SEDIMENT MANAGEMENT STRATEGIES IN THE ELBE ESTUARY

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FINAL REPORT: 12 May 2006

CONTENTS

TABLES

FIGURES

1. INTRODUCTION

A recent large increase in the amount of maintenance dredging needed in the Port of Hamburg has created a need to change the established dredged material disposal strategy. One solution that has been used has been to take some dredged sediment to a site in the North Sea near Helgoland but as this is more than 100km from Hamburg it is at high cost. Sub aquatic disposal in the river mouth is proposed as another alternative but is also costly. The Ministry is concerned about the increasing costs of these sediment management strategies in the Elbe Estuary and additionally about any potential negative effects that they might have. The Ministry therefore desired the views of an independent international expert and Hamburg Port Authority approached and subsequently commissioned Mr Burt of HR Wallingford.

The task was to provide an expert opinion on whether the management strategies are on the right path or if there are any other possibilities available at lower cost. The review began in January 2006 with a visit to Hamburg following which an initial appraisal was prepared and given to HPA. This was followed by a second visit at the beginning of February. With the benefit of several discussions and the provision of additional information this present final report has been prepared.

2. THE DREDGING AND DREDGED MATERIAL DISPOSAL STRATEGY

2.1 Port of Hamburg

The Port has a statutory and a commercial obligation to maintain certain depths so there is no question that dredging has to continue. There is also an obligation to meet certain environmental standards in the way the dredged material is handled. The strategy may be summarised as follows:

Dredging in the Port is carried out by a carefully managed system involving regular high quality monitoring of water depths and tight control over the dredging operation. Relocation is not permitted during part of the summer season due to concerns about the dissolved oxygen levels and protection of sensitive organisms in the water.

Most of the routine maintenance dredging is now carried out under contract using trailing suction hopper dredgers.

<u>Contaminated sediment</u>
Sediment too contaminated for normal disposal has formerly been treated in flushing fields and in the METHA plant. This has a capacity up to between 1.2 and 1.4Mm^3/year. This material is removed permanently from the estuary.

<u>In-river disposal of lightly contaminated and clean sediment</u>
Due to gradual improvements in the water quality of the River Elbe some of the sediment is less contaminated than previously. This applies particularly in the Port area with fresh sediments. This material is relocated in the river inside the Hamburg

State Boundary. The location was selected in consultation with the environmental authority (BSU). The agreement requires that the material is placed near the Port boundary during the ebb tide, in the belief that the material would be carried well downstream. The practice was begun with relatively small quantities on an experimental basis in 1995. The lack of any apparent negative effects was taken to indicate that the quantity placed in this way could be increased but there is now a strong feeling at the Port that the increased use of this option is at least partly to blame for the increased dredging rate. The modelling carried out by BAW demonstrated that a "pumping mechanism" existed that could carry sediment back up the estuary from the relocation site and return it to the port area. However, there are many other factors that have affected the actual dredging rate. This is discussed in more detail in Chapter 5.

Placement in the North Sea
Since August 2005 there has been a further option to relocate dredged material from the Norderelbe and Koehlbrand /Suederelbe into the North Sea near buoy E3. The rules for doing this have been agreed with the federal state of Schleswig Holstein. The quantity is limited to 1.5 Mm^3 /year over a period of 3 years. There is no seasonal restriction on disposal at this location.

Aggregate dredging
Sand is dredged from the estuary using trailing suction hopper dredgers to supply aggregate for the construction industry as part of the maintenance dredging strategy (This is further discussed in Chapter 3). This is not normally counted in the dredging disposal quantities but the quantity is significant enough that it should be taken into account in thinking about the sediment management strategy. Presumably if the commercial operation ceased then it would become part of the maintenance quantity.

Water injection dredging is also carried out on a regular basis as an economic way to deal with high spots left by the dragheads of the trailing suction hopper dredgers.

However this is not the only dredging that takes place in the Estuary. Other Authorities have responsibility for the remainder of the Estuary down to the mouth. WSA Hamburg, WSA Brunsbuettel and WSA Cuxhaven carry out dredging on a regular basis.

2.2 WSA Hamburg

Until the end of 2004 WSA Hamburg was responsible for dredging activities between km 638.9 and km 689.1. Dredging was carried out exclusively by WSA until that time. The area was subdivided into 9 dredging sectors. The dredged material was relocated in the channel at the nearest suitable location taking into account a number of factors.

Since 2004 material is disposed of further down the estuary towards the sea. The main responsibility of WSA Hamburg is the co-ordination of the water injection dredging in the main channel between km 638.9 and km 748.0.

The management strategy is reactive in that it is carried out only when necessary. Formerly it was by dredging campaigns but these regular campaigns stopped in the 1980's.

2.3 WSA Cuxhaven

WSA Cuxhaven is responsible for the dredging of the federal waterway from km 689.1 to the North Sea. Up to the end of 2004 they carried out the maintenance dredging themselves. Since then WSA Cuxhaven oversees contract maintenance dredging by trailing suction hopper dredger. Most of this is between Cuxhaven and Medem Grund. The dredged material is placed in the outer estuary. Little dredging is required in the outer estuary.

Dredging of the port at Cuxhaven is the responsibility of Lower Saxony Port. It is mainly carried out using water injection dredging.

Sand dredging for industrial use within the WSA Cuxhaven region was done in the Outer Elbe (downstream of Kugelbake Cuxhaven). The quantity over the period 2001 - 2002 amounted to $3Mm^3$ of which 2.2Mm3 was taken from the western and eastern main channel. There was no systematic sand dredging to the north, which, in any case is forbidden by the Federal Ministry of Transport.

2.4 WSA Brunsbuettel

The main dredging activity for WSA Brusbuettel is maintenance of the area in and around the lock entrance to the Kiel Canal. Most of the dredging is on the seaward side of the lock and the work is carried out by a trailing suction hopper dredger that places most of the dredged material at about Elbe km 700.

3. DREDGING TRENDS

3.1 Port of Hamburg and delegated section of river

This has been well described in a briefing paper prepared by HPA (2005). There is little point in repeating here what is covered by that and several other documents given to me. In this section I will try to draw out only the main points. The quantities for each type of disposal are shown in Figure 1 for the period from 1990 to the present.

