MORPHOLOGICAL MANAGEMENT IN ESTUARIES CONCILIATING NATURE PRESERVATION AND PORT ACCESSIBILITY

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Abstract

In 1999, Flanders and The Netherlands agreed to set up a common strategy for managing the Scheldt River in its estuarine reach. In 2002, both parties signed a memorandum of understanding in which was defined a 'Long Term Vision' strategy and its objectives. One of these is the preservation in the Western Scheldt of a dynamic and complex flood and ebb channel network, the so-called 'multi-channel system'. The present trend, a continuation of past natural morphological evolutions combined with human interference (poldering, dredging and other river works) may jeopardise this objective.
An expert team appointed by the Port of Antwerp proposed the idea of morphological dredging for curbing this negative trend, aiming at steering the estuarine morphology. In a first phase, sediment from dredging works could be used to reshape sandbars where needed. One case study is discussed in this paper, the aim being to reconstruct the eroded tip of a sandbar at a bifurcation so that the flood and ebb flows would be perseved, a condition to maintain the multi-channel system in the reach. The strategy would not only cut back on the ongoing degradation of the ecological and morphological values of the estuary, but it could also possibly help reducing the quantity of material to be dredged on the crossings by increasing the scouring or self-dredging capacity of the flow. A diffuser-type device was used to disperse the dredged material in a controlled way in shallow water along the sandbar edges.
In 2002-2003, the new disposal strategy has been investigated by Flanders Hydraulics Research as a pilot project (Plaat van Walsoorden). The research programme combined three tools: field measurements, physical scale models and 3D numerical models. The results of the research work confirmed the feasibility of the idea. However, the Port of Antwerp Experts concluded that a real life (*in situ*) disposal test was required to give final proof of the feasibility of this new disposal strategy.
At the end of 2004, 500,000m^3 of sand was disposed at the seaward tip of the shoal of Walsoorden using a diffuser. The main idea was to modify the morphology of this sandbar by disposing dredged material very precisely. The amount of 500,000m^3 was chosen because it is large enough to see an effect of the disposed sediment, while it is small enough to be reversible if something would go wrong. To evaluate the success of this *in situ* test, an extensive monitoring programme was set up, including bathymetric surveys, ecological monitoring, sediment tracing tests and sediment transport measurements.
After one year of monitoring the disposed sediments, it can be concluded that the experiment is very successful. The morphological monitoring showed that almost 80% of the disposed sediments is still on the disposal location after one year. The ecological monitoring did not reveal any significant negative impact, neither in the intertidal areas, nor in the subtidal areas. This *in situ* test confirmed the feasibility of the proposed disposal strategy. An estimated volume of 4 to 5 million m^3 could be disposed here to reach the proposed objectives, representing more than half of the volume dredged yearly in the Western Scheldt.

Keywords: Morphological dredging; Western Scheldt; Ecomorphology.

Introduction

The morphology of an estuary is continually changing, adjusting to the forcing processes which themselves are also changing. No estuary is therefore stable and habitats and the ecological functioning of the estuary will continually change from its present status even if man didn't intervene. This implies the need for a detailed conceptual understanding of the estuary system in question. Only such an understanding can lead to proper assessment of the effects of existing and future human activities, such as dredging and disposal, but also the construction of flow regulating structures and dikes. For any estuary there should be a holistic management plan, which takes into account the interests and effects of all uses and users of the estuary in an integrated way.

This paper focuses on the case of the Scheldt Estuary, where morphological management is used to conciliate nature preservation and port accessibility. The Scheldt is the aorta to the port of Antwerp, while it is one of the few remaining European estuaries covering the entire gradient from fresh to salt water tidal areas.

Overview of historical evolutions

Natural evolutions till 1000 AD

At the end of the Pleistocene, the last ice age, rivers in North-West Europe discharged in the Atlantic Ocean in the vicinity of the Doggersbank, far away from the present shores. With the warming up of the climate, the sea level rose very quickly over more than 100m from 20 Kyr BP to about 7 Kyr BP, then slower to become (comparatively) rather stable over the past two millenaries. The past rising sea level reshaped strongly the coastal areas and estuaries at the end of the Holocene. Many of these morphological changes are still ongoing. With the invasion of the street of Kales, tidal currents started to erode its banks, creating cliffs and feeding a littoral sediment transport that was at the origin of an almost continuous series of sandy bars and islands in front of the actual Belgian, Dutch and German coast (Fig. 1). An inner sea was formed, a kind of an extensive lagoon of which remains only the Wadden Sea. The sand barrier between lagoon and open sea was regularly breached during storms, scouring large channels deep into the inner sea. River sediments filled those parts of the lagoon receiving streams with large sand discharges, like the Rhine. In other parts receiving little and more silty sediment loads, like from the Scheldt River, tidal action penetrated progressively, developing further the sea branches. Import of marine sediments by the tidal currents formed large shoals in the lagoon. Sea branches not connected to a main river basin silted up (e.g. Zwin), while others like the Honte and the Eastern Scheldt expanded further as they were at that time connected to a river basin. Later on, the southern sea branch, the Honte, became dominant over the Eastern Scheldt and had now become the estuary of the Scheldt River. In the Southern part of the inner sea, shoals aggregated and channels enlarged. Around 1000 A.D., Zeeland had become a patchwork of islands, surrounded by a network of tidal channels. At that time, the River Scheldt discharged in the lagoon near Bergen op Zoom and both the Honte (present Western Scheldt) and the Eastern Scheldt were conducting the Scheldt River water to the North Sea. Till the 11th century, morphological evolutions were significant but fully natural, with almost no human impact.

Fig. 1. Situation during the Roman times.

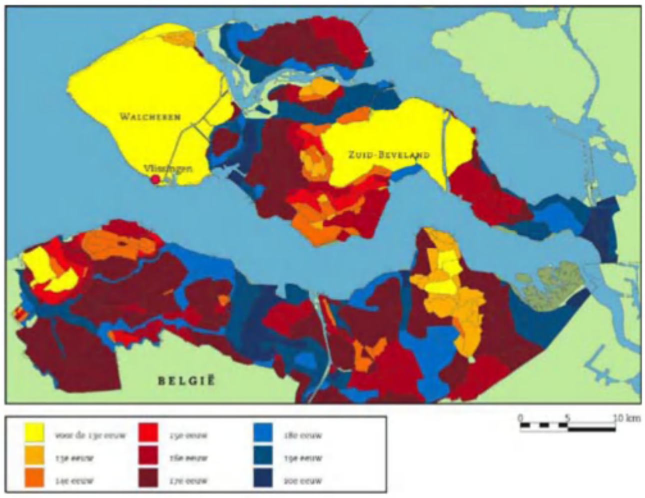

Fig. 2. Land reclamation from the 11th till the 20th century.

Human influence after 1000 AD

First signs of human impact on the estuary's environment become visible in the 11th century: locals reclaimed land that had silted up high enough and started to protect it against flooding (Fig. 2). However, inundations due to levee breaching during storm events returned repeatedly portions of land to the river. From the 16th century on, the poldering techniques had become more sophisticated and larger areas were permanently poldered (e.g. for eastern Zeeuws-Vlaanderen 50% of the total poldering occurred during the 17th century).

Poldering was less intensive during the 19th and 20th century because a large percentage of salt marshes had been reclaimed already. However, hydraulic works and storms continued to reshape the area. In 1867 and 1871, the two remaining links (Kreekrak and Sloe) between the Honte (Western Scheldt) and the Eastern Scheldt were cut off, modifying drastically the tidal channels network. A catastrophic storm with extensive inundation, in 1953, made the Netherlands decide about executing an extensive flood protection plan 'Delta'. From historical data can be concluded that these human impacts such as closure of secondary channels and poldering have strongly influenced the tidal regime of the Western Scheldt. Stronger tidal penetration enlarged the main navigation channel.

Sediment mining for providing building material started at the end of the 19th century. Since 1958, about 1 to 2 million cubic meters of sediment was mined per year, on average.

At the end of the 19th century, dredging activities (Fig. 3) were required to improve the accessibility of the port of Antwerp. Until the 1920's, these activities were concentrated on the Belgian territory ($2Mm^3.yr^{-1}$). From 1920 till 1960 the quantities on Belgian and Dutch territory were comparable ($2 + 2Mm^3.yr^{-1}$). The first large deepening campaign happened in the early 1970's, the main part of dredging works on Dutch territory ($3 + 10Mm^3.yr^{-1}$). Nonetheless, the increased dredging in the Dutch part did not apparently result in significant changes of the trend in morphology or tidal action. During the late 1990's, a second dredging campaign for improving the navigation conditions was conducted. The impact of the deepening by 4 feet is monitored (MOVE programme), but no significant negative impact was noticed yet.

