 10



1865

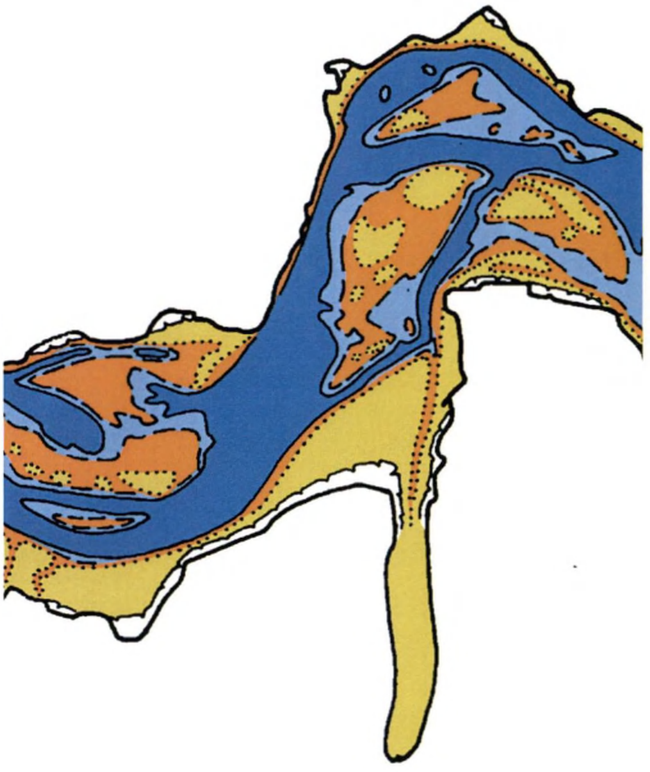


1995–97

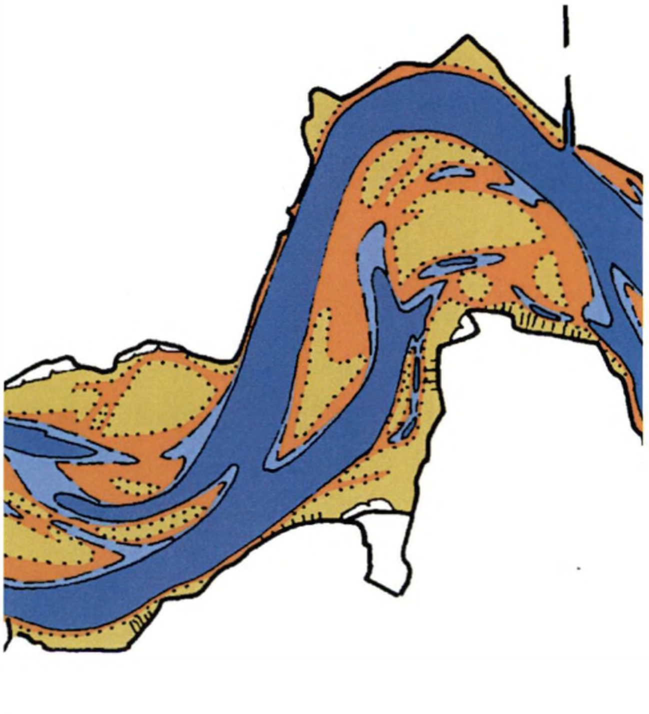


2.5-01 Evolution of the Westerschelde between Terneuzen and Walsoorden from the 17th Century to 1997

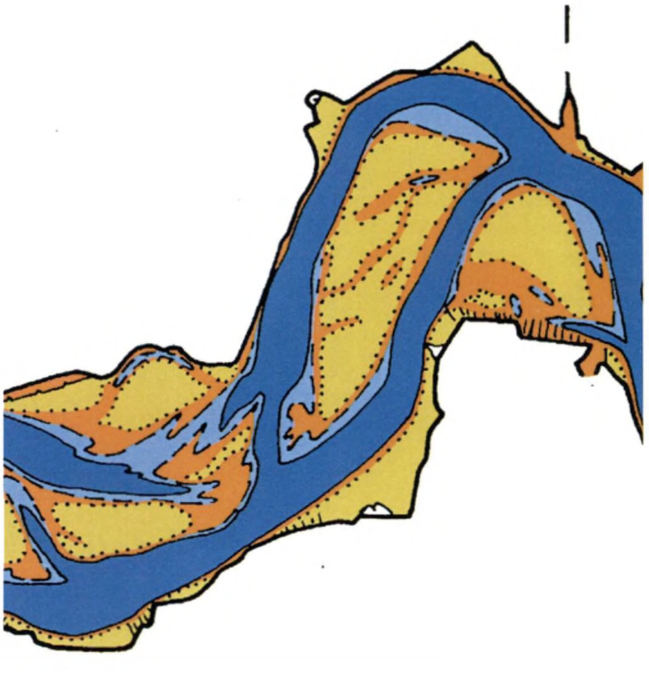
1636



1800



1938



1972

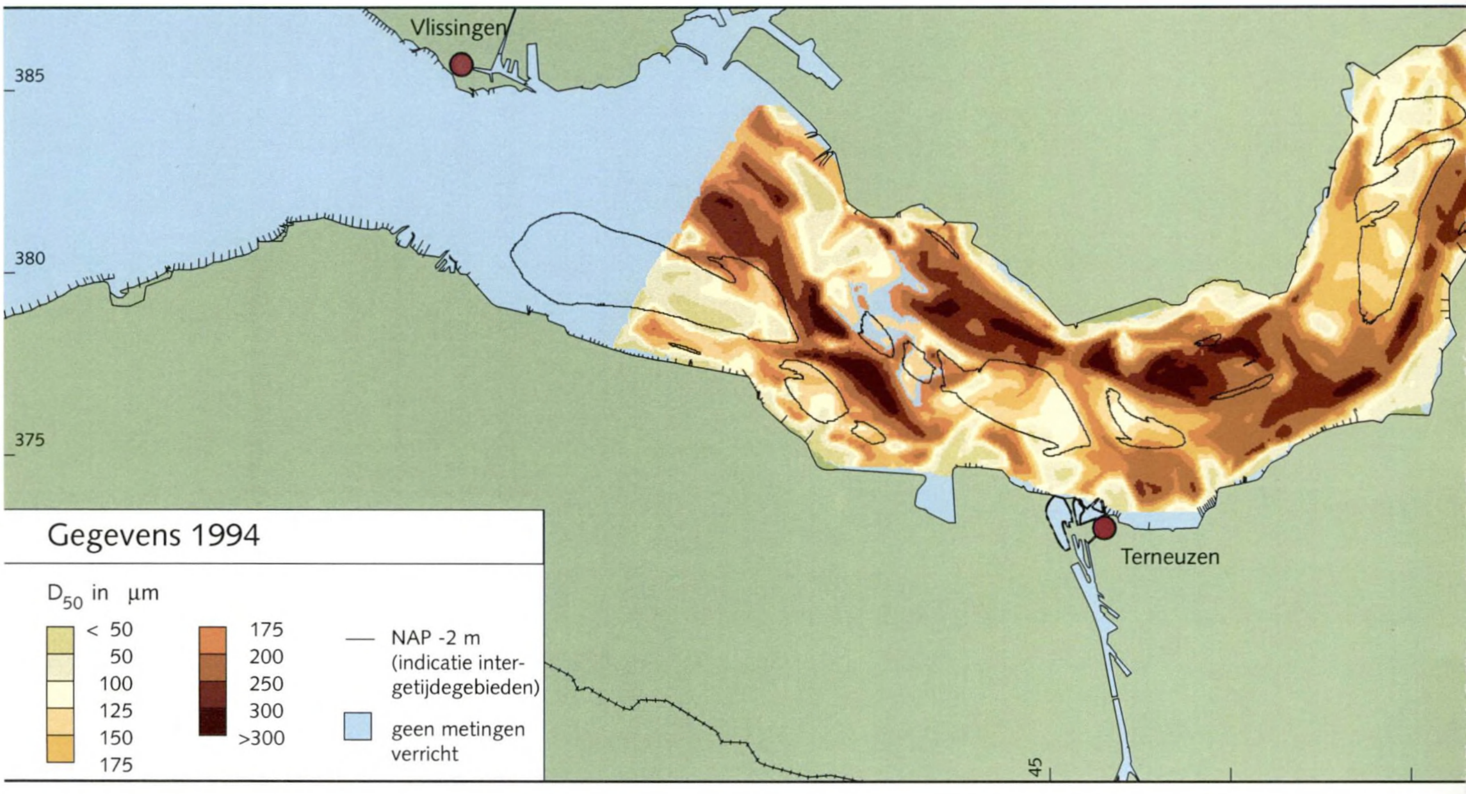
excerpt from Fig. 2.2-01


OOSTER SCHELDE
TOLEN
Ter Tolen
Goes
Berge op Zoom
WESTER SCHELDE
HONT
Hulst
Axel
Sandvliet
Lillo
Calloo
Ossendrecht
Hooger Heyde
Noort geest
Schakerloo
Cloetingen
Crugningen
Hansweert
Ouwerkerck
Zoute lande
Lant va Bevere
S. Philippe
Oosterweel
Merxem
Ekeren
Stabroeck
Berendrecht
Burcht
Beveren Cast
30
ANTWE