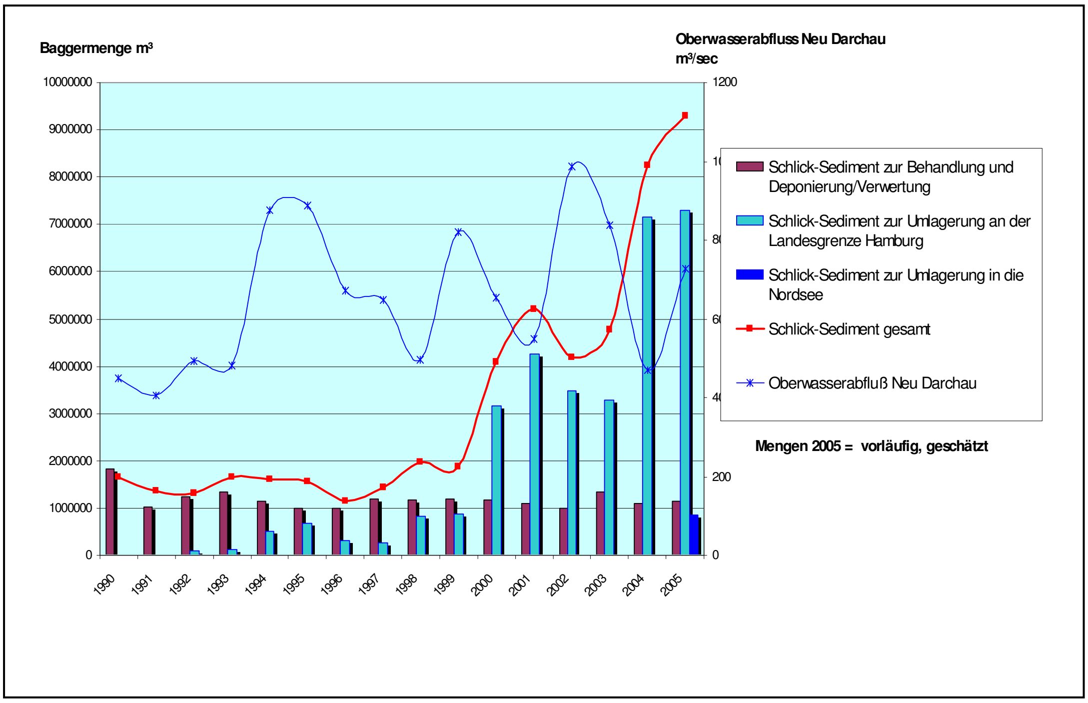

Figure 1: Disposal quantities from 1990 to the present

According to literature published by the Port and more recent data seen during the visits the dredging rate in Port of Hamburg has remained fairly steady at less than $2Mm^3$/year until 1999 when there was a steep increase to $4Mm^3$/year. By 2005 the amount had reached almost $10Mm^3$/year. Closer examination of the basic data shows that actually the high figures for 2004 and 2005 are mainly attributable to the winter period of 2004/2005 and especially so to the first half of 2005 for which the figure was about $6Mm^3$. The quantity in the second half of 2005 was lower than for the first half of 2004 suggesting that the very high figure has been a temporary feature. This is not to suggest that the rates generally have not increased; they clearly have.

3.2 Dredging in other regions

The following table provided by WSA Hamburg (Ref: AKN Jahresbericht 2005) summarises the amount of dredging carried out by the authorities responsible for the remainder of the estuary. Quantities are in millions of m^3.

	WSA Hamburg (A)	WSA Cuxhaven (B)	Total A+B	WSA Brunsbuttel
1996	4.1	2.6	6.7	7.0
1997	7.0	2.8	9.8	7.1
1998	9.4	2.3	11.7	7.4
1999	1.8*	5.3*	7.1*	6.0
2000	4.4	7.5	11.9	7.0
2001	4.6	5.3	9.9	7.2
2002	3.5	7.4	10.9	6.0
2003	3.9	8.5	12.4	6.1
2004	5.7	4.8	10.5	7.2
2005	4.0	7.2	11.2	7.6

* Dredging figures are only for the period 1 January to 15 September

After the deepening in the seventies the dredging rate in the WSA Hamburg region increased considerably, the sedimentation concentrated at smaller locations possibly indicating a greater heterogeneity of the current field. After the more recent deepening in the late nineties dredging increased at the shoals further upstream, nearer the border with the Port (Brinkmann-Study by HPA, Eichweber 1998).

The tabulated figures for 1996 – 2005 are illustrated in Figure 2. The Figures for Brunsbuettel are not included in this analysis.

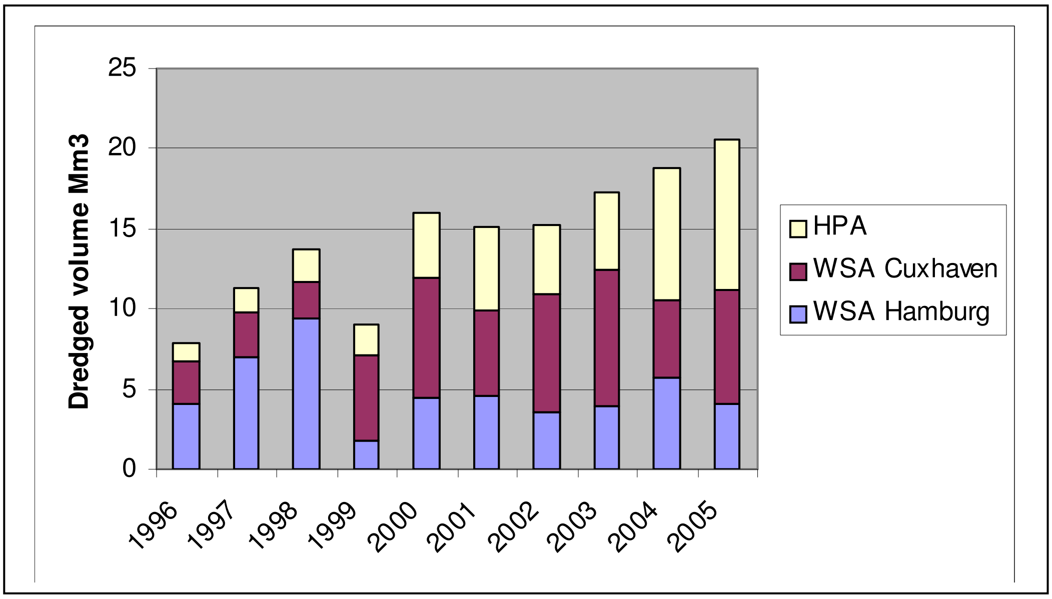

Figure 2: Total dredging quantities from HPA to WSA Cuxhaven

After a period of increase from 1996 to 2000, attributable entirely to the increased dredging in WSA Hamburg region the rate steadied at about 15Mm^3/year until 2002. During the period 2000 - 2005 the rate for WSA Hamburg returned to its 1996 level of an average of about 4Mm^3. Fluctuations may be attributable to a higher than average rate in one year following a lower than average rate the previous year. The undeniable trend shown by Figure 2 is that the substantial increase in the total for 2004 and 2005 is attributable to the substantial increase in HPA dredging.

