Hamburg Port Authority (HPA) and
Federal Waterways and Shipping Administration (WSA)

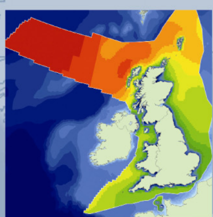
River Elbe River Engineering and Sediment Management Concept

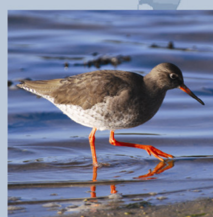
Review of sediment management strategy in the context of other European estuaries from a morphological perspective

Report R.1805

May 2011

Creating sustainable solutions for the marine environment

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Summary

The purpose of the current project is for six international experts to analyse and evaluate the proposed River Engineering and Sediment Management Concept (RESMC) for the River Elbe, particularly with respect to the individual groups of measures proposed and the likelihood for success, taking account of compatibility with the objective of sustainable development on the tidal Elbe.

Peter whitehead of ABP Marine Environmental Research Ltd (ABPmer) in the UK has been commissioned to:

> *"evaluate the RESMC in view of sediment management strategies in other European estuaries from a morphological perspective*".

During the last decade considerable change has occurred in the siltation patterns of the River Elbe. This has generally required more maintenance dredging to take place in the channels near to the mouth and particularly in the Port of Hamburg area with less between these two areas. In the port area the maintenance dredge commitment has increased from around 2 million m^3 in 2000 to over 8 million m^3 in 2004/5. This additional material from down estuary mixes with the contaminated sediments from up-river, creating a larger volume of material with a significant contaminant content to be managed at considerable additional cost. This has led to increased practical problems in maintaining navigation whilst needing to comply with European nature conservation and water quality legislation. Discussions with the Lander of Hamburg, Lower Saxony and Schleswig Holstein, and agreement between the Hamburg Port Authority and the Federal Waterways and Shipping Administration (WSA) who are responsible for maintaining navigation of the Elbe Waterway, led to the development of the RESMC, published in 2008 (HPA & WSD-N (2008). The concept is based on a holistic understanding of the estuary dynamics as whole and promotes measures for sustainable management of the tidal Elbe and Port of Hamburg for the future.

The main goals of the RESMC strategy are to reduce the maintenance dredging, reduce HW levels in the estuary thus reducing flood risk, increasing Low Water (LW) levels thus aiding navigation, and reducing contamination within the estuary in a sustainable manner whilst complying with national and international legislation.

This report provides an overview of the understanding of the historical development of the River Elbe, before the start of the implementation of the RESMC measures, and provides a discussion of the influence of various 'modifications' on the morphology, processes and sedimentary regime of the estuary. This is followed by a review of the various measures proposed in the RESMC, indicating their likely effectiveness in the 'light' of the previous historical understanding and the current processes at work in the estuary.

In order to satisfy the project scope, the RESMC has been evaluated against various sediment management strategies and practices that have been implemented across a range of European estuaries, which include Southampton Water, Medina, Humber and Mersey Estuaries in the UK and the Western Scheldt.

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1. Introduction

1.1 General Historical Background

1.1.1 Port Development

Throughout the world, port development up to the *circa* mid 20th Century concentrated primarily on increasing the size of dock/harbour areas to accommodate more, generally smaller ships (draught, length and beam) than today. In up-river ports such as Hamburg and Antwerp this philosophy resulted in the digging of tidal basins, where the tidal range is/was relatively small. In the UK, many of the port areas are at locations with generally large tidal ranges; this necessitated the construction of enclosed docks and timing restrictions for vessel movements for entry and exit to these facilities. In both the enclosed docks and tidal basins maintenance dredging became a requirement to ensure continuous safe navigation. For the most part these initial port developments did not require deepening of long stretches of approach channels, with any capital dredging restricted to the immediate entrances to the docks and basins.

In the 1960s a radical change in the shipping industry took place, due to the widespread introduction of containerisation and the greater need to transport crude oil and bulk materials/commodities. This started the trend for ever larger, wider and deeper draughted vessels, which has continued to the present day. To accommodate these changes there has been a need to significantly deepen approach channels, basins and dredged berthing pockets at regular intervals. This has generally been, more prevalent in European up-river ports, such as Hamburg on the River Elbe, primarily as deepening has been easier to implement in open dock/harbour basins. In the UK such regular channel deepening has been less, due to the restrictions imposed by lock dimensions to the enclosed docks, which determines the maximum vessel size rather than just the depth of the approach/harbour basin.

1.1.2 Flood Risk

Alongside the need for port development the concept of flood risk has evolved, particularly since the Europe-wide storm surge induced flood event in 1953, when large areas of low lying land were inundated causing large loss of life and costly destruction. Many of these areas were previously reclaimed or ‘enclosed’ from the coast, estuaries and tidal rivers. This led to the widespread construction of flood protection walls, embankments and barrages to reduce the future flood risk and therefore the potential for loss of life and significant housing and infrastructure damage. In order to reduce the length of such structures, hence cost, inlet channels were blocked (‘cut off’) by walls (permanently), and barriers or barrages constructed in order to regulate the flows as required. Such works have been widespread along for example the Rivers Elbe, Scheldt and Humber, which, with large open coast areas have contributed significantly to the morphodynamic behaviour of the various waterbodies, particularly over the last *circa* 50 years.

1.1.3 Coastal Squeeze

The constructions provided for flood protection all contribute to the phenomena known as 'coastal squeeze', whereby part of the tidal prism (the volume of water that is required to raise water levels between low water (LW) and high water (HW)) is excluded predominantly at the higher water levels. This reduces the accommodation space (area/volume of land that can be flooded) for dissipation of tidal and surge effects, and high level areas for sedimentation and energy reduction, that was the case with the former saltmarshes and mudflats that are now behind the new structures.

The tide, flow and sediment dynamics within the river/estuary are therefore modified by coastal squeeze which further affect the ecological functioning of the system over time, in addition to the effect of the initial direct removal. Furthermore, walls and embankments give rise to increased dynamic effects by increasing reflection of both tidal and wave energy along the length of the waterbody.

The first phase of this type of anthropogenic morphological adjustment started more than 2,000 years ago, e.g. the enclosure of low lying land for agricultural purposes. Ports like Hamburg began development about 800 years ago, then more prominently after the Industrial Revolution. In the UK and probably, similarly in Europe, changes to the natural river and estuary conditions were relatively small and slow enough to allow the systems to morphologically adjust to the change until the 1800s. From this time significant areas of land were reclaimed from the river/estuary system, both for agriculture and infrastructure development.

The next significant change that caused a considerable effect on coastal squeeze took place post 1953. The first effect was a significant reduction in the HW accommodation space, then, as channel deepening was required to accommodate the larger vessels from the 1960s, dredging modified the channels both in plan and cross section, particularly in tidal rivers, such as the Elbe. Where dredging took place within former intertidal areas, the tidal prism would have been increased, offsetting some of the loss of accommodation space, albeit at a lower level in the tidal frame, thus affecting the magnitude of the coastal squeeze effect at different locations. Deepening of the subtidal channel only increases the total water volume within the system. These changes both increase and reduce local flow speeds and sedimentological effects as well as changing the speed of propagation of the tide, thus affecting the water levels and the morphodynamics of the system. As channel modification occurred, the natural processes were, in many estuaries forced out of 'balance', changing erosion and accretion patterns. This often led to areas of sedimentation both along/in the channels and predominantly in the dock and harbour basins, which needed, to be removed to maintain the navigation depths. This lead to the introduction of sediment management practices which have been further developed over time at the different locations.

The general pattern of Europe-wide historical development, outlined above, is highly relevant to the development of the Elbe and the Port of Hamburg and has a fundamental influence on the existing morphodynamic processes occurring within the estuary today.

1.1.4 Hamburg and the Tidal Elbe

The Port of Hamburg is the second largest in Europe, with a trading hinterland both within Germany and mainland Europe, employing a significant workforce, therefore is economically and socially important to the country as a whole and more specifically the Hamburg area.

There is therefore an imperative need to maintain the tidal Elbe for shipping (both for existing vessel sizes and any future vessel trends).

At the present time this navigation function and vessel safety requirements is the responsibility of the Federal Waterways and Shipping Administration (WSA), WSA Cuxhaven and WSA Hamburg areas along with the Hamburg Port Authority. These administrations have maintained navigation depths and therefore vessel safety, by means of survey and maintenance dredging strategies, which have evolved based on need, type and levels of sediment contamination, as well the costs of dredging and disposal for the changing requirements brought about by successive capital deepenings and other activities/developments that have affected the sedimentation patterns within the estuary.

Since 2000, however, the maintenance dredging within the Port of Hamburg jurisdiction has increased considerably from about 2 million m^3 to around 8 million m^3 in 2004/5; which has substantially increased costs. These, along with considerable morphological changes to the banks and channels towards the entrance to the estuary and legislative changes over the last decade, were the motivation for the authorities to jointly develop a "River Engineering and Sediment Management Concept". The concept is based on a holistic understanding of the estuary dynamics as whole and promotes measures for sustainable management of the tidal Elbe and Port of Hamburg for the future.

1.1.5 Present Project

The purpose of the current project is for six international experts to analyse and evaluate the RESMC, particularly with respect to the individual groups of measures proposed and the likelihood for success, taking account of compatibility with the objective of sustainable development on the tidal Elbe. If possible the experts are to suggest possible areas of further development based on their experience and what practices have been used, and are in operation and conforming to the latest legislation applicable to Europe. Each expert will concentrate on a specific concept.

Peter whitehead of ABP Marine Environmental Research Ltd (ABPmer) in the UK has been commissioned to:

> *"evaluate the RESMC in view of sediment management strategies in other European estuaries from a morphological perspective"*

specifically concentrating on the series of questions outlined in the document "Information for Committee of Experts 1" (Bioconsult, 2010). This report presents this evaluation.

2. Report Structure

This work package report is structured in a way that first gives a general historical overview of port and navigation development, and anthropogenic influences on the morphology of estuaries and rivers that have common features throughout North West Europe. This is presented in the introduction (Section 1) and serves to illustrate that the issues requiring to be solved or managed are not unique to the River Elbe.

Section 3 of the report provides an overview of the development of the RESMC, which sets the context in which this work package review has been made.

Section 4 provides the detail of the objective of this package review and gives the questions that the expert assessment is required to answer. The general method employed to achieve the objective of the work package is outlined in Section 5.

Section 6 is the technical assessment (Objective Analysis) and therefore the main section of the report. This provides an overview of the understanding of the historical development of the River Elbe, before the start of the implementation of the RESMC measures. Section 6.1 provides a discussion of the influence of various 'modifications' on the morphology, processes and sedimentary regime of the estuary, which leads to a conceptual understanding of the current day estuary processes (Section 6.2). These processes are those that will be both directly and indirectly affected by the RESMC measures in order to meet the overall concept objectives. Section 6.3 provides a review of the various measures proposed in the RESMC, indicating their likely effectiveness in the 'light' of the previous historical understanding and the current processes at work in the estuary.

Section 7 provides an overview of related experiences in other European estuaries/rivers, by means of case examples of similar measures to those outlined in the RESMC and other types of management practices that are being used or have been used, that have legal and environmental approval.

The conclusions are provided in Section 8, summarising the expert judgment with respect to the specific questions posed for the work package and makes any recommendations that come out of the assessment process.

3. River Elbe Sediment Management Concept

During the last decade considerable change has occurred in the siltation patterns of the estuary. This has generally required more maintenance dredging to take place in the channels near to the mouth and particularly in the Port of Hamburg area with less between these two areas. In the port area the maintenance dredge commitment has increased from around 2 million m^3 in 2000 to over 8 million m^3 in 2004/5. This additional material from down estuary mixes with the contaminated sediments from up-river, creating a larger volume of material with a significant contaminant content to be managed at considerable additional cost. This has also led to increased practical problems in maintaining navigation whilst needing to comply with European nature conservation and water quality legislation. Discussions with the Lander of Hamburg, Lower Saxony and Schleswig Holstein and agreement between the Hamburg Port Authority and the WSA who are responsible for maintaining navigation of the Elbe Waterway, led to the development of the RESMC, published in 2008 (HPA & WSD-N, 2008).

The overall approach of the RESMC, is to contribute to the long-term sustainable development of the tidal River Elbe by implementing both long, medium and short term measures whilst:

- Securing the shipping channel depths for the tidal River Elbe according to planning approval;
- Reducing the dredging quantities and costs;
- Reducing contamination levels in the tidal river;
- Reducing the environmental impairments related to maintenance;
- Reducing the potential flood risk from extreme events;
- Maintaining compatibility with and/or support of the regional objectives of nature conservation and marine protection as well as water resources management;
- Providing compatibility with the requirements of European and national water protection, marine protection and nature conservation; and
- Obtaining broad social acceptance.

The concept is based on developing an understanding of the current ‘working' dynamics of the estuary in a holistic manner, without consideration of political boundaries to achieve the above objectives. This information is used to develop a series of potential measures, which if implemented are likely to contribute alone and in-combination to some or all of the objectives. The measures that have been proposed are divided into two broad categories:

- River engineering works that include:
  - The construction of training walls and breakwaters, or re-profiling the river cross-sections;
  - Re-connecting ‘cut off' tributaries; and
  - Dredging out silted up harbour basins.

- The main river engineering objectives are to firstly modify the “unbalanced sediment budget" to change the erosion and siltation patterns along the estuary to optimise the maintenance dredging requirement, for the estuary as a whole. Secondly to modify water levels (i.e. propagation of the tide) in a beneficial way, without causing adverse effects on other issues and users of the estuary; and

- Sediment Management Plan: this involves using the understanding gained on how the estuary works to re-define the amounts, methods and sites for the relocation of maintenance dredged sediments within the system to reduce the potential for sediment re-circulation, whilst maintaining the sediment budget of the system to allow it to maintain its ecological functioning, nature conservation importance and water quality in the future.

These measures will all change the flow regime and tidal volumes and therefore the rates and amounts of sediment transport, and if large enough the propagation of the tide. Consideration will need to be given to the interaction of the different groups of measures both in the short and long term.

With the implementation of a selected combination of possible measures along with their future adaptive management based on monitoring results, it is hoped the RESMC will modify the dynamics of the tidal Elbe in a positive way with respect to the maintenance of navigation, flood protection, nature conservation and tourism, whilst benefiting the port economy by reducing the maintenance costs for the channel and port areas to a sustainable level both now and in the future.

4. Package Review Objective

The purpose of this work package is to review various reports, data and modelling studies to provide an understanding of the recent morphological changes of the tidal Elbe and how the physical processes have been changed by anthropogenic influences. This will confirm or add to the existing understanding of the dynamics of the Elbe system forming a baseline on which the goals of the RESMC can be assessed. This understanding is then used to assess and comment on the likelihood that the proposed strategy will provide a sustainable solution for the physical and ecological evolution of the tidal Elbe recognising the continuing and developing need for navigation to the Port of Hamburg and other uses of the waterway such as fishing, tourism and recreation.

For legislative and planning approval the implementation of the RESMC measures need a broad acceptance both socially and environmentally. The second part of this package review is therefore to consider the groups of measures for their general use in a European context. In this way lessons can be learnt as to their acceptance, how effective they may be and any problems that may result.

This report is therefore based around answering the specific questions posed in the work package specification, namely:

- Assessment of the morphological and morphodynamic situation in the tidal Elbe up to approximately 2005 (“initial situation”):
  - What is the assessment of the influence exerted by past expansion, river engineering and dredging strategy on the present-day morphological situation and/or morphodynamics?

- Assessment of the situation as of 2005 and with further implementation of the RESMC:
  - What sediment management strategies are practised and/or developed in other European estuaries? Are there similar problems there?
  - What is the assessment of the objective “reducing tidal pumping” as a sediment management strategy from a morphological perspective in view of the experience in other European estuaries?
  - Are the envisaged river engineering measures for reducing tidal pumping expedient?
  - What is the assessment of the currently practised use of water injection in the main tidal Elbe (shipping channel) for attenuating sand riffles in comparison to the alternative of hopper dredging?

  - Is breaking dredging cycles (sediment re-circulation) as a priority sediment management strategy appropriate and expedient from a morphological perspective in view of the experience in other European estuaries?
  - What is the assessment of the removal of sediments from the Elbe estuary in view of the long-term "solids balance"?
  - Is the practice of sediment trapping for fine material management appropriate and should the concept be extended?

- Overall assessment:
  - Are the objectives of the RESMC sensible in your opinion, also in view of the situation in other European estuaries?
  - Do the measures outlined in the RESMC represent overall the right way to achieve the objectives?
  - Recommendations for the further development of the RESMC.

5. Method

The method used to undertake this review of the RESMC has firstly used the supplied literature, which are recorded in Section 8 of this report, to develop an understanding of the need for the RESMC and the objectives of the concept to use as a focus for the overall assessment. This understanding has been presented in the preceding sections.

In order to review the effectiveness of the concept it has been necessary to develop a historical understanding of the various changes that have occurred throughout the tidal Elbe, in particular, over the last 60 years. An attempt has then been made to relate these to the change in tidal propagation, affecting water levels and tidal range, and how this may have affected the process of tidal pumping, hence the maintenance dredging and relocation requirement.

Development of an understanding of what previous developments had on the 'working' of estuary will aid the assessment of the effectiveness and impacts of future engineering, dredging and sediment management measures.

A review of the dredging data, bed sediment analysis and modelling results has been used to develop a baseline of the current physical processes at work in the estuary to try and understand the patterns of sedimentation and erosion.

The aim of this analysis is to develop a baseline against which the broad scale effectiveness of the proposed measures outlined in the RESMC can be assessed; primarily with respect to the morphology of the estuary as whole. The main emphasis has been on the objectives to ensure:

- Safe navigation for large (and larger) ships along the estuary to the Port of Hamburg;
- Reduction in high water levels from tidal propagation, thus enhancing flood risk protection;
- Increase in low water levels, therefore, benefiting navigation around low water;

- Reduction in maintenance dredging of the tidal channel and harbour basins; and
- Reduction in mixing of clean and contaminated sediments and reducing the rate of settlement in the harbour. This will over time not only reduce sediment volumes to be removed by maintenance dredging but will also reduce contamination levels of the dredged materials that have to be managed.

Secondary consideration has been given to sediment contamination, nature conservation and legislative issues as these are the focus of other expert studies. The optimum measures, however, will need to combine these issues, also recognising there will be an interaction between the various disciplines.

The second part of this particular work package compares the issues and measures that have been/are being used to manage both similar and potentially different issues in other European countries. For this review examples have been briefly presented:

- Which indicate similar problems to the Elbe and how these have been overcome/managed; and
- Where the different types of measure proposed in the RESMC have been used and what the effects were.

In this way confidence can be gained that the measures proposed are not unique, in some cases 'tried and tested' and acceptable from a regulation perspective. This should help to gain social acceptance of the measures proposed and give an indication of the likely effectiveness.

The different parts of the review have been drawn together to provide an overall assessment of the RESMC with specific attention to the questions posed in Section 3. Where appropriate recommendations will be made throughout the report based upon the process and historical understanding of the Elbe and the experience gained from the implementation of similar measures undertaken elsewhere.

For the purpose of this assessment the tidal Elbe has been considered as one single functioning system, i.e. a holistic view has been taken without consideration of political jurisdictions or specific legislative requirements. In this way the optimum solution for the main objectives should have been considered.

6. Objective Analysis

6.1 Understanding of the Historical Development on the Morphology and Dynamics of the River Elbe

6.1.1 Morphology

The River Elbe drains a catchment of 148,268km^2 over a total distance of over 1,000 km of which the last 172km, from Geesthacht weir to the North Sea are tidal (the tidal Elbe). At the weir to where the river divides, at Bunthaus, the width varies between 300-500m, then each branch reduces to about 200m and then continues to widen through the Port of Hamburg. Where the two branches merge the main channel is around 500m wide. As Figure 1 shows this is the order of width of the main navigation channel until about the entrance to River Stohr (about Km 678).

The main channel then widens around the outside of the bend at Brunsbüttel. From Muhlenburger Lock to just down estuary of the entrance to the Kiel Canal the deep channel gently meanders within a total width at HW varying from about 1.9-3.8km. Within this width, however, the overall cross section is continually altering between a single channel and a double channel (secondary side branch) form around a number of islands on both sides of the river. Depths along the main channel also alternate with a depth difference in the order of 3-4m.

Down estuary of Brunsbüttel the estuary widens to form a funnel shaped mouth to the North Sea, comprising many shallow channels and intertidal banks. The main navigation channel drains through the southern side of the 'funnel'. This section of the estuary is highly dynamic, with the bank and channel pattern continually changing; with general net erosion occurring in recent decades.

This current estuary configuration, however, common with other European estuaries has changed considerably over time both due to:

- Natural processes controlled by wave and tidal action causing substantial sediment transport, which have continually changed the bank and channel configuration over time. This has led to a multitude of highly dynamic characteristic features, for example, continually changing channel widths and depths, development and erosion of islands and subtidal areas, as well as many different transient bed features such as ripples and dunes;

- Anthropogenic changes to the estuary configuration which started around the 11th Century in the form of claiming high level marsh and mudflat areas, by vegetal colonisation, diking (poldering) and hydraulic engineering to provide low lying agricultural land. These changes removed about 2,290km^2 of high level water area before 1955, see Figure 2. This diagram shows the original estuary would have been funnel shaped with large areas of intertidal mud and marsh either side of the main channel up to Hamburg, which would have been the easiest crossing point at that time. In these times the Elbe would have functioned more like an estuary as opposed to a more constricted tidal river as it does today.

Since 1955 the river has been constricted further by over 200km^2, primarily for flood protection purposes. This area of removal from tidal influence was similar to that removed in the preceding 450 years. Given that this area was likely to be at a lower level in the tidal frame the volume of water excluded from the marsh areas has occurred at more than 10 times the rate that took place previously.

All these modifications will have changed the tidal propagation and flow speeds within the channels, changing the erosion and accretion patterns and also the sediment transport within the estuary, therefore changing the sediment balance within the system. Before the turn of the 20th Century the estuary would have changed to a new equilibrium condition. Flow speeds in the main channels were likely to have been increased and more sediment would have been eroded from the main channel, adding to that which could no longer settle (or be trapped) over the high intertidal or marsh areas, now excluded from the estuary. A new equilibrium would have developed with a higher rate of sediment transport both in and out of the estuary, a greater channel width (and/or depth) particularly at lower levels and a higher suspended sediment content within the system as whole, which would have enhanced the turbidity maxima, particularly for finer sediments. Similar interactions will have occurred, but at a much greater rate due to the anthropogenic changes during the 20th Century and particularly the post 1950s. The implications on the morphodynamics of these types of change are discussed separately in the following sections, with respect to their likely individual and cumulative effects on the current working processes on-going in the estuary.

Any understanding of cause and effect relationships of the individual activities will provide information to add confidence to the likely outcome of the different RESMC measures, and potentially allow them to be ranked in terms of overall benefit and cost effectiveness.

The present configuration of the tidal Elbe means the estuary can be divided into three morphological sections, with transition zones between, being controlled by a different set of external forces:

- Down estuary of the Kiel Canal: This section is tidally influenced, but has a significant wave induced signature (particularly outside Cuxhaven) which reduces in effect in an inshore direction. Significant erosion has occurred since 1990, particularly to the north of the main channel, where Great Bird Sand Bank and Yellow Sand have been lost, as well as a connected chain of sands that were evident around 1980 (Boehlich and Strotmann, 2008). Saline intrusion, possibly increasing the import of sediment near the bed could occur along the main channel at times of low wave activity and lower headwater discharges;

- Kiel Canal to the Port of Hamburg (specifically the location of St Pauli-Elbe tunnel): This part of the estuary is severely constricted by dikes and cut offs, with the channel cross section being significantly modified by capital dredging to deepen and straighten the fairway, along with the use of material dredged to create underwater structures. This section therefore is influenced significantly by coastal squeeze, with the tidal dynamics being the main morphodynamic forcing factor; and

- St. Pauli and the Suderelbe to Geesthact weir: This area is still tidally influenced, but due to the narrower channel widths and shallower depths the tidal prism is abruptly reduced, therefore the variability in headwater discharge has a major influence on the dynamics and sediment movements in this section of the estuary. The Port of Hamburg is therefore located within a transition area, both influenced by the tidal dynamics and its interaction with the downstream discharge of the River Elbe and the sediment it carries which still has high levels of contamination, although considerably cleaner than thirty years ago.

6.1.2 Dredging

6.1.2.1 Capital

As early as the 15th Century navigable depths to Hamburg were monitored, however in those days there were no methods to remove shoals, therefore the navigation channel would have followed the migration of the river. The invention of the steam powered bucket excavator in 1836 allowed removal of isolated shoals to maintain channel depths. Before about 1860 the fairway depth was about 4.5m below Mean Low Water (MLW) and since then there have been seven main periods when the depth has been increased by nominally 1m on each occasion by capital dredging. The last deepening occurred between 1998 and 2000, creating a minimal maintained nominal depth of 14.4m below MLW throughout the channel length (Iwens and Marusic, 2007). Figure 3 shows a timeline of these capital dredges, related to the changes in the tidal levels recorded at St. Pauli.

Little detailed information on the volumes of material dredged, the locations, the material type and how the material was disposed is available within the literature for the review. In addition, different references supposedly, recording the same information give significantly different dredging figures making interpretation between data sets difficult. This is common when analysing dredge data due to the many different methods of recording and measurement used. This review of both the capital and maintenance dredging will therefore primarily use the data provided in (HPA & WSD-N, 2008).

It is reported that the last capital dredge could have removed up to 20 million m^3 from the channel, based on data provided by Iwens and Marusic (2007) in comparison with RESMC data, however some of this would have been the regular maintenance material. Also, it is known that a large proportion was relocated within the estuary, therefore the effect on gross tidal volumes and prism would have been reduced. The combined effect however, will have changed the magnitude of the local tidal processes, predominantly flow speeds and therefore cause change to the sediment transport in the area. Bed sediment sampling from along the channel indicates that the material removed by the capital dredge would have been predominantly fine and medium sand with some gravel content.

The previous deepening took place between 1974 and 1978 and increased the nominal channel depth from 12m to 13m below MLW, by the removal of about 35 million m^3 of sandy material (Eischweber, 2011). The material was removed predominantly from the base of the channel, therefore little straightening or widening of the low water channel took place.

It should also be noted that throughout the 1980s about 15.3 million m^3 of sand was removed from the estuary, primarily for dike and road construction.

No information has been sourced for the extents and volumes of the earlier capital dredges. If these just deepened the channel then the volumes would have been less than for the most recent capital dredges. However, it is likely some widening and straightening may have been undertaken which would have potentially increased the dredged volume over a pro rata change of the depth. It is considered however, that none of the previous dredges would have exceeded 35 million m^3.

To put these volume changes into perspective, the magnitude is very roughly estimated to be equivalent to less than 4% of the present day tidal prism or around 2.5% of the LW volume. These percentages are also likely to be towards a worst case as it is known large volumes of material, particularly for the most recent dredges, have been relocated within the estuary thus reducing the estuary-wide potential impact.

Based on this limited data, the predominant morphological change caused by the capital dredges is likely to have occurred at the lower states of the tide when the proportional effect of each individual deepening would have been greatest. There is little evidence that the dredges have directly significantly changed the levels above MLW and therefore the dredges in their own right have not increased the estuary tidal prism particularly for the most recent deepenings. It is possible however, that some of the tidal prism could have been removed due to the relocation of the capital dredged material to form islands in former intertidal areas. It is considered however that this may have been more prevalent for the earlier dredges in comparison to the most recent one.

For each deepening the subtidal volume has increased, consecutively reducing the relative effect of the bed friction. Depths and volumes over the intertidal, however, have not been significantly changed. Generally channel deepening tends to allow the crest of the tidal wave (HW) to progress faster than the trough (LW) thus deforming the tide giving rise to a shorter period for the tidal rise compared to the fall. The relative change in water levels is more associated with the change of cross section particularly within the tidal frame between LW and HW. Since little direct change has occurred at the higher water levels compared to nearer low water it might be expected that changes to HW levels would be smaller than those at LW as a result of capital dredging.

6.1.2.2 Maintenance dredging

Maintenance dredging of the tidal Elbe fairway is undertaken by three institutions: WSA Cuxhaven, WSA Hamburg and the Port of Hamburg itself. Until the formulation of the RESMC they generally operated independently of each other, with dredging and relocation confined within each administrative boundary. Under this system it is unlikely that the combined maintenance dredge strategy was the optimum for the estuary as a whole and may have increased requirements in neighbouring jurisdictions. The RESMC concept therefore provides a ‘vehicle’ whereby a strategy would be developed so that the equilibrium level for the estuary as a whole, will be sustainable and adaptable to future changes.

Volumes

Little information on the maintenance dredging within the tidal Elbe is available before the 1950s and extensive records for analysis purposes are only available since 1965. It is reported that for the Hamburg area alone, maintenance dredging was relatively consistent at around 1.5 million m^3 before this period of records.

The combined maintenance dredge commitment for the estuary as whole from 1965-2007 are shown in Figures 4 and 5, where the approximate timings of the last three dredges have been marked along with the approximate peaks (High Range - HR) and troughs (Low Range - LR) of the 18.6 year lunar nodal cycle, which affects the tidal range. The Figure 4 annotations indicate that between the mid 1960s and around 1980 the estuary maintenance dredge commitment increased from below 5 million m^3 to around 17 million m^3. During this period the channel was deepened twice from 11 to 13.5m below MLW, with most of this change appearing to be due to an increased import of sediment to channel in the mouth, particularly after the 1974-78 dredge. Post 1980 the overall maintenance dredge commitment for the estuary has not increased, but shows a variability ranging between about 10-17 million m^3 with a possible cyclic pattern.

The second feature is an apparent upstream redistribution of sediment from the WSA Hamburg to the Port of Hamburg jurisdiction, which appears to coincide with the last deepening to 14.5m below MLW.

This interpretation of the dredge data does not however seem to show any increase in the overall sedimentation volume in the estuary, with little change in the total volumes dredged in the WSA Cuxhaven area. Figure 5 shows an alternate interpretation of the maintenance dredge data with respect to the main deepening events. This interpretation indicates that each dredge could have caused a perturbation within the estuary dynamics which tends to increase maintenance dredging for 5-6 years following the dredge before a slightly lower new equilibrium level is established. The graph also shows an increase in maintenance dredging as a result of the last capital dredge to a similar degree as the previous two. There is also some suggestion that maintenance dredging for the estuary could be higher for the lower range tides of the lunar nodal cycle compared to the higher ranges. Should these hypotheses be the case, without further deepening the long term average maintenance dredging commitment would be around 15 million m^3 in the future. This analysis would also suggest that for 1m of deepening the maintenance dredge commitment for the estuary as a whole increases on average by 3-4 million m^3, following the initial enhanced increase for the first 5-6 years as the estuary reaches a new equilibrium following the perturbation caused by the dredge. This rate of change could reduce as the depths increase.

The diagrams also show the annual variability in headwater discharge. This would appear to have a periodicity on a 7/8 year cycle, however, the total volume dredged in the estuary does not appear to be directly associated, although a small reduction in the total is evident, for some of the years that show the very highest headwater discharges. It is predicted from numerical modelling, however, that high flows move the location of the turbidity maximum down estuary, potentially creating more sedimentation around Osteriff and less further up estuary. The effect of changes in headwater discharge would appear to alter the distribution of sedimentation, hence dredging as opposed to significantly reducing the dredge commitment for the estuary as a whole, on an annual basis. It is highly likely that short ‘spate’ conditions flush sediment from the Hamburg area to the lower estuary, where it may enter the ebb dominated flow areas. At times of lower headwater discharges, however, this effect is likely to be reversed. Since only the very highest annual flows appear to reduce the overall magnitude of maintenance dredging, the data tends to indicate that it is only these highest flows that completely remove sediment from the estuary system, as was potentially the case in 1987. It is considered that the headwater discharge is therefore only a moderator of the overall sedimentation rates and not the primary control, but will affect the location of sedimentation within the estuary. This distribution is reviewed in more detail in the following sections by reference to the historic pattern of dredge and deposit locations.

Dredge Locations

Within the WSA Hamburg and Cuxhaven areas maintenance dredging is required in varying quantities from 17 locations along the channels whilst dredging in the Hamburg Port area either comes directly from the tidal river or the various harbour basins. The amounts dredged from these locations are shown in Figure 6 along with the type of material usually dredged.

In 2008, significant changes occurred in the morphology of the estuary mouth which leads to a need for additional 'emergency' maintenance dredging in that year.

Figure 6 shows a breakdown of the dredge quantities for the individual dredge locations for the period 1993-2009. This graph shows several features namely:

- Increased quantities in the mouth since about 2000 and significantly post 2003 at Östl Mittelrine where the average volume rose from negligible to over 4 million m^3 during that period. A similar trend (albeit of lower magnitude) is seen inwards to Medemgrund, particularly at Attenbruch;

- In the Osteriff and Brunsbüttel areas a cyclic pattern is evident with an approximately eight year asymmetrical period, with minima in about 1996 and 2004, but with maximum only two years earlier. There also appears to be an approximate two year lag in this cyclic pattern and lower magnitude at Brunsbüttel. Whilst this length of periodicity is very similar to that for the headwater discharge it is difficult to interpret a direct association over an annul timescale. Analysis over shorter periods, however, is likely to indicate a closer association and/or an interrelationship between the various dredge and relocation sites.;

- Within the WSA Hamburg area, the average quantity dredged has reduced. The majority of material dredged has moved from the Rhinplatte area up estuary to Wedel, with little change of significance elsewhere. Before 1998 the average annual dredged exceeded 5 million m^3 (at Rhinplatte) but since has dropped to considerably less than 0.5 million m^3. At Wedel, post *circa* 2000, the average maintenance commitment has increased to over 2 million m^3 from generally less than 100,000 m^3 in the period 1993-2000;

- In the Hamburg Port area, in 1995/6 a sudden drop in maintenance dredging occurred both in the River and Harbour Basins, which then steadily began to rise to about 2003. During this 10 year period the pattern of change in dredge quantities is very similar to that for the Cuxhaven area (particularly in the river) where the clear cyclic trend is evident. In 2004/5 this association is 'broken' when significant increases in dredging occurred particularly in the river. Since that time, dredging in the river has steadily reduced;

- Within the harbour areas, the 1995/6 change is clear, as are the high peaks in 2004 and 2005. Around 1999/2000 additional peaks occurred but, for the most part, the dredging rate appears more constant than for the river.

Throughout this period of record, there was only one major deepening of the estuary in 1999/2000. However, the changes in the recent pattern of maintenance dredging do not, for the most part, indicate a close association with that dredge alone. The changes in the mouth area seem to start a couple of years before the dredge and no change has occurred in Osteriff/Brunsbüttel areas. The largest single change, the sudden reduction in maintenance dredge commitment at the Rhinplatte occurred in 1998/99, which coincides with the beginning of the last capital deepening, but probably most significantly the narrowing of the cross section of the estuary at this location, see Figure 10 and Section 6.1.3.3 for details. The data may also suggest that the effect of the in channel construction could have also been influenced by changes at the mouth as well as the deepening. Since this time, the change at Wedel seems to be associated with the Rhinplatte, although the main changes occurred after the dredge.

It is hypothesised that, at least within the river, the maintenance dredging pattern is more associated with morphological changes at the mouth rather than the last fairway deepening. As noted above, the Hamburg area in the first ten years of this record are more associated with the natural cyclic patterns clearly seen at Cuxhaven. During the period of the dredge, an increase in maintenance dredging in the harbour was noticeable but not in the river. The large increase in maintenance dredging that occurred in 2004/5, particularly noticeable in the river, does not seem to be associated with other trends within the estuary as a whole. This suggests that around 2004/5 there were some more localised effects in the Hamburg area, for example, a change to the dredging practice, some local harbour infrastructure modification, or just greater dredging to accommodate changing trade in the port area, rather than a significant change in sedimentation patterns.

The assessment has concentrated more on the trends rather than the absolute magnitudes and indicates the trends are more associated with morphological changes at the mouth and their effect on the tidal dynamics. The last major deepening by comparison seems to have had a secondary influence, mainly in changing the absolute magnitudes in the trends, as indicated from the volumetric analysis.

Within the patterns of the dredging records there appear to be two main features in the trend pattern:

- A *circa* 8 year cyclic pattern, such as at Cuxhaven and less so at Hamburg, which may be associated with the cyclic patterns in the headwater discharge, however , further data and analysis will be needed either to confirm or reject this ; and

- Sudden changes following long periods of relatively constant conditions, such as in the Rhinplatte area and the mouth.

The table at the bottom of Figure 6 tends to indicate that the areas which show the cyclic tendency are those where the material dredged is finest and contain large proportions of silt, whilst the 'sudden change' feature is presently associated with areas where the bed material is coarser, generally medium sand (Rhinplatte) and coarse sand in the mouth. It should be noted, however, that prior to the change at the Rhinplatte the sediment predominantly dredged was silt, whilst the bed is now considerably coarser, indicating the change in the primary sediment transport mechanism at this location. This possibly suggests that different sedimentation/transport mechanisms, occur within in the two areas; mostly settlement from the water column for the fine sediments, but more bed load transport along with settlement for the coarser areas, while the fines remain in continual motion through both areas.

