Sediment relocation and river engineering measures of the River Engineering and Sediment Management Concept (RESMC) from the perspective of effectiveness and economic efficiency

Expert assessment report

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INTRODUCTION

GOAL OF THE STUDY

The Federal Waterways and Shipping Administration (WSV) and the Hamburg Port Authority (HPA) presented a jointly developed "River Engineering and Sediment Management Concept for the Tidal River Elbe" (RESMC) in 2008. The primary source of motivation was the rise in the quantity of sediment to be dredged for the maintenance of the water depth, particularly in the Hamburg area, an altered legal framework as well as the changes in the delta with unbalanced solids budget.
The concept of 2008, which further develops and specifies in greater detail the discussion contribution "Concept for sustainable development of the tidal River Elbe as a lifeline for the Hamburg metropolitan region", analyzes the causes of the rise in quantity and the hydrodynamic and morphodynamic changes. On this basis a strategy for sediment management as well as for reduction in quantities to be dredged by taking into account the sediment composition and contamination will be developed. The latter encompasses measures of varying concrete detail and feasibility and to this extent also different time scales.

Individual aspects of the concept have already been implemented, others have yet to be implemented. The concept contains a number of innovative approaches for which little or no experience is available and parts of it are not easy to implement since interests of third parties are affected. On the other hand, it also opens up certain synergies with nature conservation interests, for example.
In view of this situation WSV and HPA have decided to arrange for an external evaluation of the concept in order to achieve broader verification and thus acceptance as well as to obtain suggestions for its further development.

The purpose of the project can be outlined as follows. External experts shall analyze and evaluate the targeted practice (which has already been realized in part) presented in the RESMC with respect to its compatibility with the objective of sustainable development of the tidal Elbe. The currently planned deepening of the shipping channel in the Lower and Outer Elbe is not the object of the evaluation.

The external experts consist of a group of 6 international specialists. The present report was written by Prof. Dr. Dano Roelvink of UNESCO-IHE, the Netherlands and focuses on sediment transport, dredging and dumping and morphological aspects in the Elbe Estuary.

SEDIMENT RELOCATION AND RIVER ENGINEERING MEASURES OF THE RESMC FROM THE PERSPECTIVE OF EFFECTIVENESS AND ECONOMIC EFFICIENCY

The following questions will be addressed within the framework of this work package:

Assessment of the situation up to approx. 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 (maintenance effort and expense, lowering low tide)?

Assessment of the situation as of 2005 and with further implementation of the RESMC:
- What is the assessment of the current practice of sediment management on the tidal River Elbe (particularly sediment traps, relocation of dredged material to buoy E3, water injection procedures, disposal at Neßsand as well as relocation of the dredged material quantities of the Kiel Canal)?

- Is the objective “reducing tidal pumping” expedient as a sediment management strategy?
- Are the river engineering measures planned for reducing tidal pumping expedient?
- What is the assessment of the current practice of using water injection in the Lower Elbe with regard to management of the various sediment fractions, is the practice of sediment trapping for fine material management appropriate and should the concept be extended? Is there related experience elsewhere?
- How is the effectiveness of the opening of the side arms of the Elbe seen?
- Is breaking dredging cycles as a strategy for reducing quantities of dredged material appropriate and expedient?
- According to what criteria should relocation sites / disposal sites be selected?
- What is the assessment of the removal of sediments from the Elbe estuary in view of the long-term “solids balance” of the estuary?
- What is the assessment of the further measures for optimizing sediment relocation (see above)?

Overall assessment:

- Are the objectives of the RESMC formulated in the work order 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

STUDY AREA

The study area focused on here runs roughly from the the weir at Geesthacht to the mouth of the Elbe, from approx. Elbe km. 585 to 740 (see figure 1 below)

Figure 1 Overview of important locations and Elbe-km system (source: Boehlich and Strothmann)

ASSESSMENT OF THE SITUATION BEFORE THE RESMC IN 2005

HISTORICAL DEVELOPMENT OF THE ELBE ESTUARY

The Elbe developed over the past centuries from a natural, multi-channel estuary that provided favourable conditions and enough depth for the ships at the time, to a highly regulated almost single-channel tidal waterway that accomodates modern container vessels. Figure 2 shows the almost natural Elbe estuary at around 1650, where it is still characterized by many islands and channels and extensive floodplains.

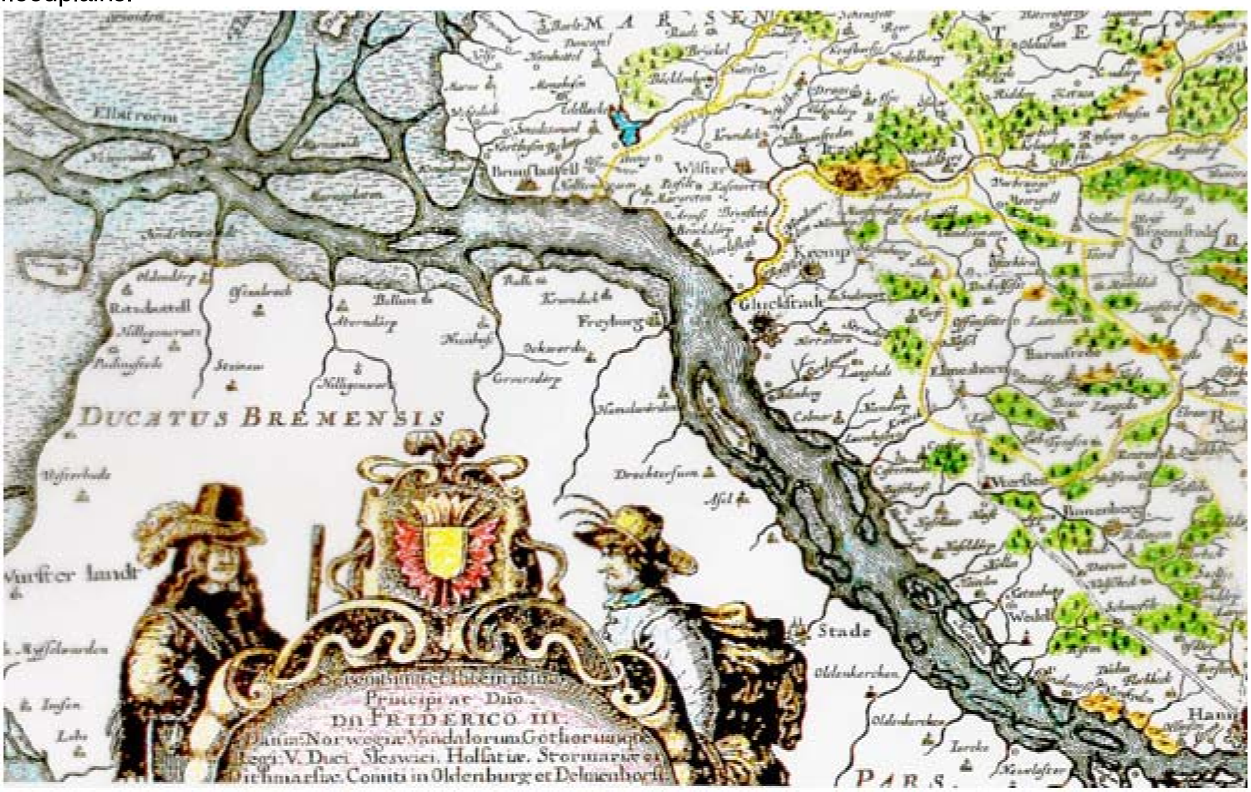

Figure 2 The Elbe at around 1650

Throughout the centuries the human population has encroached on the estuary, removin flood plains from the reach of high tides and deliberately narrowing the tidal channel in order to create an ever smoother, deeper fairway. Figure 3 shows the extent of dyking of the tidal marshes since before 1500, with still substantial works after 1955 following extensive flooding.

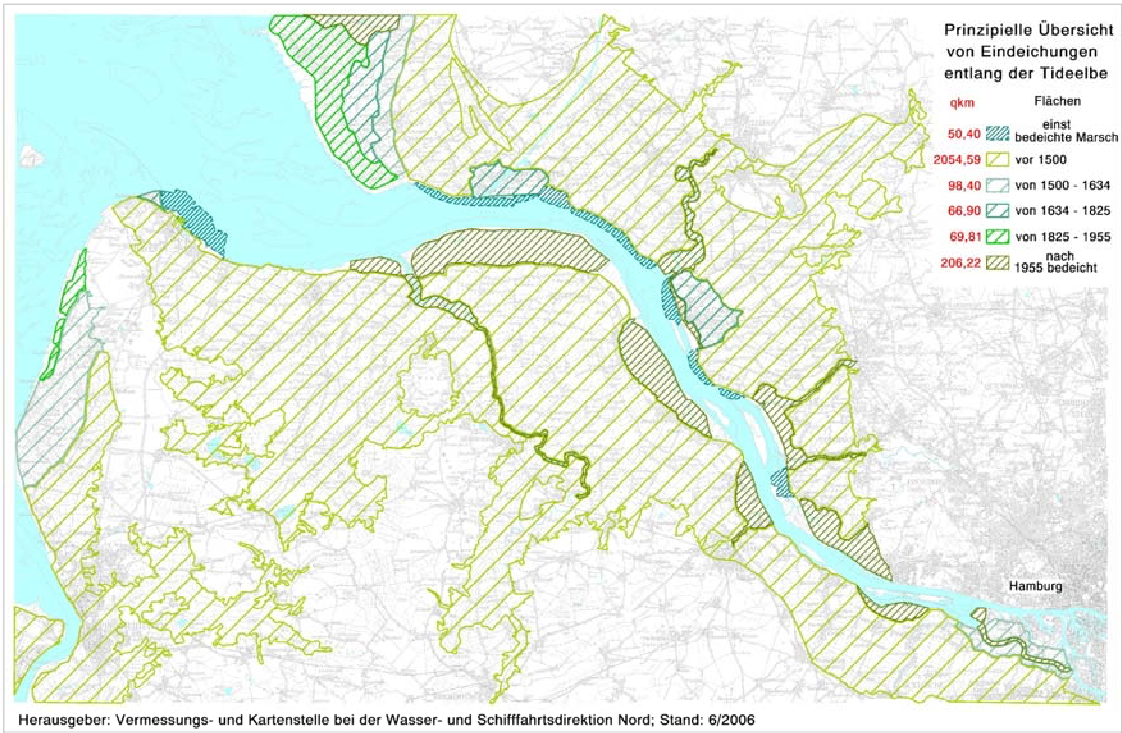

Figure 3 Loss of flood prone area (source: Boehlich and Strothmann)

Especially since the mid-19th century extensive river engineering works have been carried out in order to harness the estuary for the purpose of navigation. The main strategy was to create a continuous and smooth fairway with as much as possible a constant cross-section. This was done to a large extent using hard structures such as groynes and guide walls, but also by raising flats to supratidal level. Increasingly, shallow passages were dredged using mechanical equipment, originally bucket dredgers but nowadays using modern hopper dredgers and water injection dredgers. The result as depicted in Figure 4 is quite successful in terms of navigation, with a fairway that allows Hamburg to remain in the top three of European ports.

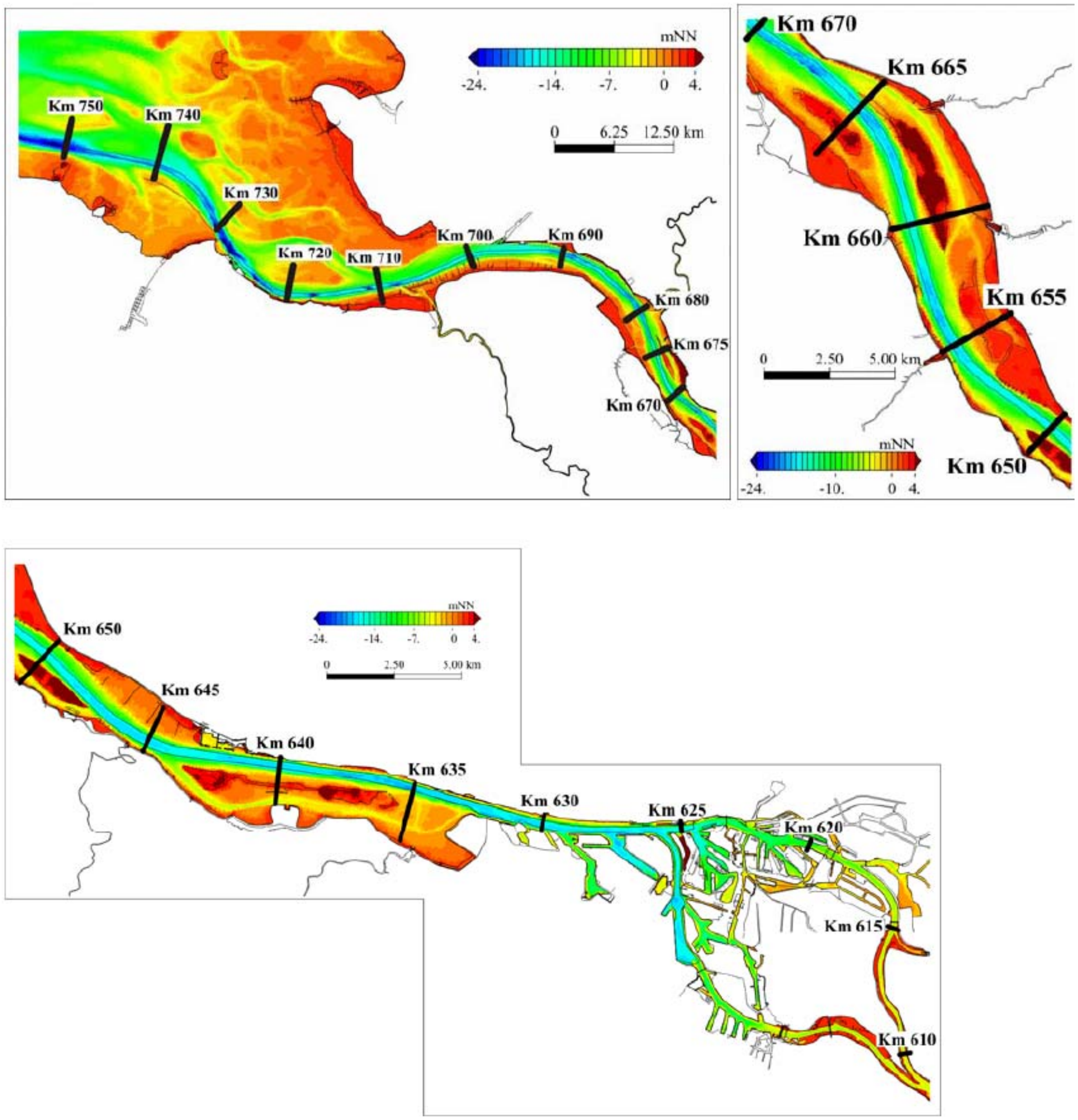

Figure 4 Present-day morphology of the Elbe estuary

TIMELINE OF CHANGES 1870-2005

A dominant feature in the development of the Elbe estuary is the succession of deepenings as shown in Figure 5, where over the course of 150 years the fairway more than tripled in depth.