The data shown for Brunsbuttel indicates a fairly steady rate of dredging of between 6 and 7.4 million m^3/year. The location of the entrance to the Kiel Canal is coincident with the zone of maximum turbidity. Because of this it is very likely that the material being dredged is very low density. This maintenance activity can be considered as a separate sediment transport cell, more or less independent of the overall trends in the estuary. I strongly suspect that any variation in dredging rates at Brunsbuttel from year to year is as much related to how much dredging has been achieved as to genuine variations in siltation rate.

4. CHANGES IN THE ELBE ESTUARY

It is beyond the scope of this review to try to list in detail all the changes that have taken place but it is important in considering the sediment regime of the Elbe estuary to be aware that many significant changes have taken place in recent years (in addition to many over previous decades).

4.1 General behaviour of estuaries

Estuaries are governed by tidal action at the sea face and by river flow. These are the main independent variables. The boundary shape of the estuarine system is determined by the geomorphology of the land and the properties of all alluvial materials that form the bed and banks of the channels. Usually the overall boundary shape changes only slowly, though there may be rapid local or short term adjustments. Gradual changes take place due to accumulation and re-distribution of river-borne solids, but their importance varies greatly in different estuarine systems. Sea-borne sediment stirred up by tidal currents and wave action can enter an estuarine system from beyond any immediate zone influenced by the estuary. Where this happens, the influx of sea-borne sediment becomes another independent variable that must be reckoned with in any analysis (McDowell and O'Connor, 1977).

The equilibrium of an estuary can only be maintained if the quantities of solids, fresh water flow and minerals in solution each remain in balance. Fresh water entering an estuary must leave at the same rate averaged over several weeks. Rainfall, evaporation and percolation all take part in the process but rarely contribute significantly to the balance except during times of very low fresh water flow. Water leaving the estuary eventually mingles with saline water but this is a gradual process and depressed salinity values can be found many kilometres offshore. As fresh water moves out of the estuary so salt water moves in due to the density difference between the two.

There is a tendency for net landward movement of sediment to occur over the middle reaches because flood tidal velocities are stronger than those of the ebb. Superimposed on this effect, the density difference between water at the seaward end and water entering from rivers causes net landward movement of water near the bed and a compensating net seaward movement at the surface. This can cause fine sediments to be carried landwards in suspension to a point of zero net movement, which is near the landward limit of density gradients. Water is predominantly fresh upstream of this point. The point (usually called the null point or the turbidity maximum) can move considerable distances in cases where there are large variations in river flow. For example in the Thames Estuary the zone moves some 20km due to normal variations in river flow and more under extreme conditions. The effect in simple terms is that a high fresh water flow tends to "flush" sediment out of the upper and middle reaches and into the lower reaches. A prolonged period of low fresh water flow causes the sediment to migrate slowly back up the estuary. In the case of the Thames the return is a slower process than the flushing (HR Wallingford, 1980).

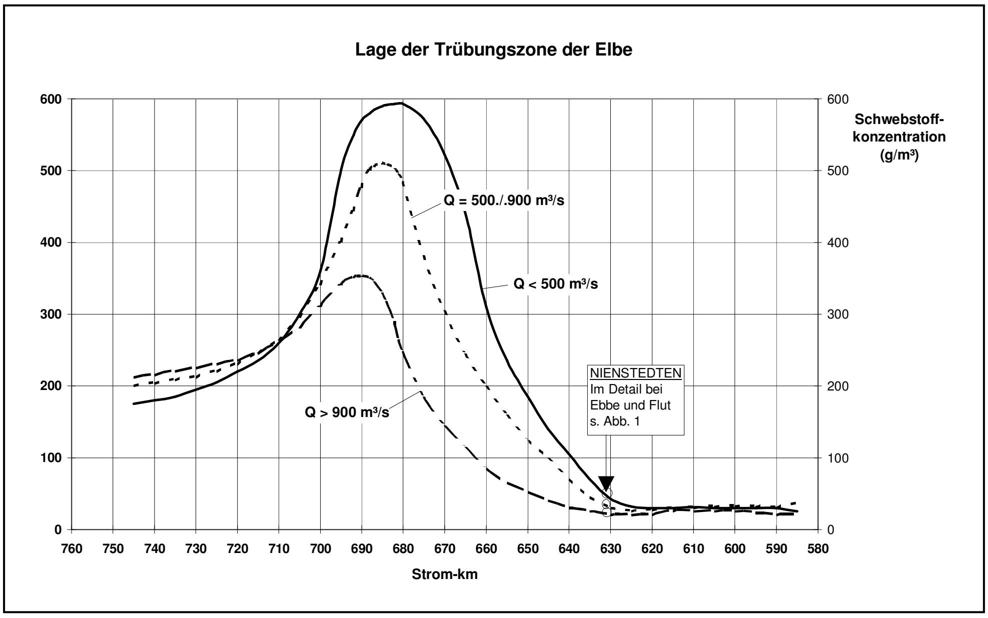

Figure 3 Turbidity maximum in Elbe Estuary

The movement of the saline penetration zone for the Thames is shown in Figure 4. The maximum salinity occurs at High Water and minimum at Low Water at any particular location. The effect of both fresh water flow and tidal range can be seen in Figure 4. The 1968 surveys were both carried out during high freshwater flow while during the 1969 surveys the freshwater flow was low. High freshwater flow is seen to push the zone of very low HW salinity down to London Bridge while during low flow the zone extends to Syon Reach. The effect of lower tidal range in both 1968 and 1969 was to reduce the distance between maximum and minimum salinity values. This is of course due to reduced tidal excursion distance when the tidal range is smaller.