This analysis therefore indicates that the successful management of dredge volumes throughout the estuary requires a detailed understanding of the morphological changes at the mouth, with respect to how they change the estuary processes, a clear understanding of the reasons for change at the Rhinplatte area and the local practices within the Hamburg area in particular. Along with this there is a need to understand the implications of the relocation strategy in conjunction with the existing methods employed and any changes to these practices, particularly in the more recent years.

Relocation Strategy and Methods

As noted earlier significant dredging has occurred on the Elbe and in the Hamburg area for approximately 200 years. For the most part until the mid 1980s the majority of this material, of which a large proportion was from capital dredging, was used for agriculture and reclamation within the system, therefore removing much of the material from the estuary and at the same time reducing the water volume 'working' of the estuary and the tidal prism, and raising the LW level.

The material (both capital and maintenance) has been used, for example to:

- Extend and enlarge Pagensand from a sand bank in 1900 to a formed island in phases, with the aid of training walls, especially after 1922. Today this would be regarded as a beneficial use as the aim was to change the morphology of the channel to increase flows thus reducing the dredging commitment at this location;
- Join the sand islands of Hanskag, Neβsand and Schweinsand, again in stages since the 1930s;
- In fill of side branches; and
- Creation of an underwater storage area, changing the channel morphology at Krautsand in 1999.

Following the realisation that the sediments dredged from the Port of Hamburg were contaminated predominantly by pollutants from up river, the concept of removing the harbour sediments to land via a treatment plant was devised and implemented; the MEHTA (Mechanical Separation and Dewatering of Port Sediments). Since 1996 *circa* 1-1.4 million m^3/annum of contaminated sediment has been removed from the Elbe system, along with up to a maximum of 0.5 million m^3/annum of sand in some form of beneficial use. In 1994, following an improvement in contamination levels, relocation to the River Elbe started, mostly to the northern edge of Neßsand Island about 10 km down estuary of the port. The location on the south side of the channel was selected to safeguard the natural environment, particularly the oxygen availability for fish.

By 2003 the relocation volume had increased steadily to about 3 million m^3 as a result of the increasing settlement rates within the port area. However, this increased to around 6 million m^3 in 2004 and 2005. Since 2006 the average has been about 2.8 million m^3. However, on average, a further 1.3 million m^3/annum has been deposited at Buoy E3 in the North Sea.

Whilst relocation into the river system helps maintain the natural sediment balance, a number of drawbacks have been identified, including:

- Increased potential for a proportion of the sediment to return back to the port, thus requiring re-dredging; this is seen as part of the reason for the substantial increase in maintenance dredge requirement since 2000; and

- Deposition of fine sediment has the potential to increase suspended sediment concentrations which may:
  - Affect the spawning grounds and juvenile fish;
  - Lead to additional siltation elsewhere, where transported by the tide, potentially smothering habitats, which may be lost; and
  - Reduce the oxygen availability in this section of the estuary;

The first drawback led to the relocation of some of the material to Buoy E3 (see below). The second drawback led to a management plan for the Neßsand relocation site which includes:

- Relocation to ebb flows (HW-1hour to LW-2hours) for Trailer Suction Hopper Dredgers (TSHD) and Water Injection Dredging (WID) in the port areas;
- Minimal relocation when headwater discharge is <500 m^3/s; and
- Relocation only between November and March, and in September and October but only under specific circumstances agreed on a case by case basis. No relocation is allowed from April to August to avoid impacts on fish.

In practice, however, the <500m^3/s/rule and the September/October option are not enforced or carried out.

Figure 7 shows where the maintenance dredge material is located within the estuary. The diagram does not show any relocation of dredged material down estuary of Brunsbüttel between 1993 and 1999, however Rickert-Niebuhr (pers comm, 2011) notes that records could not be sourced, but dredging in the Cuxhaven area was deposited in the locality but the precise locations/volumes is unknown. Little of the material would have been moved up estuary. The relocation volume 'signature' generally matches that of the Rhinplatte dredge area indicating all the material from this area was deposited at Störbogen.

After 1999, it appears that much more of the sediments from the WSA Hamburg area have been deposited in the WSA Cuxhaven jurisdiction. Also the Störbogen site has become predominantly unused, whilst the more up-estuary sites of Lühebogen, Hetlingen and particularly Pagensand site were used, particularly between 2000 and 2004 for the relocation of the sediment from the Wedel area. This tends to indicate that, whilst the sedimentation moved up estuary post 1999, the material then dredged was also deposited further up estuary than had previously been the case. As a consequence, the natural process change was moving sediment up estuary but the disposal strategy was also tending to increase the supply in the up estuary areas, leading to the substantially increased requirements for dredging both at Wedel and within the Hamburg area. The maintenance dredge relocation practice at this time therefore significantly enhanced the re-circulation/hence re-dredging of the material in the area from Wedel into the port area, both within the Port of Hamburg and the WSA Hamburg jurisdictions, leading to the large increase in the maintenance requirement in 2004 and 2005, which could only be dredged between November and March, hence further concentrating the effects.

Post 2005, the amount of sediment relocated to Neβsand was reduced due to its transfer to the North Sea, thus reducing the available supply for recirculation. However, at the same time, the relocation from the Wedel area appears to have been relocated much further down estuary because the relocation volumes to Pagensand and Hetlingen, in particular, were reduced to similar volumes as occurred before 1999. This interpretation is confirmed (HPA & WSD-N, 2010) as “a changed relocation strategy for hopper dredging was implemented in 2006 aimed at breaking sediment cycles”. Mostly the sediment from the Wedel area was transported down estuary of Störbogen (Km 677) and since 2008 between Kms 686 and 690, close to the turbidity maxima, where the flow dynamics are ebb dominant in terms of flows and excursion lengths (see Figure 1).

The effect can clearly be seen in the reduction in volume that was dredged at Wedel and the reduced volumes, particularly from the river section in the port area. This indicates it is not only the removal of sediment to the North Sea that has reduced the dredge commitment in the last couple of years. However, it does appear to be evident that if these two changes had not occurred then the maintenance requirement for both the Wedel and HPA area would have continued to increase due to the re-circulation of the sediment, particularly the more sandy fractions. This means that the measures to be implemented by the RESMC must ensure that significant sediment re-circulation is not enhanced by any of the measures undertaken, as the tidal pumping will rapidly exacerbate the problems.

In 2008 the sediment trap at Wedel was implemented, hence increasing the maintenance dredging in 2008 and 2009. Given that little sediment from the Hamburg Port area was taken to Buoy E3 in 2009 and maintenance dredging in the river and harbour basins reduced, this suggests that material was trapped.

Monitoring of the sediment trap (Winterscheid *et al*, 2011) has shown that coarser sediments tend to deposit on the south side and towards either end of the trap, particularly at the up estuary end, where the medium sand fraction is more common. The majority of the sediment depositing within the middle section of the trap is <200µm (i.e. silts and fine sands) of which *circa* 60% is mud (about 30% silt and 30% clay), hence creating a generally cohesive sediment. Sampling of the water column indicates that the coarsest sediment fraction in suspension is between 40 and 60µm (about 5%). This indicates two sedimentation mechanisms are at work in the Wedel trap:

- Sediment deposition from the water column of the fines; and
- Interruption of near bed load transport (bottom 1m) of material above *circa* 63µm, i.e. the medium and fine sand. It should also be noted mud will be mixed in this near bed load movement.

The sampling over time also suggests that the largest proportion of settlement of the finest sediments takes place during the summer months, i.e. when the headwater discharges are normally lowest and temperatures highest.

This information, however, does not indicate whether the material was trapped on the flood, thus preventing it directly reaching the port area, or trapped on the ebb, creating the reduction by reducing the sediment re-circulation. This is important when consideration of the contaminant status of the sediments in the up estuary areas is taken into account. If the cleaner marine sediments are intercepted on the flood, then they will not mix with more contaminated finer sediments up estuary nor increase the volumes of fine and medium silt depositing in the port area that may become contaminated. By reducing the mixing, the total volume of sediment that contains contaminants (predominantly absorbed to the finer silt fractions) to be dealt with should be less and reduce over time. If it is only trapped on the way out, it may have been re-circulated a number of times and become contaminated whilst in the port area.

This analysis suggests from a holistic viewpoint relocation at Neβsand is no longer a good option, particularly as the tidal pumping effect would appear to have been enhanced since around 1998/99 which is a result of a number of changes within the system around that time, not just due to the deepening. The data tends to indicate that from a sediment circulation perspective alone, the dredged material should be relocated down estuary of Brunsbüttel; however many other factors need to be considered, including contamination, nature conservation, economic and social issues.

Dredge Method

Traditionally most of the maintenance dredging on the Elbe has been undertaken by medium sized TSHD, depositing by bottom disposal to the many relocation sites within the estuary. For the most part the material has been moved down estuary but predominantly only as far as the individual administrative jurisdiction boundaries. The dredging has been undertaken mainly under contracts, although some is undertaken by the authority owned dredger.

For the WSA areas maintenance dredging, and therefore relocation, occurs generally throughout the year, with most, by up to a factor of 2 greater, being dredged in the summer months, June to August, compared to the winter (Iwens and Marusic (2007). In the Hamburg area, due to relocation restrictions at Neβsand, dredging and relocation is predominantly confined to the winter months of November to March.

Following the change in relocation strategy for TSHD in 2006, monitoring has indicated that the change was most significant for the finer deposited sediments. The medium and coarser (sandy) sediments formed ripples and dunes on the bed, the peaks of which control the available depth of the channel. The bedforms only move slowly, compared to the rapid movement of the finer sediments in suspension. Also the direction of movement is not constant, being affected by the tidal range and headwater discharge as well as the local bathymetry and sediment characteristics in different sections of the estuary. At times finer sediments have been noted to deposit in the troughs of the dunes. This suggests that movement of the dunes is sporadic, probably only during the highest flows, tidally and/or headwater discharge induced.

From 2007 WID has been used throughout the fairway length and in the port area to reduce the heights of the dunes by cutting the peaks (predominantly medium sand) into the troughs (dune valleys). Whilst the dunes reform over time, this sediment is not transported huge distances, quickly. This, however, does not remove the sandy sediment from the local area and the disturbed sediment (from the WID process) continues to move either up or down estuary at the individual location. The supply of this coarser material is therefore not reduced by the WID, and may later require to be removed from another location by a TSHD and relocated down estuary.

In the outer estuary, where the flows are more ebb dominant WID dredging is likely to be more long term beneficial from a maintenance dredging perspective as the disturbed sediment will be moved down estuary. The most significant benefit of WID dredging is the short term localised maintenance of depths, where TSHD dredging is not efficient. In the up estuary areas the sediment will accumulate in 'sink' areas over longer periods, where it can be removed more efficiently by TSHD vessels. The disadvantage in this practice, is that these 'sinks' at present are predominantly the harbour basin and turning areas, where the 'clean' marine sediments are mixed with contaminated sediments from up estuary, thus creating a greater volume of material containing contaminants that has to be managed and relocated. This sediment transport mechanism therefore supports the need for 'sediment traps' that can create a down estuary 'sink' for the up estuary movement of 'clean' coarser sediments, particularly those that move as bed or near bed load.

The WID method is also used to remove finer, silty sediments from a number of side arms/secondary channels and entrances to tidal barriers, such as the Glückstader and Pagensander Nebenelbe, as well as in some harbour basins in Hamburg. For the most part the WID dredging takes place over the winter period, particularly taking advantage of the normal higher headwater discharges that occur from February to April to maximise the down estuary movement of sediment. Further assessment is being undertaken to see if additional benefit can be achieved by wider use of this method.

6.1.3 Constructions

Whilst capital dredging predominantly changes the low water morphology of the estuary, other anthropogenic activities have had a significant effect on the plan area and volume, both historically as indicated previously, but in particular over the last *circa* 150 years and most significantly over the last 50-60 years. These all affected (and in some cases still affect) the current morphodynamics of the estuary and particularly the sedimentary patterns which give rise to the current concerns for sustainability in the future. The following sections discuss the likely effects of these various forms of construction in order to learn what RESMC measures are likely to be most effective in the future. Figure 8 illustrates the combined effect of all the developments on the tidal range and water levels at St. Pauli in Hamburg.

6.1.3.1 Harbour basins

Between 1870 and the 1930s the predominant change to the morphology of the tidal Elbe was a significant increase in harbour area at Hamburg due to the digging of a substantial number of harbour basins. During this period about 1300ha (hectares) of port related water area was created, giving rise to a considerable increase in both overall estuary volume and localised tidal prism. Based on the fairway depth and approximate tidal range at the time, this would have been an increase in HW volume of around 130 million m^3 of which about 26 million m^3 would have been tidal prism. Figure 8 shows these changes had little effect at HW and LW initially, but when combined with the first significant capital dredge the tidal range increased by the lowering of LW. This indicates the creation of the harbour basins alone did little to affect the tidal propagation; however, they would have increased the flow speeds through the tidal river. Any sediment in the tidal water would have been drawn in to the basins where it would have settled, therefore less sediment being returned on the ebb tide. The basins would have also intercepted sediments from up estuary. These effects would have been enhanced by the first capital deepening, thus enhancing the phenomena known as 'tidal pumping'. The harbour basins therefore became sediment sinks removing sediment from the water column, thus trapping them within the estuary.

6.1.3.2 Estuary 'cut offs', poldering and harbour Infill

After the 1940s, particularly the late 1950s to the mid 1980s a large number of constructions took place within the estuary, along with the fairway deepening. Figure 8 shows the combined effect was a significant increase in tidal range in Hamburg, this time both an increase in level at HW and a decrease at LW. The most significant changes occurred during the period of drainage channel, tributary cut offs and significant reclamation of land from the tidal influence (poldering) along the length of the estuary, including the shortening of the overall tidal length by construction of the Geesthacht weir. At the same time many of the harbour basins were no longer suitable for the larger modern ships, so a continuous period of harbour basin back filling took place particularly up to the early 1990s.

From a morphological perspective these changes predominantly occurred at the higher water levels affecting large areas. This had the effect of considerably reducing the volume/area over which the tide could flow, all along the estuary. The accommodation space for the tide was therefore significantly reduced; both alongside the channel and up estuary of the weir, thus substantially increasing coastal squeeze. At the entrance to the estuary, however these changes only had a minor effect on the tidal range, see Figure 9. This means as the tide progressed up the estuary the same volume of water was being compressed into an ever smaller cross section, particularly towards HW, both increasing flood tide flow speeds and water levels along the estuary.

Dung this period the weir would have changed the resonant length of the estuary, therefore affecting the speed of propagation through reflection of the tidal wave. As further channel deepening occurred the location of the St. Pauli tunnel (because it effectively limited the extent of the deepening) would have increased the reflection of the tidal wave, enhancing the local tidal range. These changes effectively shortened the flood phase of the tide compared to the ebb, particularly in the narrower river section above Brunsbüttel. This was also the section where most of the tidal volume had been removed due to cut offs and poldering, hence flood flows became more dominant, forcing more marine sediment further up river. The removal of this accommodation space would have also increased the concentrations of fine suspended material in the estuary, as it could no longer settle out over the wide intertidal areas. Initially much of this material would have stayed in suspension due to the increased flows. The successive fairway deepening would have reduced the flows over time. However, the increased asymmetry of the tide negated this effect on the flood, without significantly affecting the ebb, giving longer periods below critical sediment threshold flow speeds particularly on the ebb, allowing more settlement of the sediment at the more up estuary locations, hence the increased sedimentation rates within the estuary as a whole.

These changes to the physical processes, along with the maintenance dredge strategy discussed above predominantly explain the change in water levels over time in the estuary and the current sedimentary patterns that give rise to the estuary maintenance dredge commitment, at least up estuary of Brunsbüttel for relatively constant cross sectional areas at the mouth of the estuary. Should the entrance section significantly change, the existing tidal regime will also change, initially within the entrance, but over time would progress up estuary. An increase in the cross section (to flow) is likely to increase the overall tidal energy, which could import more sediment and also promote channel erosion, releasing further sediment for redistribution within the estuary.

6.1.3.3 In channel structures

Over history many in channel structures including training walls and groin fields have been constructed either to stabilise areas of eroding sand banks or to reduce the migration of channels. Of particular note are the groin fields, divisions and training walls constructed in the 1920s and 1930s in the Osteriff area along with the stabilisation of Neufelder Sand. The combined effect was to constrict the main channel in the area where the channel widens from up estuary. The effect would have been to increase the main channel flows, potentially moving the area of sedimentation further down estuary. This area is currently one of high sedimentation of a cyclic pattern as discussed above (Section 6.1.2.2) and this was presumably the case in earlier years, hence the implementation of the structures.

The other main feature of the outer estuary was the construction, and then in later years, the extension of the Kugelbake training wall, which was constructed to stabilise the location of the navigation and 'train' the ebb flows thus increasing the potential scouring capacity of the ebb tide. At the same time it would have partially obstructed sand driven across the intertidal sand flats during significant wave conditions preventing it from settling within the deep navigation channel.

Following the extension in the late 1950s the Gelb (Yellow Sand) and Grosser Vogel Sand (Bird Sand) opposite the training wall began to erode, widening the main channel, at the same time the Mittel Sand and the end of the training wall began to grow. The combined effect was a deflection of the main channel to the north, increasing the curvature of the bend and reducing the size of the sand islands. These effects would not have been due to the training wall alone, but due to the interaction of the longer term morphological changes of the banks and channels, particularly to the north of the channel and the change in flow characteristics as a result of the capital dredging during the same period. It is not possible to isolate the impact of the various structures and dredging on the morphological effects that have resulted.

More recently, modifications to the channel cross section have been made with the aim of constricting the channel to increase flows, thereby reducing the potential for accretion (hence maintenance dredging) at that location. The most notable of this type of channel modification took place in 1999 in conjunction with the last deepening in the main Rhinplatte sedimentation area. Two contained underwater deposition areas were created at Krautsand, up to 250 wide, reducing depths from over 10m below NN to *circa* 5m below NN (see Figure 10), using about 4.5 million m^3 of the capital dredged sand, reducing the HW estuary width by around 15% at this location. This in conjunction with the dredge appears to have increased the 'erosion capacity' preventing the need for maintenance dredging at this location, which for a long period was the main location of settlement of material within the estuary. As noted above, however, in the dredging and disposal discussion, this material would appear to have been re-distributed up estuary, helping to create increase in sedimentation in the Port area since.

Other in channel construction measures that have been tried to reduce sedimentation include a Current Deflector Wall (CDW) at the entrance to the Kohlfleet Harbour Basin. Following construction in the early 1990s it is reported to have reduced sedimentation in that basin by 30-40%, by changing the flow patterns across and in the immediate entrance (Boehlich, 2003).

The effects of some of these devices would appear to have been beneficial, at best for short periods, but not necessarily longer term. A greater understanding of the changes that have resulted, through further chart analysis, monitoring and numerical modelling investigation will be required if similar devices are to be used as part of the RESMC. As the Krautsand underwater storage areas indicate a gain/benefit in one area, this could lead to a dis-benefit in another area of the estuary in the future, which could be of greater consequence. This is the reason why specific design analysis and numerical modelling investigation are required before particular RESMC measures are implemented to ensure the goal of sustainability in the future for the estuary as a whole is likely to be achieved.

6.1.3.4 Conclusions

The conceptual understanding of the past historical anthropogenic constructions indicates the criteria that the future RESMC measures need to take into account to provide maximum benefit from their introduction to achieve the ultimate 'goals':

- There is a need to provide new accommodation space within the tidal Elbe, predominantly above Brunsbüttel. To be most effective at reducing HW levels these must increase the tidal prism of the estuary. Increased volume below LW will increase the efficiency of 'trapping' of sediment that is transported in suspension up estuary, but is unlikely to contribute significantly to the lowering of HW levels. Sediment accumulating in the new areas will not reach the Hamburg Harbour areas to mix with the contaminated sediment from up river, therefore over time reduces the amount of contaminated maintenance dredged sediment that will require to be managed;

- Provision of new accommodation space above Hamburg, e.g. reinstating cut offs or providing increased water areas/volumes to the tide, will reduce HW levels and raise LW levels. However, to fill the additional flood tidal prism more sediment laden flow from down estuary will be 'drawn' through the deep relatively slack water areas of the harbour basins, increasing sedimentation potential in the Port, hence an increased potential maintenance dredge commitment. It should be noted, however that this conclusion is simplistic, being based on the assumption that the change in the tidal dynamics does not change the suspended sediment concentrations, bed load transport and rates of settlement down estuary. These effects will need to be specifically modelled to provide greater certainty of the effect on sedimentation patterns. Care should be taken in interpreting the results of sediment transport modelling for the reasons indicated by Roelvink (2011), particularly as the existing models do not entirely re-create the current sedimentation patterns in all areas of the estuary despite good hydrodynamic calibration;

- Large areas, dredged to the full depth of the tidal range will be required for relatively small reductions in the HW levels at all locations;

- LW levels are not likely to be significantly changed by increasing the accommodation space down estuary of Hamburg, but the greater proportional effect on the 'passing' discharge for an area up river of Hamburg would have a greater impact, but only locally;

- Areas can be created to form intertidal habitat, to partially re-instate areas lost to past anthropogenic changes in the estuary, if managed realignments are used into agricultural areas. Removal of intertidal or marsh areas within the existing river walls e.g. reinstating cut offs will remove intertidal habitat, creating subtidal habitat, whereas use of agricultural land will create new estuary habitat, which may also serve as a compensation function for effects on nature conservation effects;

- Water volume enhancement areas could also be designed as sediment traps to aid maintenance dredging efficiency elsewhere;

- In channel structures can directly change the morphological cross section changing the local flow dynamics. This has been shown, in conjunction with other changes to the forcing processes at the same time, to have a significant impact on sedimentation rates at certain locations. However such changes can lead to dis-benefits elsewhere in the estuary, which over the longer term may be of greater consequence;

- Any proposed RESMC measures therefore require detailed analysis using numerical models, monitored data and a conceptual understanding of the estuary to estimate the short term effects and any longer term consequences of the individual measures as a whole and in combination, particularly when considering sustainability in the future; and

- Any measures should be designed so they can be adapted in the future should monitoring or unforeseen changes in the forcing processes occur, i.e. allowing the process of adaptive management over time.

6.2 Conceptual Understanding of Estuary Processes

6.2.1 Morphological Change

Figure 11 shows the changing cross sectional area (CSA) to the flow along the estuary for the period 1975-1988. This graph shows several features:

- An area of constant CSA between approximately Brunsbüttel and Glückstadt. This is also the general area of the sediment turbidity maxima, over time;

- Up estuary of Glückstadt (approx. Km 676) the CSA reduces at a constant rate through to the Port area at Hamburg. There is evidence of the capital dredge, shown by the constant change in CSA between the 1975 and 1980 lines in this area, however there is no further change up to 1988, suggesting the dredge had no effect on the morphological stability of the channel, and any accretion that occurred was removed by maintenance dredging;

- The largest change in CSA occurs seaward of about Km 708 near to Cuxhaven, where the constricted tidal Elbe starts to 'fan out' into the funnel shaped entrance (see Figure 1). In this area the CSA significantly increased throughout this analysis period with the maximum erosion of the overall section occurring around Km 718 in the area the Medemgrund sandbank and Medemrine channel. Figure 12 indicates that this area of the estuary has continued to change in its morphological characteristics since 1988.

6.2.2 Tidal Propagation

Over time, due to the anthropogenic interventions, as well as natural morphological changes, variation in the location of the controlling amphidromic point, Sea Level Rise (SLR) and the change in weather patterns, the propagation of the tide through the Elbe tidal river has changed. This is particularly noticeable in the main constricted section above Km 676 around Glückstadt. Figure 13 shows the present day average HW and LW levels along the estuary. At Cuxhaven the mean tidal range is approximately 3m and then reduces by about 0.25m at Glückstadt, predominantly due to an increase in the LW level. Up estuary the tidal range continues to rise, both by increased HW levels and reduced LW. The rate of change of increase in both the HW and LW trends accelerates up estuary of Hetlingen. At St. Pauli in Hamburg the tidal range is currently about 3.6m, with HW levels over 0.5m higher than at Glückstadt and LW levels about 0.4m lower. The effect of this tidal propagation on the shape of the tidal curve is shown in Figure 14. This indicates that there is no significant change in the asymmetry of the tide until after Brunsbüttel and thereafter most of the change occurs at the higher water levels. Throughout this sector there are locations where the cross section of the main channel significantly narrows and as noted previously is the main area in which the higher elevation accommodation space has been removed from the estuary.

As discussed in Section 6.1.3 the various anthropogenic changes have together combined to increase the enhancement of tidal range along the estuary over time. Figure 9 shows a comparison of the development of mean HW, LW water and tidal range since 1980 at Cuxhaven and St Pauli (Hamburg) (from Boehlich and Strotmann, 2008). This clearly shows that the tidal range has not changed at Cuxhaven, whilst the large increase has occurred at St Pauli. Both HW and LW have increased at about the same rate, suggesting a steady increase in mean sea level of about 0.3m in 130 years, a rate of 2.3mm/year which is similar to the on-going rates of SLR. This point is important in understanding the morphological and sedimentary patterns within the estuary over time. Firstly it indicates that, providing the entrance cross section has not changed the same amount of water enters and leaves the estuary through the mouth. This would mean that if the offshore sediment supply was constant then there would be no difference in the amount of sediment entering the tidal Elbe. Any increase in sediment would therefore be due to increased sediment transport within the German Bight, possibly from on-going erosion of the sandbanks and mudflats, which would be significantly influenced by both wave and tidal processes.

Eichweber and Lange (1998) have analysed the tidal sub-harmonics throughout the estuary and conclude that the developments over time have changed the tidal regime from one that formerly dissipated total energy to one where the energy is enhanced by reflection, thus causing the increase in tidal amplitude noted above, particularly near the point of reflectance. This is located at the St. Pauli tunnel which was constructed at the turn of the 20th century and since then has controlled the up estuary extent of channel deepening. As further capital dredging occurred the reflection of tidal energy increased, without changing the estuary length. This has changed the magnitude of resonance within the system, hence the tidal range.

Analysis of the tidal sub-harmonics has identified an association between the locations where maintenance dredging is required, which has not changed significantly over time. These locations are shown in Figure 1, where it can be seen that they correspond approximately to the present day minimum depth locations in the channel. This analysis only explains that the locations of maintenance dredging are in the long term due to the reflection of the tidal wave, which has not been changed by successive capital dredges or other anthropogenic activities. The magnitude of the effect on the flow regime caused by the developments has, however, affected the magnitude of maintenance dredging required at the different locations along the estuary. Changes in local cross section, particularly at the long term maintenance dredge areas, are therefore likely to significantly affect the volumes of sedimentation or erosion potential. This would appear to be the case for the underwater storage structure at Krautsand, constructed in conjunction with the last channel deepening. However, because the tidal resonance has not changed, any reduction in sedimentation in one area is likely to provide a greater supply to one of the other long term sedimentation areas. The direction of the transport of this material will be determined by the sediment characteristics, the magnitude of the flow speed and the time that they exceed the thresholds of movement for those material types.

These processes can be affected by man made modifications to the cross sections at individual locations. However, because these effects will most likely re-distribute sediment rather then remove it from the system, such changes are likely to benefit one location but adverse effects could be introduced elsewhere.

Any RESMC measures should therefore take account of the existing locations of maintenance dredging and be investigated using numerical modelling to determine the likelihood and magnitude of any adverse effects elsewhere within the system as a whole.

6.2.3 Salinity

The salinity in the tidal Elbe covers the full range from freshwater to 32PSU (practical salinity units), typical of coastal areas, however concentrations above about 5PSU do not penetrate on average above about Glückstadt with freshwater conditions occurring around Km 660 at HW and Km 680 at LW. These average conditions are however significantly influenced by the headwater discharges and North Sea surge events. Under high flow conditions the intrusion extent is suppressed, whilst under surge conditions salinity is increased. Modelling has shown that as the fairway has deepened, the extent of saline intrusion has increased (Sohrmann and Weilbeer, 2006).

This information indicates that the majority of influence of salinity on the sedimentary effects in the estuary will be predominantly down estuary of Glückstadt where it will influence the amount of sediment moved into the estuary near the bed of the main channel. Deepening the channel therefore is likely to increase the supply of sediment in the outer estuary due to the change in salinity intrusion.

6.2.4 Headwater Discharge

The tidal processes in the Elbe are significantly influenced by the rate of headwater discharge passing down estuary over Geesthact weir. These are highly variable throughout the year ranging from around $200m^3/s$ to around $2,000m^3/s$ and show a regular 'seasonal' pattern in a 'normal' year. The highest discharges are usually between late February and early May, with rates generally below $500m^3/s$ from June through to February, although any individual month could have considerably higher temporary flows.

Sedimentation rates, recorded at the Wedel sediment trap, indicate that accretion dominates in the trap when headwater discharges at Neu Darchau are less than about $500m^3/s$, with rates in excess of about $100,000m^3$ per week, whereas discharges in excess of $1,000m^3/s$ generally give rise to transport over the trap, with erosion occurring when discharges are in excess of $1,500m^3/s$.

Any RESMC measure should therefore be designed to take account of the normal flow regime, as has been the case, where possible for dredging of the Harbour Basins and relocating to the Neβsand area since 1994.

6.2.5 Sediments

A large number of sediment samples have been analysed along the Elbe Estuary, particularly in 2004/5. A selection at uniform intervals along the estuary, both from areas where sedimentation occurs and deeper areas are shown in Figure 15, for the locations shown in Figure 1. These show that within the main channel the majority of the bed material is fine and medium sand; with the finest material in the shallower areas adjacent to the channel. The D60 (particle size) in these shallow areas is generally below 200 microns, whereas within the deep channel the characteristic size (D60) in the mouth area is in the range 200-400 microns. In the narrower section the sediment generally coarsen up estuary between approximately Km 700 to Km 650 with the D60 commonly between 400 and 500 microns beyond the latter location. Coarser sediments are found at either end of Pagensand Island. Figure 16, shows that within the main Port areas the sediments are considerably finer, comprising of 42-58% clay particles with D60 values in the range 65-95 microns.

This distribution clearly indicates the generally fast flow regime within the Elbe that creates almost permanent suspension of the fine silt and mud sediments in the main channel, which can only settle out in the tidal basins and side arms of the estuary. This gives rise to permanently high suspended sediment concentrations. The material in the sandbanks at the entrance is finer than the main channel and it would appear that it is this material that, once eroded, provides the main source of material that is ‘pumped' through the estuary. If this hypothesis is true then sedimentation along the channel will be greatest when significant morphological change occurs at the mouth of the estuary. This material is coarse enough not to be almost permanently in suspension under the Elbe flow regime, but is close to the flow induced thresholds for movement; therefore will be transported on some tides but not others, giving rise to differential amounts of movement at different locations along the estuary. Since, for the most part, the higher flow speeds occur on the flood tide then this material will be transported in stages in an up estuary direction, becoming trapped for periods of time in certain areas, (those prone to sedimentation). Because the sediment size is near the flow induced threshold of motion, even very small changes in flow speed will cause a significant change in the sediment erosion, accretion and transport of this material along the main channel. The most significant proportion of material is likely to move as near bed load, which would give rise to the frequent dune bedform features which are prevalent along the tidal channel.

The tidal Elbe has a turbidity maximum, predominantly in the area between Brunsbüttel and Glückstadt, the centroid of which moves over a range of about 10km depending on the headwater discharge of the river, with the suspended sediment concentrations ranging from 350-600 microns for different tide and flow conditions.

This distribution of sediments and the mechanisms of transport suggest that RESMC measures which modify the general flow regime, even only marginally, can significantly influence where and particularly the rate of sand accretion along the channel, but are unlikely to affect the transport of the fine silts and muds that form the bulk of the material that settles within the shallower side arms and the Hamburg Port Harbour Basins. Unless the mud material, can be stopped from entering the tidal Elbe from either up river or the German Bight then the only way sedimentation in the Harbour Basins can be reduced is to ‘trap’ the material in large settlement areas both up and down estuary where it can be managed in a more economic manner.

6.2.6 Flow Speeds and Sediment Dynamics

During the last decade two dimensional (2D) and three dimensional (3D) numerical models have been used to study the flow and sediment patterns within the estuary for a range of recent bathymetries. Figure 17, shows the ratio of flood:ebb maximum flow at each cross section along the estuary, the flood and ebb excursion distances and the flood:ebb excursion ratio from the numerical modelling. This diagram indicates that for the 2002 bathymetry flow speeds on all range tides are flood dominant from around Km 670 around Glückstadt, up to Km 620 within the Hamburg Port area. Down estuary of the Storh tributary (around Km 680) maximum flow speeds are generally slightly ebb dominant for mean and neap range tides, however are still flood dominant for the largest ranges, particularly around Km 705, just as the narrow tidal Elbe begins to widen. The ebb excursion distance, based on the average cross section flows is ebb dominant, as would be expected due to the headwater discharge. Also, for a location in the Neβsand area the flood excursion distance is about 5km less than the ebb excursion. This indicates that provided flow speeds are high enough to keep sediments in suspension then these sediments will be transported down estuary, despite the flood speed dominance, due to the longer ebb period. This information is summarised on Figure 1.

Figure 18 (from Sohrmann and Weilbeer, 2006) shows how the mean flood and ebb mid fairway flow speeds have changed from 1970 to 1997 and then to 2002, spanning the period of the last two capital dredges. These plots show that the combined effect of all changes to the estuary would have successively increased flow speeds within the main channel on both the flood and ebb, particularly in the narrow tidal river section down estuary of Hamburg. Boehlich and Strotmann, 2008 present the change in the maximum flow speeds between 1970 and 2002. These show a more significant change than can be seen from the mean flows, which suggest the greatest differences occur for the spring tide range. These results showed that maximum flow speeds in the channel increase significantly in a down estuary direction on the ebb, from around 0.8m/s in Hamburg to 1.7m/s at Cuxhaven. Furthermore, the modelling showed negligible difference between the 1970 and 2002 situations for ebb flows.

The change in ratio of flood:ebb flows in favour of flood dominance within the main channel are only marginally evident up estuary of Km 660 in the area of Pagensand South.

In general, however, the increased flood flow speeds enable a greater sediment transport capacity in an upriver direction, thus given the same supply from down estuary, more will settle out in the low flow areas of the tidal basins, hence the need for more maintenance dredging. This modelling corroborates the hypothesis presented in Section 6.1.2.2 that the relocation of sediment at Neβsand will have increased the sediment supply thus creating a sediment re-circulation cell, which was enhanced in magnitude due to the 1999/2000 dredge. Of most significance, however, is the change in location of the main sedimentation zone from Rhinplatte up estuary and the initial relocation of a large amount of the deposited material to the Pagensand area and up estuary where the flood dominance was enhanced, hence adding further supply to re-circulate back to the Port area, giving rise to the large increase in sedimentation from 2000 up to 2005.

On the flood tide however, peak flows were increased of the order of 0.2m/s (*circa* 20%) between 1970 and 2002, particularly through the tidal river section, where peak speeds were relatively constant at around 1.3m/s (± 0.1m/s). The greatest change occurred between Kms 650 and 680. In the main channel adjacent to the Harbour Basins this modelling indicated that for the 2002 bathymetry maximum flood flows were around 1.4m/s, whilst equivalent ebb flows were about 0.8m/s. For the 1970 bathymetry the equivalent data were about 1.2m/s flood and 0.85m/s ebb. Also, in terms of peak flows, flood dominance started around Km 665 in 1970 whereas for 2002 flood dominance started further seaward at around Km 710. This latter location is in the area where significant changes to the entrance bank and channel morphology had taken place between the two years, outside the confines of the navigation channel.

The previous analysis of flow speeds concentrates on average and single point (in the tide) information. Figure 19 presents time series data for different locations at varying depths within the same section of the River as an illustration of local differences that can affect the movement of sediment, particularly from a dredge material relocation. The top pane shows the flow speeds within the Hetlingen relocation areas, within the shallower areas along the north side of the channel. The bottom pane shows the time series for the same period within the centre of the channel, see Figure 20 for locations. Within the relocation areas the flow speeds are flood dominant with the peak 0.2m/s greater than on the ebb. Also the modelled flood suspended sediment concentrations (SSC) through the site are higher. The area under the curve represents the excursion distance which is also greater on the flood. Any sediment deposited at these locations at the edge of the channel would therefore have a net up estuary movement for material in suspension back towards Wedel and Hamburg Port.

At Position 18, within the centre of the channel the time series indicates no flow speed dominance and a greater ebb excursion distance (than for the flood). Flood tide SSC is again higher, reflecting the sedimentation occurring up estuary. This indicates that relocation in the centre of the channel would have moved more sediment down estuary, reducing re-circulation, compared to using the adjacent relocation areas. This process would have been even more effective if the dredged material was released into the water column, slowly, nearer to the surface, rather than from vessel bottom discharge.

This example serves to show how modelling data can help to develop a specific dredge material relocation strategy/methodology and define or study any proposed relocation area.