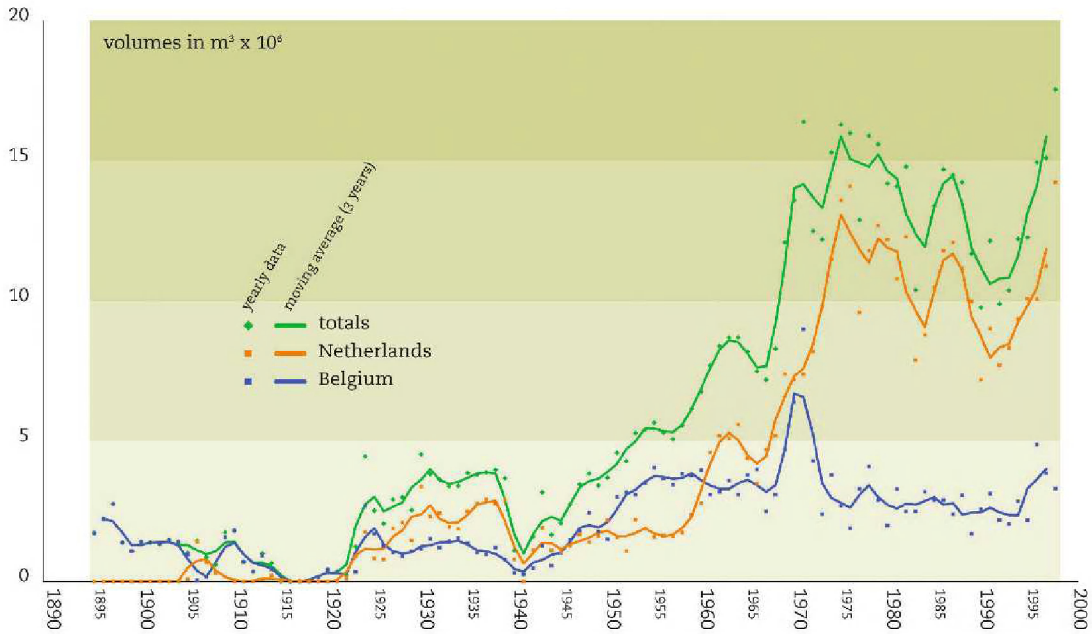

Fig. 3. Dredging activities in the Scheldt Estuary since 1895.

Maintaining navigation conditions in a morphological dynamic estuary

The morphological evolution of the estuary between 1800 and 2000 (Fig. 4) is one of further shoal aggradation and enlargement of the main channels. The estuary has been described as a typical multiple flood and ebb channel network. The main and deeper ebb channels have usually sills at the seaward end where they join together with the flood channels. These ones are shallower and have a sill at the landward side, where they join the main ebb channel. There are also many minor channels, the 'chute' channels, sometimes called 'short-cut' channels connecting the major ebb and flood channels. Historical maps reveal that the ebb or flood function of channels is not always obvious and sometimes even unclear. Ebb channels may turn into flood channels, and vice versa (see middle part of the estuary on Fig. 4). The reducing mobility of the channels and shoals is for a large part due to the hard bordering of the estuary (levees, bank protections, groynes, jetties and harbours); sandbars are rising too high, channels deepen, shallow water areas diminish.

A Dutch-Belgian Technical Scheldt Commission was set up in 1948 to manage technical issues such as the works needed for ensuring the access to the Port of Antwerp. Till 1970, dredging was restricted to maintaining depths on crossings in the navigation channel, formed by the main ebb channels. Traditionally, the sediments were disposed in the flood channels with the idea that it would take a rather long time before coming back into the main ebb channel.

With the demand for increased navigation depth, a first deepening started in 1970 and the dredged sediments were still disposed in flood channels. The disposal sites were decided in common by the Dutch and the Belgium administrations on the basis of the assessment of the ongoing morphological changes. The procedures were adjusted due to the increasing concern about environmental aspects and with the regionalisation making the Flanders region responsible in Belgium for public works and infrastructure. In 1995, Flanders and The Netherlands reached an agreement to deepen further the Western Scheldt shipping route. Works were executed in 1997 and 1998. However, the amount of sediment disposed in the eastern part of the Western Scheldt was reduced when aggradation was observed in some flood channels, supposedly because too much sediment had been disposed there. This siltation could eventually jeopardise the existence of the multi-channel system in that reach. Therefore, from 1997 on, more material was moved to disposal sites in the western reach of the estuary.

In 1999, the Dutch and Flemish governments decided to set up a Long-Term Vision (LTV) project with three objectives: to ensure maximum safety against flooding, optimal accessibility of the ports within the estuary and optimal nature development. These three subjects are all related to the morphology of the estuary. Directly concerned by these issues, the autonomous Port of Antwerp, independent from the Flemish administration, requested a group of experts (called Port of Antwerp Expert Team, or 'PAET') to give an opinion about the prospects for a further deepening and widening of the navigation route, mainly needed for the larger container ships. One of the main questions considered in LTV was where to dispose the large volumes needed for such an enlargement? Dutch researchers had claimed that flood channels would disappear if too large quantities of sediment were to be disposed there. Their conclusions were based on some assumptions and calculations with modelling tools, of which one is based on the so-called 'cell-theory' (Wang *et al.,* 1995; Winterwerp *et al.,* 2001). A 'cell' is composed of an ebb channel and a flood channel and the enclosed inter-tidal flats. According to this theory, sediment circulates in 'cells', with a net landward movement in the flood channels and a net seaward one in the ebb channels. The Port of Antwerp experts consider this schematisation as too simplistic. Based on their analysis of past morphological changes in general and of the (temporary?) decay of some flood channels, they stated that not (only) disposal of sediments was to be blamed, rather the always more stringent immobilisation of the main channels and shoals. To revert the reduction in dynamic morphological behaviour of the estuary, it was proposed to steer the development of channels and shoals. Recent studies show that the disposal of dredging materials has a much larger impact on the estuarine morphology than the deepening of the channels (ProSes, 2004). The main attention should therefore go to new strategies for disposal, although the Port of Antwerp expert team believes that dredging may also be beneficial for morphology, e.g. rectifying the shape of sandbars.

In 2002, the Dutch and Flemish governments signed a memorandum of understanding to implement together the Long-Term Vision programme. They set up jointly an organisation called ProSes (Project Direction for the Development Scheme of the Western Scheldt Estuary) funded by both regions and which main task was to establish for 2004 the development scheme with the objectives to be reached in 2010. Part of the research referred to in this paper was conducted within the frame of ProSes, though many activities were financed directly by the Flemish government and the Port of Antwerp.

Morphological management of the Western Scheldt

Morphological management of a river

Morphological management of rivers aims at finding measures to have their morphology evolving to a situation that is considered as 'desirable', which is obviously rather subjective as the goals may be very different. A river engineer may have very different views from an environmentalist or a biologist. Nevertheless, there is a growing interest in the 'management' approach versus the 'engineering' or 'river taming' approach, especially because of past negative experiences with river training.

In 1968, Flanders Hydraulics Research faced the challenge to improve the maritime access on the Congo River. It could profit from a very long experience with dredging in such a powerful river with very high discharges and sediment transport rates: the so-called 'Directed Dredging Method' [Méthode des Dragages Dirigés, (*in French*)], based on a thorough analysis of field data.