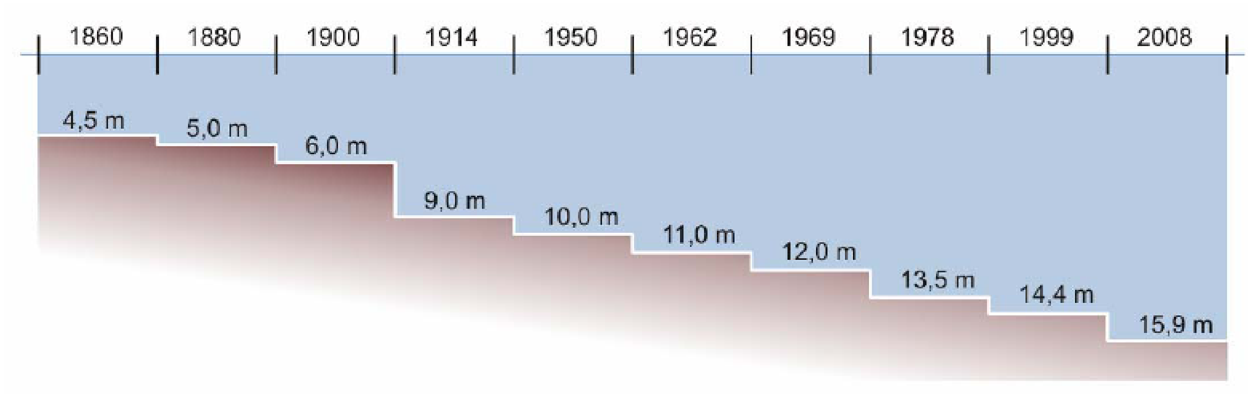

Figure 5 Development of depth of fairway (source: Sohrmann and Weilbeer 2006)

During the same period we see a strong increase in tidal range, where MHW increased from approx. 1.6 m to over 2.1 m NN and even more spectacularly, the MLW levels dropped from -0.3 m NN to -1.5 m NN. Over this period the harbour area increased from 100 to 1400 ha in 1970, after which it dropped slightly to around 1200 ha at present; see Figure 6. In this figure the timing of all major engineering works is marked.

There can be several causes for the marked increase in tidal range:

- A reduction in dissipation due to the deepening and fairway optimization
- A reduction in intertidal areas
- Changes in the configuration of the Elbe mouth
- An increase in the tidal wave length due the deepening, leading to different resonance behaviour.
- The reduction of the wetted area in the harbour.

We will discuss these effects in more detail furtheron.

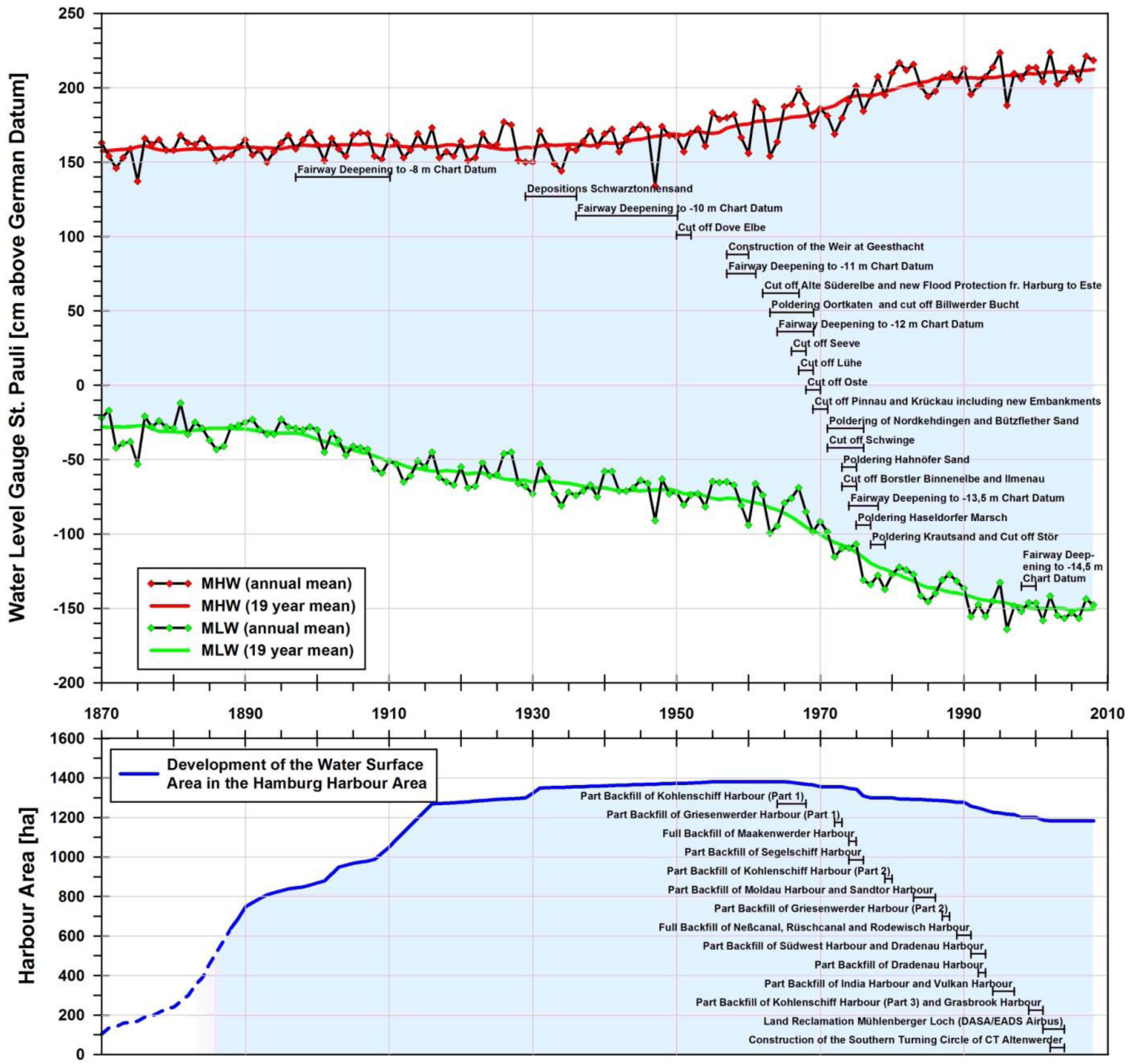

Figure 6 Development of tidal range and water surface area Hamburg harbour (source: HPA & WSV (2010) – Sediment Management in the Elbe Basin)

DEVELOPMENT OF HYDRODYNAMIC AND MORPHOLOGICAL CHARACTERISTICS 1970-2005

GENERAL GEOMETRY AND MORPHOLOGY

For the estuary upstream of km 710 the main trend between 19070 and 2002 is a further deepening of the fairway and a heightening of the shoals, in a number of cases to above MHW. Rather spectacular but not uncommon changes took place around the Medem shoal (see Figure 7), roughly between Elbe km. 710 and 730. In the same figure the cross-sections are given based on which the cross-sectional areas in Figure 8 were computed for the same three years.

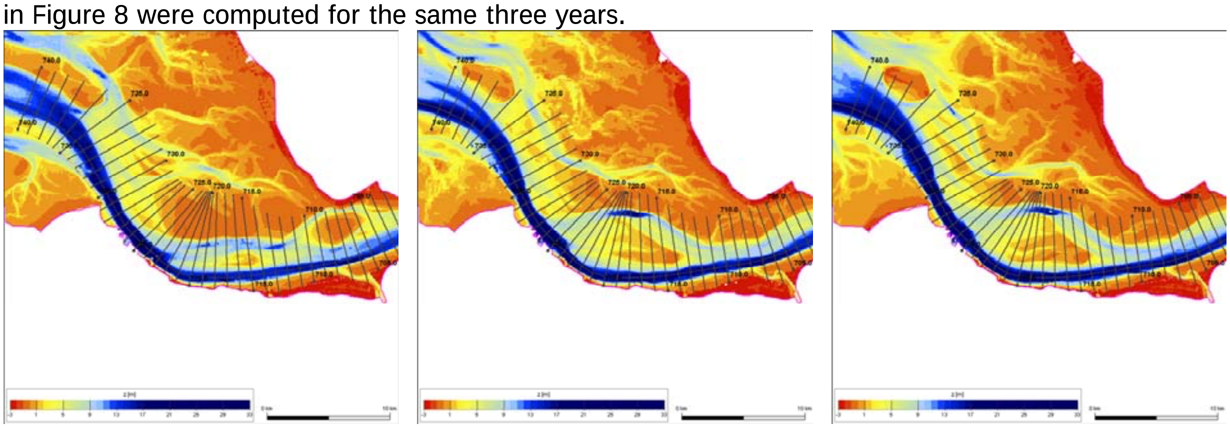

Figure 7 Development of mouth area, 1970 (left), 1997 (middle) and 2002 (right) (Weilbeer, pers. comm.)

This shows a modest increase in cross-sectional area between km 630 and 710, but rather larger increases between 710 and 730. This latter change corresponds to approx. a loss of 150 Mm3, especially between 1970 and 1997. It could be one of the causes for the increased tidal range.

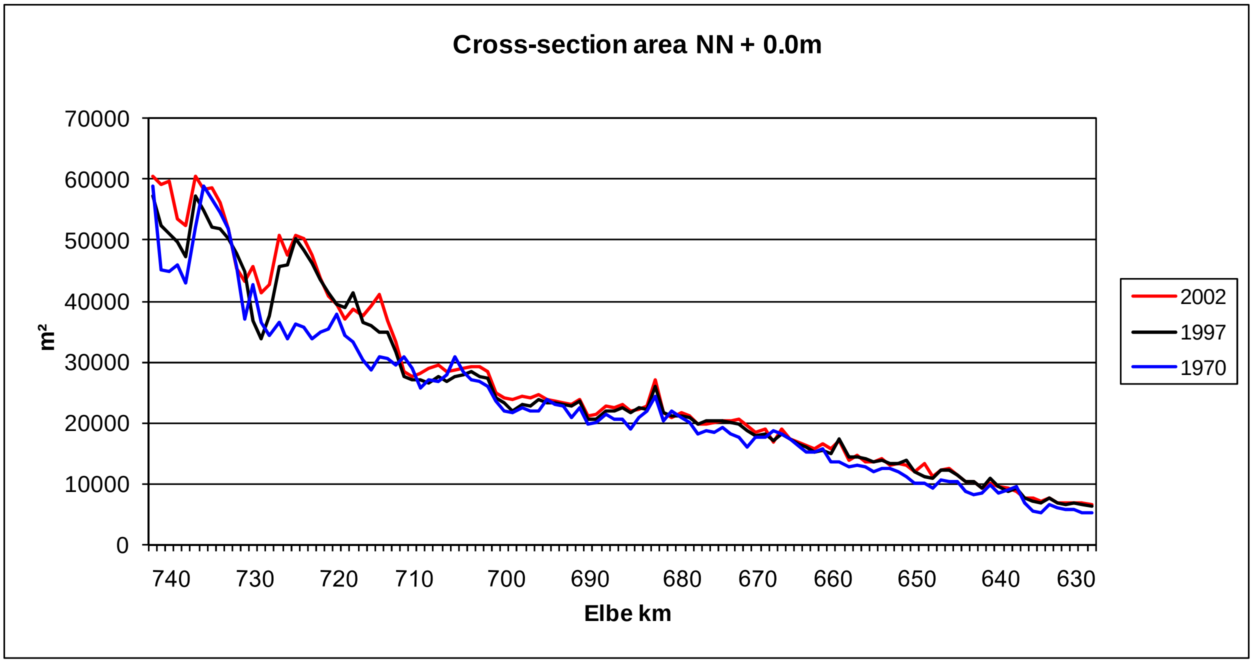

Figure 8 Change in cross-sectional area along the Elbe, 1970-2002 (source: Holger Weilbeer, pers. comm.)

The fairway deepening is further illustrated in Figure 9. The very deep pits between 710 and 720 km are related to the Cuxhaven guide wall and the developments around the Medem shoal.

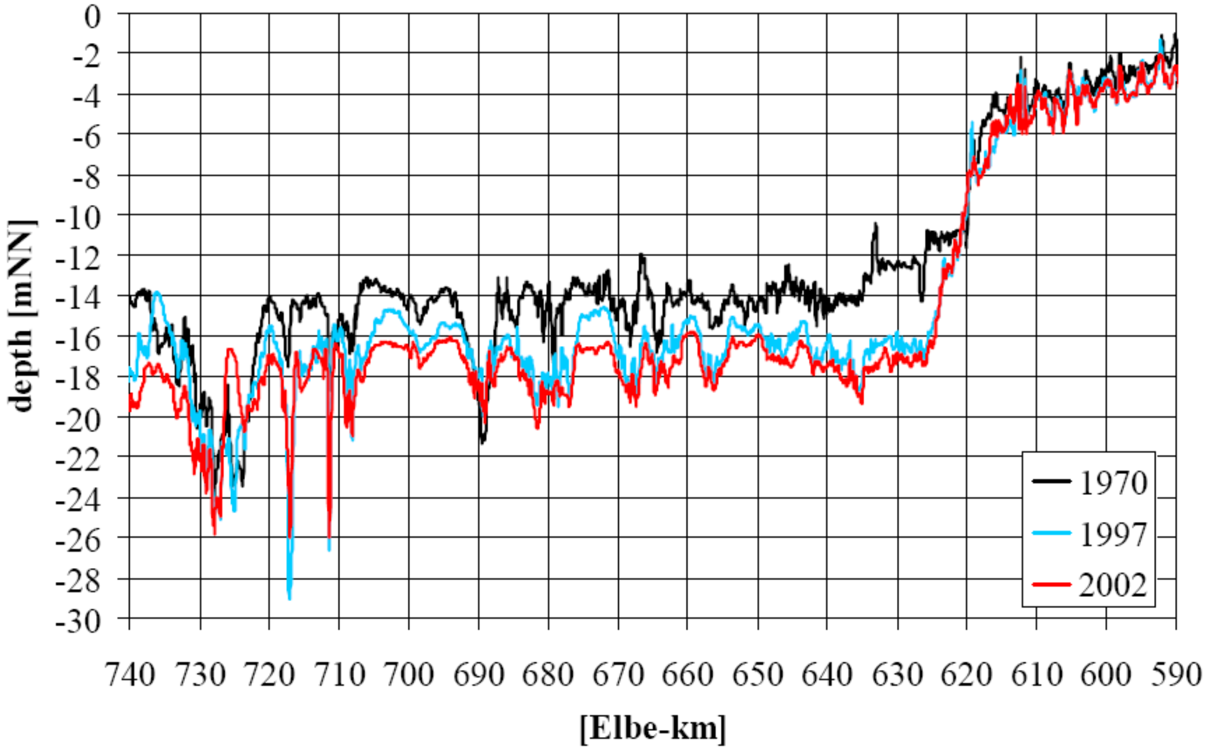

Figure 9 Development of depth of fairway (source: Sohlmann and Weilbeer 2006)

TIDAL CHARACTERISTICS

The tidal wave at the mouth has an range in the order of 3 m and is fairly symmetrical, which means that the overtides at the seaward end are relatively small. As the tide propagates into the estuary, overtides are generated and the tidal wave steepens, leading to relatively strong flood currents of shorter duration than the ebb current; the development of the water level curves can be seen in Figure 10 from Boehlich and Strothmann and the ebb and flood durations in Figure 11.

