Project part-financed by the European Union (European Regional Development Fund)

Comparative Analysis of Sediment Management-Strategies in the Estuaries of Humber, Scheldt, Elbe and Weser

– Study in the Framework of the Interreg IVB Project TIDE

In charge of the project:

Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency, Germany

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Disclaimer

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Content

Abstract

The estuaries of the Humber (UK), Scheldt (BE/NL), Weser (D) and Elbe (D) display similar characteristics regarding large ports with great economic relevance, shipping channels that have to be maintained and a strong tidal influence. Furthermore, most of their estuarine areas are designated NATURA 2000 sites. Thus, decision makers face similar challenges like the improvement of sediment management while at the same time estuarine ecosystem functions need to be maintained. Within the scope of the European project (INTERREG IV B) TIDE (Tidal River Development) the sediment management strategies of the four TIDE estuaries have been compared mainly based on four background reports taking into account recent EU directives.

The constant development of the TIDE estuaries in line with the needs of the shipping business has led to deeper shipping channels, growth of ports far inside the estuaries and an enormous economic relevance of shipping and ports at both the regional and national level. The development of the fairways has contributed to considerable changes in the hydrological and morphological dynamics of the estuaries and therefore also the ecological situation. As a result of historical development, administrative boundaries and responsibilities for the fairways and ports within the estuaries differ among estuaries and are not always consistent within estuaries. Estuarine sediment management strongly interferes with all of these aspects and is thus very challenging.

The comparison of the sediment management strategies of the four TIDE estuaries clearly shows that the situation in the individual estuaries varies quite a bit and therefore specific strategies are necessary and meaningful. Sediment management practice has developed historically in all estuaries and has been adapted to changing boundary conditions and the improving knowledge base. Overarching written strategies exist only to a partial degree. Current changes in the boundary conditions include the more extensive consideration given to requirements based on environmental and nature conservation law, greater need of cost reduction and more frequent occurrence of undesired morphodynamic developments primarily due to increased tidal pumping.

The TIDE estuaries have been morphologically modified to a great extent in the past. A close interaction between morphological management (river engineering) and sediment management exists and this should be adequately considered in the future. At the same time, the conditions of nature conservation and environmental protection need to be incorporated into the integrated river engineering concept with regular monitoring and evaluations. Thus, the main challenges are still to reduce dredging and keep the sediment within the estuary, but in the framework of a bigger picture and using sustainable methods. Thus sediment management has itself to understand and to act as part of integrated estuarine management, which can be understand also as Integrated Coastal Zone Management.

Implementation of the Water Framework Directive and Habitats Directive represents a challenge for established sediment management that has developed historically, but it begins to contribute to greater consideration of environmental concerns in sediment management.

The report provides "good practice" examples concerning the various aspects of sediment management and summarizes the more general results of six lessons learned that will form a basis for the following recommendations.

Sediment management:

- has to focus its attention to an even greater extent on the boundary conditions and limits of the natural environment and on the individuality of the single estuary
- has to be incorporated into a long-term river engineering and sediment management strategy that combines morphological and sediment management
- has to become a more fundamental part of integrated estuary management that carefully balances social, economic and environmental values and is set in the context of the whole river system looking at planning scales of at least a generation in order to consider sustainability
- could be used as part of a strategy of adaptation to climate change
- has to be geared to mitigation of environmental impairment to an even more pronounced extent
- cooperation and responsibilities of the administrative structures should be developed in such a way that they facilitate a holistic view of the estuary
- studies on the advantages and disadvantages of water injection dredging (WID) on the various system structures and functions should be performed

1. Introduction

1.1 Background and scope

The TIDE project estuaries of the Humber (UK), Scheldt (BE/NL), Weser (D) and Elbe (D) display similar characteristics regarding large ports with great economic relevance, shipping channels that have to be maintained and a strong tidal influence. Furthermore, most of their estuarine areas are designated NATURA 2000 sites. Thus, decision makers face similar challenges like the improvement of sediment management while at the same time estuarine ecosystem functions need to be maintained.

What is sediment management?

In earlier times sediment management mainly meant dredging and placement of sediments in the framework of deepening and maintaining the fairways and ports in an economical way. Nowadays sediment management not only has to integrate accessibility of ports by ships via fairways, but also protection against floods as well as legal environmental and ecological requirements and thus aspects of geomorphological, hydrological and ecological management. Morphological management (deepening, maintenance dredging, managed retreat, placement strategies, etc.) clearly influence accessibility, safety and ecological functioning. Managing hydrology (mainly storing storm water and managing freshwater discharge) impacts safety and ecological functioning. Finally nature restoration and conservation has an impact on ecological functioning and may have an influence on safety and accessibility.

In this report the term sediment management in the stricter sense encompasses – besides the treatment of contaminated sediments – particularly the relocation of sediments (dredging and placement in the water body), the factors causing this relocation and the factors influenced by relocation. Sediment management thus displays a broad overlap with morphological management, which is primarily aimed at shaping hydro- and morphodynamics, and includes both the options of sediment relocation and river engineering measures in the form of fixed structures (Fig. 1).

Against the background of the above mentioned challenges, in particular by comparing the situation and the experience of the estuaries involved (as well as others), the Interreg IV B Project TIDE (Tidal River Development) aims to develop practically oriented prospects and make recommendations to reduce conflicts.

Since conflicts arise between different perspectives (particularly shipping, coastal protection, nature conservation and water quality), especially in connection with sediment management, it is of great importance to conduct an exchange on experience gained in the respective estuaries in the framework of TIDE so as to learn from one another. That is the purpose of this comparative report.

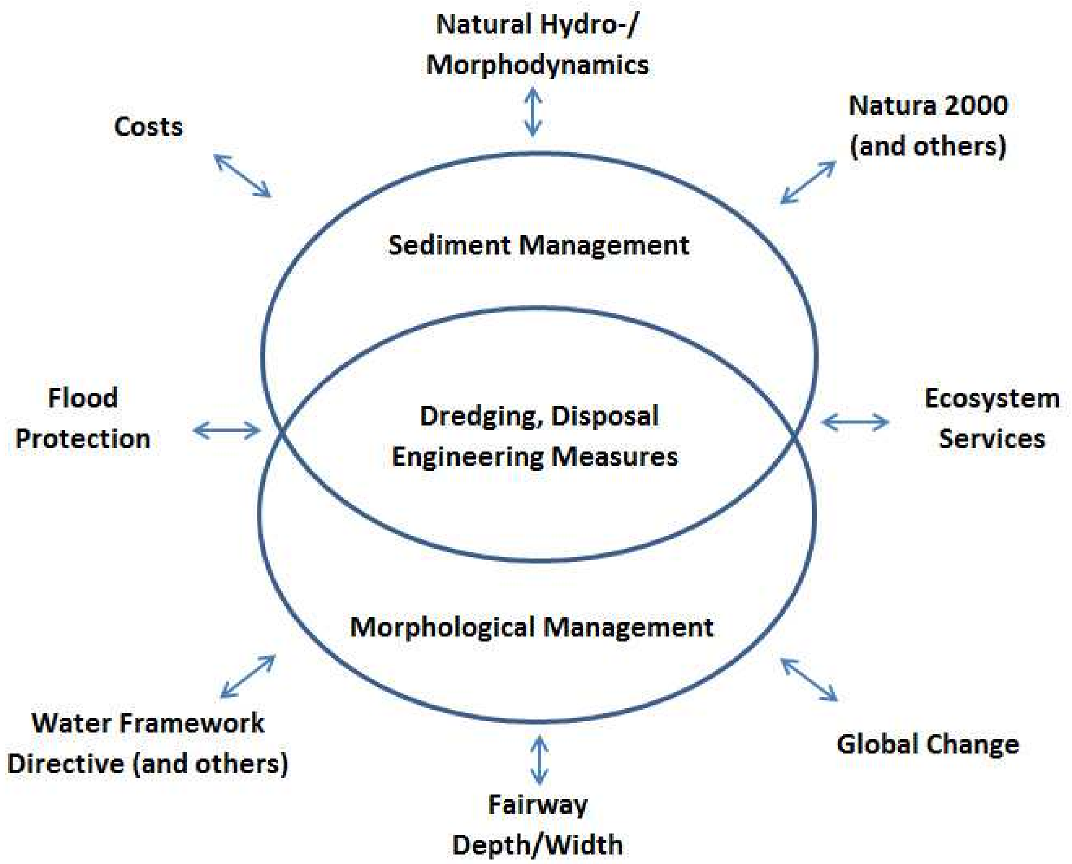


Fig. 1: Visualization of the understanding of sediment management as used in the present report (see text).

1.2 Database

A comparative study on sediment management in the four TIDE estuaries is conducted in the framework of WP 5 (measures, responsible TIDE partner NLWKN). Four reports concerning the TIDE estuaries as well as additional data have been provided as the basis for this study. Information taken from these basic reports (see appendices) is not separately cited in the overall report. Furthermore, talks with individual players involved and additional research were necessary in order to prepare the overall report. However, the data available within one estuary and especially between estuaries is not always consistent and thus the overall comparability is limited and the presented figures may not be fully comparable.

One of the major objectives of TIDE is to learn from one another by comparing the specific situations in the different estuaries and the purpose of the overall report on sediment management is to support this effort. This means it is necessary to comparatively present both the various boundary conditions (regarding the geomorphological and hydrological situation as well as relating to legal, economic and ecological aspects) and the management strategies developed on this basis.

2. Estuarine sediment management within the EU policy framework

Estuaries are often ideal locations for ports since they provide shelter for ships and access further inland along major rivers. The importance of ports and the demand for maritime transport has increased significantly and is likely to continue in the future. The European Commission supports this transport through its ports policy and the promotion of the "Motorways of the Sea" and Short Sea Shipping (EC 2011).

Estuaries are among the most productive ecosystems in the world. Thus, they have high ecological as well as economic values. The pressure on coastal zones and estuaries has led to a shift towards more integrated spatial planning. European directives, such as the Water Framework Directive (WFD), Marine Strategy Framework Directive (MSFD) as well as Birds and Habitats Directives (together Natura 2000) emphasize the necessity of an integrated approach. They follow natural rather than administrative boundaries and their specific perspectives consider an overall view.

The WFD and the more extensive MSFD aim to achieve a good ecological state or potential by 2015 and 2020, respectively, through formulation of environmental objectives and specific action plans. The geographical range of the MSFD overlaps the WFD in coastal waters. There is also a geographical overlap between WFD water bodies and Natura 2000 sites. While the principal aim of those directives is the protection of ecosystems, their objectives, measures and tools are not completely matching.

Back in the 1970s international conventions were designed to minimize pollution of the seas. The London Convention (LC) is a 1972 agreement to prevent marine pollution due to dumping of wastes and other matter. The OSPAR Convention is an international cooperation to protect the marine environment of the Northeast Atlantic. The convention assumed a more holistic responsibility for environmental protection in the region, including its biodiversity, with the adoption of Annex V in 1998.

Climate change will affect the North Sea coast, especially the estuaries, primarily via the accelerated rise in sea level and, to an increasing extent, presumably bring about extreme events in a variety of ways. It can be assumed that the coastal protection requirements will continue to mount and other coastal protection strategies may become necessary and/or meaningful in the estuaries in the long term. At the same time it is possible that areas subject to managed realignment will also grow because of sediment deposits (EEA 2012).

In 2007 the European Commission launched the Integrated European Maritime Policy for the European Union for better coordination of the sectoral policies (COM(2007)575). The policy encompasses all elements of marine activity and provides for a holistic and integrated approach to address economic and sustainable development on an EU-wide basis. The policy will cover a wide spectrum of issues related to sustainable development including: marine transport, the competitiveness of marine businesses, employment in the marine sectors, scientific research and protection of the marine environment. The so-called Limassol Declaration, launched in 2012, will support this approach.

Thus, we can conclude that integration of maritime traffic, on the one hand, and protection of the environment, on the other hand, represent an urgent challenge, for which sediment management in estuaries is an essential topic.

3. Estuaries and their ports: a challenge

3.1 Background and scope

The constant development of the TIDE estuaries in line with the needs of the shipping business has led to deeper shipping channels, growth of ports far inside the estuaries and an enormous economic relevance of shipping and ports at both the regional and national level. The development of the fairways has contributed to considerable changes in the hydrological and morphological dynamics of the estuaries and therefore also the ecological situation. As a result of historical development, administrative boundaries and responsibilities for the fairways and ports within the estuaries differ among estuaries and are not always consistent within estuaries. Estuarine sediment management strongly interferes with all of these aspects and is thus very challenging.

3.2 Humber estuary

Located on the east coast of Northern England, the Humber is one of the largest estuaries in the United Kingdom (measuring some 280 km²). It is approximately 6.5 km wide at its entrance, opening to 9.5 km wide immediately past its entrance at Spurn Point, and its upper reaches (some 48 km upriver) are 2.5 km wide (Fig. 2).

The major Humber ports are Hull, Goole and Grimsby, and Immingham and the principal commercial dock operations of these ports are owned, managed and operated by Associated British Ports (ABP). The Harbour Authorities maintain safe port access for commercial and recreational maritime transport.

The Humber Estuary and surrounding area are of great importance in terms of nature conservation with large areas of the estuary and the adjacent coastline having been designated as nationally and internationally protected sites. These sites include Special Protection Areas (SPAs), Ramsar Sites and Special Areas of Conservation (SAC), namely Humber Estuary Ramsar, Humber Estuary SPA and Humber Estuary SAC (Fig. 14).

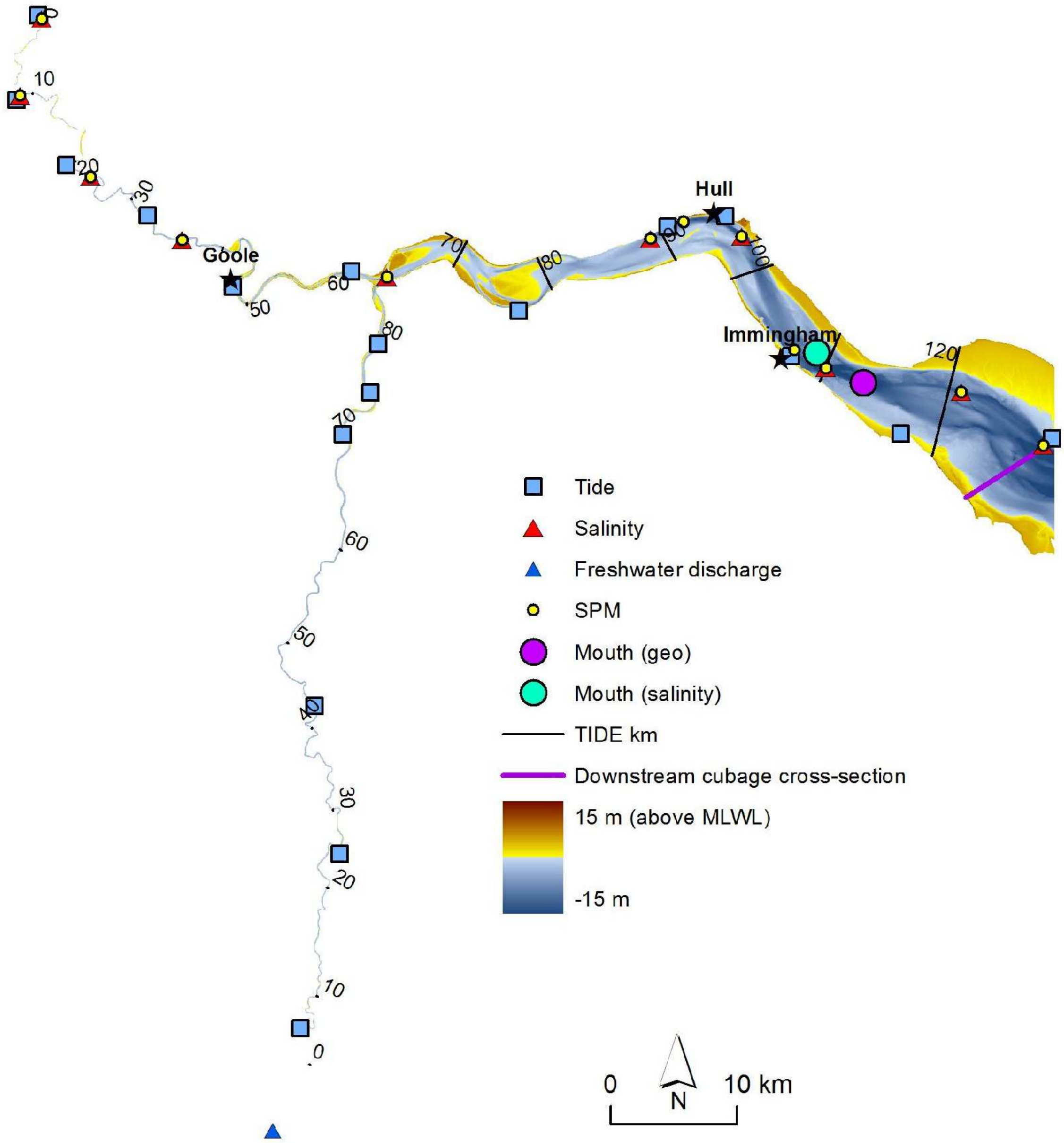


Fig. 2: Morphology and TIDE-kilometre of the Humber estuary (the additional parameter are not substantial) (VANDENBRUWAENE et al. 2012).

The Humber estuary is a typical converging estuary, mainly from TIDE km 112 to TIDE km 82 (Fig. 2). The Humber-Ouse estuary can be considered as a multi-channel system from TIDE km 95 up to the junction with the Trent. The Ouse, Trent, and the most downstream part of the Humber (downstream TIDE km 95) can be considered as single channel systems (i.e. only one subtidal channel). The decrease from mouth to up-estuary boundary in estuary width and/or estuary depth results in a decrease of the wet section. Especially in the outer estuary large tidal flats are located; the largest close to Spurn Point (TIDE km 130). The outer estuary channels have been relatively stable for a long time but those to the west of Hull are much less reliable with the main navigable channel changing from the south side of Read's Island to the north bank and back again with a cycle time of up to 20 years (www.humber.com/Estuary_Information). The Humber estuary has a large tidal range, with the mean being 5.7 m at Spurn (TIDE km 130), increasing to 7.4 m at Saltend (TIDE km 98) and then dropping to 6.4 m at Hessle (TIDE km 84) and 5.6 m at Trent Falls. The mean and maximum ebb and flood flow velocities respectively range between 0.1 and 1.5 m/s and between 0.1 and 2 m/s. Sediment transport in the Humber is described in detail in section 6. According to this description, erosion of the cliffs north of the mouth of the Humber takes place particularly during storms. Of the fine grained sediment that is released from these cliffs, a little of the suspended material is transported into the Humber Estuary where it becomes available for deposition on the mudflats and salt marshes whilst the rest is transported towards the Wash and the German Bight. A net transport to the estuary takes place in this process. The Humber features a very dynamic morphology. Sediment input both from the sea and especially from the rivers contributes to this. Extreme tidal range and differences between spring and neap tides give rise to characteristic spring/neap deposition cycles. Changes in bed levels of 0.1 m or more during a spring/neap cycle and/or extreme events are not uncommon, and variations of bed levels of over 1 m have been recorded on an annual basis in the Outer Estuary. Over longer periods, cyclical variation of more than 10m has been noted. The Estuary intertidal and subtidal areas also act as both sources and sinks for sediment, with different areas changing between them over time. Suspended matter concentrations found in the Humber are highest compared with the other TIDE estuaries (Tab. 1).

3.3 Scheldt estuary

The Scheldt estuary is located in the southwest of the Netherlands (Westerschelde) and in the northern part of Belgium (Zeeschelde and tributaries). It is subject to a complex division of responsibilities, which has its consequences for waterway management (Fig. 3).

The federal Belgian state has given the responsibility for infrastructure and environment to the regions, thus waterway management is a regional issue. The Zeeschelde and its tributaries under tidal influence are the Belgian part of the Scheldt estuary and lie completely within the Flemish region. Hence the Flemish government is responsible for waterway management. The Westerschelde and most of the estuary mouth belong to Dutch national waters and are managed by the Ministry of Infrastructure and Environment. The Belgian part of the North Sea is federal territory managed by the Belgian federal government.

The Port of Antwerp is the largest port of the Scheldt estuary. Located approximately 80 km from the mouth, it is the most inland port of the estuary. The Port of Terneuzen and the Port of Vlissingen both lie adjacent to the Westerschelde and are operated by Zeeland Seaports. The Port of Ghent is accessible through the locks in Terneuzen and the channel Gent-Terneuzen.

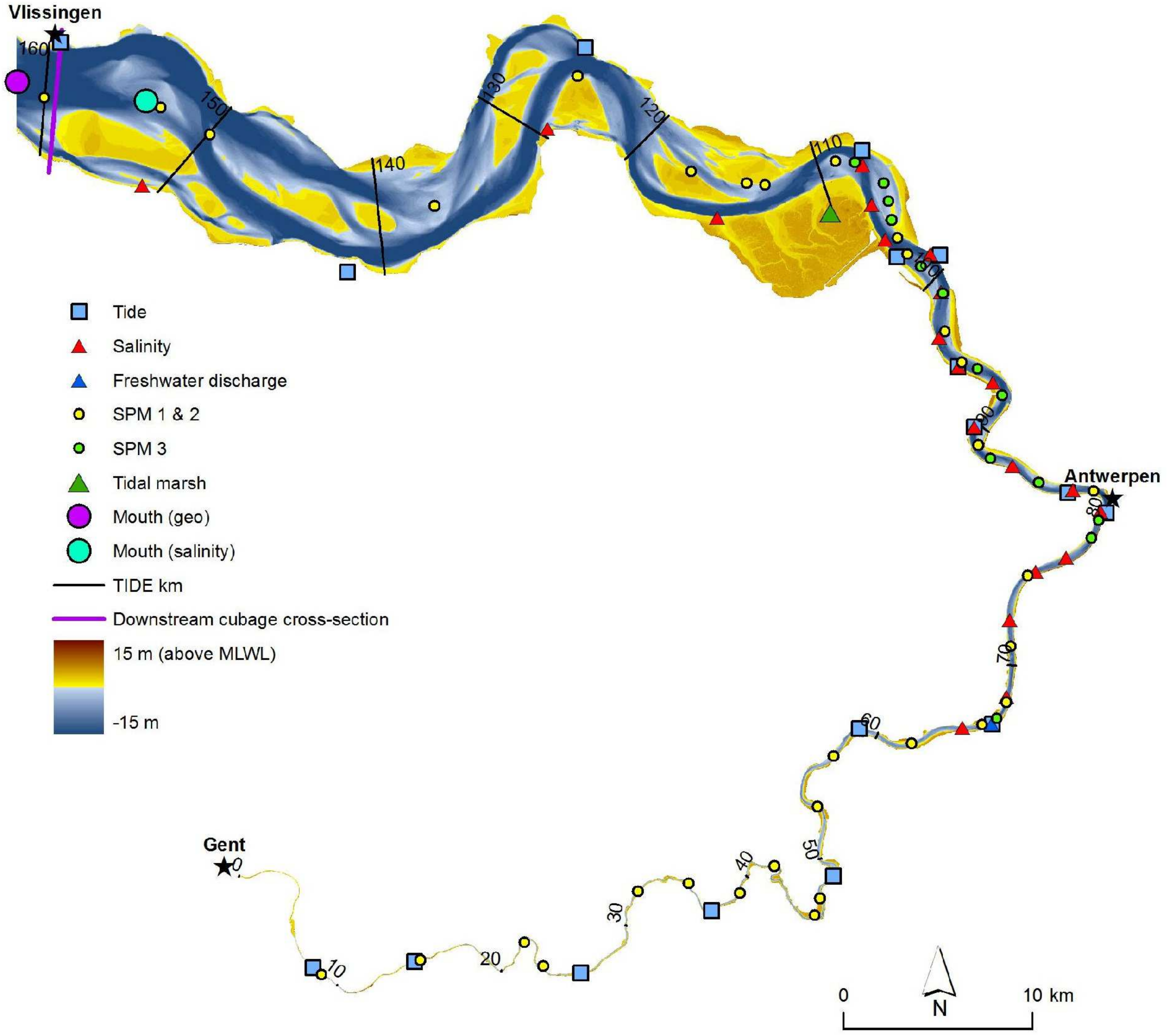


Fig. 3: Morphology and TIDE-kilometre of the Scheldt estuary (the additional parameter are not substantial) (VANDENBRUWAENE et al. 2012).