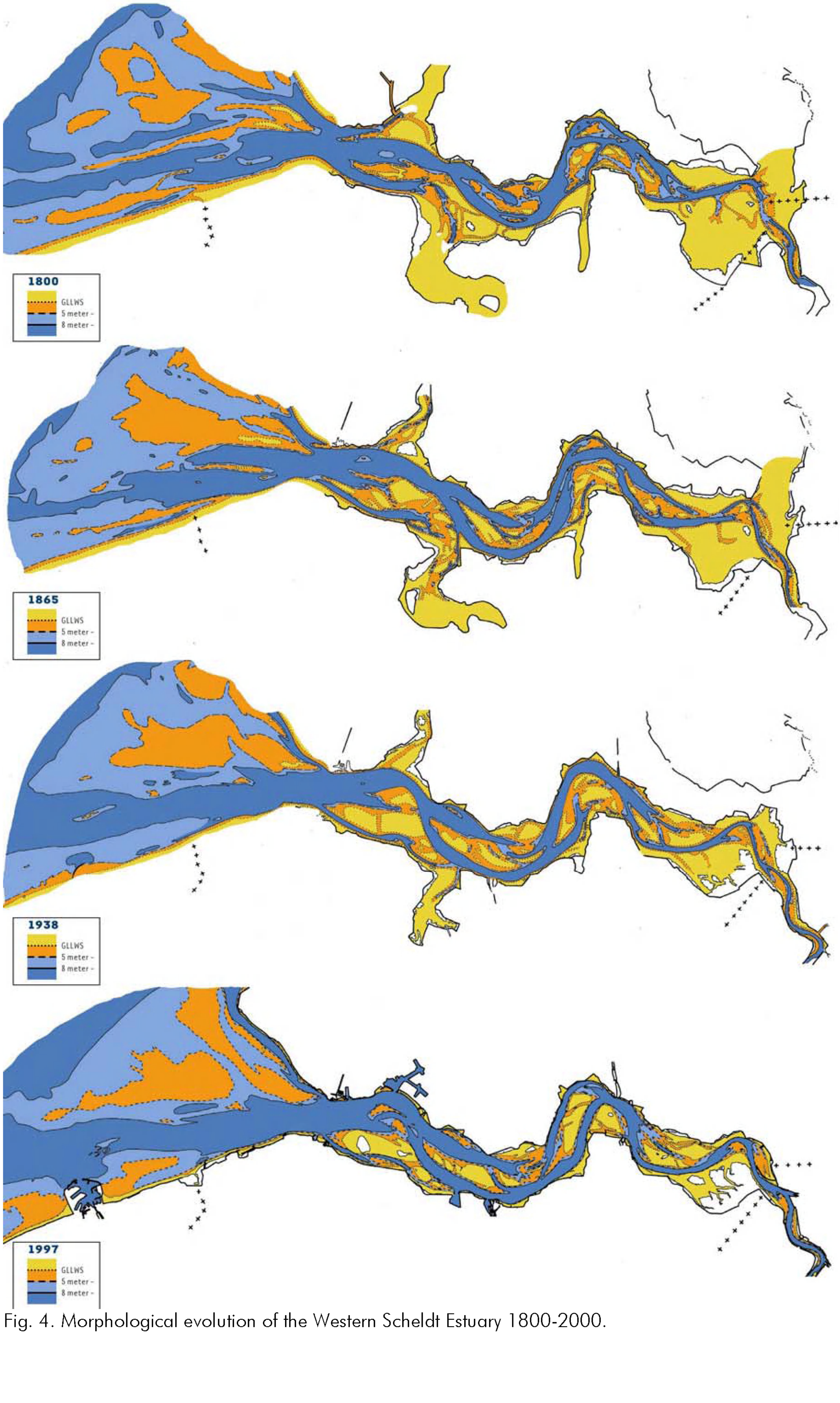

Fig. 4. Morphological evolution of the Western Scheldt Estuary 1800-2000.

This method was further developed carrying out scale model studies and extensive field surveys, to become the 'Morphological Dredging Method' (Peters and Wens, 1991). The idea of morphological management was further developed in other projects on very different rivers, such as the Pirai in Bolivia (Peters, 1994) and the Ichilo River, also in Bolivia (Peters, 1998). The same philosophy was applied: understanding the river behaviour and working with the river, not against nature, using simple and cheap methods. In the first case of the Pirai River, the traditional way to protect against flooding with high levees and strong bank protections was replaced by lighter protections in combination with adaptation of the river plan form. In some cases, the river shore alignment was changed with excavations so that the flow would not attack the banks. The strategy was based on a continuous monitoring. In the second case of the Ichilo River, the occurrence of a natural cut-off was halted with light guiding structures, which aimed at orienting the flow away from the meander bottleneck. In this way, it was possible to save time for designing artificial cut-off's, which allowed the river to remain along the Puerto Villarroel harbour, of major importance for the transport of goods from and to the Bolivian Amazone region. In all cases, a follow up has shown that the methodology of river management was feasible and could be successful, at the condition it was based on the best possible understanding of the physical (morphological) behaviour of the rivers. It also showed the advantage of using recurrent measures, such as dredging or excavations.

Morphological dredging

During a meeting with the LTV's working group on morphology, in the year 2000, the Port of Antwerp experts suggested 'morphological dredging' as an alternative to the present dredging strategies. It is based on the principles developed for the maintenance and the capital dredging in the navigation route in the Congo inner delta, for example by redistributing the sediment transport and using dredging and disposal to change the plan form of the river.

Disposal is a way to redistribute the sediment in the Western Scheldt, so as to feed, as an example, areas eroding too much, not only in the flood channels, also on some parts of shoals. The Port of Antwerp expert team worked out a proposal to restore the western tip of Walsoorden plate that erodes since several decades. Several millions of cubic meters of sediment could be stored at that place (Fig. 5 – white hatching). The technique could be applied in other places along the estuary. One advantage of the proposal is that the additional volumes produced by the capital dredging required for a further improvement of the navigation route could be kept within the estuary instead of exporting it out of the estuary, into the sea. Nobody knows today what would result for the Western Scheldt from such an export in terms of tidal propagation and environmental impact. The estuary is said to have very little sediment exchange with the sea and the quantity of sediment supplied by the river is rather small, limited to very fine material, mainly silt and clay.

The second part of morphological dredging is to correct the shape of shoals when this impacts negatively on the overall flow and sediment patterns. This may be illustrated by the example of the sand spit at the seaward end of the ebb channel at Walsoorden (at the Southwest end). It is formed by the combined action of flood and ebb and, together with the protruding groyne and the levee on the left bank, it constricts too much the flow during the end of the ebb flow. It may be that this results in a less effective flow on the crossing of Hansweert, just west of the tip of the Walsoorden sandbar. In that case, modifying the shape of the sand spit by disposing dredged sediments might improve the self-dredging capacity of the crossing, reducing finally the dredging effort.

Modifying the hard bordering of the estuary

The Port of Antwerp expert team considers that the layout of the hard bordering is not always beneficial for achieving the objectives set out in LTV. The development of shoals and channels is controlled by levees and other hydraulic structures. The plan-form layout of these levees was not planned; they were established erratically, often by building new levees after breaches occurred during extreme storms. Some brutal changes in the orientation of the levees create hard points protruding into the estuary and controlling the position and shape of sandbars. The analysis of the Walsoorden test-site lead to the conclusion that the piers of the Hansweert lock access channel (on the right bank), protruding in the main channel, affect the orientation of the flood flow towards the Walsoorden plate, enhancing its erosion. More than thirty years ago, a dike protruding in the river at Walsoorden (on the left bank) was modified to improve the morphology so that dredging would diminish on the nearby crossing of Hansweert. However, the overall morphology in the river stretch changed meanwhile so that this dike could have today a negative impact on the crossing. PAET decided to make an inventory of similar situations, for analysis of possible solutions.

Criteria for selecting disposal areas

The selection of disposal areas must be based on several requirements, related to safety against flooding, accessibility and nature preservation: producing a morphology reducing the maintenance dredging effort, maintaining a dynamic multi-channel system in which tidal energy could be dissipated as much as possible, ensuring the preservation of a variety of ecotopes. All these criteria are linked to the morphological development of the estuary, to be steered by dredging and disposal of dredged materials.

Monitoring

Our understanding of the morphological processes in rivers and estuaries is not sufficient to predict very precisely the response induced by dredging and disposing the sediment in specific places. Morphological dredging and disposal is reversible up to a certain point. Selection of disposal sites must be flexible and it must be possible to halt operations if unwanted morphological changes are observed. Therefore, a comprehensive monitoring programme is absolutely needed. This includes, among other: flow measurements, topo-bathymetric observations (among other with multibeam charts and LIDAR observations), bottom sampling for sediment size and biological data acquisition, sediment transport measurements and possibly sediment tracking.

Technology for morphological dredging

The dredging companies contacted for advice about the disposal of material in controlled way close to the riverbed have developed a system by which the sediment is disposed quietly with a diffuser in shallow water (Fig. 6). This technique has already successfully been applied in coastal areas (Goossens and Bosschem, 2002).

Potential benefits for the environment

A careful choice of disposal sites, based on good field data and possibly completed with modelling, may produce a selective spatial dispersion of the sediments along the sandbar. Some particle fractions will preferentially move in the deeper areas, other moving towards the shallower ones, possibly up to the top of the bar. During the process, the change in morphology by aggrading up some parts of the bar will change the flow patterns and modify consequently the local sediment transport capacities. This will obviously also change the sedimentation pattern, also of the finest particles moving in suspension in the water column. The segregation of sediment fractions of both disposed and natural sediments will result in the formation of different substrata, some more silty than other, creating a variety of ecotopes.

In a common meeting of the ProSes working groups on morphology and ecology, it was decided to involve biologists and ecologists in the Walsoorden test disposal, monitoring closely the physical, chemical and biological parameters. Surveys would take place before, during and after the test disposal. However, the rigid conditions for the disposal of dredged materials delayed the test for several months.

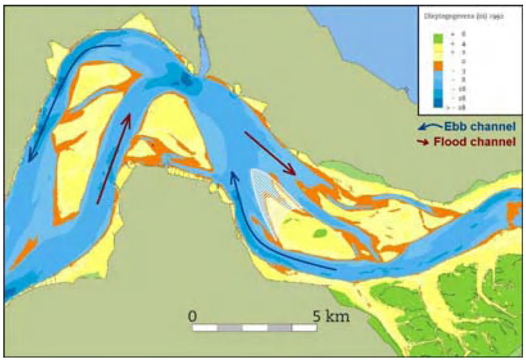

Fig. 5. Walsoorden area.

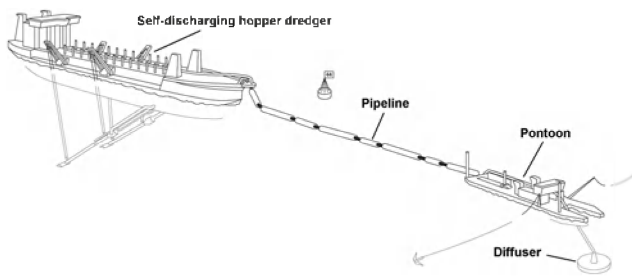

Fig. 6. Schematisation of disposal technique.