Figure 21 illustrates the processes occurring in the Hamburg Harbour area, within the areas where most maintenance dredging is required. Position 24 is in the Kohlfleet where the flow modelling indicates it acts as a sediment trap. Positions 21-23 reflect the flow filling the basins, reducing the flood flows and removing sediment from the water column in the up estuary direction of the main channel. Ebb tide SSCs are low, reflecting settlement during slack water and insufficient flow to re-suspend the recently deposited material hence the accumulations that need to be dredged.

Figure 1 summarises some of the main points made during the discussion of the estuary processes at work that will need consideration when evaluating or designing specific RESMC measures.

6.3 Scope of RESMC Strategy

The main goals of the RESMC strategy are to reduce the maintenance dredging, reduce HW levels in the estuary thus reducing flood risk, increasing LW levels thus aiding navigation, and reducing contamination within the estuary in a sustainable manner whilst complying with national and international legislation. The measures proposed generally fall into two categories:

- River Engineering; and
- Dredge strategy/methods.

6.3.1 River Engineering Measures

The proposed river engineering measures can be broadly divided into two types:

- Works to create increased estuary volume, predominantly tidal prism at various locations along the estuary, which can be provided in two ways:
  - Excavation of channel side areas, thus removing intertidal from within the existing river walls; or
  - Setting back the existing flood defences to allow tidal flooding of former poldered or protected low lying land, which is now predominantly used for agriculture. In the UK this has been called Managed Realignment;

- Creation of structures within the river, with the aim of directly changing the cross section at specific locations, thus influencing the flow regime. This can be undertaken to:
  - Promote an increase in local flows to either reduce sedimentation or promote local erosion;
  - Create sediment settling areas by either or both providing greater cross section area by increasing width and/or depth over a sufficient area to create settlement areas, i.e. sediment traps; and
  - To specifically divert flows by the construction of training walls to influence the morphological development of the estuary.

From the historical analysis of change that has occurred in the estuary and the conceptual understanding of the system as a whole, all the types of measures will have some degree of success locally, however, most will have a ‘knock on' effect elsewhere. There is therefore a need for careful design around clearly defined specific objectives that should be examined for local effectiveness using detailed numerical modelling. In addition, more widespread modelling to investigate the ‘knock on' and longer term effects should be undertaken. As a number of individual measures are proposed the combined effects should also be investigated on an estuary-wide basis, as a large degree of interaction is likely.

6.3.1.1 In channel constructions

From the previous understanding, in channel constructions which affect the cross section and estuary volume will need to be sediment containment structures to ensure that they will not be eroded in the long term therefore negating the initial effect. Also, quite large works will be required to make relatively small changes to the flow regime, however, as the Krautsand works seem to show, if located correctly they can have a large effect on the sediment regime. It is likely, however, that such measures will not necessarily reduce the amount of maintenance dredging that is required on the estuary as whole, but will change the location where it is likely to occur, thus a benefit in one area, could give rise to a problem or increase an existing problem elsewhere. Such a measure is therefore likely to be locally effective but not necessarily holistically, unless combined with measures that can remove any sediment that is displaced or the settlement of the material occurs in deep areas that do not affect navigation i.e. sediment trapping.

With respect to the estuary as whole the RESMC in channel construction measures are likely to require to be combined with up estuary sediment trapping measures. The reason for this is the predominant flood flow dominance, particularly the higher speeds, which is the primary cause of the tidal pumping, which has increased significantly over the last *circa* 50 years, due to natural changes but predominantly anthropogenic interventions and unless measures are put in place is likely to increase in the future as greater demands are required of the waterway. The type of trapping measure will depend on the material type that is likely to be moved. If the material is fine to medium sand or fines are known to move near bed, then both vertical (in bed traps), such as Wedel, would be appropriate, however for finer sediments, predominantly in suspension high in the water column, then horizontal volume areas will be required.

Consideration will need to be given to the overall cost effectiveness of in channel structures with respect to the relative costs and environmental implications of removing the sediment by maintenance dredging from a different location within the estuary. Such devices will therefore have an impact on any dredge management strategy. Since one of the main aims is to reduce marine sediments reaching Hamburg to mix with the contaminated sediments, in estuary construction devices may not be appropriate, particularly in the flood dominant zone above Glückstadt.

In the mouth of the estuary just downstream of the narrow section significant morphological change has occurred in recent years which has increased the overall cross sectional area and changed the configuration of the banks and channels. This must have released a significant volume of material. The area is generally ebb dominant, therefore it is likely that most sand material will have been moved locally or seawards in the main channel. The suspension of any fine silt and clay material will have had a greater potential to move up the estuary particularly on spring tides, thus increasing the supply of fines within the tidal Elbe. Also as the cross section has increased it gives rise to the potential for increased wave and tidal energy moving up estuary, therefore, increasing tidal pumping.

Underwater construction measures, incorporating sediment retention designs for dredged material could be considered to reduce the estuary cross section and stabilise the channels. The effect of such devices in the long term will need to be carefully studied, particularly in a morphodynamic area. Similar ideas in the past were put in place (by use of training walls) on the River Wyre in the UK. These were effective for a few years; they were then ‘bi-passed’ by a change to the meander pattern of the channel, eventually creating a worse channel configuration than had originally been the case.

Any such measures would therefore require careful future monitoring and designed with the various legislative consents in place in order to carry out adaptive management based on the analysis of the monitoring. Where such morphological changes are large, relative to the amounts of maintenance dredging required for navigation purposes it may not be sensible to remove the dredged material from the local system as this could change the mechanisms at work, creating a worse effect in the future i.e. developing a long term disbenefit (which may not be sustainable) for a short term gain. This is also unlikely to be just in terms of dredging, but also nature conservation interests of the area (e.g. birds and fish etc).

6.3.1.2 Measures to increase tidal volume

More than 20 different locations have been considered in the RESMC with the intention of increasing the volume of the estuary in which the tidal wave progresses. It is clear from the historical analysis that this will have some benefit, reducing HW levels, therefore reducing flood risk and increasing LW levels, particularly within the Hamburg area. However, the proportional effects along the estuary need to be considered in combination with their potential to change the estuary flow and sedimentation patterns (hence dredging), which is of equal importance for the RESMC.

The majority of the proposals are for locations within a relatively small area up estuary of the main Hamburg Port area. The rest are spread on both sides of the river between Brunsbüttel and Wedel. The individual locations being considered are shown schematically on Figure 22. The aim of the individual works is either:

- To redesign the Elbe side arms, to re-create active secondary channels in order to both dissipate the tidal energy, which has been enhanced by the past coastal squeeze particularly in the main channel, thus reducing the effect of tidal pumping further up estuary; or

- Create tidal storage areas, thus increasing the local tidal prism, by removing silted up and overgrown tidal flats, or dredging of silted up Harbour Basins. The idea is to allow these to develop their own equilibrium over time rather than continual maintenance. At present large scale Managed Realignments into agricultural land are not generally being proposed.

Numerical modelling of some of the locations has been undertaken up estuary of Hamburg. These show that re-creating large areas of tidal volume benefits water levels, particularly locally. This was in an area where the new storage area/volume was relatively large with respect to the local river volume. To provide similar magnitude benefits at down estuary locations, evidence from elsewhere, see Section 7 suggests very large areas and volumes will be required.

For the locations up estuary of Hamburg it should be noted that that the volume of water to fill and drain the new areas, will have to be 'drawn' through the Hamburg Port area. As these locations will not remove any sediment from the system a greater supply of sediment in suspension may be supplied to the existing 'sediment traps' of the Harbour Basins. This assumes that the changes to the tidal dynamics do not reduce the sediment load, predominantly in the water column, reaching the Harbour Basins. It is possible therefore that these measures could enhance the existing sedimentation rates (assuming all other practices remain the same). Whilst water levels would benefit the maintenance dredging 'goal' may not. Should this be the case, more sediment would mix with the contaminated material from up estuary, thus more material containing contaminants would need to be managed.

The maintenance dredge 'goal' would benefit if the change to the tidal propagation, associated hydrodynamics and sedimentary effects reduce the supply of sediment reaching Hamburg. This, however, is uncertain and carefully analysed numerical modelling would be required of each proposed measure (or combination of measures) to ascertain a suitable level of certainty of the effects.

Creating the additional tidal prism/storage down estuary, may not have as large effect (pro rata the area) on water levels, but with connections to the main river and careful shaping of the areas, they could be designed as sediment traps at the same time. In this case the supply of sediment to be moved up estuary will be decreased along with tidal energy, potentially reducing the tidal pumping effect, by reducing channel flow speeds on the flood. Any material retained below Hamburg will not mix to become contaminated and the supply to the Port areas will be reduced, reducing maintenance dredging in those areas. To maintain their effectiveness over time, periodic maintenance of the storage areas would be required. However, as this would not be navigation critical it could be carried out in a manner which would be optimum in cost and ecological terms rather than a necessity at a certain times to maintain safe navigation.

Cleaning out the Harbour Basins would provide increased tidal prism thus reducing tidal range and marginally reducing flood risk in the city of Hamburg, but would have the same effects on sedimentation as the proposed locations up estuary. Overall, this is likely to provide least benefit as many of these basins would be filled with highly contaminated material that would have to be managed alongside the current maintenance volumes, and then they would provide additional sedimentation areas, so the benefit gained reduces over time. Also, compared to areas further up estuary, there is no possibility of trapping any contaminated sediment from up river before it reaches the Port, nor can the area be used for habitat creation for nature interest or have an amenity value.

It is suggested a better policy (albeit in contrast to current thinking) in this area would be to close off, by engineering, any basins that are not likely to be used for modern shipping patterns and then infill with contaminated sediments from the larger basins that may be used in the future and then seal, effectively reclaiming the land. This would reduce the amount of contaminated material to be managed/disposed, reduces the overall tidal volume created, and therefore less material is drawn into the port area for future settlement then dredging in all Harbour Basins.

This analysis suggests that whilst all possible 'flood storage' type measures will give some reduction in water levels, those further up estuary will have the greatest effect (pro rata the area/volume). Those down estuary provide significant additional potential benefits with respect to the other RESMC 'goals'. The least overall benefit would arise from the removal of sediment from all silted up basins.

6.3.2 Dredge Methodology

The current dredging practice on the Elbe involves:

- The use of medium size TSHDs at areas of sedimentation along the channel and within the Hamburg Harbour Basins, relocating the sediment by vessel bottom disposal to a number of locations, predominantly at the shallower areas alongside the Elbe navigation channel;
- Water Injection Dredging (WID) along the length of the channel to 'level off' the crest of dune bed forms into the troughs thus improving the navigation depths. WID is also used to clear access to a number of navigable side arms and from time to time the Harbour Basins; and
- Removal of sand, for building purposes and contaminated material from the basins for treatment on land by TSHD and mechanical methods, which will continue in the near future.

6.3.2.1 Trailer suction hopper dredging

Wedel and the Port of Hamburg

The practice of relocation of sediment back to the 'free' tidal system, particularly in the Hamburg area has only been prevalent since about the mid 1990s and slightly earlier for the main channel. Prior to this, the material was either removed out of the system, or used within, creating islands in the channel to modify the watercourse.

Before the last capital dredge (1999/2000) the relocation sites were placed, predominantly within the various jurisdictional areas with consideration of the working of the tidal Elbe system, not being the main objective. In most cases the locations were at economically expedient locations relative to the dredge to sites.

More recent understanding of the processes at work in the system have clearly identified that the tidal Elbe has become ever more flood dominant for peak flows as a result of the many anthropogenic modifications to the system. This has increased the potential for the tidal pumping of sediment through the estuary, which has helped change the magnitude of the amounts and type of material needing to be dredged.

As the conceptual understanding has identified, the combined effect of the last capital dredge and associated in channel constructions caused a considerable change in the locations where the maximum rates of sedimentation occurred, predominantly moving more material further up estuary. This resulted in greater use of the more up estuary deposit locations, which are in the flood dominant section of the estuary. It is clear that this combination of changes significantly increased the re-circulation of sediment within the Hamburg and Wedel areas in which the relocation strategy perpetuated the re-circulation, creating the rapid increase in the maintenance dredge commitment in these areas. Previously when a large amount of maintenance dredging was required at Rhinplatte much of the material was relocated to Störbogen, in an area where there was potential for a proportion of the material to be moved down estuary. This helped reduce the re-circulation, hence the overall supply to the more upstream and more flood dominant locations.

In 2006 the relocation strategy within the WSA Hamburg area, in particular, was changed, relocating the Wedel deposits down estuary to around Km 700 at Brunsbüttel. Modelling has shown this is near to the transition from ebb to flood dominance within the estuary, whereby some of the sediment will be moved down estuary and a proportion of that which moves back would be re-deposited at more down estuary locations, therefore less returned to the Wedel and Hamburg areas. This therefore helped reduce the re-circulation of the sediment within the Hamburg area. In addition, since 2005 sediment has also been removed to Buoy E3 outside the estuary, again breaking the cycle for re-circulation. These changes have therefore combined to reduce the maintenance dredging commitment.

It is clear that relocation to Neβsand contributes to the maintenance requirement within the Port of Hamburg; however the primary cause of the significant increase between 2000 and 2005 was the increase in flood dominance, particularly of peak flows along with the increased relocation of sediment to the enhanced flood dominant area between Glückstadt and Wedel.

This analysis suggests that to minimise sedimentation within the channel and Port areas in particular, relocation of sediment should be within the ebb dominated part of the system, particularly with respect to the highest flows, preferably during ebb tides at times of greatest headwater discharges. The current modelling suggests that even relocation to Km 689/690 will cause some up estuary re-circulation depending on the headwater discharge at the time of relocation, particularly when it is low. Also this is up estuary of the entrance to the Kiel Canal. Material that moves on the ebb from here is likely to add to the supply with potential for increase in the sedimentation at the entrance to the Canal. From a processes perspective a better location down estuary for a sediment deposit would be around Km 700, however detailed analysis of the local flow patterns and bathymetry would be required to optimise the dredge strategy. At all relocation sites, if practically feasible, the optimum relocation strategy from any proposed site in this area would be to deposit the sediment at times of highest headwater discharges (e.g. February to April and on ebb tides. This is where the timing benefits of dredging from sediment traps can be used to develop an optimum strategy. Any strategy, however, must be able to accommodate unforeseen events that cannot wait a specific timing window.

The above assessment has not considered the economics, dredge practicality, hydrodynamic and sediment process effects or environmental (nature conservation and sediment balance) issues. Relocation to the area of Km 700, for example, would involve a dredge cycle time (excavate, transport, deposit and return) of the order of 8-10 hours for a TSHD from the Hamburg Basins, without any navigational restrictions. Also the majority of material to be dredged from these areas would be fine silt and clay, which would have a relatively low density within the dredge hopper, as 'bulking' of the cargo would be difficult. Any attempt to bulk the load would most likely result in a significant increase in suspended sediment concentrations within the water column. This would have 'knock on' effects such as de-oxygenation of the water during the dredge as well as reducing the density of the material to be dredged, thus intensifying the problem. These effects would be reduced and the efficiency maximised by the use of a larger TSHD. Whilst the channel depths would be suitable for the operation of such large dredgers, depths at the most appropriate deposit locations may not. The optimum dredge methodology is therefore influenced by the existing deposit ground bathymetry or new locations will have to be designated at deeper depths.

This indicates that whilst such a strategy is likely to help break the re-circulation of sediment arising from the relocation activity, the cost effectiveness will need to be considered. Using larger dredgers relocating to the ebb dominant areas of the estuary will not eliminate sediment being 'pumped' up the estuary, all it does is reduce the potential re-circulation. Maintenance dredging will therefore always be required in the Port of Hamburg. This will also be greater than the pre Neβsand relocation volumes due to the enhancement in 'tidal pumping' unless other RESMC measures are also put in place to reduce the effect and to trap the fine sediment down estuary.

These considerations therefore indicate detailed cost benefit analysis of the combined effect of the RESMC measures needs to be undertaken, taking environmental and contamination issues into account, both in the short and long term. It is possible the optimum solution will be a compromise where some sediment re-circulation will take place (thus increasing the volume dredged above the minimum) to maximise the dredge efficiency, both practically and from an overall cost perspective. This analysis will need to take into account the various environmental considerations in different sections of the estuary. Similar compromises are part of the relocation strategy for maintenance dredge material that operates in the Humber Estuary, UK.

Elbe Entrance

In the entrance area of the Elbe, the maintenance dredging in recent years has been influenced by morphological change to the bank and channel configuration; therefore maintenance locations/volumes are likely to be highly variable over time. Removal of the maintenance dredged sand from the area as a whole is unlikely to have a significant effect on the morphological patterns that will be predictable. Also it would increase the overall cross section, therefore increase the potential tidal energy, up estuary, which could increase the overall tidal pumping effect. The most economic strategy is therefore likely to involve dredging and relocating locally with the aim of 'blocking' developing channels, or using the material to divert flows to maintain the maximum flow speeds in the channel, to increase transport and erosion to reduce sedimentation.

Such a strategy will require flexibility from a legislation perspective in order to place material in different areas as the morphology of the estuary changes. The relocation areas will need to adapt, based on monitoring results both of the maintenance dredge requirements in the channel and careful analysis of the changing morphological trends. Detailed numerical modelling may be able to be used to determine the most effective relocation sites for particular morphological patterns. In such a strategy any relocated material will be 'sacrificial' as it will be moved around and an unknown proportion will be re-circulated within the system. This strategy maintains the sediment within the local morphological system. Complete removal would affect the overall sediment balance, potentially increasing local energy which could increase the general erosion properties of the estuary mouth. Whilst this may not affect the main navigation channel, the local consequences would be unknown, but would most likely enhance up estuary sediment transport, particularly of the finer sediments. This would therefore increase the sediment supply to the 'tidal pump'.

In the mouth area the optimum strategy would appear to be one of adaptive management, minimising the distance between the dredge and relocation areas to maximise the dredging efficiency. However, because it is likely that relocation would be needed to significantly varying depths, the economies of scale of using a large TSHD would not be possible, with most work being undertaken by smaller vessels. This is another reason why transport distances should be minimised.

6.3.2.2 Water injection dredging

In the most recent years greater use has been made of WID, particularly for levelling channel bedforms, which the tidal dynamics then re-form. This method does not relocate significant volumes of sediment within the estuary and does not reduce the local supply of material, predominantly moving near to the bed. Up estuary of Brunsbüttel the flood dominance, particularly of peak flows tends to move fine sandy material up estuary but coarser sand that forms the ripples is relatively stable, only moving up estuary very slowly at certain locations above Km 665. Use of WID therefore has short term benefits to navigation at reduced costs, however, in the longer term the material may move both up and down estuary, where eventually it will deposit in less dynamic areas where bedforms do not occur and then will possibly be required to be removed by conventional dredging. These areas will either be in sediment traps, existing sedimentation areas or the Port Harbour Basins. Thus in the longer term the material will eventually have to be relocated by TSHD dredging. WID dredging is unlikely to significantly effect the transport of the finest sediments in suspension, which is the dominant material dredged from the Hamburg Harbour Basins.

The main advantage of WID is its short term cost effectiveness, without reducing the long term need to remove the sediment from up estuary locations. It does, however, mean that TSHD of the sediment is likely to be able to be undertaken more efficiently from a sediment trap location at a time that is most economically and ecologically advantageous, rather than necessary due to minimum depths within the navigation channel. An additional benefit is that the rippled bed is predominantly maintained, therefore has a positive effect by helping reduce the tidal energy that leads to tidal pumping. Also monitoring also suggests that under certain flow conditions the ripple and dune structures can capture finer sediments in the troughs, thus reducing the overall transport of the finer sediments at those times.

7. Management Strategies used in Europe

As noted in the introduction a similar pattern of historic development to that which has occurred in the Elbe has occurred in a number of other European Ports and navigable waterways. This development pattern has resulted in coastal squeeze created by the removal of accommodation space which has led to wide estuaries being changed to tidal rivers, particularly where inland ports have developed requiring considerable deepening over time forming a more canalised channel. In this respect the Scheldt and the Elbe are similar as the changes have generally enhanced the tidal range and HW water levels along these estuaries.

In the UK, however, whilst anthropogenic changes due to coastal squeeze have occurred, the effects of large scale channel deepening over long distances and the canalisation of estuaries by dredging, like in the Elbe, is less prevalent and therefore the effects in the past with respect to increased water levels have been of less concern and less well documented. These effects, however, are now of greater concern due to continuing SLR which has the potential to increase flood risk, hence the RESMC goal to reduce water levels.

In each European estuary, measures have been developed, modified and then completely altered to provide, for the most part, the most economic means of maintaining navigation to meet the demand of the trend for the use of ever larger vessels. In more recent years these measures and strategies have had to be undertaken within the bounds of European environmental legislation and conservation of natural habitat objectives.

A review has been undertaken of some of the practices which have been used both historically and more commonly today in some European locations to achieve 'goals' similar to those of the RESMC. Many practices, particularly most recently, in the UK, however, have been undertaken in order for development projects and plans to comply with planning regulations and environmental legislation, especially the European Habitats Birds Directives. In these cases one of the main RESMC 'goals', i.e. the reduction in HW levels to reduce flood risk and reducing and/or management of maintenance dredge material, have been secondary issues providing additional benefit. Many of the types of measures proposed in the RESMC are common practices throughout Europe and have been used or considered to reduce flood risk, improve navigation by stabilising the channel, or remove/reducing sedimentation, hence maintenance dredging and then manage these practices in the most cost effective and manageable manner, consistent with legislation.

This section provides a selection of case examples from the UK and Europe where similar measures to those proposed in the RESMC have been carried out both in the past and at the present time along with some of the consequences. The examples indicate: the effects of channel deepening on HW levels in Southampton Water; the results from a theoretical study into feasibility and effects of large scale Managed Realignments in UK estuaries; measures implemented to reduce flood risk in the upper Humber, and; the effects developments on water levels in the Medina Estuary. All have consequences for flood risk management and sediment management and illustrate the use of some of the measures (either by accident or intent) under consideration for the RESMC as well as some similar issues that require management as is the case in the Elbe.

7.1 Benefits of Large Scale Managed Realignment in the UK

Managed Realignment (MR) in the context of environmental management in the UK means the breaching of sea defences (usually sea or estuary walls) to allow regular tidal inundation of previously defended land thus increasing the estuary tidal prism/flood storage and reinstating accommodation space. This is the same as any RESMC measures that restore previously reclaimed/poldered land back to the tidal influence of the Elbe.

Such realignment projects have been successfully undertaken around the UK coast for a number of years. Their primary aim has historically been the creation of intertidal habitat (mudflat and saltmarsh), in many cases to enable other flood defence schemes or coastal and port developments to comply with the EU Habitats Directive. More recently managed realignment projects have been also developed and implemented to provide combined functions including sustainable flood risk management. An example of this is the Alkborough MR on the Humber Estuary, see Section 7.3.4.1.

The RESMC measures to increase flood storage are therefore similar to MR, which is widely accepted tool for reducing HW levels hence flood risk management of the coastal and estuarine areas. There are a number of other environmental and ecological benefits of such schemes that should also be considered in any cost benefit assessments and individual scheme designs. One of the most important with respect to the RESMC is that fact that MRs tend to accrete and therefore provide a means of reducing sediment in the water column to up estuary areas. This section discusses how managed realignment could reduce flood risk by reducing water levels and considers effects on the flow and sedimentary regimes, based on publicly available information produced for a ‘Feasibility of Large Scale Managed Realignment’ in support of the Strategic Environmental Assessment of Tidal Power in the Severn Estuary (Department for Energy and Climate Change (DECC), 2010). This study investigated the concepts of large scale managed realignment using case studies based on real geographical locations (but not real sites).

The study showed that large scale MR at a conceptual scale is a potential tool for reducing HW levels and affecting sedimentation in an estuary, hence reducing flood risk and allowing some sediment management.

7.1.1 Flood Risk Reduction

As part of the Feasibility Study computer modelling of theoretical MR sites at a number of UK estuaries was undertaken. Case one looked at three scenarios ranging between 1,000 and 9,000ha. All schemes increased the tidal prism by up to 6% and reduced HW levels by approximately 0.5cm for the smallest MR to 10cm for the largest. The location of the MR in the estuary was shown to be an important factor in determining the effectiveness (negligible changes in low water occurred). For the second case four scenarios of between 4,000 and 10,500ha were investigated. The scale of the realignment scenarios resulted in increases in tidal prism of up to 190% with predicted lowering of HW levels by approximately 25cm (with a similar increase in low water). Case study three was located in a smaller and narrower estuary with characteristics more like a tidal river and investigated areas between 500ha and over 2,500ha, these increased the tidal prism by up to 34%, reduced maximum water levels by up to 50cm (due to their location in the estuary) and delayed peak HW by approximately one hour.

The study clearly illustrated that large scale MR can reduce HW and increase LW levels, however, the nature and scale of any changes will be dependant upon not only the size of the realignment in comparison to the tidal prism of the estuary and its location (topography and position) but an array of other site specific factors. Key considerations that will need to be taken into account include:

- Position of the realignment site within the tidal frame and hence volume (and timing) of water entering the site (adding to the tidal prism);
- The design of the realignments (breaches, drainage networks etc);
- Timing of the flooding and ebbing of the site in relation to the estuary dynamics;
- Nature of the environment fronting the sites (e.g. expanses of mudflat or steep foreshore, geology, wave exposure etc);
- The hydrodynamics of the estuary; and
- Sediment availability (realignment sites are generally accretionary in nature). This means that at the correct locations they have the potential to operate as water column sediment reduction devices (horizontal type sediment traps).

7.1.2 Managed Realignment to Remove Sediment

The computer modelling for the Feasibility Study also showed that large scale realignment could also potentially change the sedimentation patterns in an estuary by increasing the tidal flood dominance; although any changes are likely to vary throughout the estuary depending upon the local geomorphology and hydrodynamics. However, at a conceptual level, the theory is supported by the three case studies which predicted increases in peak ebb flow speeds by approximately 7% for the first case study. This was due to the sites emptying at the same time as the existing estuary, which increased the maximum ebb flow speeds and extended the duration of these higher speeds as the increased volume of water drained from the estuary. This increased ebb dominance was predicted to increase the amount of sediment leaving the estuary. The sites themselves would also demand additional sediment from the estuary, creating sedimentation in the MR. A similar pattern was found in case study two with average peak flows increasing by about 45% on both flood and ebb tide with the duration of peak flows being extended on the ebb tide as the sites drained. This indicates that not all MRs will be beneficial with respect to reducing the flood dominance of an estuary and that the connection of the storage area along the estuary is an important factor.

Although general patterns are evident from the case studies, they also showed that the local morphology has a significant influence and illustrated the hydrodynamic complexity of estuaries. A number of modelling assumptions also had to be made including that the estuaries were in dynamic equilibrium and had a ready supply of sediment. The location, topography and breach design of the sites within the tidal frame also significantly affected the timing and nature of the flooding and draining of the sites and their interaction with the adjacent estuary.

Understanding these local variations means that large scale realignment could be a useful tool for managing local sedimentation issues. Realignments are recognised to be sinks for sediment, with high levels of accretion monitored within many sites. As mentioned above, higher flow speeds (and a longer duration of these higher speeds) have been shown to increase the ebb dominance of estuaries at some locations which will result in the greater export of sediment out of the estuary. For example, in case study three the realignment increased the ebb phase of the tide by 0.5 hours and increased the flow speed by 0.1m/s (approx 4% increase) in the outer estuary. These hydrodynamic changes were even more evident in the intertidal areas where the draining flow from the realignments increased the peak ebb flow speeds by 22% (increase of 0.2m/s) with flow speeds exceeding 0.5m/s for an extended period of four hours rather than the current two hours. Upstream, the changes were even greater and at the location of maximum effect the already highly ebb dominant system (with respect to peak tidal flow) was increased by up to 45% (1m/s over the existing 2.2m/s) where the flow is constrained in low water channels. More importantly for understanding changes to sediment patterns, the majority of the time (6 hours on the ebb) flow speeds would have been consistently over 0.5m/s above existing flows (ranging from 0.7m/s to 2.5m/s), therefore enhancing the potential for the net down estuary movement of sediment.

7.1.3 Overview

The study highlighted a number of factors which will need to be considered if the MR/flood storage measures are used on the Elbe to manage sedimentation or water levels. The primary factor is that for any significant water level benefits the area/volume of a MR site (or combined sites) must be <u>very</u> large. The sites investigated as part of the Feasibility Study discussed above were all larger than 500ha and significant benefits were only accrued when two or three sites were combined creating areas up to 10,000ha in size.

A review of MR projects in Europe and the USA has shown that there is little or no experience of such large scale projects (over 500ha). The success of any such scheme would be completely dependant upon the nature, size and position of the MR sites within the estuary and there would be considerable uncertainty without significant detailed investigations of the existing local hydrodynamics and taking account of climate change.

7.2 Southampton Water

The only estuary in the UK where deepening and development has occurred in a similar manner to the Elbe and Scheldt is Southampton Water. This estuary is however considerably shorter than either the Scheldt or Elbe and also has a considerably different shape of tidal curve and larger tidal range. Like the Elbe, Southampton Water has been deepened several times, but is essentially a straight deep subtidal channel with relatively extensive shallow subtidal and intertidal areas. Southampton Water has suffered proportionately much less coastal squeeze except in the main port area. Like Hamburg there is a significant depth change over a very short distance at the head of the navigation channel, however, by contrast the river entering has no headwater discharge of significance, or down river supply of sediment. The water column suspended sediment concentrations are low, with maxima of the order of 60 mg/l on spring tides, hence a relatively small maintenance dredge commitment of less than 0.5 million m^3/year.

The estuary was deepened by 2.4m in 1996/7 which resulted in an increase in maintenance dredging at the more upstream locations in the deeper berth areas. Another deepening of 1m has been studied and is going through consenting process. Figure 23 shows the modelling of the likely effect on water levels which indicates that, unlike in the Elbe and Scheldt, the tidal range is decreased in the up estuary direction as a result of the deepening (by a maximum of 0.015m). This is most evident in the more cross sectionally constrained areas of the Port above Dock Head with the LW level rising and the HW level reducing by a smaller amount.

This indicates that effects of deepening are site specific and the overall effect will be as a result of how it interacts with other factors such as coastal squeeze effects, the changes in channel cross section and the relative proportion of accommodation space. This could have implications on the Elbe as the combined effect of different RESMC measures may be quite different for various channel depths. Measures implemented today, therefore, may not give the magnitude or direction of some impacts, should further deepening of the estuary take place.

7.3 Humber Estuary

On the Humber Estuary coastal squeeze has helped increase water levels along with SLR however, unlike the Elbe, significant channel deepening has not taken place for navigation purposes along its length. For the most part large vessels are restricted to moving through the estuary around HW (or at the higher states of the tide) with vessels either entering impounded docks or sitting in deepened dredge pockets at the edge of the estuary over LW. By contrast to the Elbe, tidal propagation in the Humber has been little changed by capital dredging, however, due to natural changes in bed level and constrictions controlled by 'geological' hard points the propagation of a much larger tidal range has similar characteristics, with the tide becoming asymmetrical (shorter flood phase) particularly up estuary of the Humber Bridge where the estuary significantly narrows and becomes shallower. The estuary has high and extremely variable background SSC that give rise to significant sedimentation at the various port/dock locations, therefore maintenance dredging and the management of the dredged material are required. In addition, these activities have to be carried out within an area that is entirely designated for its nature conservation value. The following section indicates how this managed on the estuary.

7.3.1 Maintenance Dredging

With a macro tidal range, fast flows and a high background SSC, the bed of the Humber Estuary is highly dynamic both in the short term and on longer time scales. The relatively shallow depths and large tidal range meant that in the past the ports developed as enclosed docks, which either had to be 'levelled' or impounded to maintain water levels. The high SSC enter the dock systems and settle out requiring maintenance dredging. As a consequence maintenance dredging has taken place from the docks since about 1778 and increased as further docks were constructed. Even in the early 1900s an average of over 2.5 million tonnes of predominantly fine sediments were relocated to the south side of the main channel opposite the Hull facilities.

No regular maintenance of the navigation channels (except for the immediate dock entrances) was required until 1969 when the Sunk Channel, in the outer estuary was deepened to allow HW access of deep draughted vessels to the natural deep water around the area of Immingham and the newly developed riverfront terminals. Up until that time, the marked navigation channels were moved, where necessary, after regular surveys to follow the deepest water as the morphology of the estuary changed. This practice still occurs up estuary of Hull where no channel dredging has taken place, with the exception of the approaches to Goole Docks and alongside wharves.

A substantial annual maintenance dredging requirement is therefore necessary at a number of locations within the estuary in order to maintain the economy of the region which is responsible for a significant proportion of UK trade, a practice that has been in existence for *over* 200 years.

Since 1969, when a number of riverfront terminals were constructed up until the late 1990s the average maintenance dredging commitment for the estuary was about 7.3 million m^3 per annum *in situ,* from the docks and in estuary facilities and Sunk Dredged Channel (SDC). The actual range, however, was large, with a requirement of over 11.8 million m^3 in 1994, due mainly to the cyclic variations in the dredging required to maintain the SDC.

Since 2000, a number of new facilities have been developed, which have increased the maintenance dredge requirement, however, some of these have not yet stabilised to a consistent maintenance dredge requirement. It is estimated that the annual maintenance dredge commitment for the estuary is now between 8-9 million m^3 *in situ*, however, the cyclic pattern of sedimentation in the SDC caused by the changing morphological configuration of the lower Estuary, has meant that no maintenance dredging has been required in the channel since 2006. Figure 24 indicates the main area requiring maintenance dredging down estuary of Hull.

The main challenge is therefore how to deal with the large annual quantity of sediment in the most social, environmental and economic manner within the estuary.

7.3.1.1 Material type

The material dredged can be categorised into three types based on the locations dredged, i.e. the enclosed docks, riverside berths and lock entrances, and the SDC:

- In Dock: Material is derived from the high suspended sediment load, predominantly fine silts and clay, with a median particle size of around 20 microns. This is predominantly removed by a TSHD supported by a grab dredger;

- Locks, entrances and river berths: The material is similar to the docks, but at times can include coarser bed load material. The median particle size is still generally low (5-30 microns) but the distribution can have a proportion of fine sand, depending on the natural changes which are always occurring within the estuary. Most of the material is dredged by TSHD; and

- Sunk Dredged Channel: In the early days of the channel the sediments dredged were silts and fine sand, but over the last *circa* 15 years (when dredging has been required) the material has been predominantly sand, with a median particle size of 120-180 microns and an *in situ* density of around 1,550kg/m^3. TSHDs are used when dredging is required.

The environmental quality of the material is tested at each dredge location at least every three years for content of heavy metals and tri-butyl tin (TBT). All locations, particularly the finer sediments from in-dock contain some contaminants and on occasions some metals have exceeded the lowest threshold for acceptance for placement in the marine environment. However, for the most part the contamination levels have not been a cause for concern and have been of similar or lower levels than background concentrations sampled from non dredged areas within the estuary, which over the last 30 years have been generally becoming cleaner. All material has therefore been classed as acceptable for placement within the estuarine environment of the Humber.

7.3.1.2 Estuary environmental status

The whole Humber Estuary subtidal and intertidal area, including the navigation channels is designation as an area of nature conservation importance under both the EU Habitats and Birds Directives. One of the features listed is the estuary status, which effectively means that the structure and functioning of the estuary is protected. For a while some scientists believed that sediment was being naturally lost from the estuary, thus hindering the ability of the mudflats and saltmarsh to rise in line with SLR, and thereby reducing these habitats and the favourable condition of the estuary as a whole. If the maintenance dredged material is removed from the system this potential effect would be exacerbated thus having an adverse effect on the integrity of the Humber Estuary system as a whole.

7.3.1.3 Present solution

In the Humber Estuary a number of licensed deposit grounds have been defined (see Figure 25), predominantly in areas of maximum flows in close proximity to the source of the dredged material. The Estuary has a high background sediment load and the annual amount deposited to the flow is only a small proportion of this estuary load. For each site the material deposited is of similar character to that which moves naturally through the area. At all sites the relocated material is generally dispersed into the background over the course of a single spring/neap tidal cycle, with no significant variation to the range of background SSC. As a consequence the dredged material is released as close as possible to the location that it settled, thus maintaining the sediment in the system allowing it to continue to carry out its morphological and nature functions. The practice is therefore one of sustainable relocation as it keeps the sediment within the system, allowing it to 'work' naturally. If the material were isolated from the system maintenance dredging would continually reduce the supply of material which would adversely impact on the natural functioning of the system.

7.3.1.4 Operation and management

The majority of the material is dredged by TSHD. The location of the deposit grounds close to the dredge areas is important for the efficiency and practicality of the dredging. Due to the fine character of the dredged material and its low *in situ* density, dredger hopper cargoes have a very high proportion of water. The estuary tidal range creating the need for locks, means the dredger has to pass in and out of the docks along with the commercial ships thus restricting the time that dredging can take place. The relatively shallow estuary depths away from the main navigation channels also cause further restrictions at certain locations. Thus the physical estuary conditions severely restrict the dredging operation at any one location. It is therefore important not to waste the available time for dredging by effectively transporting no more than 'dirty' water long distances.