2.5-02 Map of the Westerschelde in the 17th Century

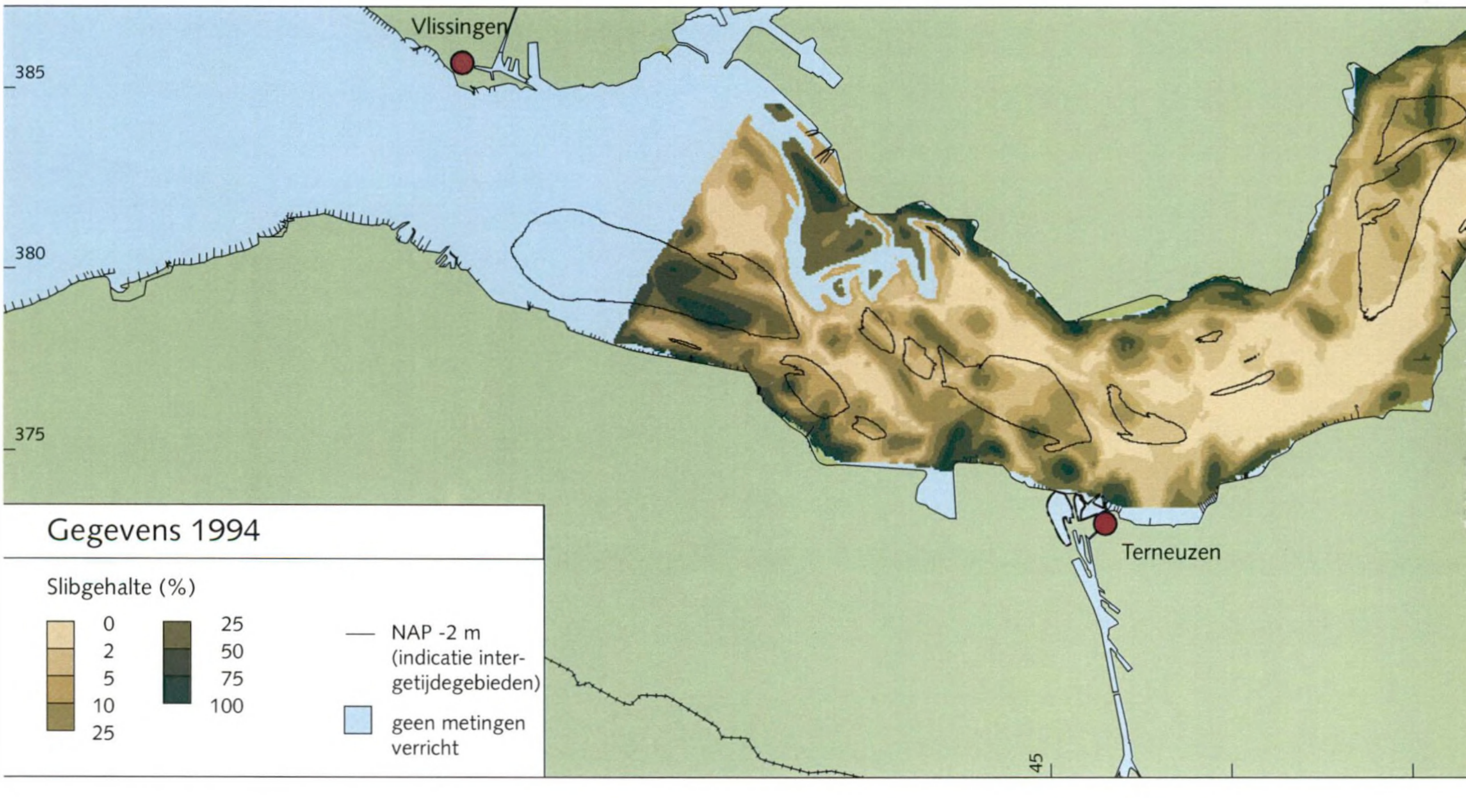
Ref.: MERCATOR-HONDSIUS-JANSSONIUS Atlas or a Geographic Description of the World, 1636, Amsterdam

2.5-03 Bottom sediment size

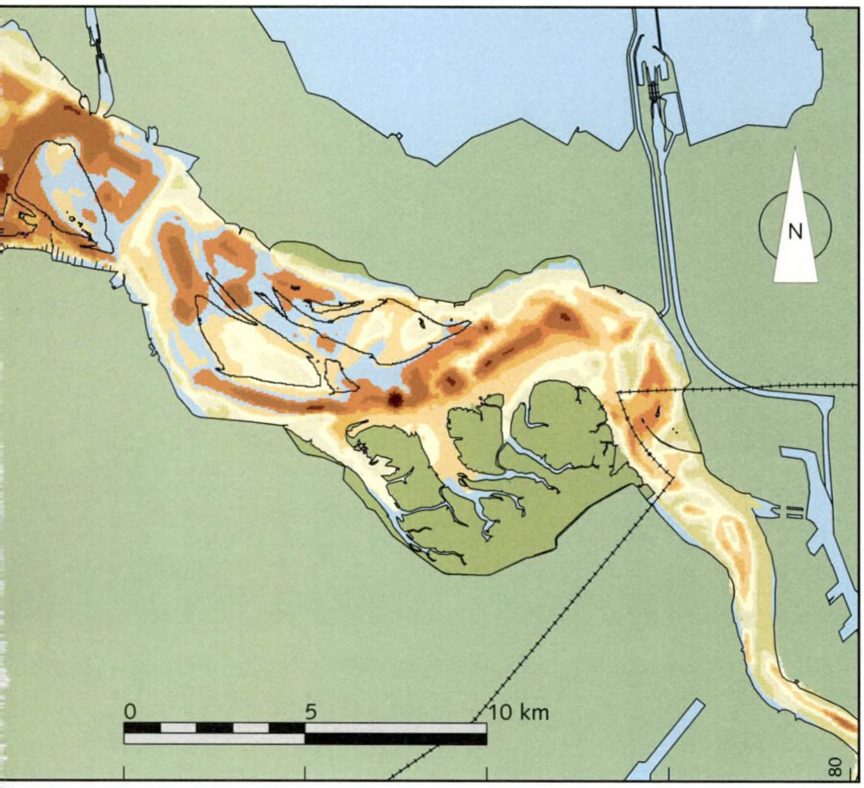


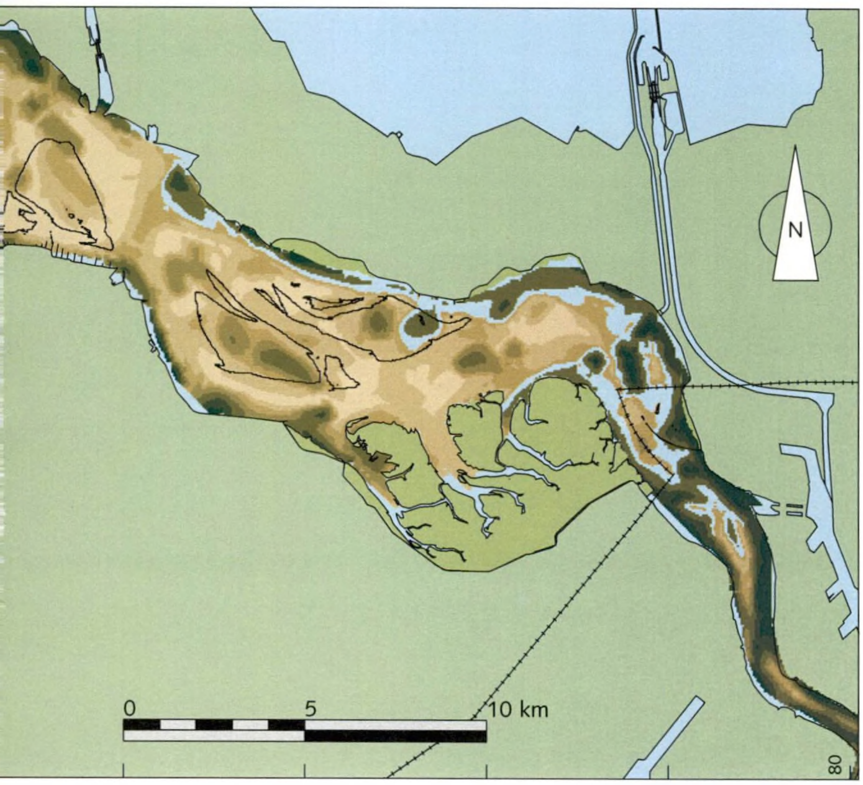
from Fig. 32 in De ScheldeAtlas, een beeld van een estuarium, 1999, Schelde Informatie Centrum

2.5-04 Silt content in bottom sediments

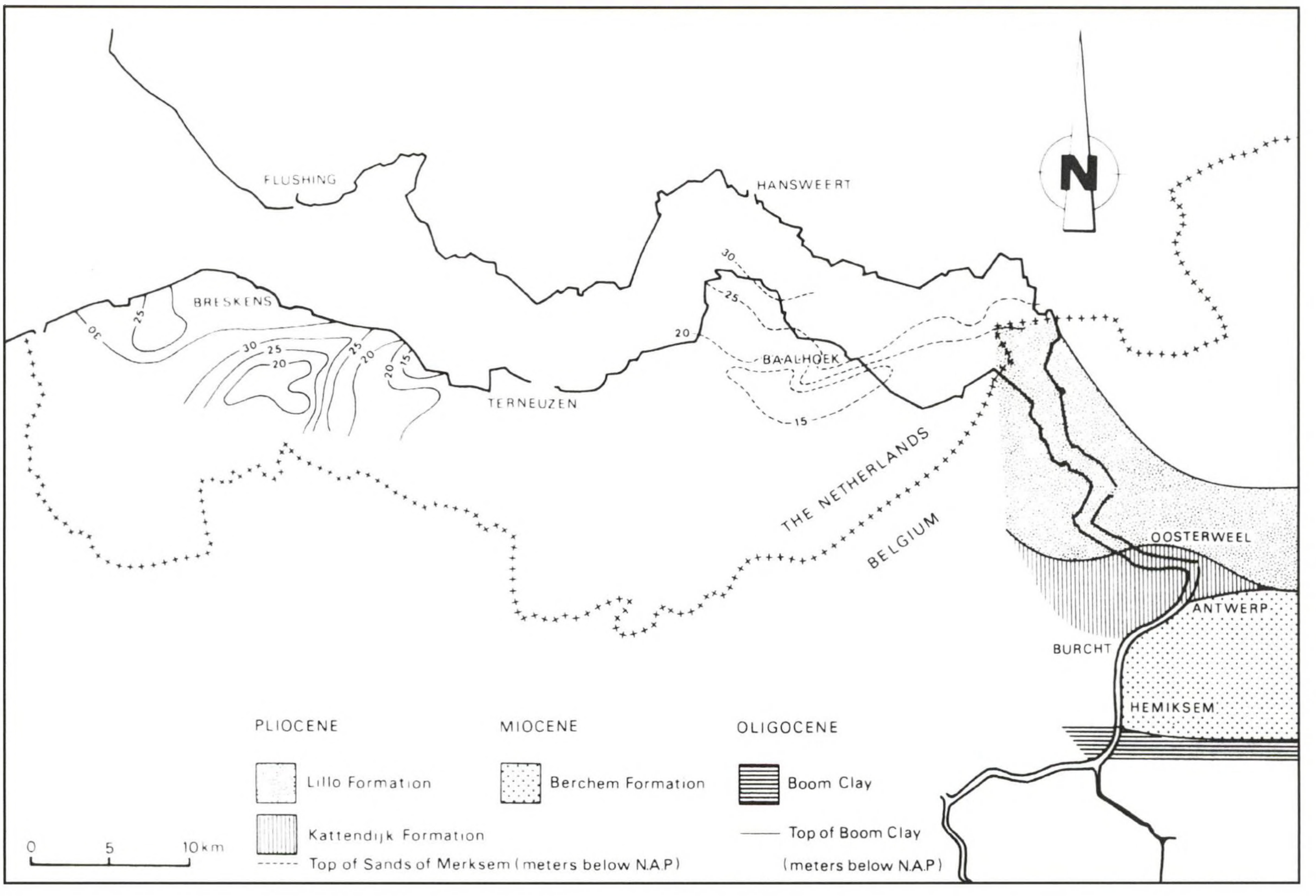


from Fig. 33 in De ScheldeAtlas, een beeld van een estuarium, 1999, Schelde Informatie Centrum