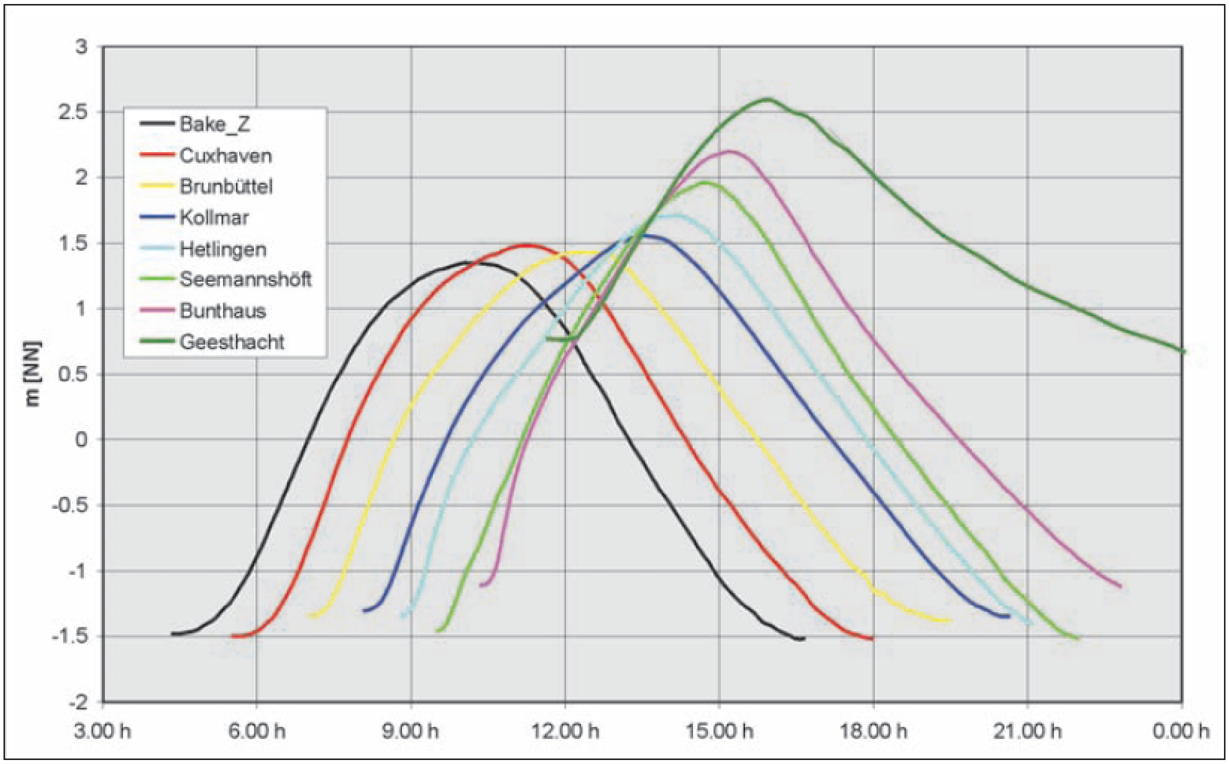

Figure 10 Development of the tidal curve in the Elbe

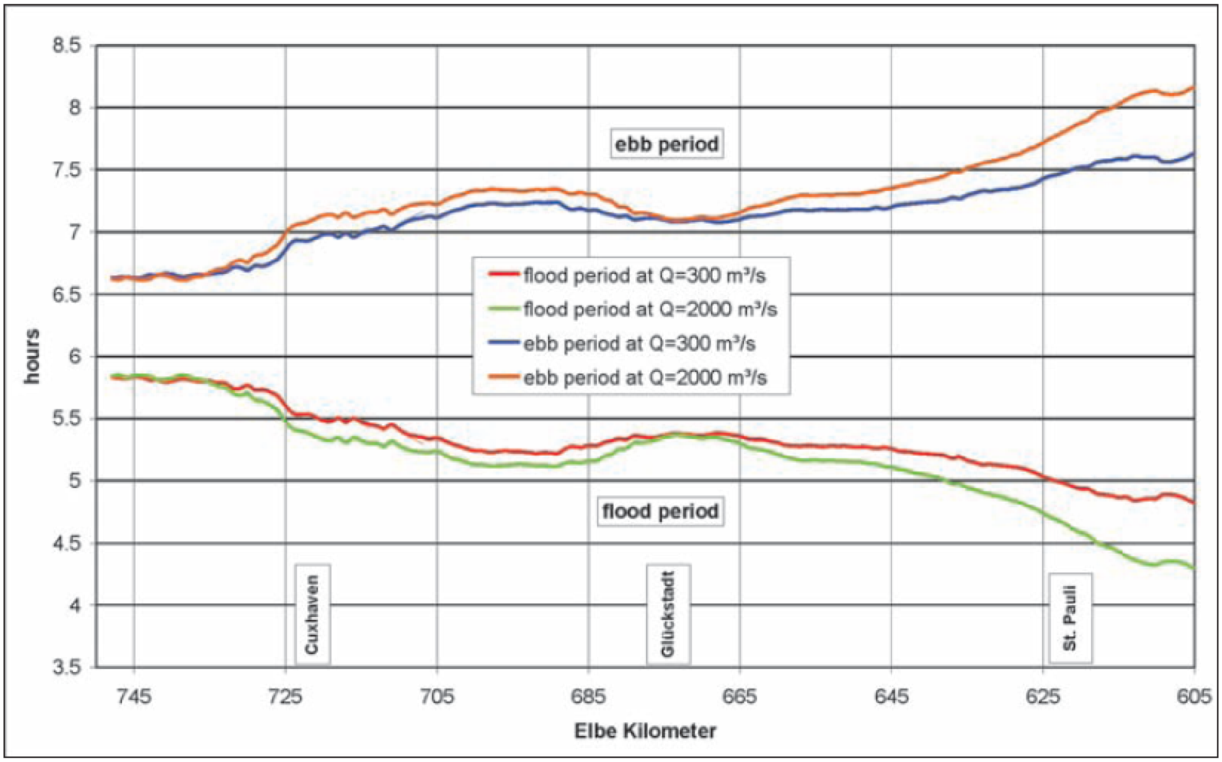

Figure 11 Duration of flood and ebb periods

The successive deepenings , especially since the '60s, have reduced the friction and increased the tidal wave length, leading to a strong increase in tidal range.

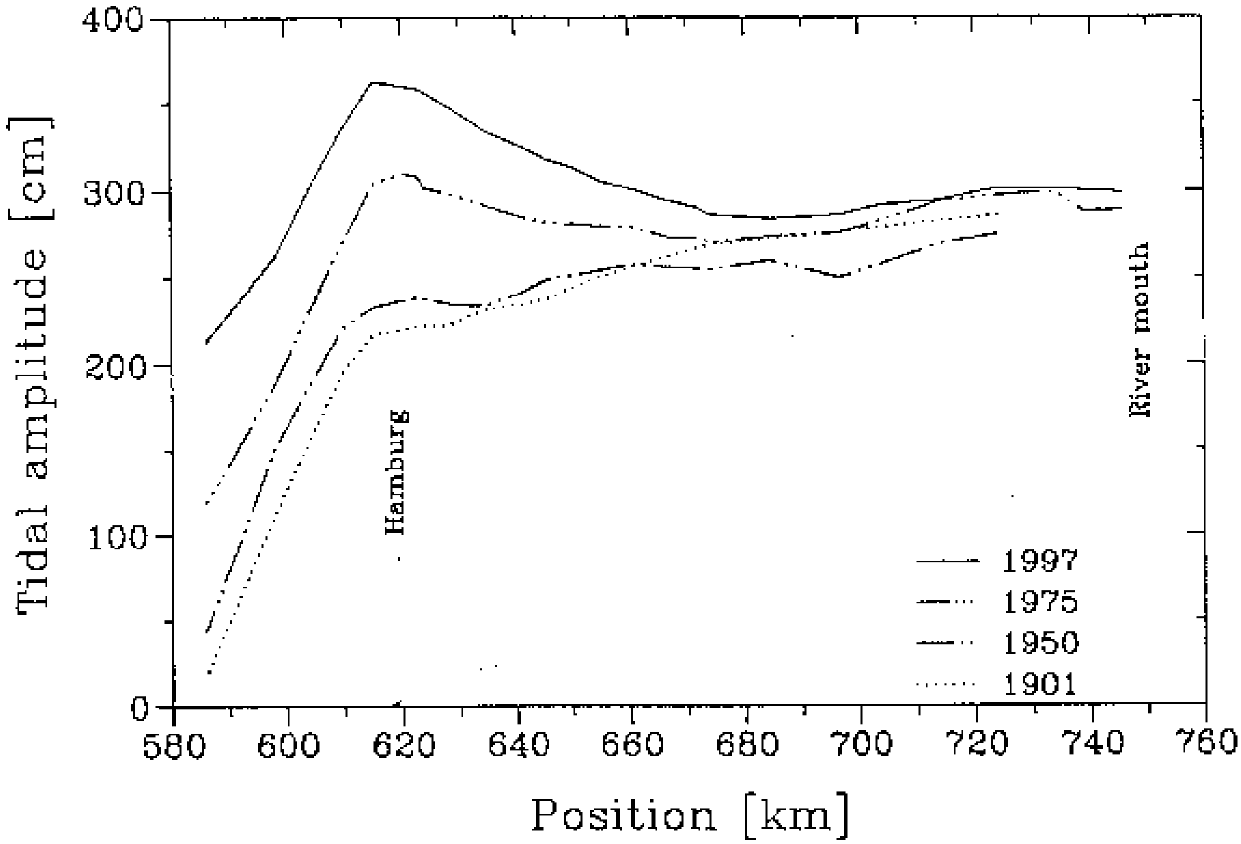

Figure 12 Observed tidal range along the Elbe over time

In order to see whether we can understand the main causes of the change in amplitudes, we created a simple model using the curvilinear Delft3D system, in order to carry out some qualitative analyses, without pretending to have a calibrated model. The model grid and bathymetry for 1970 is shown in Figure 13 below, and it is able to represent most of the features of the tidal Elbe, especially downstream of the very schematized port of Hamburg. Grid sizes vary between 100 - 200 m. As boundary conditions a single harmonic water level variation was specified, at the M2 frequency, with an amplitude of 1.5 m, which means the tidal range is approximately 3.0 m at the mouth. We assume here that at the mouth the amplitude is governed by the tide at the North Sea and that relatively small changes have taken place here, as is also evident from Figure 12. A constant discharge of 750 m3/s was taken at the landward boundary near Geesthacht. Since we are mainly interested in the tidal propagation and the role of the mouth configuration and channel deepening on the tidal amplitudes we use a depth-averaged approach. No extensive calibration procedure was carried out but the (uniform) Chezy roughness coefficient was varied between 65 and 75 $m^{1/2}/s$, with the latter giving the more realistic results.

In our simulations we just considered three cases: the 1970 bathymetry, the 2000 bathymetry and the 2000 bathymetry where the mouth area was kept at the 1970 situation, viz. with a much smaller cross-section seaward of km. 710. The bathymetry was created by interpolation from the raw data files ***Elbe_Topography.25m.2000.nn.dat*** and ***Elbe_Topography.50m.1970.nn.dat*** provided by BAW.

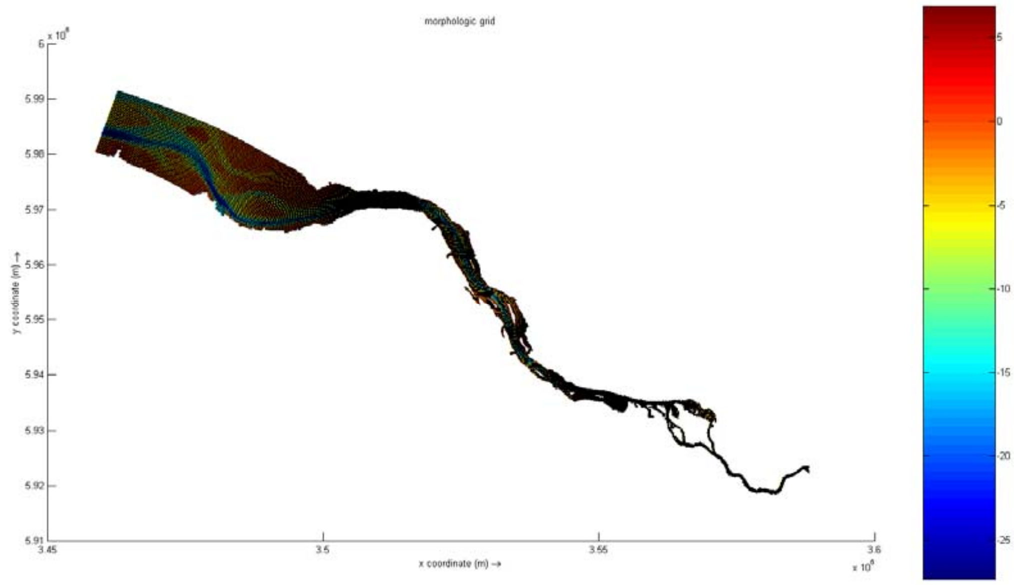

Figure 13 Grid and bathymetry for simple Delft3D model

Results for the tidal range are given in Figure 14; for this, data were extracted at grid points closest to the provided thalweg points at 1000 m intervals. There is a good qualitative agreement with the observed trends. What is clear is that the changes in the mouth area have a profound influence, both on the low and the high water levels, though the deepening clearly leads to a different slope of the curve inside the estuary. The 2000 configuration in the mouth area has much less resistance.