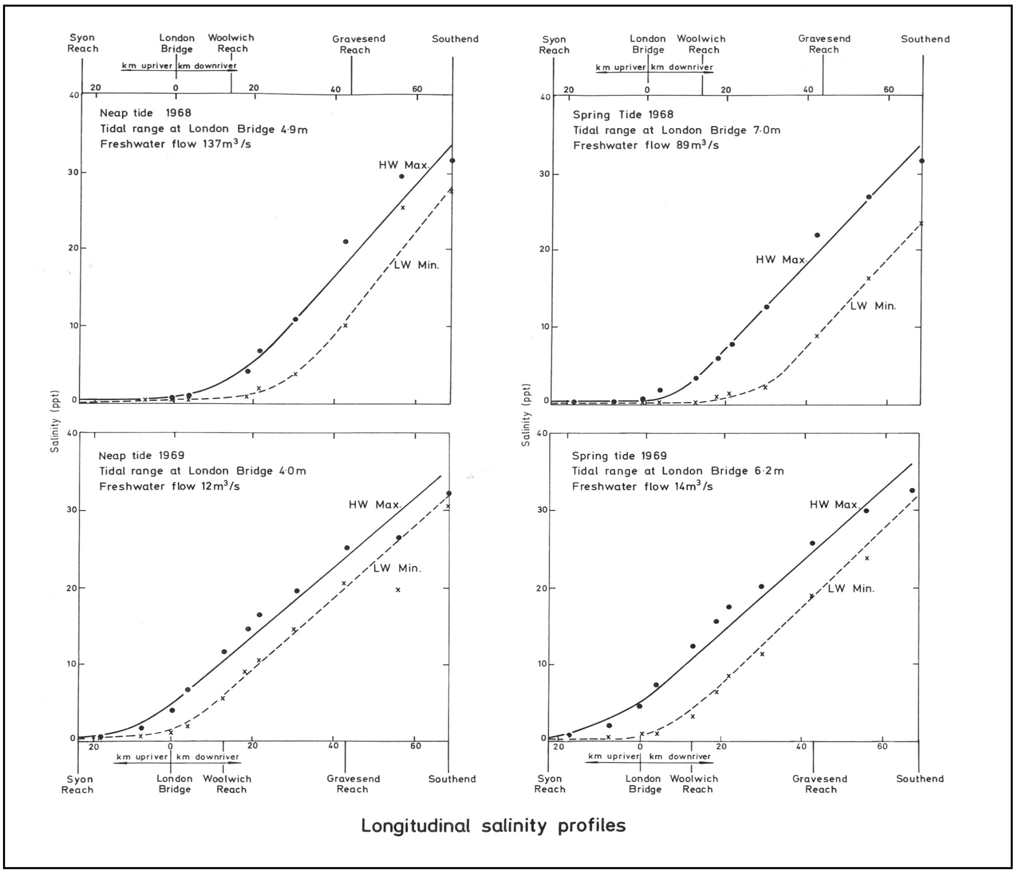

Figure 4: Salinity variations in the Thames Estuary

Sediment transported by water can be divided into three broad groups:

- Particles fine enough to be kept in suspension indefinitely (clay)
- Particles fine enough to be easily lifted into suspension and transported in suspension by flowing water (silt and fine sand)
- Particles so large that they usually travel by rolling along the bed.

Particles of silt or clay tend to stick together (flocculate) which gives them a much faster settling velocity than they would otherwise have. The flocculation process is enhanced in saline water and by the presence of organic matter (known to be a significant percentage in the Elbe estuary).

In a fast flowing estuary such as that of the Elbe it is not unusual to find that there are sand dunes on the bed. These can be several metres high but more usually would be in the region of 1m – 2m. These dunes tend to migrate slowly and might colloquially be described as part of the energy dissipating system, rather like turbulence in the water.

There are other processes, such as those that take place on inter-tidal mud banks, that also impact on the sediment balance of an estuary but it is sufficient to understand that there are powerful forces at work in a large estuary such as the Elbe and that the seemingly stable regime is actually a result of the balance of these forces. If the forces are disturbed by man then nature quickly comes into play to restore a new balance.

4.2 Reclamation of intertidal areas

Much reclamation has taken place in the Elbe estuary over many years. Perhaps the greatest impact was the building of dikes, building of weirs cutting off the tributaries and river engineering measures that took place in the seventies. In addition to these several redundant docks were filled. This is illustrated in Figure 5. The changes are listed in Table 2.

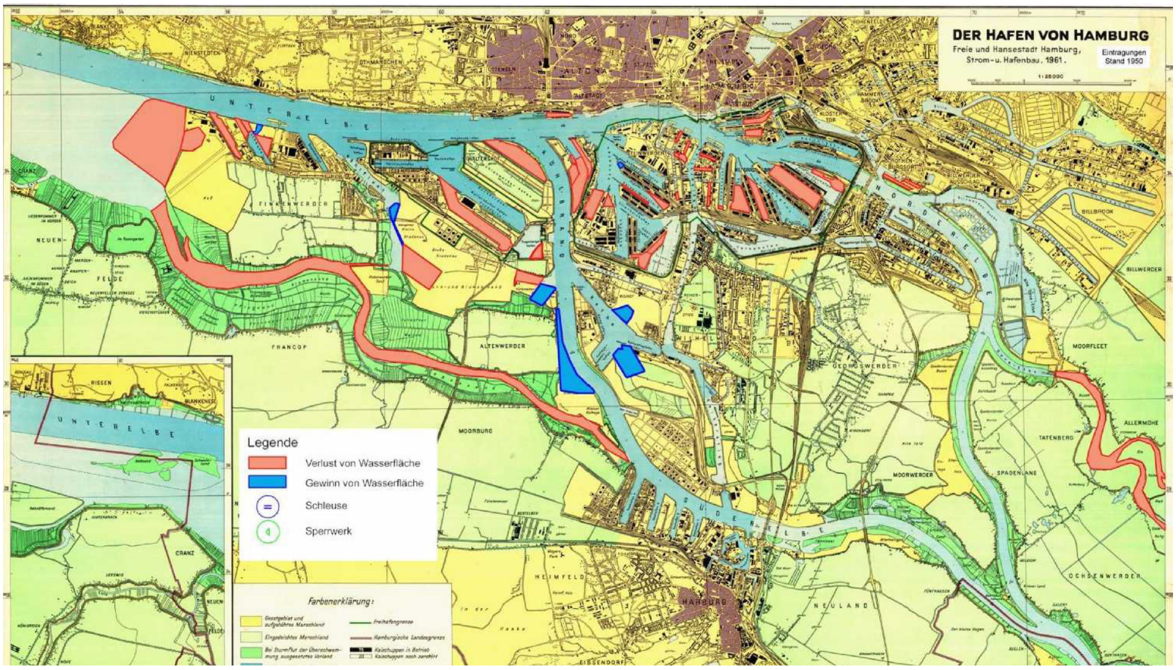

Figure 5 Changes to the water body since 1950

The main changes were as follows:
<u>Reclamation of intertidal areas:</u>
Hamburg:

Harbour basin refilling (major part 1973 - 2001):	185 ha
Closure of rivers and ditches and land reclamation:	475 ha
Total (1950 - 2005):	660 ha

1951: 127 ha Closure of the Dove Elbe by constructing the Tatenberger lock
1962: 200 ha Closure of the Alten Suederelbe following the flood disaster on 16 February 1962
1999: 148 ha Reclamation for the Airbus site

Outside Hamburg: Total: 18,300 ha (1950 - 1980)
Closure of rivers and ditches (by storm flood barriers) and dike construction near to the Elbe.