N
0
5
10 km
80

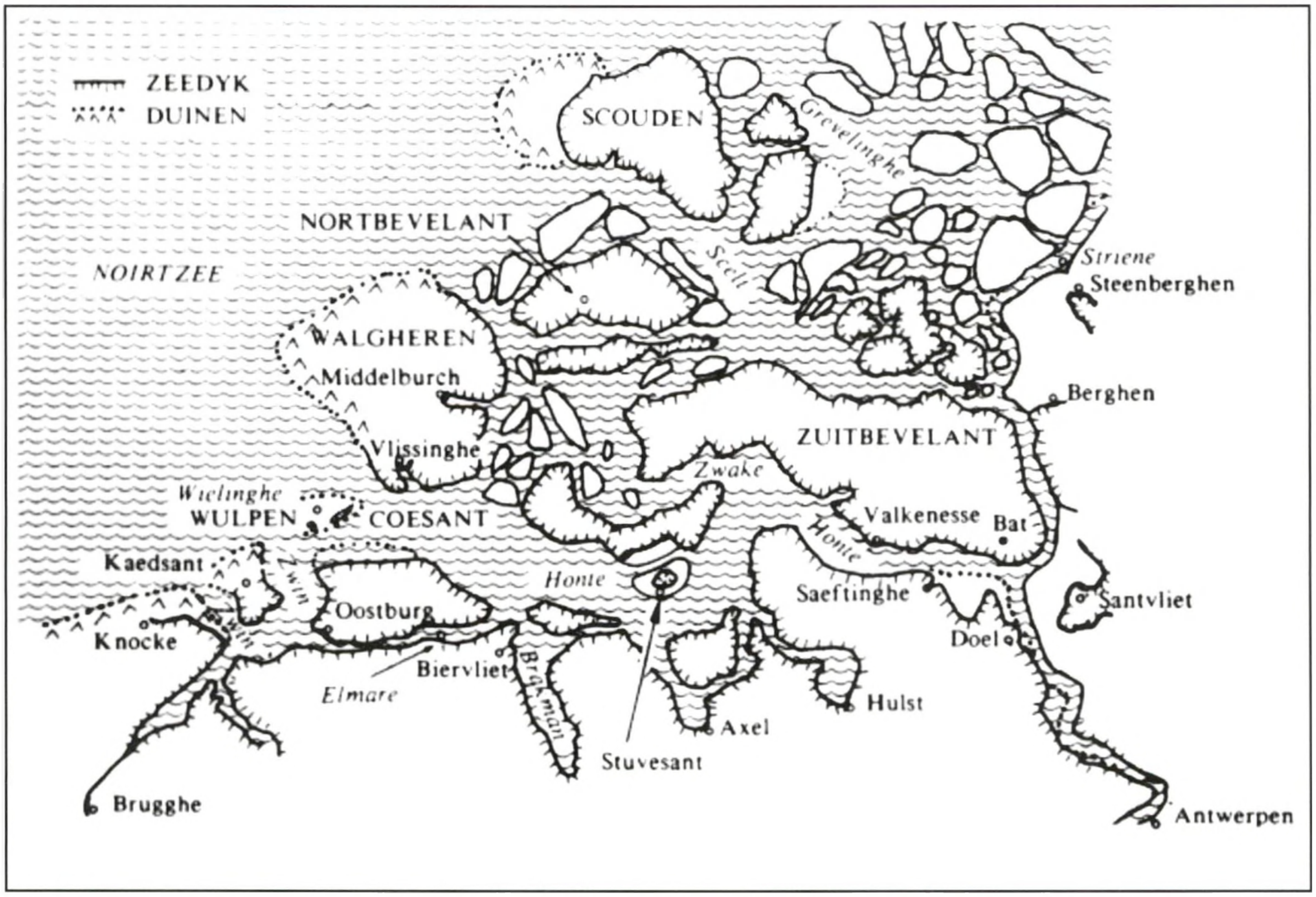

N
0
5
10 km
80

2.5-05 Clay as possible morphological control points



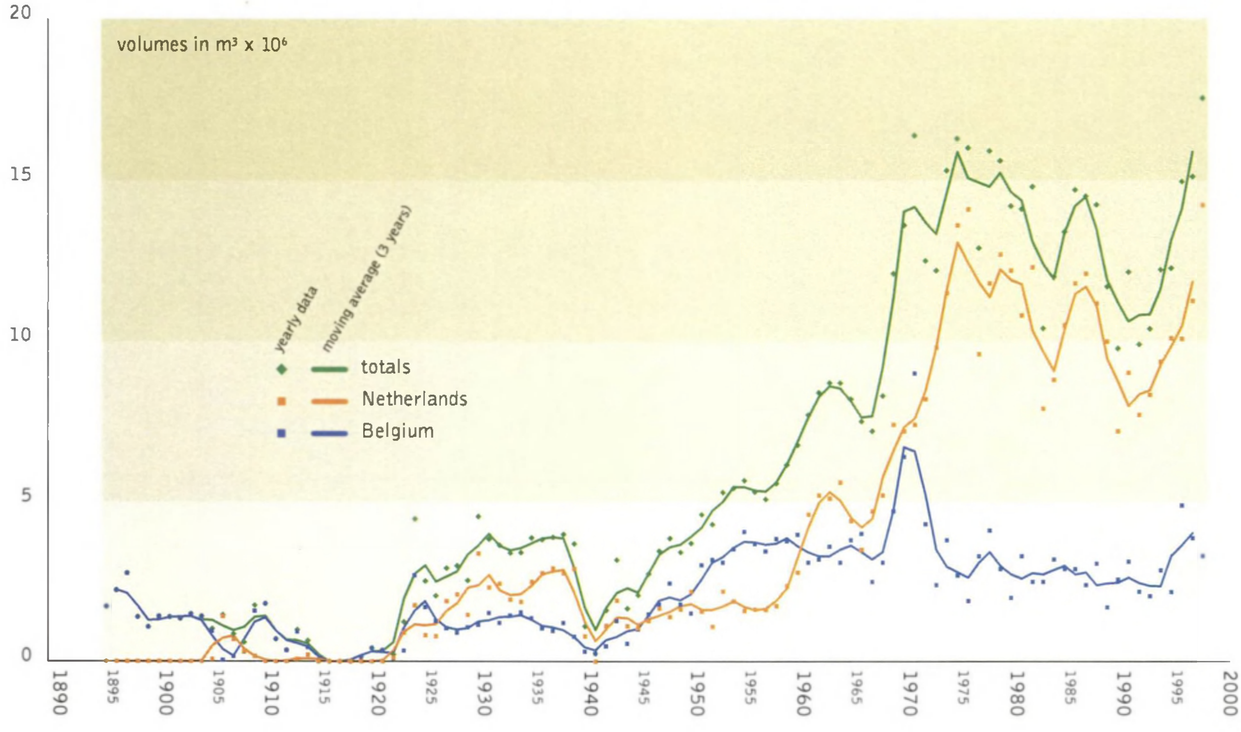
Ref.: WARTEL, S., F. DE MEUTER and A. RINGELE. 1983. Note concerning the origin of the Scheldt estuary bottom sediments, Bull. K. Belg. Inst. Nat. Wet. 55-1

2.6-01 Zeeland 0.7 kyr BP



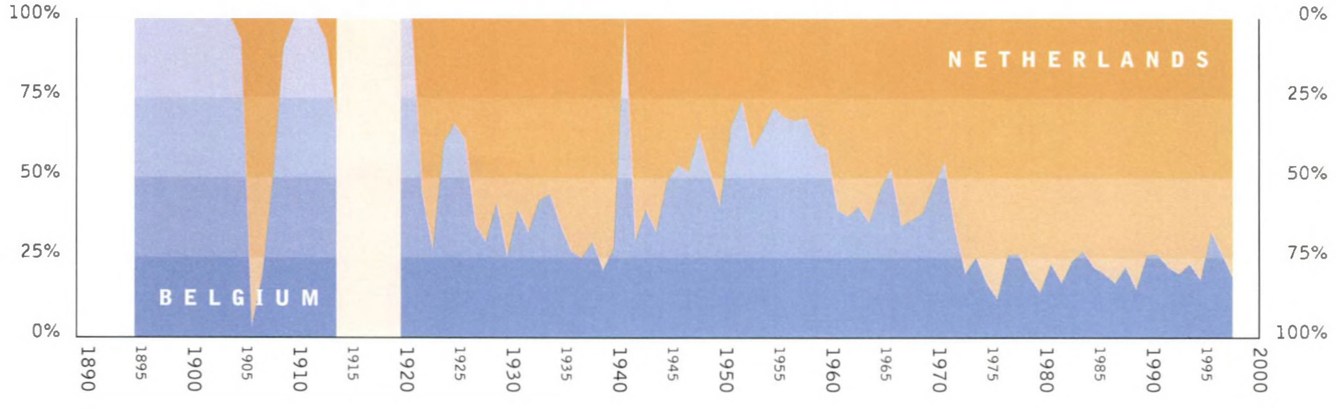
from Fig. 5 in COEN I., 1988, Ontstaan en ontwikkeling van de Westerschelde, Tijdschrift WATER 43/1