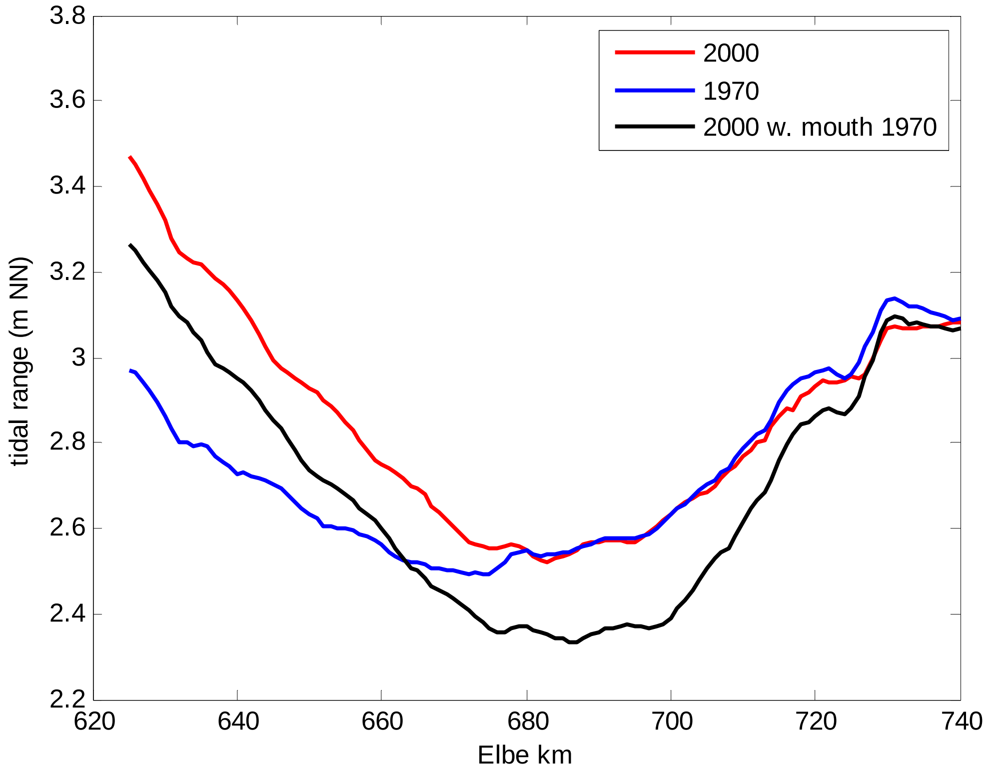

Figure 14 Tidal range along the Elbe for different configurations

Figure 15 shows the evolution of the tidal water level through the tidal cycle according to observations shown by Boehlich and Strothmann; Figure 16 shows the equivalent results for the Delft3D model, which qualitatively agrees well. In both cases there is a minimum in tidal range at around km 670. The area of Medengrund and Medenrinne is a considerable obstacle in the model, especially for the 1970 situation. The exact model behaviour here has not been verified but the reduction of this obstacle in 2000 is quite reasonable in view of the large increase in average cross-sectional area.

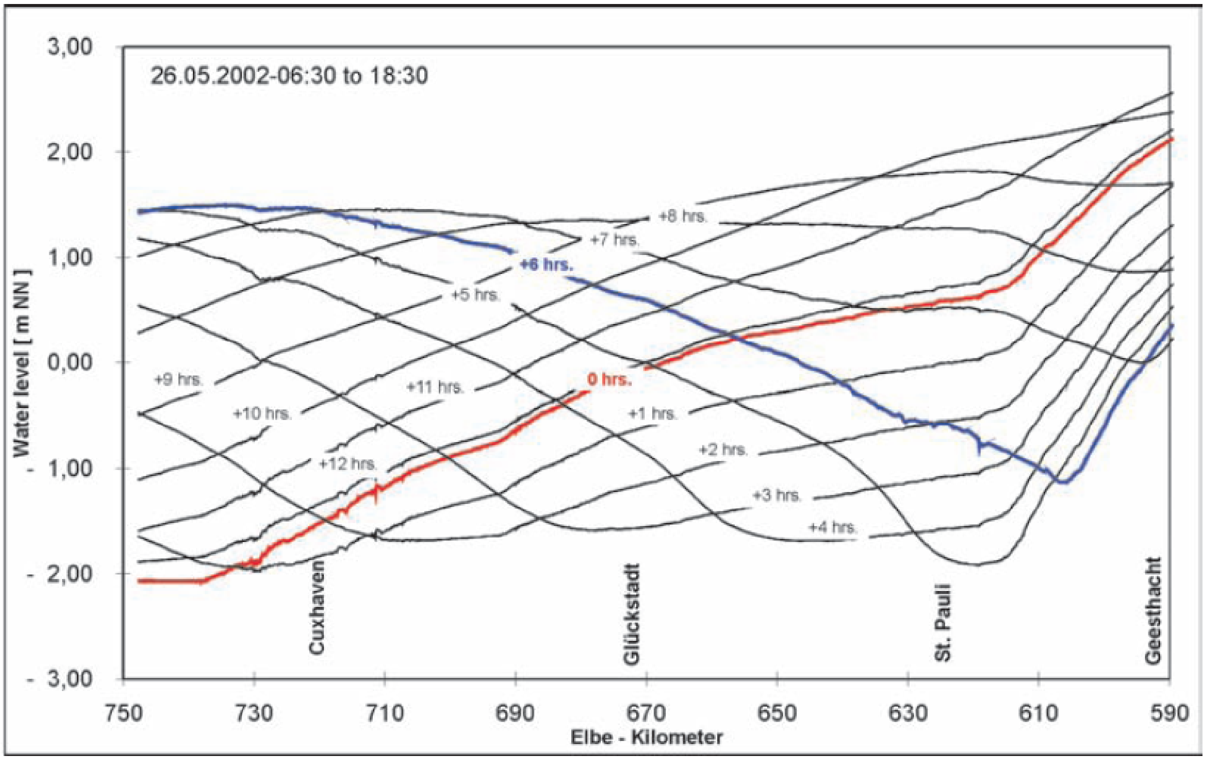

Figure 15 Observed water level along the Elbe at different phses of the tide

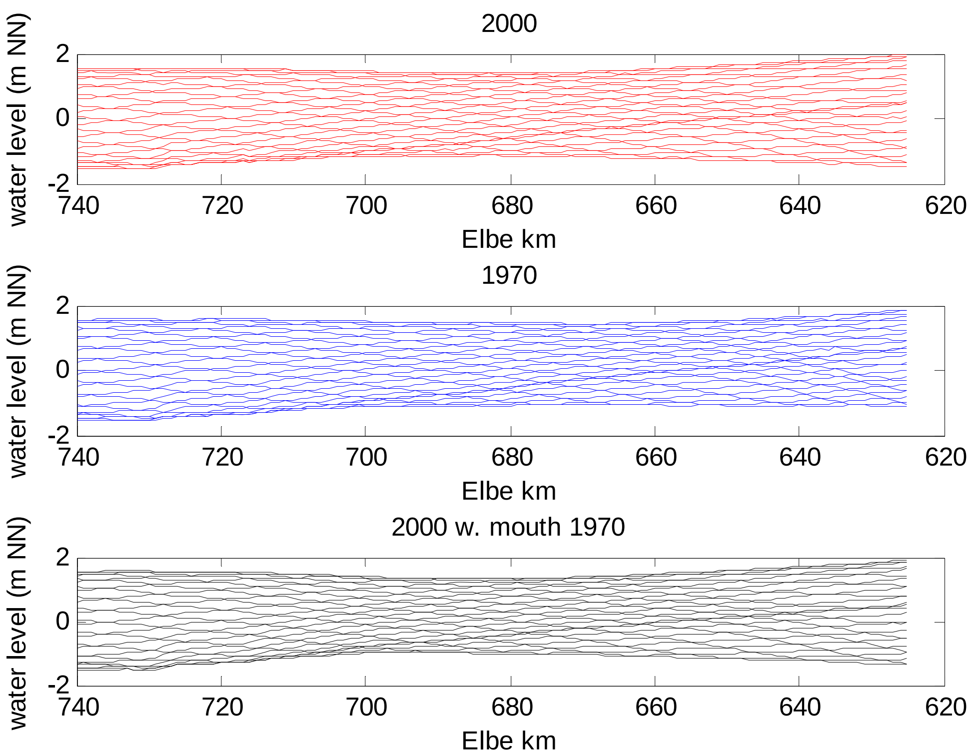

Figure 16 Computed water levels along the Elbe at different phses of the tide

In Figure 17 we plot the HW and LW levels along the Elbe for the three scenarios. Clearly, both the channel deepening and the obstruction at the mouth play a role: in the outer part, the mouth configuration is dominant, whereas near Hamburg the low water levels are less affected by the mouth, but the high water levels are reduced if we put in the 1970 mouth.

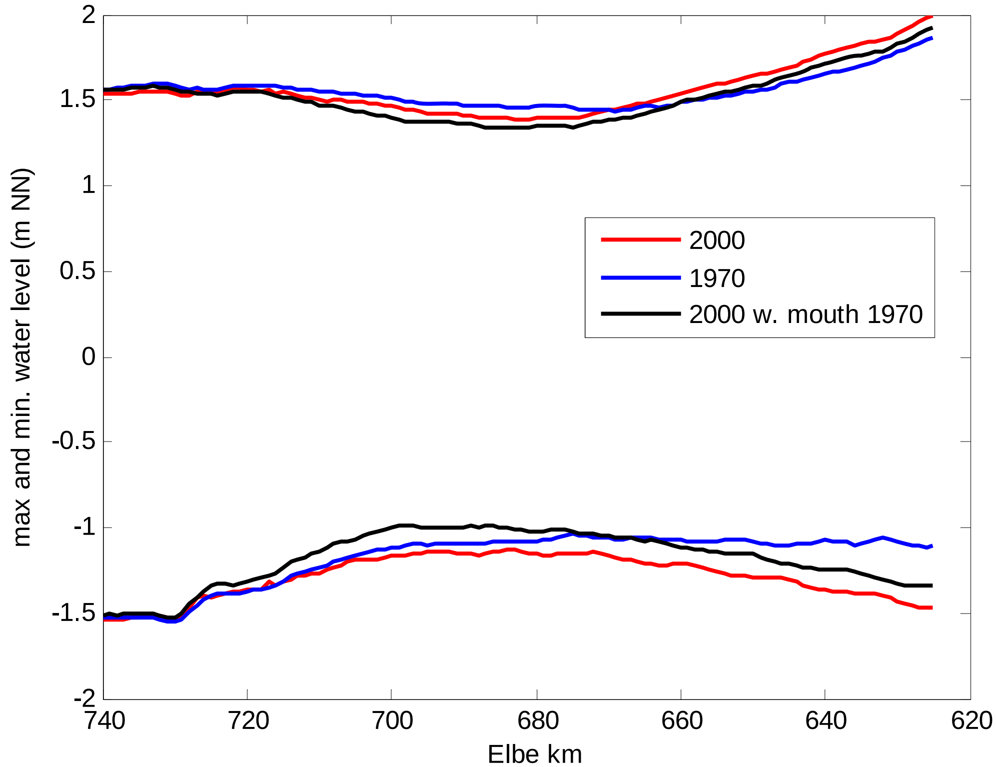

Figure 17 Computed HW and LW along the Elbe

The resonance behaviour can be roughly assessed by comparing Figure 15 and Figure 16 to theoretical curves of standing and propagating waves; since the tidal wave is strongly damped around the Hamburg area, the pattern indicates only a weakly reflective character; the increase of the amplitude towards km 620 may at least partly be explained by the narrowing of the Elbe. Assessing the wave celerity and wave length for a compound profile is not trivial, but based on the observed and simulated timelines of the water level we can estimate the propagation speed to be approx. 7-8 m/s in the present situation, leading to a wave length of approx. 315-360 km, which means a quarter wave length of approx. 80-90 km, which is close to the length of the estuary (approx. 120 km). The dip in tidal amplitude could well be due to a node in the M4 tidal component. Increasing the water depth further would tend to bring the estuary even closer to resonance and could further enhance the tidal range.

P-A CURVES

For the analysis of the behaviour of an estuary, one interesting aspect is the relationship between the tidal prism P, that is the volume of water moving throug a cross-section during a half tidal cycle, and the cross-sectional area A. From literature it is found that there often exists a nearly linear relationship between P and A. Though such data could be extracted from the BAW model, it turned out to be rather complicated so instead we used the simple Delft3D model to assess these curves. In Figure 18 we show the results for the same three scenarios. We clearly see that the tidal prism is increased all along the the

Elbe in the 2000 situation compared to 1970. The effect of the mouth is again mostly felt in the outer part. Considering the P/A relationship we see an almost linear trend in all cases; the fact that the P/A curve is now lower than before indicates that velocities must have increased, as has been shown elsewhere.

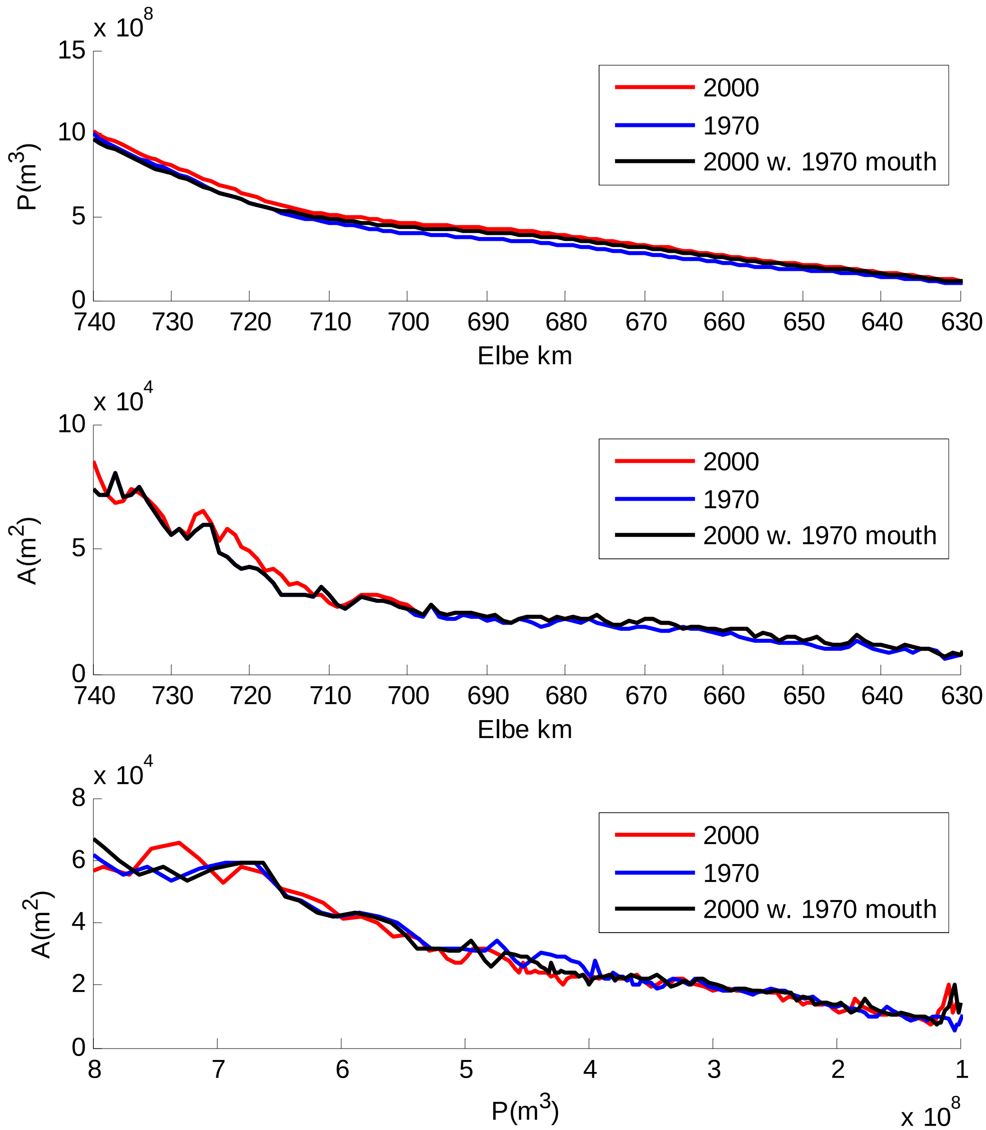

Figure 18 Tidal Prism vs. distance (top panel), Cross-sectional area vs distance (middle) and Cross-sectional are vs. tidal prism (bottom)

RIVER DISCHARGES

River discharges vary between less than 500 m3/s and more than 2000 m3/s; the effect of high discharges can be summarized as follows:

- Increase of fine sediment load from upstream
- Shifting of the salinity distribution and turbidity maximum in downstream direction.