The Scheldt estuary and surrounding area are of high nature conservation importance with large areas of the estuary and the adjacent coastline having been designated as nationally and internationally protected sites. These sites include NATURA 2000 Areas (Special Protection Areas (SPAs) and Special Areas of Conservation (SAC)) namely "De Kuifeend en Blokkersdijk", "Durme en Middenloop van de Schelde", "Het Zwin", "Schelde- en Durmeestuarium van de Nederlandse grens tot Gent", "Schorren en polders van de Beneden-Teeschelde", "Vlakte van de Raan", "Westerschelde & Saeftinghe" and "Zwin & Kievittepolder". Also, there are Ramsar Sites, namely "slikken en schorren van de Beneden-Zeeschelde", "Westerschelde en Verdronken Land van Saeftinge" and "Zwin" (Fig. 15).

While the outer part of the Scheldt estuary (Westerscheldt) is a multiple-channel system, the upper part (Zeeschelde) has a meandering character with a single channel. The ebb channel is mainly used as maritime shipping channel, except for a stretch between Baarland and Hansweert where the flood channel is used. The secondary channels are used for inland and other navigation purposes. Large mudflat and water areas are characteristic of the Westerscheldt (Fig. 3) while the

Zeeschelde is narrow and has hardly any mudflat and foreland areas. The tidal range at the mouth (Westkapelle and Vlissingen) has been nearly constant over the last century and is now about 4.2 and 4.5 m respectively. The tidal range in the inner part increased by approx. 0.5 and 1.0 m. The actual tidal range at Antwerp is 5.8 m. Further downstream mean tidal range further decrease.

Following VANDENBRUWAENE et al. (2012) the mean and maximum cross sectional averaged flood and ebb flow velocities along the estuary respectively range from 0.1 to 1 m/s and from 0.3 to 1.5 m/s. The maxima are observed around TIDE km 70, which coincides with the maximum in tidal range. The lowest flow velocities in the estuary are observed near the up-estuary boundary. A special feature of the Schelde is that the individual arms of the Westerschelde are dominated by flood and ebb current and thus the tidal currents shift (Fig. 4). That means the sandbanks of the Schelde are also subject to very dynamic and cyclic shifts. According to DELTARES (2012), the sediment volumes of the Westerschelde and Zeeschelde have more or less continuously declined over the past decades. At the same time there has been a long term trend of import of sediment from West (the mouth) to East (the Sea Scheldt).

In the multi-channel part of the estuary (Westerschelde) suspended particle matter (SPM) values are low (30–50 mg/l) and no difference between the surface SPM and the depth-averaged SPM is observed. There is clear increase in depth-averaged SPM towards Zeeschelde which reaches a first peak at TIDE km 95 and a second one at TIDE km 57. Both turbidity maxima reach SPM values up to nearly 300 mg/l. For the surface SPM, the increase at TIDE km 110 is small and values further upstream do not exceed SPM values of 120 mg/l.

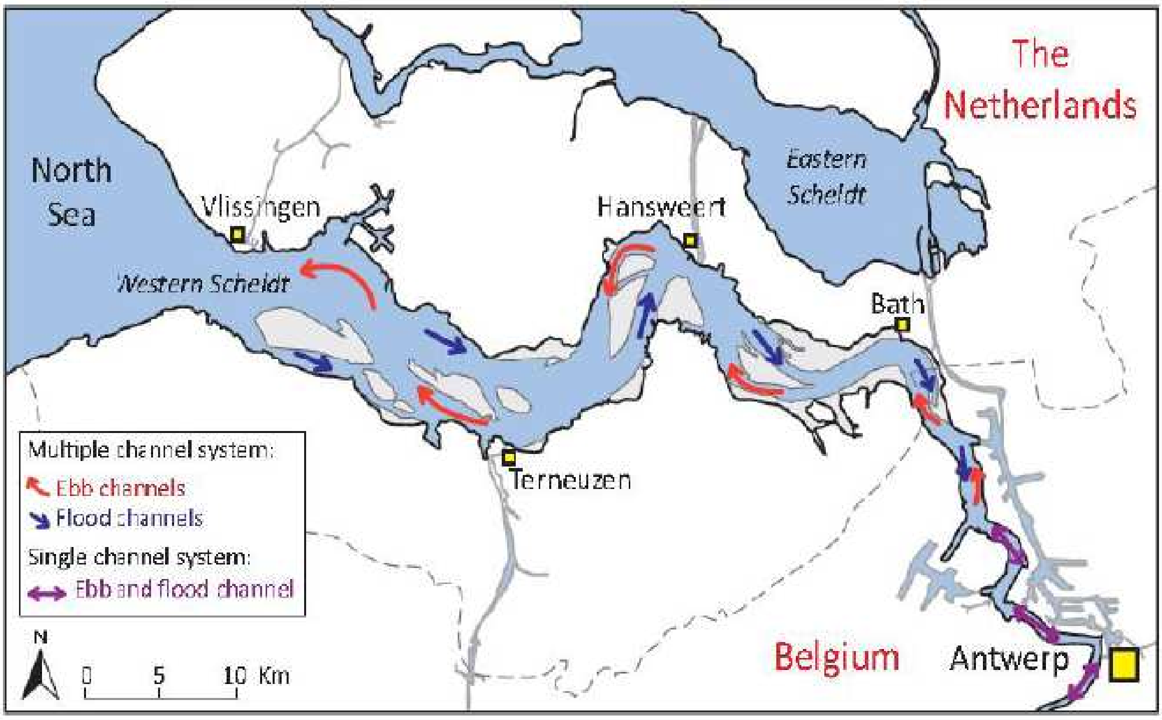


Fig. 4: The Scheldt estuary with ebb and flood channels, up to Antwerp (DELTARES 2012).

3.4 Weser estuary

The Weser estuary encompasses the Lower and Outer Weser. The Lower Weser reaches from the tidal barrier in Bremen-Hemelingen to Bremerhaven at Weser km 65 (Fig. 5). The Outer Weser stretches towards the North Sea and ends at about Weser km 130. The twin ports of Bremen and Bremerhaven constitute the second largest port complex in Germany. Brake and Nordenham, two ports situated at the lower end of the Weser in Lower Saxony, also play a prominent role in the shipment of bulk cargo.

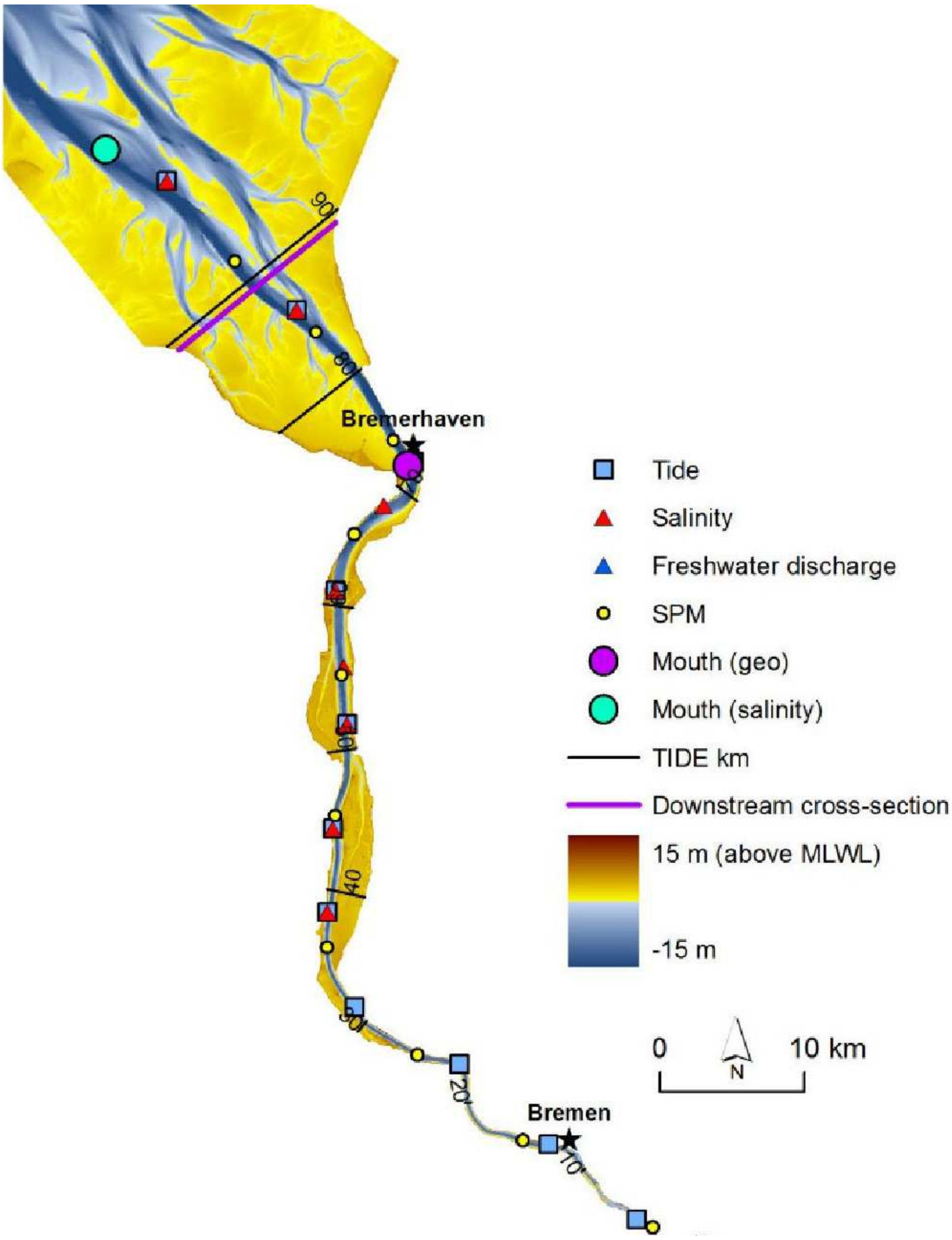


Fig. 5: Morphology and TIDE-kilometre of the Weser estuary (the additional parameter are not substantial) (VANDEN-BRUWAENE et al. 2012).

The Weser River is a federal waterway managed by the Waterways and Shipping Administration (WSV). As subunits of the WSV, Waterways and Shipping Offices (WSÄ) are responsible for the maintenance of the different sections of the rivers. Between the City of Bremen and Brake the Waterways and Shipping Office (WSA) Bremen is in charge of management of the waterway of the Weser. Downstream of Brake, the WSA Bremerhaven manages the Lower and Outer Weser. Most parts of the Weser estuary belong to the federal state of Lower Saxony, whereas the area around Bremen and Bremerhaven belongs to the federal state of Bremen. Most of the port area (the twin ports of Bremen and Bremerhaven) of the state of Bremen is supervised by bremenports GmbH & Co. KG as regards infrastructural development and maintenance, whereas in Brake Niedersachsen Ports and in Nordenham resident companies are in charge of management.

The Weser Estuary and surrounding area are of great importance in terms of nature conservation with large areas of the estuary and the adjacent coastline having been designated as nationally and internationally protected sites. These sites include a high number of Special Protection Areas (SPAs), Ramsar Sites and Special Areas of Conservation (SAC) (Fig. 16).

The Outer Weser is characterized by its funnel shape with two main arms and extensive mudflats. The western main arm has been expanded into a shipping channel. The Lower Weser is characterized by a narrow and greatly channelized river bed (prismatic channel) nearly without any mudflats. Of the previously numerous side arms, only three still remain but they are very small in comparison to the main channel and have a tendency to silt up. The foreland areas in the Outer and Lower Weser are relatively narrow though larger areas can be found in the Lower Weser on the river islands Strohauser Plate, Harriersand and Elsflether Sand. The funnel shape of the Weser leads to a pronounced rise in the tidal range from approx. 2.9 m in the transitional area to the North Sea to 3.8–4.1 m in the Lower Weser (Tab. 1). The tidal range of the Weser, particularly in the Lower Weser, has changed significantly due to the anthropogenic impacts and has increased in Bremen since the first deepening from approx. 0.2 m to a current level of 4.1 m. According to WIENBERG (2003), the Weser estuary is dominated by the ebb current due to the asymmetry of the tidal curve (tidal asymmetry). Due to the asymmetry of the tidal curve and the dominance of the ebb tide in tidal activity, residual sediment transport seems to take place seawards on a large scale in the Outer Weser, though according to BFG (1992) it is not so pronounced that it would lead to a deepening of the channels. In the area of approx. TIDE- km 116–126 this transport direction is overlapped by the west-east transport along the coast, which also results in a shifting of the large river bars and channels in a northeast direction (ZEILER et al. 2000). This leads to increased maintenance effort and expense. Pronounced formation of subaquatic dunes occurs in the Lower Weser. The ripple section (subaquatic dunes) (km 8–55) is characterized by high morphodynamics and constant internal relocation of the predominantly sandy sediments. Ripples are formed whose height is altered primarily by the head water (heights up to over 4 m). The Weser is characterized by a pronounced turbidity zone in the brackish water section (not mentioned in VANDENBRUWAENE et al. 2012, see Tab. 1). The centre of the maximum estuarine turbidity is located in the area around the so-called "Nordenham mud section" (km 61–64), pronounced rhythmic tidally influenced sedimentation and remobilization of particulate matter occur. Very high concentrations of suspended matter of up to 1.5 g/l on the bottom and up to 0.4 g/l near the surface (GRABEMANN et al. 1999) are reached there. The turbidity zone is variable in terms of its spatial location due to fresh water discharge and tidal currents.

3.5 Elbe estuary

The Elbe estuary encompasses the section between the Geesthacht tidal barrier and the island of Scharhörn. The port of Hamburg, the largest port in Germany, is located 130 km inland. Other ports along the Elbe, such as Cuxhaven and Brunsbüttel, also play a prominent role in shipment and distribution of goods (Fig. 6).

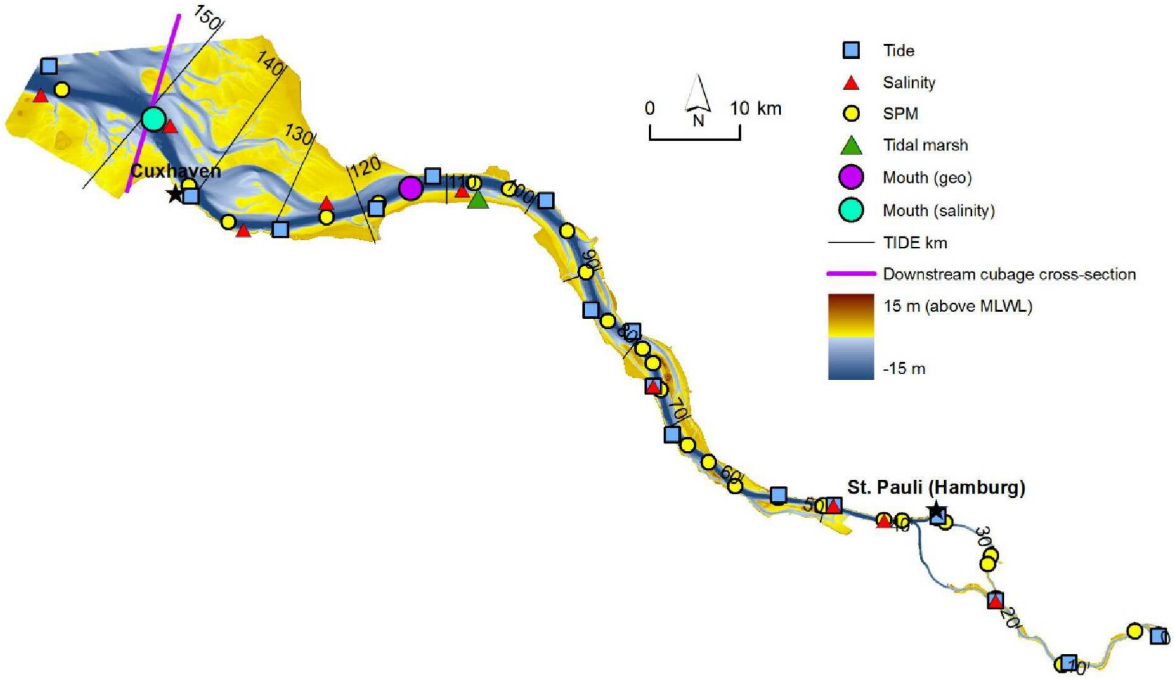


Fig. 6: Morphology and TIDE-kilometre of the Elbe estuary (the additional parameter are not substantial) (VANDEN-BRUWAENE et al. 2012).

In Germany, the Elbe River is a federal waterway and maintained by the WSV. Between the City of Hamburg and Brunsbüttel the WSA Hamburg manages the waterway of the Elbe River. Down-stream from Brunsbüttel, the WSA Cuxhaven is responsible for the Elbe River. In the state of Ham-burg management of the waterway is delegated to the City of Hamburg, represented by the Ham-burg Port Authority (HPA). The northern shore belongs to the federal state of Schleswig-Holstein, the southern shore to Lower Saxony and the federal state of Hamburg encompasses the eastern part of the estuary.

The Elbe Estuary and surrounding area are of great importance in terms of nature conservation with large areas of the estuary and the adjacent coastline having been designated as nationally and internationally protected sites. These sites include a high number of Special Protection Areas (SPAs), Ramsar Sites and Special Areas of Conservation (SAC) (Fig. 17)

The Elbe estuary consisted of several channels. Due to a number of deepening one of them has been expanded into a shipping channel, while the side arms are subject to increased silting in some cases. Seaward of TIDE km 114 the Elbe opens like a funnel and features large mudflats. Only small mudflats are still found in the Inner Elbe estuary, primarily in the river island sections, but there are large foreland areas (Fig. 6). The tidal range at the mouth (Cuxhaven) is now about 2.9 m at mean tidal conditions and has only slightly changed over the last century. In contrast, due to various anthropogenic impacts (fairway deepening, land reclamation and filling, embankment and changes of the morphology), the tidal range in the inner part of the estuary (Hamburg, St. Pauli) increased significantly from about 1.9 m in 1870 to about 3.6/3.7 m nowadays (DELTARES 2011).

Tab. 1: Overview hydrodynamic parameters (source: VANDENBRUWAENE et al. 2012). Figures given have been calculated for a comparison of the TIDE estuaries.

	Humber	**Scheldt**	**Weser**	**Elbe**
Length estuary [km] (Distance up-estuary boundary to mouth; mouth based on the width change / salinity)	114 / 109	162 / 153	73 / 102	114 / 149
Tidal range (mean tidal conditions) [m]				
mouth	4.3	3.8	3.8	2.9
maximum	5.0 (TIDE km 90)	5.5 (TIDE km 75)	4.1 (in the most upper part)	3.6 (Hamburg Sankt-Pauli)
up-estuary boundary	1.3 (Ouse)	2.7	4.1	2.2
Tidal flow velocities [m/s]				
mean ebb	0.1	0.1	0.1	0.2
max ebb	1.5	1.0	0.6	0.9
mean flood	0.1	0.3	0.2	0.4
max flood	2	1.5	1.3	1.3
location			mouth to TIDE km 10	mouth to TIDE km 40
Freshwater discharge [m³/s]				
minimum	38	34	122	247
mean	209	107	331	722
maximum	320	253	798	1709
Salinity [PSU/km]				
mean salinity gradient (30 PSU to 1 PSU)	0.48	0.40	0.43	0.38
Turbidity [mg/l]				
surface suspended particle matter at low water conditions	20–720 (max. TIDE km 88)	30–300 * (max. TIDE km 95 and 57)	20–100 ** (max. TIDE km 30)	25–250 (max. TIDE km 95)

* mean over a tidal cycle; ** underestimated? See section 3.4

Following DELTARES (2011) the flood tide has a steeply ascending curve and the ebb tide has a more gently falling curve. This causes a considerable flood current dominance in the upper parts of the estuary. For these areas it can be assumed that upstream transports of sediments not only dominate in shallow-water zones but also in the navigation channel. This applies in particular to fine-sand and coarse-silt material. Upstream TIDE-km 95 residual transport rates towards the port of Hamburg are presumed to be considerable ("tidal pumping"). From the mouth to TIDE km 40, the mean and maximum ebb and flood flow velocities respectively range between 0.2 and 0.9 m/s, and between 0.4 and 1.3 m/s (VANDENBRUWAENE et al. 2012). The Elbe has a very pronounced turbidity maximum that is found at TIDE km 95 under low water conditions.

3.6 Comparison of estuaries

All of the TIDE estuaries have ports located far inland and consequently the maintained fairways reach up to 130 km inside the estuaries. As a result of increasing ship sizes and natural boundaries, ports were relocated downstream in some cases or newer ports were developed further downstream in the past. Examples include Bremerhaven in the Weser estuary, Immingham on the Humber (which both are about 100 to 150 years old) and currently the new JadeWeserPort at the Jade Bight, which is neighbouring the Weser estuary.

All of them have administrative borders dividing the responsibilities of maintenance and management among different parties. These are different units in the various estuaries that in some cases come into being due to national borders (Scheldt), borders between German federal states (Weser, Elbe), different administrative levels and institutions with varying responsibilities and legal forms. Although additional organizational structures designed to improve the exchange and cooperation between these individual institutions have therefore been established in all estuaries, this diversity of responsible institutions makes cooperation and development of integrated management difficult. However, European directives, such as the WFD, Habitats Directive and MSFD, also emphasize the necessity of an integrated approach when they follow natural rather than administrative boundaries.