The operational management therefore makes maximum use of the relative closeness of the different dredge locations, to dredge on the most appropriate states of the tide for each location. Due to the large range of natural variability within the system, the requirement to dredge is controlled by regular bathymetric surveys, the frequency of which varies depending on the rate of accretion being experienced and the absolute level. The interval between surveys therefore varies between locations and with time from as often as weekly to several months. The dredge operation is planned each year using analysis of historic data (dredge and survey) to predict requirement and timing, but whether dredging actually takes place is dependent on the most recent survey information.

7.3.1.5 Constraints

The main constraints on the practice are imposed by the location and quality of the material to be dredged, the dynamics of the system, restrictions created by the commercial shipping movements as well as the requirement to work within the legislation to comply with the EU Habitats and Birds Directives as well as national deposit site licensing requirements. There is also a general public perception that dredging and disposal activities 'can only be harmful to the environment'.

7.3.1.6 Cost benefit and lessons learnt

The maintenance dredging strategy has been developed over many years to maximise the benefits whilst minimising the costs. The different dredge locations within the Estuary means the dredger is less restricted by tides and commercial movements, being able to dredge at one location when restricted at another. Transport distances are minimised thus reducing cycle times. The short cycle time also means the dredger does not require to completely maximise its load, which would be counter productive in-dock, as this would lower the density of the material to be dredged, reducing the dredging efficiency further. The dredger is therefore more productive, spending time dredging as opposed to transporting relatively low quantities of sediment. This allows the dredging capacity to be better targeted to where it is needed rather than dredging 'because the dredger is available'.

The return of the material to an area in close proximity to the dredge minimises the direct impact on the natural system and keeps the material; available to carry out its natural function. The alternatives would be removal of the material to land or deposit in the open sea outside the system. The very wet nature (low density) of the sediment, the quantity and rate of supply would require large lagooning/de-watering facilities which inevitably would be well away from the individual dredge locations, with little present demand for the end product. Removal of the sediments offshore would mean placing fine sediment into predominantly sand or gravel bed areas. The material would disperse widely, potentially creating high turbidity plumes, with consequential effects on fish etc. This removal of the sediment from the system would also reduce the supply, increasing the rates of erosion of mudflats and saltmarsh, creating increased exposure of the flood defences and change the dynamics of the system.

Sustainable relocation of the dredged material in the estuary therefore has less environmental impact than the alternatives and keeps the material in a more 'like for like' situation. From the port viewpoint this does increase the potential for re-circulation of the sediment back to the docks and berths, however this is a small proportion compared to the background supply. This small increase in the overall maintenance dredging requirement is significantly outweighed by the overall cost benefit of the improved dredge efficiency.

Overall, it is considered the dredge management for maintenance dredging in the Humber Estuary gives rise to the Best Practical Environmental Option and uses the dredged material in the most sustainable manner.

7.3.2 Example of a Capital Dredge Management Plan

In recent years a number of developments have taken place on the Humber Estuary or been consented that have required the relocation of large volumes of different types and volumes of material. For the purpose of obtaining consents a dredge management plan has been required which minimises the potential impact on the estuary at each deposit location, whilst maximising the potential for dispersed sediments to settle on the intertidal areas at rates that will not smother the intertidal, thus affecting the ecological habitat, therefore its use by birds. The following is the dredge management plan as prepared for the recently consented Immingham Oil Terminal Approach Dredge (IOTA) at the mouth of the Humber as an example of the considerations made:

1 Introduction

For the purpose of developing an optimised dredging and disposal strategy the IOTA dredging requirement has been defined into the five component areas, namely:

- Stallingborough Emergency Turning Area;
- Sunk Dredged Channel (SDC);
- Hawke Channel;
- Chequer Shoal; and
- Eastern Approaches.

For each dredge area, the recommended disposal location is given based upon the type of material being extracted and other considerations such as the proximity/suitability of potential disposal grounds. The strategy has been developed to allow for the deposited material to be distributed throughout the estuary to supplement the sediment supply. As a consequence the estuary bathymetry and tidal variation restrict the size of dredger/barge that can be used at a number of locations to a maximum loaded draught of about 6.5m. The dredge and disposal locations are shown in Figure 25. This section of the Management and Monitoring Plan (MMP) summarises the proposed optimum (combined practical and environmental) dredge strategy and disposal strategy in the form of a specification, which is presented in tabular form in Table 1. This table also shows present controlling depths and tidal restrictions.

2 Stallingborough Emergency Turning Area

Approximately 65,000m³ *in situ* of soft clay, silt and sand requires to be dredged from the north and south edges of the turning area. To maximise the potential for the deposited material to remain within the estuary, therefore, potentially increasing the supply of sediment to intertidal areas, some of the dredged material will be deposited in a deep pocket within the former Foul Holme Channel, which has been denoted Holme Channel Deep.

This pocket is currently over 3m deeper than the surrounding bed level and to maintain the general flow characteristics of the area should not be in filled to above the 4m Chart Datum (CD) contour. It should be noted, however, that the general area surrounding the proposed deposit ground has changed naturally by up to 1m during the last 2-3 years. Due to the depth limitations over the site it is unlikely to be available for deposit on neap tides and is only available for about 1.75 hours either side of high water (HW) on spring range tides.

These restrictions mean that a second, less restricted deposit site is also required. The existing Middle Shoal Deposit site with controlling depths of *circa* 5m below CD allows deposition except at the lowest states of tide on neaps and approximately HW± about 4 hours on spring tides. Nevertheless careful dredge planning around the tidal conditions will be required to avoid low water (LW) deposit restrictions.

The optimum distribution of material to provide most benefit to the system, assuming three loads per tide, would be to:

- Dredge the emergency turning area from about LW-2 hours with overspilling until about LW+1.5 hours and then deposit to Middle Shoal;
- Dredge again for about 3 hours and on Spring tides, travel to Holme Channel Deep and deposit or, if the tide is too low, deposit to the up estuary end of Middle Shoal; and
- Dredge the third load on the tide and deposit at Middle Shoal.

Please note the exact timings will vary depending on optimum fill time for the dredger.

3 Sunk Dredged Channel

From within the existing Sunk Dredged Channel, where the maximum amount of material (*circa* 1.985 million m³) is to be dredged, three broad material types have been identified:

- Sand dredged by Trailer Suction Hopper Dredger (TSHD) from the southern side. This material is exactly the same as has been dredged to maintain the existing channel at least over the last *circa* 20 years;

- Soft silt dredged by TSHD predominantly from the northern side. Deposition of these sediments up estuary could enhance the sediment supply over the mudflat areas and allow some sediments to reach the seawall and saltmarsh areas throughout the estuary; and

- Firm/stiff glacial clay. It is not certain at this stage that this material can be dredged by TSHD or whether a backhoe or cutter suction dredger will be required. This will be confirmed following contractor appointment.

The TSHD dredged sand and silts will be relocated using the same disposal methodology (hence timings in the tide) as for the Stallingborough Emergency Area. The aim is for the sand to be deposited at Middle Shoal at the lower tidal states and the silts moved up estuary (to Holme Channel Deep) over the high water periods on spring tides. It is likely that all material will need to be deposited at Middle Shoal on neap tides. When it is necessary to deposit all material at Middle Shoal, the finer silt sediments should be deposited between about LW-1 hour to HW-1 hour at the up estuary end of Middle Shoal with sands during the rest of the tide. This means the finer sediments will initially be distributed up estuary where the existing bed sediments are finest and the sands down estuary where they are most abundant. To undertake this methodology, a careful dredge plan, relative to the tide, will be required, as well as flexibility in which section of the channel is to be dredged at any particular time.

It should be noted, depending on the actual rates of dispersal and tidal restrictions, it may not be possible to relocate all the silt material to the Holme Channel Deep site. This will be managed during the dredge by reference to the proposed regular bathymetric monitoring of the deposit ground.

Three options exist for the deposit of the firm/stiff glacial clay depending on the dredge method:

- For a TSHD, the same disposal strategy will be used as for the sand and silts as specified above;

- For a backhoe dredger the ‘lump’ material will be deposited at locations SDC ‘A’ and SDC ‘B’; and

- For cutter suction dredged material, the smaller ‘lumps’ and greater volume of a slurry type matrix will require relocation to SDC ‘C’. The material could be delivered either by barge or directly pumped through a pipeline.

4 Hawke Channel

The dredging requirement for the Hawke Channel is about 565,000m³ of soft clays and silts, which is likely to be dredged by a TSHD. This material will be deposited at the Bull Sand Fort Deposit site without tidal restriction, although if more can be deposited between LW and LW+4 hours, then this would retain marginally more of the material within the estuary system.

5 Chequer Shoal

At the Chequer Shoal Bar about 865,000m³ of uniform compacted sand requires to be dredged by TSHD. This material will be relocated to the extended Bull Sand Fort Deposit site without tidal restriction. Where appropriate, should dredge planning allow mix/cover the finer sediments from the Hawke Channel and the 'lump' stiff clay from the Eastern Approaches (see next section).

6 Eastern Approaches

Two material types need dredging from the Eastern Approaches in distinct areas:

- About 170,000m³ of sand by TSHD, which will be relocated to the Bull Sand Fort Deposit site; and

- About 255,000m³ of stiff glacial clay, probably by a large backhoe dredger loading barges. At this stage, until the contractor is chosen, the method of dredging this material is in doubt. Different deposit scenarios will be required depending on the method of dredging:

    - For backhoe dredged stiff clay the optimum disposal strategy is to deposit approximately half the material to the scour holes in the Bull Sand Fort Deposit site and the remainder to sites SDC 'A' and SDC 'B'. Whilst these two sites (between them) could accommodate all the material (including that from the SDC itself), depositing all the stiff clay at these locations would use up a large proportion of the spare capacity, which will be required in the future for proposed developments from up estuary. Recent bathymetric surveys suggest that the volume in the Bull Sand Fort scour holes, to a depth well below the surface of the bank, is not sufficient to retain all of the clay material along with the other deposits to the site. The deposit ground is predominantly sandy, therefore, the split location plan means a higher proportion of sand, similar to the bank composition, is relocated at the site; and

    - Should the stiff clay be dredged by any other method, then, due to the material at the point of disposal being in a 'slurry' type matrix, the Bull Sand Fort Deposit will be required for all the material. In this case, however, a large proportion of the material will be quickly dispersed by the prevailing flows.

Table 1. Summary of optimum Immingham Oil Terminal approach channel deepening dredge and disposal strategy

Dredge Location	Dredge Material Volume	Proposed Capital Dredge Depth	Dredge Material Type	Dredge Method	Controlling Depth at Dredge Location	Deposit Location	Deposit Volume	Deposit Site Distance From Dredge Location	Deposit Site Controlling Depth	Deposit Site Approaches - Controlling Depth	Approximate Deposit Site Accessibility (Basis 6.5 m Draught)
Stallingborough Emergency Turning Area	65,000 m³	11.6 m below CD	Soft clay, silt and sand	TSHD	10.3 m - 10.5 m below CD	Holme Channel Deep (new site) *	22,000 m³	6.5 km	5 m below CD	4 m below CD	1.75 hours ± HW on spring tides
						Middle Shoal (Humber 1A/HU080)	43,000 m³	3.5 - 6 km	4 - 5 m below CD	5 m below CD	4 hours ±HW on spring tides
Sunk Dredged Channel - north side	970,000 m³	11.6 m below CD	Soft clays and silt	TSHD	9 m below CD	Holme Channel Deep (new site) *	311,000 m³	6 - 14 km	5 m below CD	4 m below CD	1.75 hours ± HW on spring tides
						Middle Shoal on flood tide	659,000 m³	2.5 - 6 km	4 - 5 m below CD	5 m below CD	4 hours ±HW on spring tides
Sunk Dredged Channel - south side	895,000 m³	11.6 m below CD	Fine sand	TSHD	9 m below CD	Middle Shoal on ebb tide	895,000 m³	2.5 - 6 km	4 - 5 m below CD	5 m below CD	4 hours ±HW on spring tides
Sunk Dredged Channel - full area	120,000 m³	11.6 m below CD	Firm glacial clay	Cutter Suction Dredger **	9 m below CD	SDC area 'C'	120,000 m³	3 - 4.5 km	5 - 7 m below CD	9 m below CD	Barge or pipe and booster station. No restriction for barges
Hawke Channel	565,000 m³	11.8 m below CD	Soft clays and silt	TSHD	9.7 - 10.8 m below CD	Bull Sand Fort (disused deposit site HU111)	565,000 m³	2.5 - 7 km	4 - 16 m below CD, ave 7 m below CD	9 m below CD	No restriction
Chequer Shoal	865,000 m³	13 m below CD	Fine to medium compacted sand	TSHD	10.4 m below CD	Bull Sand Fort (slight increase in area to NE)	865,000 m³	6.5 km	4 - 16 m below CD, ave 7 m below CD	9 m below CD	No restriction
Eastern Approaches	170,000 m³	13.1m below CD	Fine to medium sand	TSHD	10.5 m below CD	Bull Sand Fort (slight increase in area to NE)	170,000 m³	7.5 - 10 km	4 - 16 m below CD, ave 7 m below CD	9 m below CD	No restriction
	255,000 m³	13.1 m below CD	Stiff glacial clay	Backhoe and barges	10.5 m below CD	Bull Sand Fort and SDC areas 'A' and 'B'	255,000 m³ in clay 'lumps'	20 km	5 - 6 m below CD	5 - 6 m below CD	No restriction for barges

* When tide allows access, otherwise middle shoal
** If Backhoe used then SDC 'A' and 'B' must be used

7.3.3 Beneficial Use of Capital Dredged Material

The mobile sediments (fine sand, silt and clay) within the Humber Estuary are for the most part underlain by glacial clay/boulder clay, which is predominantly in-erodible to the present day hydrodynamics of the Estuary. This material effectively restricts erosion within the estuary where it outcrops. Where this occurs it gives rise to specific bathymetric features. In the outer estuary, there are two areas where glacial channels created deeper areas within the boulder clay surface. These areas are shown as Sunk Dredged Channel (SDC) A and B on Figure 26, which also shows the maintained SDC adjacent, which runs between the boulder clay outcrop to the north and the mobile subtidal sand bank to the south.

When the SDC needs to be dredged the most is required from immediately opposite these areas (often referred to as 'windows' on the Humber). Numerical modelling in the past has shown the flows through the channel reduce sufficiently in these areas to cause sediment to settle from the waters column, when the cyclic patterns of morphological change in the Lower Humber are conducive to sedimentation in this area. The modelling also indicated that if the 'windows' were in-filled then the flow regime through the channel would be altered and less sedimentation would result.

Flow speeds in the area are however generally high, therefore the fine maintenance dredge material could not be used as fill as there would be a high likelihood that considerable rapid re-circulation to the channel would occur. However, many capital developments require dredging into the boulder clay. The SDC A and B sites have therefore been designated to be used for the hard clays (in lump form) dredged by mechanical methods, such as a backhoe. This material, being in-erodible, minimises the risk to the channel, will stay in place and will eventually raise the bed in the 'windows' to the surrounding level of the boulder clay outcrop. When complete this will act like a training wall.

The capital dredged material is therefore relocated where it will provide some benefit to the maintenance dredging commitment for the channel in the future.

This idea of using dredged material to modify the cross section to change the local hydrodynamics is essentially the same general concept as currently being used in the Western Scheldt and is similar to measures being proposed in the RESMC particularly in the entrance area of the Elbe, where the maintenance dredging requirement as mainly due to morphological change to the pattern of banks and channels.

7.3.4 Flood Risk Reduction

Issues concerning flood risk are considered to be more a problem, where coastal squeeze has reduced the estuary accommodation space which is exacerbated by SLR, rather than the limited effects of channel deepening of the estuary. This loss of accommodation space (intertidal) which is all European Nature Conservation designated (Natura 2000) along with flood risk are the most significant estuary concerns today and in the future accounting for SLR. This has led to a number of Managed Realignments (MR) along the estuary to compensate for specific habitat lost due to development along the estuary both now and in the future, but HW level reduction was not a primary objective with the exception of at Alkborough, see below. All these sites effectively set back the flood defences into agricultural land.

7.3.4.1 Alkborough managed realignment

In the area of Alkborough, near the confluence of the Rivers Trent and Ouse a MR was designed to both compensate for the loss of Natura 2000 habitat and to reduce HW levels, by providing flood storage at the highest water levels. The site also provides regulated tidal exchange between it and the main estuary to ensure no effects on navigation depths within this part of the estuary occurs.

Figure 27 shows the location of the Alkborough MR and the modelled effect on the water levels either side the breaches for a surge tide. The maximum reduction in HW surge level was of the order of 0.1m for about 30km up estuary in each river, with effects restricted to about 10km down estuary. It should be noted that the MR has a large area of 370ha situated in a constricted section of the estuary where tidal prism in the rivers is relatively small compared to down estuary. This illustrates that if similar forms of MR/flood storage are introduced on the Elbe reductions in maximum water levels can be expected up estuary of the works, however the amount of reduction, will be to some extent proportional to the cross section and up estuary tidal prism. It also indicates large areas of additional accommodation space are required to provide modest reductions in water levels.

7.4 Medina Estuary

The Medina Estuary on the Isle of Wight, UK is a small estuary with a predominantly natural single deep channel that has been developed significantly over time. Like the Elbe, reclamation along part of its length has reduced the tidal prism and accommodation space, particularly in the outer section. In addition, wharves have been dredged and marinas constructed at the edges of the main channel. Little or no deepening of the main channel has occurred. In the 1930s sedimentation was occurring in the main outer harbour channels. To reduce this, the ‘surface piercing’ Shrape Breakwater was constructed, see Figure 28. This effectively reduced the cross section at the entrance and had the effect of concentrating flows within the main channel, increasing the scour. Since the breakwater has been in place, the main channel has only required occasional ad hoc dredging to maintain the depths in the navigation fairway through the Cowes Outer Harbour. The breakwater was also designed to 'deflect' the Solent flow directions offshore in the entrance, which reduced the amount of sediment entering into the estuary over the intertidal area. This probably reduced the overall sediment supply to the estuary as a whole. Unfortunately there are no records to clearly show what the effect on the hydrodynamic and sediment regime of the estuary took place, nor the effect on water levels. Bathymetric analysis, however, indicates the estuary as a whole has been eroding over the last *circa* 130 years, but has stabilised over the last 30 years, when fewer development changes have occurred. In the last 10 years a number of small developments have been proposed and will continue to be considered in the future. Some of these are shown for the outer estuary on Figure 28, which if they were all to occur, will further constrict the estuary and deepen the channel at the edges, just up estuary of the narrow Chain Ferry constriction, an area that has not changed significantly over time. In addition the breakwater will further change the cross section and general morphology of the entrance. The marina will also substantially increase both the LW volume and tidal prism of the Harbour area.

With the exception of the marina, new entrance channel and breakwater development which has been consented, the other individual developments are too small in their own right to be able to fully understand what the individual effects on the estuary system might be. Detailed numerical modelling has however been undertaken of all the potential developments combined (Maximum Development Scenario (MDS)) and just for the consented outer harbour development (i.e. breakwater, new entrance channel and marina). The main difference between the two scenarios, apart from individual component scale is the addition of channel morphology changes up estuary of the Chain Ferry constriction.

Figure 29 shows that with all developments (MDS) included, HW and LW levels were increased throughout the estuary, primarily due to an increase in subtidal volume, up estuary of the Chain Ferry. With the outer harbour developments alone, which effectively increase the tidal prism in the estuary (particularly outside the Chain Ferry constriction) showed reductions in both HW and LW levels along the estuary. These changes (both scenarios) had little effect on the flow speeds and sediment transport through the estuary as a whole.

With respect to the Elbe, this example indicates that changing the cross section and volumes within the estuary entrance can change water levels throughout the system, albeit the Medina estuary is considerably shorter than the tidal Elbe. It also shows that a combination of effects, therefore any future changes to, or additional RESMC measures, could change the overall direction of effect. Detailed studies will therefore be required of the combined effects of measures as well as for the individual effects, before particular measures are confirmed and implemented. The study also indicates that with respect to flood risk management, measures which both constrict the estuary width whilst deepening the channel, tend lead to higher water levels throughout the system, thus increasing flood risk. Also constant (in time), narrow constrictions are a major control on the whole dynamics of the system.

7.5 Mersey

The Mersey Estuary in the UK is an example of where a series of training walls have been constructed to stabilise the channel alignment by confining the main flows to the navigation channel for much of the tide. This, over time effectively fixed the channel location, where in the past it had moved around.

The maintenance dredging requirement for the channel increased year on year from almost zero in 1890 and continued until the mid 1920s. The first wall was constructed with a height of 3m below Ordnance Datum Newlyn (ODN) (near LW) with the aim of stopping the northward migration of the channel. Since several phases of new and extensions of the training walls occurred as shown in Figure 30, with the main objective of concentrating the flows to stabilise the channel and reduce maintenance dredging. The addition of the walls reduced the dredge commitment of the channel from a maximum of around 25 million tonnes/year in 1924 to around 2 million tonnes/year, consistently since 1976.

During this period the banks, Taylor Bank and Great Burbo Bank built up behind the training walls, the later ones being constructed higher to about half tide level. Today the walls are overtopped by sediment moved during storm conditions, with the waves driving sediments over the wall, which then collect in the channel, as they are not eroded by the trained flows. This is the predominant source of the maintenance dredging required today.

The constriction of the tidal flows from the large tidal range affected the tidal propagation into the Mersey Estuary. In the 19th Century the estuary was considered to be in dynamic equilibrium, although accretion was occurring in the outer estuary, leading to the need for the training walls. From 1906 to 1977 the significant accretion occurred within the estuary, coinciding with the construction of the walls and improvement in the maintained depths to the docks and further up estuary, however, since 1977 slight erosion has occurred.

Like the Elbe it would appear that the constriction and deepening of the channel increased amount of sediment transported in the flood flows whereas previously this material would have settled in the entrance area to be dredged. Once in the Mersey Estuary itself, through the constriction of the Narrows between Liverpool and Birkenhead, flow speeds would have significantly dropped as the estuary suddenly widens, promoting increased sedimentation. The ebb flows in this area would not have been enhanced therefore, no increase in sediment export would have resulted; hence the accretion within the estuary. The ebb flows, however, once through the Narrows constriction, particularly below half tide level would have increasingly become constricted to the channel, hence increasing the flushing of the navigation channel, giving rise to the reduction in maintenance dredging. The reduction in estuary volume would have reduced the tidal prism over time, thus given the same sediment supply from offshore the sedimentation rate would have slowed. Also as noted above the banks outside of the channels built up against the training walls, therefore it is possible the rate of supply of sediment has also reduced in recent years and a new equilibrium condition has developed for the existing forcing processes and SLR.

This example serves to show that the training works may be able to be used to reduce maintenance dredging within the mouth of the Elbe, by constricting flow the main channel, however, as illustrated here and in the case of the Medina a narrower, deeper channel tends to increase the flood dominance of flows and increase water levels in an up estuary direction. Also if a sediment supply exists more is likely to be moved up estuary. In the case of the Elbe this is likely to increase the tidal pumping effect. Thus whilst maintenance dredging effort may be reduced in the entrance, it is likely to be at the expense of a greater up estuary requirement, which may be more expensive and environmentally problematical to remove.

7.6 Western Scheldt

7.6.1 Morphology and Dredging

The morphological evolution of the Western Scheldt has been influenced by both natural processes and anthropogenic changes over the past two centuries. Initially the human interference mainly consisted of reclaiming land that largely silted up by natural processes. This reclamation resulted in a permanent loss of intertidal areas, an irregular pattern of embankments and a fixation of the large-scale alignment of the estuary. Since the beginning of the 20th century the human interference shifted from land reclamation to sand extraction (since 1955 about 2 million m^3/yr, until 2000) and dredging and disposal in order to deepen and maintain the navigation route to the port of Antwerp (Jeuken & Wang, 2010). This dredging has significantly changed the morphology of the estuary, whilst also changing its tidal asymmetry.

The Western Scheldt has independent flood and ebb channels, resulting in a typical multi-channel system (seen in Figure 31), with channels separated by intertidal shoals. This layout provides safety against flooding by dissipating energy from incoming tidal waves, offers more habitat areas for nature, and has advantages for navigation as it spreads the commercial and recreational vessel traffic (Tide Facts, 2010).

During the first deepening of the navigational channel between 1970 and 1975, the depth of the shallow sills was increased by 2-3m to 12-14.5m. Disposal of the dredged material mainly in the eastern reach of the multi-channel Western Scheldt was blamed for the degradation of its secondary flood channels. During the last deepening, carried out in 1997/1998, these depths were further increased by 1-1.5m. As a result of the enlarged navigation depth the maintenance dredging increased from less than 0.5 million m^3/yr before 1950 to around 7-10 million m^3/yr at present (Jeuken & Wang, 2010). This deepening of the Western Scheldt has lead to an increase in tidal volume entering the estuary, and an associated increase in tidal range. Smit *et al*. (1997) report that deepening of the navigation channel has resulted in greater flow through the main channel, and less through the side channels. Consequently erosion has occurred beside the main channel, encroaching on the flats and marsh.

Traditionally, sediments from maintenance dredging were mainly disposed in secondary channels with the idea that it would take a significant period of time before it returned to the navigational channel. However, it was predicted that there was a limit to the amount of sediment that can be disposed in these secondary channels, above which they would silt up and disappear, with the estuary morphologically evolving from a multi-channel to a single-channel system, an evolution that was not desirable.

In 2001, an independent expert team appointed by the Antwerp Port Authority suggested an alternative strategy for the Western Scheldt to avoid disposing large amounts of sediment in the secondary channels. They proposed the disposal of dredged sediments along the edges of sandbars, creating ecologically valuable areas and even improving the state of the multiple channel system by a better distribution of ebb and flood flows. This, in turn, would result in higher flow velocities in the channels, reducing sediment deposition there and with it the quantity of material needing to be dredged. In 2003 a pilot test with a disposal of 0.5 million m^3 of sand along the edge of the Walsoorden sandbar was undertaken. Since this initial test, 4 times more sediment has been placed in front of the sandbar. Comprehensive monitoring has been ongoing since 2004, including morphological and ecological observations, in which no negative effects have been detected to date (Peters, 2008).

Following this investigation, deepening of the Western Scheldt navigation channel to a minimum depth of 14.5 m was initiated in 2010. Dredge disposals are now being used to reshape or extend sandbars at 3 new locations in addition to Walsoorden: Rug van Baarland, Hooge Platen Noord, and Hooge Platen West (shown in Figure 31). The disposal strategies for each location vary according to the conditions and goals at each site. An intensive monitoring program is in place to evaluate the effects of the disposal, including the stability of the disposed material and the evolution of the existing and newly created habitats. Results from this monitoring program will allow adjustment of the strategy if necessary and will lead, in 2012, to an evaluation report under supervision from an independent group of experts (Tide Facts, 2010).

7.6.2 Localised Techniques to Reduce Sedimentation

In order to manage localised sedimentation within the Port of Antwerp itself, other techniques are being considered on a case-by-case basis. As an example, a new container dock (the Deurganckdok) was recently constructed in a location close to the turbidity maxima. The sediment dynamics close to the new dock are dominated by a high SSC (near-bed concentrations around 1,000mg/l) which is advected along the dock by the tidal currents, where exchange flows between the dock and Scheldt are mainly a combination of horizontal eddies and salinity driven flows, with velocities around 0.4m/s. Most sediment enters the dock around HW, and settles out during HW slack. In order to minimise this sedimentation in dock, a Current Deflecting Wall (CDW) is to be constructed. The main effect of the CDW is to deflect the turbidity maxima towards the river, thus potentially reducing the amount of sediment influx into the dock. Numerical modelling results indicate that the construction of a CDW at the new container dock could potentially reduce siltation by up to18% (van Maren *et al*., 2010).

8. Conclusion

The report has concentrated on developing an understanding of the historical development of the tidal Elbe with respect to the morphology and how these have caused changes to the water levels and sediment characteristics which are important for maintaining navigability to the Port of Hamburg, maintenance dredging and flood risk along the Elbe. This understanding has then been used to evaluate the potential effectiveness of the various RESMC measures and indicate considerations and studies that will be required for any specific measure design. For the most part where the historical understanding or conceptual process analysis has identified implications for the objectives of the RESMC or the specific design of measures, these have been discussed at that point. This conclusion focuses on the specific questions raised for this work package.

What is the assessment of the influence exerted by past expansion, river engineering and dredging strategy on the present-day morphological situation and/or morphodynamics?

From the historical assessment it is clear that the combined effect of anthropogenic influences; reclamation, structures, flood defences, Port developments and various phases of channel deepening have changed the morphology and morphodynamics of the estuary as a whole. These have combined to cause 'coastal Squeeze', which along with the deepening up to a fixed location (the St. Pauli tunnel) has accentuated the tidal propagation and the reflection of the tidal wave, thus increasing the tidal range up estuary, particularly at Hamburg. At the mouth, however, it is important to note the tidal range and levels have only been affected by SLR. The most significant effects on the morphology/morphodynamics have occurred in the now narrow constricted section of the estuary above Brunsbüttel.

The assessment tends to indicate that the most significant factor in the enhancement of the tidal dynamics has been the large removal of accommodation space, particularly tidal prism along the estuary. This has caused channel constriction, particularly at the higher tidal states, reducing the volume for the incoming tide. The progressive deepening has increased the speed of the flood tide propagation into a smaller volume. This process has increased flood flows, particularly the peak rates, increasing the flood flow dominance of the tide, both over a larger estuary extent and with increased magnitude in an up estuary direction.

This increased flood dominance has led to an enhancement in the phenomenon of tidal pumping where sediment entering on the flood has been moved ever further up estuary and if it has settled the reduced ebb flow speeds either cannot erode the sediment or cannot remove it, hence the need for maintenance dredging.

On the basis that tidal range at the entrance has not significantly changed, if the CSA and SSC have not altered then the amount of sediment entering the estuary will be the same. The change in flow speeds and relative dominance will have redistributed the material around the estuary. Over time the locations prone to sedimentation have not significantly altered, being controlled by the tidal harmonics and reflection of the tidal wave which have remained relatively constant (except in magnitude). The flow speeds at the individual locations have, as has the sediment distribution, moved both at the bed (the coarser sands) and in suspension (the fine sand and silts). The magnitudes of sedimentation at each location will have been changed due to the deepening, but not the overall volume available for transport, however more is concentrated in the up estuary sections.

The construction of in channel structures at specific locations has influenced local flows to prevent sedimentation, however the overall supply has not been changed and the material that once settled at these locations has moved up estuary as tidal pumping has increased. As there are more settlement areas, up estuary, e.g. the Harbour Basins, this has led to an increase in sedimentation needing maintenance dredging in these areas. This increase however, is only likely to be from a greater volume of the coarser material, moving nearer the bed than from the fines in suspension, unless the SSC of fine sediment has increased at the up and downstream boundaries, then there would have been little change in fine sediment supply to the basins, as little extra could be eroded from the sandy channel.

The analysis of dredge material disposal and dredging practices indicate that relocation to the Neβsand site set up a sediment re-circulation cell, which would have enhanced the amount of maintenance dredging required in the Port area once introduced. The last main dredge and in channel structures enhanced the tidal pumping and moved more sediment up estuary. To minimise transport distances the increased material from the Wedel area was deposited further up estuary than when it was dredged from the Rhinplatte area. This effectively enhanced the supply and setup another re-circulation cell, which interacted with that for Neβsand. This significantly increased sedimentation in the Port area until the supply was reduced by the change of the WSA Hamburg disposal practices in 2006 and alleviated further by the relocation of sediment out of the system to the North Sea, by depositing at Buoy E3.

This summary of the effects of past anthropogenic interventions on the estuary shows that there has been a significant influence on the estuary morphology and morphodynamics. This understanding therefore needs to be integral to any design of future RESMC measures.

What sediment management strategies are practised and/or developed in other European estuaries? Are there similar problems there?

A review of other estuaries around Europe has shown the general problems associated with the Elbe and their causes are not unique. However, the scale of the effects varies considerably depending on the location of the Port along the estuary, the tidal range and sediment dynamics. In the UK, whilst similar morphological and structural changes to the estuaries have occurred historically, few have developed where deep draught vessel access is possible throughout the tide at an up estuary location. Most up estuary Ports have developed on the basis of only allowing access on the higher range tides and LW levels are accommodated by either deep berthing pockets or within lock enclosed docks. Thus whilst significant reductions in accommodation space and coastal squeeze have occurred on a par with the Elbe, constriction and over deepening of channels has not taken place. Maintenance dredging and relocation of the arisings is still required and has to be managed. In the Humber Estuary, where a large proportion of UK maintenance and capital dredging takes place, sediment management programmes have been developed to account for the hydrodynamic and sediment regime of the estuary, and where possible these will minimise impacts on nature conservation features in general and for some specific functions, with the aim of providing some benefit. These measures follow similar principles to those being considered for the RESMC, but will be distinctly different due to the site specific environmental differences. In the Western Scheldt, which is probably the closest estuary of the Elbe type, sediment management techniques are being used which maintain the flood and ebb dominant channels, by extending sand banks to narrow (therefore lengthen) individual channels, thus maintaining higher flows in longer channels, both on the flood and ebb to reduce channel sedimentation. To some extent this has already been undertaken in the Elbe by the extension of banks to form Islands. The difference would appear to be that some of the secondary channels have been allowed silt up or deliberately filled, thus the Elbe is more of a single channel system than is presently the case in the Western Scheldt.

The report gives examples of measures of similar type to those proposed in the RESMC that have been undertaken or proposed, particularly with respect to modification of water levels. It is fair to say however, that in most cases this was a 'bi-product' of the measures, rather than the prime objective. They do however show that RESMC measures which increase flood storage, particularly tidal prism and accommodation space will benefit water levels in the Elbe. The examples, however, suggest that relatively large areas will be required to provide modest changes. Where MRs have been implemented in the UK, mainly for nature conservation compensation purposes, they have generally been accretional. This indicates that such measures on the Elbe are likely to reduce, SSC up estuary, which could benefit maintenance dredging as well water levels, therefore could be designed to be multi-beneficial if implemented in the appropriate location.

To a degree all the proposed RESMC measures are not unique and have been effective and accepted both in the past and with respect to current environmental legislation, albeit with careful design, study and consultation.

What is the assessment of the objective "reducing tidal pumping" as a sediment management strategy from a morphological perspective in view of the experience in other European estuaries? Are the envisaged river engineering measures for reducing tidal pumping expedient?

For the most part, tidal pumping, to the same degree as is evident on the Elbe is not seen as major problem, except where long over deepened (relative to the natural estuary morphology) channels have been dredged for navigation. In the UK there are few navigable estuaries of this type. The only one that is close (in type) is Southampton Water, however is much shorter in length. Whilst increased depths here have increased the maintenance dredge commitment has been focussed in the more up estuary locations. The volume by comparison to the Elbe is however small and contaminated sediments are not considered an issue; the significance of the effect is therefore low.

From the historic assessment for the Elbe, it would appear that the increase in tidal pumping effect is predominantly due to the deepened channel causing more asymmetrical tidal propagation within a constricted cross section. Whilst the incorporation of flood storage measures down estuary will have some effect, it is considered that reduction in the tidal pumping effect with respect to sedimentation in the future will be difficult to achieve, particularly in an economic and environmentally acceptable manner. It is likely to be more cost effective to remove/intercept sediment by 'trapping mechanisms' in areas where the sediment will be more efficient to dredge/ manage. In this way whilst the water that is pumped through the estuary remains, less sediment is transported with it in an up estuary direction.

As mean sea level rises, without the introduction of new flood storage areas (accommodation space) the coastal squeeze effect will increase leading to increased tidal pumping. The concept of increasing flood storage will therefore assist in overcoming the future effects of SLR.

What is the assessment of the currently practised use of water injection in the main tidal Elbe (shipping channel) for attenuating sand ripples in comparison to the alternative of hopper dredging?

WID has been assessed as being beneficial and cost expedient in the short term, for flattening sand ripples throughout the estuary. In the long term however, the sandy bed load will still be retained locally and slowly move up or down estuary (depending on location) It will eventually settle out in less dynamic areas where it will potentially need to be removed by TSHD. WID has little effect on the transport of fine sediments in suspension through the estuary. Benefits exist in the short term, particularly as it is not efficient to be use a TSHD to 'hunt spots' or sand ripples. TSHD dredging will be needed at some point but the use of WID, possibly in conjunction with sediment traps, such as Wedel, should increase the efficiency of the dredge, when required, and it is likely to be carried out at the optimum time from environmental and relocation timing perspectives. In addition, the bedform roughness of the estuary is maintained for longer, thus aiding the dissipation of tidal energy.

WID is therefore a tool which will have benefit as part of an integrated dredged management plan for the estuary as whole, taking account of the combined effects of other proposed measures.

Is breaking dredging cycles (sediment re-circulation) as a priority sediment management strategy appropriate and expedient from a morphological perspective in view of the experience in other European estuaries?