In Figure 24 the discharge variation between 1995 and 2010 is shown, with a range between 400 and 1200 m3/s.

SALINITY DISTRIBUTION

The salinity distribution is well modelled by the 3D BAW model; typical results for average discharge conditions are shown in Figure 19, showing a clear trend for an upstream shift of the salt-fresh interface. The salinity distribution in turn affects the distribution of fine sediment, because of the gravitaional circulation.

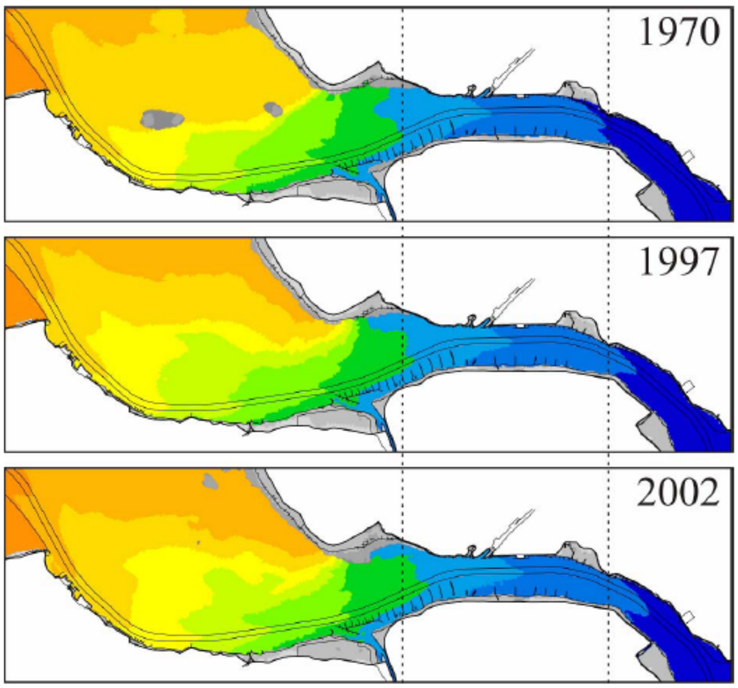

Figure 19 Salinity distribution for average discharge conditions; 1970, 1997 and 2002

TIDAL PUMPING

A series of questions have been addressed in the information package for the Committee of Experts, with the aim of explaining said changes, and assessing possible mitigating measures. One of these questions concerns the reduction in “tidal pumping”. Without further analysis it can be stated in general that reducing tidal effects will reduce the observed increase in tidal range in the river over the last century, and will reduce (fine) sediment dynamics.

As stated before, there can be several causes for the marked increase in tidal range:

- A reduction in dissipation due to the deepening and fairway optimization; this is likely to have played a role in the recent fairway deepenings and can in part explain the increase since 1970.
- A reduction in intertidal areas; there was no detailed data available on this but it may well have played a role since a number of dikings, polderings and closures of tributaries were carried out after 1970, as summarized in Figure 6.
- Changes in the configuration of the Elbe mouth; these seem to have played a a large role according to our simple calculations where the fairway deepening and the effect of the changes in the configuration in the mouth, especially near Medengrund and Medenrinne, were considered separately.

- An increase in the tidal wave length due the deepening, leading to different resonance behaviour. As we've discussed above, this may be an important issue, since it looks as if at present the quarter wave length is just smaller than the estuary length, so that increasing the wave length would lead to enhanced resonance.
- The reduction of the wetted area in the harbour. It is very important that the harbour area functions as a damper to the system, absorbing much of the incoming tidal wave; the reduction in wetted area, even though relatively small, could have had a negative influence.

DISTRIBUTION OF BOTTOM SEDIMENTS

In Figure 20 an overview is given of the particle size of the bottom sediments from data. Clearly the fairway is mainly sandy, whereas the shoals are composed of much finer material. Also from the dredging data in the WSA area (Figure 21) it follows that a majority of the sediment dredged from the fairway is composed of sand. Towards the Wedel area more silty material is found, mixed with fine sand. On the other hand, the material dredged from the Hamburg port area is predominantly fine sediment.

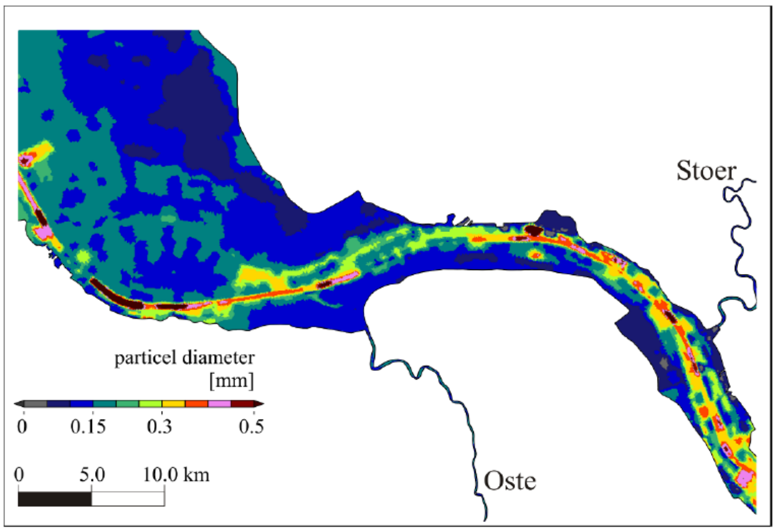

Figure 20 Distribution of bed sediment particle diameter (source: Sohrmann and Weilbeer 2006)

	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

Figure 21 Composition of dredged sediment in WSA competence area.

SEDIMENT CONCENTRATION PATTERNS

The (equilibrium) transport of sediments is governed by a balance by the seaward transport induced by the river flow, up-estuary transport by gravitational circulation, and the transport induced by tidal asymmetry, which is also often directed up-estuary. Temporary deposition on tidal flats, in secondary channels, etc. can induce large net sediment transport (often referred to as longitudinal dispersion). An analysis of changes in these processes in response to changes in the river's bathymetry and lay-out will provide useful information on the causes of the current sedimentological problems in the river. One can think of changes in tidal asymmetry (ratio M_4/M_2 tide, tidal phases $2\phi_2 - \phi_4$, etc.), changes in permanent and temporary storage areas, etc.

Changes in the configuration (depth, storage area, etc.) of the Norder and Süder Elbe may induce changes in the net circulation around the city of Hamburg. As such circulations induce net transports of fine sediments, it is recommended to quantify these changes.

The exchange rate of the harbour basins has changed over the years due to a change in the hydrodynamics and an increase of the suspended matter concentration.The trapping efficiency in a number of silted-up unused basins has been considerably reduced.

Finally, the transport of fine sediments in an estuary is controlled largely by water-bed exchange processes. These processes are a function of the bed shear stress, and analyses of changes in these bed shear stresses as a function of changes in the river lay-out, as computed with the numerical hydrodynamic model, can be very revealing in interpreting the response of the sediment dynamics to changes in the river system.

Figure 22 below presents the general trend in concentration patterns and salinity based on observations, for different headwater discharges. The general pattern is nicely confirmed by the BAW 3D model in Figure 23. The latter shows an upstream shift in the concentration from 1970 to 2002.

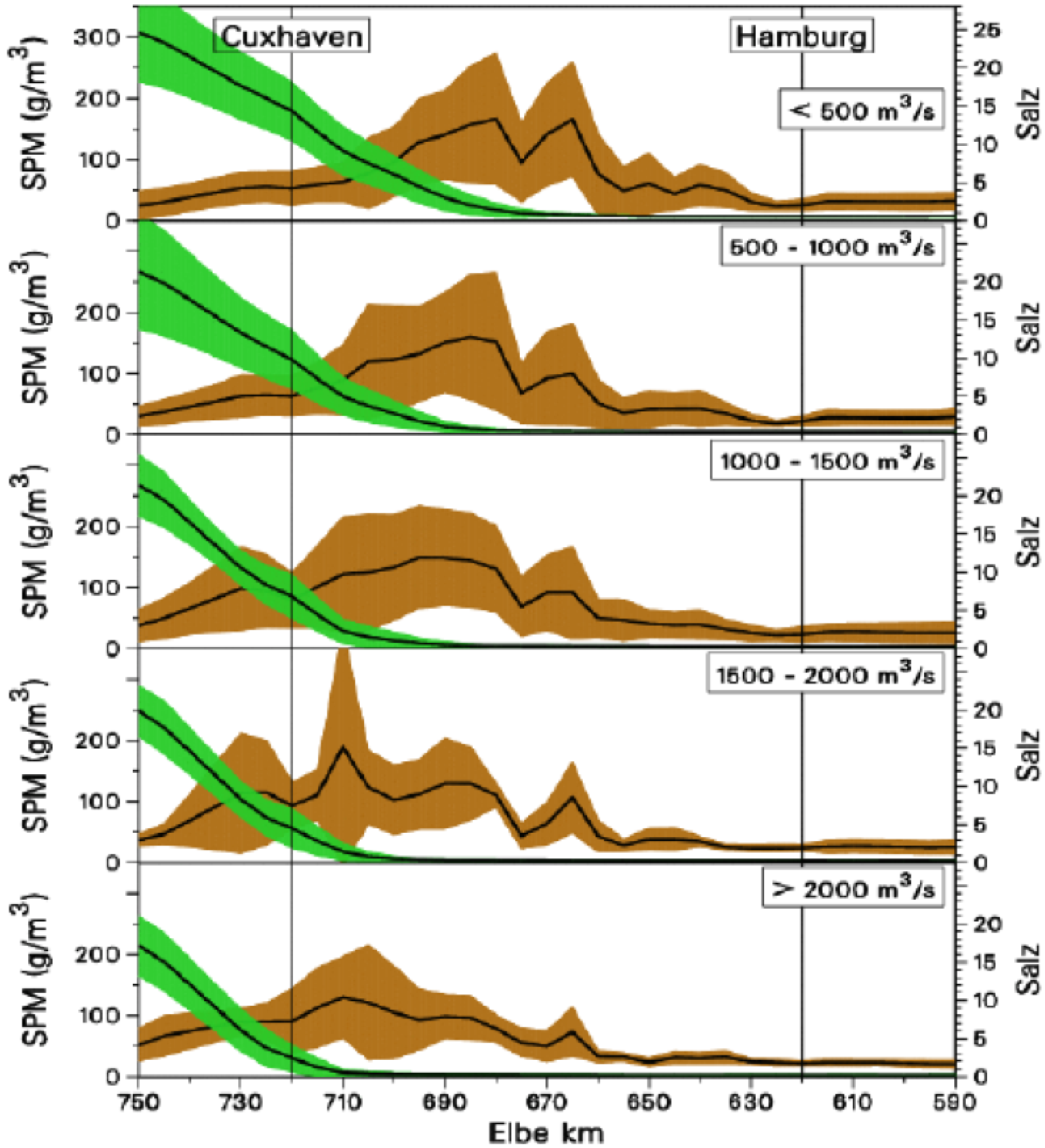

Figure 22 Distribution of particulate matter (brown) and salinity (green) in relation to the headwater discharge (from KAPPENBERG, J., FANGER, H.-U., 2007)

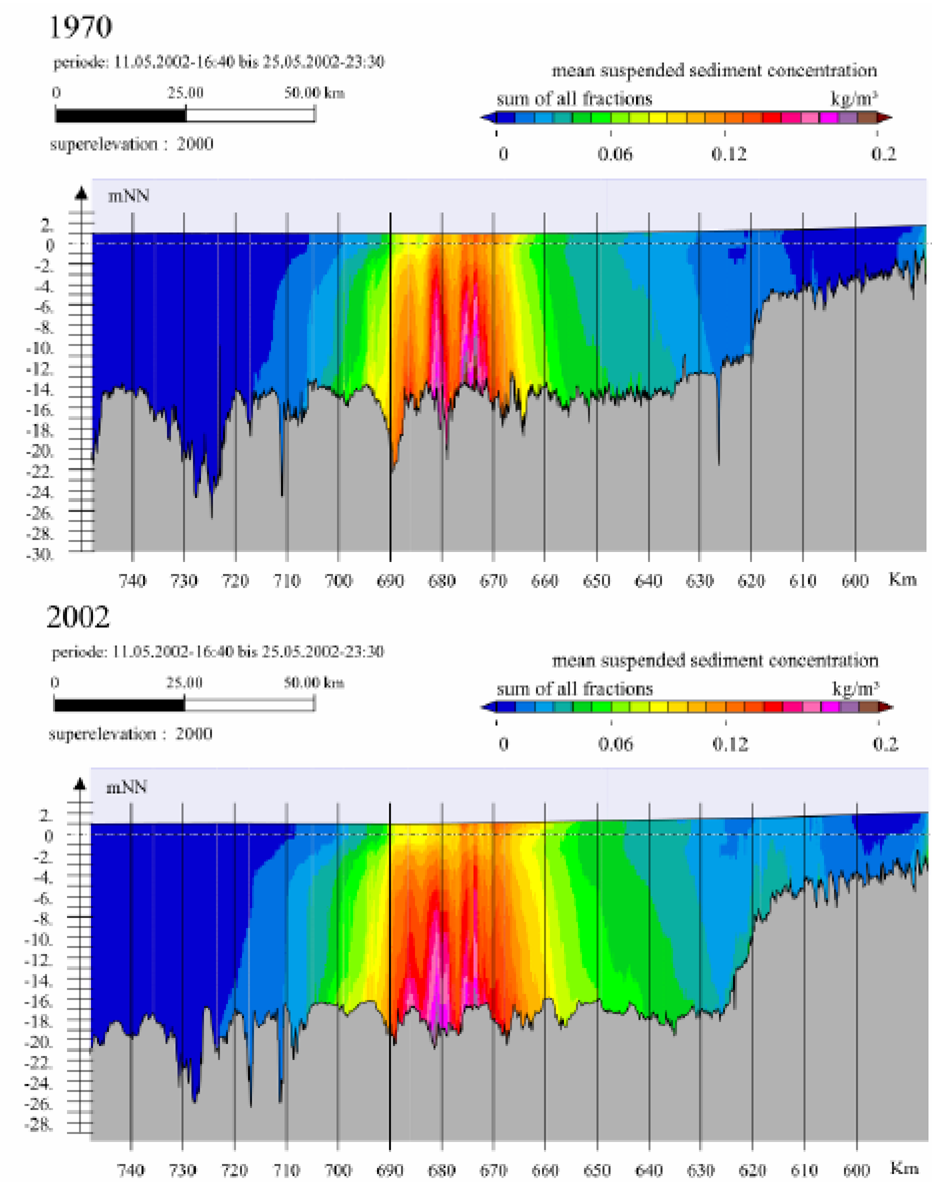

Figure 23 Mean suspended sediment concentration along the channel axis, 1970 vs 2002.