3.2-01 Time series of annual dredged volumes from 1895 to 1998



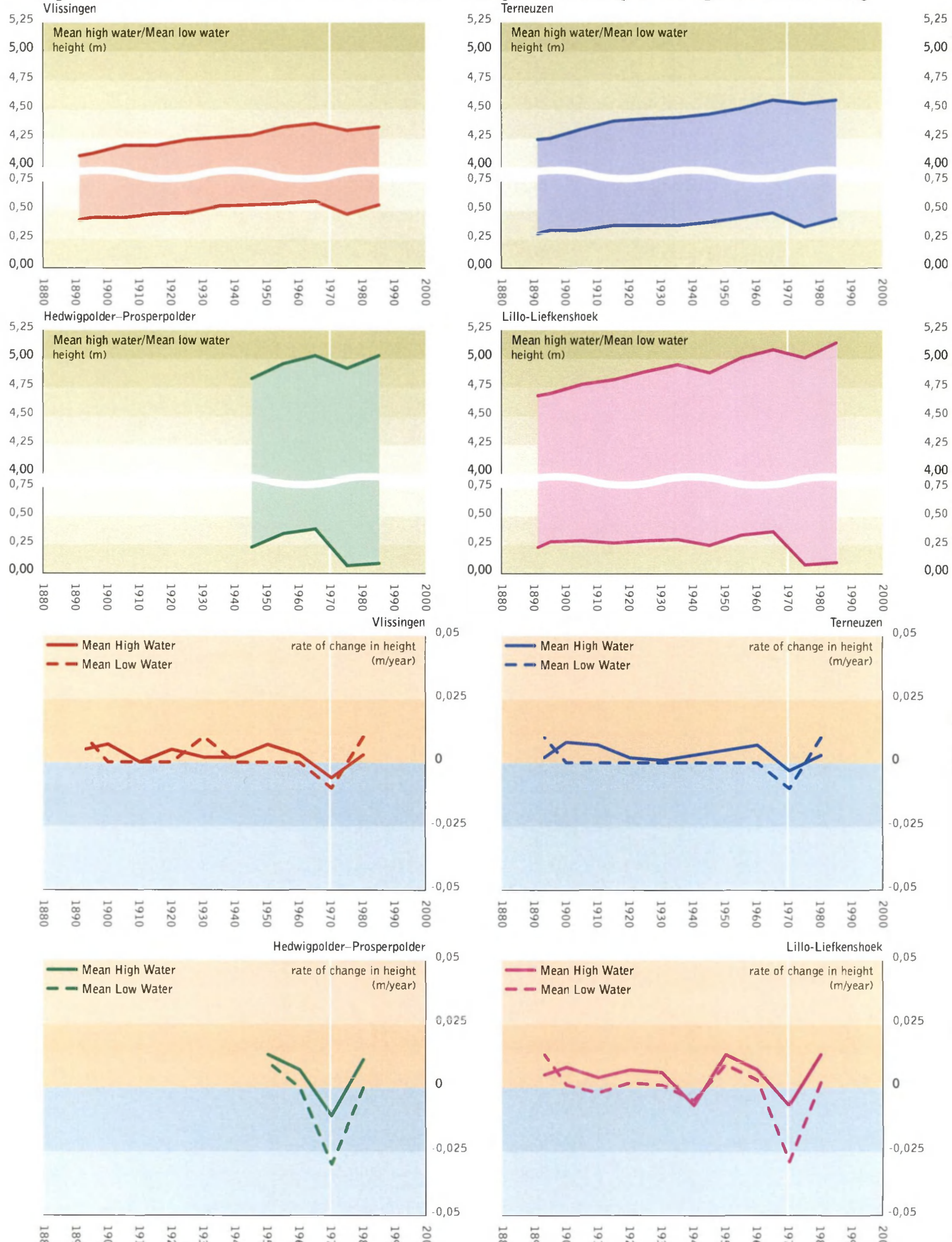
The lines with 3-year moving average data indicate the broad trends

3.2-02 Percentage of volumes dredged in Belgium and in The Netherlands



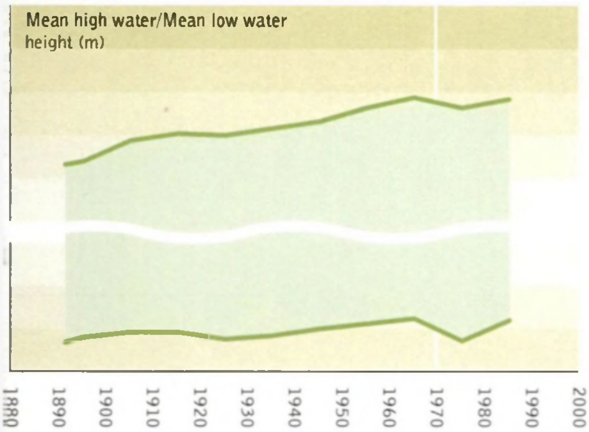
from data AWS

3.3-01 High water and low water at selected stations between Vlissingen and Antwerpen - Changes and rates of change