Research on the Walsoorden test case

Tools and tests

The PAET has stated from the beginning of the Walsoorden project proposal (Peters and Parker, 2001) that field measurements and physical and numerical models needed to be combined, as each of these study tools has advantages and limitations. They must be seen as complementary tools for the assessment of the alternative dredging and disposal strategy. The research programme included a field measurement campaign (floats, sediment transport), physical, fixed bed scale model tests for both the flow and the bed sediment movement and hydrodynamic numerical model simulations. Flanders Hydraulics Laboratory (Ministry of Environment and Infrastructure) executed this programme with the support of the Port of Antwerp and its expert team.

Field measurements provide an insight in the processes as they occur in nature. Due to changes in natural conditions (e.g. tidal variations), a measurement campaign may only give information limited to the prevailing conditions. Measuring techniques have obviously also their limitations.

DGPS tracked floats supplied information on flow patterns during the tide. These flow patterns were measured during a full spring-neap tidal period and provided on one hand information about the *in situ* flow conditions and on the other a series of data that were used to calibrate and validate the models. Sediment transport rates were measured during one tidal cycle, using both Delft Bottle (DB12) and Acoustic Sand Transport Meter (ASTM), in three points at the seaward tip of the Walsoorden sandbar (Fig. 8 – yellow dots). The bottom topography was measured near the tip of the plate using multi-beam (Fig. 8 – green area).

A second tool used in the project is the physical scale model. With best possible scales according to scaling laws, processes such as flow and bed load transport are well represented. Models present the possibility to control and change the testing conditions. Errors may become problematic when horizontal and vertical scales differ too much in a distorted model. Though the distortion is rather high (but not exceptional) for the Western Scheldt-model (horizontal scale = 1/400 ⇔ vertical scale 1/100), exaggeration of some processes – such as secondary currents – in the model induces discrepancies with reality. They seem however acceptable for the objective of the model tests on disposal of dredged material.

The hydrodynamic experiments in the scale model made use of small floats aiming at reproducing the measured float tracks in nature. Cameras registered the flow patterns. A second series of tests simulated the behaviour of disposed sediment in front of the tip of the plate. Therefore it was found that polystyrene (with a median diameter of 450μm) was the most appropriate material for the scale model. This material allowed a good reproduction of the moment of initiation of movement, nevertheless the transport rates weren't simulated correctly.

Finally, numerical models were used. These also have a high flexibility because test conditions can easily be adapted. Restrictions arise in the numerical representation of natural processes, for which the physics is still not always well understood, as is the case for sediment transport. This makes the applicability of morphological processes in numerical models doubtful. For some model parameters the physical meaning is rather low and they have to be calibrated.

A global 2Dh model of the whole tidal influenced zone of the River Scheldt was set up in SIMONA-software (as used by Rijkswaterstaat) to simulate the tidal propagation and horizontal salinity gradient. This model generated boundary conditions for a detailed model of the study area (Terneuzen – Schelle) which was set up in Deflt3D software (WL|Delft Hydraulics, 2003). In a first approach the detailed model was set up as a 2Dh model. Complex secondary currents (produced by ebb-flood-channel bifurcations, as well as salinity gradients) required a 3D approach. Sensitivity analysis allowed to conclude that the use of a 3D model with at least 10 layers was best suited to produce the most reliable flow fields.

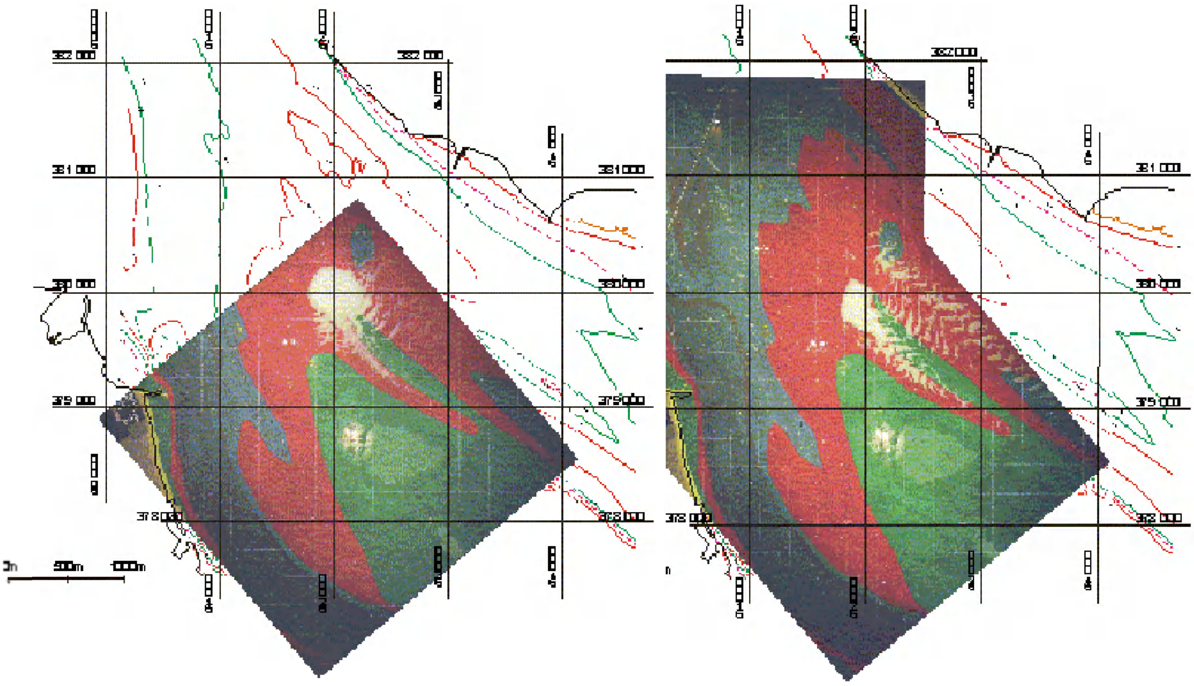

Fig. 7. Disposal experiment near the tip of the plate of Walsoorden in the physical scale model.

Results

The field measurements revealed that the two secondary flood channels, located at each side of the Walsoorden sandbar tip, have a different hydrodynamic behaviour (Fig. 8 – float tracks during flood). The northern sand spit clearly guides the flow during the well-developed flood and ebb flow. The southern sand spit does not guide very much the flow, neither during flood or ebb phases. Nevertheless, it remains in place since long and its existence is likely linked to secondary flow structure (due to hard bordering of the left bank) and to bed load paths. Interesting to note is the significant ebb flow effect along the northern border of the Walsoorden sandbar in the main flood channel.

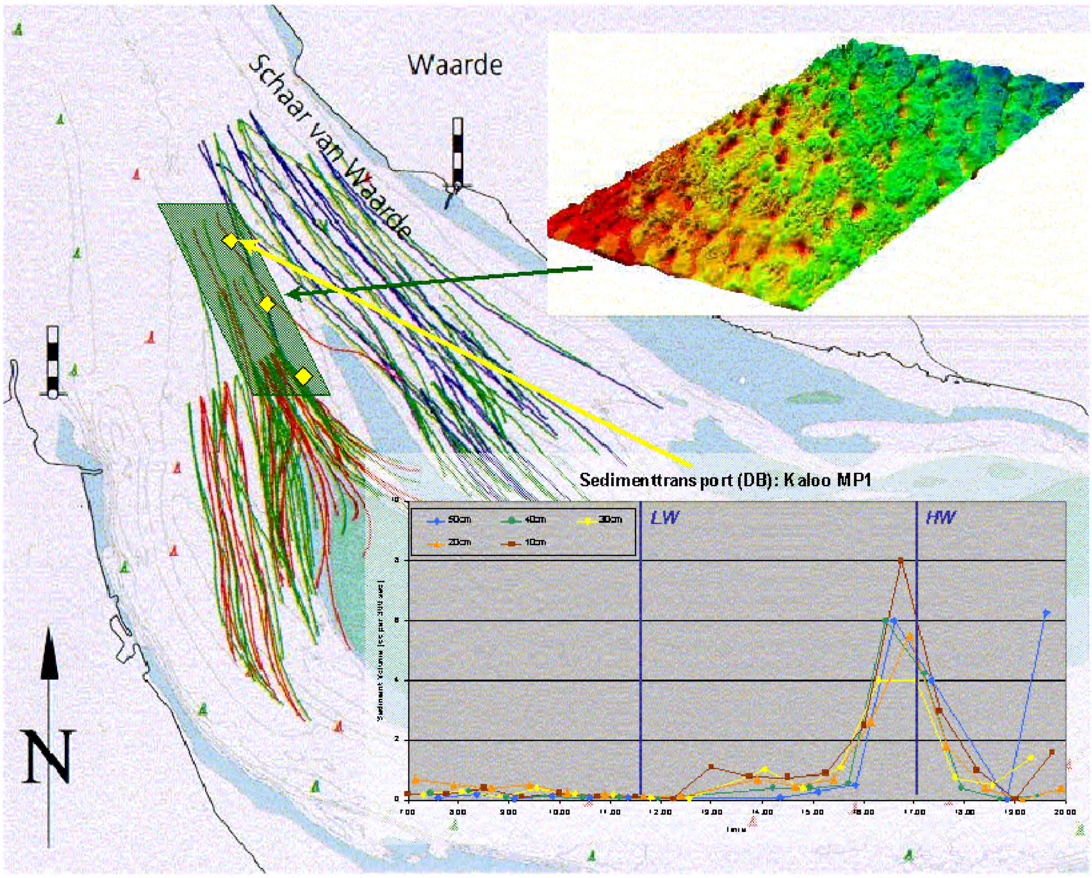

Fig. 8. Field measurements (background: floats; right top: multi-beam; right bottom: sediment transport).