3.7 Relevance for future sediment management

The ports located far upstream (except at the Humber) and the currently deep fairways, which have to be maintained at substantial cost over many kilometres, represent a challenge for sediment management.

Another challenge for sediment management is the large number of authorities and bodies involved in sediment management. The hydrodynamics and morphodynamics of all TIDE estuaries are quite individual in spite of the basic common features and show a number of specific characteristics that also essentially determine the boundary conditions for sediment management.

4. Maritime Traffic: why to dredge

4.1 Background and scope

The TIDE estuary ports are among the most important ports in Europe in terms of cargo volume. They are of national importance for international commodity trade and of supraregional importance for the labour markets. For this reason it is rather important, both economically and socially, to ensure the accessibility of these ports for the economically relevant ship sizes.

Identification of main issues

The significance of the ports essentially manifests itself in the cargo handling volumes and the value added created in the region by cargo handling work in the port and, in particular, regional further processing. Figures concerning value added are not contained in the basic documents so that we can only compare vessel draught and cargo handling volumes here as far as data is available (Fig. 7 and Fig. 8).

4.2 Comparison of the estuaries

The **Humber Estuary** is one of the busiest waterways in the United Kingdom. The most important port on the Humber for cargo is Immingham. Immingham and Grimsby are handling approximately 58 million tons a year (1999–2008, see Fig. 7).

The port of Antwerp in the **Scheldt estuary** is the second largest port in Europe handling cargo volumes of more than 240 million tons a year (1999–2008). The ports of Ghent and Zeeland also handle a relevant number of shipping goods in the Scheldt estuary.

In the **Weser estuary** Bremerhaven has the greatest turnover with almost 40 million tons of ocean cargo per year (1999–2008). Regarding container turnover the port of Bremerhaven ranks as fourth largest in Europe. The port of the City of Bremen is an important port in the lower Weser estuary especially regarding inland shipping.

The largest port in Germany and third in Europe is the port of Hamburg in the **Elbe estuary**. It achieved a mean annual turnover of 115 million tons in between 1999 and 2008. Further important ports in the estuary are Cuxhaven and Brunsbüttel.

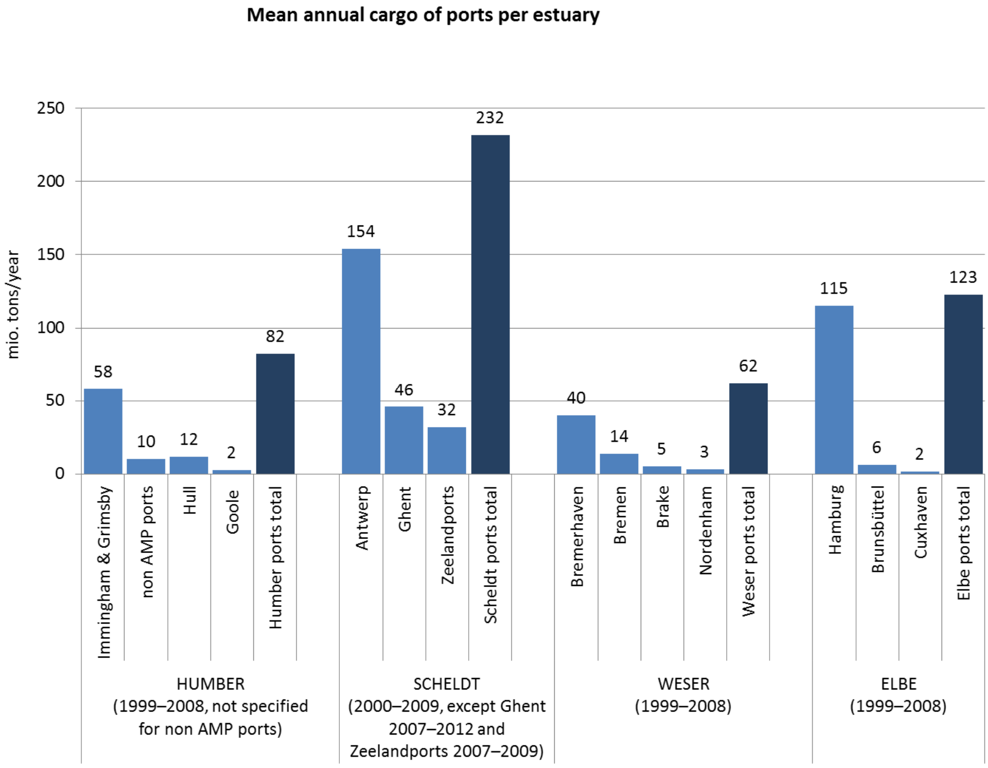


Fig. 7: Mean annual cargo of all ports in the four TIDE estuaries (Humber data provided by the Environment Agency (UK), source for non AMP ports: TIDE-report Humber; Scheldt data source from www.portofantwerp.com, www.portofghent.be and www.zeelandseaports.com; Weser data from TIDE-report Weser; Elbe data provided by HPA).

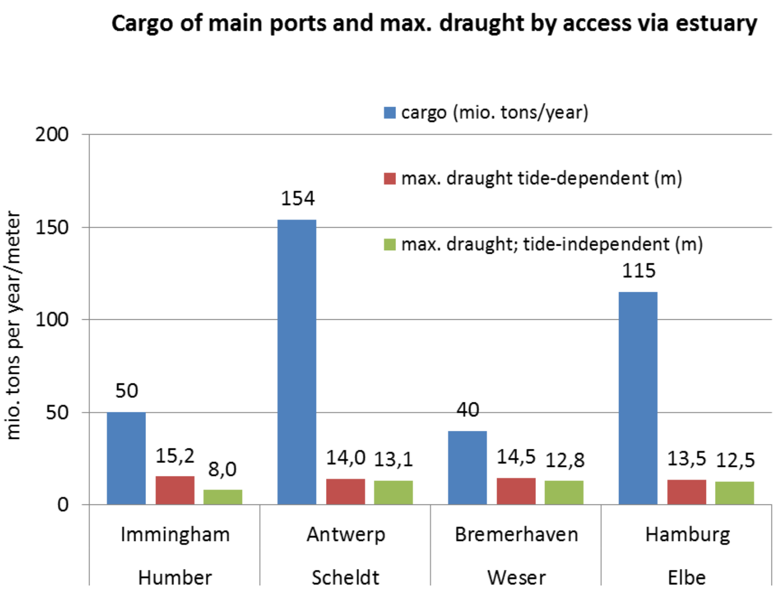


Fig. 8: Comparison of annual cargo (1999–2008, Antwerp 2000–2009) between the main ports of Humber, Scheldt, Weser and Elbe estuary and maximum draught of vessels by access via estuary. **Note:** <u>Antwerp:</u> tide-dependent clearing bulk 14,0 respect. container 14,5; tide-dependent access 15,5. <u>Hamburg:</u> tide-dependent clearing 13,5, tide-dependent access 14,5 (data sources Humber: Environment Agency (UK) and TIDE-report Humber; Scheldt: Flemish Government and www.portofantwerp.com, Weser: TIDE-report Weser; Elbe: HPA and TIDE-report Elbe).

All of these estuaries are navigable by ships having more than 100,000 tons dead weight (tdw). Vessels of these size classes reach the ports of Immingham, Antwerp, Bremerhaven and even Hamburg, which located most inland of all of the TIDE estuary ports. However, Immingham on the Humber cannot be reached independent of the tide by these vessels. Establishment of appropriate water depths has been dispensed with and the large tidal range is utilized.

4.3 Relevance for future sediment management

The increased economic relevance of the ports within the estuaries requires development of a well-functioning sediment management to make sure they remain competitive in the future. One challenge is to keep the cost of maintenance low (but also to consider ecosystem services; see below).

5. Shipping channels and their development

5.1 Background and scope

All four TIDE estuaries were relatively shallow multi-channel systems in the past; the deepest shipping channel in each case was variable. A shipping channel was specified and successively deepened in all estuaries in the course of expansion of the estuaries into large shipping waterways. The hydrodynamics and morphodynamics of the TIDE estuaries have been significantly influenced by these measures, though to a varying extent.

Identification of main issues

In the course of successive adaptation to increasing vessel sizes the fairways of the estuaries have reached considerable depths now. The tidal range in the inner estuaries has been altered due to structural measures carried out in the past. These parameters can be used as indicators for the alteration of the hydro- and morphodynamic system.

5.2 Comparison of estuaries

The **Humber estuary** is from TIDE km 95 (Hull) up to the junction with the Trent a multi-channel system. The Sunk Dredged Channel, created in 1969, is the deep water channel through the outer Humber that allows access to the ports. It is maintained at a depth of 8.8 m below chart datum. The port facilities of Immingham provide access for larger vessels up to 15.2 m using high tide conditions. In the 1870s John Marius Wilson described the depth of the Humber for the most part from 2 to 12 fathoms (equals 3.7 to 22.0 m) (http://www.visionofbritain.org.uk/place/place_page.jsp?p_id=26164, 07.03.2013). The Humber estuary has a large tidal range, with the mean being 5.7 m at Spurn, increasing to 7.4 m at Saltend and then lowering to 6.4 m at Hessle and 5.6 m at Trent Falls. The area up-estuary of the Humber Bridge has become more flood dominant over the last 150 years, while there has been increased ebb dominance in the reaches down estuary of Hull. Data regarding the precise historical tidal range is not available. The only actively managed (dredged) fairway on the estuary is 'Sunk Dredged Channel' – this being the only channel in the Humber estuary which maintains its position as a result of dredging. All the other channels are not dredged and naturally change position on a regular basis so the shipping lanes follow the deep water channel and are regularly adjusted by moving the buoys as the channels change. The channel chosen by vessels and the track followed will vary from tide to tide, depending on the tidal height and draught of the transiting vessel. The main approach channel to the Humber leads through New Sand Hole and divides into three channels south of Spurn Head: Hawke Road, Bull Channel and Haile Channel where depths vary between 9 and 16 meters at Low Water. West of Grimsby the channels merge to give deep water (12–19 m at Low Water springs) exploited by the Immingham Oil Terminal. The channel then crosses to the north bank at Hull where Low Water depths are 9 m or more. These outer estuary channels have been relatively stable for a long time but those to the west of Hull are much less reliable with the main navigable channel changing from the south side of Read's Island to the north bank and back again with a cycle time of up to 20 years (www.humber.com/Estuary_Information).

While the outer part of the **Scheldt estuary** (Westerscheldt) is a multiple-channel system, the upper part (Zeeschelde) has a meandering character with a single channel. The ebb channel is mainly used as maritime shipping channel, except for a stretch between Baarland and Hansweert where the flood channel is used. The secondary channels are used for inland and other navigation purposes. The maritime shipping channel is maintained with regular dredging works since 1900 (information on the historical depth is not available). In the 1970s a first intensive deepening was carried out followed by two others (1997–1999 and 2008–2010). The tidal range at the mouth (Westkapelle and Vlissingen) has been nearly constant over the last century and is now about 4.2 m and 4.5 m respectively. The tidal range in the inner part increased approx. 0.5 and 1.0 m. The actual tidal range in Antwerp is 5.9 m. The third deepening is giving tide-independent access to vessels with a maximum draught of 13.1 m and tide-dependent access to vessels with a draught of 15.5 m.

In the **Weser estuary** several channels exist in the Outer Weser. Due to a number of deepening one of them has been expanded into a shipping channel and the side arms in the Lower Weser are subject to increased silting and mostly filled up. The Lower and Outer Weser have been deepened and morphologically changed gradually since 1883 (Franzius correction) from 3.9 m below sea level to 14 m below chart datum. The last deepening of the Outer Weser was conducted in 1998/99. The tidal range of the Weser, particularly in the Lower Weser, has changed significantly due to the anthropogenic impacts and has increased in Bremen since the first deepening from approx. 0.2 m to a current level of 4.1 m. Now Bremerhaven is navigable for vessels of 12.8 m independent from tidal conditions. The fairway to Bremen in the Lower Weser is kept at a depth of 9 m below chart datum since more than 30 years now. A further fairway deepening of the Weser estuary is approved, but legal proceedings have been instituted.

The **Elbe estuary** consists of several channels. In the outer estuary they are mainly subject to natural dynamics. In the inner estuary due to a number of deepenings one of them has been expanded into a shipping channel, while the others are subject to increased silting in some cases. The fairway has been deepened gradually from about 4.3 m in 1843 (DELTARES 2011) and is now navigable for vessels of 12.5 m independent from tidal conditions. Today, the tidal range at the mouth (Cuxhaven) is about 3.0 m during springtide and has changed only slightly over the last century. In contrast, due to various anthropogenic impacts (fairway deepening, land reclamation and filling, embankment and changes of the morphology), the tidal range in the inner part of the estuary (Hamburg, St. Pauli) increased significantly from about 1.9 m in 1870 to about 3.7 m nowadays (DELTARES 2011). Further fairway deepening of the Elbe estuary is approved, but legal proceedings have been instituted.

5.3 Relevance for future sediment management

As a consequence of various expansion measures, the once relatively shallow TIDE estuaries now have a deep shipping channel. Whereas in the Westerschelde the multi-channel system remains, the former multi-channel estuaries of Weser and Elbe have developed mainly to a single-channel system consisting of a deep shipping channel and a few remaining branches. Thus, the discharge activity is concentrated in the main arm and the tidal range in the inner estuaries has been altered (see section 5.2). On the Humber estuary the 'Sunk Dredged Channel' is the only actively managed (dredged) fairway. The location of the shipping channels and branches within the estuaries needs to be kept stable through river engineering structures and maintenance work.

The increasing vessel dimensions lead to further development of the navigation channels within the estuaries. Today, the largest vessels that access ports in the estuaries can have a draft of more than 15 m using high tide conditions (see Fig. 8). The estuarine system has the ability to maintain its resilience in the face of external stress to a certain point. But natural boundaries have become apparent already, subsequently to fairway deepening, e.g. through increased deposition of sediments and thus an increased need of maintenance dredging. Sediment management ought to consider the natural dynamics of estuarine systems in order to preserve a sustainable ecosystem and maintain the waterways economically.

6. Sediment management: the approaches behind

6.1 Background and scope

The purpose of sediment management in the TIDE estuaries is to ensure usability of the shipping channels by commercial vessels. Sediment management includes deepening the shipping channels (capital dredging) on the basis of the necessary approvals as well as maintenance, i.e. constantly ensuring these shipping channel depths. In the past decades the shipping channels in the TIDE estuaries have been repeatedly deepened at different intervals (years to decades) and to a varying degree (except Humber, see section 5). Maintenance dredging, by contrast, has to be carried out continuously.

Both in connection with deepening of the shipping channel and with its maintenance there is close interaction between the type and extent of dredging work and the supporting river engineering measures so that the latter also have to be taken into consideration.

Sediment management has developed historically in the individual estuaries and continuously adapted to changing boundary conditions and the improving knowledge base. However, overarching written strategies exist only to a partial degree.

Besides morphological and economical aspects in sediment management, nature conservation and environmental protection have increasingly gained relevance. Contamination of dredged material and the ecological impacts of dredging and placement are now being considered as relevant problems since laws and regulations concerning the environmental issues have been introduced.

Identification of main issues

Reducing costs and dredging volumes as well as the consideration of geomorphological, environmental and ecological aspects are the central issues in the sediment management of the TIDE estuaries.

6.2 Comparison of estuaries

In the **Humber estuary** the existing maintenance dredging is long established. An analysis of the energy flux indicates that as a whole, the Estuary is developing slowly towards a morphological equilibrium, resulting in low maintenance dredging. Although on a smaller scale some sections appear to be moving away from this equilibrium state. The general strategy of maintenance dredging is outlined in the "Humber Estuary: Maintenance Dredge Protocol and Water Framework Directive Compliance Baseline Document" by ABP (2011). The Baseline Document assesses the baseline activity against all of the designated species and features. The Harbour Authorities handle maintenance dredging in navigable channels, along riverside berths and within enclosed docks. Regular, carefully planned maintenance dredge campaigns when required remove recently deposited sediment. Most of the dredging occurs in the lower and middle estuary (downstream estuary of the Humber Bridge). The Channel requires regular dredging to maintain its depth against ongoing siltation events. This material is relocated nearby the channel in a similar flow environment. Thus, additional indirect loss from the estuary that may occur is minimized. Dredged fine material is deposited at various placement sites within the estuary system to prevent direct material loss. The relocation of material from the ports returns the material into the estuary. The dredged clay is placed at the Sunk Dredged Channel windows to primarily fill natural depressions and level out the estuary bed. It can also act as a training wall to the Sunk Dredged Channel and encourage scour. ABP have installed a WID system at the Immingham Outer Harbour and are looking at alternative locations for additional WID activities. In recent years no sand accretion has occurred and land treatment has not been carried out on the Humber Estuary yet.

The first deepening in the **Scheldt estuary** was carried out without a specific relocation strategy. Dredging work was conducted by relocating the dredged material to the more shallow secondary channels. Yet, since 1990 dredging and relocation have been executed following a strategy serving morphology. The dredging strategies are applied to maintenance and capital dredging. In preparation of the second deepening the so-called 'East-West' strategy was established. As the capacity of the secondary channel in the eastern part of the Westerschelde was not enough to get all the material from the second fairway deepening placed, dredged material was transported from the eastern part to the western part of the Westerschelde. The licensed volume of all placement sites was sufficient to utilize placement sites less when required and to anticipate unwanted morphological evolutions. The capacity of the placement sites is determined using the sand-balance approach as a tool. In 2001 the idea to apply morphological management was brought up and to make use of the win-win solution in which dredged material is used to meet goals that improve the state or functioning of the estuary. The (re)construction of shallow water habitats on sandbars with relocated dredged material is further explained in section 10.5. Since 2007 the capacity of the placement sites in secondary channels in the Westerschelde has been calculated using the cell concept. Morphological cells were regarded as existing in parts of the main channel, the secondary channel and the sandbar in between those channels. The annual capacity of all placement sites is larger than the expected relocation volume per year. This allowed adjustment of the distribution of dredged material among the placement sites following insights obtained during the monitoring programme. Now, after the third deepening, placement sites in the primary channel (maritime fairway) and on sandbars are used as part of the "flexible relocation" strategy in addition to placement sites in secondary channels. Dredging in the Scheldt estuary is organized to minimize costs and efforts since placement sites are selected in the vicinity of the dredging sites. Sediment is dredged within the fairway or in open harbours. The maritime fairway needs to be dredged at natural sedimentation locations and these dredging locations may vary slightly over time. Only small amounts of sand are extracted for construction purposes. Dredging in harbour basins behind locks is not considered because this sediment is not relocated into the estuary. Currently an optimized relocation pattern within the Scheldt estuary is investigated for upcoming permits for relocation of dredged material. The results are expected in April 2013.

Sediment management in the **Weser estuary** has developed by constantly adapting itself to the respective requirements. Dredging in the fairways and harbours is primarily carried out by hopper dredgers. The dredged material is taken to various placement sites, as long as it is not contaminated, and deposited on land. The annual volume of muddy and contaminated harbour sediments removed depend on both the requirements of the harbours and the capacity of the landfills and third parties. Sediments from harbours have been transported to the Lower Rhine and to the aquatic Confined Disposal Facility (CDF), the Slufter in Rotterdam. Today, sedimented particulate matter is also regularly remobilized by WID, thus reducing maintenance dredging by hopper dredgers with removal. Additional reduction of maintenance dredging resulted from structural measures, e.g. by building a new watering facility for a harbour basin (Überseehafen) in Bremerhaven to reduce the sedimentation rate. Thus, at present there is no written strategy, but the Federal Institute of Hydrology and the WSV are developing a sediment management concept. The draft will presumably be submitted in 2013. However, river engineering is not part of this sediment management concept. Both aspects will be incorporated into an integrated river engineering concept, which is expected in 2015.

Along the **Elbe estuary** and in the harbours dredging work is necessary in the sedimentation areas. Mostly hopper dredgers are used for this purpose and smaller equipment for excavation is employed only under confined conditions. Moreover, WID is applied in close setting with tidal conditions to eliminate sand ripples in the navigation channel and harbour basins as well as in anabranches. No harbour basins are operated behind locks. Dredged material from maintenance work is relocated within the river system or, when higher contaminated, brought on land to the treatment plant METHA – Mechanical Separation and Dewatering of Port Sediments. After an increase of dredging in 2004 and 2005 between Neßsand and the port of Hamburg dredged material was also taken to the North Sea near Buoy E3. The WSV and HPA jointly developed the "River Engineering and Sediment Management Concept for the Tidal River Elbe" (RESMC) in 2008 (see section 10.1). It specifies a number of causes for the rise in dredged volumes and on this basis not only develops a strategy for sediment management, but also for reduction of the dredged volumes, taking into account sediment composition and contamination. Measures to reduce the rise of the tidal range are also part of the concept. Some aspects of the concept have already been implemented, others still have to be initiated. These include among others creation of flooding areas by the realignment of dikes or reconnecting side arms to reduce the rise of the tidal range, construction of a sediment trap for maintenance reasons and implementation of a new relocation scheme within the tidal Elbe.

The sediment management strategies in the four TIDE estuaries display both parallels and clear differences.

Parallels in the estuaries are:

- sediment management aims at establishing and maintaining the specified minimum depths in the shipping channel and at the same time reducing costs
- sediment management is supported to a certain extent by extensive monitoring of the hydrodynamic and morphodynamic changes
- legal requirements based on environmental and nature conservation law have been increasingly taken into account in recent years
- a main channel is maintained by means of continuous maintenance dredging (primarily hopper dredgers)
- this main channel was repeatedly further deepened in the past (except Humber)
- dredged material is primarily relocated within the estuaries at designated placement sites
- dredged material was and is still used for river engineering measures (backfilling of overdepths, securing shore, concentration of the force of the current on the main channel, among other things)

Differences include in particular

- the specific hydro- and morphodynamic
- different use of river engineering measures like groynes (especially in the inner Weser estuary very extensive in order to reduce maintenance dredging)
- different challenges due to varying intensity of tidal pumping and thus varying extent of sedimentation (the challenges on the Elbe in this context are rather extensive)
- the Humber estuary has not been expanded to such an extent that large vessels can call at the ports independent of the tide
- different approaches like "flexible relocation" strategy in the Scheldt (see above)

6.3 Relevance for future sediment management

The comparison of the sediment management strategies of the four TIDE estuaries clearly shows that the situation in the individual estuaries varies quite a bit and therefore specific strategies are necessary and meaningful. Sediment management practice has developed historically in all estuaries and has been adapted to changing boundary conditions. Current changes in the boundary conditions include more extensive consideration given to requirements based on environmental and nature conservation law, greater need of cost reduction and more frequent occurrence of undesired morphodynamic developments primarily due to increased tidal pumping (see section 9).

Sediment management has to tackle these challenges. One way is to formulate integrated sediment management strategies that also take into account long-term changes based on an in-depth understanding of the interactions between hydrodynamics and morphodynamics and ecology (see section 8.3.3).