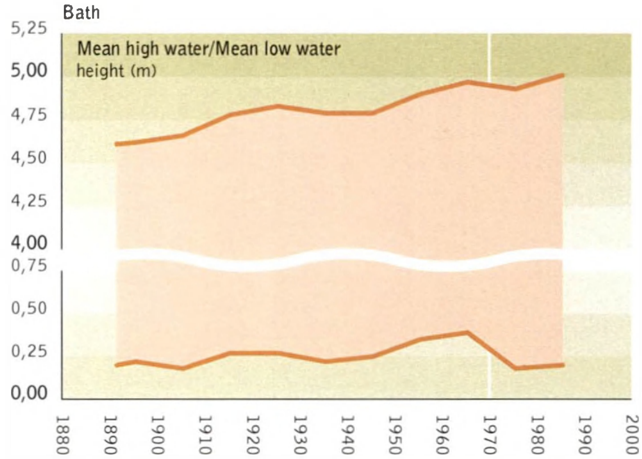


from data AWS

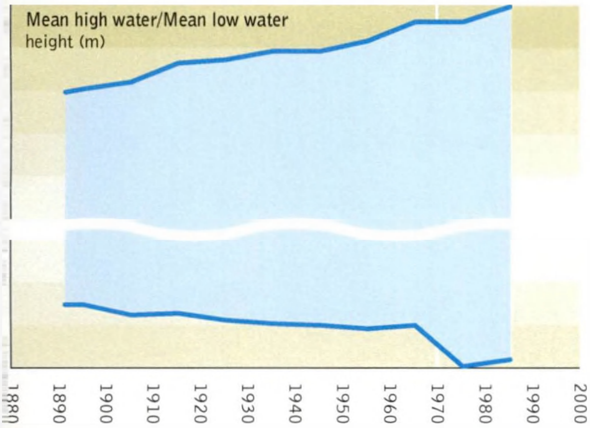
Hansweert



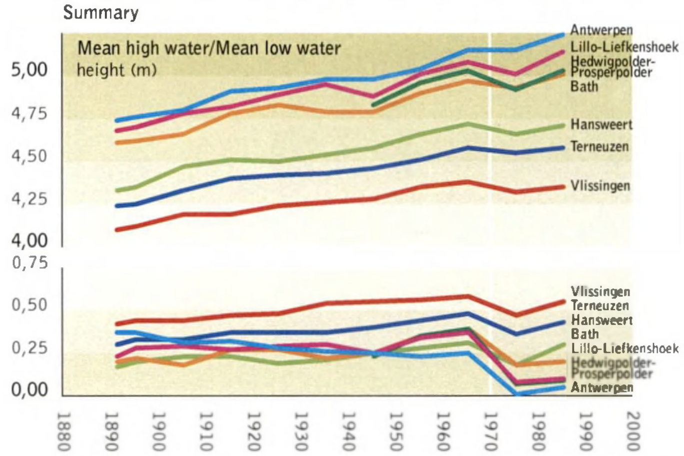
Bath



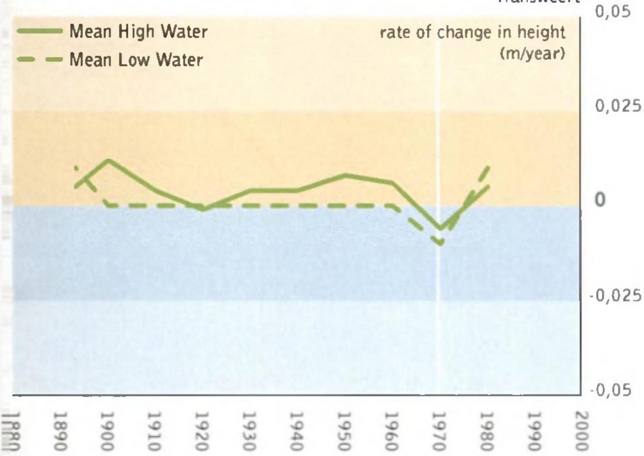
Antwerpen



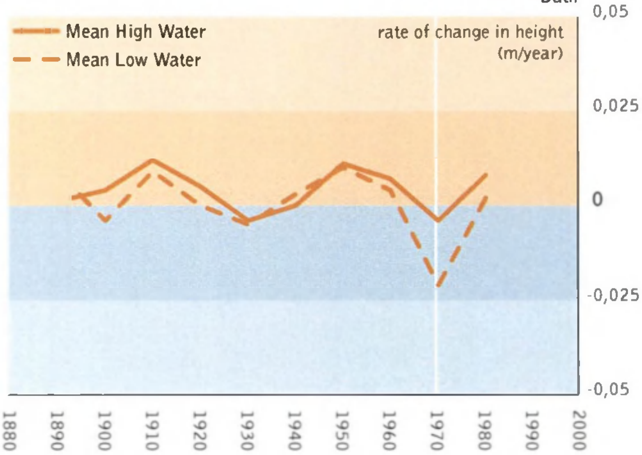
Summary



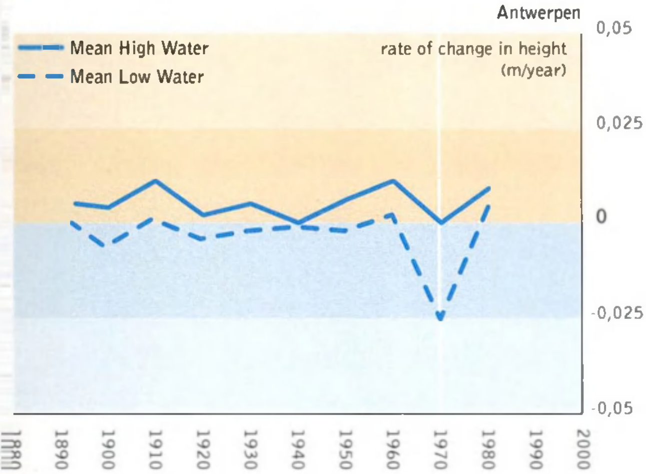
Hansweert



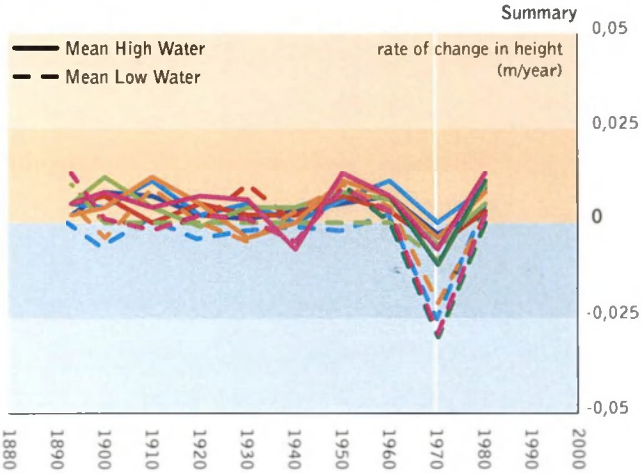
Bath



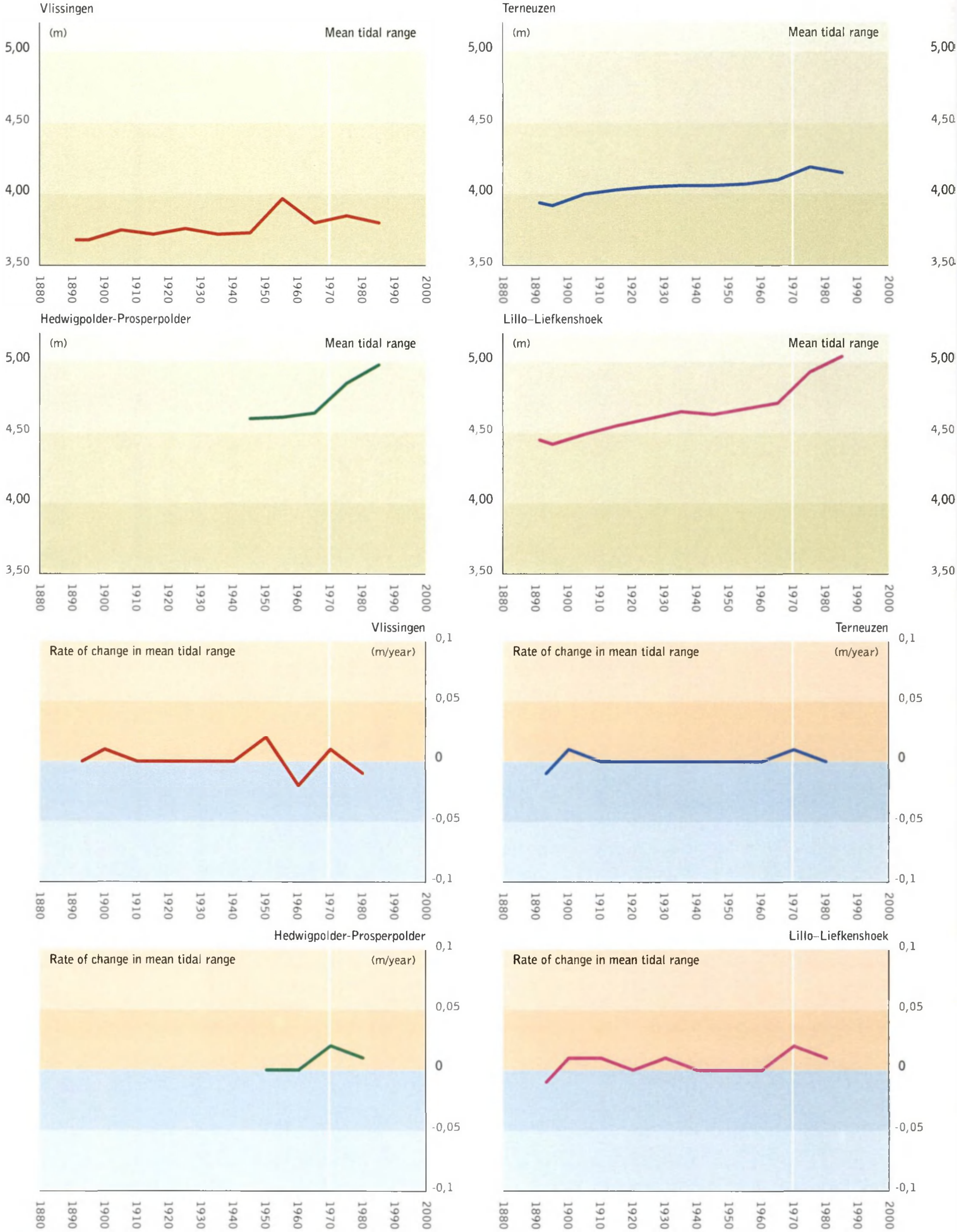
Antwerpen



Summary

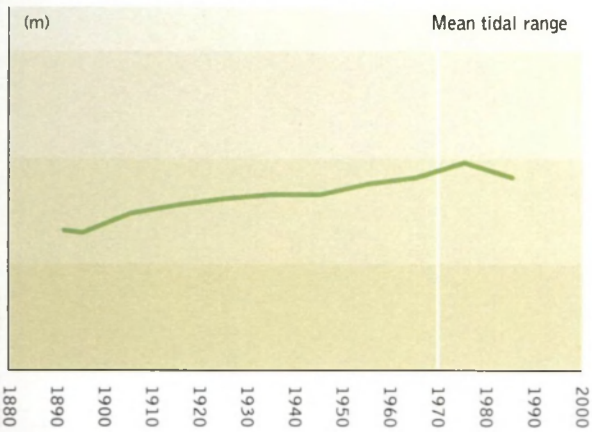


3.3-02 Mean tidal range at selected stations between Vlissingen and Antwerpen - Changes and rates of change