It is clear from the historical and conceptual process analysis, that the interaction of the various developments along the estuary in combination with changes to dredge management practices caused a sediment re-circulation cell between Hamburg and the Neβsand relocation site. Initially this was manageable, however, following all the changes in the various activities and developments around the last channel deepening this re-circulation was significantly enhanced and self perpetuating, specifically due to the relocation of the sediments in the enhanced flood dominant flows. Any future RESMC measures (individually and in combination) will need to be thoroughly studied to ensure such cells are not set up or accentuated in the future. It is possible that these could occur throughout the estuary. In addition measures, where possible, should be used to reduce the magnitude or eliminate the possibility of such cells occurring.

In this assessment, however, consideration of the economics and environmental issues should be made, because as indicated in the Humber Estuary case example complete elimination of re-circulation, could potentially reduce the supply of sediments that the estuary needs to environmentally and ecologically function. Also, the estuary will always re-introduce sediment with the tidal flows; therefore there will always be sediment to manage. In such a case it is possible the best practical environmental and cost effective solution may be to allow/manage some re-circulation.

What is the assessment of the removal of sediments from the Elbe estuary in view of the long-term "solids balance"?

The tidal Elbe is for the most part strongly flood dominant and fine sediment is transported from the North Sea, through the mouth. This material is moved up the estuary where it settles out in the Harbour Basins, near the head of the estuary. This sediment will at some point have passed through any location where potential sedimentation could occur. If, therefore, sediment is dredged from the Harbour Basins and removed from the system, it will not affect the long term solids balance within the estuary as this material would have already had the potential to settle out down estuary. That being the case, the dredged material is only the sediment which the estuary did not require to morphologically evolve under the existing hydrodynamic conditions. Albeit, this assumes the existing sediment supply from outside the system is not changed. If the import of marine sediment reduces, the amount of material in the system would reduce and eventually no maintenance dredging would be required. Removal of fine sediment from the system as a whole, particularly from up estuary sedimentation areas is therefore not expected to affect the morphological functioning of the estuary in its own right.

Is the practice of sediment trapping for fine material management appropriate and should the concept be extended?

As discussed in earlier sections, the tidal pumping will always move fine sediment into the Port area, therefore, if recirculation cells are eliminated the only other way of reducing dredging in the Harbour is to trap the sediment from the water column before it reaches the basins. However, flow speeds are high, so large horizontal 'stilling basins' will be required, whereby flow speeds are reduced and sedimentation can occur along the estuary from the rising tide. Coarser material moving near the bed is more likely to be intercepted by a vertical trap in the estuary bed, such as at Wedel. It is considered that flood storage area measures should be designed in a way that they also act as sediment traps, both up and down estuary of Hamburg. Trapping of the sediment in this way will also reduce the volume of contaminated sediments that need to be managed, particularly until up river source control can further clean up the sediment entering from the river. Such multi-functional measures should provide the most cost effective way of managing the maintenance dredging, particularly in the Hamburg area.

Overall Assessment

From this analysis and understanding of the tidal Elbe, the RESMC provides a means to manage sedimentation (hence maintenance dredging) and reduce the current levels of flood risk and ameliorate the future effects of SLR. It would appear the current level of tidal pumping is unlikely to be substantially reduced; however, the sediment concentrations it moves up estuary are likely to be able to be managed or intercepted. In order for the RESMC to be effective, a number of different measures of the type already envisaged will be required. It is clear from the historical analysis, however, that some measures could have local beneficial effects but could cause 'knock on' effects which could lead to greater problems elsewhere and/or in the longer term.

Careful design, supported by detailed modelling investigations of the effects of individual measures as well as the combined effects for the estuary as whole will therefore be required. The results of the modelling should also be assessed against the historical understanding from the past activities on the estuary.

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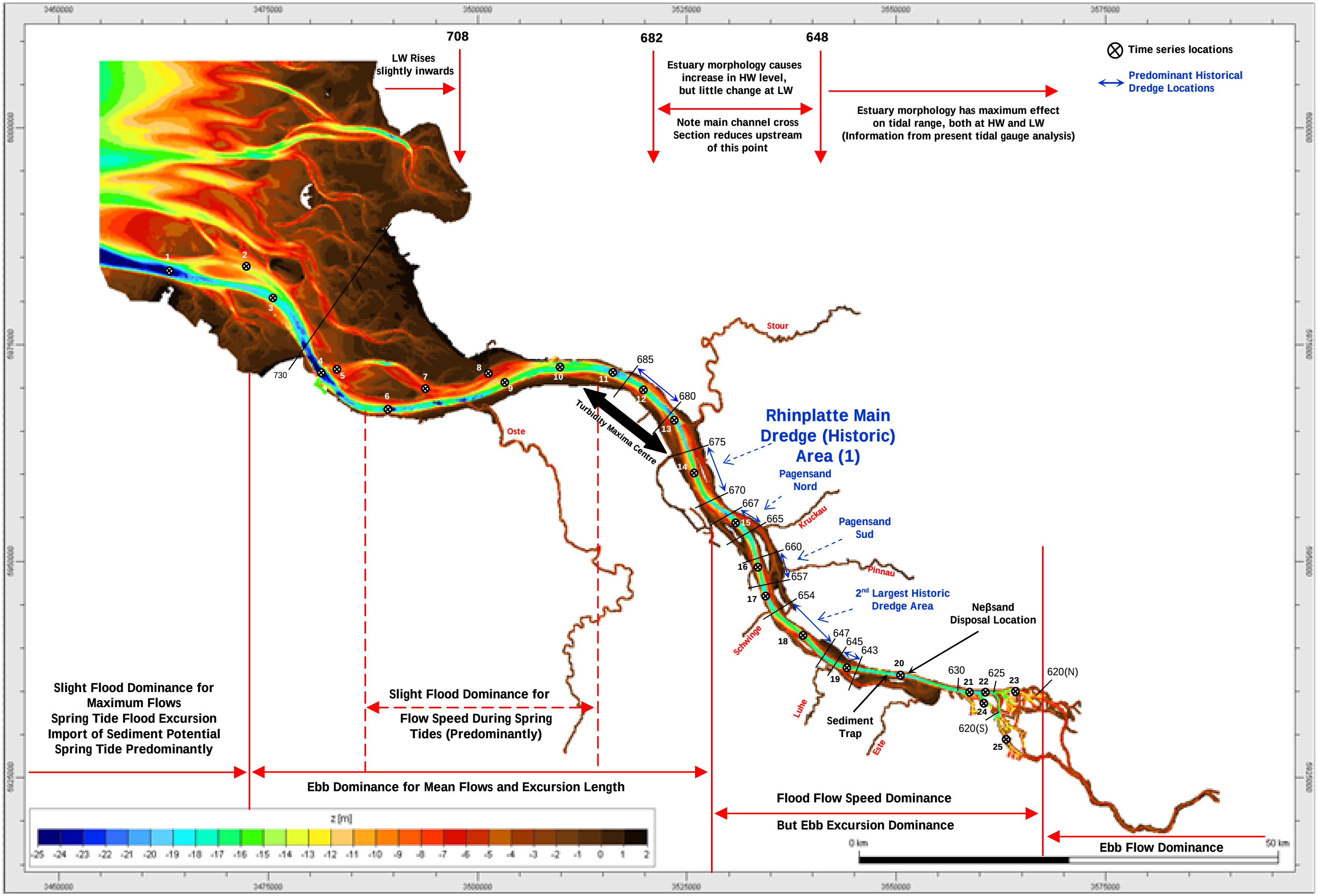
Figures



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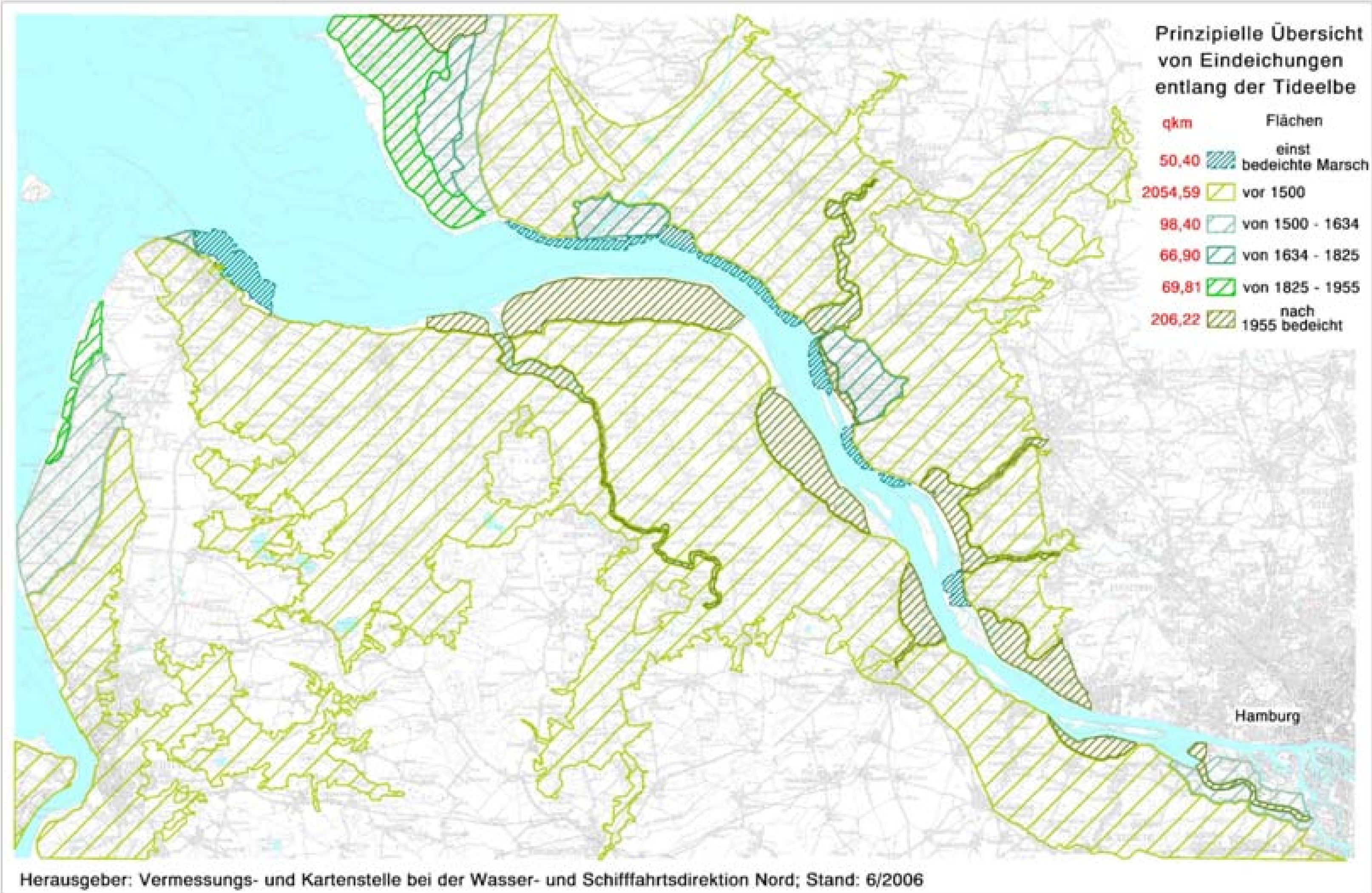
River Elbe Morphology and a Summary of Physical Processes

Figure 1



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[HPA & WSD-N, 2006]

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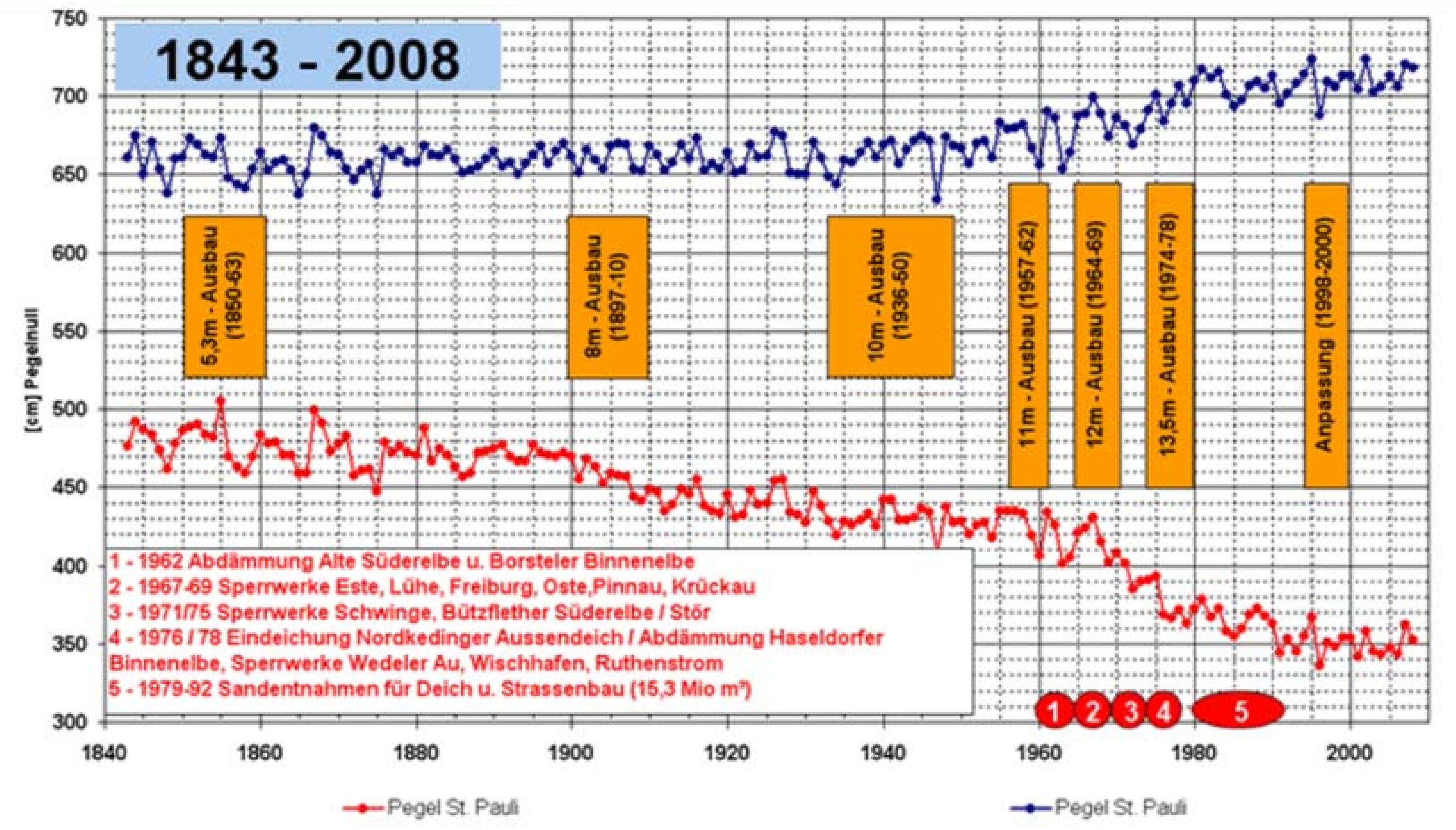
Anthropogenic Changes to the Estuary Configuration of the River Elbe

Figure 2



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[Eichweber, 2011]

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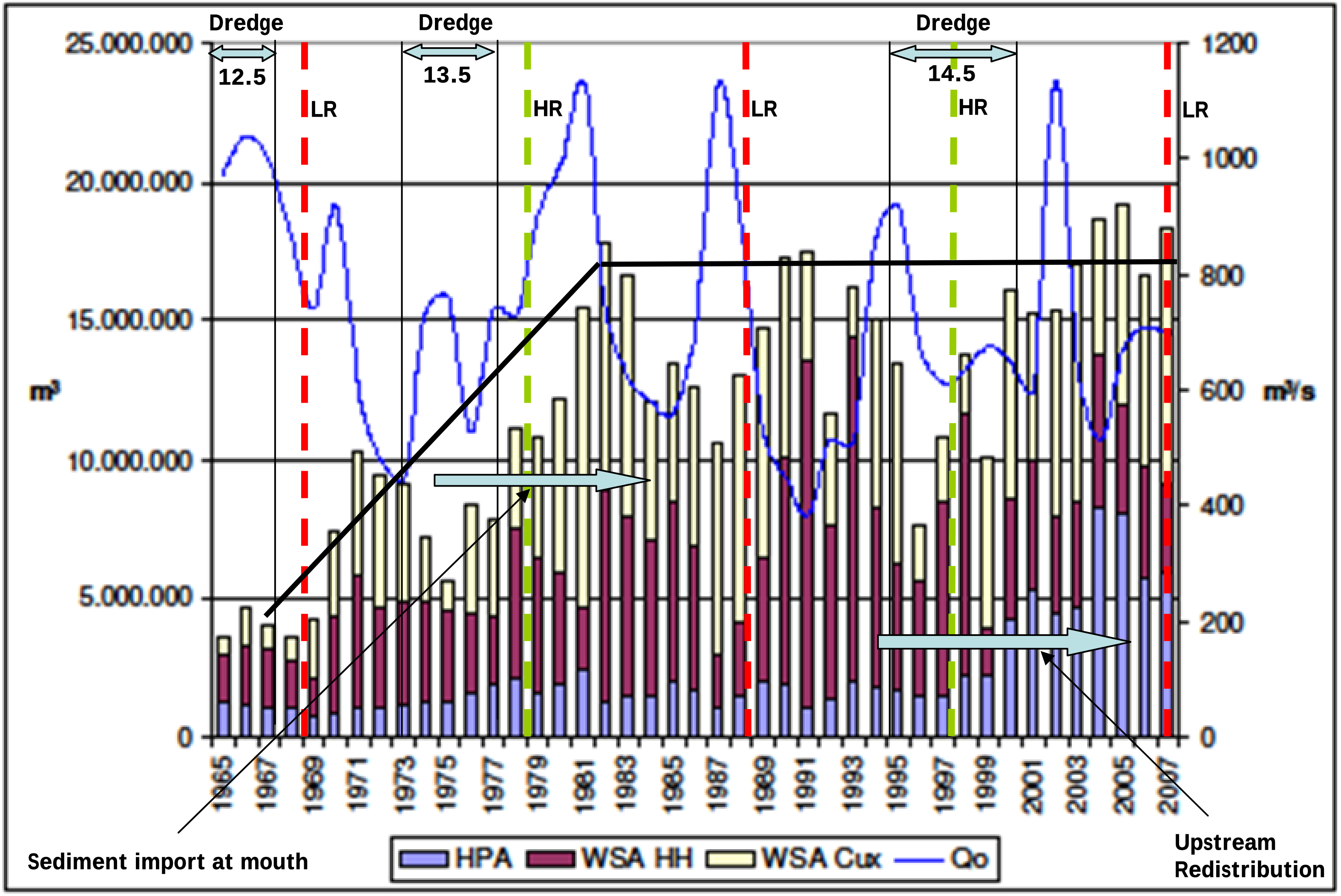
Capital Dredging on the River Elbe Related to Changes in the Recorded Tidal Levels at St. Pauli

Figure 3



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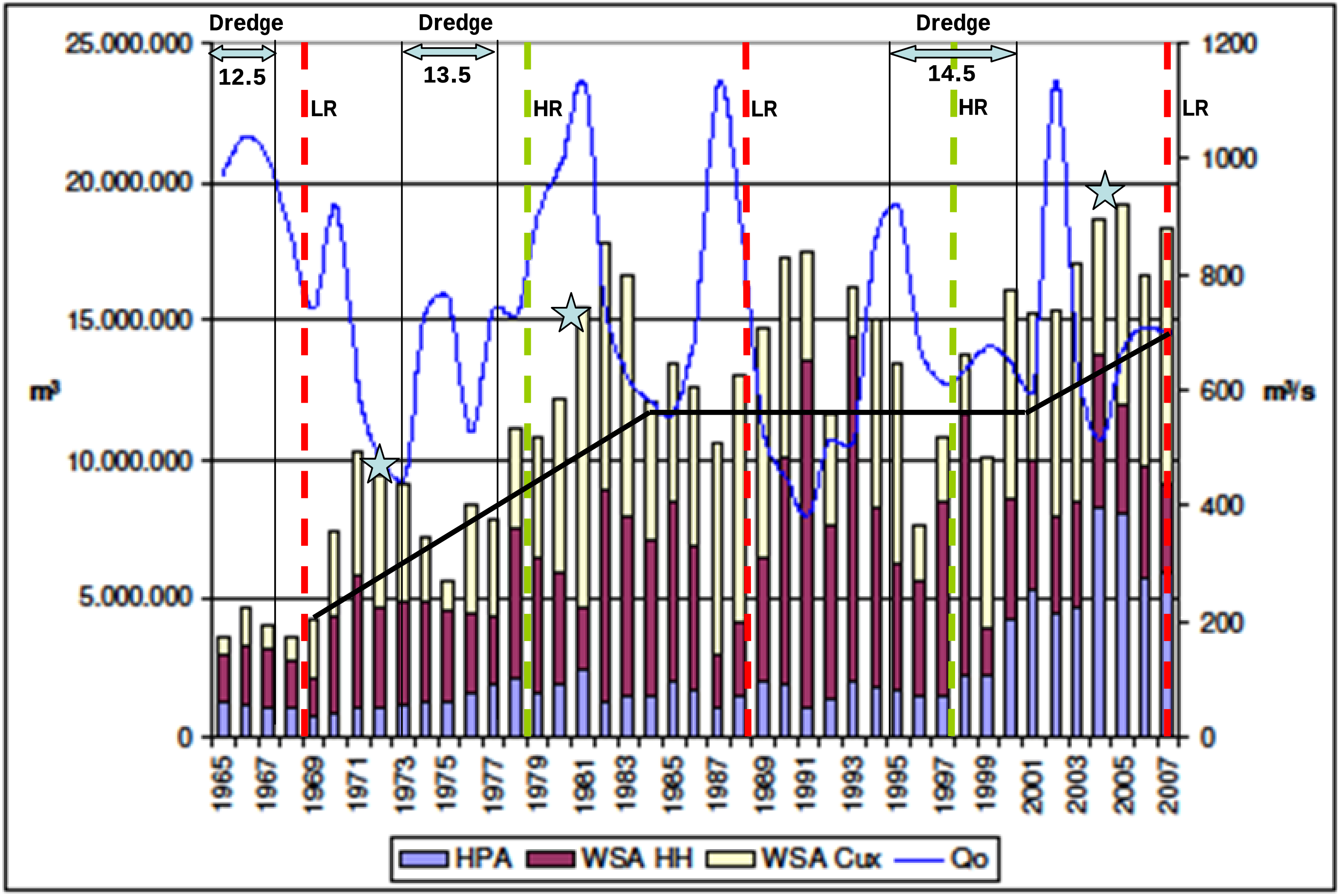
Maintenance Dredging in the River Elbe (1965 to 2007) – Interpretation 1

Figure 4



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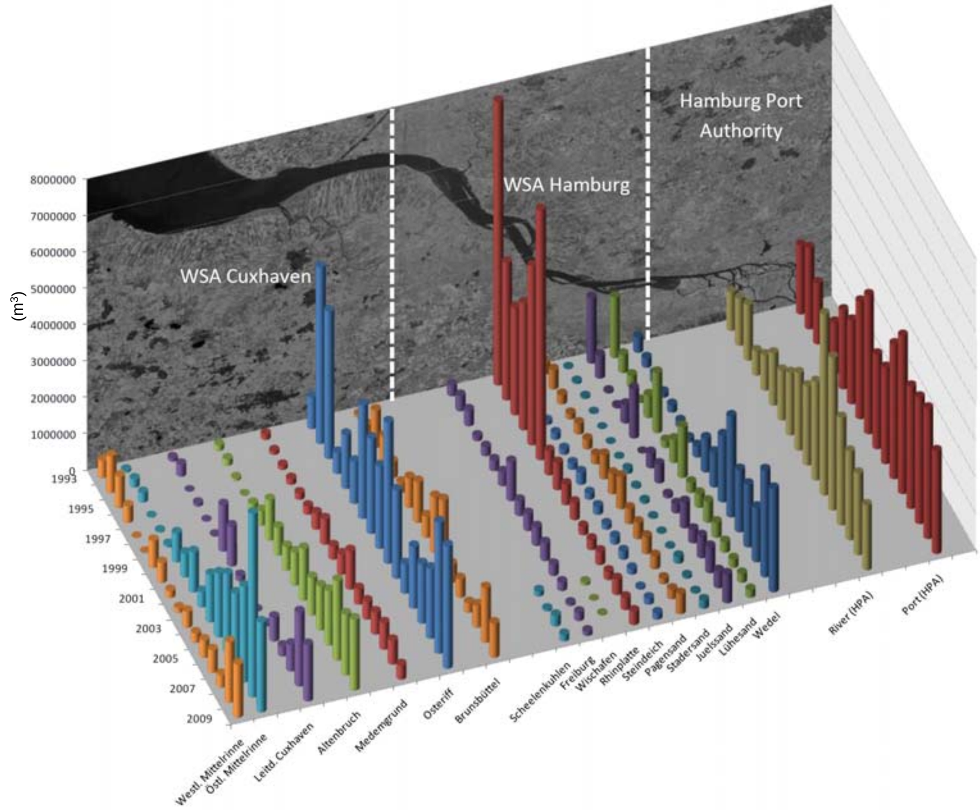
Maintenance Dredging in the River Elbe (1965 to 2007) – Interpretation 2

Figure 5



	Designation/Name	Elbe km	Type of Dredged Material
BA1	Wedel	638.9 – 644.0	Silt/fine sand
BA2	Lühesand	644.0 – 649.5	Predominantly medium sand
BA3	Juelssand	649.5 – 654.4	Silt/fine sand
BA4	Stadersand	654.5 – 659.0	Predominantly medium sand
BA5	Pagensand	659.0 – 664.5	Fine/medium sand
BA6	Steindeich	664.5 – 670.0	Predominantly (medium) sand
BA7	Rhinplate	670.0 – 676.0	Predominantly medium sand, some fine-sand / silty areas
BA8	Wischhafen	676.0 – 680.5	Almost exclusively (medium) sand
BA9	Freiburg	680.5 – 685.5	Almost exclusively (medium) sand
BA10	Scheelenkuhlen	685.5 – 689.8	Almost exclusively (medium) sand
BA11	Brunsbüttel	689.8 – 698.5	Predominantly medium sand, some fine-sand / silty areas
BA12	Osteriff	698.5 – 709.9	Fine sand/silt
BA13	Medemgrund	709.0 – 717.0	Predominantly (fine) sand
BA14	Altenbruch	717.0 – 726.0	Predominantly (fine) sand
BA15	Leitdamm Cuxhaven	726.0 – 732.0	Predominantly (fine) sand
BA16	östliche Mittelrinne	732.0 – 739.0	Fine to coarse sand
BA17	westliche Mittelrinne	739.0 – 748.0	Fine to coarse sand

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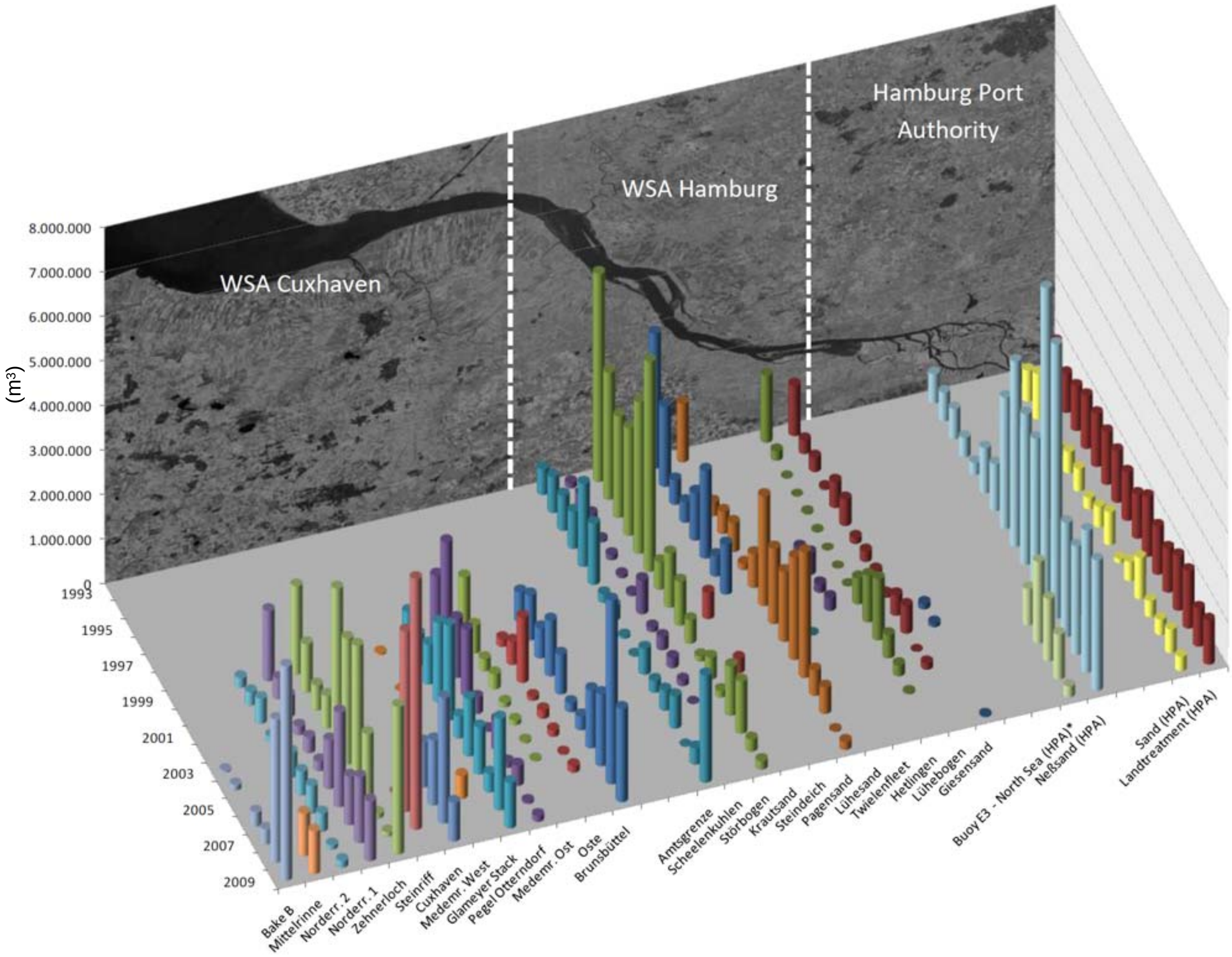
Dredge Amounts in the Tidal Elbe (1993 to 2009) and an Overview of the Type of Material Dredged

Figure 6



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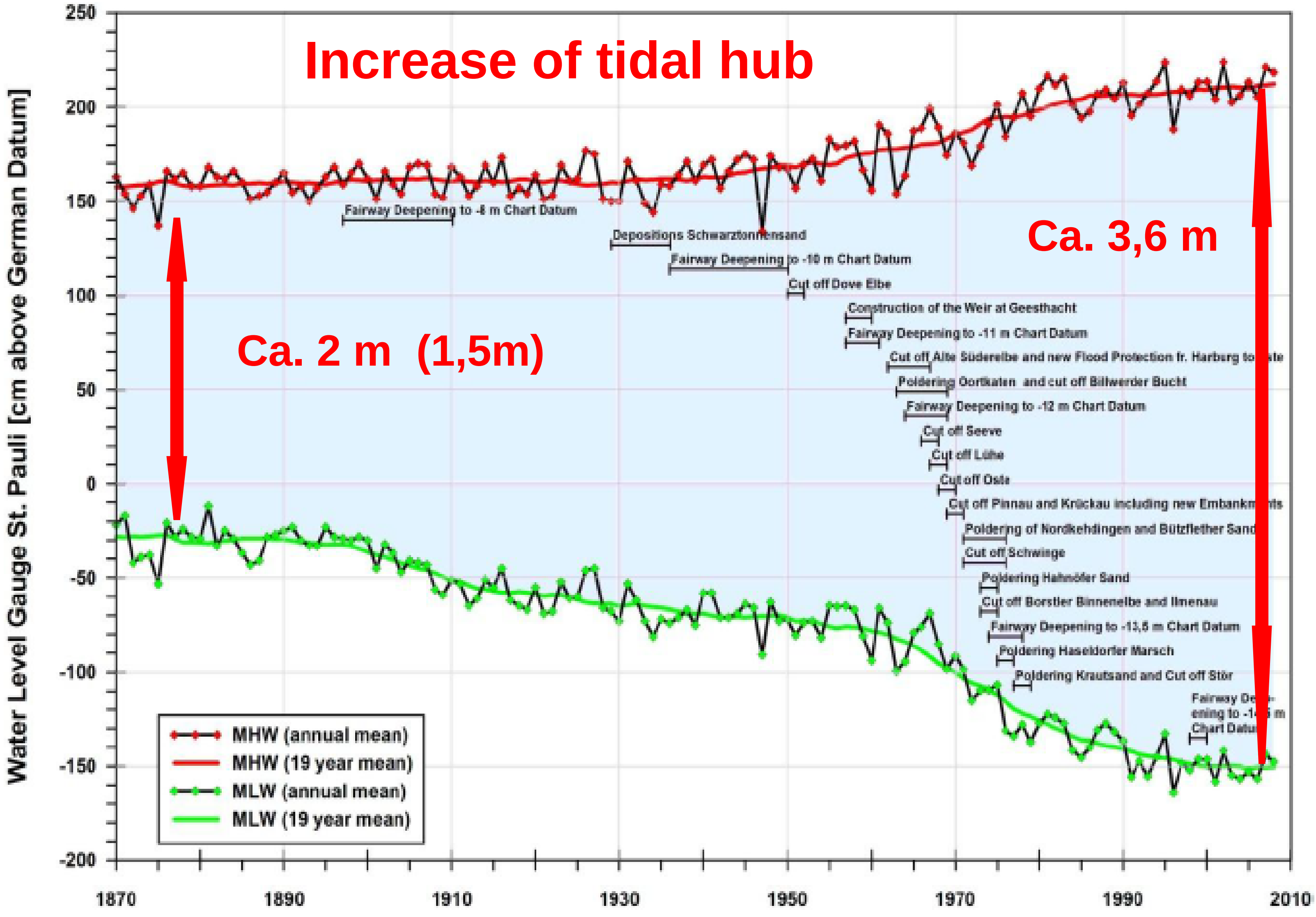
[HPA & WSD-N, 2010]

Relocation Volumes in the Tidal Elbe (1993 to 2009)

Figure 7



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[HPA & WSD-N, 2010]

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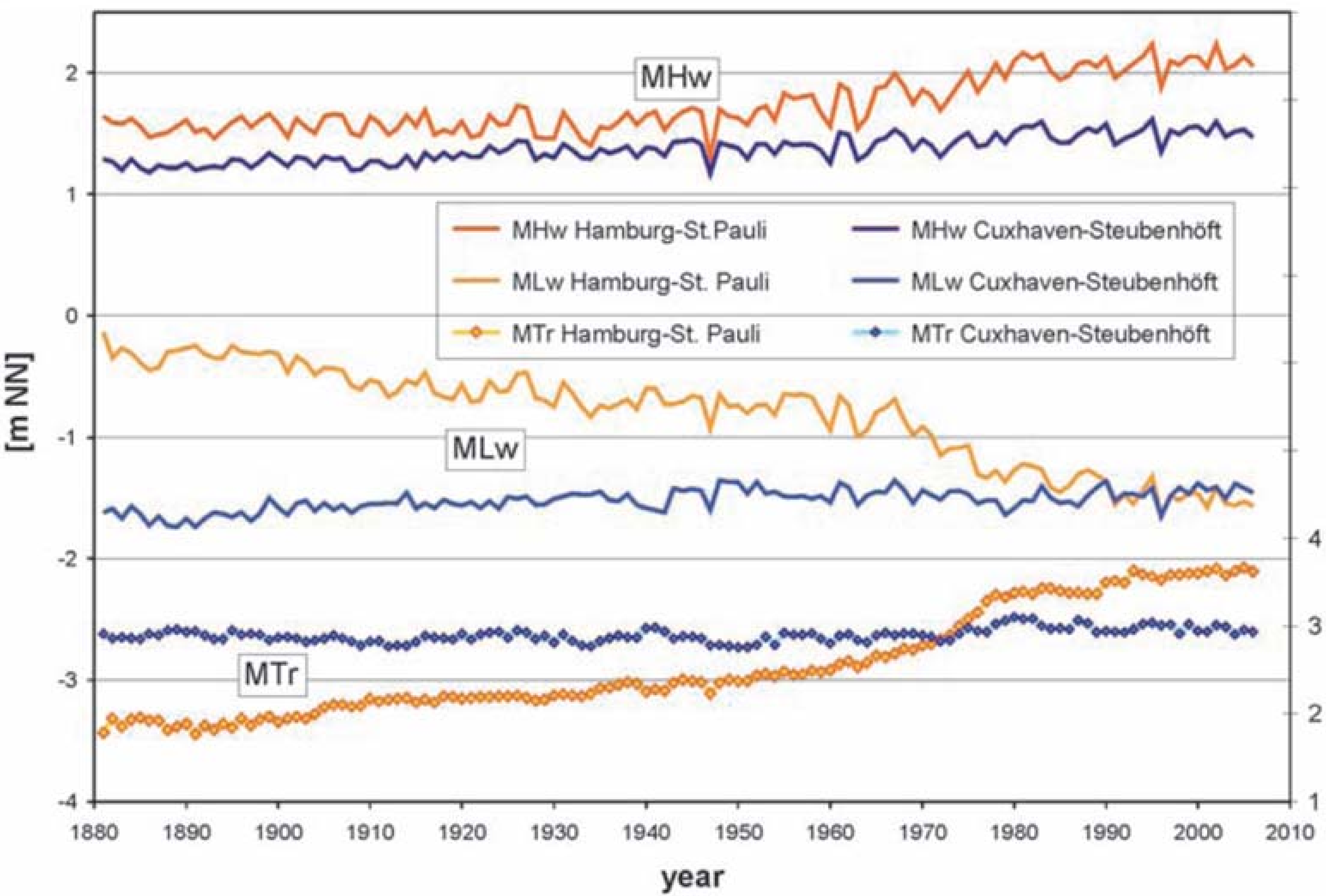
Combined Effect of Developments on the Tidal Range at St. Pauli