The TIDE estuaries have been morphologically modified to a great extent in the past. A close interaction between river engineering and sediment management exists and this should be adequately considered in the future. At the same time, the conditions of nature conservation and environmental protection need to be incorporated into the integrated river engineering concept with regular monitoring and evaluations. Thus, the main challenge is still to balance the estuarine sediment budget for the different estuarine stretches, but in the framework of a bigger picture and using sustainable methods. Thus sediment management has itself to understand and to act as part of integrated estuarine management, which can be understand also as Integrated Coastal Zone Management (SCHUCHARDT 2010).

7. Dredging: keeping the depth

Dredging works are carried out within the sedimentation areas along the TIDE estuaries to keep the shipping depths in the fairways and ports. It is distinguished into maintenance and capital dredging as far as data is available.

7.1 Overview on quantities of dredged material

The quantities of capital and maintenance dredging, including WID or plough dredging if applicable, in fairways, ports behind locks and tidally influenced areas of the ports are presented in the following for the TIDE estuaries. However, the figures presented may not be fully consistent. Due to different data sources within one estuary the data available was restricted and, thus, especially between estuaries only comparable to a limited extend. Relating the quantities of material moved by WID with conventional dredging methods is problematic due to different calculations, nevertheless, the relatively new dredging method is increasingly applied and all sediment volumes moved should be displayed in comparison. Tab. 2 gives an overview of the dredging data that was available for different time spans and illustrates the difficulties comparing the dredging works carried out in the estuaries.

Tab. 2: Overview on dredging data from the TIDE estuaries available for the present study (no data = dredging was conducted, but no data are available, – = no dredging occurred).

	Humber	**Scheldt**	**Weser**	**Elbe**
Conventional maintenance dredging	**2004–2010**	**1999–2010**	**1999–2009**	**1999–2009**
Fairway	**2004–2010** SDC*	Wielingen (estuary mouth), Wester- and Zeeschelde	TIDE km 0–119	Elbe km 639–748
Ports 'open' to the estuary	**2004–2010**	Westerschelde and Zeeschelde	**1999–2011** Bremerhaven, Bremen; No data Brake, Nordenham	Hamburg (includes Elbe fairway down to km 639); No data Cuxhaven and Brunsbüttel
Ports behind locks	**2004–2010**	No data	**1999–2011** Bremerhaven, Bremen and Brake	–
WID maintenance and plough dredging		**2006–2009**	**1994–2009**	**1999–2009**
Fairway	No data WID; No data Plough	No data WID; Plough in working hours	WID applied **since 2003** TIDE km 0–119 in m³ **	WID **since 2001** Elbe km 639–726 in m³ **
Ports 'open' to the estuary	No data WID; No data Plough	Plough in working hours	WID applied **since 1994** Bremerhaven, values estimated in m³	WID **since 1999** Hamburg (includes Elbe fairway down to km 639) in m³ **
Ports behind locks	No data WID; No data Plough	No data Plough	No data WID **(since 2006)**	–

	Humber	Scheldt	Weser	Elbe
Conventional capital dredging	**–**	**1999–2010**	**2001–2011**	**2008**
Fairway	–	**2001, 2008–2010**	**2001–2008** Bremerhaven turning site	Construction of sediment trap
Ports 'open' to the estuary	–	**2003–2008** Deurganckdok	**2009** Brake	–
Ports behind locks	–	No data	**2008–2011** Kaiserschleuse	–
WID capital dredging	**–**	**Used for deepening in sensitive areas**	**–**	**–**
Fairway	–	No data	Planned in the potential Weser deepening	–
Harbours 'open' to	–	–	–	–
Harbours behind	–	–	–	–

* Sunk Dredge Channel
** WID in m³ is calculated based on working hours

The total volume of maintenance dredging in the **Humber estuary** carried out per year is lowest compared to the other TIDE estuaries. The volume dredged annually ranges around 3.7 million m³ for the period between 2004 and 2010 (Fig. 9). WID and ploughs are employed in the fairway and ports, but there is no data available on this as it is not licensable (written notice Environment Agency, GB). Capital dredging has not been conducted since 1969.

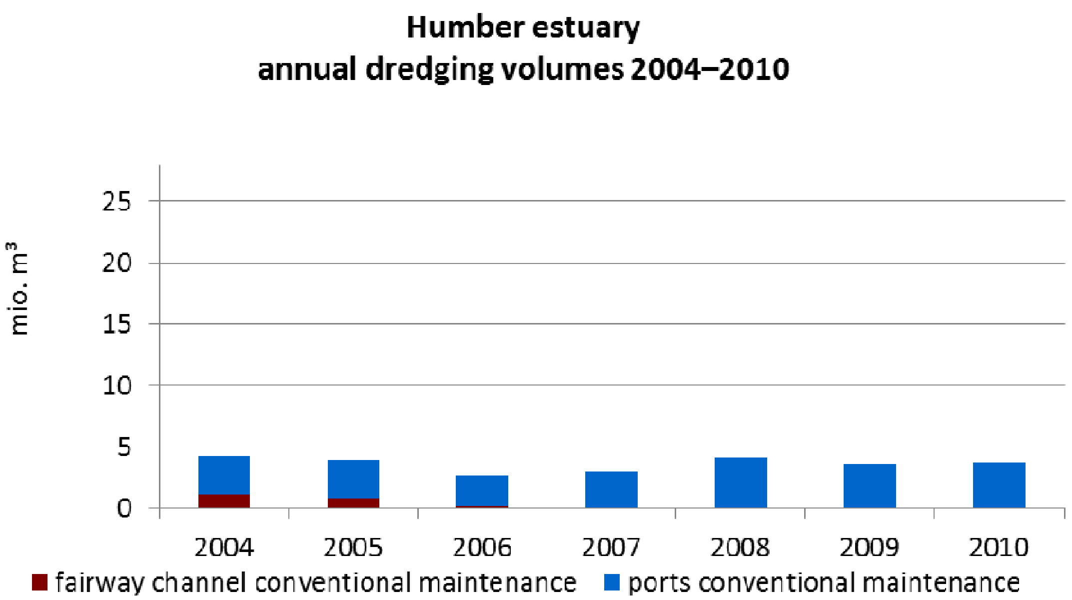


Fig. 9: Annual dredging volumes of the Humber estuary (ABP) (2004–2010) (no data for WID and plough dredging, capital dredging was not conducted during this period) (data provided by the Environment Agency (GB)).

The quantities of dredged material in the **Scheldt estuary** from maintenance and capital works ranged around 18.7 million m^3 between 2000 and 2009 with a maximum of 22 million m^3 in 2009 (Fig. 10). Sediment volumes moved by WID are missing. Total working hours for plough dredging in the estuary averaged around 7000 per year between 2006 and 2009. Dredging data from ports behind locks (e.g. Genth) was not provided, the dredged sediment is not relocated within the estuary.

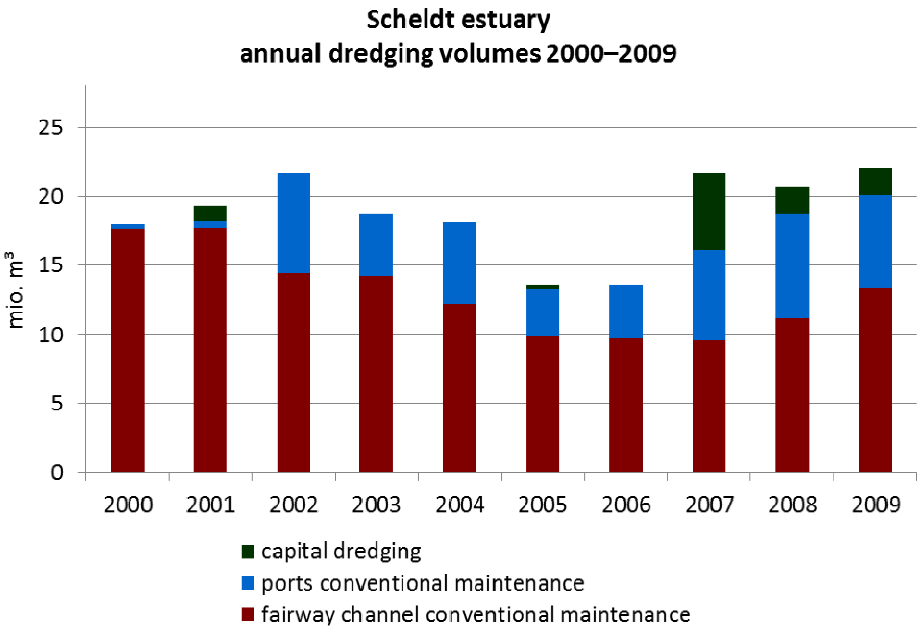


Fig. 10: Annual dredging volumes of the Scheldt estuary (2000–2009) (data of ports behind locks is not available, fairway conventional maintenance includes sand extraction, WID data is only available in working hours) (data provided by the Flemish Government).

The proportions of the dredging volumes of the fairway and the harbours of all the maintenance- and capital dredging in the **Weser estuary** including the sand extractions of third parties and WID in the fairway (no data available for WID in ports) were 5.5 million m^3 in 2000 rising to about 10 million m^3 in the final years of the time period presented in Fig. 11.

The total dredging volumes in the **Elbe estuary** ranged highest compared to the other TIDE estuaries with 15.8 million m^3 a year in 2000 to 23.6 million m^3 in 2009 (Fig. 12). Capital dredging has only taken place in 2008 when the sediment trap was cleared.

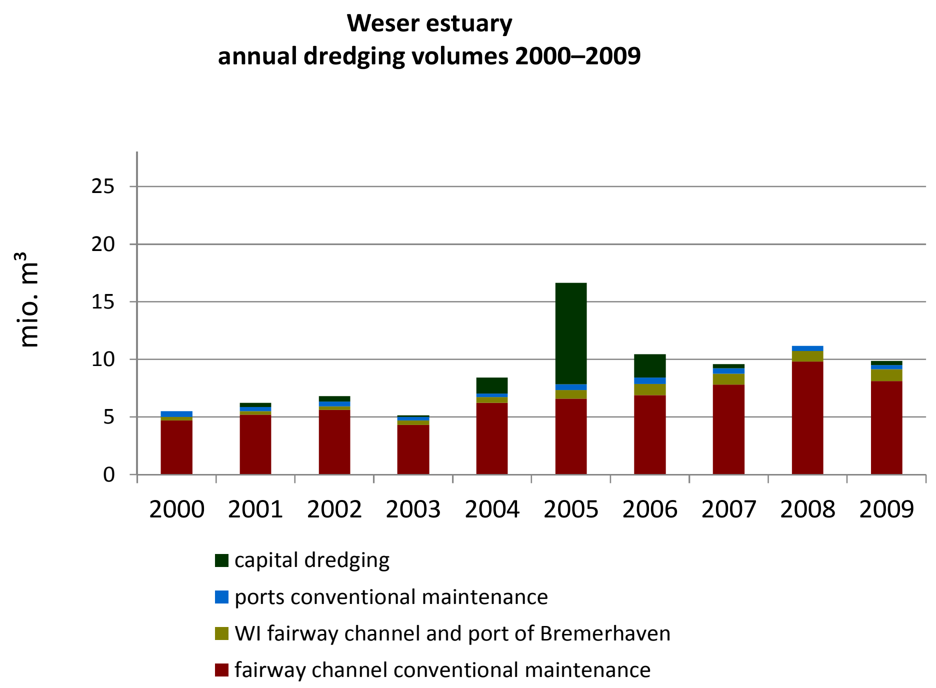


Fig. 11: Annual dredging volumes of the Weser estuary (2000–2009) (capital dredging of Bremerhaven turning site between 2005 and 2008 were given for a period and not specifically assigned to years, fairway conventional maintenance includes sand extraction for third parties, WID data for the port of the City of Bremen is not available) (data source: TIDE-report Weser).

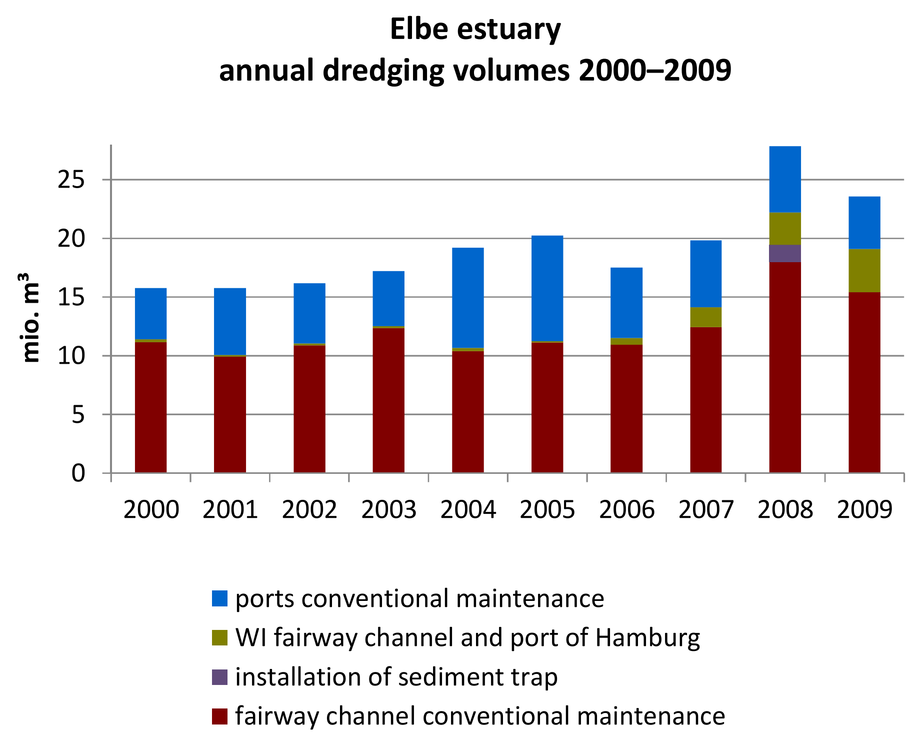


Fig. 12: Annual dredging volumes of the Elbe estuary (2000–2009) (ports conventional maintenance: dredging work in the port of Hamburg including Elbe fairway down to km 639 = TIDE km 53) (data provided by HPA).

7.2 Capital dredging of fairways

7.2.1 Background and scope

The formerly relatively shallow TIDE estuaries have been adapted to developments in shipping traffic for more than 100 years now. Thus, capital dredging has been conducted various times in the estuaries to be able to keep up the ports' economic benefits.

Identification of main issues

Recent channel deepening, dredging strategies, methods of dredging, physical and chemical quality of sediments and restrictions are the main issues.

7.2.2 Comparison of estuaries

In the **Humber estuary** the Sunk Dredged Channel was created in 1969 at a depth of 8.8 m below chart datum; figures on sediment volumes are not available.

The **Scheldt estuary** was last deepened between 2008 and 2010 giving tide-independent access to vessels with a maximum draught of 13.1 m. For this third deepening of the fairway nearly 16 million m^3 of material was dredged by trailer suction hopper dredger. Further capital dredging was conducted in the period 2003–2008 when the tidal dock "Deurganckdok" was constructed and about 7 million m^3 was dredged. In 2001 the last step of the second deepening of the maritime fairway to the port of Antwerp was finished. Altogether a volume of more than 23 million m^3 of material was relocated for capital work within the estuary between 2000 and 2010. WID has also been used as a precautionary technique for dredging in a sensitive area e.g. deepening the navigation channel in the neighbourhood of cables. However, no differentiated data is available for this practice. Dredging strategies as described in section 6.2 are used for maintenance and capital dredging. In 2010 the principle of relocating dredged sediment to construct shallow water habitats on sandbars was applied on a larger scale in the Westerschelde during the third deepening.

In the **Weser estuary** the fairway of the Lower Weser was deepened more than 30 years ago to a depth of 9 m below chart datum. Capital dredging of the fairway in the Outer Weser was conducted the last time in 1998/99 to 14 m under chart datum with volumes of more than 7 million m^3. An application for further deepening of the Lower and Outer Weser has been submitted and approved but proceedings have been instituted against it and are currently pending (03/2013). The aim in the Outer Weser is to enable accessibility independent of the tide for large container ships with a maximum unloading draught of 13.5 m. Within the scope of the deepening of the Outer Weser the port-related turning site of the container terminal in Bremerhaven was set up with an integrated emergency turning site at the depth level of the 14 m chart datum in 2006. For the Port of Brake the accessibility independent of the tide is envisaged for vessels with a maximum unloading draught of 12.8 m and for the port of Bremen for vessels with a maximum unloading draught of 11.1 m. The volume of capital dredging in the fairway has been stated as 6.5 million m^3. The dredging principles of this deepening include different methods. The Outer Weser will be deepened by hopper dredgers and the primarily sandy sediments are relocated to placement sites in the Outer Weser. In the so-called "mud section" in the Lower Weser deepening of the fairway will be carried out by hopper dredgers and also this material will be relocated to placement sites in the Outer Weser. In the sandy sections hopper dredgers will be largely substituted by WID with the aim of reducing costs and impairments of the environment (see section 10.4).

Capital dredging of the **Elbe estuary** fairway has occurred last in 1998/99 and in 2008 for the sediment trap. An application has been submitted and approved for further deepening of the Elbe estuary for vessel draughts of 13.5 m (independent from the tide), but proceedings have been instituted against it and are currently pending (03/2013). Besides deepening the existing shipping channel, parts of it will be widened within the 136 km long expansion section. 33.4 million m³ of sediments will probably be dredged. Strategies for this capital dredging campaign include the construction of underwater placement sites. The dredged material will predominantly be collected by using hopper dredgers. River engineering compensation measures are a part of this project, which limits the increase in tidal range resulting from deepening of the shipping channel. This involves placing part of the dredged material on underwater storage areas and to some extent covering it with natural stones.

7.2.3 Relevance for future sediment management

Any expansion of an estuary substantially changes its hydrodynamics and morphodynamics. However, the increase of depths in the fairways of the estuaries is restricted by natural boundaries. Modelling is an important tool to determine the best sediment management strategies when capital dredging is conducted in an estuary. Further intervention into the estuarine ecosystem ought to be considered carefully to ensure its ecological functioning in the future. Experiences, such as in the inner estuaries of Loire and Ems estuary, however, have clearly indicated that these natural boundaries are not always recognized in advance, even when numeric models are used. As a result of capital dredging, a massive increase in tidal pumping has taken place in these estuaries with enormous economic and ecological consequences. This indicates the further need of research on the topic of estuarine functioning.

Capital dredging is a key measure in any expansion and the dredging methods employed are similar. A new feature that is envisaged for the current deepening of the Lower Weser is the absence of continuous deepening by hopper dredgers in the innermost section: only the crests of the underwater ripples are to be cut off as necessary by means of water injection.

River engineering measures have been and still are taken as elements of river expansion to a varying extent. They involve the use of dredged material (stable or dynamic) or "hard" structures like groynes and training structures. For the first time measures aimed at counteracting the reduced energy dissipation due to deepening through river engineering work (underwater deposits) are planned for the Lower Elbe as part of a river expansion project.

7.3 Maintenance dredging of fairways

7.3.1 Background and scope

In all TIDE estuaries the officially approved shipping depths must be maintained by means of different dredging methods. The process involves collecting the sediment and transporting it to another site in the system where it is preferably deposited. The work is primarily carried out using hopper dredgers and additionally, whenever necessary, bucket chain dredgers and pontoon dredgers.

In addition to conventional dredging, WID has been increasingly applied in recent years mainly due to economic aspects. In this process large amounts of water are injected into surface sediments on the bottom. This generates suspended sediment in the water with a high density which flows over the bottom like a fluid layer. Thus, suspended sediments are moved from one area to another. This can be conducted locally (e.g. crests of underwater dunes are mobilized and drift into neighbouring ripple valleys with the current) or the suspended sediment can be directed into an area with a high flow rate and turbulence where further transport occurs.

Identification of main issues

Reducing maintenance dredging is a central issue for the TIDE estuaries for economic and ecological reasons.

7.3.2 Comparison of estuaries

The general strategy of maintenance dredging in the **Humber estuary** is outlined in the Baseline Document by ABP (2011). Maintenance dredging in the fairway is accomplished on an ad hoc basis. Dredging activities are not constrained by the tide. The majority of dredging takes place in the lower and middle estuary. The Sunk Dredged Channel (references to this channel also include the Hawke Channel) is dredged as often as necessary in order to maintain the advertised depth. Due to the dynamic nature of the channel, where sand migrating into the channel is highly variable, there is not an established consistent regime for dredging frequency. The necessity for dredging is determined by frequent bathymetric surveys. Material tends to accumulate on the south side of the western two-thirds of the Sunk Dredged Channel. To maintain the levels of the navigable width, most of the work is required on the southern edge of the channel. Maintenance dredging is generally carried out by trailing suction hopper dredgers and by means of WID in areas where tidal flow and bathymetry aid the controlled dispersion of mobilized sediment. To support these techniques, bed levelling (plough dredging) is used post-dredge to smooth areas and pre-dredge to move material into accessible locations to be collected by trailing suction hopper dredgers. Data of sediment moved by WID and ploughs is not available as it is not licensable (written notice Environment Agency, GB). While in 2004 dredge volumes in the Sunk Dredged Channel were 1.2 million m^3, no maintenance was undertaken for the period 2007 to 2009. In 2010 a small campaign took place with 0.024 million m^3 dredged material. However, it is quite possible that the channel will need more substantial dredging in the near future; i.e. similar to those seen historically as part of the cyclic pattern of morphology. In 1994, however, 11.8 million m³ of material required dredging of which nearly half was from the Sunk Dredged Channel (Townend and Whitehead, 2003 in ABP 2011). Siltation in the docks and deep berths is far less variable compared to those for the Sunk Dredged Channel. The material dredged from the Sunk Dredged Channel in the years before the period of self-maintenance was predominantly sand with a mean/medium grain size of 100–200 microns. In the early years of the channel, silt with a median particle size of < 63 microns was mainly dredged. This material is still from time to time present, but less frequently than seen in the past (ABP 2001).

The maritime fairway of the **Scheldt estuary** needs to be dredged at natural sedimentation locations. As these dredging locations may vary slightly over time, bounding boxes are used to indicate the dredging locations. Between 2000 and 2010 dredging volumes including sediment extraction varied between 10 million m^3 in 2007 and more than 22 million m^3 in 2010 with a mean of 14 million m^3 for this period. The dredged material in the maritime fairway is mostly sandy. Some silt is dredged in the maritime fairway near the open harbour areas in the vicinity of the port of Antwerp. Dredged material is removed using trailer suction hopper dredgers. WID has been used as an alternative to trailer suction hopper dredger on a location where cables lie close under the river bed, although data is not available for this method. Near quay walls and in the access channels to the locks a plough is used to move (silty) material to areas nearby that can be reached with a trailer suction hopper dredger. Dredging efforts with plough are reported with about 1300 working hours during a working year.