Maßnahme	Teilgröße der Abdämmung in km²	Bauzeit in Jahren	Gesamtgröße der Abdämmung in ha	Änderung des Sturmflutscheitels bei HH St. Pauli in cm	Anteil von der Gesamtwirkung b. St. Pauli in %
Errichtung des Wehrs Geesthacht [1)]	-	**1957 - 1960**	**-**	**0 bis 5**	**0 bis 10**
Absperrung der Ilmenau (Schließwasserstand: 3,3 mNN)	6.5	1973	650		
Absperrung der Seeve (Schließwasserstand: 3,3 mNN)	5.5	1966	550		
Vordeichung bei Oortkaten	1.6	1963	160		
Vordeichungen Geesthacht bis Billwerder Bucht [1)]	**-**	**1963 - 1973**	**1360**	**5 bis 10**	**10 bis 20**
Absperrung Dove Elbe [2)]	**1.3**	**1950 - 1952**	**130**	**nicht untersucht**	
Absperrung Billwerder Bucht mit Kanälen (Schließwasserstand: 3,5 mNN) [1)]	**1.7**	**1963 - 1969**	**170**	**0**	**0**
Absperrung alte Süderelbe und neue Deichlinie von Harburg bis Este (Schließwasserstand: 2,8 mNN) [1)]	**2 [2)]**	**1962 - 1967**	**200 [2)]**	**5 bis 15**	**10 bis 30**
Eindeichung Hahnöfer Sand und Absperrung Borstler Binnenelbe	5.6	1973 - 1974	560		
Absperrung Schwinge (Schließwasserstand: 2,2 mNN) und Eindeichung des Bützflether Sandes	11.4	1971	1140		
Absperrung von Pinnau und Krückau (Schließwasserstand: 2,5 mNN) mit Eindeichung des zwischenliegenden Vorlandes	16.5	1969	1650		
Eindeichungen des Hahnhöfer Sandes und vor den Schwinge-, Pinnau- und Krückaumündungen [1)]	**-**	**1969 - 1974**	**3350**	**5 bis 15**	**10 bis 30**
Absperrung von Lühe (Schließwasserstand: 2,0 mNN bis 2,2 mNN) und Stör (Schließwasserstand: 2,5 mNN) [1)]	**14.0**	**1967 & 1975**	**1400**	**0**	**0**
Eindeichung Haseldorfer Marsch [1)]	**21.0**	**1975 - 1977**	**2100**	**0 bis 10**	**0 bis 20**
	29.9	**1977**	**2990**	**0 bis 10**	**0 bis 20**
Absperrung der Oste (Schließwasserstand: 2,0 mNN) [3)]	**?**	**1968**	**?**	**nicht untersucht**	
Eindeichung Nordkehdingen [1)]	**55 [1)] (66,5) [4)]**	**1971 - 1976**	**5500 [1)] (6650) [4)]**	**-10 bis 0**	**-20 bis 0**
Fahrwasservertiefung auf 10 mKN	-	1936 - 1950	-		
Fahrwasservertiefung auf 11 mKN	-	1957 - 1961	-		
Fahrwasservertiefung auf 12 mKN	-	1964 - 1969	-		
Fahrwasservertiefung auf 13,5 mKN	-	1974 - 1978	-		
Fahrwasservertiefungen von 10 mKN auf 13,5 mKN [1)]	-	**1936 - 1978**	-	**10 bis 15**	**20 bis 30**
GESAMT - Vergleich 1950 auf 1980 [1)]	**172 [1)] (183,5) [4)]**	**1950 - 1980**	**17200 [1)] (18350) [4)]**	**50 bis 60**	**Prozent bezogen auf 50 cm Gesamtwirkung**

[1)] Siefert, W. & Havnoe, K.: Einfluss von Baumaßnahmen in und an der Tideelbe auf die Höhen hoher Sturmfluten, Die Küste, Heft 47, 1988

[2)] Recherche: Martin, C. 2005

[3)] Recherche: Ohle, N. 2006

[4)] Neemann, V.: Ausbau der Unter- und Außenelbe zur Herstellung der Fahrwassertiefe von 13,5 m unter KN, Bericht der Bund-Länder-Arbeitsgruppe Beweissicherung, 1996

4.3 Estuary deepening

Deepening of the estuary for navigation purposes has been going on for many years. Significant changes took place in the 1970s. The most recent change was the capital deepening that took place in 1999.

The work of deepening the fairway in the Under Elbe was done in 1999, followed by the measures in the Port of Hamburg, which were carried out mainly by trailing suction hopper dredger on the south side and three bucket ladder dredgers on the north side. Not all of the estuary needed dredging, only the places where the bed level was higher than that required. In many cases this meant removing the tops from sand dunes.

The work from 2001 – 2002 was mainly in the Koehlbrand area. Some material was taken out into Altenwerder and some into barges by suction dredger. The suspended solids concentration was reported to be very high during barging operations. Some hard stones caused damage to the trailing suction hopper dredger pumps. All of this resulted in elevated suspended solids concentration until the end of 2003.

At the same time 2m of capital dredging took place in Vorhafen. The dredger encountered hard clay and sand. The sand was required for construction purposes so the area was dredged and extra 4m deeper than needed. At the same time this created space for disposal of dredged material from elsewhere. This also added to the suspended solids concentration.

Dredging was also carried out in Waltershofer Hafen. In this case it was necessary to use a bucket ladder dredger to remove 1.0 – 1.5m of material. The bucket ladder utilises barges to transport the dredged material and the loading of the barges resulted in significant spillage. The material was disposed to the area adjacent to Muehlenberger Loch. Because of the method of placement this resulted in outflow of drainage water carrying suspended sediment back into the Estuary.

In the basin in the Suederelbe the bed was dredged to -30m to accommodate thixotropic material in adjacent areas. The material was moved into the pit using a water injection dredger (Jetsed).

4.4 Works at Glueckstadt

Works were carried out 1999 to 2001/2 to train the flow in an area of natural shoaling by building up the level of the sub-tidal banks on the side of the channel with material dredged from the channel. The placed material was protected from erosion. This seems to have resulted in virtual elimination of the need for dredging in this reach.