Figure 8



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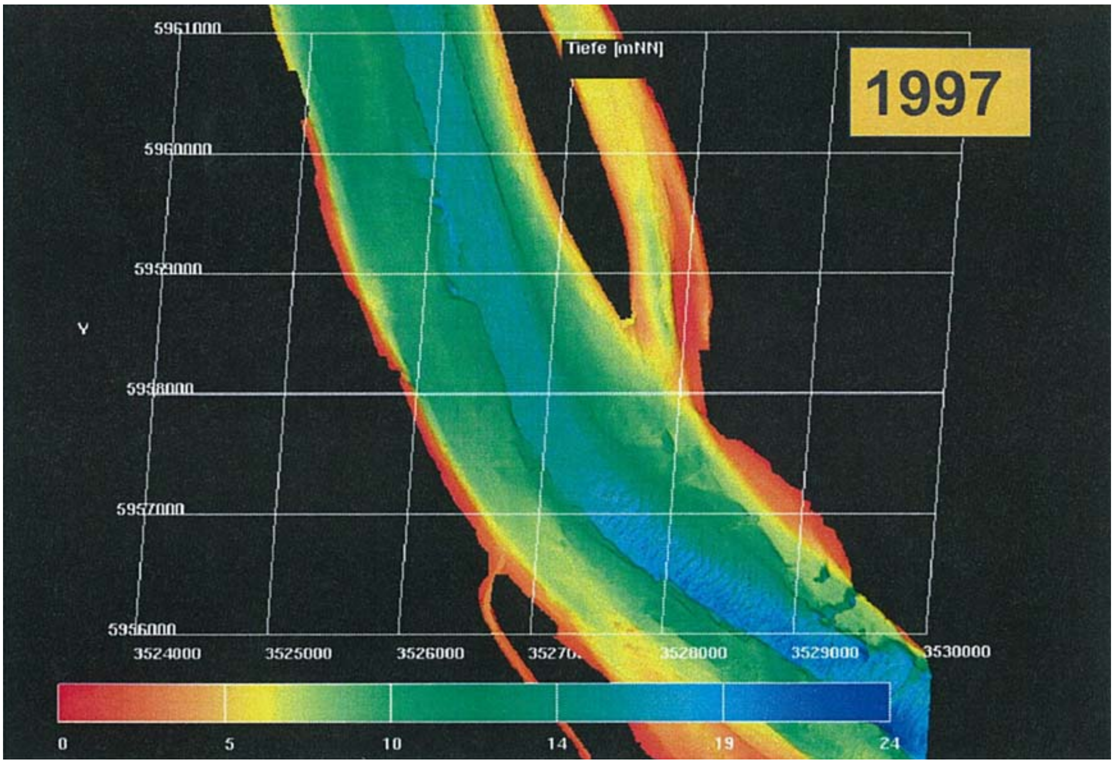
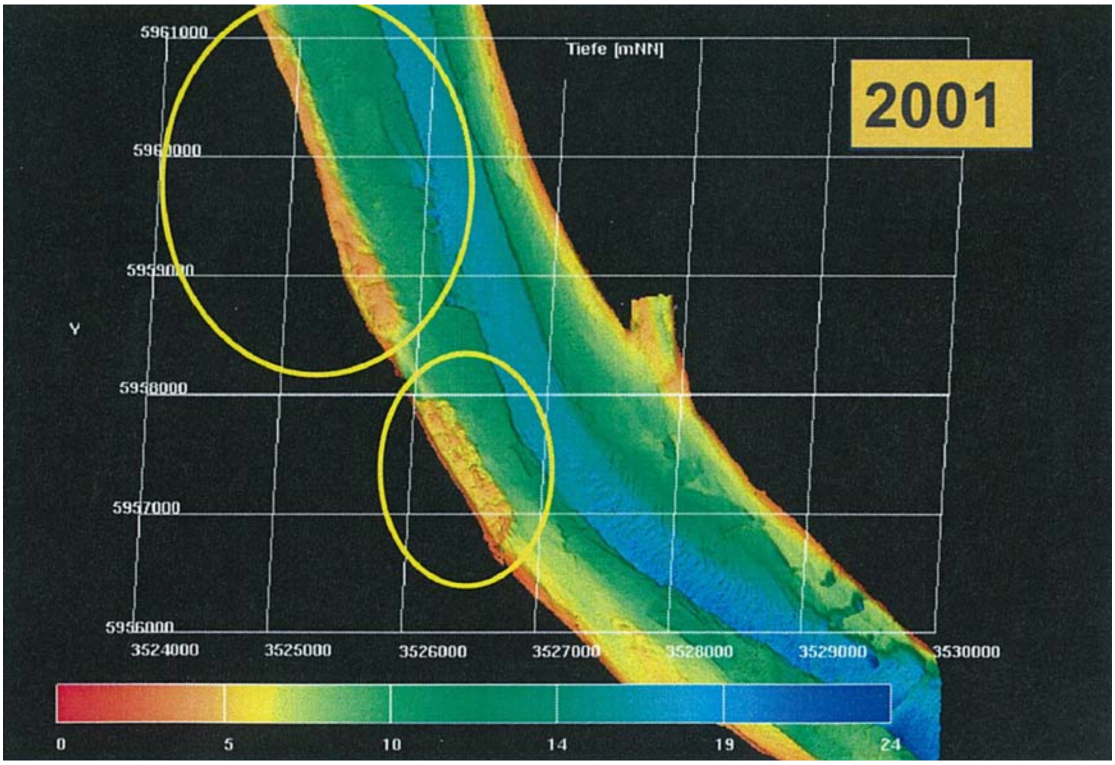
Development of the Water Levels and Tidal Range Since 1880 at Cuxhaven and St. Pauli (Hamburg)

Figure 9





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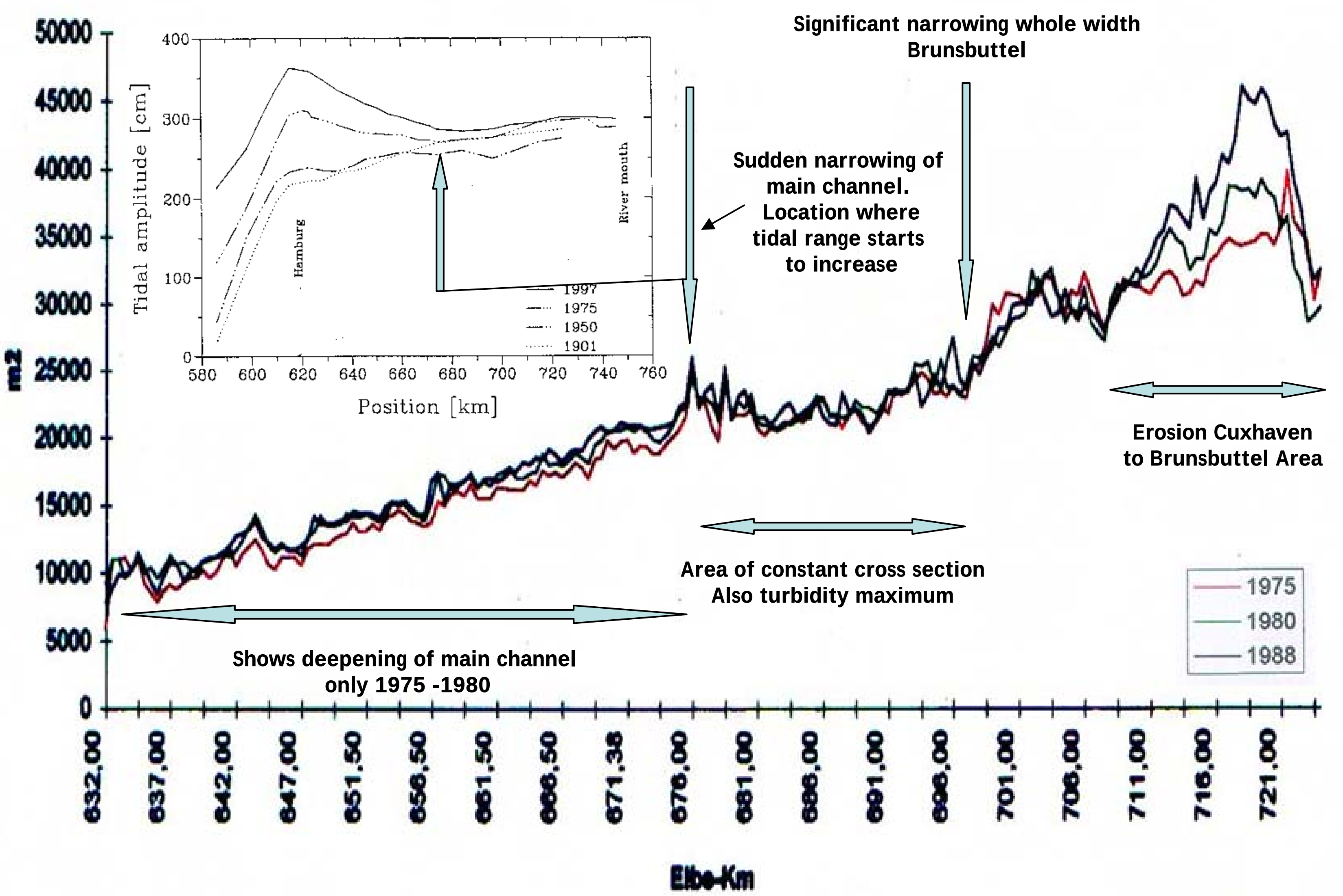
[Boehlich, 2003]

Krautsand Underwater Deposition Areas

Figure 10



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[HPA & WSD-N, 2008; Eichweber, 2011]

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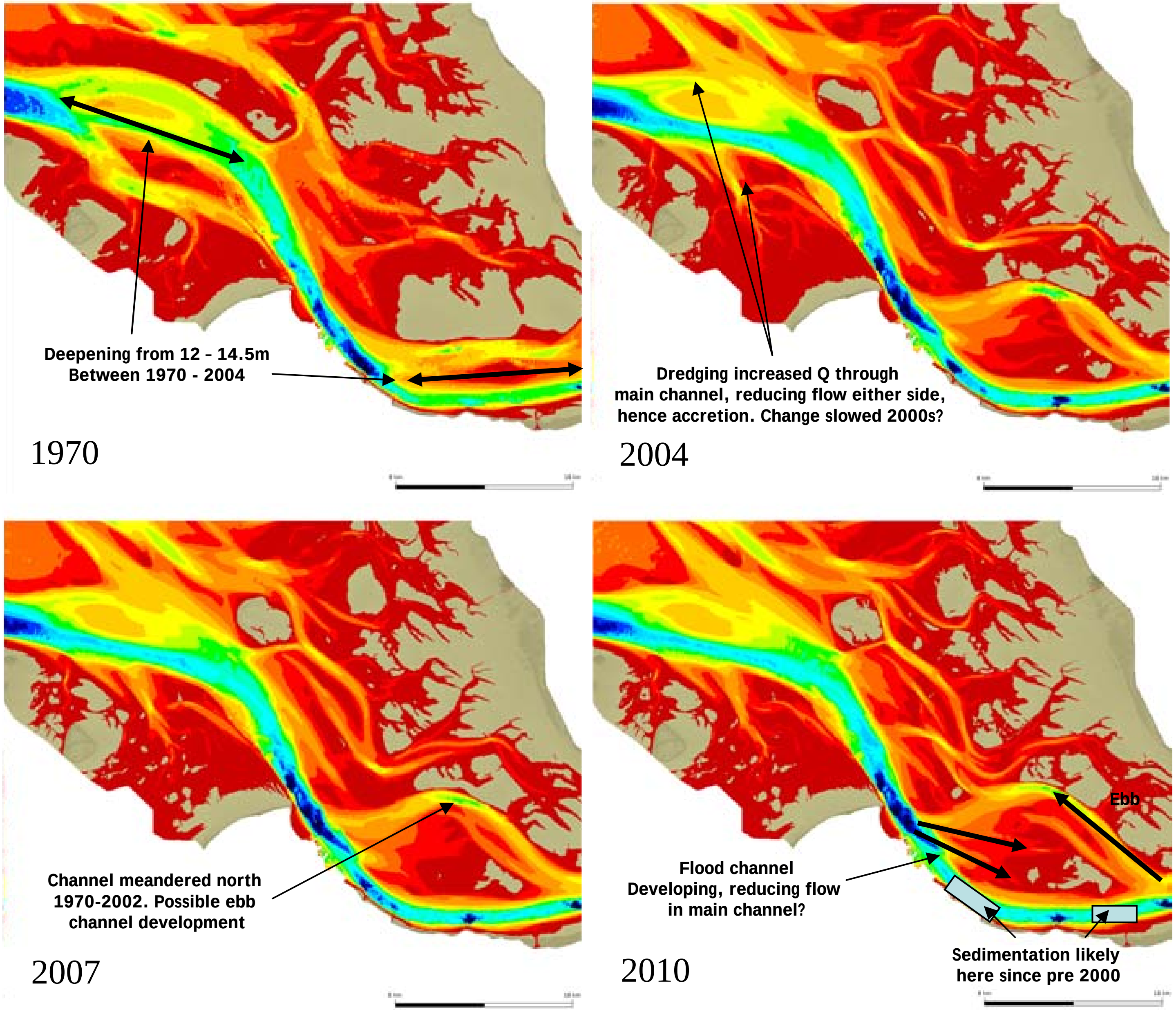
Change in the Cross Sectional Area of the River Elbe Between 1975 and 1988

Figure 11



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[Derived from BAW model outputs]

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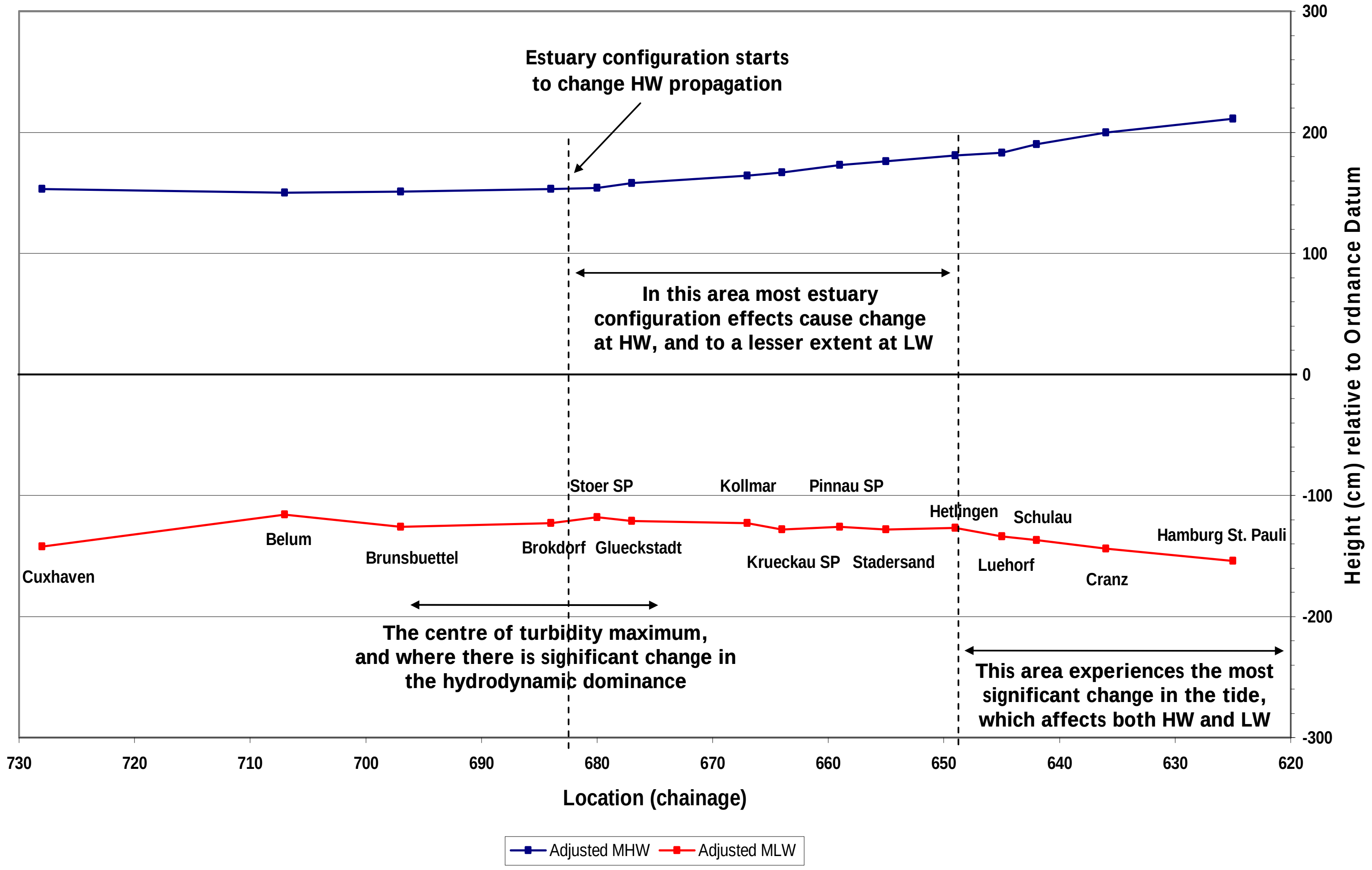
Morphological Evolution of the Outer Elbe Estuary (1970 to 2010)

Figure 12



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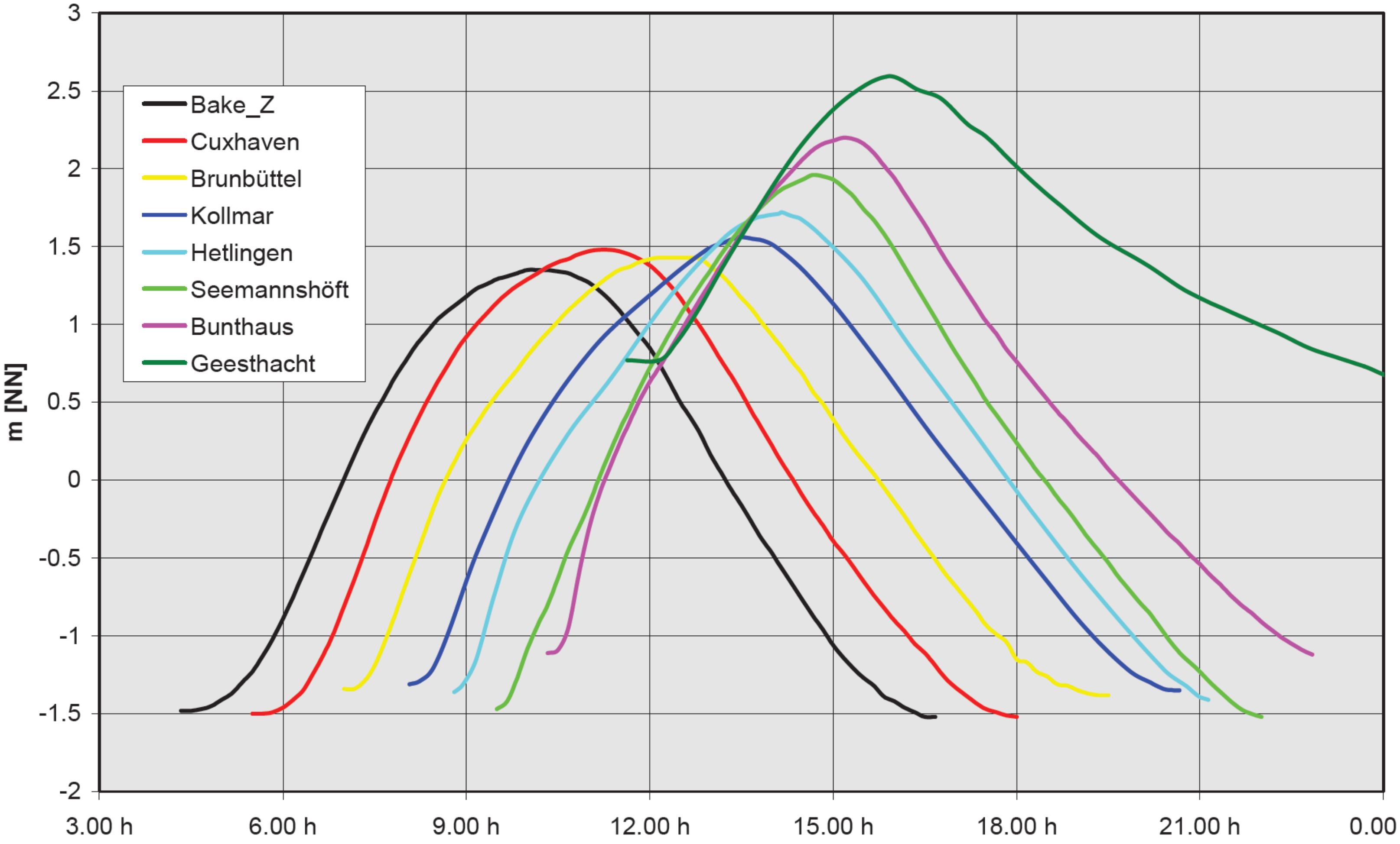
Change in Water Levels and Tidal Range along the River Elbe (2010)

Figure 13



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[Boehlich & Strotmann, 2008]

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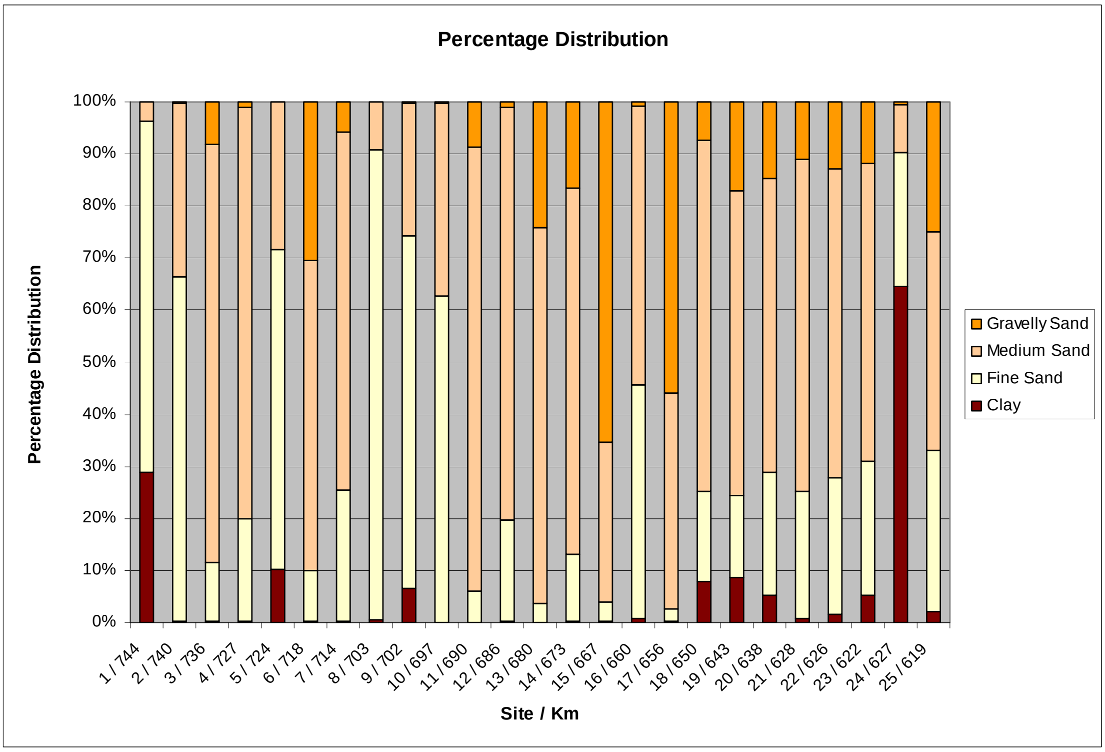
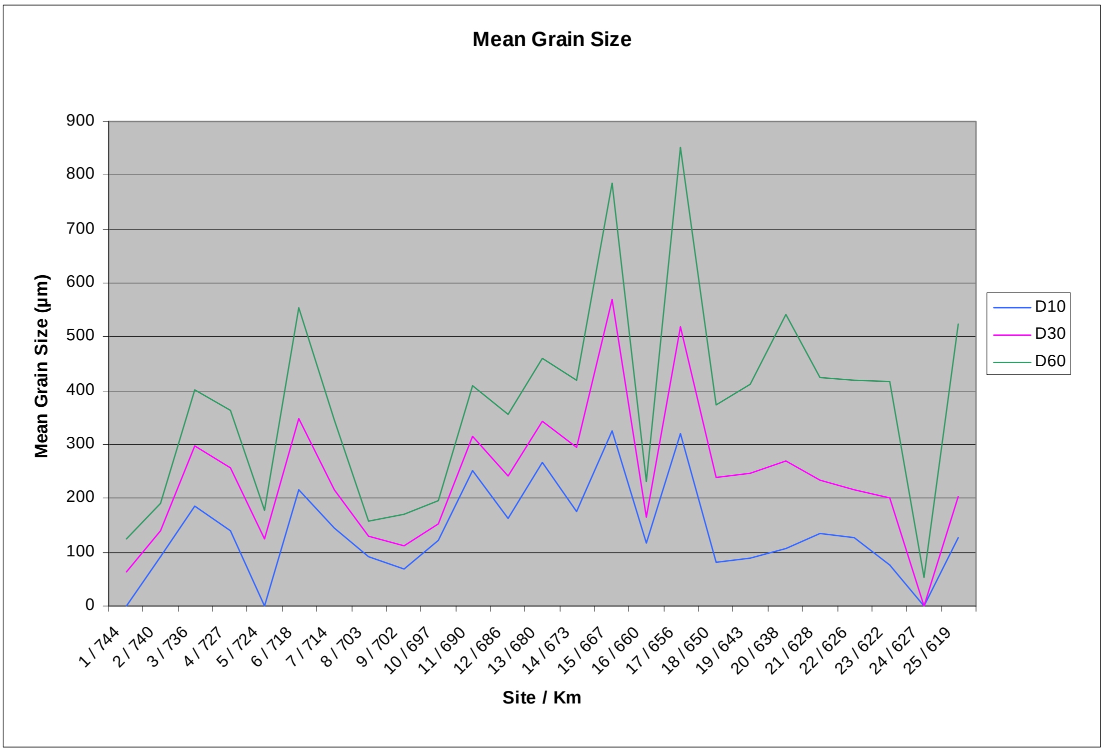
Development of the Tidal Curve along the River Elbe

Figure 14





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See Figure 1 for location

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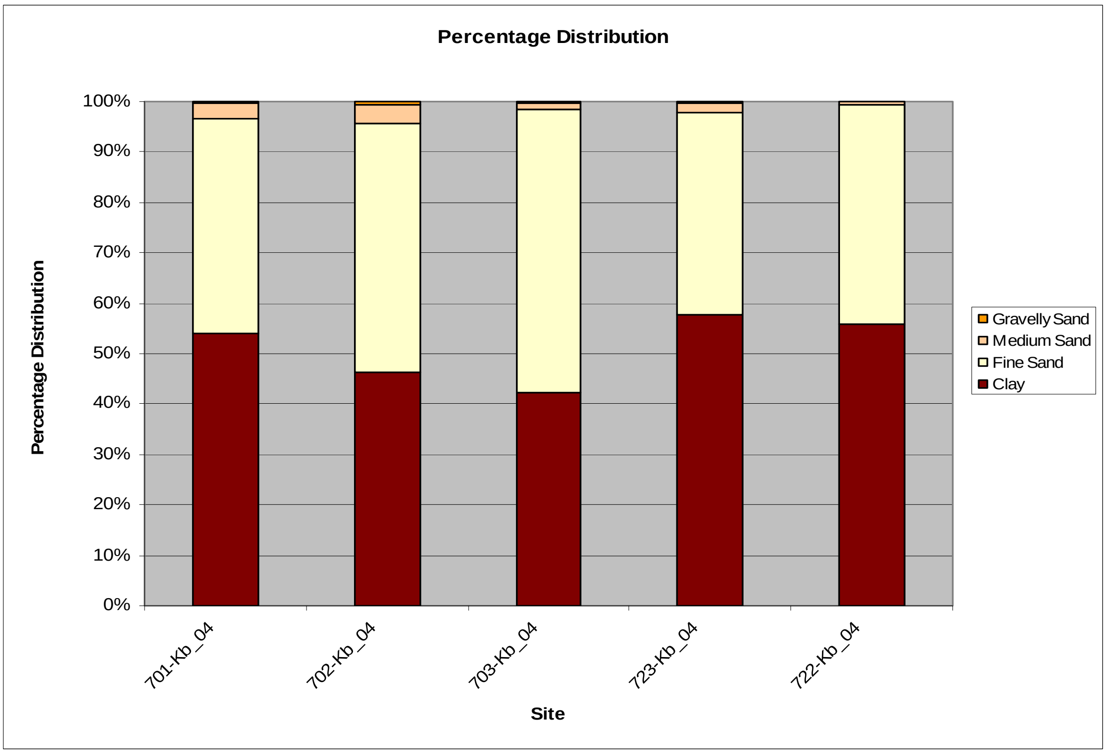
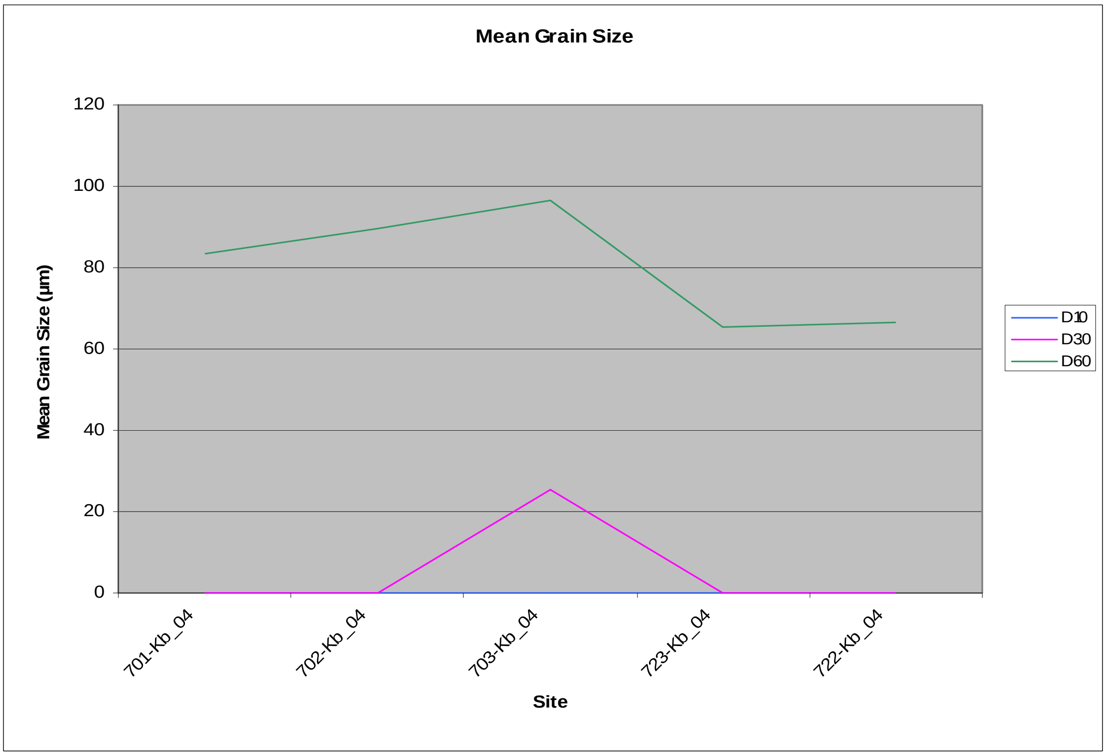
Sediment Size Analysis along the River Elbe

Figure 15





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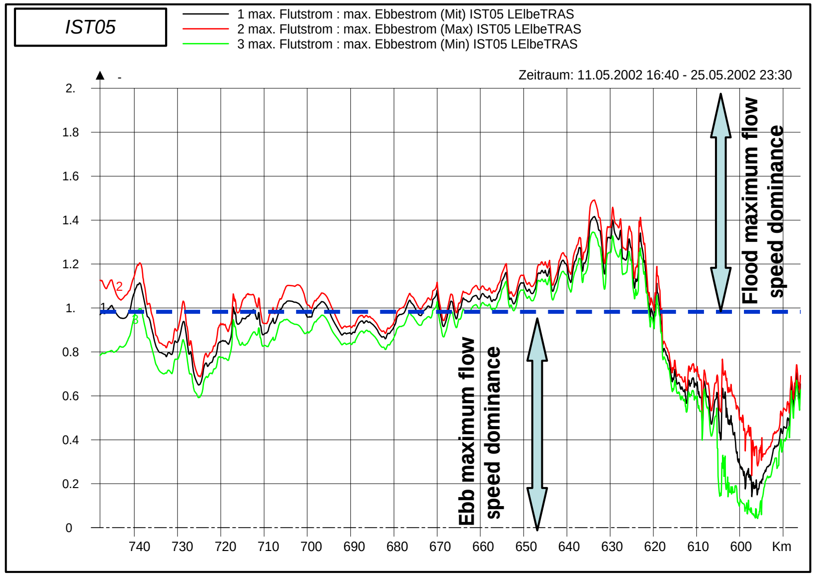
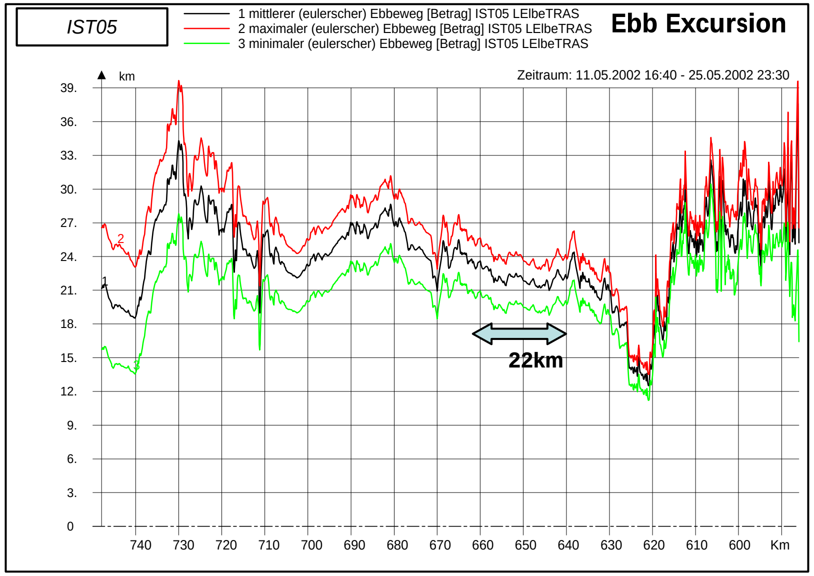
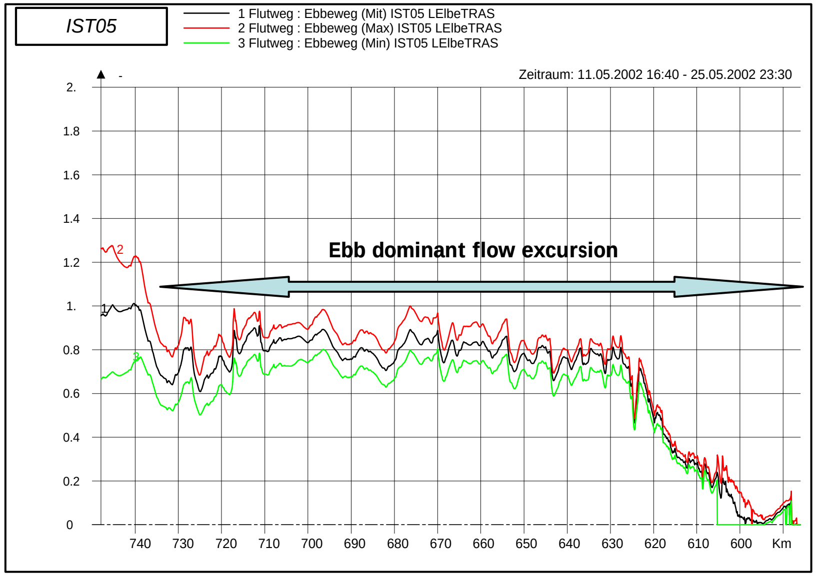
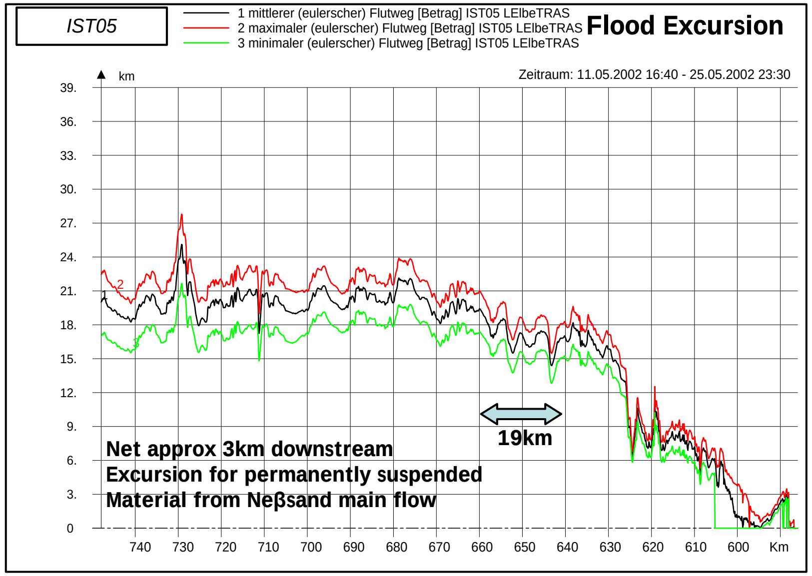
Sediment Size Analysis at Kohlbrand (Port Areas)