The fairway of the **Weser estuary** is dredged from the freshwater to polyhaline zone while the euhaline zone does not have to be maintained. Within the period from 2000 to 2008 the maintenance values more than doubled from 4.7 million m^3 to more than 10 million m^3 of dredged material. Most of the material dredged in the fairway is sandy except the material from the mud section Nordenham. Certain sections of the fairway are dredged more than others. Removal of material increases towards the outer parts of the Weser estuary. Nowadays WID is applied in many sandy sections of the Lower Weser and in a few section of the Outer Weser in order to decrease maintenance dredging by hopper dredgers.

The **Elbe estuary** is currently divided into 17 dredging sections. Maintenance dredging ranged from 7.7 million m^3 in 1999 to about 20 million m^3 of material in 2008. The rise of dredged material in the upper reaches of the tidal Elbe resulted from increased upstream transport of sediments coming from downstream. An optimized relocation pattern in the tidal Elbe was developed within the frame of the RESMC (see section 6.2) aimed at breaking tidal pumping by creating a balance between relocation/sedimentation and erosion at the placement sites. As a river engineering measure to control sedimentation processes, a sediment trap has been installed downstream from Hamburg to capture marine sediments before they mix with the upstream material. In addition to conventional dredging like hopper dredgers, WID is used to eliminate sand ripples in the fairway.

A direct comparison of the maintenance dredging volumes of fairways and ports (including WID) for the four estuaries is not possible due to differences in data systematics and availability. Assuming, that the amount of maintenance dredging can be seen as an indicator for monetary as well as environmental costs on one side and mean cargo (volume, TEU) as an indicator for economic benefit on the other side such a comparison (including further indicators) would be interesting for evaluating the economic and environmental performance of European harbours. Therefore, it might be useful to improve future systematics of data acquisition.

Water injection

In the **Humber estuary** maintenance dredging is also carried out via WID in areas where tidal flow and bathymetry aid the controlled dispersion of mobilized sediment. ABP have installed a WID system at the Immingham Outer Harbour and are looking at alternative locations for additional WID activities. However, due to the short duration it has been operating there are no results to share.

WID it is not a common practice in the **Scheldt estuary**. Although, it has been used as a precautionary technique for dredging in sensitive areas such as in the neighbourhood of cables. However, sediment volumes moved by WID are missing. Instead working hours of bed levelling by plough in fairways and harbours was given, which averaged around 7000 hours per year between 2006 and 2009.

WID is applied regularly in the **Weser estuary** in order to decrease maintenance dredging by hopper dredgers, costs and impairment of the environment. In the sandy sections of the fairway in the Lower Weser and – depending on the swell – of the Outer Weser the ground has been regularly remobilized by means of WID since 2003/2004. The extent of the sediment set into motion by WID in the fairway of the Weser increased from 72,800 m³ in 2003 to 738,200 m³ in 2009. Capital dredging by means of WID is planned in the fairway of the approved Weser deepening, against which legal proceedings have been instituted.

Maintenance dredging by means of WID is applied in the **Elbe estuary** in close setting with tidal conditions to eliminate sand ripples in the navigation channel and harbour basins as well as in anabranches. It was first tried out in 2001 in Lühesand km 645–652. From 2006 on, the technique was carried out in the navigation channel. From 2007 to 2009 about 1.5 million m³/a of sandy material from the main channel and 1.2 million m³/a of silty sediments from secondary channels and anabranches were moved by means of WID. If possible, the silty areas are cleared during winter with regard to environmental impacts such as oxygen deficits. Furthermore, the contamination of the dredged material from Wedel is regarded as critical (ENTELMANN 2010).

Today, WID is utilized to reduce conventional dredging and reduce costs in all TIDE estuaries. Only a rough comparison of the quantities of dredged material moved by water injection is possible due to different methods applied. Application of WID in sandy sections of the estuaries seems to have advantages compared to hopper dredging concerning costs, sediment balance and the environment (see section 10.4). However, as far as fine grained (possibly contaminated) sediments are concerned, environmental issues need to be critically checked. The impacts of WID on the environment have been assessed and impairment of the benthos appears to be relatively minor compared to hopper dredging due to the existing species-poor community adapted to the dynamic conditions. However, suspended material may lead to a decline in the light conditions and depletion of oxygen, for example. This impairs flora and fauna and during spawning harms development of the eggs. Thus, WID must only be carried out when these circumstances are minor. The same can be said about plough dredging (bed levelling). As with WID, if the sediment ploughed is soft it may be sufficiently disturbed to raise smaller sediment fractions into suspension.

7.3.3 Relevance for future sediment management

In all TIDE estuaries substantial volumes of dredged material are relocated in the course of maintenance so as to maintain the approved fairway depths. Since maintenance dredging causes permanent costs and disturbances of the environment, all those involved are making an effort to reduce the volumes. While the way in which maintenance dredging is implemented does not differ significantly between the estuaries, different reduction approaches, which essentially also reflect the different hydrodynamic and morphodynamic boundary conditions, are pursued in some cases. There are considerable differences between the relocation strategies (see below) and in the type and extent of the river engineering measures taken. In the inner Weser estuary, for instance, the extent of maintenance dredging has been greatly reduced by means of an extensive groyne construction programme while in the Scheldt estuary the natural force of the current is supported by reinforcing sand bars and in the Elbe various measures such as realignment are envisaged in order to reduce tidal pumping.

WID is a relatively new dredging method and national regulations need to improve consideration given to this technique. A consistent definition and comprehensive regulations for implementation taking into account economic, nautical, morphological and ecological aspects have to be developed. The volumes moved by WID and plough ought to be determined clearly to be able to estimate impacts better and to improve the comparability. As far as silty sediments are involved, the problem of increasing oxygen consumption in the water column (therefore WID with silty sediments in the Elbe estuary is mostly executed during winter) and the resuspension of contaminants must be considered. To be able to employ WID in order to reduce other dredging techniques and costs, it is vital to improve the sediment quality in the estuaries and ports and to improve knowledge on the effects of WID.

7.4 Maintenance dredging of ports open to the tide

7.4.1 Background and scope

Ports need to have the same or even higher water depth compared to the fairway. Because current velocity is reduced, possibly due to local effects like eddies, sedimentation rates in ports may be very high. Thus maintenance is costly. The material dredged in ports and harbours open to the tide often differs from the sediments in fairways. Generally fine-grained material (mud) prevails over the sandy fraction. The chemical quality of fine sediments is often affected by past industrial activities in the catchment area and port activities. To maintain advertised depths of water in harbour basins and along riverside berths, hopper dredgers (trailing suction and grab hopper dredgers), WID and ploughs are used.

Identification of main issues

Reducing maintenance dredging and contamination are the main issues concerning sediment management within ports.

7.4.2 Comparison of estuaries

In port areas open to the tide in the **Humber estuary** maintenance work increased from 2.2 million m^3 in 2004 to 3.3 million m^3 in 2010. Further dredging was carried out in the ports behind locks with a mean of 0.7 million m^3 a year for 2004–2010. Data for WID and plough dredging of ports open to the estuary was not available. Dredging within riverside berths is undertaken by trailing suction and grab hopper dredgers as well as by WID and ploughs, as described in section 7.3.2. The material dredged from the docks is composed predominantly of fine silt, clay and some sand. The in-situ bed density is generally about 1,300 kg/m^3. Since 2005 the sediment quality in some docks has exceeded acceptable levels of contamination (ABP 2011). However, although there have been contamination issues at some locations in recent years, contamination levels within sediment samples across the Humber Estuary are typically below Cefas ALs (Cefas: Centre for Environment, Fisheries & Aquaculture Science, AL: Action Level) or slightly above AL 1 and have nonetheless been deemed acceptable for placement to sea.

The dredging strategies for maintenance and capital dredging in the **Scheldt estuary** are outlined in section 6.2. The quantities of dredged material from the open harbour areas in the Scheldt estuary varied between 0.4 to 4.5 million m^3 a year from 2000 to 2010, respectively. Further maintenance efforts were reported by plough dredging with about 5500 working hours during a year. WID is carried out in ports open to the tide. The dredged material of the open harbour areas near Antwerp is mostly silty. The dredged material of the Zeeland harbours is a mixture of sand and silt. About 518,000 m^3 of material is additionally dredged annually in harbours behind locks.

In the port areas open to the tide in the **Weser estuary** the water depths have to be restored regularly in order to maintain shipping operations. Hopper dredgers and WID are primarily used for maintenance work. WID has been applied since 1994 reducing maintenance dredging by hopper dredgers with removal. However, WID is not understood and documented as maintenance dredging by bremenports, who is managing the twin ports of Bremen and Bremerhaven. Though, the sediment volumes being moved by WID today widely exceed the volumes being moved by hopper dredgers. Specific data is not available. In Bremerhaven dredging of sandy material has increased again since 2005. While in 2000 conventional maintenance of 0.2 million m^3 had to be undertaken in the ports open to the tide, in 2006 more than 0.4 million m^3 had to be dredged with this method. In all these years it is estimated that additional 0.3 million m^3 of material is moved by WID in Bremerhaven each year. Data regarding WID operations in the ports of the City of Bremen is not available. Additionally, at the 2006 constructed port-related turning site in Bremerhaven around 1.5 million m^3 of material was removed in 2008 decreasing in 2009 and 2010 to about 200,000 m^3.

Dredging in harbours behind locks, internal relocations as well as WID play a prominent role in the maintenance of ports in the Weser estuary. More than 200,000 m^3 of material a year (2007–2011) is additionally dredged in harbours behind locks. More than half of the material dredged in all port areas is sandy with little contamination, but the remaining fine-grained material, which is primarily found in the harbour sections behind locks, largely contains harmful substances.

The relevant port in the **Elbe estuary** regarding maintenance dredging is the port of Hamburg due to its size. Dredging is necessary throughout the port, though activities are restricted to the economic necessities. Maintenance dredging is carried out by hopper dredger as well as by WID. While in 1999 the sediment dredged amounted to about 2.5 million m^3, in 2005 maintenance had risen to more than 9 million m^3. Dredged material consists predominantly of silt and fine-sand. It differs in quality and the problem of contamination from upstream sources has a significant impact on the sediment management. Old harbour basins accumulate material over a longer time and reflect the quality of suspended solids from the past, thus sediments may be more contaminated. As explained in section 7.3.2, river engineering measures have been implemented to break tidal pumping and keep upstream sediments from mixing with those coming from sea. Central measures to reduce the dredging amounts in the port were the sediment trap constructed in 2008 downstream of Hamburg and transport of maintenance dredging material to outside the system (North Sea).

Though difficult to compare, the amounts to be dredged from port areas differ greatly between ports for different reasons: size of port area, location of ports, suspended matter concentration, tidal pumping, local effects, tidal amplitude and other reasons, only some of which could be mentioned in the baseline reports.

7.4.3 Relevance for future sediment management

Reducing maintenance dredging and contamination are the main issues concerning sediment management in ports with respect to costs and environment.

Reduction of maintenance may involve structural measures, flexible depth management according to requirements, refilling of docks no longer necessary, construction of riverside quays with elevated current velocities instead of harbour basins, etc. However, such measures strongly depend on the local situation and have also to be developed locally.

By striving to retain sediments within the water courses of the estuary, it is vital to reduce contamination in harbours in order to overcome restrictions concerning the relocation of sediments in the estuary (see below). Thus reduction of contamination must be an integral part of sediment management. That requires a transnational approach since third parties in the catchment area might have to be involved. To make sure no contaminated material is moved when not appropriate, WID needs to be recognized by all parties using this technique as a dredging method.

8. Dredged material: burden and benefit

Placement is carried out subsequently to dredging at placement sites within the TIDE estuaries, on land or in the North Sea. Material from capital dredging has to be distinguished from material deriving from regular maintenance work. The material excavated is different from settled sediments and consists of sandy as well as fine sediment that often needs specific management. Thus, prior to the placement of dredged material in water bodies the alternatives to use, treatment, re-use or the need of confined disposal have to be reviewed, taking technical, economic and ecological aspects into consideration. This is accomplished via a set of investigations according to different directives.

8.1 Overview on quantities and kind of dredged material

In the years before the period of self-maintenance (see above) of the **Humber estuary** the material dredged from the Sunk Dredged Channel was predominantly sand with a medium grain size of 100–200 microns. In the early stages of the channel, silt with a median particle size of < 63 microns was mainly present. This material is still dredged, but less frequently than in the past. Placement of dredged material within the Humber estuary varied between 2.5 million m^3 in 2006 to 4.0 million m^3 in 2008. Thus far, WID has been little used as a relocation method and land disposal is not carried out in the Humber Estuary.

The dredged material in the maritime fairway of the **Scheldt estuary** is mostly sandy. Some silt is dredged in the maritime fairway near the open harbour areas in the vicinity of the port of Antwerp. The dredged material of the open harbour areas near Antwerp is mostly silty. The dredged material of the Zeeland harbours is a mixture of sand and silt. The volume of material placed within the Scheldt estuary varied around 15 million m^3 between 1999 and 2009. The material yearly utilized is about 1 million m^3 and was highest in 2007 with 5.9 million m^3, which includes 5.6 million m^3 of the capital dredging of the tidal dock "Deurganckdok".

In the **Weser estuary** material from the fairway and certain sections in front of the riverside quays is mainly sandy with low to very low fine grain portions. Most material from the port areas behind locks is fine-grained sediment and is predominantly taken to a landfill due to contamination levels. In the ports open to the tide in the recent years WID has become an extensively practised relocation method in the Weser estuary. Annual volumes of all placement sites within the Weser estuary ranged from 2.1 million m^3 in 2005 to 9.5 million m^3 in 2008 (between 1999 and 2010). Material disposed on land from ports and the fairway varied from 4.2 million m^3 in 2005 to 0.2 million m^3 in 2008 and 2010 during the last decade. In 2004 to 2006 large volumes from maintenance dredging were given to third parties, primarily in the framework of construction work. This presumably reduced the volumes of material relocated during these years and resulted in high volumes of material brought on land. The landfill in Bremen-Seehausen enables management of about 200,000 m^3 of contaminated sediment annually and in 2011 71,327 m^3 of highly contaminated dredged material from Bremerhaven was taken to a Confined Disposal Facility (CDF), the Slufter in Rotterdam, for the first time (see section 8.4).

The material from the fairway of the **Elbe estuary** consists mainly of silty fine sand. Downstream of Juelssand, sandy bed material predominates. Freshly accumulated sediments are relocated. The annual amount brought to placement sites within the estuary increased from 8.6 million m^3 in 1999 to 18.3 million m^3 in 2009. Furthermore, 6.5 million m^3 of dredged material from the port of Hamburg was placed out of the estuary to Buoy E3 in the North Sea between 2005 and 2010. The volume of material deposited on land because of contamination and for construction of landfills was on average 1.6 million m^3 a year from 1999 to 2009. For the same period of time, the volume of material deposited and treated on land because of contamination was on average 1.1 million m^3 a year. WID is also used as a relocation method.

8.2 Handling of contaminated material

8.2.1 Background and scope

Inorganic and organic contaminants from all over the riverine catchment area accumulate in fine-grained estuarine sediments. Thus, the concentration of such largely persistent pollutants is often found to be elevated. Further increase may occur due to local input, e.g. in ports. Although input of several contaminants into rivers and estuaries has decreased over the last two decades as a result of increasing environmental awareness, present values are still elevated compared to background levels. Therefore, relocation especially of fine-grained sediments dredged from ports within the estuarine system might be restricted for environmental reasons.

The framework for national guidelines on how to handle such sediments is provided by international regulations like the London Convention (LC) and the Oslo-Paris Convention (OSPAR). Before placement of dredged material in water bodies the options of use, treatment, re-use or the need of confined disposal have to be assessed, taking technical, economical and ecological aspects into account (Fig. 13). However, somewhat different quality criteria and guidance values for contaminants in sediments are used by the countries of the North Sea region.

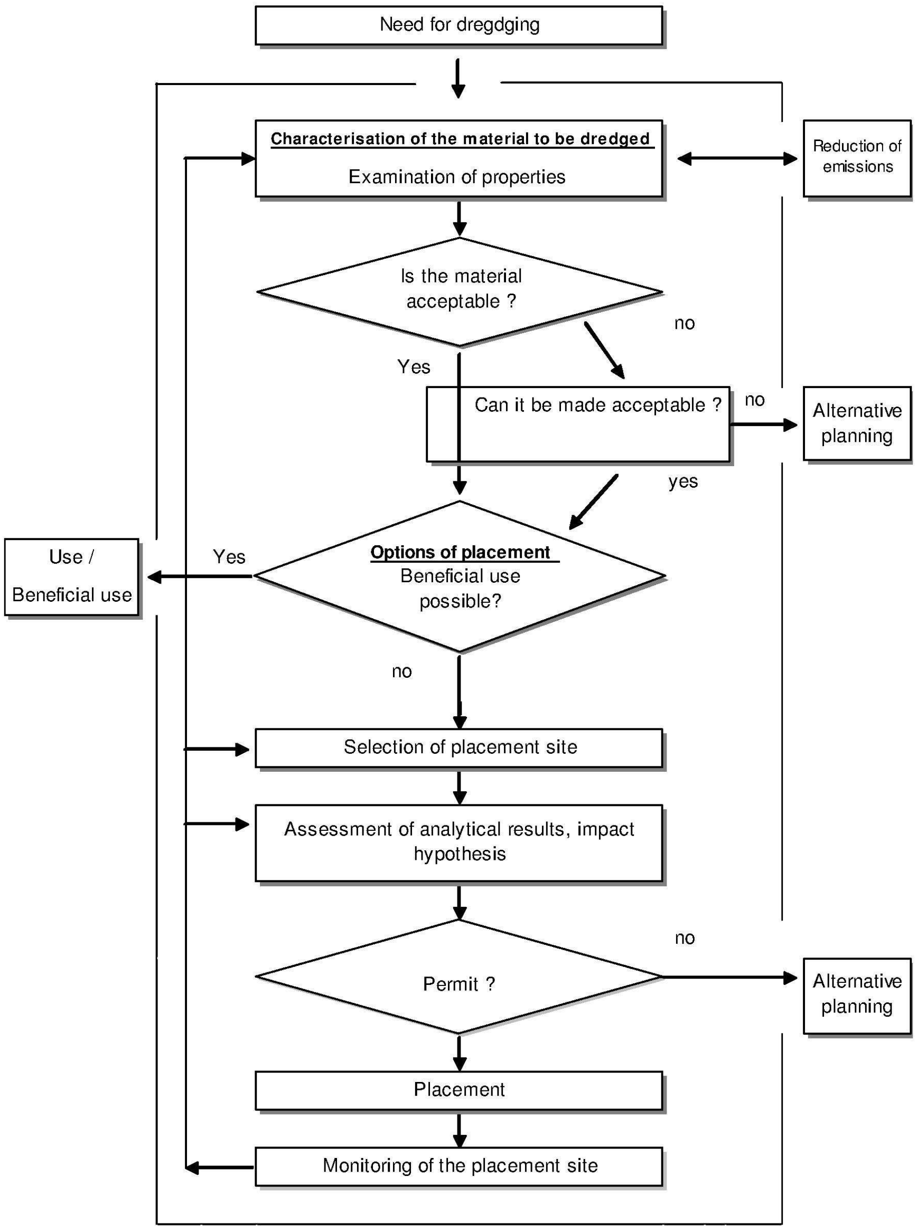


Fig. 13: Flow chart of dredged material assessment from the OSPAR-dredged-material guidelines (ANONYMUS 2009).

Identification of main issues

With respect to costs and the environment, sediment management must target further reduction of the contamination level of estuarine sediments. The aim is to ensure that all dredged sediments can be relocated within the estuarine system without any restrictions due to elevated concentrations of contaminants. There are some differences between national guidelines concerning the restrictions of sediment relocation; however, this issue is not part of the present study.

8.2.2 Comparison of estuaries

The quality of sediments dredged in the **Humber Estuary** is regularly monitored by Cefas. Although there have been contamination issues in recent years, contamination levels in sediment samples across the Humber Estuary are typically below Cefas action levels (ALs) or slightly above AL 1. These action levels are not absolute 'pass/fail' levels, but are used as guidance in conjunction with other assessment criteria. In general, contaminant levels in dredged material below AL 1 are of no concern with respect to their potential to cause pollution, and are unlikely to influence the decision to issue a licence. Where contamination levels in sediment samples exceeded Cefas AL 1, these concentrations would have been taken into account by the licensing authority, and have nonetheless been deemed acceptable for placement to sea. Before 2005, it had not been necessary to place licence restrictions on dredged material. At the end of 2005, however, it was necessary to restrict dredging at Alexandra Dock and William Wright Dock (Hull) because of unacceptably high tributyl tin (TBT) levels. Today, only the restriction on William Wright Dock has remained. Additionally, West Dock (Goole) has also been excluded from licences since 2006 due to high zinc levels. Since 2008 the docks at Goole have also been the subject of further investigation, primarily with relation to zinc, copper, PAH and DDT (g-HCH) contamination. Further monitoring and subsequent analysis was undertaken to satisfy licence conditions of the present FEPA licence (FEPA: The Food and Environment Protection Act 1985).

In the **Scheldt estuary** the environmental permits for relocation of dredged material impose requirements on the quality of the sediments dredged within the estuary. In Flanders a specific set of limits for the quality of dredged material is imposed as a requirement in the environmental permit. Annual compliance monitoring of dredged sediment in the Flemish part of the Scheldt estuary shows that these requirements are met and that the dredged sediment may be relocated within the estuary. Sediment that is dredged from the non-tidal docks in the port of Antwerp contains a higher level of contamination. This sediment has been stored in subaquatic confined disposal sites until 2011 and is treated in a mechanical dewatering plant (AMORAS) since 2012. Guideline values for toxic substances of dredged material are current regulated under the MMM Act on the protection of the marine environment in sea areas in Belgium (this only applies to the Belgian part, but not to the Scheldt estuary lying in the Netherlands and the Flemish region). In Case I analysis results remain below the guidance level and approval for sea placement can be granted. If three threshold values are exceeded, Case II is implemented and a sea placement licence will not be granted. In Case III a suggestion is made to increase the number of samples and carry out a new analysis if the results are between guidance level and threshold level. A permit may be given if the second analysis shows a lower contamination. If the first result is confirmed by the new analysis, additional bioassays should be used following international standard procedures. The results of these tests are seen as a support measure for decision-making and are not a criterion for exclusion of placement at sea (HPA & DGE 2011). In the Netherlands assessment values for dredged material are regulated by the ZBT (Zoute Bagger Toets 2007) and it is the only country using only one set of action levels. Guidance levels and strict threshold levels are used in combination. All values used in the ZBT document are derived from background concentrations. Threshold values are given for priority substances which are mostly organic contaminants but also selected metals. These values are treated as strict limit values without exceptions. For non-priority substances an exceedance of up to 50% is tolerable as long as it only concerns two substances. The ZBT does not include bioassays (HPA & DGE 2011).