SEDIMENT TRANSPORT PATTERNS

In the BAW model, which has been in development or quite some time, much attention has been put on the reproduction of fine sediment concentrations and relatively less to sand transport processes and morphological changes. From the analyses carried out the general trend appears to be that sand moves in downstream direction whereas mud tends to propagate upstream to end up in the Hamburg area.

Siltation in the Hamburg harbor basins is basically a function of three parameters:

A. supply of sediment which is a function of source and transport:
    a. fine sediment may be supplied from the sea, from the Elbe upstream, from within the river (by erosion of its beds or banks), or from dumping locations,
    b. fine sediment transport in estuaries is governed by river flow, gravitational circulation (plays in the lower part of the Elbe, in the salinity intrusion part), tidal asymmetry, and

temporary trapping of fines in secondary channels, intertidal flats, large scale circulations, etc.

B. exchange processes between river and harbor basins – these processes are governed by river flow, and geometry of the harbor basin, in particular its mouth.
C. trapping of fine sediments within the harbor basins, which is a function of size and shape of the basins.

With respect to point C, sources and sinks of fine sediments in the river should be identified.

DREDGING AND DUMPING, SEDIMENT MANAGEMENT PRACTICES AND EFFECTS

Over the past 45 years the overall dredging figures have gone up from around 4 Mm3 in 1965 to around 20 Mm3/year over the last couple of years. Also, the relative proportion of the dredging quantities in the HPA area of authority has gone up sharply to even around 50% around 2005. This was particularly problematic since the sediment in that area is generally more polluted than that in the estuary downstream.

The approach towards maintenance dredging before 2005 can be best characterized as rather reactive and had a strong element of trial-and-error, which is understandable given the complexity of the situation. In a number of cases local dredging problems could be reduced considerably, i.e. by reducing the width of the cross-section, but there was no way to assess beforehand what the effect of such a measure would be on the larger-scale problem.

An important aspect in deciding the dumping locations has been the desire to minimize the impact of the dumping on the water quality and the quality of the sediments at the location. As an example the dumping at the Nesssand was done in an area of strong flows able to disperse the sediments quickly so that the impact on the surrounding area was minimal. However, this meant in some cases that strong recirculation of sediments to the dredging locations could occur.

In Figure 24 yearly dredging quantities in the tidal Elbe are shown. Clearly overall quantities have gone up significantly, particularly in the WSA Cuxhaven area of authority and that of the HPA, although in the latter quantities have gone down in recent years.

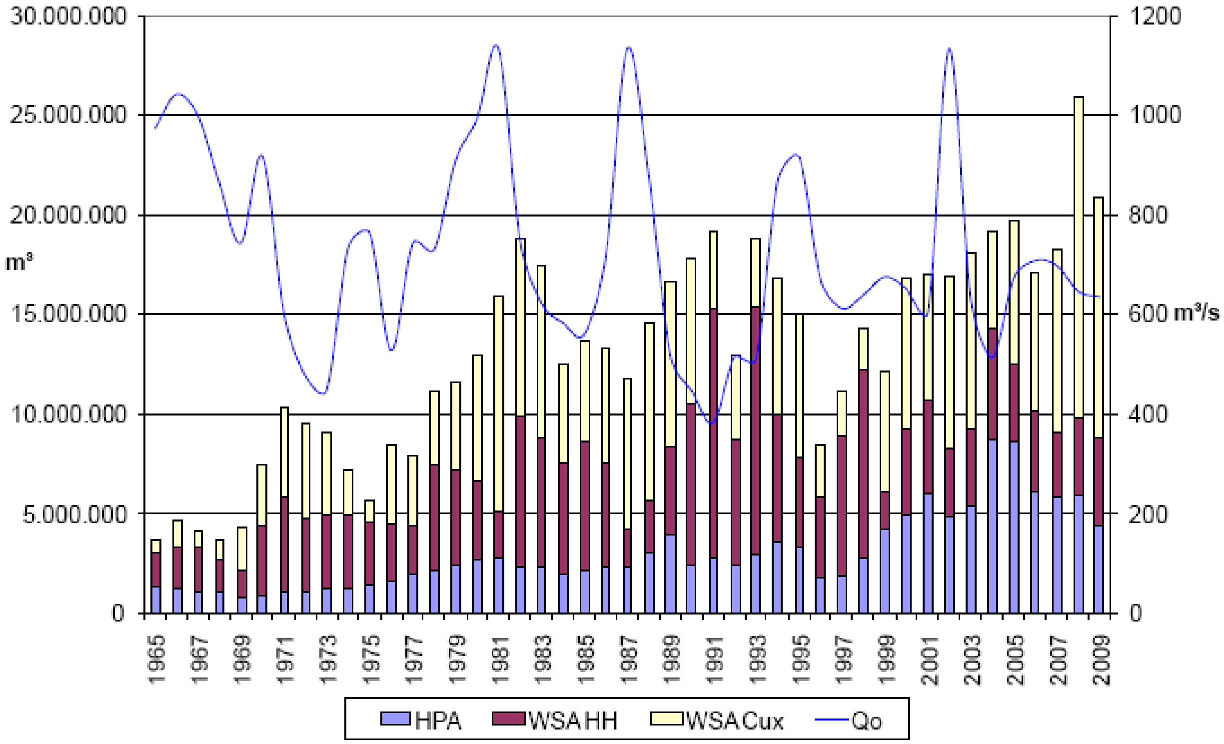

Figure 24 Yearly dredging quantities in the areas of HPA, WSA HH and WSA Cuxhaven, and river discharge variation.

A detailed overview of dredging quantities over the last two decades is given in Figure 25. Some striking features:

- Large variations in dredging quantities in the WSA Cuxhaven area, mostly related to the natural changes in the area, notably around the Medemgrund, where the formation and development of the new Medenrinne has been affecting locations between Osterriff and Cuxhaven.
- The striking disappearance of the dredging location Rhinplatte due to an engineered narrowing of the cross-section.
- (possibly related) large increase in sedimentation at the Wedel location, where recently a sediment trap has been installed.
- Large increase in dredging in the HPA area since 1999, followed by a decrease after 2005.

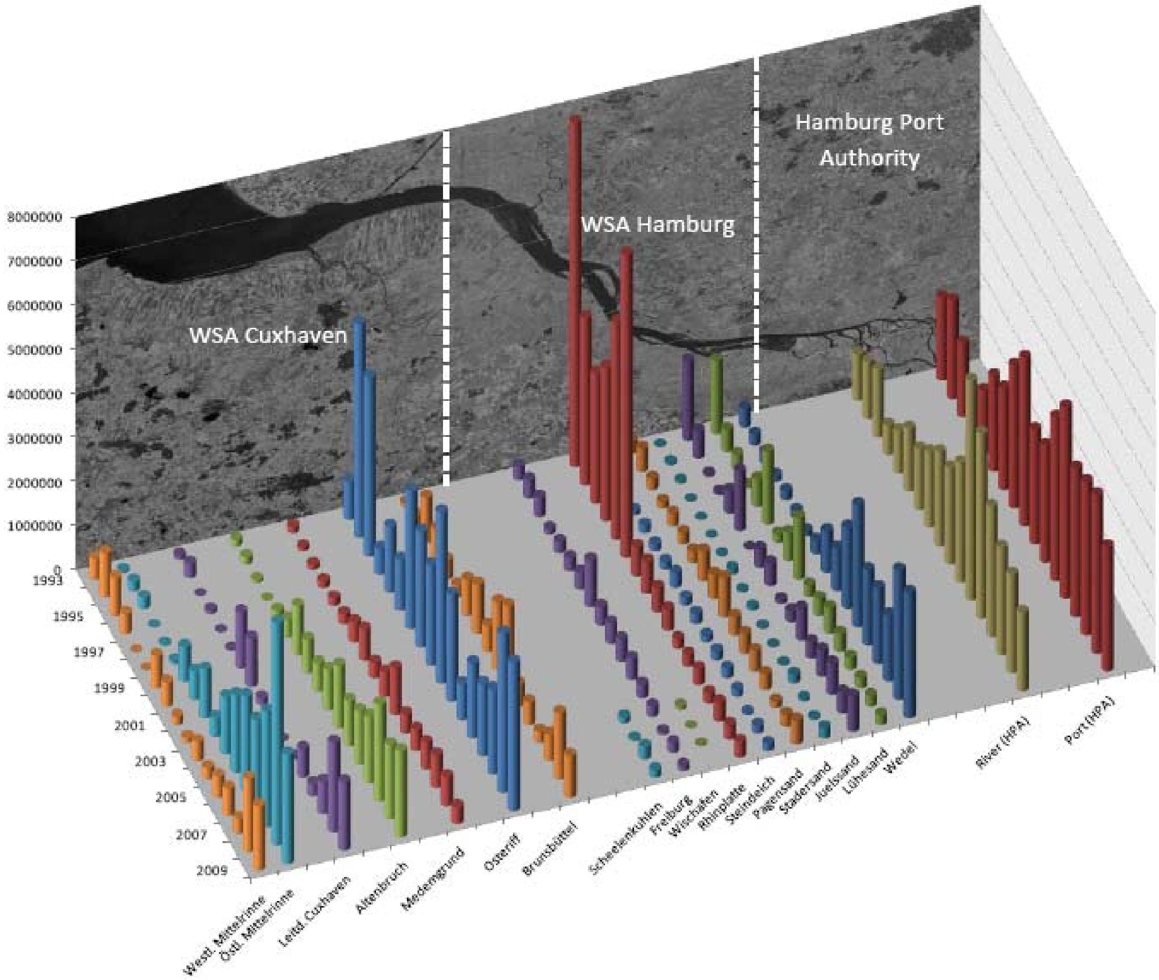

Figure 25 Detailed overview of dredging quantities per location, 1993-2009

From the overview of dumping quantities in Figure 26 we highlight the following features:

- Dumping at the Pagensand location appeared to have too much effect on dredging at upstream locations and was discontinued after 2005, in favour of dumping at more downstream locations.
- The large quantities dumped at Nesssand, just within the HPA limit, was also thought to lead to serious recirculation of sediment (referred to as 'dredging cycle') and was minimized after 2005, with stricter rules on when and how to dump there; part of the material was brought to offshore location E3 instead.

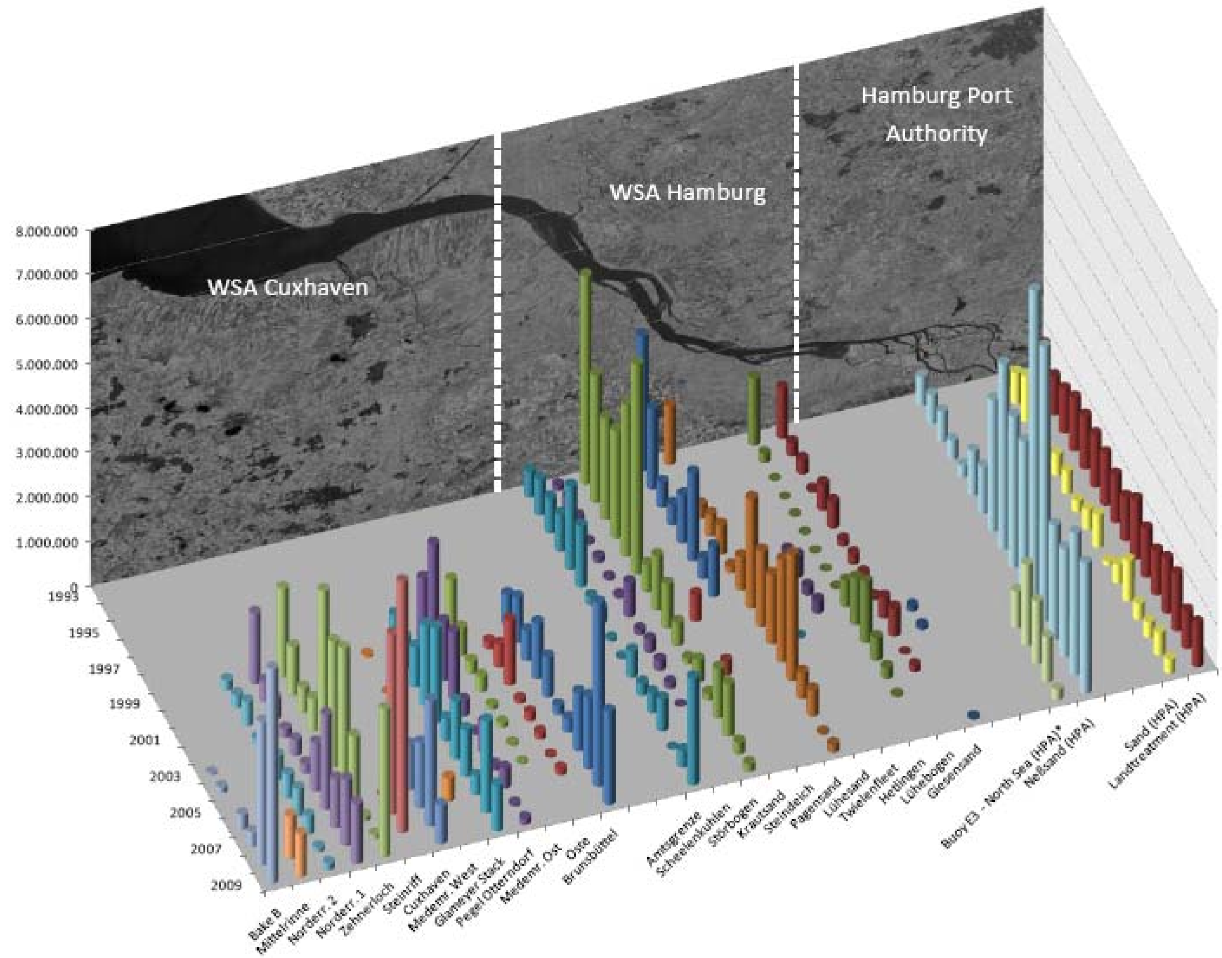

Figure 26 Detailed overview of sediment dumping 1993-2009

ASSESSMENT OF SEDIMENT MANAGEMENT PRACTICES SINCE 2005

GENERAL COMMENTS

In the following we will try to give an assessment of the sediment management practices since 2005. However, it must be stressed that much of the evidence for the effectiveness of the various measures is rather indirect and only a small part of these measures is backed up by convincing modelling exercises. Furtheron we will make recommendations about improving modelling capability in order to make it more directly applicable in designing and evaluating sediment management strategies.