Figure 16









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April 2011	BJC	A4	1
QA		PAW	

3984 – Figure17.ppt

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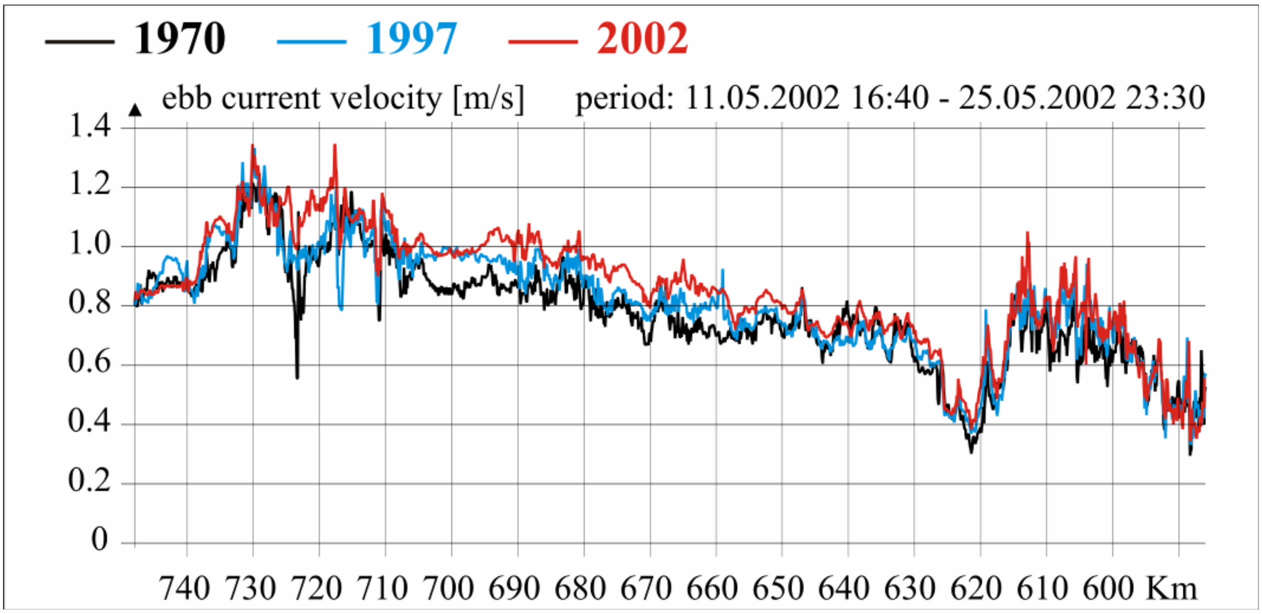
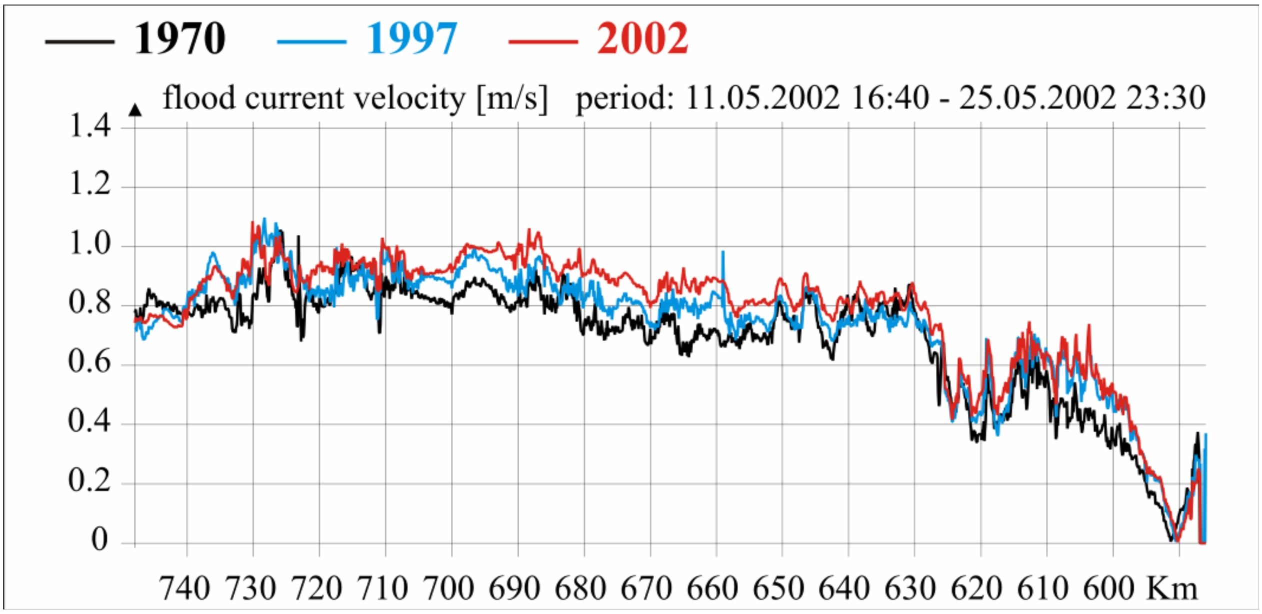
Numerical Modelling Results of Flood:Ebb Relationships along the River Elbe

Figure 17



Mean ebb flow speed in the middle of the fairway 1970, 1997 and 2002.



Mean flood flow speed in the middle of the fairway 1970, 1997 and 2002.

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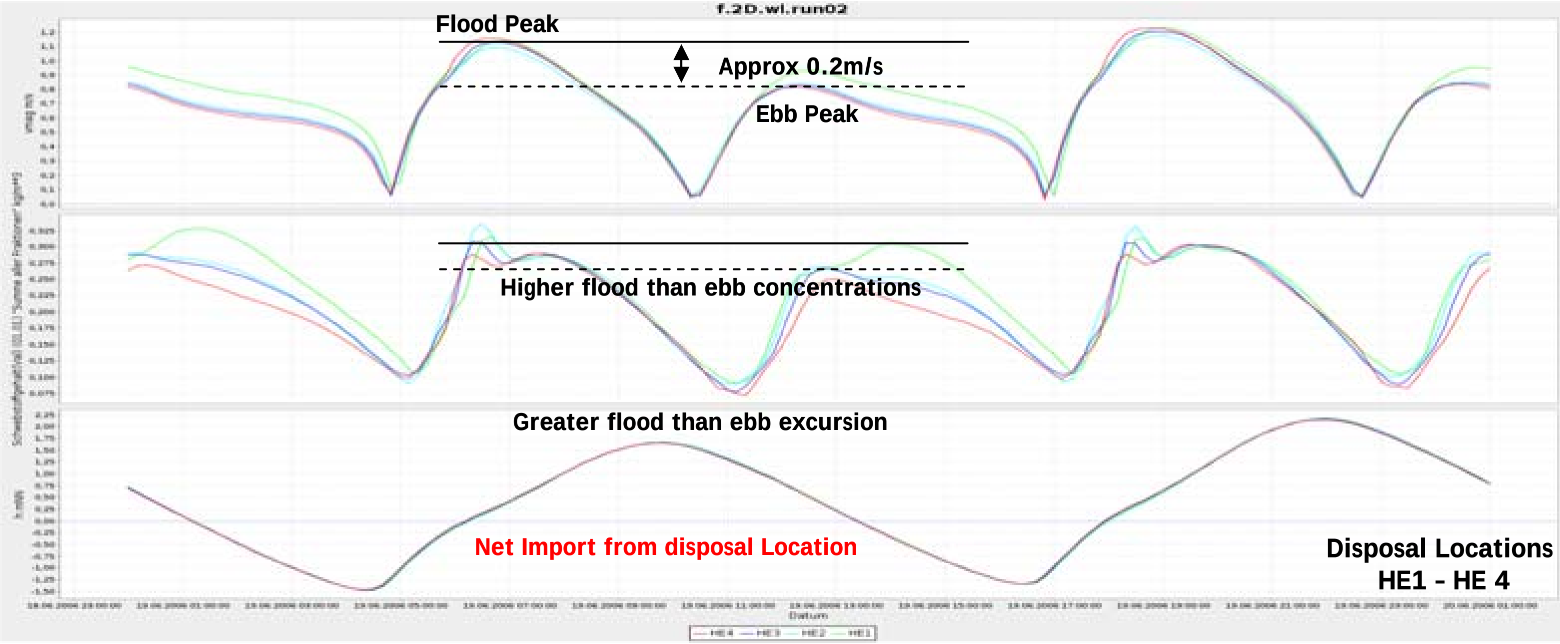
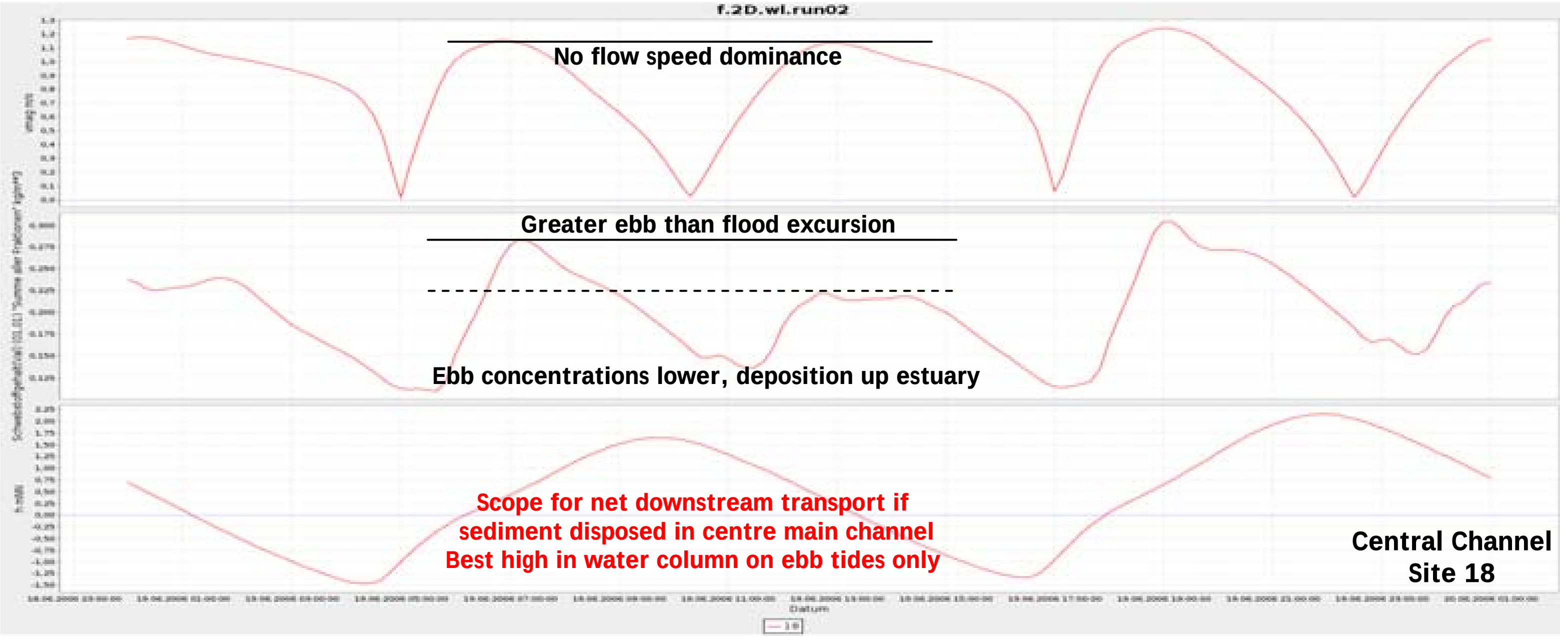
Change in Mid Fairway Flow Speed Between 1970, 1997 and 2002 (Model Results)

Figure 18





Date	By	Size	Version
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3984 – Figure19.ppt			
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[BAW (2011)Time Series (wl, cu, su) at Disposal Sites and Specific Locations. Based on Run02. Sim Period 06/2006]

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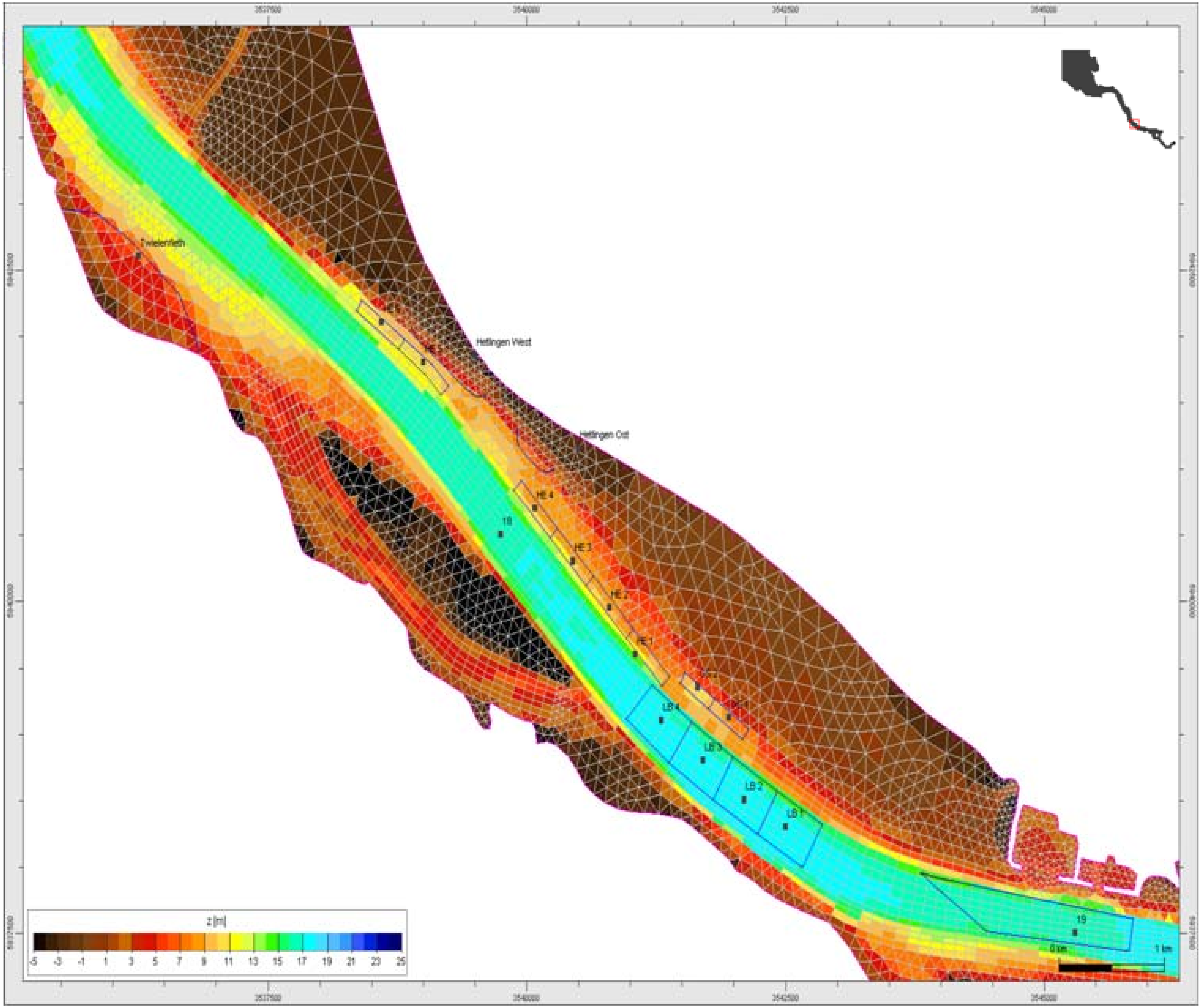
Time Series Data for Hetlingen Area on the River Elbe

Figure 19



Location of Time Series Data that can be seen on Figure 19

Date	By	Size	Version
April 2011	BJC	A4	1
QA		PAW	
3984 – Figure20.ppt			
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[BAW (2011)Time Series (wl, cu, su) at Disposal Sites and Specific Locations. Based on Run02. Sim Period 06/2006]

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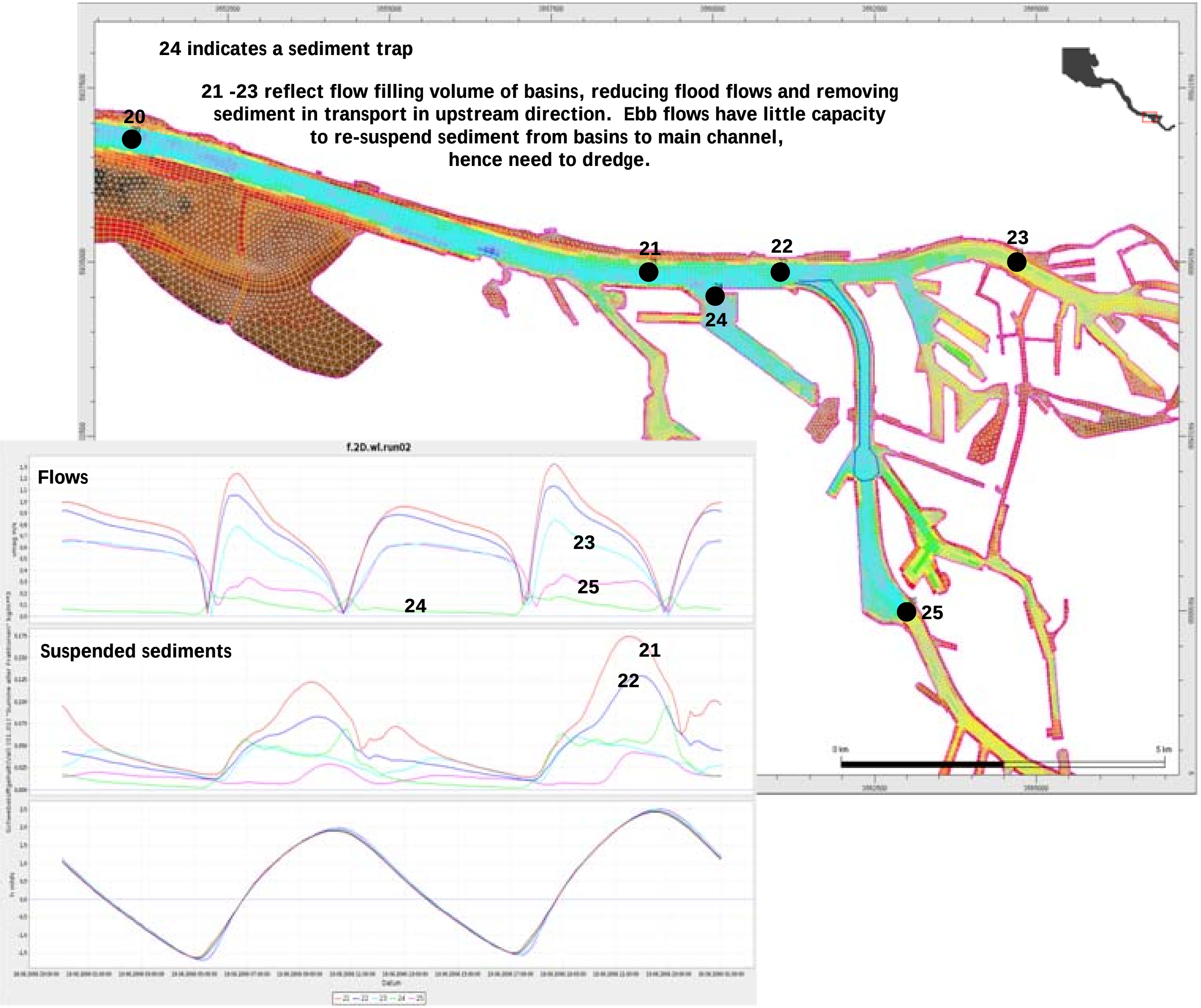
Location of Time Series Data

Figure 20



Date	By	Size	Version
April 2011	BJC	A4	1
QA		PAW	

3984 – Figure21.ppt

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[BAW (2011)Time Series (wl, cu, su) at Disposal Sites and Specific Locations. Based on Run02. Sim Period 06/2006]

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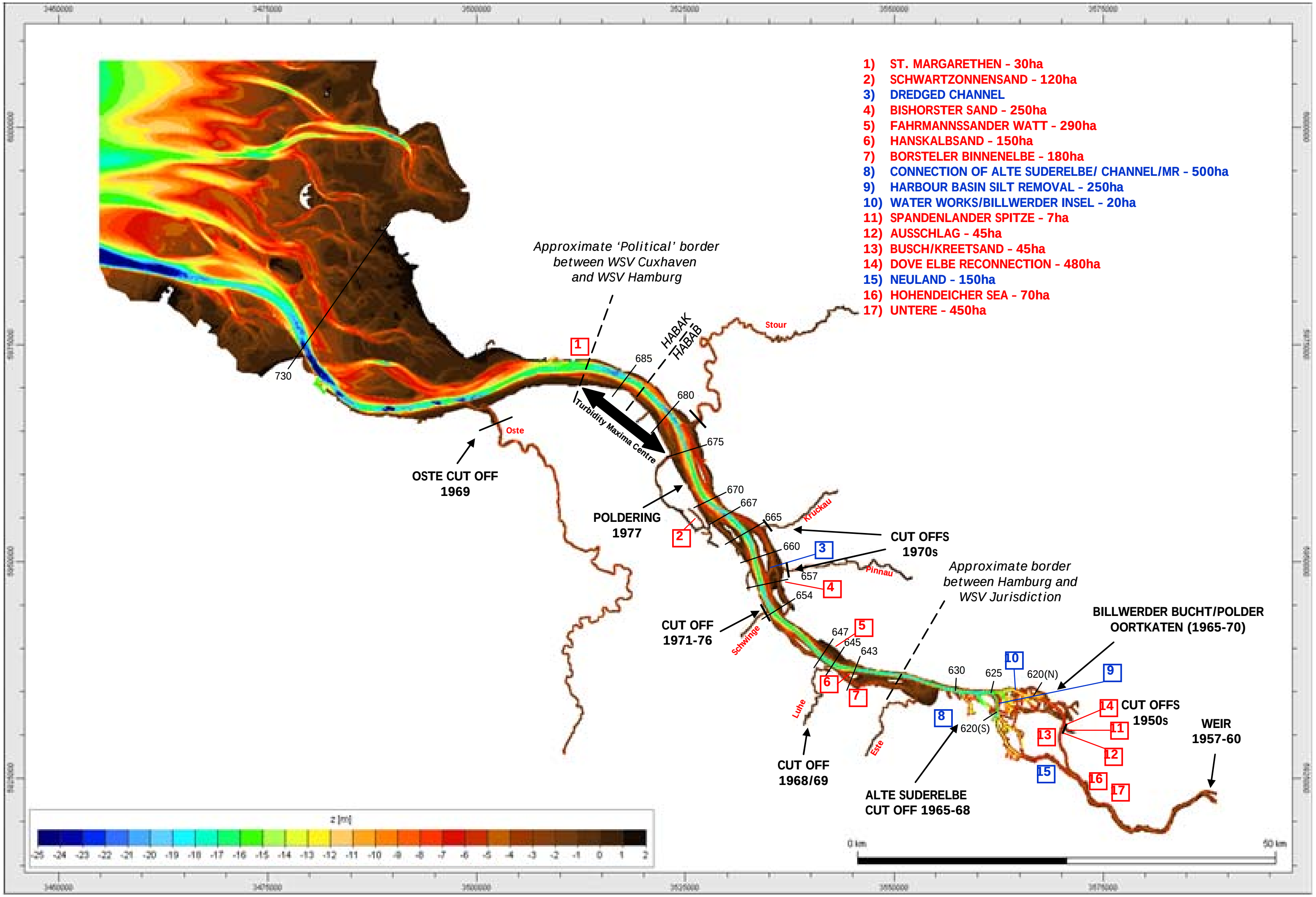
Water Levels, Flow Speeds and Suspended Sediment Concentrations in the Hamburg Harbour Area

Figure 21



Date	By	Size	Version
April 2011	BJC	A4	1
QA		PAW	

3984 – Figure22.ppt

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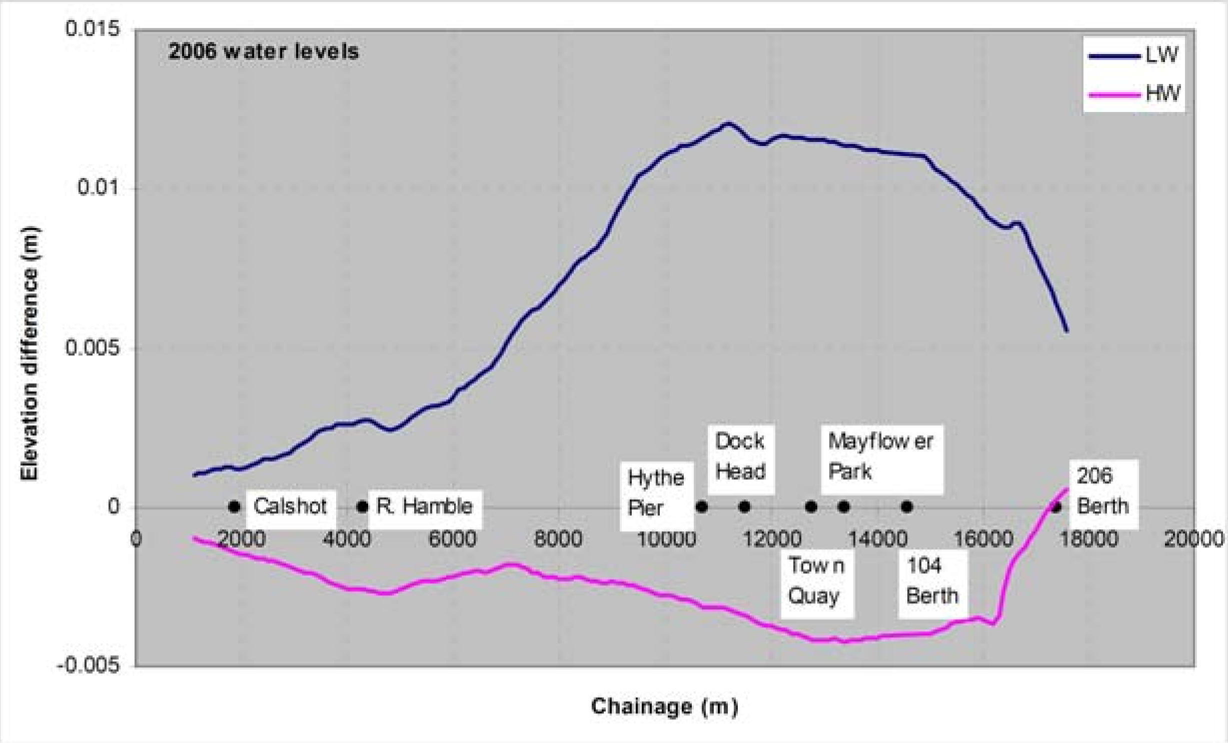
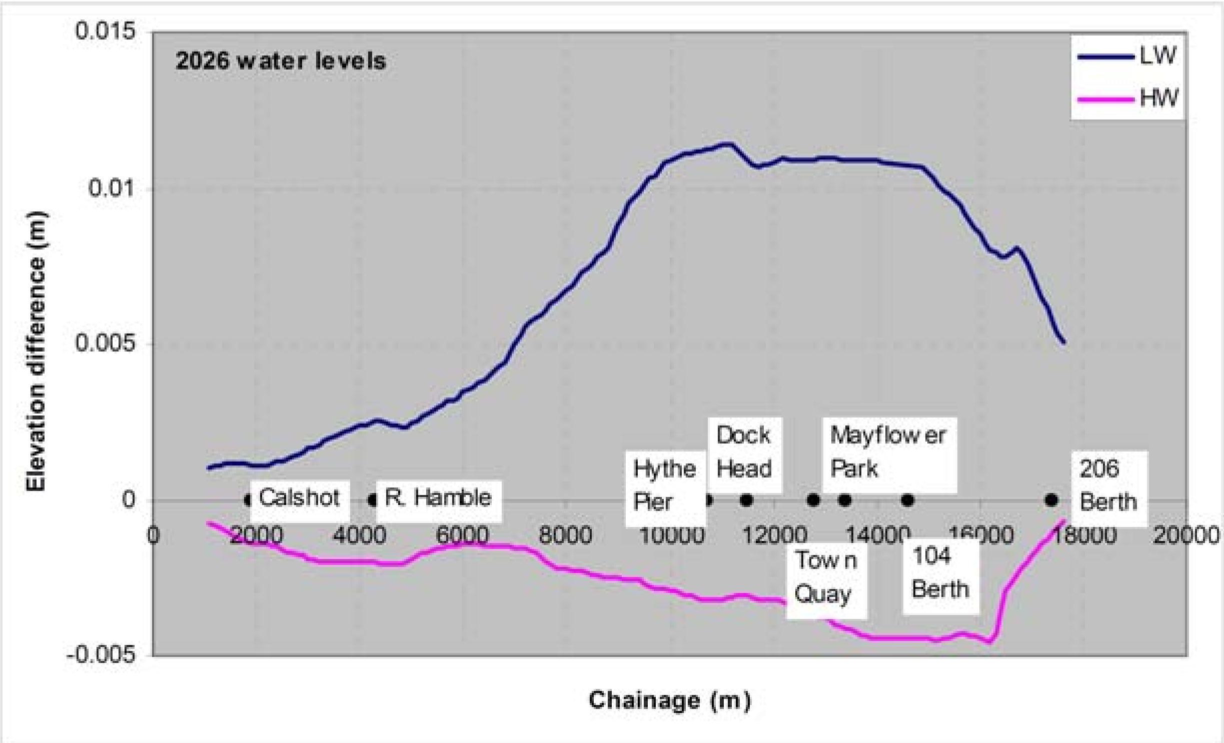
Locations of Proposed Measures to Increase Tidal Volume

Figure 22





Date	By	Size	Version
April 2011	BJC	A4	1
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3984 – Figure23.ppt			
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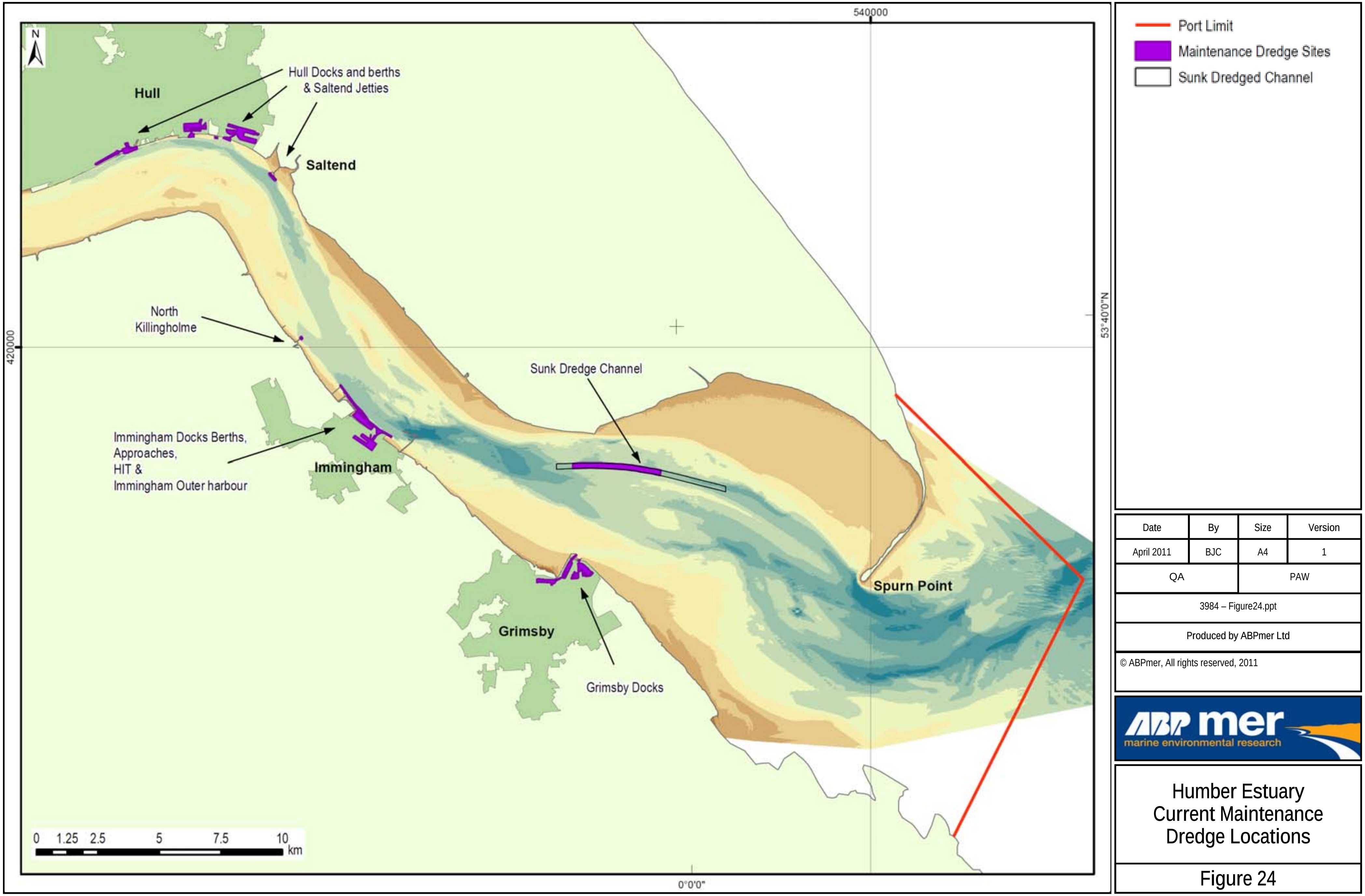
Differences in the Elevation of HW and LW, ‘With’ and ‘Without’ Southampton Approach Dredge, for 2006 and 2026