Different quality criteria are used in **Germany** for assessing suspended solids in the river and dredged material in the coastal zone: the "Regulation for handling dredged material inland", also called HABAB (BfG 2000), and the new "Joint transitional regulation for the handling of dredged material in coastal areas", also known as GÜBAK (Anonymus 2009). These directives stem from the international London Convention (LC), Oslo-Paris Convention (OSPAR) and Helsinki Convention (HELCOM). The HABAB and GÜBAK will be soon replaced by a new directive that encompasses the coastal and inland regulations. The guiding values (RW) are based on sediment contamination found in the German part of the Wadden Sea and the coastal sediments of the North Sea (except TBT). Three cases are defined when interpreting the sampling analysis. In Case I analysis results are below RW1. The material can be relocated in open water without any restrictions. In Case II analysis results are between RW1 and RW2. This material has a higher degree of contamination and an impact hypothesis as well as a monitoring programme has to be prepared as appropriate. If necessary, go to Case III. In Case III analysis results are above RW2. This material has significantly higher contamination and is subject to a procedure similar to Case II but additionally the source of contamination needs to be determined and if possible remediated. Safe disposal (landfill) and treatment options have to be considered. Bioassays have to be implemented in Case III. These tests are used to assess the toxicity of the dredged material.

In the **Weser estuary** disposal of muddy harbour sediments into the Outer Weser was abandoned in 1997 mainly because of high TBT contamination. Now contaminated material classified as Case III is predominantly taken to a landfill (see below). Sediments in the fairway vary in contamination. Due to the low contamination levels in sandy sediments of the ripple section from km 8 to km 55, its dredged material is classified mostly as Case I. In addition, the contamination levels from the Outer Weser are regarded as low, but because of the TBT load dredged material has to be regarded as Case II, but its ecotoxicological impact as Case I. Since the placement sites in the Outer Weser display a similar contamination level, relocation of the material is possible. The Lower Weser from km 55 to km 58 (mud section Nordenham) displays a greater contamination level, which has to be classified as Case II while the ecotoxicological impact is regarded as Case I. Relocation of this dredged material is only possible after a prior intensified examination. In recent years WID has become an extensively practised relocation method in the Weser estuary. However, this technique is not understood and documented as a relocation method by bremenports and application of WID in areas of fine sediment is carried out without prior contaminant assessments.

Areas in the **Elbe estuary** that are dredged regularly accumulate fresh sediments from upstream and downstream. These fresh sediments with a low contamination level are allowed for relocation. Areas such as old harbour basins tend to accumulate material over a long period and their content differs in contamination depending on the depth. Thus, older material with a high contamination level is not qualified for relocation and requires treatment and disposal on land (see below). Contaminants of concern include heavy metals and organic contaminants mostly deriving from the Elbe catchment area. Also organic tin components are of concern, mostly generated by the shipping industry and harbour activities. Due to large amounts of sediment dredged in Hamburg port during 2004 and 2005, a permit was granted to deposit material at a site outside the estuary in the inner

German Bight, near buoy E3. Monitoring of the impacts of placement at the site was undertaken from 2005 onwards. The dredged material disposed was largely classified as Class II or Class III. The placement permits for dredged material containing contaminant concentrations in excess of national guidelines (Class III) were notified to OSPAR.

8.2.3 Relevance for future sediment management

The concentrations of harmful substances in the rivers and estuaries of the North Sea catchment area have predominantly diminished in past decades as a result of extensive environmental protection measures. Nevertheless, part of the dredged material from the TIDE estuaries and ports cannot be relocated within the estuaries or to the open sea without restrictions because the concentrations still exceed the (national) limits. Particularly TBT is still a problematic substance, in spite of the ban on use. Therefore the decreasing trends in contamination should proceed in the future. Contaminants of concern are heavy metals and organic contaminants mostly stemming from the catchment area, but also the shipping industry and harbour activities generate components of concern. Thus, it is important to work with third parties and implement local measures to reduce contaminant input. In this context the WFD is of increasing relevance because it targets a good chemical status and requires measures for reduction in the entire catchment area.

8.3 Placement in waters

8.3.1 Background and scope

Substantial volumes are dredged in the framework of maintenance and possibly in the course of river expansion as well in all TIDE estuaries (see above). While in the past large portions of the dredged material were deposited in the side shallow water areas and on foreland (primarily to concentrate the force of the current on a main channel and gain agricultural areas), especially in the Elbe and Weser, today, relocation of the sediments in the estuaries predominantly takes place within the estuarine water body. The reasons for this are cost reduction, ecological considerations and the realization that removal of sediments may lead to undesired morphological consequences.

Identification of main issues

The material dredged in the TIDE estuaries today is mainly shipped to placement sites within the estuaries. The selection of the placement sites takes into account the costs as well as other aspects with varying relevance, depending on the local situation: minimizing loss of material from the estuarine system, reducing impact on benthic communities, reducing impact on water quality and using the material for morphological purposes.

8.3.2 Comparison of estuaries

In the **Humber estuary** the dredged material is relocated nearby the channel in a similar flow environment to keep the sediment budget. There are a number of placement sites that can be used under FEPA/Marine licence for the placement of maintenance and capital dredge material within the Humber. Only a small proportion of these placement locations are currently used for maintenance dredging purposes by ABP and non-ABP (third party) organizations. Sites are established on a like-for-like basis, i.e. sandy dredged material is placed in a location that is predominantly sandy. Dredged material has also been used for hydro-engineering purposes. The dredged clay is placed at the Sunk Dredged Channel windows to primarily fill natural depressions and level out the estuary bed. A secondary beneficial effect is that it acts as a training wall to the Sunk Dredged Channel. Some placement sites were used temporarily to reduce natural scour that occurred around the base. Sediment has not been used to re-establish habitats at an intertidal level due to the high accretion levels from the Humber's high turbidity. In addition to the placement sites, there are two pipelines located in Alexandra Dock and in Albert Dock, Hull. The pipelines were installed in these docks to improve the efficiency of the dredging operation. The docks are open to the tide and the pipelines reduce dredger transits, which assist in maintaining the dock water level and reduce the ingress of sediment. A trailing suction hopper dredger can undertake dredging within the docks, hook up the pipeline and pump the dredged material out into the estuary over the dock wall into the strong tidal flows. The Albert Dock pipeline is still being used, while the pipeline at Alexandra Dock is closed. No material is placed in the North Sea.

Most of the material dredged in the **Scheldt estuary** is relocated to placement sites within the estuary; no material is placed in the North Sea. As described in section 6.2 dredging and relocation have been executed following the 'East-West' strategy serving morphology since 1990. The idea to apply morphological management was implemented by (re)constructing shallow water habitats on sandbars with relocated dredged material on four locations in the Westerschelde (see section 10.5). Today, placement sites in the primary channel (maritime fairway) and on sandbars are used besides placement sites in secondary channels. Currently an optimized relocation pattern within the Scheldt estuary is being investigated (DELTARES 2012).

Dredged material from the **Weser estuary** is taken to various placement sites; no material is placed in the North Sea. A total of nine placement sites (placement sites K1–K6 and T1–T3) are permitted in the Outer Weser. Sandy material can be disposed at all placement sites, except for K3, while muddy soil is placed at K1 and K3 as well as T1 and T2. In the Lower Weser there are five more placement sites (Weser km 42.0; 47.8; 48.6; 49.2 and 51.5), for which only sandy dredged material from the Lower Weser is permitted. In the Lower Weser placement sites are mainly located in natural depressions, while in the Outer Weser placement sites are partly used either to influence the local hydrodynamic regime (e.g. reduce bank erosion) or for later dispersion so that the material can take part in natural sediment dynamics. Within the framework of maintenance, sand nourishment takes place at intervals of several years in non-reinforced shore sections of the Lower Weser exposed to the current in the main stream in order to secure the banks.

Sediments from the fairway of the **Elbe estuary** are relocated in the system at various relocation sites. Relocation pattern partly reflects the administrative situation along the Elbe estuary and is not only a result of morphodynamic considerations. The "RESMC", developed in 2008, includes implementation of a new relocation scheme within the tidal Elbe aimed at breaking tidal pumping by creating a balance between relocation/sedimentation and erosion at the placement sites. Dredged material from the port of Hamburg is relocated in the Elbe estuary at the downstream border of the state of Hamburg in the vicinity of the island of Neßsand. The placed sediment mixes with the naturally occurring suspended solids and is distributed over a wide area by the tides. To minimize environmental effects, relocation is not allowed during the summer when effects on juvenile fish may occur and to avoid negative impact on the oxygen concentration, which is particularly low during the warmer time of the year. The material only gets relocated during ebb flow to minimize the effect of uncontrolled sediment distribution into shallow water areas. If possible, the amount of sediment is reduced during low headwater discharge (< 500 m^3/s). Between 2005 and 2011 sediments from the port of Hamburg were brought also to a placement site near Buoy E3 in the North Sea. Sediments of this area are partly silty and similar in physical characteristics to the sediments from the port of Hamburg. The placement area is monitored regularly after each placement campaign. Between 2005 and 2009 a total of 5.3 million m^3 of dredged sediments have been transported to Buoy E3, reflecting about 6% of the total amount of sediments relocated within Elbe estuary and North Sea (compiled from different sources).

8.3.3 Relevance for future sediment management

For future sediment management the following issues have to balance in an appropriate manner: minimizing loss of material from the estuarine system, reducing impact on benthic communities, reducing impact on water quality and using the material for morphological and/or nature conservation purposes.

Today only minor or no material is disposed outside of the estuary in all TIDE estuaries. The reasons include cost reduction, ecological considerations, the realization that removal of sediments may lead to undesired morphological consequences and ensuring the long-term adaptability of the estuarine system to an accelerated rise in the sea level (growing with the tides) (only in the Elbe estuary between 2005 and 2010 a part of the sediments has been transported from the Hamburg area to the North Sea so as to reduce the recirculation of sediments through tidal pumping). Water injection is in use in all estuaries and can be seen as a technique supporting the approach of keeping the sediments in the system.

Environmental impact due to placement is reduced in the framework of OSPAR by taking environmental aspects into consideration when defining the placement sites including avoiding areas of special sensitivity. Although, recent monitoring has shown that impact in estuarine environments may be limited if such areas or time spans of special sensitivity are avoided, short and long term consequences of placement sites must be evaluated carefully.

Using the dredged material for estuarine engineering measures (also called morphological management) is an old approach. In the framework of the "Unterweser correction" by Franzius in 1883 the dredged sediments were used for concentrating the current in the main channel by filling up anabranches. However, up-to-date morphological management has to take more issues into consideration, mainly accessibility of the fairway, protection against flooding and nature conservation or ecological purposes. The placement of dredged sediment is a key issue for influencing estuarine morphology and hydrodynamics. Sediments can be used for dynamic shore nourishment on non-reinforced shores, for influencing the hydrodynamics in accordance with an integrated approach (see Scheldt) and for the (re)construction of habitats (e.g. tidal or shallow water).

In the Scheldt and Elbe estuaries such an optimized relocation pattern has been or is being investigated in the context of sediment management and results and/or implementation of measures are expected in the coming years.

There is a strong need for further research on integrated approaches concerning sediment and morphological management. It should be also determined whether defined placement sites or sediment spreading is better for the system. A sophisticated relocation strategy includes regular monitoring and minimizes environmental effects. Therefore, it is fundamental to consider an integrative sediment management as a key aspect of an integrated management approach.

8.4 Land treatments and confined disposal facilities (CDF)

8.4.1 Background and scope

Contaminated material not qualified for relocation is taken on land and deposited. Assessment criteria are provided by national guidelines. To confine the dredged material, one option is to construct a flushing field on dry land; another is to build a facility similar to a landfill and to use this to dispose dewatered sediment. The only in-situ approach to be applied on a real scale is capping contaminated sediments. Capping can be conducted in a subaquatic Confined Disposal Facility (CDF) or near-shore in an atoll-like facility like the Slufter in Rotterdam. Safe disposal in such a technical facility is carried out to lock up contaminated dredged material and control environmental impacts.

Identification of main issues

Land treatment of contaminated material with subsequent disposal on land is carried out in the Weser and Elbe estuaries. Fortunately, the Humber Estuary does not need to implement such practices. Due to large amounts of contaminated sediment dredged in the German TIDE estuaries, space for treatment and disposal is getting scarce. Thus, ports authorities are looking for other disposal options now. Bremerhaven has already started transferring silty contaminated material to a Confined Disposal Facility (CDF).

8.4.2 Comparison of estuaries

Land treatment of contaminated material with subsequent disposal is not carried out in the **Humber Estuary** because contamination of dredged material is mainly below national threshold values.

In the **Scheldt estuary** sediment that is dredged from the non-tidal docks in the port of Antwerp contains a higher level of contamination. This sediment has been stored in subaquatic confined disposal sites and is treated in a mechanical dewatering plant (AMORAS) since 2012.

Up to the 1990s material from the ports of the **Weser estuary** not qualified for relocation was taken on land and deposited on flushing fields without further treatment. Since 1994 an integrated dredged material disposal site has been operating in Bremen-Seehausen. It enables treatment of about 200,000 m^3 of sediment annually. A mud-water mix is pumped onto the drainage fields with a total size of 36 ha and dried for about one year. After drying, the material is placed in the deposit hill, which has been equipped with baseline layer and upper sealing. Sediment classified as Case III, mainly because of high TBT contamination, is predominantly taken to this landfill. In addition, dredged material is taken to a Confined Disposal Facility (CDF), the Slufter in Rotterdam, since 2011. Only highly contaminated material is allowed in the CDF.

In the **Elbe estuary** land treatment of sediments is undertaken at the METHA plant (METHA is the acronym of MEchanical Treatment of HArbour sediments). Contaminants of concern include heavy metals and organic contaminants. After sand separation, dewatering by the METHA plant follows and the material is subsequently disposed on land or used beneficially. Today, approximately 1 million m^3 of sediments are treated annually at the METHA plant. Apart from the dewatering of silty dredged material in the METHA, sediment is additionally dewatered in the so-called dewatering fields encompassing a total area of about 100 ha. They were built on old flushing fields, after which they were sealed by means of a silt sealing and an additional drainage layer to protect the ground-water. Two silt-mound disposal sites exist for environmentally safe landfilling of the treated dredged material: Francop and Feldhofe. With an area of 120 ha Francop is the largest and oldest disposal site in Hamburg having a storage capacity of 8 million m^3 of dewatered material (corre-sponding to 16 million m^3 of sediment). The Feldhofe disposal site (ca. 80 ha) has a capacity of 9 million m^3.

8.4.3 Relevance for future sediment management

Even though the methods of safe land disposal are undergoing continuous optimization, like the type of hill disposal in Bremen-Seehausen, which reduces land consumption, space is getting scarce for contaminated dredged material to be treated and deposited on land. Further reduction of con-tamination of the sediments and cutting back the volumes to be relocated need to be achieved.

8.5 Alternative utilization

8.5.1 Background and scope

Alternative use of material on land is carried out with hardly contaminated sandy dredged material for construction purposes or with contaminated sediments depending on previous treatment and threshold limits. Re-use of contaminated sediments may include bio-remediation, chemical extraction or stabilization to reclaim treated sediments for civil engineering construction, such as a liner in landfill structures, noise embankments or dikes. Another option is to replace natural clay with dredged material to produce bricks, lightweight aggregates (LWA) or concrete. All of these techniques have been tested in different scales and some applied at an industrial scale.

Identification of main issues

In all of the four TIDE estuaries dredged material has been used for reclamation or construction work and has thus been removed from the estuary. Further options of alternative utilization are continuously being developed, but are not ready for industrial use yet.

8.5.2 Comparison of estuaries

In recent years no sand accretion has occurred in the **Humber estuary**. Before some sand was used for reclamation or construction work on the river, but it was not of ideal quality. Generally, the material is too fine for beach nourishment. ABP will continue to use part of this material wherever possible to decrease the utilization of a more valuable natural resource. On a broader, more holistic basis, therefore, environmental impacts should be minimized. At the same time, maintaining the sediment budget of the estuary is also taken into account.

From the **Scheldt estuary** only a small amount of sand was extracted for construction purposes during the period of 2000 to 2010 (max. 10% in 2004, generally <5%).

In the **Weser estuary** uncontaminated sandy dredged material is used for construction purposes, mainly to increase and prepare the subsoil of industry and infrastructure facilities. Within the outer Weser estuary sand accretion for construction work amounted to approx. 1 million m^3 per year (period 1998 to 2011). The annual proportion of sand accretion in relation to the total amount of dredged material in this period varied between 1% and 56%. Even though this material would have been dredged anyway within the scope of maintenance, the sediment is still removed from the estuary. Employment of cohesive material is made difficult due to its frequent contamination. Use in agriculture is thus not possible at present or only to a limited extent. Various techniques for re-use of contaminated sediments were tested on different scales along the Weser and some have been applied on an industrial scale. The most effective application is in the field of civil engineering. Dredged material was used for different layers in the Bremen-Seehausen landfill, dike construction and maintenance as well as for recultivation of gravel and clay pits. Further treatment methods are constantly being developed, but are not ready for industrial use yet.

Alternative utilization of contaminated dredge material has been evaluated in the **Elbe estuary**, including the production of pellets as filter material and also the production of bricks. These options have been developed to an industrial scale, but it turned out to be economically unfeasible to expand it into a large-scale alternative. However, dredged material from the MEHTA plant is certified for use as mineral sealing, e.g. as a substitute for clay. Application is also possible in dyke construction. Investigations with focus on the various aspects are ongoing.

8.5.3 Relevance for future sediment management

The volume of dredged material removed from the estuary needs to be limited to reliably maintain the sediment budget of the estuarine system. Nevertheless, alternative utilization of contaminated dredged material will most likely continue to create space in landfills and decrease the use of other natural resources. It is important to work on an assessment of treatment products since formerly stable pollutants can be mobilized again when circumstances change while products are being used. Such an examination has to take into account the whole life cycle of the product, including the phases of storage, use, potential re-use under different boundary conditions and finally disposal.

9. Sediment management and the environment

9.1 Background and scope

The TIDE estuaries and surrounding areas are of great importance in terms of nature conservation with large areas of the estuaries having been designated as nationally and internationally protected sites. However, dredging and sediment relocation within the estuaries may lead to impairment of the benthic population and decline of the water quality (oxygen depletion, increased turbidity etc.). Capital dredging may alter morphodynamics and hydrodynamics strongly. Boundaries for sediment management are also set by different European directives (Birds and Habitats Directives, Water Framework Directive (WFD), Marine Strategy Framework Directive (MSFD)) with the aim of protecting the estuarine ecosystems.

Sediment management has to integrate securing the economic as well as the environmental functions taking into account the natural boundaries of each individual estuary, the specific uses and the changing legislative framework.

9.2 Contamination of sediments

Contaminants released into rivers, such as heavy metals, pesticides and other organic micropollutants, accumulate in sediments. Sediments therefore act as a sink for these hazardous pollutants and transportation, dilution and distribution take place along the way to the sea. Numerous relatively small inputs that may comply with emission regulations accumulate and reach higher levels when arriving in the estuary. There uncontaminated marine sediments mingle with fluvial contaminated sediments.

Contamination of estuarine sediments has been recognized as an environmentally relevant problem when relocating dredged material since the 1980s. A number of laws and regulations for relocation within the water body as well as deposition on land have been established with the aim of diminishing the risk for the environment. Efforts have been undertaken to decrease the input of contaminants and their release during relocation through appropriate treatment and deposition on land.

As mentioned above, it has often not been possible to minimize the contamination of sediments, especially in silty port areas, adequately. Therefore they cannot be relocated fully within the water body. For instance, although TBT has been banned worldwide as an anti-fouling agent, the contamination levels of the sediments are partly still too high for relocation. Further reduction of point and diffuse sources within the estuary and from upstream are required to be able to relocate dredged material within the water body to its full extent. Consequences of WID on the resuspension of pollutants associated with fine grained sediments should be critically evaluated.

Sediment should be preserved as an important component of the river system and consequently land treatment and disposal is not a sustainable sediment management practice in the long run. The reduction of land disposal needs to be a long-term goal. This also requires decontamination of historically polluted places. The WFD and Marine Strategy aim at additional reduction and will support further reduction.

9.3 Dredging

The impacts of sediment removal described in the following apply to the numerous dredging techniques. Such aspects as sediment extraction, turbidity plumes, alterations of water quality, sediment composition and hydromorphology as well as additional noise emissions due to increased shipping traffic can be considered to be general dredging impacts (see also section 9.4).

Turbidity plumes can be generated as a result of dredging work, thus possibly leading to higher sedimentation rates locally, depending on composition and quantity of the dredged material as well as the prevailing currents and morphology. Furthermore, due to resuspension an increased amount of nutrients and contaminants can be released and oxygen depletion may occur. Turbidity also influences the light climate negatively which in turn can lead to a reduced photosynthetic performance and abundance of autotrophic organisms. Moreover, the increase of suspended matter in the water column can cause negative effects, like clogging for filter feeding macrozoobenthos and damage to fish spawn.

Direct sediment removal by dredging leads to reduction of macrozoobenthos in the dredged area since organisms only occur up to a depth of 20 to 30 cm. Not only the flora and fauna are mechanically damaged but also benthic fish spawn of gobies, herring or smelt, for example. Re-colonization depends on various factors and can take up to several years in estuaries. Due to changes in bathymetry and sediment structure, the composition of the flora and fauna could be modified longer as well. The overall degree of the damage depends on the size of the dredged area, frequency and duration of dredging, ecological sensitivity of the system, implemented technique and effects of additional anthropogenic influences. However, compared with other aquatic environments regeneration potential in the TIDE estuaries can be classified as moderate to high, if no long lasting changes of morphodynamics occur.

Sediment management should therefore aim at an overall reduction in dredging and reduction of the environmental impacts of dredging, taking season, location, methods etc. into account.

9.4 Placement in waters

Aspects regarding placement of dredged material in waters largely overlap with environmental impacts caused by dredging operations. Issues concerning the process of placement include sediment covering, turbidity plumes, alteration of water quality, sediment composition and hydromorphology as well as additional noise emissions due to increased shipping traffic.

The greatest threats to flora and fauna arise from the increased amount of suspended sediments introduced to the water column and the sediment covering during the placement process. The mortality of the organisms depends on their species-specific sensitivity. The turbidity plume produced is controlled by the location and depth of the placement site, temperature, salinity, viscosity and fine fraction of the disposed sediment as well as hydrodynamic conditions like tide, currents and swell. In general, the rise in content of suspended matter lies one order of magnitude above the one produced in the course of dredging activities. Through increased suspended matter and resuspension within the area of the placement site the reduced water quality can lead to impairment of the environment as described for the dredging methods in section 9.3. Generally, in areas of more pronounced turbidity plumes organisms are exposed to physiological stress, abundances especially of filter feeding species can be reduced and/or species assemblage might be modified with the corresponding ecological changes. Furthermore, in the direct vicinity of the placement site mortality of organisms might occur because of rapid sediment covering, especially small less mobile fish species like gobies (*Pomatoschistus* spec.) can be affected. Due to increased deposition rates of the disposed material, the habitat might be altered in height and sediment structure.