4.5 Effect on tidal levels

Many of the changes described above led to deeper draining out of the ebb tide and a lowering of the LW level (hence a need for deeper dredging). It is also suggested that this could have been a factor in the tidal pumping mechanism increasing the tendency for sediment to move up-estuary. Mean Low Water has gone from 4.28m above datum in 1950 to 3.45m in 2005 a drop of 0.83m. At the same time the HW level has increased from 6.67m to 7.11m above datum, an increase of 0.44m. This is illustrated in Figure 6.

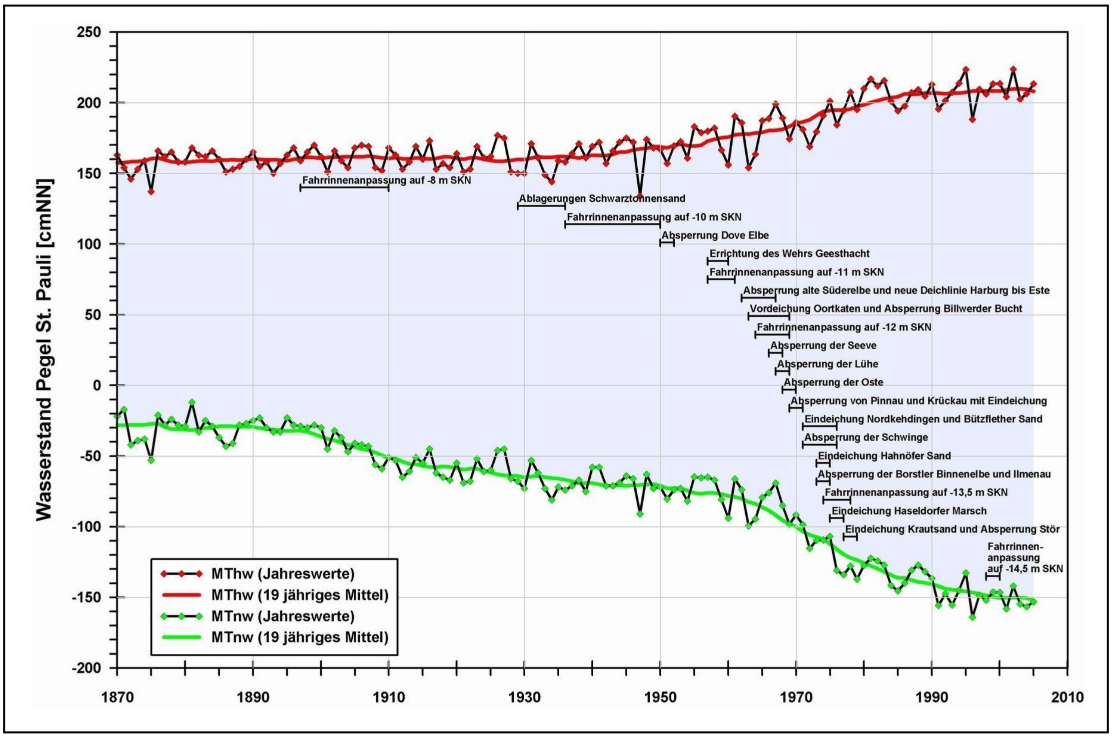

Figure 6: Change in High and Low Water levels (gauge St. Pauli) since 1870

5. REASONS FOR THE INCREASE IN DREDGING RATE

In the course of the discussions I have identified more than 10 factors that may have influenced the apparent rate of siltation. Some of these factors are interactive with each other and it is extremely difficult to separate out their relative importance on the basis of the present level of knowledge. In summary, I have formed the view that the very high rates in the period 2004 to mid 2005 are primarily temporary after-effects of the recent capital dredging works but that there is also an underlying trend for increased siltation due to a combination of a number of factors.

Before beginning the discussion it seems reasonable to ask the question why the very high rate was a surprise. I was informed that studies for the last deepening of the fairway were done using a hydrodynamic computer model to determine the effects on flow and tidal levels but that sediment transport modelling was not included because it was not developed at that time. Actually BAW is now studying these questions with a 3D – sediment transport model.

5.1 Temporary after effects of capital works

I have described in the previous section how the process of capital dredging released large amounts of material into suspension over a long period of time, which was available for transport by currents. However, in quiescent conditions (i.e. in areas of low or zero velocity flow) this would result in the formation of a layer of water at the bed with a very high suspended solids concentration. If there was sufficient turbulence to keep this in a fluid state then it could exist for several years. Being fluid and more dense than the normal estuarine water it would tend to flow under the influence of either the hydraulic gradient or the physical gradient. Experience in other locations has shown that it can flow on a slope as shallow as 1:1000 and also due to a hydraulic gradient. This is partly the logic behind the development of the water injection dredger. However if there is not sufficient gradient away from the area of water injection then the fluidised material will tend to collect in the deepest part of the area, in this case the Koehlbrand and Suederelbe area.

A detailed study of the dredging of this area was made by HPA. In the period before maintenance dredging began in September 2004 the siltation rate was estimated to be 16,000m^3/week. A maintenance dredging campaign then removed 677,000m^3 over a period of just under two months resulting in a measured volume change of only 100,000m^3. In other words almost seven times as much material was dredged than should theoretically have been necessary. A similar study was done on the same basis for the 2005 dredging campaign this time resulting in a factor of less than two.

This strongly indicates to me that in 2004 as the dredger was trying to remove the accumulation it created a small depression in the bed into which the high concentration layer flowed. Thus in dredging the Koehlbrand area the dredger was actually removing this layer from a much larger area. This would not have been evident from surveys because the official survey method is to use a high frequency echo sounder.

The fact that this did not occur to the same extent in 2005 suggests that the residue of fluid mud had been much reduced in quantity or had consolidated. However, given that the Koehlbrand area is now more effective at trapping sediment (see next section) it seems likely that the mechanism will continue to some degree for the foreseeable future.

5.2 Trapping efficiency

Deepening the bed level in a limited area, if it is below the LW level, increases the cross sectional area through which the flow passes without increasing the volume of tidal water. This decreases the flow velocity in the dredged area and creates hydrodynamic conditions more conducive to settlement of suspended material.

Sediment is supplied to the port area from three main sources:

- Sediment resuspended from the bed or spilt during dredging operations
- Sediment supplied by the incoming tide (including recycled dredged sediment) (see 5.3)
- Sediment being carried down the Elbe River.