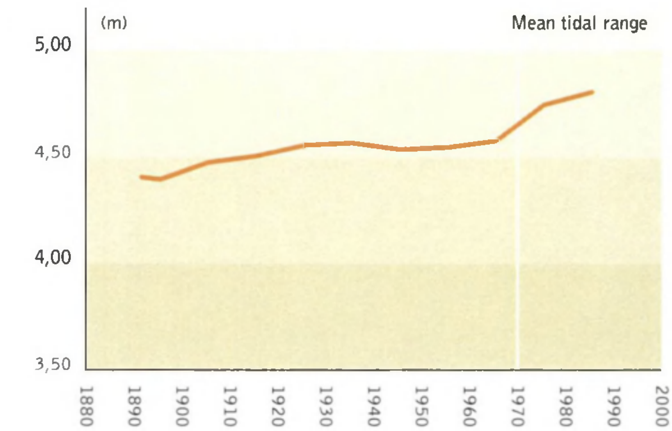


from data AWS

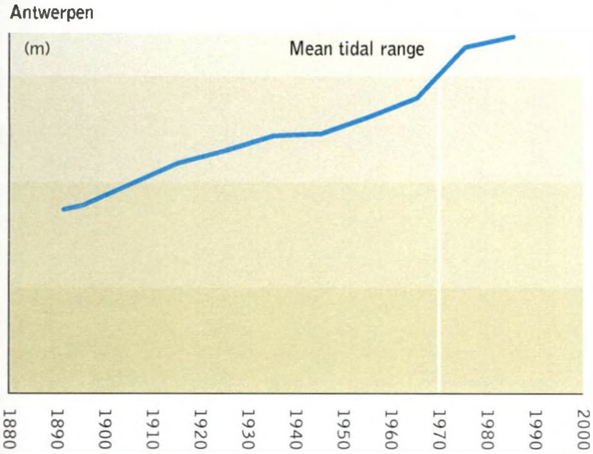
Hansweert



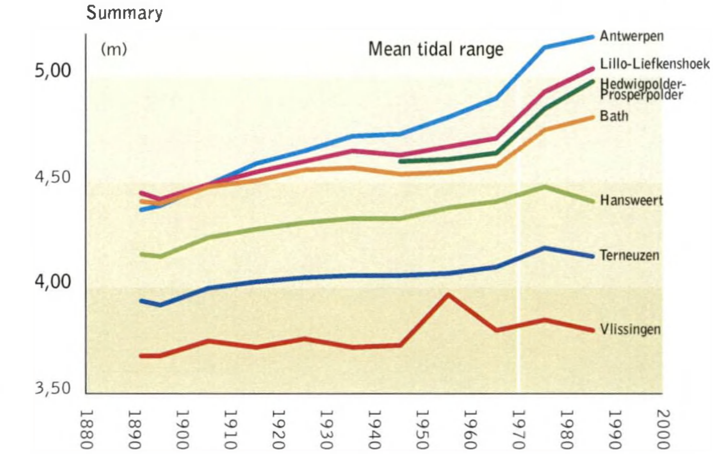
Bath



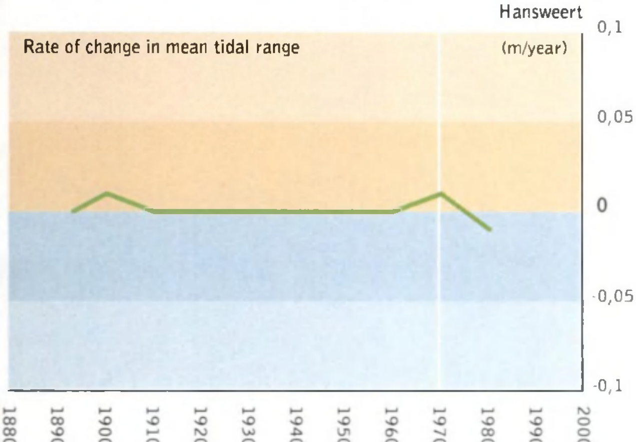
Antwerpen



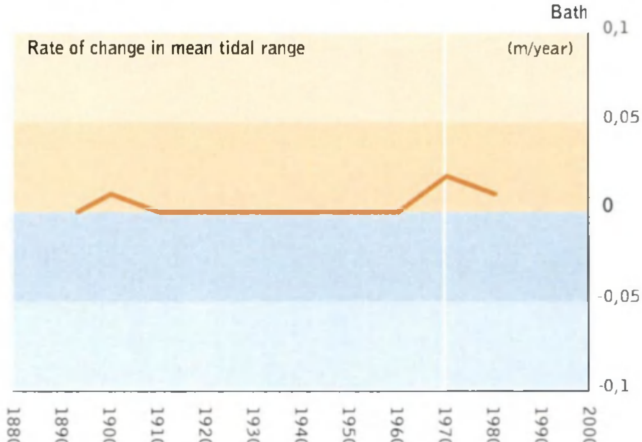
Summary



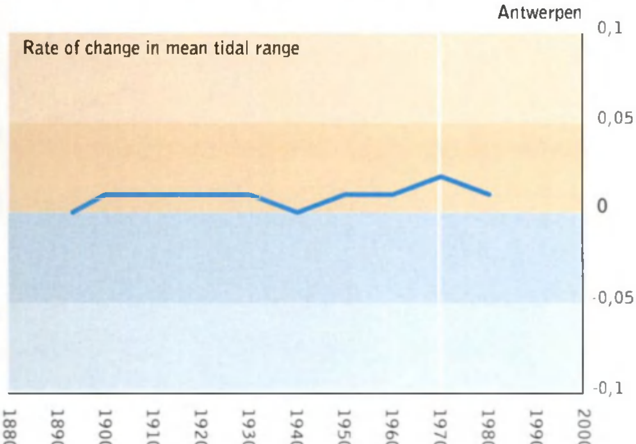
Hansweert



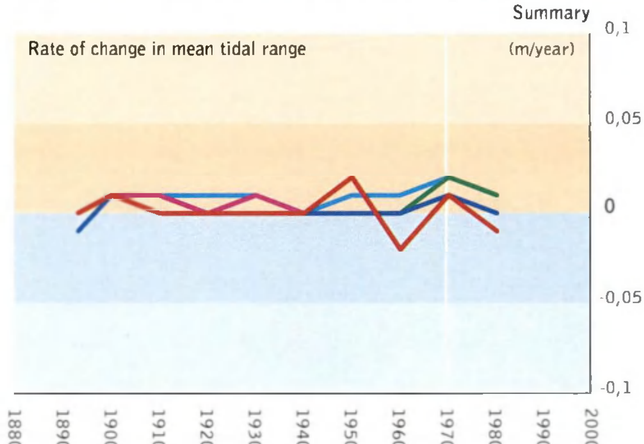
Bath



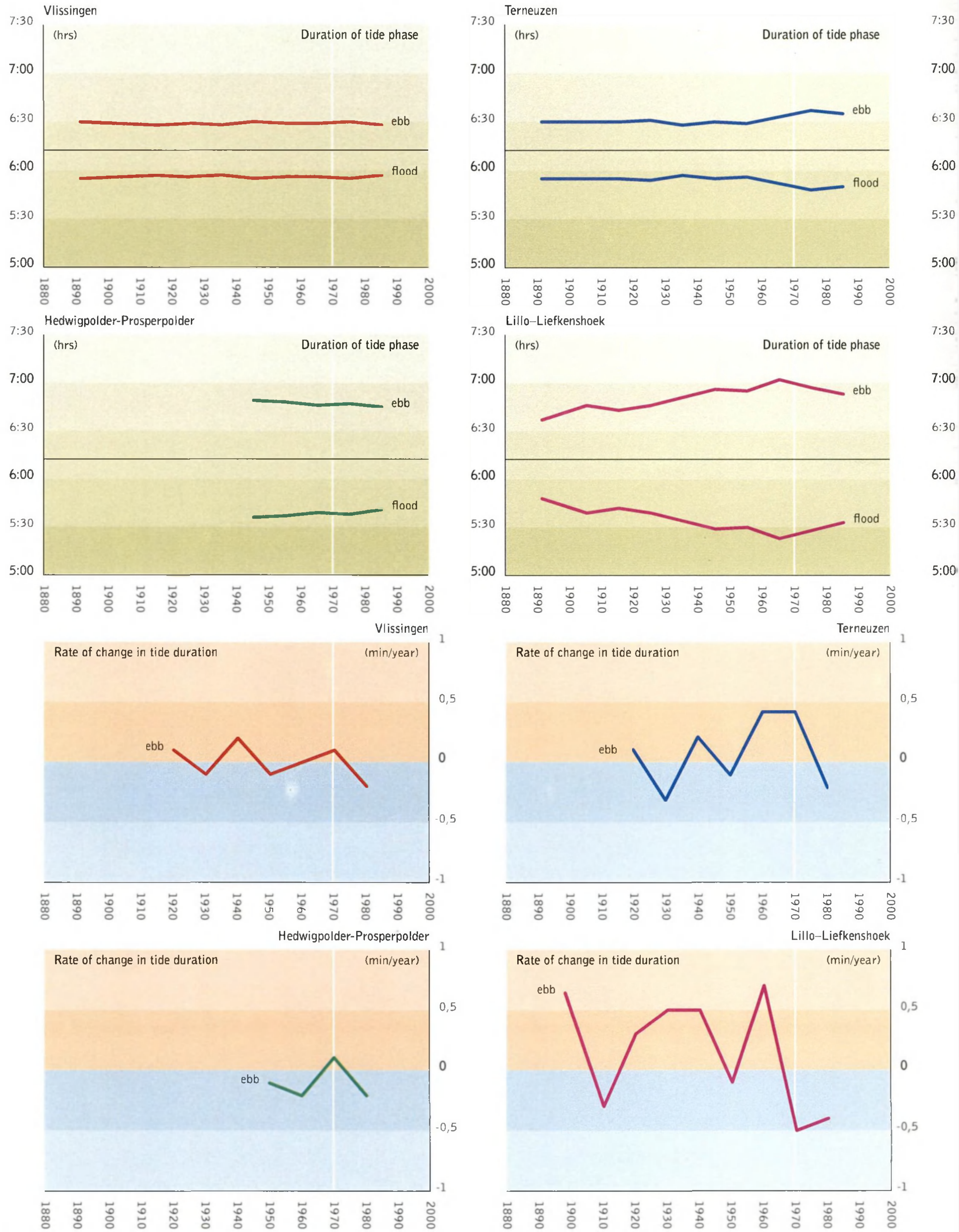
Antwerpen



Summary

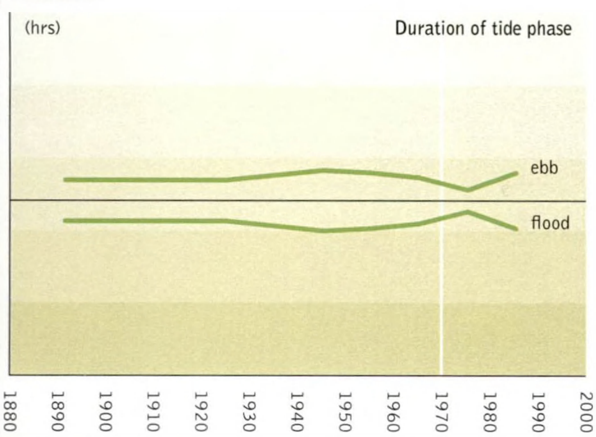


3.3-03 Duration of flood and ebb tide at selected stations between Vlissingen and Antwerpen - Changes and rates of change