REDUCTION OF SEDIMENT RECIRCULATION

This strategy is backed up by some simulations on recirculation of fine sediments carried out by BAW, and further modelling work is foreseen. The relocation of sediment from Wedel and Juelsand to locations downstream of km 677 seems to be effective and does not lead to excessive travel times. Figure 27 shows the volumes of sediment involved in part of this strategy.

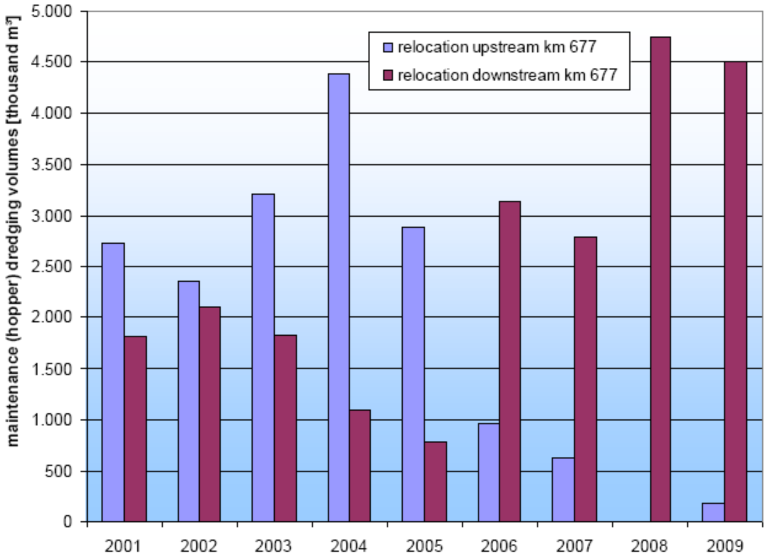

Figure 27 Relocation of maintenance dredging volumes (hopper dredging) in the area of the WSA Hamburg (2008 and 2009, incl. installation of the Wedel sediment trap) – since 2006, volumes have primarily been relocated to areas downstream of Störbogen (km 677)

INCREASED WATER INJECTION DREDGING

Water injection dredging can be a very cost-effective way of dredging, since it removes large parts of the usual dredging cycle (transport and dumping) and instead lets natural processes take care of that part, e.g. by density currents leading the mud-water mixture to the main channel.

The water injection dredging taking place to remove sediment in front of tributary mouths and ports seems very logical, and apparently the timing of it is selected to let the tide carry the sediment in the right direction.

Water injection dredging is also used extensively (see Figure 28) to smooth out sand waves. In this case the sediment stays very close to where it is stirred up and the sand waves can quickly reappear, making it necessary to repeat the operation often. It is then advisable to investigate whether in this case W.I. dredging is cheaper than now and then removing the crests of the sand waves by conventional hopper suction dredging. Investigation of the cost-efficiency of WI compared to hopper dreding has reportedly been undertaken by WSV based on actual market prices. The conclusion was that, though there is a reappearance of the sand waves, WI dredging is so much cheaper (approx. four times compared to hopper dredging) that it is preferable to hopper dredging. In addition, the medium-sized sand contained in the sand waves remains close to the dredging area, which reduces the risk of an ongoing 'fining' of the bed material, which in the long term could lead to reduced sand wave and ripple heights and therefore a further reduction in dissipation of the tidal energy.

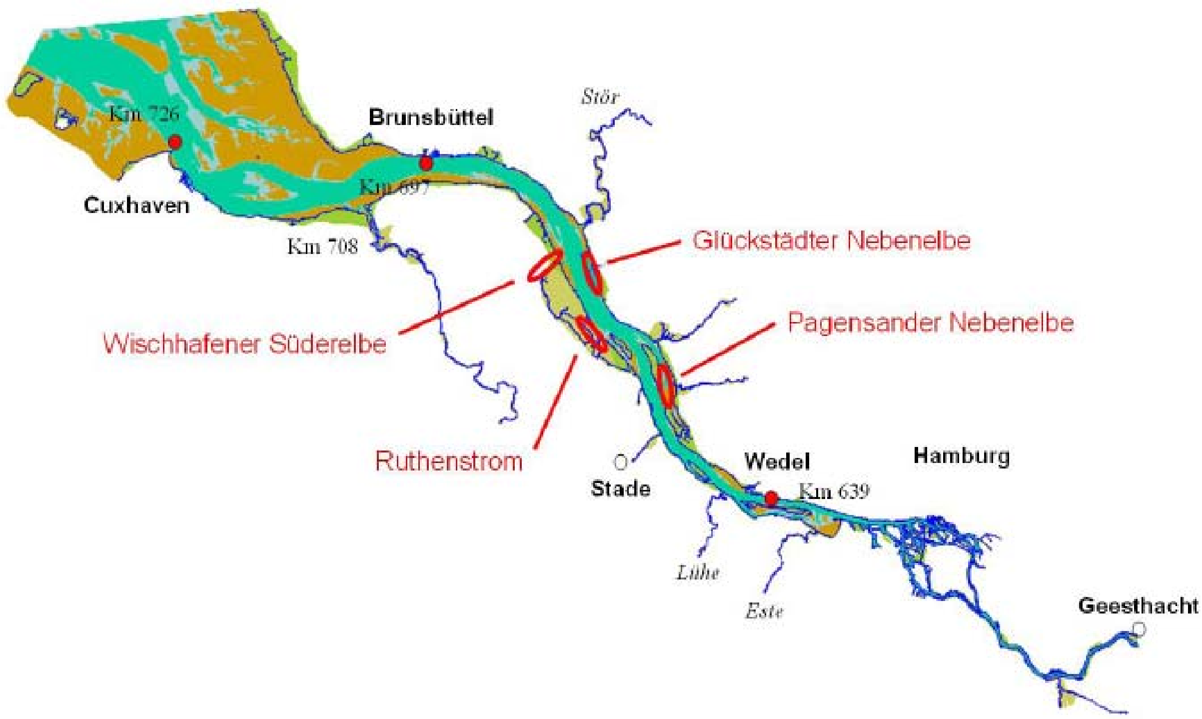

Figure 28 Locations of water injection dredging

RELOCATION TO NEW DUMPING LOCATIONS

The relocation of sediments to offshore dumping location E3, followed by a very extensive monitoring campaign, seems to be a rather desperate effort to reduce recirculation in the HPA area and is extremely costly. Alternative solutions of dumping this sediment within the estuary should be evaluated. If the sediment quality is much inferior to that in possible dumping locations, a solution could be to dig deep temporary pits which could be filled with the dredged material and afterwards capped with the local sediment. Though still expensive, this could be an alternative worthwhile to look into, especially when combined with sand mining for measures elsewhere in the estuary, e.g. in river engineering measures in the mouth.

Alternative options could also be to combine new projects to reduce tidal pumping with dumping of sediment. In cases where there is valuable material in such project areas, either good sand or clay that can be used in dikes, it may be cost-effective to mine such material and replace it with the dredged sediment, when necessary followed by capping.

SEDIMENT TRAPS

Sediment traps are often used to create a sedimentation buffer to enable more cost-effective dredging (e.g. after some consolidation) and/or to postpone dredging operations to a time when the dredging and associated dumping has a minimum impact (e.g. in winter).

A second objective may be to prevent sediment from travelling upstream where it is easily mixed with more polluted sediments.

So far the trap at Wedel appears to have functioned as a buffer but it is questionable whether it is preventing much fine sediment from travelling upstream. For that to work a significantly larger trap seems to be necessary. This could be executed as a much deeper pit with significantly reduced velocities or as a large basin connected to the estuary with a configuration that allows it to be dredged periodically with ease. Ideally such traps should also be installed upstream of Hamburg harbour, where the sediment is highly polluted but the quantity of it still manageable.

In the area downstream of Hamburg, the tidal flows are dominant and are typically in the order of 1 m/s with typical shear stresses in the order of 3 Pa; to reduce this to values conducive to large sedimentation (e.q. below 0.4 Pa) would require a reduction in velocity to below 0.35 m/s, in other words a tripling of the cross-sectional area would be necessary. This is clearly very difficult. On top of that, the time for the sediment to settle is in the order of depth divided by fall velocity, which can be up to many hours for fine sediment, so the volume of the trap would have to be significant. Therefore, though a deeper trap would likely catch more sediment, catching a significant proportion of it is unlikely and therefore it will be difficult to stop fine sediment travelling upstream to Hamburg.

So far there is little experience with such larger traps. From the (scant) available literature and a brief survey of experiences in the Netherlands and surrounding countries the following can be summarized:

- In the mouth of the Rotterdam Harbour (Caland-Beerkanaal) a so-called 'Bufferput' has been in place, with an overdepth in the order of 2 m, a width in the order of 1 km and an overall length of approx. 5 km. From data analysis and modelliing (Van Kessel, 2005) an estimated increase in sedimentation of both sand and mud fractions in the order of 10% was reported. Increase of the overdepth to 3 m gave less effect than from 0 to 3, but larger depths were not investigated.
- For the intakes of cooling water for power stations usually sediment traps are applied, but only to capture the sand fraction.
- In the case of maintenance of navigation channels outside sea ports, often a sediment trap is dredged alongside the navigation channel, on the upstream side, to allow longer intervals between dredging. This is only effective for sandy material, as fine sediment remains in suspension under such conditions.

Since port basins are in themselves quite efficient sediment traps, also for fine sediment, one recommendation could be to regularly dredge out unused harbour basins.

DREDGING OF HARBOUR BASINS

For the harbour basins that are dredged routinely, the quality is good enough for the sediment to be relocated within the Elbe estuary; for harbour basins that have not been dredged in a long time the sediment treatment plant on land is used.

If a harbour basin is silted up completely the wetted area is reduced, which has an enhancing effect on tidal pumping. Reducing the level to below MLW restores this function.

If the basin is dredged out much deeper, the sedimentation will be increased and the basin can effectively be used as a sediment trap. Whether this is desirable depends on the source and quality of the trapped sediment.

ASSESSMENT OF POSSIBLE MEASURES TO REDUCE TIDAL PUMPING

RIVER ENGINEERING MEASURES IN THE MOUTH OF THE ELBE TO RESTRICT TIDAL ENERGY AS IT BUILDS UP.

As was shown in the discussion on tidal pumping, the changes in the mouth area between 1970 and 2000 significantly affect the tidal propagation and amplitude. This in principle opens the way to engineer changes to reverse this effect, but it must be stressed that these measures should be on a very large scale in order to have a similar effect, given that the volume change in the area was around 150 Mm3.

The causes for this loss and the fate of the lost material are not quite clear and should be investigated thoroughly based on bathymetric analyses and long-term morphodynamic modelling; it is not inconceivable that at least part of the increase in conveyance of the mouth is the result of a cyclic process rather than a continuing negative trend; obviously this would make a great difference in the design of any measures.

In the presentation by Nicole von Lieberman the options of nourishing the sand banks and defending the sand banks are suggested. Additionally, one may think of filling up secondary channels such as the Medemrinne, possibly accompanied by hard structures to close off the channel or to consolidate the configuration. Some specific remarks on these optionsare given in the following sections.

NOURISHING THE SAND BANKS

This is possible in principle and has been applied elsewhere, e.g. at the Galgenplaat in the Eastern Scheldt, NL. It can be done by rainbowing from the edge of the shoals or, if higher parts are to be nourished, using pipelines; the latter is of course much more expensive. Rather than dumping very large amounts at once one may consider dumping a large part of the sediment dredged at the WSA Cuxhaven and the lower part of the WSA Hamburg in the Medemrinne or on the edges of Medemsand annually; with amounts in the order of 5-10 Mm3/year thus relocated this would lead to volume changes in the desired order of magnitude over a 15-30 year span. An important advantage of this method would be that the local and larger-scale effects can be monitored and adjusted and expensive and inflexible hard measures would be avoided. Of course possible effects of increased scour or dredging quantities elsewhere must be assessed, and ideally the whole operation would be guided by a combined monitoring and modelling effort.

DEFENDING THE SAND BANKS

Given the large variability in the mouth area this is not a very attractive option at first site. Defending eroding sand banks by hard structures runs the serious risk of leading to high costs of maintenance. For relatively stable banks that are slowly eroding groynes may stabilize them to some extent, especially in combination with regular nourishments. In contrast with the previous option, this one would require rather large initial costs and would have to be very carefully designed with full understanding of short-term and long-term consequences, as such measures are not flexible and risk of failure is very real.

FILLING UP THE MEDEMRINNE

A large dam closing off a major channel like the Medemrinne could also be envisaged, where the location of this dam could be on the upstream or downstream side or in the middle, based on detailed study. When executed properly this could lead to large sedimentation in the remaining channel area, effectively reducing the cross-sectional area and increasing the resistance. Special care should be taken to avoid development of a new channel cutting around the dam.

Given the much reduced tidal velocities in such a case the sedimentation of sand and fine material could be quite large and possibly relieve the dredging needs in the immediate vicinity. **Such a large sedimentation area could very well be used to dump large quantities of fine sediments, which would subsequently be capped naturally by cleaner sediment from the mouth area.**

As was suggested in von Lieberman's presentation, large dams when connected to the land could be used as efficient locations for wind energy.

Whatever the option considered it is very important to not just evaluate the immediate hydraulic effect but also to consider how subsequent morphological changes may undo these immediate effects to an unknown extent. As a simple example, restricting the width of a channel may enhance the resistance initially, but is likely to be followed by scouring that counteracts this effect, unless measures to prevent that are taken.

RIVER ENGINEERING MEASURES TO DISSIPATE THE TIDAL ENERGY ON ITS WAY UP TO HAMBURG

All we have seen of such possible measures are some sketches or brief descriptions. Without solid numerical or physical modelling of the effects of such measures and without assessing the morphological consequences that will in turn modify these effects it is impossible to evaluate such measures. Again, it is likely that such measures must be on a considerable scale to have measurable impacts on the system as a whole.

THE CREATION OF ADDITIONAL WATER SURFACES OR ALTERNATIVE TIDE POTENTIAL FOR THE ABSORPTION AND DISSIPATION OF TIDAL ENERGY

A number of such measures have been studied by the BAW using the unstructured-grid model.

A first conclusion was that such measures only had any significant impact when placed in the upstream part of the estuary.

For a number of possible measures the effect was studied individually, and also the combined effect was studied of a rather hypothetical set of measures that would be very extensive in total. This hypothetical set of measures led to a reduction in tidal range of approx. 0.5 m and a mix of effects on sediment concentrations and transport patterns, most of which can be assessed as positive (though not all).