The sediment measurements revealed that sediment transport takes place during the first ebb phase and during the flood phase (Fig. 8). After the initial ebb phase, when the water level has dropped, the tip of the sandbar is located in the shadow of the Walsoorden sandbar and sediment transport is very low. During flood, both DB12 and ASTM data show that the transport rate is the lowest at the location closest to the plate. At the start of the flood, higher transport rates are observed furthest from the sandbar, but the difference with middle location is very small. In contrast, the highest rates during the maximum flood occur in the middle location.

As far as hydrodynamics is concerned, it can be said that the comparisons between the results observed in scale model and those computed on the one hand, and with the measurements on the other hand are rather encouraging (Fig. 9 – top). The results indicate to date that the overall flow patterns are quite well reproduced, though differences were found, mainly during slack low water and early flood period (Fig. 9 – bottom). This positive statement does not mean that the numerical simulation models are in any way 'validated' or 'calibrated' and that from now on they can be used and trusted for all purposes. More specifically, in our opinion they should not be used without precaution or limitation, as an operational tool to study the alternative disposal strategy at Walsoorden.

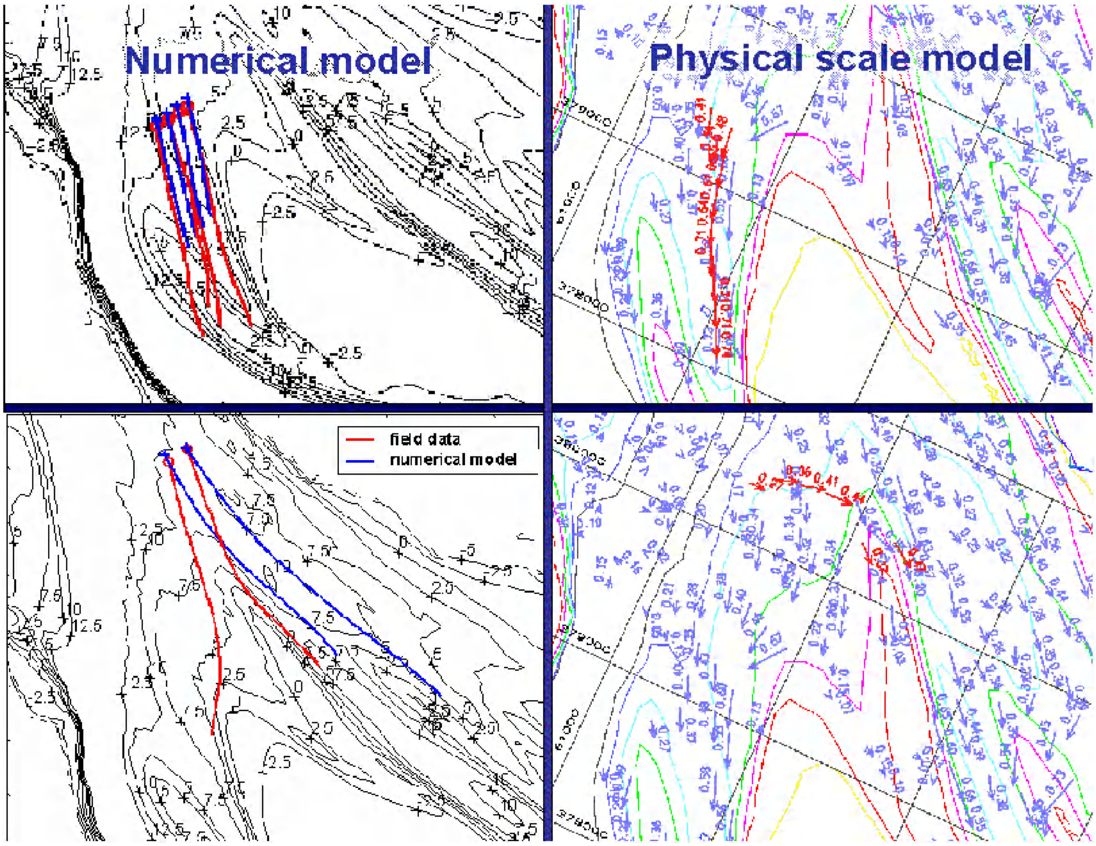

Fig. 9. Modelling results (red: field data; blue: modelling result).

Conclusion about the feasibility study of the Walsoorden test site

Although a number of aspects of the study, that were indicated by the PAET as being essential for assessing the feasibility of the proposed disposal strategy, were not undertaken – specifically additional sediment transport measurements – the results derived from the studies concerning hydrodynamics and sediment transport (Flanders Hydraulics Research, 2003) indicate that the placement of material as proposed for the morphological dredging strategy can likely be used to influence the estuarial morphology (PAET, 2003). Degraded areas and their associated biotopes could be regenerated. PAET insisted on having a small scale *in situ* disposal test to gain final evidence that the proposed strategy is feasible.

The analysis of the data has also shown that all investigative tools were needed to reach this conclusion and that morphological assessment of the Western Scheldt should not be based on modelling alone. One should realise that our knowledge about and understanding of the physical processes governing morphological changes is still not sufficient to set up trustworthy models. Combining different tools is the only way to reduce the uncertainties.

Where most of the research occurred within the scope of ProSes, a second opinion team was asked to give their comments on the methodology used for and the results gathered from the research. They confirmed that the idea to use dredged material to restore sandbars is very valuable and that an *in situ* disposal test is necessary to remove the remaining uncertainties about the proposed strategy.

The walsoorden *in situ* disposal test

Execution of the disposal test

The execution of an *in situ* disposal test had to bring final proof of the feasibility of the alternative disposal strategy. The idea of the *in situ* test was to dispose quietly and precisely 500,000m³ of sand with a diffuser on the bottom. The dredging vessel (self-discharging hopper dredger) was connected to a floating pipeline through which the sand is transported to a pontoon 'Bayard II' (Fig. 6). On this pontoon the sand is pumped to a diffuser (Fig. 10) that disposes the sediment in a precise way on to the bottom. The use of the diffuser required an adjustment of the disposal license. The amount of 500,000m³ was chosen because it is on one hand large enough to affect significantly the bottom morphology, however on the other hand small enough to be reversible if something would go wrong. The choice of the disposal location was based on the results of the feasibility study. The float measurements, the results of the numerical simulations and the physical scale model tests with moveable material on fixed bed indicated that an area between the northern sand spit and the tip of the plate was most suitable for an *in situ* disposal test (Fig. 11). From 17 November to 20 December 2004, 500,000m³ of sand was almost continuously disposed in the proposed area.

Fig. 10. Detail of the diffuser.

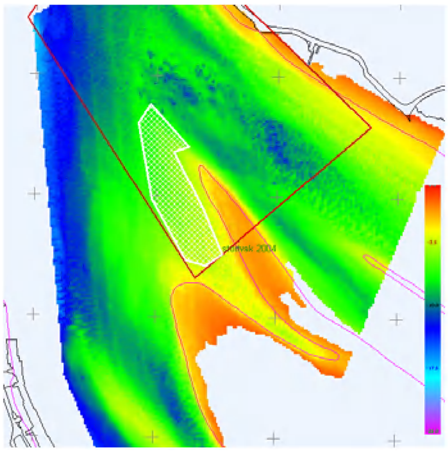

Fig. 11. Licensed disposal area (red) and disposal test area (white)

Monitoring of the disposal test

To evaluate the success of the test an extensive monitoring programme was set up. This programme, which was executed over a period of one year, included bathymetric surveys, ecological monitoring, sediment tracing tests and sediment transport measurements. Several criteria were defined before the test for evaluating its success. One of them stated that two weeks after finishing the disposal execution of the test, at least 80% of the disposed sediment should stay within the control area (this was defined as the disposal area, extended slightly towards the sandbar of Walsoorden). Also the ecological parameters should not indicate a change in ongoing natural trends.