No direct measurements are available of the first two sources but it is possible to make an estimate of the supply from the Elbe River. Data from Messstation Schnackenburg (Strom-km 474.5) is available on the web. The measurements include suspended solids concentrations and the data is given as total annual sediment load. From 1985 to 2004 the load varied between 320,000 tonnes (1991 and 2001) and 1,100,000 tonnes (1987). The average is a little over 500,000 tonnes/year. Assuming a solid content of 250 kg of dry solids /m³ in situ sediment gives and estimated average volume of 2million m^3/year and an approximate range of 1 - 4 million m^3/year. An increase in trapping efficiency could be responsible for trapping a higher proportion of this than previously. However this does not take account of the actual flows during the period when high dredging rates have been experienced. Section 5.4 considers the effect of river flow.

5.3. Tidal pumping (recycling) mechanism

The BAW computer model describes a pumping mechanism that can result in a net transport of sediment placed at the HPA boundary back upriver to the port area. The mechanism is related to a certain type of sediment that remains in the lower layers of the flow. I am satisfied that the mechanism exists but am less convinced that it accounts for a large part of the increase in siltation/dredging rates. It is true that the increase in siltation coincides with the increased amount of dredged material being placed at this site.5

The question that remains unanswered is whether there is a significant amount of new material available in the system to account for the substantial rise in dredging quantities both in the HPA region and in the whole ElbeEstuary. Recycling of some of the material is one explanation but I am not convinced that this is the whole reason for the increase. This should be further studied taking into account the following factors:

- As the material is placed only during the ebb tide some of the relocated material it therefore first travels downstream;
- The model demonstrates clearly that the sediment plume resulting from relocation stretches over some 40km before it ratchets up river so that the upper end reaches the port after several tides. As it does so the lower end is also extending further down the estuary. This spreading of the plume in both directions was also evident from the results of tracer experiments that were carried out in 1994. The tracer was found to migrate in both directions.
- To achieve a high recycling rate would require a significant increase above the normal suspended solids concentration of the estuary. However, no data has been recorded to confirm or deny this.
- BAW believes that the mechanism may have been enhanced only slightly by the deepening of the estuary and by a particularly low flow year in 2004 but must have existed previously. However, in former times the rate of placement at the relocation site was much lower in former time than in 2004/2005. The mechanism was not known about when the decision was made to relocate in this way and it was not evident from the relatively low quantities.
- According to the model the mechanism exists only when the fresh water flow is less than $700 m^3/s$. During periods of higher river flow the mechanism is

considerably weakened. Under such high flow conditions I would expect a certain amount of flushing of the sediment from the Port area downriver.

It should be noted that an internal BAW research study is in progress entitled "Influence of anthropogenic measures on sediment and salt transport characteristics in the Elbe estuary – Hindcast studies on different historical states with a three-dimensional model". This study should produce some valuable insight into this mechanism.

5.4 Fresh water flow

While low freshwater river flows carry lower sediment loads, as explained in Chapter 4, it is normal for sediment to migrate up the estuary under such conditions. The high rate of siltation followed a period of particularly low freshwater flow but it is not possible without further studies to quantify the effect of this.

The average river flows are shown alongside the dredging rates in Figure 1. A more detailed diagram of the river flow is given in Figure 7. This shows more clearly the extremely low flows in the summers of 2003 and 2004.

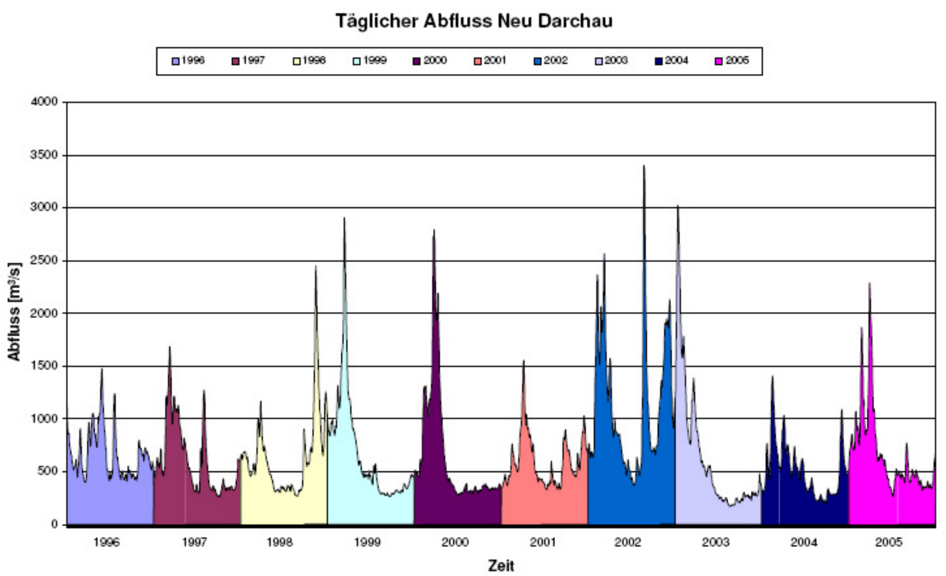

Figure 7: Gauged flows in the River Elbe since 1996

5.5 Dredging rate vs siltation rate

In most of the previous discussion we have assumed that the siltation rate has increased and it almost certainly has increased. However, nearly all of the statistics presented to me concern the dredging rate. It is known that a backlog has been building up at an estimated rate of about 1Mm^3/year . However, the backlog still exists in some if not most of the areas where it did before (i.e. those that serve the river navigation).

Dredging historically has been limited by the available plant, both for dredging and processing (flushing fields and METHA). Now the bulk of it is under contract using trailing suction hopper dredgers.

Dredging has been limited to that which was urgently needed. Also affecting the rate of dredging has been the increased obligation to shipping companies to ensure continuous access. All of these have the potential to give the impression that the siltation rate is higher or lower than it actually is.

5.6 Dredging elsewhere

It has already been noted that WSA Hamburg and WSA Cuxhaven both dredge and dispose of material in the estuary. It is confirmed that some disposal has taken place near the port border, possibly during the flood tide. It is important for this study that the estuary is considered as a whole before developing a strategy for one part on its own.

5.7 Glueckstadt training wall

The works described in the previous chapter were carried out in 1999 to 2001/2 to train the flow. The result has been a dramatic reduction in siltation and the need for dredging in this reach. This means that material that was previously depositing in this area is no longer doing so implying that the suspended solids concentration must be higher as material is transported through this zone in both directions. This would result in increased concentrations and increased siltation further up or down the estuary. It is not possible to quantify this effect without specifically modelling it.

5.8 Sediment re-suspension by ships

The size and draught of vessels using the port has increased, probably resulting in increased re-suspension of sediment in the form of plumes behind the ships. There may be an argument that ships coming in on the rising tide have added a component of net upriver transport, especially if it is aided by the pumping mechanism.