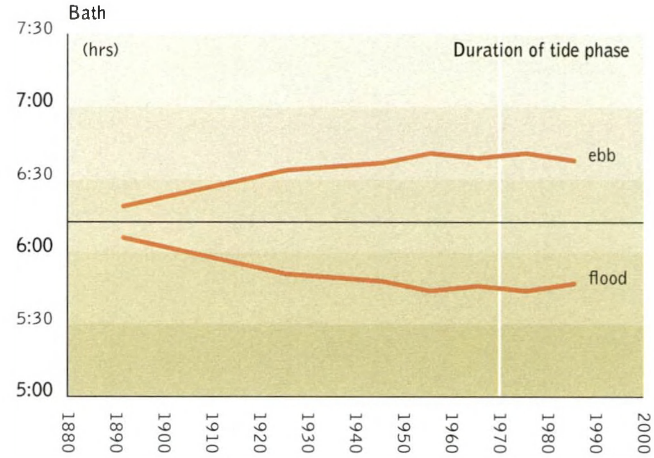


from data AWS

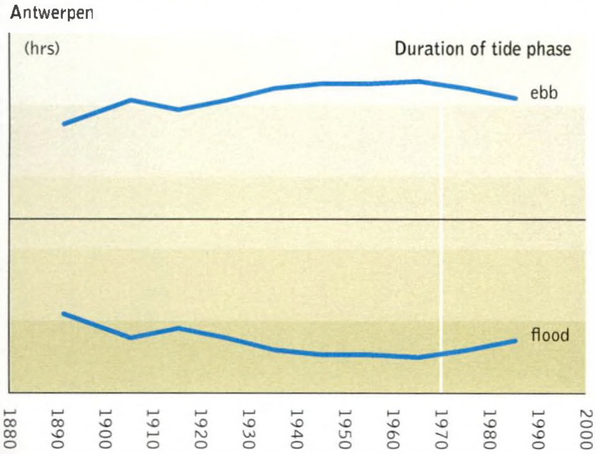
Hansweert



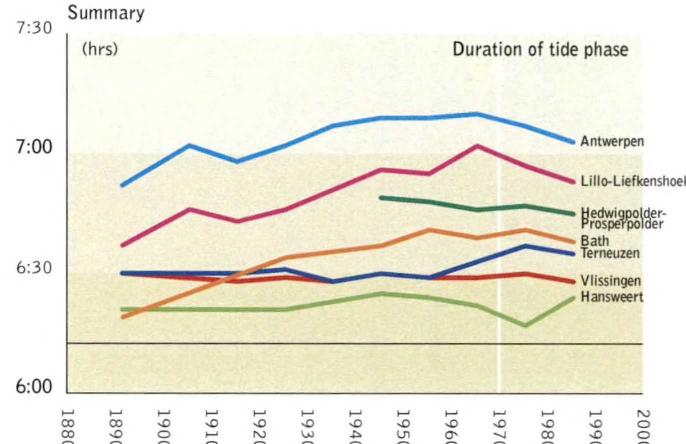
Bath



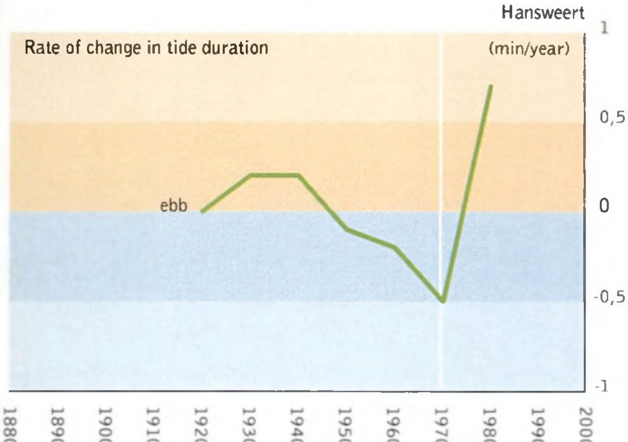
Antwerpen



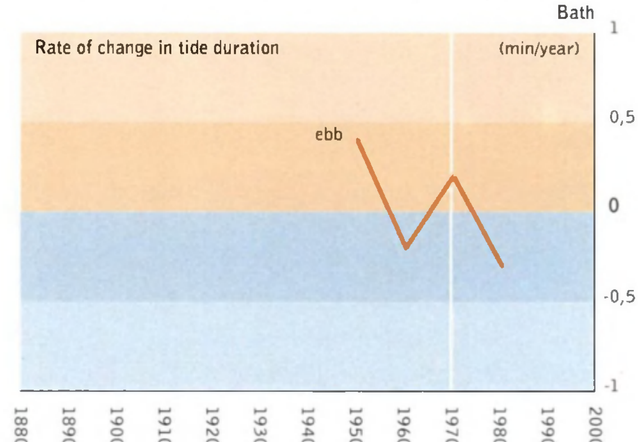
Summary



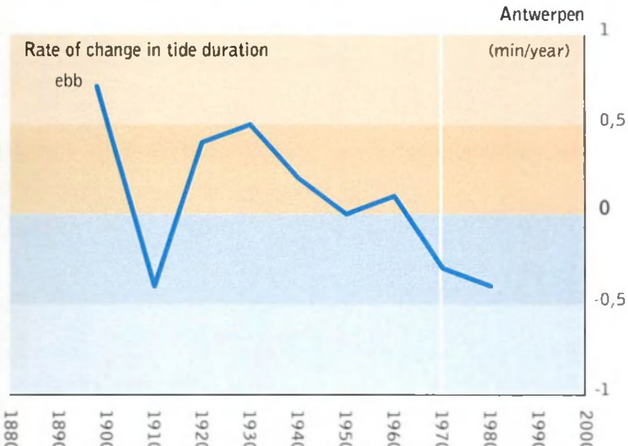
Hansweert



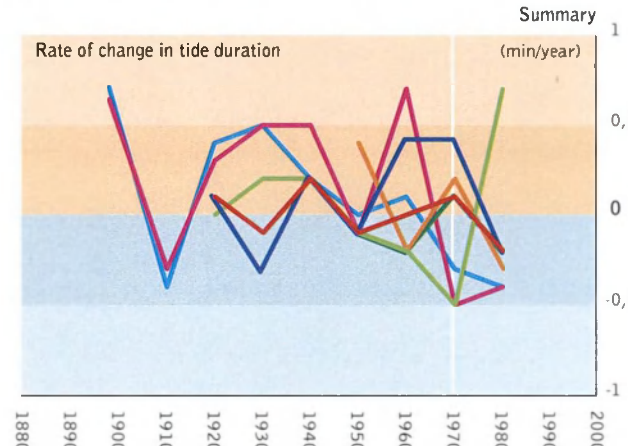
Bath



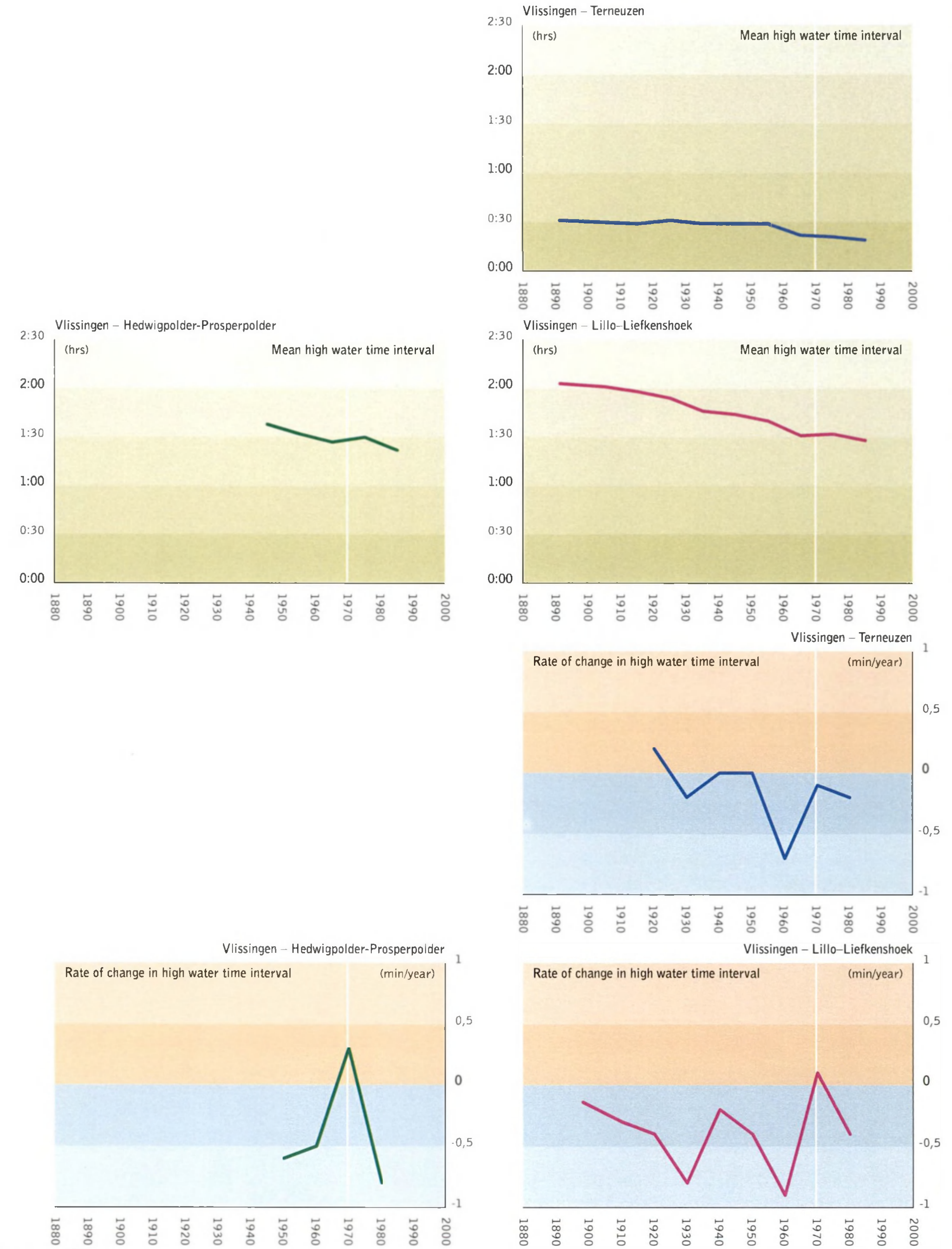
Antwerpen



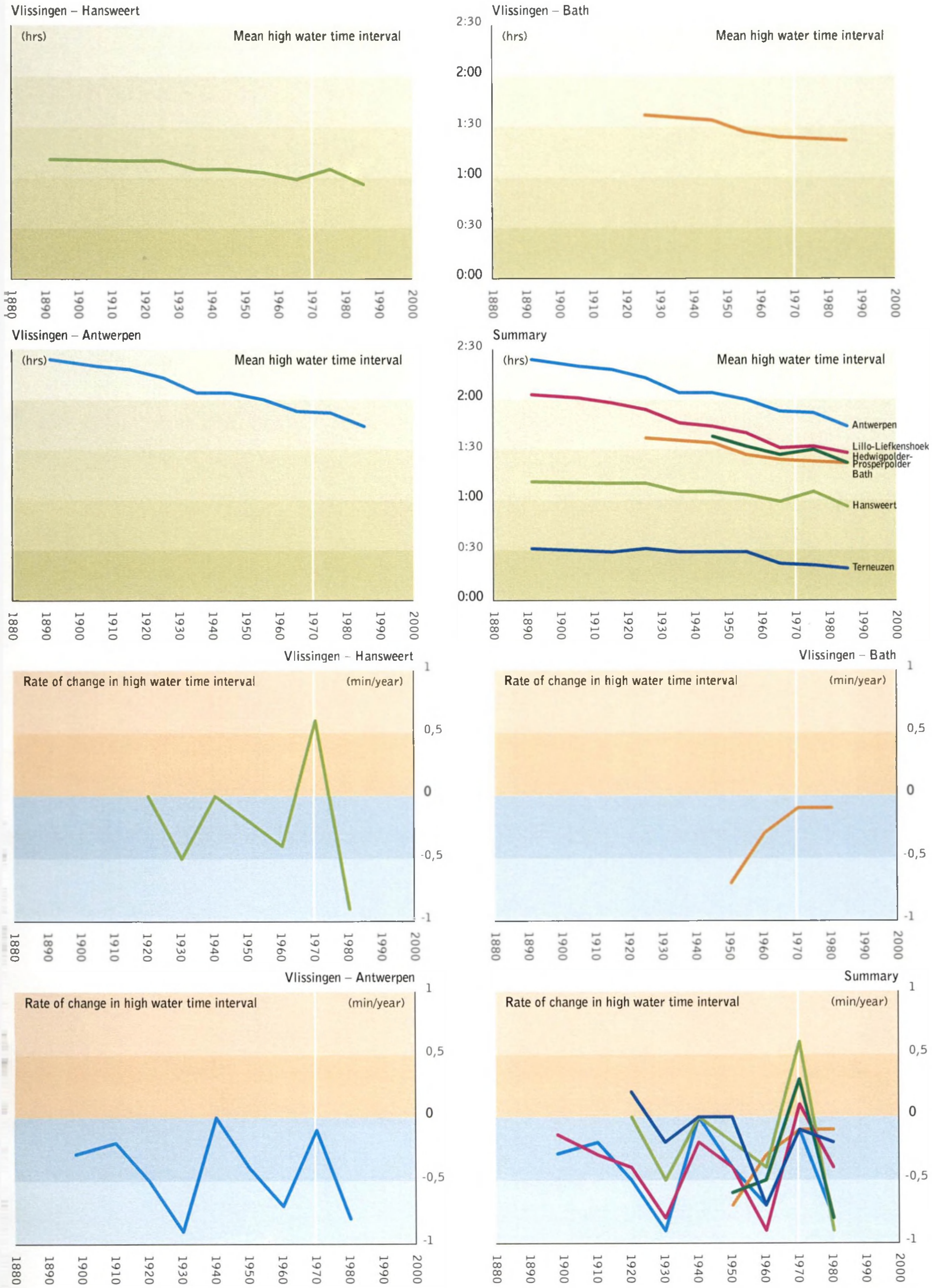
Summary



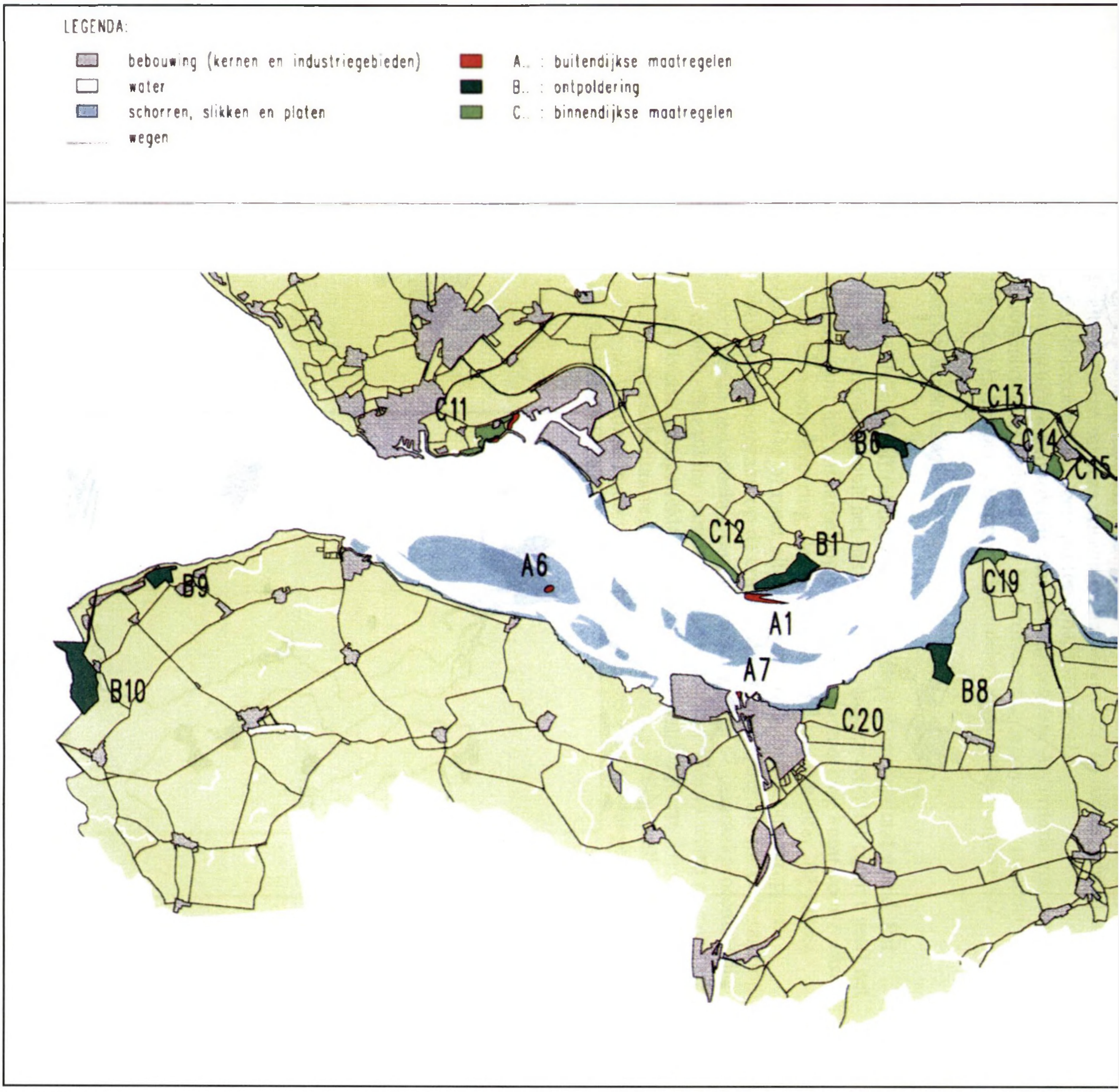
3.3-04 High water time interval at selected stations between Vlissingen and Antwerpen - Changes and rates of change



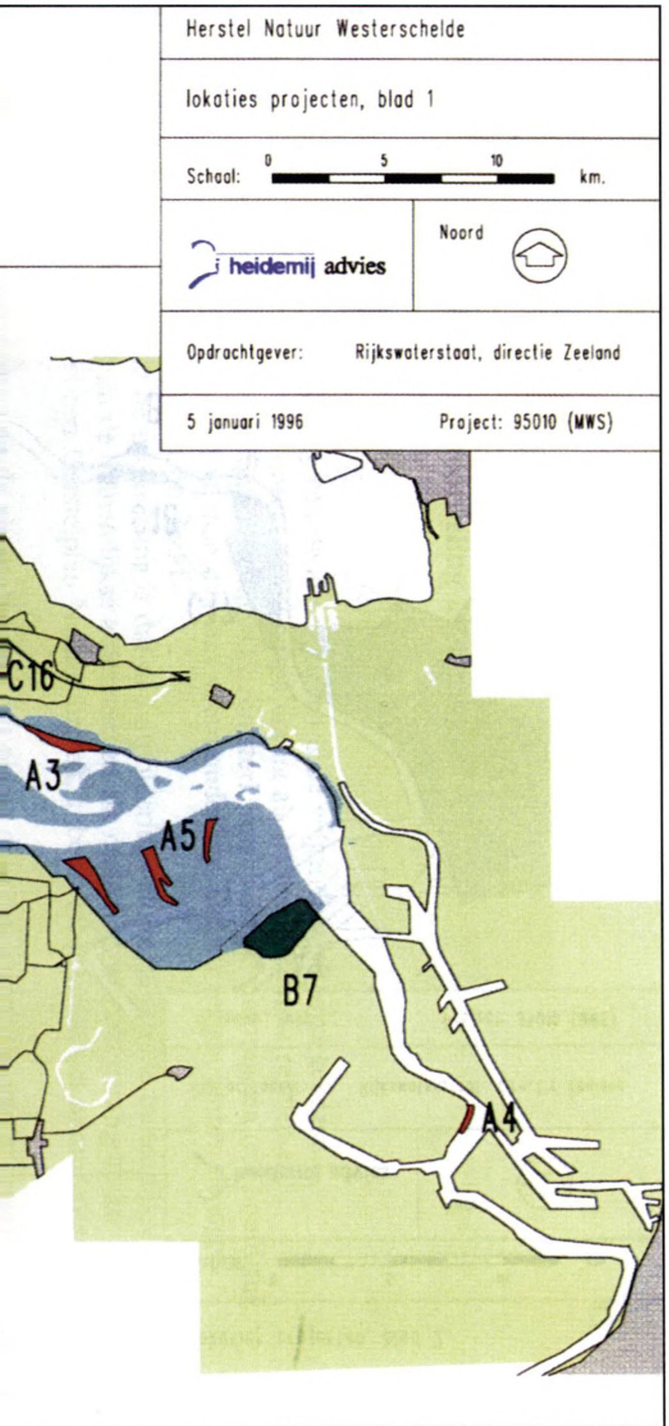
from data AWS


Vlissingen – Hansweert
(hrs)
Mean high water time interval
Vlissingen – Bath
2:30
2:00
1:30
1:00
0:30
0:00