Bathymetric surveys

The bathymetric surveys were executed using the multibeam-technique, producing high resolution bathymetric charts. From the start of the experiment (November 2004) until March 2005, weekly surveys were executed in an area around the disposal location (area ~ 900ha). From March until June 2005 the measurement frequency was reduced to one survey every 2 to 3 weeks, while from June 2005 until January 2006 one survey per month was executed. Beside this possible impact area, a larger zone was measured every two months, to capture possible larger scale influence of the *in situ* test. These surveys allowed volume computations for the control area. The evolution of the sediment volume is shown in Fig. 13. The amount of disposed sediment should be corrected due to the differences in density in the hopper and *in situ*. Therefore a correction factor 0.9 was applied to the hopper volumes. As can be seen in Fig. 13 the first survey after the execution of the disposal test shows a smaller volume measured *in situ* than what was disposed. This small difference (25,000 m^3) represents the sediment losses during the disposal of the sand, where a fraction (finer sands) was transported by the currents.

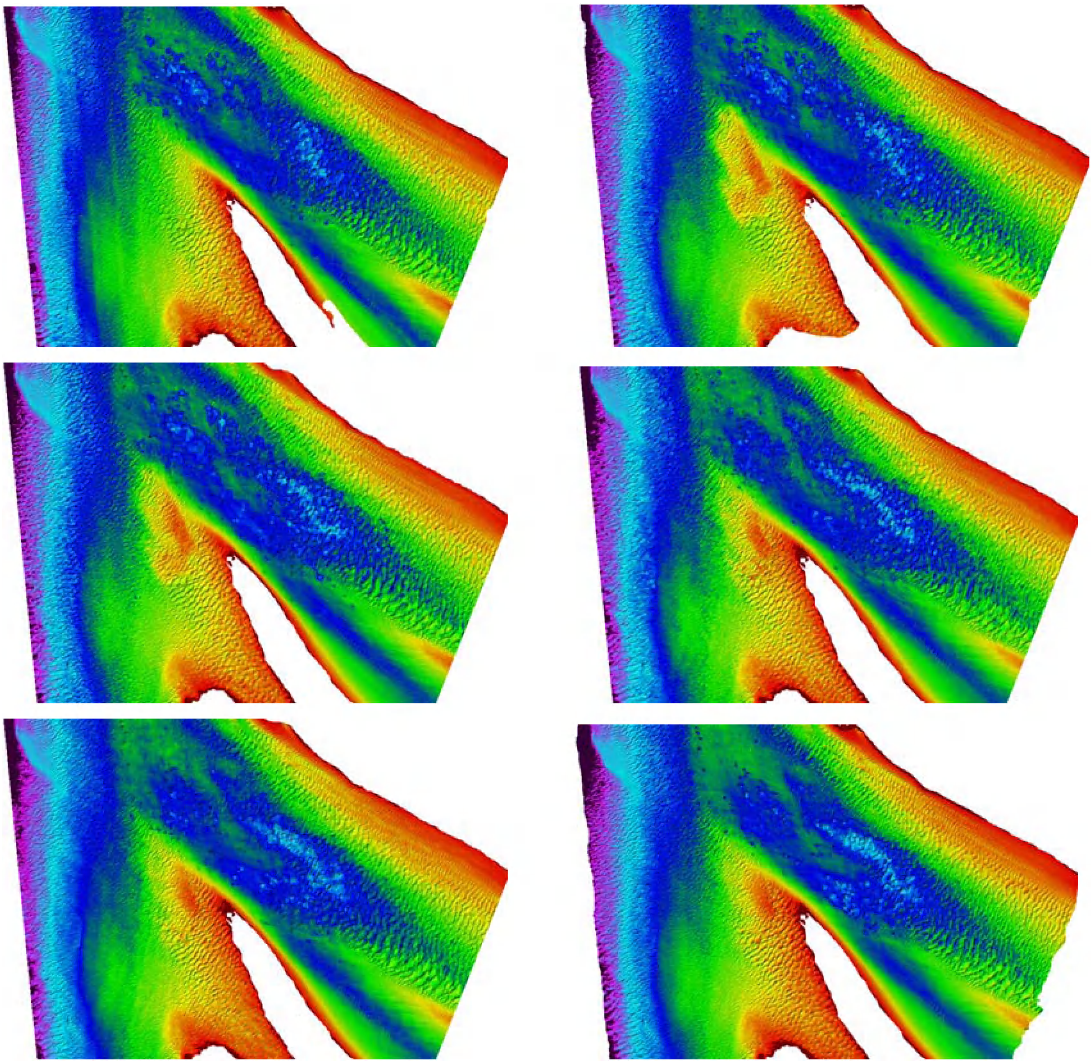

Fig. 12. Evolution of bathymetry [November–December 2004 (top); March-June 2005 (mid); September–December 2005 (down)].

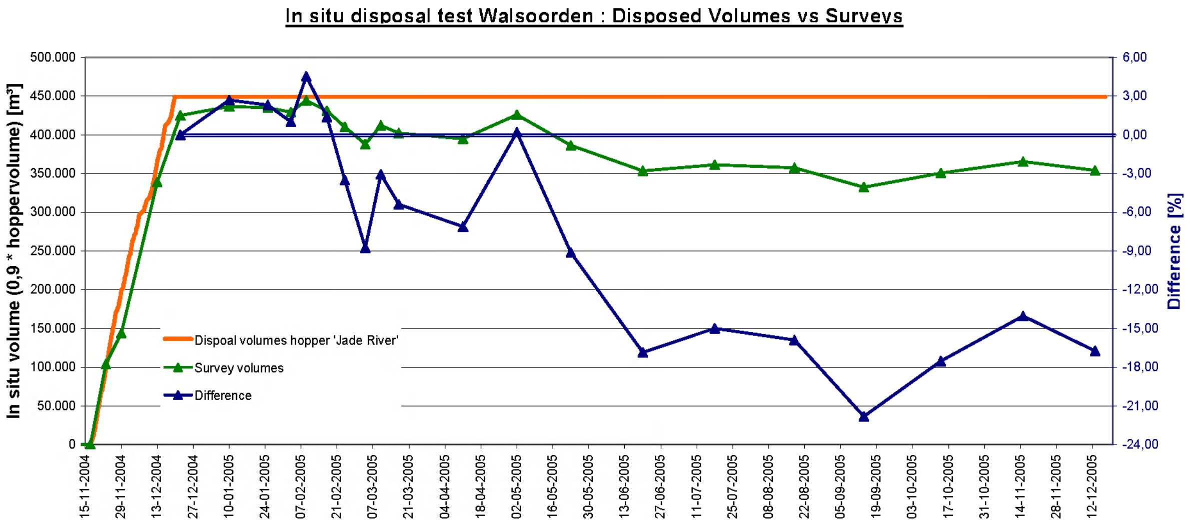

Fig. 13. Evolution of measured volumes.

During the first two months the volume within the control area was even higher than after execution of the test, probably due to natural processes. Afterwards a decrease of volume was measured, a loss of ~ 10% after six months, almost 20% after one year. The main part of the eroded sand is transported during flood towards the Walsoorden sandbar. This evolution is in agreement with the predictions of the feasibility study. Fig. 14 presents the evolution of a longitudinal section through the disposal area. The bedforms, present before the test (red), were flattened out by the disposal of the sediments with the diffuser (green). Immediately after the test, new bedforms started to develop in the disposal area, resulting in a new pattern (yellow) some three months after the test. After six months, the new bedforms are well developed (blue). Sediment is eroded from the down-estuary side (400-600m) of the disposal area and transported with the flood flow towards the up-estuary side (1000m). It may be concluded that the disposed sediments stay well in place, and the imposed criterion was successfully fulfilled.

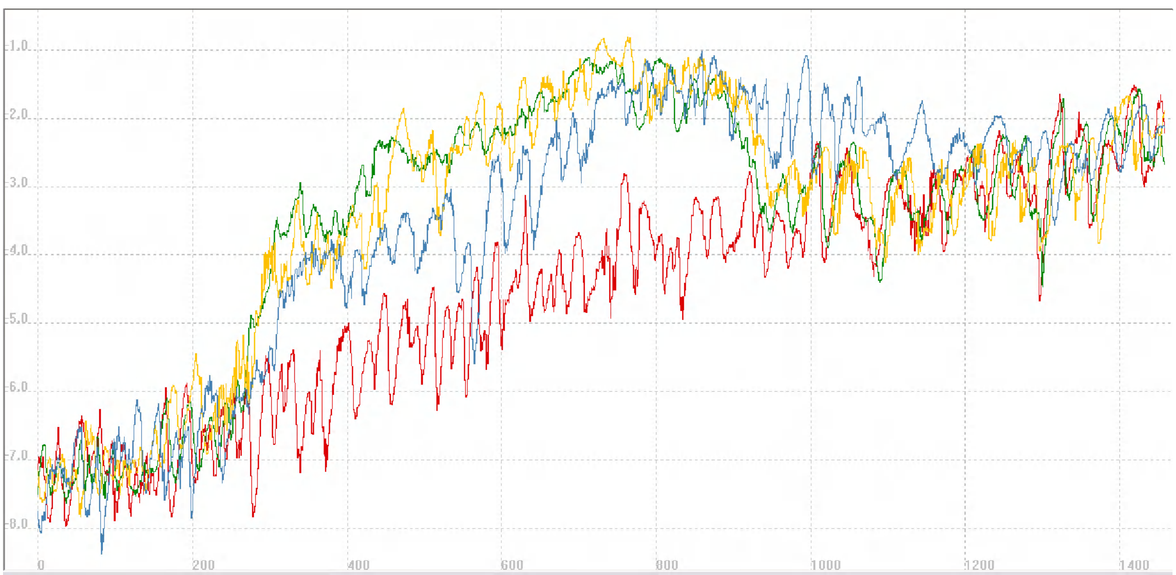

Fig. 14. Longitudinal profile through disposal area (red = November 2004; green = January 2005; yellow = March 2005; blue = June 2005).