Figure 23



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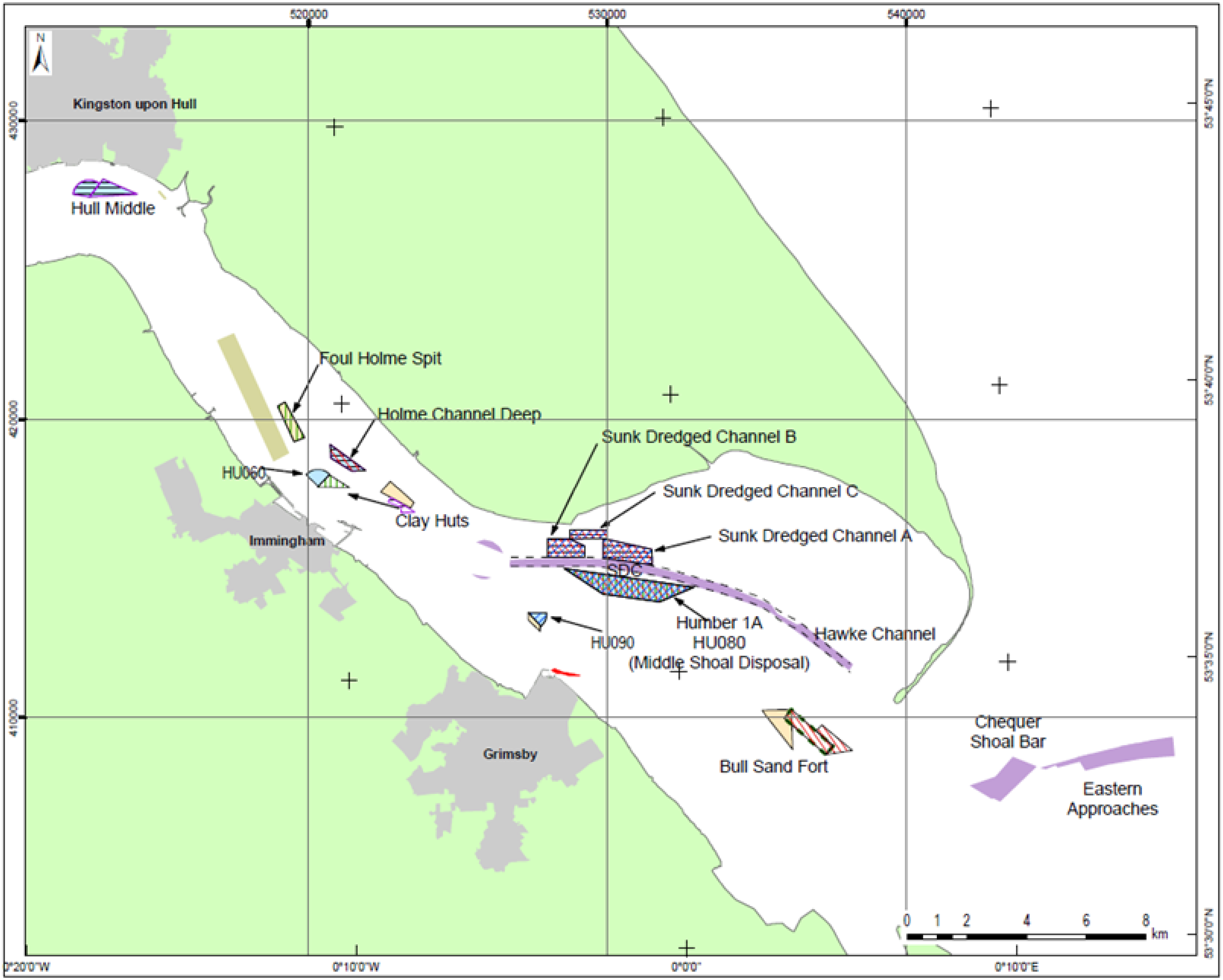
Humber Estuary
Current Maintenance
Dredge Locations

Figure 24



Disposal sites

- GRIMSBY
- IOTA
- HRBT
- IOH
- Disused
- Bull Sand Fort
- Maintenance Disposal Sites

Capital Dredge Areas

- Grimsby
- IOTA
- HRBT

- Urban Industrial Areas

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April 2011	BJC	A4	1
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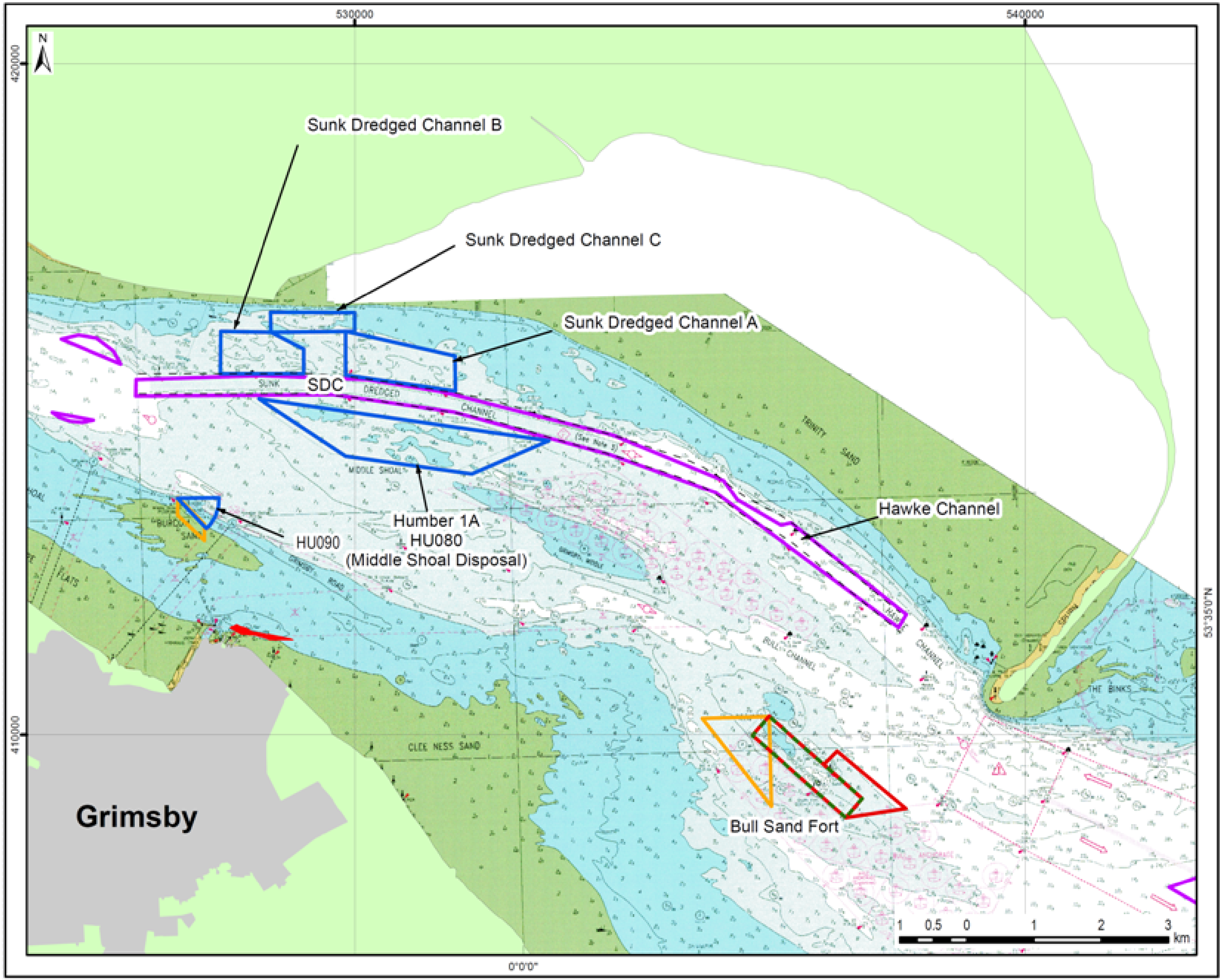
Humber Estuary
Dredge Disposal Sites

Figure 25



Date	By	Size	Version
April 2011	BJC	A4	1
QA		PAW	

3984 – Figure26.ppt

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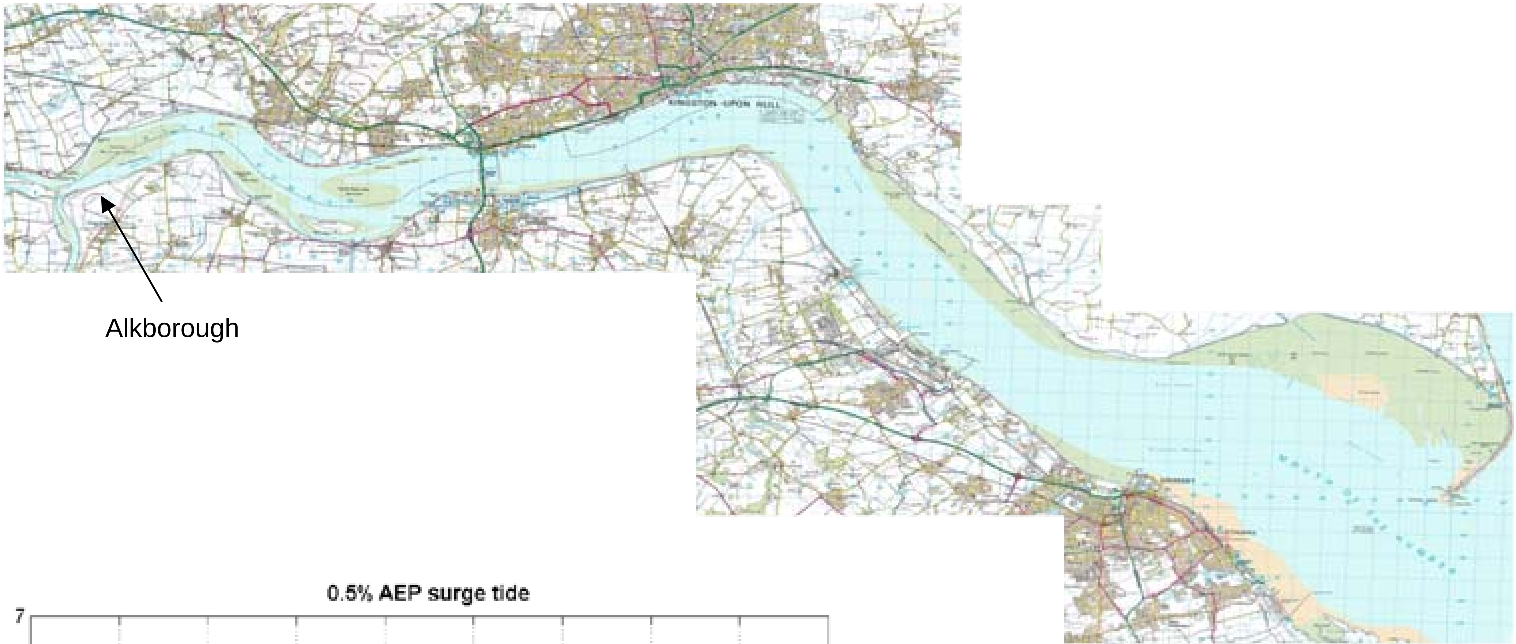
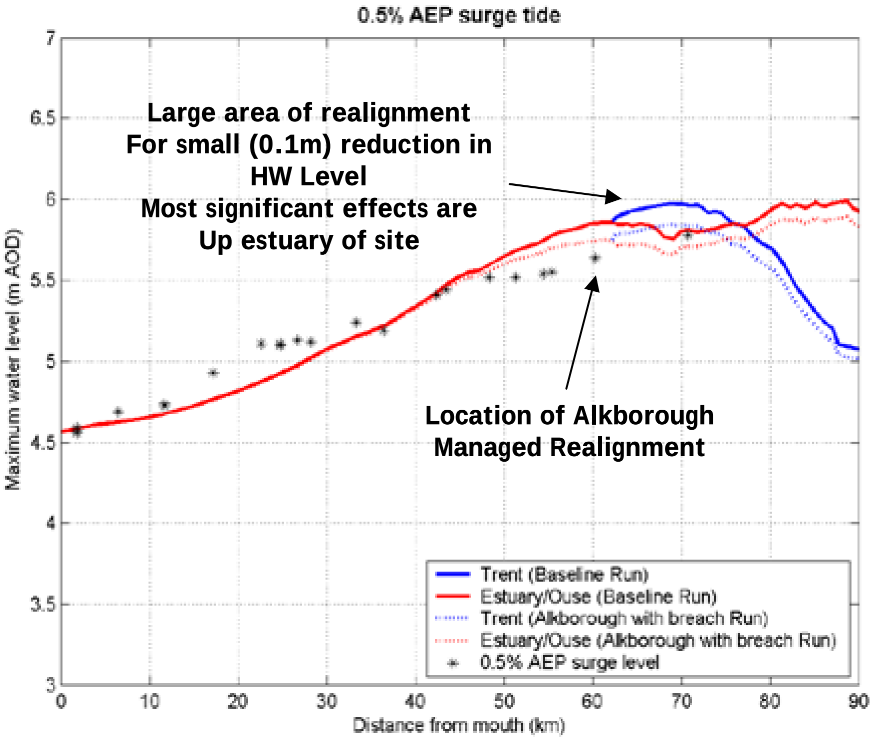
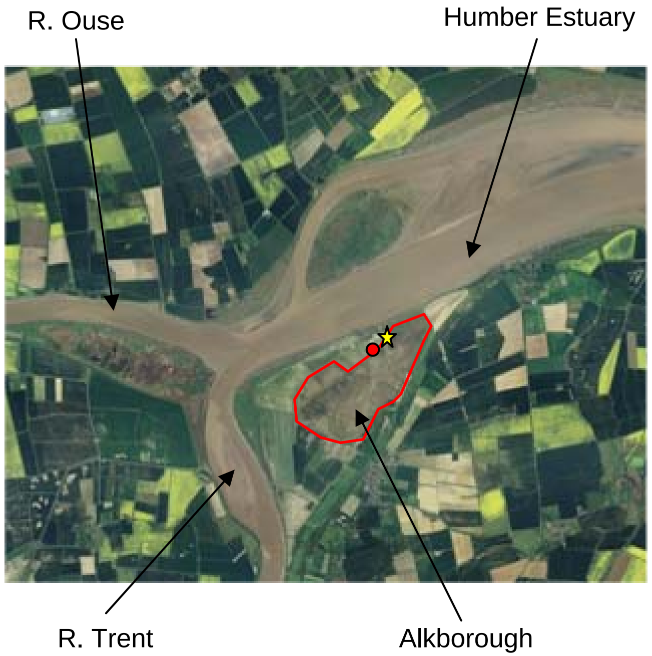
Lower Humber Estuary Bathymetry and Dredge Disposal Sites

Figure 26







Alkborough Managed Realignment Area

Spill Weir

Low Level Weir

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April 2011	BJC	A4	1
QA		PAW	

3984 – Figure27.ppt

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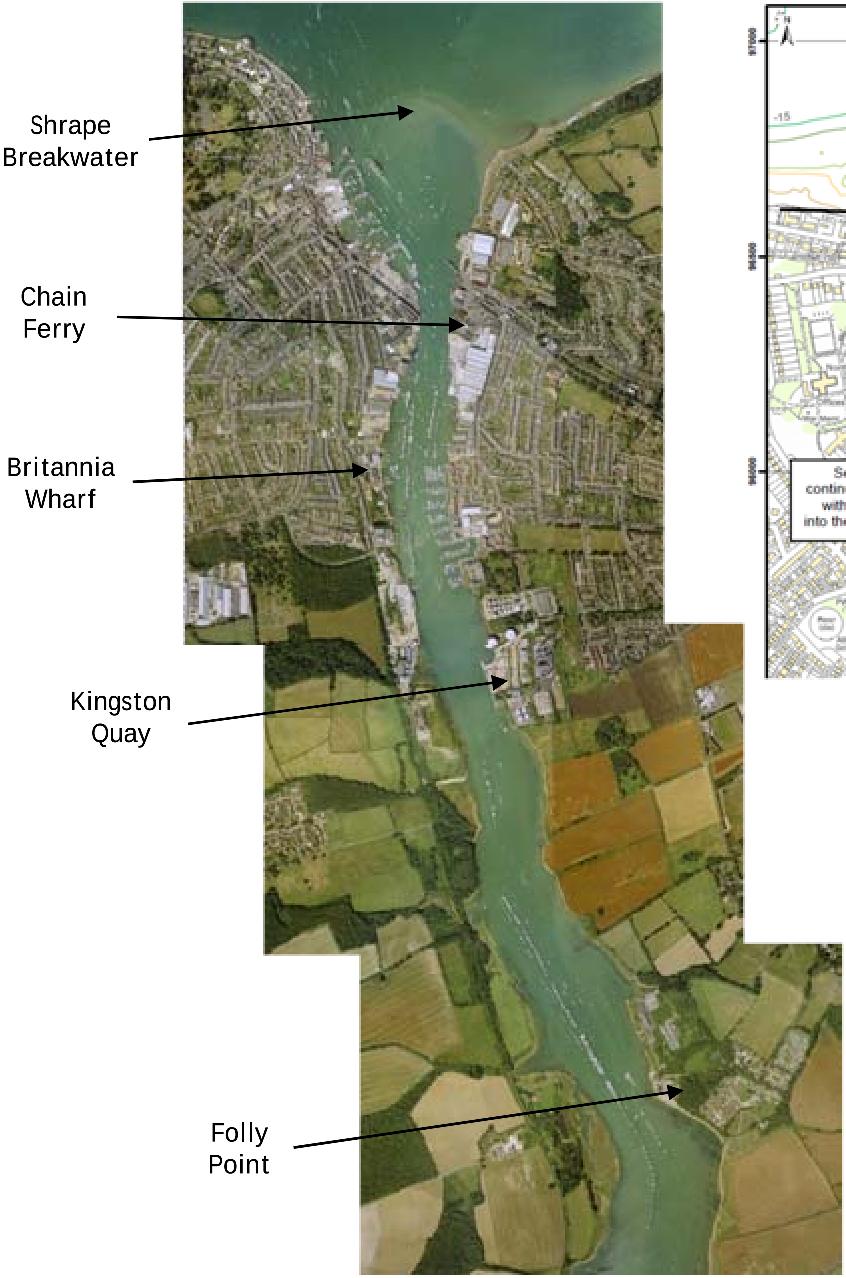
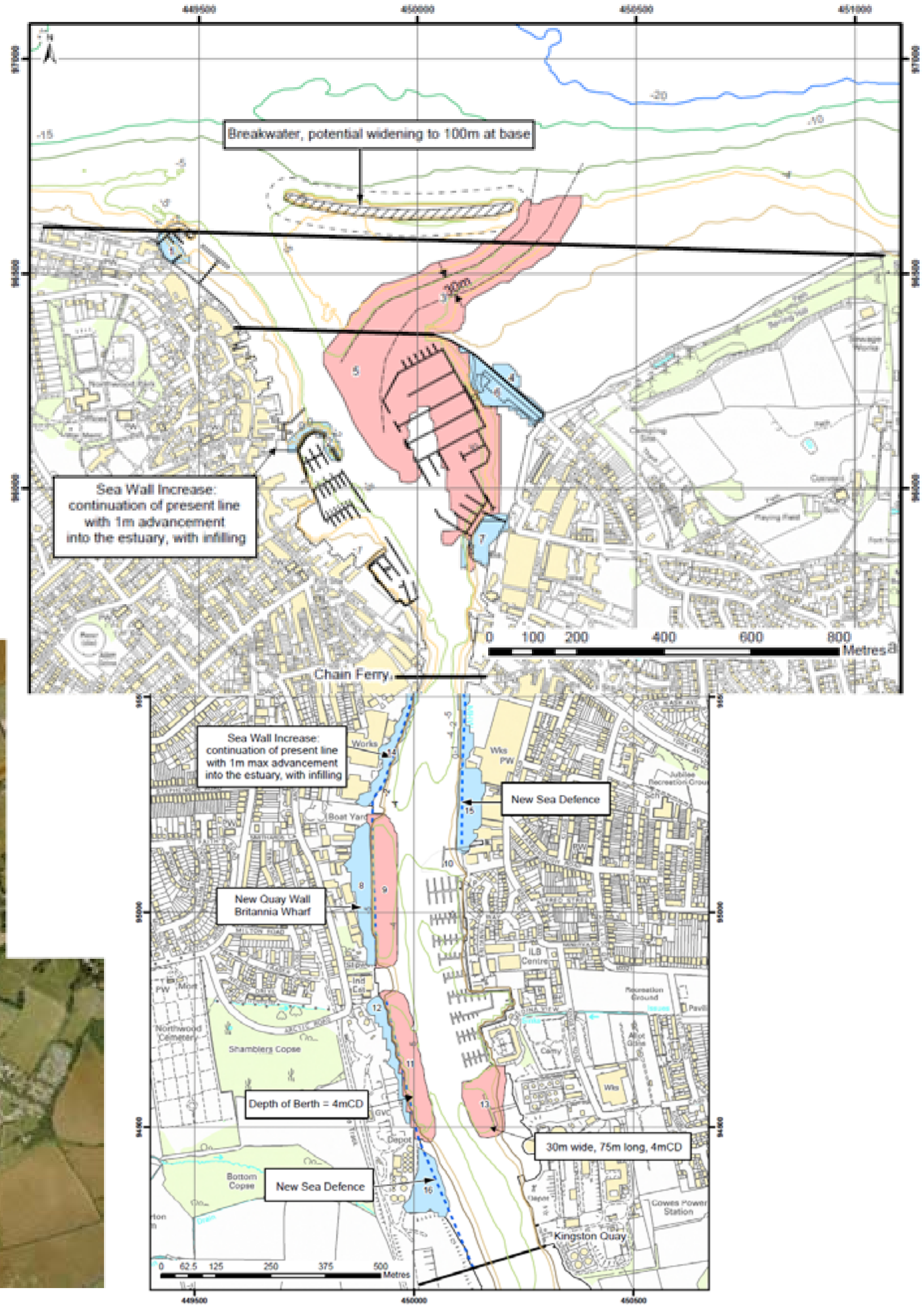
Location of Alkborough Managed Realignment Site and the Modelled Effect of the Scheme

Figure 27





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QA		PAW	

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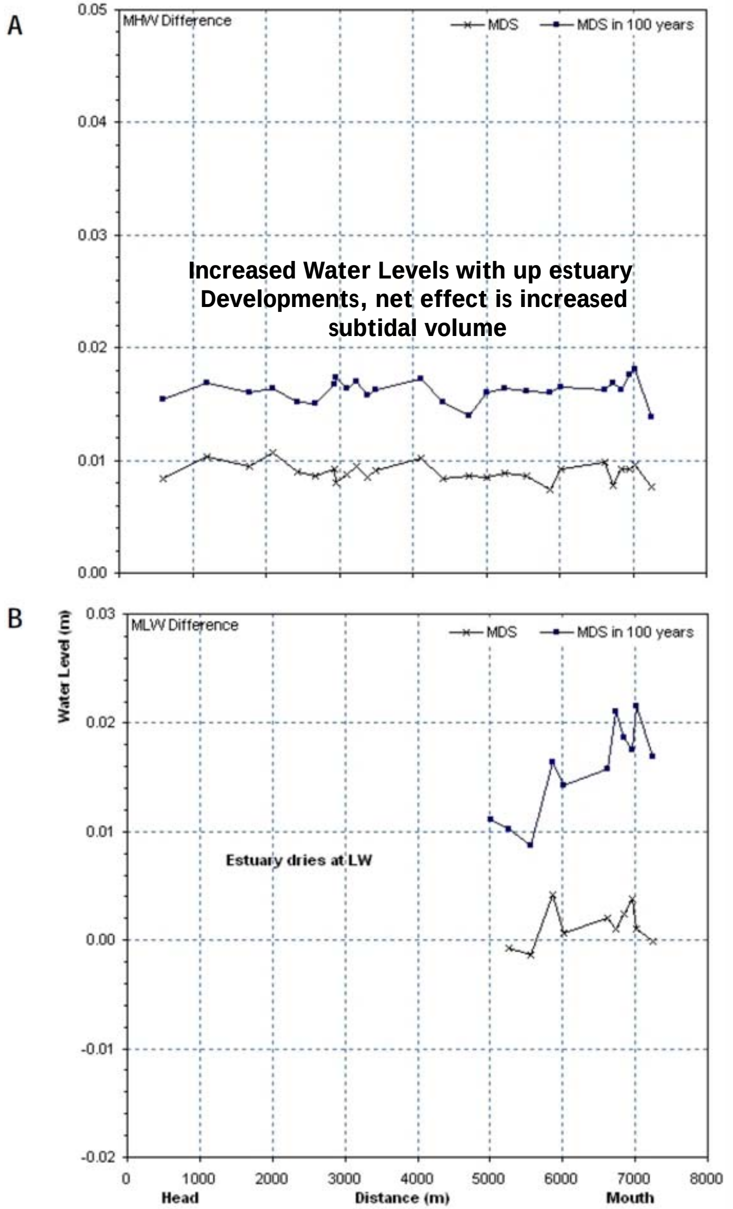
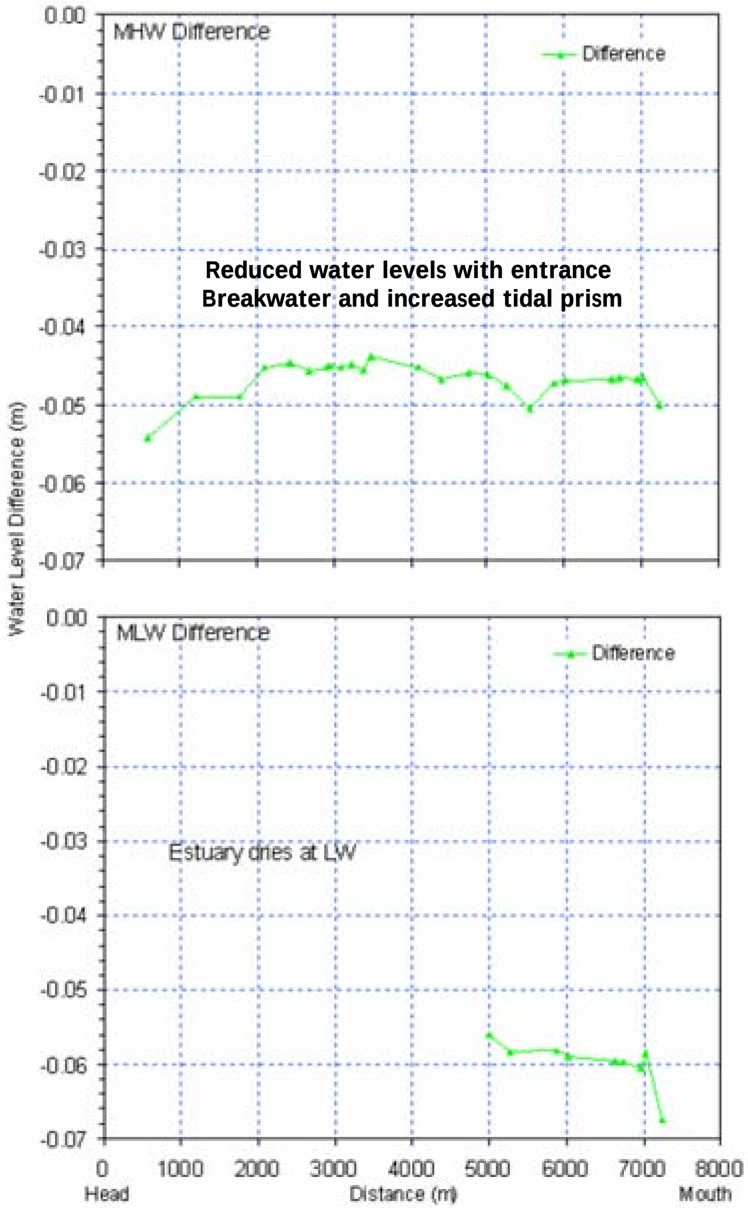
Component Developments for the Medina Estuary Maximum Development Scenarios (MDS)

Figure 28



Difference in water levels along the estuary between the MDS and the MDS in 100 years for MHW and MLW

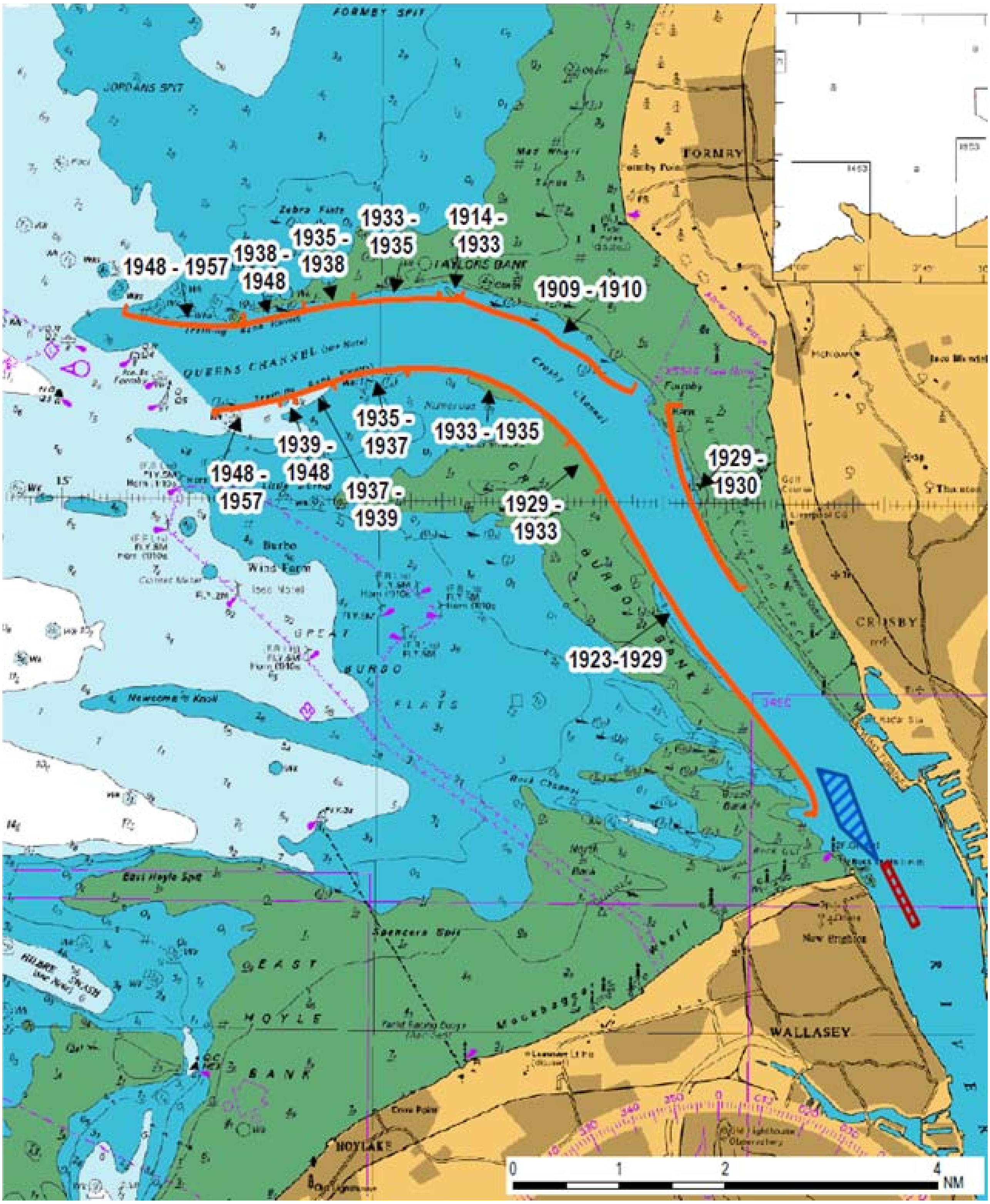


Difference in water level along the estuary between the Baseline and Layout 6 for MHW and MLW

Date	By	Size	Version
April 2011	BJC	A4	1
QA		PAW	
3984 – Figure29.ppt			
Produced by ABPmer Ltd			

Modelling Results of the MDS and Outer Harbour Construction in the Medina Estuary

Figure 29



Date	By	Size	Version
April 2011	BJC	A4	1
QA		PAW	
3984 – Figure30.ppt			
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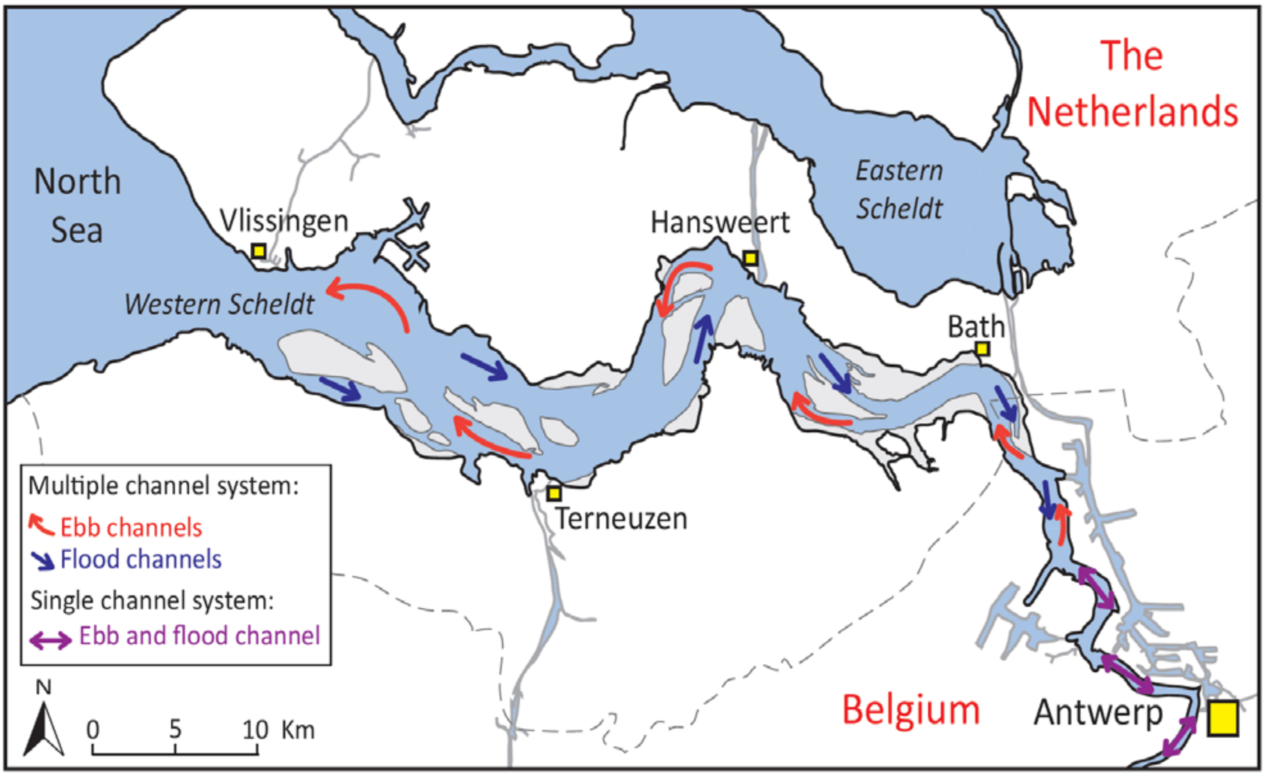
Mersey Estuary Training Walls

Figure 30

(a)



(b)

Date	By	Size	Version
April 2011	BJC	A4	1
QA		PAW	
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[Tide Facts, 2010]

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Western Scheldt (a) Channel System, and (b) Sandbar Disposal Sites

Figure 31

Appendix A

Curriculum Vitae - Peter Whitehead

Appendix A. Curriculum Vitae - Peter Whitehead

Year of Birth:	1958
Nationality:	British
Profession:	Applied Scientist
Position in Firm:	Associate (Processes, Geomorphology and Dredging)
Years with Firm:	31

Key Qualification

- Advisor to ABP Ports (UK) on all aspects relating to dredging from licensing through the operation to monitoring including consultation concerning 'beneficial alternative uses of dredged material'.
- Environmental Impact Assessment and the provision of information for Appropriate Assessments of dredging and marine civil engineering developments particularly with respect to marine processes and their effects on estuary and coastal morphology, and sediment contamination issues.
- Experience of numerous studies of developments in various estuaries in the UK using field and historic data, numerical, physical and conceptual modelling techniques for technical and environmental evaluation.
- Coastal and estuarine monitoring studies involving the collation and analysis of bathymetric, hydrodynamic, beach profile, bed sediments, wind, wave and tidal data.
- Evaluation of physical and environmental effects of marine civil engineering projects in the Humber Estuary, Southampton Water, Swansea Bay, Tees, Mersey, Morecambe Bay, Hamble, Medina, Milford Haven, Wyre, Walney and Fal Estuaries.
- Evaluation of 2D/3D numerical model results to design port layouts, approach channels and evaluate maintenance and capital dredging commitments in both cohesive, non-cohesive and mixed sediment environments.
- Development of dredge management and monitoring programmes for port developments to comply with environmental legislation, e.g. channel deepening in the Humber Estuary.
- Experience of 2D and 3D physical modelling studies of port and coastal developments.
- Former PIANC observer to the London Convention for the Disposal of Wastes at Sea and member of PIANC Environment Committee. Member of Central Dredging Association (CEDA) UK Committee, member of Marine Licensing Liaison Group and Task Team considering the monitoring of physical disturbance and dredged material deposit grounds.
- Member of the Sunk Dredged Channel Maintenance Dredge Management Group, Humber Estuary, responsible for monitoring analysis.
- Contributor to a number of PIANC reports relating to dredging issues in the environment.

Education and Professional Status

BSc (Hons) Geography, University of London
Chartered Geographer (C.Geog), Fellow of the Royal Geographical Society, Chartered Institute of Water and Environmental Management C.WEM (CIWEM)

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