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Vlissingen – Antwerpen
Summary
Antwerpen
Lillo-Liefkenshoek
Hedwigpolder-Prosperpolder
Bath
Hansweert
Terneuzen
Rate of change in high water time interval
(min/year)
Vlissingen – Hansweert
Vlissingen – Bath
Vlissingen – Antwerpen
Summary
1
0,5
0
-0,5
-1

4.4-01 Areas proposed for depoldering



Ref.: Herstel Natuur Westerschelde - Alternatieven, 1996, HEIDEMIJ - RIKZ - RA


Herstel Natuur Westerschelde
lokaties projecten, blad 1
Schaal: 0 5 10 km.
heidemij advies
Noord
Opdrachtgever: Rijkswaterstaat, directie Zeeland
5 januari 1996
Project: 95010 (MWS)
C16
A3
A5
B7
A4

4.5-01 Test area for alternative dredging strategy - Proposal PA Expert Team

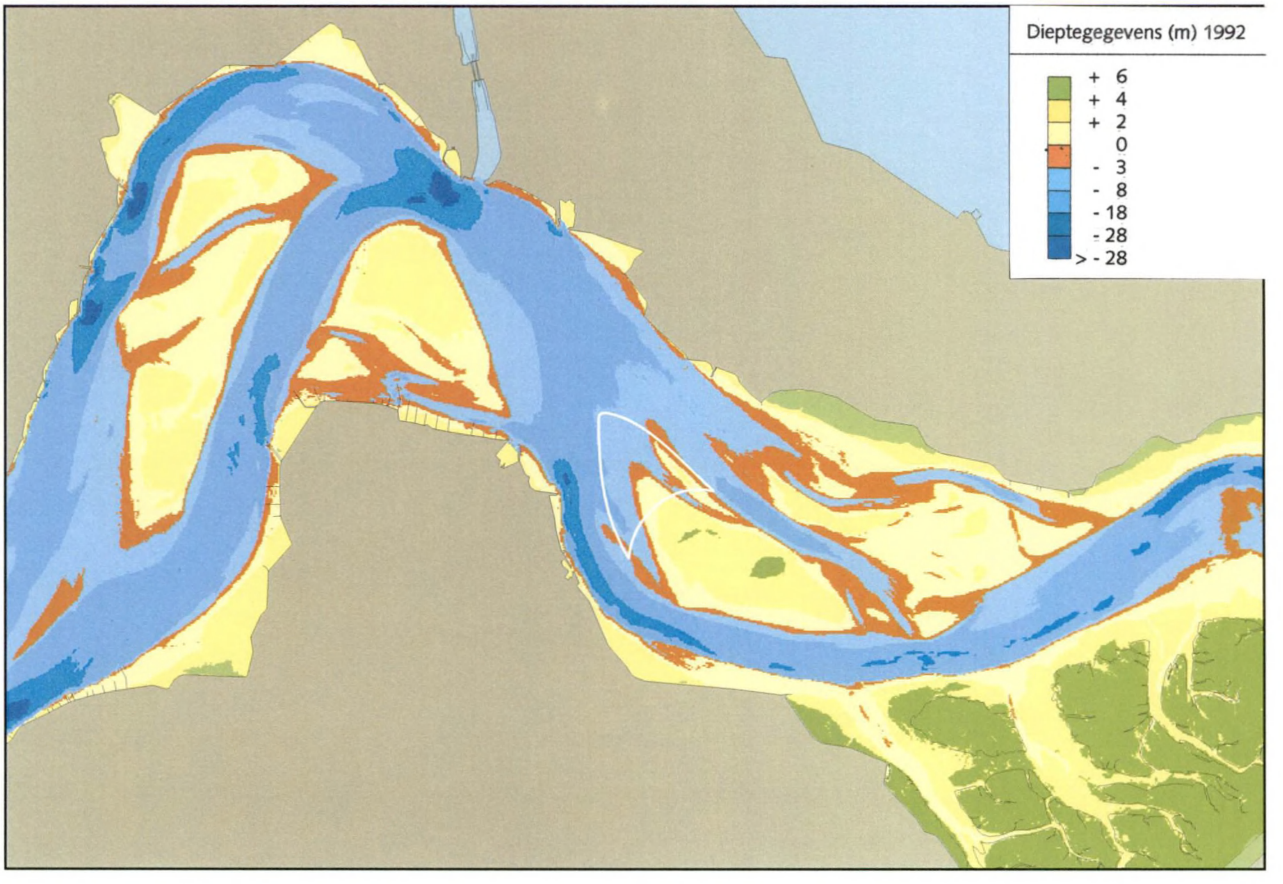


Chart data from RIKZ, situation 1992; original data in NAP, approximately transformed in GLLWS by lowering with 2 m