Ecological monitoring

The ecological monitoring programme included both intertidal as subtidal measurements. Ecologists feared increased sedimentation, especially of coarser sediment on the sandbar, which could have a negative impact on its biotopes. The intertidal monitoring comprised of several stations on the Walsoorden sandbar where erosion-sedimentation, sediment composition and macrobenthos was measured. None of the results from this monitoring indicated that the *in situ* disposal test was responsible for a significant change in ongoing trends. The subtidal monitoring was focussed on sediment composition and macrobenthos samples, using the BACI-technique (Before-After-Control-Impact). Beside the disposal area (yellow area on Fig. 16), two control areas were chosen: one at the traditional disposal site 'Schaar van Waarde' (green area), the other (red area) where no influence from disposal activities should be expected.

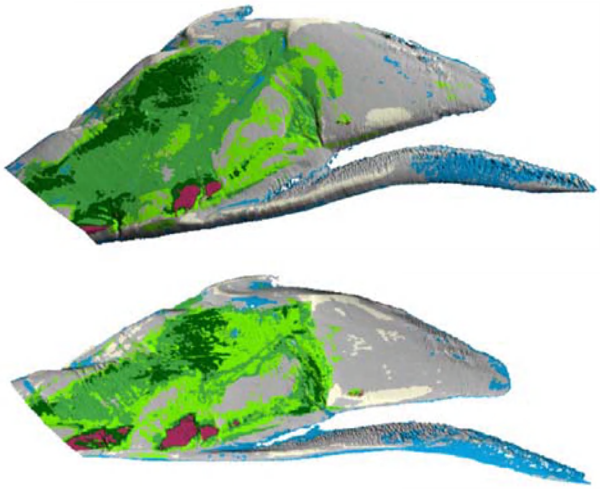

Fig. 15. Remote sensing image Walsoorden sandbar (top: 2004; bottom: 2005).

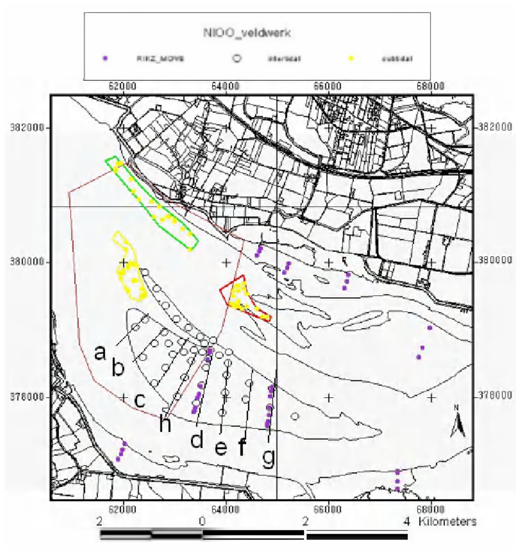

Fig. 16. Sampling stations ecological monitoring programme.

For the subtidal samples an increase in grain size was found for the impact area. This is explained by the coarser sediment (d50 ~ 250μm) that was disposed compared to the local sediment (d50 ~ 200μm) before the test. The macrobenthos samples did not show deterioration (biomass, diversity and density) for the impact area compared to the two other control areas. It should be noticed that the quality of macrobenthos samples in the subtidal areas was significantly worse than to the intertidal macrobenthos samples. Summarizing: no significant negative ecological impact could yet be detected from the *in situ* disposal test near the Walsoorden sandbar.

Tracer experiment

A sediment tracer test was executed to get an idea of the sediment transport patterns. The tracer material was an industrial glass-granulate (SiO_2) whereto 0.05 weight percent of IrO_2 was added in melted state. After cooling down, the mixture was grinded to obtain a grain size comparable to that of the disposed sediments (~ 250μm). Afterwards a fluorescent coating was added. In total 500kg of tracer material was prepared. The fluorescence allows already a first indication of available tracer material in the samples taken in the field. Afterwards the positive samples are activated in the laboratory so that the concentration of tracer material can be determined. A first tracer experiment was executed in February 2005 with 500kg of tracer material. The material, packed in small containers (50kg each), was lowered down to 0.50m above the bottom during slack where they were opened. Five sampling campaigns were planned, using the Van Veen grab to collect approximately 50 samples during each campaign. The first samples did not contain any tracer material. Possible explanations could be either that bedforms covered the tracer or that the tracer material was too fine and dispersed during a storm in the weeks after the injection. A second campaign using vibro-core sampling technique did not produce better results. Therefore a new injection was executed in September 2005. This time the tracer material (500kg) was mixed in advance with 500kg sand with grain size comparable to the deposited sediments. The injection was executed by a diver, who placed the sediments onto the bottom. A first sampling campaign, the day after the injection, revealed some transport of the tracer material in up-estuary direction (Fig. 17). In a second campaign tracer material was found in several points of the sampling grid (Fig. 18). The highest concentrations were found near the injection point, with the predominant transport indicating mainly an up-estuary movement towards the sandbar. In a third sampling campaign (November 2005), no significant concentrations of tracer material were found. The question remains why no concentrations were found. This may sustain the hypothesis of bedforms covering up the tracer material. Despite the limited recovery of tracer material, the initial results confirm the trends from the bathymetric surveys: the disposed material that is eroded, is transported in the up-estuary direction towards the sandbar.

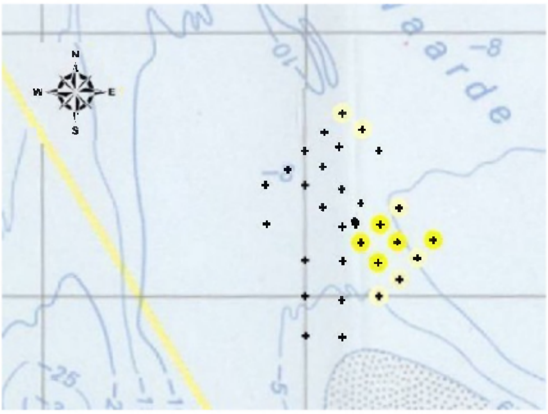

Fig. 17. Tracer concentration one day after injection.

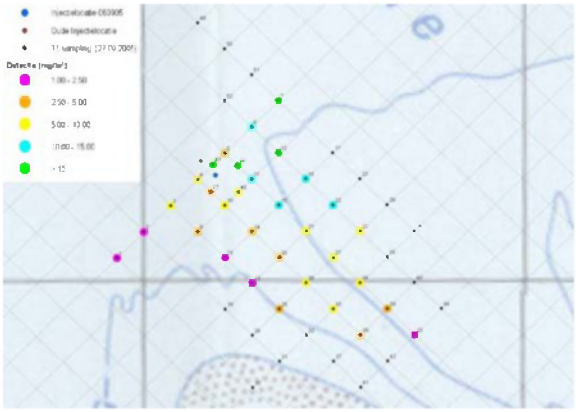

Fig. 18. Tracer concentration one month after injection.

Monitoring of flow and sediment transport

Sediment transport and flow velocity were measured during a full tidal cycle in several stations near the Walsoorden sandbar. A first campaign was conducted in June 2003, before the disposal test, with three stations (1, 2, 3) down-estuary from the Walsoorden sandbar. In September 2004, a second campaign was realized, also in three locations: station 2, the proposed disposal area and stations 4 and 5, both control points (places that could be influenced by the disposal test, one on each side of the bifurcation produced by the sandbar). These two control points were also measured during (December 2004) and after (May 2005) the execution of the disposal test. Velocities were measured using acoustic techniques (Aanderaa), while sediment transport was measured with the Delft Bottle, on a frame for near bed transport, suspended on several depths for suspension transport. This sediment trapping has the benefit that larger sediment samples can be collected over a longer sampling time, producing a good average transport rate and sufficient sediment to be analysed afterwards on grain size.