Transport of contaminated sediments from an estuarine system to the North Sea has taken place in recent years (see sections 6.2 and 8). Based on the high toxicity for aquatic organisms, the slow degradation rates and release in the water bodies, such disposal should be set narrow limits taking into account aspects of precautionary environmental protection. The introduction of TBT into the marine environment may have harmful impact on organisms such as causing imposex in the common whelk (*Buccinum undatum*).

It can be concluded that the type and amount of material disposed, size of the area covered, frequency and duration of placement, ecological sensitivity of the organisms and additional anthropogenic pressure determine the extent of the environmental damage. However, there are examples in which material has been used for building habitats and other environmentally friendly activities. However, the overall consequences must be carefully examined.

Sediment management should therefore aim at an overall reduction in the material to be relocated, placement of the material within the system and a reduction in the environmental impacts of placement taking season, location, methods, etc. into account. Approaches should be developed for using the material (if not contaminated) for "working with nature" (e.g. using the material for beach nourishment).

9.5 Sediment budget and natural dynamics

Estuaries are located between rivers and the ocean and receive sediment input from both. Rivers transport sediments, the product of erosion processes, to the ocean as suspended and dissolved matter. Then again, dams and reservoirs decrease the sediment discharge of rivers. Nowadays rivers are straightened and estuaries are deepened to ensure safe navigation for large ships to ports located upstream. Dikes protect the adjacent land, cities and industrial buildings from flooding. Furthermore, reclamation of land, deforestation and agricultural activities lead to increased sediment and freshwater input into estuaries. All these activities result in a considerable modification of the natural hydrodynamics and sediment dynamics, mixing and circulation processes within an estuarine system. If the natural balance of sediment dynamics in an estuary is disturbed, the system tries to re-establish the balance or reach a new equilibrium. Consequently, navigational estuary development may result in increased sedimentation and in turn leads to constant or either increasing maintenance work. These regular interventions generate not only high costs, but also substantial pressure on the estuarine ecosystem since it forms an ecological unit with the subtidal and surrounding terrestrial habitat types and cannot readjust to new conditions within a short time. On the one hand, therefore, sediment management may cause problems for the estuarine environment. On the other hand, intervention in the natural dynamics of hydro- and morphdynamics resulting from sediment management may change the sediment dynamics considerably and may lead to a substantial increase in suspended sediments concentration (turbidity) and maintenance dredging. Examples for such interdependence are the inner part of the Ems Estuary (e.g. BOS et al. 2012) and the Loire estuary.

An in-depth understanding and an adequate consideration of the natural dynamics and processes within an integrated river engineering and sediment management concept is fundamental to avoid unforeseen changes and to minimize the negative impacts of sediment management activities on the estuarine environment at all.

On the other hand, relocation of sediments also makes it possible, in the framework of maintenance, to support the presence of certain habitats if this conforms with the objectives of Natura 2000, for example (see Humber). What is decisive is that sediment management is regarded, organized and carried out as part of integrated estuary management in which a consensus on the goals of such management has been reached.

9.6 Sediment management and Habitats Directive

A great part of the TIDE estuaries is protected under the Habitats Directive of 1992. Often port and fairway development and maintenance overlap with the Habitats Directive and fail to coincide. Under the regulations all competent authorities are required to carry out an appropriate assessment if work is carried out within or adjacent to a designated site and if it is likely to have a 'significant effect' on the site, either alone or in combination with other plans and projects. The Habitats Directive does not preclude development and use of estuaries within or around designated sites. Rather, it ensures that these developments are carried out in a way compatible with the protection of important species and habitats (EC 2011).

Sediment management activities may generate considerable effects on the nature conservation objectives of estuaries. Impacts by capital and maintenance dredging and the relocation of sediments affect the hydrodynamic regime and geomorphology of the estuary modifying the balance and the flux of sediments. This may lead to alterations of the habitats and its distribution composing estuarine ecosystems (e.g. mudflats or sandbanks) (EC 2011).

The employment of integrated management concepts combined with monitoring programmes could contribute to conserve and protect ecological processes, areas and species whilst providing space for sustainable navigation. When developing appropriate solutions for sustainable sediment management and nature conservation, the competent authorities need to consider the dynamic nature of estuaries and its species and habitats. The morphological, chemical and biological processes have to be taken into account as well as the ecological functions of estuaries, such as spawning grounds, nurseries and seasonal habitats for migratory species. Monitoring programmes should examine the short and long term evolution of morphological dynamics and sediment circulation, for example. Based on the results of the monitoring, conservation objectives and management measures can be reconsidered if necessary (adaptive management) (EC 2011).

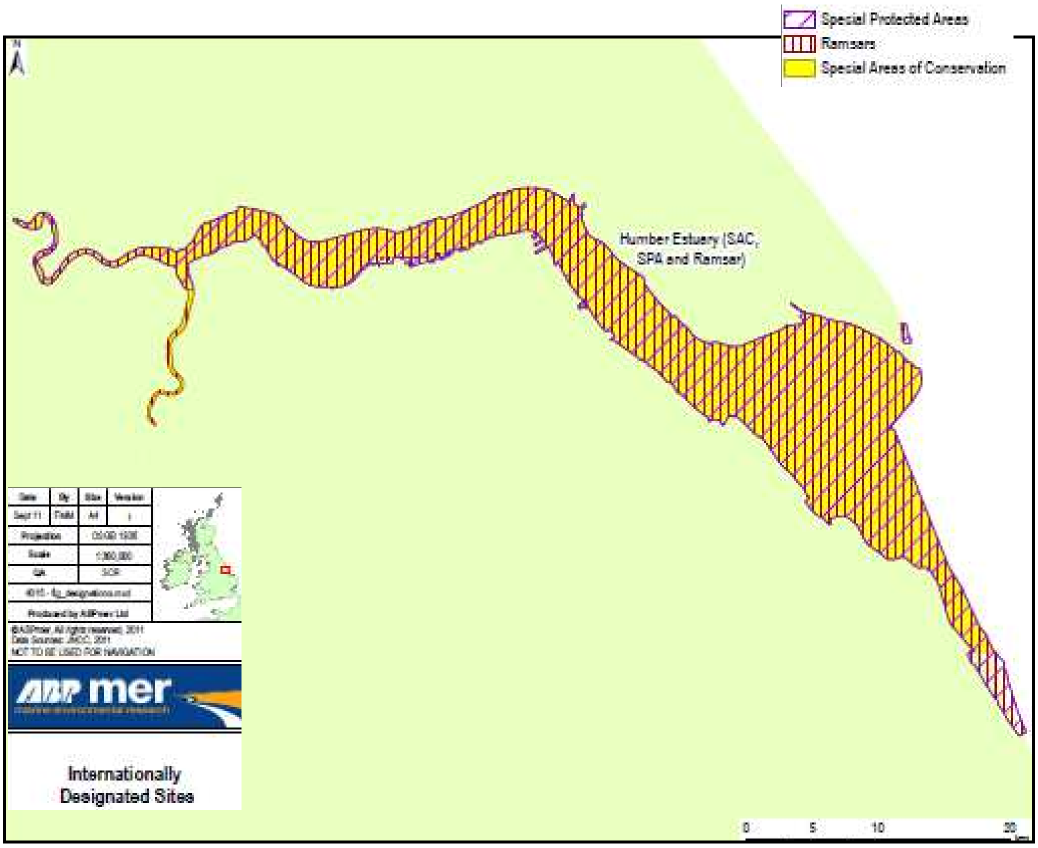
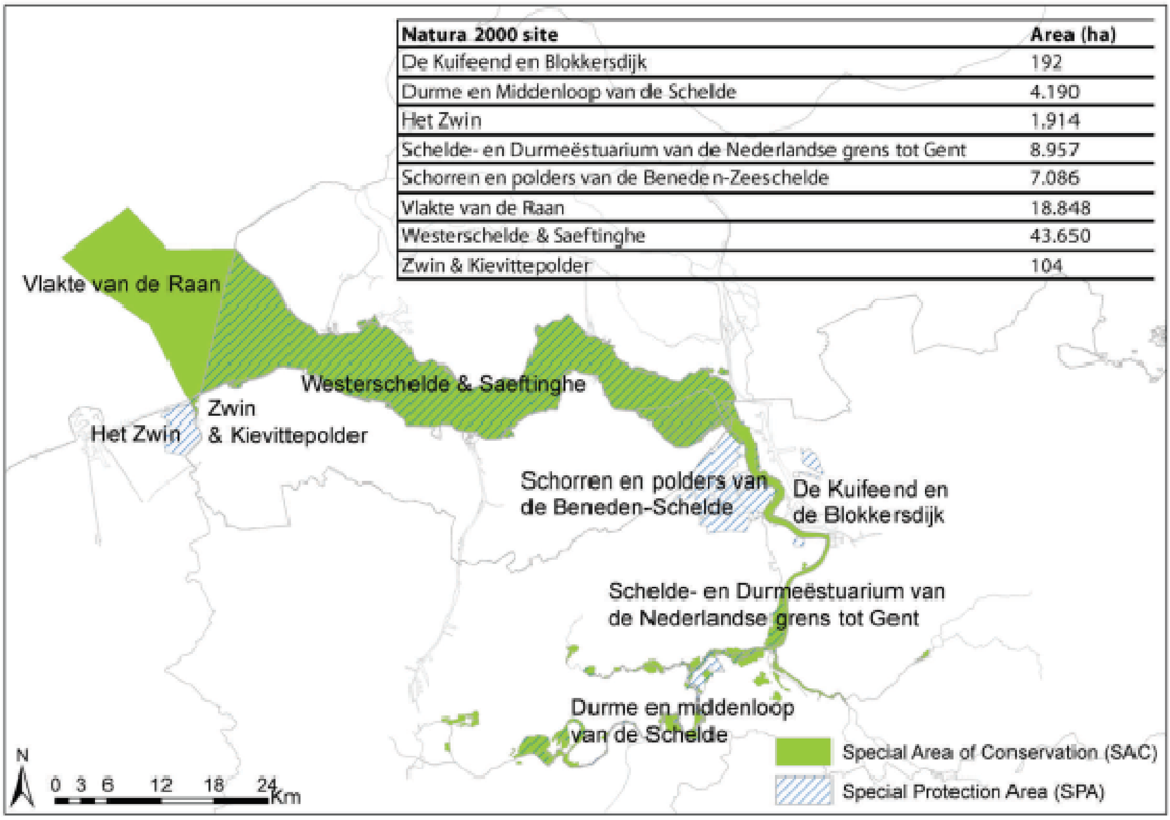


Fig. 14: Natura 2000 sites in the Humber estuary (source: ABP MER).



Natura 2000 site	Area (ha)
De Kuifeend en Blokkersdijk	192
Durme en Middenloop van de Schelde	4.190
Het Zwin	1.914
Schelde- en Durmeëstuarium van de Nederlandse grens tot Gent	8.957
Schorren en polders van de Beneden-Zeeschelde	7.086
Vlakte van de Raan	18.848
Westerschelde & Saeftinghe	43.650
Zwin & Kievittepolder	104

Fig. 15: Map of the Special Areas of Conservation (SACs) and the Special Protection Areas (SPAs) in the Scheldt estuary as part of the Habitats and Birds Directives (situation 2009) (source: Research Institute for Nature and Forest (INBO); Ministry of Agriculture, Nature and Food Quality (LNV), created by VLAAMS INSTITUUT VOOR DE ZEE (VLIS) 2009).

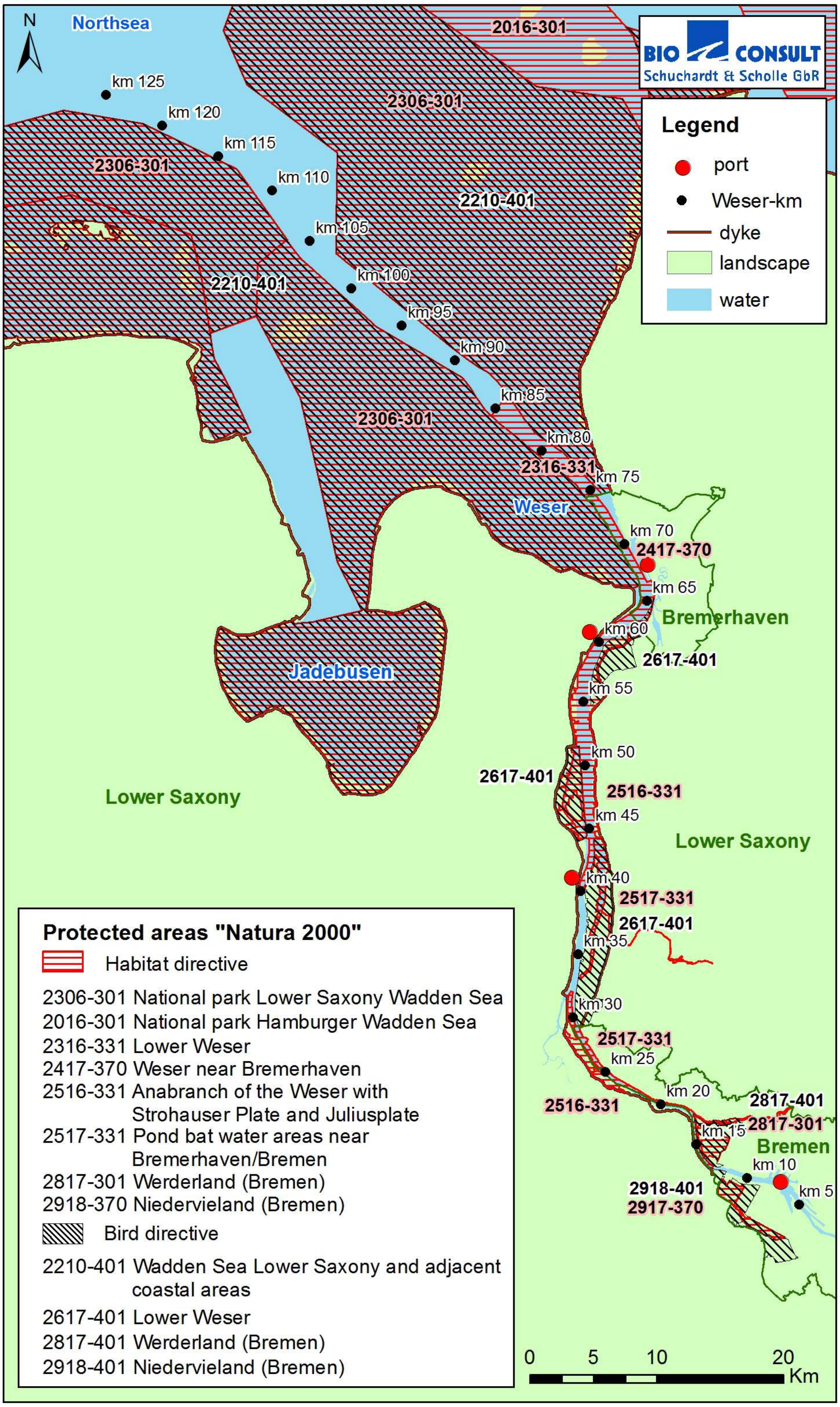


Fig. 16: Natura 2000 sites in the Weser estuary.

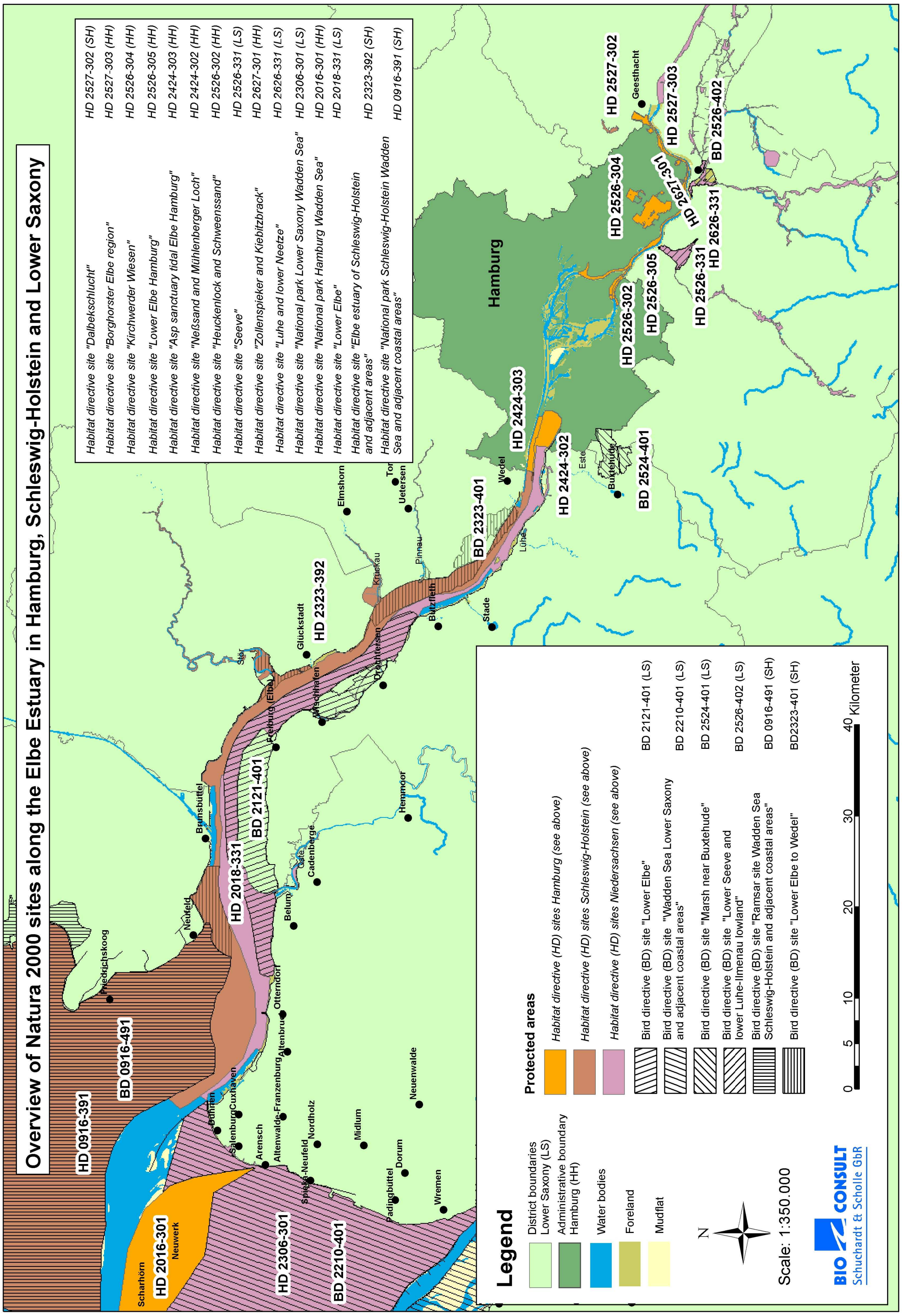


Fig. 17: Overview of the Natura 2000 sites along the Elbe estuary.

In all TIDE estuaries the implementation of the Habitats and Birds Directives has increased the awareness of nature conservation issues during the last two decades. Taking this into account is or at least should be integral part of each management concept.

For capital dredging Appropriate Assessment (AA) has to be carried out if work is performed within or adjacent to a designated site and if it is likely to have a 'significant effect' on the site, either alone or in combination with other plans and projects. Ongoing maintenance dredging practice differs in the various estuaries: whereas AA is required also for ongoing measures in the UK (see section 10.6). AA is not carried out for ongoing maintenance in Germany, however, aspects of Natura 2000 are considered during the approval procedure for new placement sites.

9.7 Sediment management and WFD/MSFD

The main objective of the WFD is to achieve "Good Ecological Status" and "Good Chemical Status" (or Potential) of all water bodies (including marine coastal waters) by 2015. To accomplish this goal, it is also necessary to take into account sediments. Sediment management in estuaries has to integrate the requirements of the WFD governing utilization and protection of water courses. For contaminated sediments the WFD promotes management of the whole river basin aiming on a "Good Chemical Status". Thus, especially in the estuaries the River Basin Management Plan must integrate the environmental aspects of sediment management (HTG 2004). An analysis of which input sources have what proportion of sediment contamination should be conducted in line with monitoring so that measures can be targeted for this purpose. The measures implemented should reduce the contaminants input so that the quality targets for sediments and dredged material are met. However, the environmental requirements of these European Directives will lead to a further reduction of contaminants on a river basin scale and therefore sediment management in the estuaries may become less restricted with respect to the relocation of especially fine grained sediments.

The "Good Ecological Status" (or Potential) is defined using some biological quality components such as fish, benthos and macrophytes. Sediment management may interfere with these quality components, thus the possibilities of sediment management to contribute to the "Good Ecological Status" have to be checked.

9.8 Sediment management and ecosystem services

Human well-being depends on services provided by a functioning ecosystem. Ecosystem services can be grouped into four categories: 1) Provisioning: production of food and water, 2) Regulating: control of climate and disease, 3) Supporting: nutrient cycles and crop pollination, and 4) Cultural: spiritual and recreational benefits (MEA 2005). Natural resources are vulnerable and not infinitely available, thus, sustainable use of goods and services is fundamental. The main objectives of the WFD and Habitats Directive are supporting the functioning of the estuarine ecosystem by protecting its species and habitats. The provision of estuarine ecosystem services like fisheries, clean drinking water, recreations (including tourism and environmental education), coastal protection, carbon sequestration and climate regulation that may be endangered by dredging activities, relocation and changing hydrodynamics, can be secured to a certain extent, if sediment management integrates nature conservation concepts. Thus sediment management as part of integrated estuarine management has to include the preservation of ecosystem services.

10. Examples of good practice

One of the major objectives of TIDE is to learn from one another. Examples of good practice could be an important way of learning from one another. Since there are big differences between the estuaries, the examples may not be applicable to other estuaries directly. However, examples of good practice may act as a source of ideas and thus help to further improve sediment management in the respective estuary.

The examples of "good practice" have been selected mainly from the four reports on sediment management in the TIDE estuaries according to the following criteria: good governance, integrated approach, low costs, sustainability, environmentally friendly, supporting nature conservation, enhancing public participation and knowledge based. However, not all information has been available for each example and no example fits all criteria. Thus, the selected examples at least reflect partly the opinion of the authors.

10.1 Overall strategy

It is obvious that an overall strategy on sustainable, environmental friendly and integrated sediment management in full compliance with recent EU directives and policies is necessary for each of the TIDE estuaries. Although there are considerable differences between the estuaries, the far-reaching and challenging "River Engineering and Sediment Management Concept for the Tidal River Elbe" (RESMC) can be used as an example.