ADDITIONAL MEASURES WHICH INFLUENCE THE TRANSPORT PROCESSES WITHIN THE TIDAL ELBE.

The management of the storm surge barriers in the tributaries of the tidal Elbe is such that at present flood levels are reduced to the extent that no sedimentation takes place on the salt marshes. This prevents a potentially beneficial effect of extracting fine sediment from the estuary and at the same time raising the level of these salt marshes.

ASSESSMENT OF ASSESSMENT TOOLS

Assessment of proposed measures would be facilitated from a conceptual framework on the dynamics of the river, and on how these dynamics have changed over time. The available calibrated numerical model can be used for hindcasts, analyzing the impact of the various changes in bathymetry, river training, etc. on the hydrodynamics, and in a later phase on the sediment management in the river.

The present model setup focuses very much on the hydrodynamics and the fine sediment concentration and transport patterns, at typical timescales of a couple of spring-neap cycles. It is very sophisticated in some respects, such as the unstructured-grid approach, and the detail of the schematization is very fine.

However, on the aspect of assessing morphological change over longer period and the modelling of shifting channels and shoals the modelling capability developed so far is limited. Although much of the estuary and in fact of the dredged material is sandy, the modelling of this sand and its morphological behaviour is very limited. As a result, for instance, the model is not able to correctly present areas of sedimentation in agreement with dredging patterns, nor is it able to predict changes in such patterns as a result of policy or river engineering changes.

The main obstacle in developing this kind of modelling capability is not the model system itself, which is very sophisticated, but to accept that in order to simulate morphodynamic processes at larger timescales, some shortcuts must be made in terms of:

- grid resolution,
- accepting 2DH or quasi-3D representtion instead of full 3D;
- speeding up morphological time using a 'morphological factor',
- reducing spring-neap cycle to single representative tide,

while activating those processes that do affect significantly the morphodynamic behaviour, such as:

- dynamic updating of bed composition leading to horizontal and vertical sorting,
- generating initial conditions for bed sediment composition.
- accurately representing inerodible layers,
- representing automated dredging and dumping procedures.

While it remains extremely challenging to obtain a good representation of morphodynamic developments and to predict the locations and quantities of dredging, it is broadly possible as has been shown in studies of the Western Scheldt, Haringvliet mouth, Marsdiep, San Francisco Bay, Humber and many more.

Apart from the two types of simulations mentioned before (detailed short-term sediment transport modelling and longer-term realistic morphodynamic modelling, a third type of simulations can be very revealing, viz. a type of simulation where the model creates a morphology starting from flat bed conditions, given the hard constraints and geometry of the basin and given realistic tidal boundary conditions. Such model runs often lead to quite realistic channel patterns even though they do not match reality exactly. The big advantage of such simulations is that the end result is recognized as near-equilibrium by the model, so that effects of certain measures (e.g. dredging and dumping, other river engineering measures) can be studied without suffering from the initial adaptation of a model that starts from a real situation that is not in accordance with the model equilibrium. This then allows, for instance, to investigate the longer-term effects of dredging and dumping strategies on sediment recirculation, on the shape of the estuary and development of tidal pumping, on the redistribution of sediment sizes in the estuary and allows an objective long-term evaluation of engineering measures, including their morphological feedback mechanisms.

In terms of validation of both the shorter-term sediment transport modelling and the longer-term morphodynamic modelling, the monitoring of the estuary seems to be quite adequate in terms of monitoring sediment size distributions, regular bathymetric mapping of the entire estuary (shoals as well as fairway), current and sediment concentration profiling. Additionally, tracer experiments can be quite revealing and can nowadays be carried out effectively, e.g. using fluorescent tracers (e.g. Bertin et al., 2009 and references therein). Such experiments can be used to examine the fate of material dumped at different locations.

ROBUSTNESS OF STRATEGIES IN FACE OF SEA LEVEL RISE AND CLIMATE CHANGE

The RESMC has been developed to counter pressing needs in terms of sediment management and in view of the increase of tidal pumping. So far the strategies have not been tested for their long-term robustness in the face of sea level rise and climate change. It is likely that there will be a continuing pressure for further deepening of the fairway leading to further changes in the tidal regime, though they may be mitigated to some extent. At the same time the rising sea level will lead to an increasing 'coastal squeeze', which will lead to loss of ecologically valuable marshland and intertidal area. For that reason, longer-term strategies should deal with compensation measures to counter this 'coastal squeeze', such as has been done or is being discussed in the Humber estuary and the Western Scheldt.

A truly sustainable vision for the Elbe estuary can only be developed in partnership with all stakeholders involved; although we recognize that already the present collaboration between the authorities responsible for the Elbe fairway is an important step, further expansion of the partnership seems inevitable.

SUMMARY OF ANSWERS TO INITIAL QUESTIONS

In the following the answers to the initial questions will be addressed based on the discussions above.

ASSESSMENT OF THE SITUATION UP TO APPROX. 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 (maintenance effort and expense, lowering low tide)?

The port expansion and associated successive regulations and deepenings have had a very clear effect on the tidal propagation in the Elbe estuary. Especially the deepening has led to a reduction in resistance and an increase in tidal wave length, bringing it closer to the quarter-wavelength resonance situation. This has led to an overall increase of maintenance dredging, though not excessive in quantity. The apparent shift of the fine sediment turbidity maximum and sediment transport pattern may in part have led to the increased dredging costs in the HPA area up to 2005.

The lowering of the low tide is in part related to the general increase of tidal amplitude, but is likely enhanced by the increased opening of the mouth area, especially related to the Medemsand region.

It is likely that in some areas before 2005 dredging strategies applied led to considerabe recirculation, which could in part explain the increased quantities in some areas, notably Nesssand.

ASSESSMENT OF THE SITUATION AS OF 2005 AND WITH FURTHER IMPLEMENTATION OF THE RESMC:

- What is the assessment of the current practice of sediment management on the tidal River Elbe (particularly sediment traps, relocation of dredged material to buoy E3, water injection procedures, disposal at Neßsand as well as relocation of the dredged material quantities of the Kiel Canal)?

In general it can be stated that the practice of sediment management on the tidal Elbe seems to be effective in reducing sediment recirculation, given especially the reduction in dredging effort in the HPA area in recent years; especially the reduction in dumping at Nesssand seems to have a positive influence.

Relocation of dredged material to buoy E3 appears to be feasible but very expensive and finding relocation areas within the estuary could be preferable, both from a cost point of view and given the desirability to keep sediment in the system.

From the data provided it is difficult to assess whether using WI dredging to shave off sand dunes is more effective than taking the sediment elsewhere; this depends on how often the procedure has to be repeated. Based on conversations with WSV the procedure appears to be much more cost-effective than hopper dredging, and furthermore reduces the risk of a 'fining' of bed sediments in these areas.

Relocation of the dredged material quantities from the Kiel canal appears to be based on reasonable assessment of transport paths.

- Is the objective "reducing tidal pumping" expedient as a sediment management strategy?

Under this term both the measures in the river mouth and those in the upstream area are mentioned. It is useful to separate both types, since in the first case the tidal motion (horizontal and vertical) in the tidal Elbe is reduced, with likely beneficial consequences both in terms of water levels and dredging quantities, whereas the second type has noticeable effects on the water levels but the effects on sediment transport and dredging quantities are less clear.

- Are the river engineering measures planned for reducing tidal pumping expedient?

As stated above, measures in the mouth of the Elbe may be quite effective, but need very careful design, especially when hard structures are involved. It seems likely that increasing the sand volume by large but feasible amounts can reverse part of the trend in increasing tidal range and reducing low waters. Possibly such measures must be accompanied by hard structures such as large cross dams, which could additionally be used for locating wind energy farms in some cases.

- What is the assessment of the current practice of using water injection in the Lower Elbe with regard to management of the various sediment fractions, is the practice of sediment trapping for fine material management appropriate and should the concept be extended? Is there related experience elsewhere?

Using WI dredging to clear the ports and tributary mouths of fine sediment appears to be quite efficient since the sediment flows into the main channel to be dispersed quickly. For shaving off sand dunes it may be effective, depending on how often the procedure has to be repeated.

Sediment trapping is widely used to create a buffer space in order to more conveniently plan the dredging operations and to allow fine sediment to settle. In this respect the trap at Wedel already seems to be having a positive effect. If the traps are meant to capture larger percentages of fine sediment, for instance to avoid mixing with more polluted sediments, then much deeper and/or wider traps must be considered, ideally both upstream and downstream from the Hamburg port area. Some of the projected new tidal areas upstream of Hamburg may be suitable for this, provided they are regularly dredged out. Alternatively, old harbour basins now silted up could be used as efficient sediment traps when dredged out regularly.

- How is the effectiveness of the opening of the side arms of the Elbe seen?

Their effect on the tidal pumping will probably be limited, but allowing more frequent flooding of tidal marshes would introduce a (modest) sink of fine sediment and additionally allow the marshes to follow the sea level rise trend.

- Is breaking dredging cycles as a strategy for reducing quantities of dredged material appropriate and expedient?

This is definitively a sound strategy and it has been used successfully in many places, e.g. in the case of the relocation of Rotterdam harbour sediments from Loswal Noord (just north of Hook of Holland) to Loswal Noordwest, closer to Scheveningen. Reducing and better timing of the dumping at Nesssand has led to considerably smaller dredging quantities in the HPA area.

- According to what criteria should relocation sites / disposal sites be selected?

Some criteria relevant to dredging efficiency and morphological impact are:

  - Minimum recirculation of sediment to originating dredging sites or nearby dredging locations
  - Preferably in sedimentation areas
  - Easy access and minimum sailing distance
  - For coarse material, use in scour locations can be appropriate

- Preferably keep sediment within the system
- Where possible 'make work with work'

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

In principle, given the discussion of the sediment loss from the Elbe mouth, it is advisable to leave the sediments in the system. It is possible that part of the sediment loss in the mouth is related to dredging practices, and if so this should be stopped. The dumping of relatively small quantities of sediment at E3 will not have a very large impact on the system.

It must be stressed that also taking sediment to 'dry' dumping sites dumping sites in the Elbe estuary effectively removes them from the system.

- What is the assessment of the further measures for optimizing sediment relocation (see above)?

These measures, such as relocation of sediment to more downstream locations in the WSA Hamburg area seem quite sensible. However, more can be done to substantiate the processes of sediment dispersal, both in terms of modelling the fate of the dumped sediments and the morphodynamic impacts, supported by local measurements e.g. tracer studies.

OVERALL ASSESSMENT

- Are the objectives of the RESMC formulated in the work order sensible in your opinion, also in view of the situation in other European estuaries?

These objectives were formulated as follows:

1. reducing dredged quantities for example by river engineering measures for reducing tidal pumping also in the delta; sediment traps; creation of flooding areas

   The way this objective is formulated it is a bit of a mix of objective and three methods; the objective of reducing dredging quantities is obviously valid; the effectiveness of the measures for actually reducing the dredged quantities needs to be further substantiated but positive effects are quite likely.

2. measures for management of the sediment budget by optimising relocations

   This seems to be working already given reduced dredging amounts in recent years; further development of operational modelling capability in combination with monitoring can further refine this strategy.

3. measures for improving sediment contamination (in particular remediation measures in the entire catchment area)

   Obviously this is a sound strategy, though it will only work on a very long timescale

In my opinion, the HPA and WSV are facing problems that are quite similar to those encountered by the other major ports in Europe and are dealing with them in an adequate way, given the sometimes difficult administrative circumstances. On the longer term, further integration of their objectives with those of other organizations and stakeholders in the estuary seems inevitable.

- Do the measures outlined in the RESMC represent overall the right way to achieve the objectives?

As stated before, the measures appear generally logical, but in many cases need further substantiation.

RECOMMENDATIONS FOR THE FURTHER DEVELOPMENT OF THE RESMC

Our main recommendations for the further development of the RESMC based on the discussion above are:

- Develop long-term integrated plan for Elbe mouth nourishment strategy plus hard structure plus deposition site of fine sediment plus possibly other uses (e.g. wind energy)
- Develop upstream locations as sediment traps both upstream and downstream of Hamburg
- Develop operational sediment transport and morphodynamic modelling system for short- and long-term simulations; pay more attention to sand behaviour.

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APPENDIX A - CV OF DANO ROELVINK

NAME - DATE OF BIRTH - NATIONALITY:	J.A. (Dano) Roelvink – May 10, 1959 - Dutch
EDUCATION:	PhD Civil Engineering, Delft University of Technology MSc Civil Engineering, Delft University of Technology
PRESENT POSITION	Professor of Coastal Engineering and Port Development, UNESCO-IHE (0.8) and Senior Specialist Coastal Morphology, Deltares (0.2)
KEY QUALIFICATIONS: 	Prof. Roelvink has 25 years of experience in coastal engineering and research. He has participated as team member and as project manager in a number of major consultancy projects related to coastal morphology. He has managed the development of the Delft3D model system for two- and three-dimensional simulation of waves, currents, water quality, ecology and morphodynamics, and has heavily contributed to development of the morphological part of this system. He has been actively involved in the EU-sponsored MaST-G6M and MaST-G8M, SASME, COAST3D and DELOS research projects on coastal morphodynamics, His field of expertise is in coastal hydrodynamics and morphodynamics modelling, in one, two or three dimensions. In 1993 he obtained a PhD-degree at Delft University of Technology, based on a thesis on the effect of surf beats on coastal profiles. He has published over 80 articles on coastal hydraulics and morphodynamics in international journals and conference proceedings, and he has been a part-time Associate Professor at Delft University of Technology from 1990-2005 and presently holds an honorary Professorship there. He has been Delft Hydraulics' principal investigator in the discipline of morphology and is a strong proponent of international scientific cooperation with various parties in order to further the state-of-the-art in morphodynamic modelling and has set up collaborative projects with the US Geological Survey, the US Office of Naval Research and the Army Corps of Engineers. He currently leads the development of XBeach, an open-source model for storm impacts

PUBLICATIONS	Selection of recent journal publications
2009	Dano Roelvink, Ad Reniers, Ap van Dongeren, Jaap van Thiel de Vries, Robert McCall, Jamie Lescinski. Modelling storm impacts on beaches, dunes and barrier islands. Coastal Engineering, Volume 56, Issues 11-12, November-December 2009, Pages 1133-1152
2009	Dissanayake DMPK, Ranasinghe R, Roelvink JA. Effect of Sea Level Rise in Tidal Inlet Evolution: A Numerical Modelling Approach. JOURNAL OF COASTAL RESEARCH Volume: 2 Special Issue: Sp. Iss. 56 Pages: 942-946
2008	van der Wegen, M., Z. B. Wang, H. H. G. Savenije, and J. A. Roelvink (2008), Long-term morphodynamic evolution and energy dissipation in a coastal plain, tidal embayment, J. Geophys. Res., 113, F03001, doi:10.1029/2007JF000898.
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