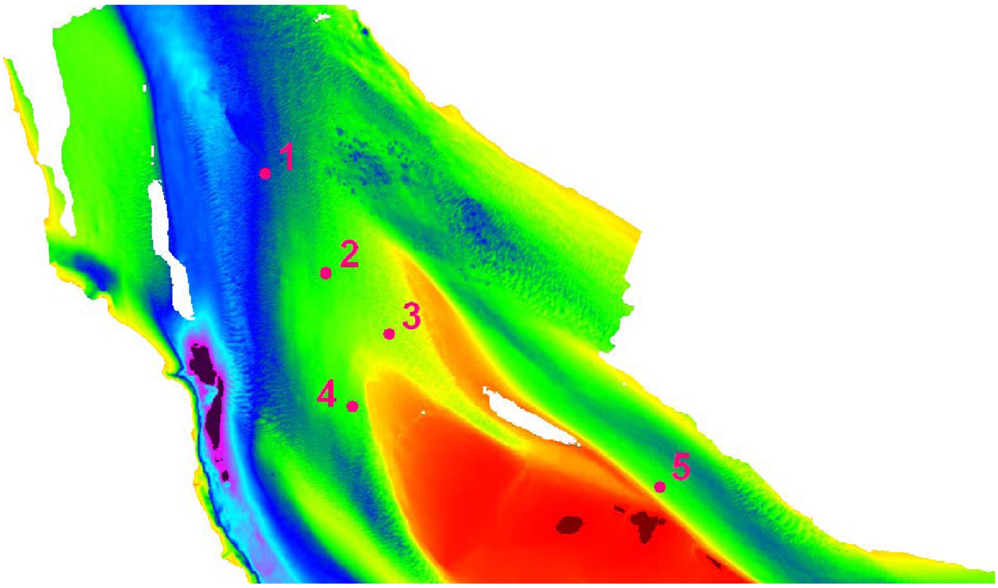

Fig. 19. Sediment transport and flow velocity measurement locations.

The results of the sediment transport measurements (Flanders Hydraulics Research, 2006) show no significant changes in the two control points. The pattern for these two locations is different. For point 4 the main sediment transport takes place from HW-2h to HW. During the ebb period only limited sediment transport was found. For point 5 there is a first peak near the end of the flood (cf. point 4), but at the start of the ebb strong sediment transport was measured. Despite being situated in the so-called flood channel, strong ebb currents occur in this channel. For the other points (1 to 4) the Walsoorden sandbar creates a 'shadow zone' for the ebb flow, with limited velocities and therefore limited sediment transport during the ebb.

Conclusions in situ *disposal test*

From morphological point of view, it can be concluded that the experiment using a diffuser for modifying the morphology of the sandbar by disposing precisely dredged material was very successful. The ecological monitoring did not reveal any significant negative impact, neither in the intertidal areas, nor in the subtidal areas. This *in situ* test confirmed the feasibility of the proposed disposal strategy. A second disposal started at the beginning of 2006, however not with the diffuser technique but with the commonly used disposal technique. An estimated volume of 4 to 5 million m^3 could be disposed here to reach the proposed objectives, representing more than half of the volume dredged yearly in the Western Scheldt.

Conclusion and recommendations

For a long time dredging operations have been considered as producing only negative impacts on the environment. Flanders Hydraulics Research (at that time the Belgian National Laboratory) had acquired experience in using dredging for influencing morphological evolutions in the Congo river, improving the accessibility of the maritime ports. This experience was used on the

Scheldt Estuary. The Western Scheldt is one of the last relatively natural estuaries with a dynamic multi-channel system and exceptionally valuable eco-systems. A management with broader objectives that include accessibility, safety and nature preservation progressively replaces the past management of the maritime access route to the Port of Antwerp, which was based almost exclusively on an engineering approach. In 2001 an international expert team appointed by the Port of Antwerp authorities, set forward new ideas about the morphological management of the estuary by using dredging and disposal of dredged material to steer the morphological behaviour of the estuarine multi-channel system.

As a pilot project, to demonstrate this new disposal strategy, the location at the sandbar of Walsoorden was selected by the Port of Antwerp Expert Team on the basis of expertise. The western tip of the Walsoorden plate has been eroded since decades. Reshaping the tip of this sandbar by morphological dredging might improve the self-dredging capacity of the crossing of Hansweert, reducing finally the dredging effort. The feasibility of this project was studied by Flanders Hydraulics Research, combining desk studies, scale modelling, numerical modelling and field surveys. None of the results of this extensive study opposed the feasibility of the proposed disposal strategy at the Walsoorden sand bar.

To finally prove the proposed disposal strategy, an *in situ* disposal test was conducted. At the end of 2004, 500,000m^3 of sand was disposed at the seaward tip of the Walsoorden sandbar. The experiment was intensively monitored, both on morphology as on ecology. More than one year after completion of this test, it can be concluded that a new morphological dredging and disposal strategy could be successfully embedded in the future morphological management of the Western Scheldt. However, as stated by the Port of Antwerp Expert Team, the new ways of dredging and disposing sediments should be combined with other measures, such as adapting the hard bordering of the estuary and finding alternatives to the traditional protection works of banks and shoals.

The Walsoorden experiment also confirmed the need for building the capacity of the professionals in morphological assessment techniques, giving sufficient room to expertise and visual analysis of charts, maps and remote sensing observations. A further collaboration between engineers, biologists and ecologists is needed to develop further the idea of morphological dredging and the strategies to manage the morphology of estuarine systems.

Acknowledgement

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Related websites

DELFT3D-software:	http://www.wldelft.nl/soft/d3d/intro/index.html
MOVE-programme:	http://www.scheldenet.nl/ (MOVE)
PROSES:	http://www.proses.nl/
SIMONA-software:	http://www.minvenw.nl/rws/rikz/projecten/simona/index.html

References

Flanders Hydraulics Research. 2003. Alternative disposal strategy Walsoorden. Results physical and numerical modelling. November 2003. (www.proses.nl => rapporten => September 2003).

Flanders Hydraulics Research. 2006. Alternatieve stortstrategie voor de Westerschelde. Proefstorting te Walsoorden. Verslag 13u meetcampagnes (In Dutch – 'Alternative Dumping Strategy – *In situ* Disposal Test – Results from the 13h Measurement Campaigns'). February 2006.

Foster R., F. Rossi, K. Bonnie, C.H.R. Heip and P.M.J. Herman. 2006. Alternatieve stortstrategie voor de Westerschelde. Monitoringsprogramma proefstorting Walsoorden. Rapport 11/11 (In Dutch – 'Alternative Dumping Strategy – Ecological Monitoring *In situ* Disposal Test – Report 11/11'). January 2006.

Goossens M. and E. Bosschem. 2002. The innovative D.P.G.P BAYARD II at the Le Havre Port 2000 harbour extension project. December 2002.

Haecon. 2005. Alternatieve stortstrategie voor de Westerschelde. Monitoringsprogramma proefstorting Walsoorden. Verslag ADCP metingen Walsoorden (In Dutch – 'Alternative Dumping Strategy – *In situ* Disposal Test – Results from the ADCP Measurements'). December 2005.

Institut für Wasserbau. 2003. Current measurements in the Westerschelde – September and October 2002. February 2003.

Peters J.J. 1994. Manejo de los Ríos en la Cuenca del Río Piraí (Management of the rivers in the Pirai river basin). Peters J.J. (Ed.) with the financial support of the European Commission. 1994.

Peters J.J. 1998. Amélioration du transport fluvial en Amazonie bolivienne. Bulletin of the Belgian Royal Academy of Overseas Sciences 44(3):1998.

Peters J.J. and F. Wens. 1991. Maintenance dredging in the navigation channels in the Zaire inner Delta. COPEDEC III Conference, Mombassa, September 1991.

Peters J.J. and W.R. Parker. 2001B. A Strategy for Managing the Westerschelde's Morphology. An Addendum to the Final Report. May 2001.

Peters J.J., R.H. Meade, W.R. Parker and M.A. Stevens. 2001a. Improving navigation conditions in the Westerschelde and managing its estuarine environment. How to harmonize accessibility, safetyness and naturalness? January 2001.

Port of Antwerp Expert Team. 2003. Alternative dumping strategy. The feasibility of morphological dredging as a tool for managing the Westerschelde. September 2003. (www.proses.nl => rapporten => September 2003).

ProSes. 2004. Strategisch Milieueffectenrapport Ontwikkelingsschets 2010 Schelde-Estuarium. Hoofdrapport (In Dutch – 'Strategic Environmental Impact Assessment Development Scheme 2010 Scheldt Estuary – Main Report). September 2004.

Wang Z.B., R.J. Fokking, M. de Vries and A. Langerak. 1995. Stability of river bifurcations in 1D morphodynamic models. Journal of Hydraulic Research 33(6): 739-750.

Winterwerp J.C., Z.B. Wang, M.J.F. Stive, A. Arends, C. Jeuken, C. Kuijper and P.M.C. Thoolen. 2001. A new morphological schematization of the Western Scheldt Estuary, The Netherlands. 2nd IAHR Symposium on River, Coastal and Estuarine Morphodynamics, Obihiro, Japan, September 2001.

WL | Delft Hydraulics. 2003. User Manual Delft3D-FLOW: version 3.10. Delft, 2003.