River Engineering and Sediment Management Concept for the Tidal River Elbe

The Federal Waterways and Shipping Administration (WSV) and the Hamburg Port Authority (HPA) presented a jointly developed "River Engineering and Sediment Management Concept for the Tidal River Elbe" (RESMC) in 2008. The main inducement was the increasing energy input into the mouth of the estuary resulting in a loss of balance of the sediment budget, the increasing efforts of maintenance dredging in the vicinity of Hamburg and the altered legal framework.

The RESMC specifies several causes of the increasing maintenance efforts and develops a strategy not only for the control of sediment budgets, but also for the reduction of dredged volumes, integrating aspects of sediment composition and contamination. The latter encompasses measures of varying concrete detail and feasibility and to this extent also different time spans. Some aspects of the concept have already been implemented, others have yet to be commenced.

The concept involves a variety of innovative approaches requiring experience not at hand and some of them are not easily performed since interests of third parties are affected. On the other hand, it also opens up certain synergies with nature conservation interests, for example. River engineering measures of the RESMC to reduce the oncoming tidal energy are activation of side arms and re-connection of arms of the Elbe to reduce upstream transport of sediments and create sedimentation areas. Creation of flooding area in foreland, side arms of the Elbe and other tributaries, silted-up harbour basin (derelict land) and canals as well as relocating dikes are further measures aiming to reduce upstream transport of sediments. The implementation of a new relocation scheme within the tidal Elbe is intended to reduce dredging quantities and improve the economic efficiency of shifting sediments. Measures of the optimized sediment management are also relocation of dredged sand fractions to erosion areas and using sediment traps in the shipping channel. In view of differentiated treatment of different sediment fractions the use of WID in the Lower Elbe will be optimized. After an increase of dredging needs in 2004 and 2005 due to re-circulation of sediments between Neßsand and the port of Hamburg, material was also brought from the tidal Elbe River system to the North Sea near Buoy E3. This provisional solution and optimized relocation (local, timing-related) in the Lower Elbe by hopper dredger is intended to avoid cyclical dredging. The handling of contaminated sediments in the RESMC aims to reduce the impacts on the environment that may result from release of contaminants during relocation of contaminated sediments. The objective is to support measures to reduce pollutant emissions in the catchment area (work of IKSE and FGG Elbe) and to continue the removal of contaminated dredged material from the system (treatment on land at the METHA plant and subsequent storage). Measures to reduce tidal pumping and thus, sediment transport further upstream by the flood as well as sediment traps avoid mixing of contaminated and uncontaminated sediment.

The RESMC thus points in the right direction at several levels: it encompasses the entire Elbe estuary, also takes into account the whole river catchment area, based on a profound system understanding, was jointly developed by two different institutions, may enable a number of synergies with nature conservation, offers a long-term outlook and attempts to incorporate various aspects, such as costs, sustainability of solutions and the environment. Although, new measures still have to prove influencing the central parameters as expected, compatibility with Natura 2000 should be analyzed in detail and extensive involvement on the part of other authorities and NGOs has not taken place yet. The approach may serve as an innovative example of good practice here.

10.2 Capital dredging

Today all TIDE estuaries have deep fairways that have been successively created in the course of various expansion steps (in some cases over a period of 120 years). These expansion measures have led to substantial changes in morphodynamics and hydrodynamics and thus in the ecological situation and, for instance, risk of storm surges. Capital dredging is in each case the key measure in the individual expansion steps, supported by river engineering and backfilling of side arm areas. Due to the various "side effects" of capital dredging, examples of good practice exist only to a restricted extent and are limited to measures for mitigating individual "side effects", as the following example shows.

Time window twaite shad (*Allosa fallax*) (Elbe and Weser)

The currently planned further deepening of the Elbe and Weser estuaries targets avoidance of capital dredging in the innermost estuary during the reproduction period of the twaite shad in spring. The twaite shad that have migrated from the North Sea to the Elbe estuary in the spring time spawn in the area downstream from the Hamburg ports and in the Weser estuary downstream of Bremen. Dredging during this period would increase the mortality rate of eggs and larvae. Because of the protection status of the species (Habitats Directive Annex 2), capital dredging is not envisaged during the reproduction period.

10.3 Maintenance dredging of harbours

Maintenance dredging of harbours in many cases means dredging of fine sediments and therefore dredging of contaminated sediments. With respect to costs as well as environmental aspects, reduction of the amounts to be dredged and reduction of contamination are necessary on a long-term basis. Therefore, two examples have been selected.

New Watering Facility (Weser)

Reduction of maintenance dredging may also include structural measures. One effective example is the construction of the so-called "Freilaufkanal" in Bremerhaven (Weser estuary). For the locked "Überseehafen" in Bremerhaven (not open to the tides) a new watering facility ("Freilaufkanal") was designed and constructed between 2001 and 2003 for compensating loss of water due to the operation of the sluices. The old structure used water from the lower layer of the estuarine water column with a very high suspended matter concentration. The new facility uses water with a relatively low suspended matter concentration from upper parts of the estuarine water column of the river Weser. This measure reduced the sedimentation rate in the Überseehafen by half.

Reduction of contamination

The Water Framework Directive (WFD) and currently the Marine Strategy Framework Directive (MSFD) as well have created the legal framework for specific goals and measures for also achieving a "good chemical state". In particular, the estuaries profit from implementation of these directives thanks to the consideration given to the entire respective river catchment area. They should therefore be mentioned here as innovative examples of good practice at the governance level.

10.4 Maintenance dredging of fairways

Maintenance dredging in the fairway leads to ecological impairment due to the removal of sediment and alters the morphology on a large scale. The use of water injection may reduce ecological impairments and changes in the hydrodynamics even in the case of sandy sediments in the fairway.

Water injection regarding underwater dunes (Weser)

Water injection dredging is commonly used in the development and maintenance of harbours and waterways (see section 7). It provides a cost-effective method with less disturbance of the natural sediment balance. Water is introduced into the sediment at low pressure and high volume creating a water sediment mixture with fluid properties and an extremely low viscosity. Since this mixture has a higher density than its surroundings a density or turbidity current is created which carries the mixture away.

In the highly dynamic ripple sections of estuaries the procedure principally reinforces and accelerates naturally occurring relocation of sandy sediments. Studies in the ripple section of the Elbe and Weser estuaries showed locally restricted effects of water injection dredging (SCHROTTKE et al. 2011). Accumulation of mobilized sediment was observed to take place in the close vicinity of the dredged area. Due to the prevailing sandy material in the ripple section, sediment plumes were locally and temporally limited and changes in sediment structures which may affect the bottom fauna could not be detected (SCHROTTKE et al. 2011). By means of water injection dredging, usually less material is relocated and dredged areas are smaller (ENTELMANN 2010). Although the benthic fauna is removed from the dredged area and dispersed with the mobilized sediment, the organisms may be able to survive and establish themselves at the new location. In contrast, with hopper dredging the organisms are sucked up in the vessel and transported to the placement site. Additionally, negative effects on the benthic fauna, such as smothering, changes in sediment morphology and composition, occur at the placement sites which are avoided with water injection dredging (MEYER-NEHLS 2000). In general, water injection dredging might be regarded as having a lower ecological impact in comparison to hopper dredging. Nevertheless, so far only few investigations on the impact of WID have been executed. Therefore, further studies on the advantages and disadvantages of WID to estuarine functions have to be carried out.

10.5 Placement in waters

Placement of (sandy) sediment dredged in the fairway is an essential requirement of any sediment management. Using this material to support natural morphodynamics in accordance with ecological functioning and long-term adaptation to climate change is a challenge for up-to-date sediment management. The so-called "flexible relocation strategy" for the Westerschelde seems to serve as an example of good practice.

Flexible Relocation Strategy Westerschelde

The idea to apply morphological management or dynamic sediment management in the Schelde estuary was introduced in 2001 during the early stages of preparation of the third deepening based on an improved understanding of the system. It is based on monitoring the morphological development and adjusting strategies on these observations mainly aiming at preservation of the circulation cells that are part of the multi-channel system. The flexible relocation strategy operationalizes this. It tries to combine the 'freedom' that is offered by sediment management (much more reversible than 'hard' measures) and the option of varying the measure along the estuary. Four placement strategies are distinguished (DELTARES 2012):

- in the deepest parts of the primary channel
- in the secondary channels, but in such way that primary and secondary channels stay in balance
- enlarging intertidal areas
- taking the sediment outside the macro-cell and/or outside the estuary (incl. sand mining and relocation within the estuary, but over larger distances)

The reconstruction of the Walsoorden sandbar was chosen as a case to put morphological management into practice. After a feasibility study including physical and numerical modelling, two in-situ pilot projects were implemented. An intensive morphological and ecological monitoring programme was carried out to follow up the impacts of both relocation trials (Vos et al. 2009). The pilot projects indicated that the Scheldt estuary benefits from relocating dredged material to sandbars due to the creation of low-dynamic and valuable shallow water and intertidal habitat. Secondly this morphological disposal strategy also offered a way to relocate dredging material on a spot where it would be morphological stable, decreasing the maintenance dredging efforts on the longer term.

VOS et al. (2009) wrote about the final evaluation of the Westerschelde relocation test 2006:

"With regard to morphology, it can be asserted that the disposed material is quite stable but, compared to the test in 2004 which took place closer to the sandbar and also in a less dynamic zone, a greater percentage of material was transported. Some of this transport takes place in the direction of the sandbar which is desirable in order to give the sandbar a new shape. In addition, however, some material was also transported outside this zone. Where this material came to rest has not yet been clearly established. In reference to the development of the Schaar van Waarde/Schaar van Valkenisse secondary channel, it can be concluded that the section was not significantly impacted by the relocation test. However, it has been established that relocation in the Schaar van Waarde secondary channel has caused a local reduction in the section. To what extent the deposits impacted upon flow patterns cannot be determined."

Concerning the ecology, it can be noted that the trends for the various parameters (sediment composition, benthos, height of the sandbar) were not significantly influenced by the new relocation test, both for subtidal and inter-tidal areas. There seems to be an increase in coarseness of the bed materials off the placement site but due to a lack of sufficient data preceding the test period this cannot be verified (VOS et al. 2009).

Due to the success of the principle of relocating dredged sediment to (re)construct shallow water habitats on sandbars, the relocation strategy used during the third expansion of the navigation channel in the Scheldt estuary included placement at four locations along different sandbar edges.

Additional research has been carried out in order to optimise the relocation strategy per location as these locations are not all similar.

The flexible relocation strategy as part of morphological management can be regarded as a win-win solution in which dredged material is used to meet a goal that enhances the state or functioning of the estuary. However, temporary environmental impact resulting from dredging and placement is occurring in the same way as it occurs from regular relocation. Integration of the flexible relocation into integrated management plans according to Natura 2000 might be an option.

10.6 Sediment management and Habitats Directive

A large part of the TIDE estuaries is protected under the Habitats Directive. Sediment management measures overlap with the Habitats Directive and may fail to coincide. Thus, appropriate consideration of the Habitats Directive in all sediment management measures poses an exceptional challenge.

On the one hand, the focus here is on assessment and possibly mitigation of significant impacts through sediment management. On the other hand, win-win situations are also conceivable where, for instance, special habitats could be created through sediment management (see section 10.5).

Maintenance dredging and Integrated Management Plan (Weser)

Management plans are recommended for Natura 2000 sites but not mandatory under the Habitats Directive. They appear to be an appropriate solution to reflect transparent conservation objectives and develop measures to preserve or enhance the natural values in line with the system's processes. A management plan creates opportunities to reconcile sustainable economic development, safety issues, accessibility with nature conservation objectives. It offers the possibility to integrate recurring and routine maintenance activities with conservation objectives (EC 2011).

The state governments of Lower Saxony and Bremen as well as the Waterways and Shipping Administration Offices of the federal government have jointly developed a cross-border integrated Weser management plan for the Natura 2000 sites of the Weser estuary and its tributaries Lesum and Hunte up to Oldenburg. During this process and in the framework of their respective responsibilities the partners have pursued the goal of harmonizing ecological and economic interests in the Weser estuary, including the requirements of the shipping sector, in connection with implementation of the Habitats Directive, the Birds Directive and the Water Framework Directive. At the same time they have taken into account the necessity of action to secure and restore the natural dynamics of the estuary habitats, existing uses, existing rights and obligations, including maintenance responsibilities.

Through joint development of this plan across existing administrative boundaries and formulation of long-term goals a major step has been taken towards integrated management (a similar integrated management plan has been formulated for the Elbe estuary).

Maintenance dredging and appropriate assessment (Humber)

Under Regulation 61 of the Habitat Regulations all competent authorities are required to carry out an Appropriate Assessment if the proposed works are within or adjacent to a designated European Marine Site (EMS) and if they are likely to have a 'significant effect' on the site, either alone or in combination with other 'plans and projects'. The UK Government considers that maintenance dredging proposals, which could potentially affect an EMS, require assessment in accordance with Article 6(3) of the Habitats Directive. In effect this means that ongoing maintenance dredging should be considered as a relevant 'plan or project' and requires that its effects on the EMS be considered according to a specified procedural framework that may result in a requirement for an appropriate assessment prior to any consent being granted. As an information base, a Maintenance Dredge Baseline Document has been produced and is continuously updated (ABP 2011).

10.7 Adaptation to climate change

Integrated Sediment Management strategies must also have a long-term outlook and should therefore additionally take into account the consequences of climate change for the estuary and its functions to an appropriate degree. On the one hand, it is important to understand the consequences of current sediment management for the sensitivity of the estuary and its functions with respect to climate change and in particular with regard to an accelerated rise in the sea level. On the other hand, it is necessary to examine whether and possibly how the sensitivity can be reduced by means of sediment management measures (adaptation measures). These aspects are already being dealt with and considered in the framework of various activities in all TIDE estuaries: in connection with research projects, approval procedures for further expansion measures and also the determination of dike heights. Against this background we can mention the following example as good practice on the basis of its integrated approach.

Humber Estuary Flood Risk Management Strategy

The Humber Estuary Flood Risk Management Strategy (Planning for the Rising Tides) provides the framework for investment in protective structures to reduce the risk of flooding to people, property and the environment. A key issue is the rise in sea level, which is reducing the standard of protection provided and is increasing erosion. The plan is developed from detailed geomorphological and ecological studies as well as extensive consultation with interested organizations and the community. It takes into account the urban and industrial development on the floodplain, high-grade agricultural land, the historic environment and the Humber's status as an outstanding site for wildlife, which is protected under the Habitats Directive. A key aim is to work with natural processes wherever possible and is to ensure that there is no net loss of protected inter-tidal habitats. The options investigated include changes to the existing alignment of the embankments. The overall strategy provides for a continuing line of defence around the estuary and tidal rivers, but with the use of managed retreat in some places. The creation of a new inter-tidal habitat by this means is to gain more stable and cost-effective protection, and to offset the loss of protected sites, including by coastal squeeze[1]. Further studies are in progress to appraise potential managed retreat sites.

11. Lessons learned

11.1 What are the characteristics of sediment management in the TIDE estuaries?

In this report the term sediment management in the stricter sense encompasses – besides the treatment of contaminated sediments – particularly the relocation of sediments (dredging and placement in the water body), the factors causing this relocation and the factors influenced by relocation. Sediment management thus displays a broad overlap with morphological management, which is primarily aimed at influencing hydro- and morphodynamics, and includes both the options of sediment relocation and river engineering measures such as groynes (Fig. 1).

The estuaries of the Scheldt, Weser and Elbe are characterized by considerably deepened shipping channels that require permanent maintenance dredging. Maintaining the specified depths, particularly in the area around the berths, requires extensive sediment relocation in the Humber, too. This results in significant costs and brings about impairment of ecological functions.

The sediment management in the TIDE estuaries can be characterized as follows:

- sediment management is of fundamental importance for maintaining and developing usability for shipping
- large amounts of sediment that may vary greatly interannually are dredged in order to maintain the shipping channel depths
- a general attempt is made to reduce dredging volumes
- primarily hopper dredgers are used and water injection is also increasingly applied
- relocation now predominantly takes place within the system
- sediment management is increasingly utilized to avoid or reduce undesired "side effects" of river deepening measures
- attempts are made to reduce the ecological impairment associated with relocation

[1] Coastal squeeze: Coastal habitats trapped between a fixed landward boundary, such as a sea wall and rising sea levels and/or increased storminess. The habitat is effectively 'squeezed' between the two forces and diminishes in quantity and or quality.

- the various European directives are increasingly incorporated as boundary conditions, thus taking into account aspects of nature conservation and environmental protection

- the knowledge base is permanently broadened

11.2 What demands are placed on sediment management from an environmental perspective?

In spite of the individuality of the four TIDE estuaries and the different boundary conditions, it is possible to identify a number of demands placed on sediment management from an environmental perspective:

- reducing relocation volumes with the aim of mitigating the related impairments

- optimizing relocation with the aim of reducing the related impacts (e.g. no relocation during sensitive time windows)

- further reducing contaminants in the sediments to enable relocation of all sediments

- reducing removal from the system as far as necessary to maintain sediment balance and adaptability to rising sea level

- relocating sediments in such a way that dominance of flood current and thus tidal pumping do not develop or artificially reinforced dominance is reduced

- using sediment management to initiate new habitats (e.g. tidal flats) and to support and "replace" natural dynamics (e.g. creation of primary habitats by beach nourishment) whenever this supports the objectives of Natura 2000, etc.

- incorporating sediment management into a holistic concept with determination of objectives for the various functions

11.3 What are the opportunities of "working with nature" for sediment management in estuaries?

In 2008 PIANC, the world association for waterborne transport infrastructure published a position paper entitled "Working with Nature" (recent version: PIANC 2011). It calls for an important shift in thinking in the approach to navigation development projects to help deliver mutually beneficial solutions. It promotes a proactive, integrated approach which focuses on:

- achieving the project objectives in an ecosystem context rather than assessing the consequences of a predefined project design

- identifying mutually beneficial solutions rather than simply minimizing ecological harm

"Working with Nature" thus considers the project objectives firstly from the perspective of the natural system rather than from the perspective of technical design. It is an approach which needs to be applied early in a project when greater flexibility is still possible. If the design concept for a project has progressed before environmental issues are considered, the environmental impact assessment necessarily becomes an exercise of mitigation or damage limitation, potentially resulting in sub-optimal solutions and missed opportunities. "Working with Nature" is about more than avoiding or mitigating the environmental impacts of a pre-defined design. Rather, it sets out to identify ways of achieving the project objectives while working with natural processes and delivering environmental protection, restoration or enhancement outcomes and is thus also recommended by the EC (2011) in the framework of the Habitat Directive.

Overall, "Working with Nature" represents a fundamentally different approach that may be, and is also starting to become, of great significance for sediment management in estuaries not only in connection with expansion measures, but also for maintenance dredging. The flexible relocation strategy in the Scheldt (see section "Examples of good practice") follows this approach and some of the measures contained in the RESMC for the Elbe estuary (see section "Examples of good practice") can also be regarded as "Working with Nature". The same applies to shore nourishment with sandy dredged material instead of shore stabilization using armourstones, as is done locally in the Weser estuary, for instance. The approach for morphological management of estuaries outlined in APA (2012) specifies detailed aspects of the "Working with Nature" approach for estuaries. In the report it is described how the morphology of an estuary supports all different functions of the estuary, and as such the management of an estuary should be based on a good understanding of the morphological processes. However, it should be made clear here that the "Working with Nature" approach represents a way of implementing infrastructure development projects. Whether they can actually be implemented "with nature" or whether "Working with Nature" is used more as an euphemism is something that has to be examined critically in each individual case.

11.4 What does "good sediment management" in estuaries mean?

On the basis of the evaluation of the sediment management strategies in the four TIDE estuaries and the current developments in the estuaries as well as taking into account the various EU directives, it is possible to define the following criteria for "good sediment management".

Good sediment management:

- is based on an in-depth understanding of the short-term and long-term morphodynamic development of the estuary

- attempts to make use of changes in the course of natural development of the system and to refrain from influencing them any more than is absolutely necessary

- targets an appropriate combination of soft hydraulic engineering through sediment relocation and hard hydraulic engineering by means of groynes, etc.

- attempts to mitigate the ecological impairment related to relocation of sediments as far as possible

- takes into account the interactions with the entire catchment area and coastal waters

- prepares itself as early as possible for long-term changes like climate change

- does not focus solely on short-term, inexpensive maintenance of shipping channel depths, but contributes, as far as possible, to a balanced development of the estuary, taking into account different functions and prospects to an equal extent

- sees itself as part of integrated estuary management

11.5 What is the importance of sediment management for integrated estuarine management?

Integrated estuary management attempt to pool the various perspectives, reduce conflicts, enable synergies and ensure long-term sustainable development of the various functions.

Sediment management is of key importance in this context for several reasons. Relocation of sediments:

- is indispensable for maintaining shipping channel depths

- generates considerable costs

- leads to ecological impairment

- alters the morphology and thus the distribution of habitats

- may impair water quality

- can be used to revitalize certain ecosystem functions

- can be used to mitigate negative hydrodynamic and morphodynamic developments from past measures

- enables dynamic solutions

In view of this background, it is plausible that sediment management may be of central importance to achieve the objectives of integrated estuary management, but that in the end the key boundary conditions are created through the definition of the goals of integrated management.

11.6 What are the prospects of sediment management in the TIDE estuaries?

The comparison of the sediment management strategies of the four TIDE estuaries shows that in spite of all differences between the estuaries the challenges of the future will presumably display parallels. Sediment management in the TIDE estuaries already had to take into account increasingly complex boundary conditions in the past years, a development that will continue in all likelihood. In future:

- cost-benefit considerations for sediment management will play an even bigger role
- administrative responsibilities will be further consolidated
- sediment management will see itself and act as an element of integrated estuary management to an even greater degree
- the limits placed on expansion of the estuaries by the natural environment will become more evident and possibly restrict the feasibility of further deepening
- the aspect of risk due to storm surges resulting from climate change will require further increased attention and possibly also alter the boundary conditions for sediment management

12. Recommendations

Sediment management:

- has to focus its attention to an even greater extent on the boundary conditions and limits of the natural environment and on the individuality of the single estuary
- has to be incorporated into a long-term river engineering and sediment management strategy that combines morphological and sediment management
- has to become a more fundamental part of integrated estuary management that carefully balances social, economic and environmental values and is set in the context of the whole river system looking at planning scales of at least a generation in order to consider sustainability
- could be used as part of a strategy of adaptation to climate change

- has to be geared to mitigation of environmental impairment to an even more pronounced extent
- cooperation and responsibilities of the administrative structures should be developed in such a way that they facilitate a holistic view of the estuary
- studies on the advantages and disadvantages of WID on the various system structures and functions should be performed

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14. Annex: reports on Humber, Scheldt, Weser and Elbe

14.1 Dredging and disposal strategies of the Humber estuary

14.2 Dredging and disposal strategies of the Scheldt estuary

14.3 Dredging and disposal strategies of the Weser estuary

14.4 Dredging and disposal strategies of the Elbe estuary

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