5.9 De-stabilising of the bed by dredging,

The deepening and widening in some places of the estuary in 1999 may have exposed more erodible material or loosened the material due to the dredging process in some places. This could have increased the sediment load of the estuary. I note that it was not necessary to dredge the whole length of the estuary, only those parts where it was too shallow.

5.10 Disturbance of dune formation

This is a very similar mechanism to that in 5.9. It is hypothesised that deepening of the fairway involved removing the tops of a number of sand dunes. The sand dunes being a natural feature of the Elbe estuary will try to re-establish themselves and in the process release sediment (particularly fine sediment) into suspension as they migrate.

5.11 Erosion of Medem Grund

Changes are taking place in the lower estuary where nature is trying to break through Medem Grund to divert the main channel to the north. It has been suggested that this could be an additional source of material entering the estuary system. According to BAW the development of the Medem channel is not only a source of material it also causes an ongoing effect of lowering the Low Water tidal level in Hamburg.

6. HAMBURG PORT AUTHORITY DREDGING MANAGEMENT

6.1 Dredging depth

The declared depths as given to mariners are specified by the Harbourmaster and are understood to be in conformity with such international guidelines as PIANC (1997). The depths are not negotiable and the dredging manager has the responsibility to provide those depths at all times.

Allowing for the practicalities of dredging and to make a buffer for siltation some overdredging is allowed. In most cases this is set to 0.5m. Full payment is made for dredging within this amount. Any additional dredging is not paid (unless otherwise agreed).

6.2 Overall strategy

A detailed account of the developments leading to the present dredging strategy is given in HPA (2005).

The dredging management strategy has changed over the years, based on a number of factors:

- Continuous attempts to reduce costs
- Changing quantities and distribution of the need for dredging
- Continuous improvements in dredging technology
- Continuous improvements in monitoring techniques
- Learning by experience

There are also a number of constraints that limit how the dredging operation can be carried out. These include:

- The rate at which the METHA plant can receive dredged material
- The manoeuvrability of different kinds and sizes of dredging plant
- The ability of different kinds of plant to handle different kinds of material efficiently

The dredging programme is under continuous review and is designed to be flexible enough to deal with both short term and long term maintenance dredging needs.

A large part of the dredging work is now done by dredging contractors. This is tendered annually. Tender documents are drawn up by the Port after reviewing the hydrographic charts and estimating how much material will have to be dredged during a coming year. Calculations are done by the Port to estimate the size of trailing suction hopper dredger that will be needed, assuming almost continuous working. The bidding contractors are given an indication of the total quantity expected in the year but not precisely where the dredging is required and asked to provide the appropriate size of dredger.

6.3 Price Adjustment Factor

The Port makes allowance for the different working conditions (type of sediment, distance to disposal site etc) and the Contractor gives a rate for each location specified by the Port. Payment is based on actual quantities dredged with rewards for obtaining a high density and a penalty for low density loads.

The factor is specific for each location and for each dredger. It is derived by field calibration, comparing in situ volumes measured directly by hydrographic survey with typical measurements of density in the hopper.

6.4 Dredging plant

The above procedure usually results in the provision of a trailing suction hopper dredger in the range of $2500m^3$ to $3500m^3$. This is an economic size with an appropriate degree of manoeuvrability for most of the work.

Since the need arose to take some material to the North Sea greater economy can be achieved by using a larger trailing suction hopper dredger, in the range $8000m^3$ to $10000m^3$. This is organised as a separate contract and the dredger is only expected to work in the waterway (ie not the docks).

The port continues to own and operate two bucket ladder dredgers. These are needed to deal with harder ground and in close proximity to quay walls where access with a trailing suction hopper dredger is difficult. They are also used for material that is contaminated by oil and therefore unsuitable for pumping into the METHA plant (where it would clog the filters). Two such dredgers are owned though one would have enough capacity for the work load. The reason that both are needed is that some docks are too small for the larger plant and some areas too deep for the smaller plant. To minimise costs the Port retains only one crew that is capable of operating either dredger but obviously not both at the same time.

When neither of the bucket ladder dredgers are needed for maintenance they are used for capital deepening works. In this way the crew are not left idle.

The Port also uses a Water Injection Dredger to remove high spots following the work of a trailing suction hopper dredger, this being more economical and more practical than having them removed by the trailing suction hopper dredger itself.

6.5 Monitoring

There has been a major change from monitoring by having an inspector on board each dredger to use of the "silent inspector". This is very expensive when dredgers are working continuously on a three-shift/day system. Information is now transmitted by radio telemetry directly from the ships instruments to the central monitoring station. In this the Port knows precisely where each dredger is working and the hopper load. In particular the level of the draghead is monitored, which means that the Port can avoid unnecessary overdredging.

Silent Inspector equipment is now also installed in WSA Hamburg as well as HPA contract dredgers.

6.6 "In house" vs. Contract dredging

HPA have considered this carefully. With such a regular commitment to a large amount of dredging every year it might at first seem sensible to think about an "in house" operation where the Port acquires a purpose built dredger or fleet of dredgers to carry out the works. One of the main reasons for not doing this is the question of capacity.

To be economical the port would have to select an appropriate sized dredger so that it is working at near maximum capacity. If, as has happened in Hamburg, the rate increases, then the plant is no longer adequate for the task. Provision of over-capacity is expensive and hard to justify. A large Contractor usually has sufficient plant to be able to quickly call in additional dredgers if the need arises due to extra siltation (for example due to a storm) or breakdown of dredging plant.

Another reason against in house dredging is that the crew of a contract dredger have a wide experience of dredging operations while an in house crew's experience is limited to the particular situation.

A final point is that there is little flexibility on the rates payable to in-house staff whereas a contractor is able to pay the market rate for appropriately qualified and experienced staff.

6.7 Comment on dredging management

There is always some scope for improving the efficiency of a dredging operation but it is my considered view that in the present circumstances it would take a great effort of detailed study of dredging and siltation records and past contracts to achieve a small percentage benefit. There are much greater benefits to be achieved by gaining a better understanding of the sediment transport processes in the Elbe estuary system, hopefully reducing the amount of dredging necessary and developing a sediment regime management strategy that will benefit not only HPA but WSA Hamburg and probably WSA Cuxhaven.

It is my view that those responsible for the management of HPA's dredging works are well aware of the tools at their disposal for controlling costs, have invested in them and use them fully for the benefit of the Port while seeking to carry out their statutory obligations to navigators within the framework of environmental regulations.

The contractual and monitoring procedures put in place leave very little room for mal practice by the dredging contractor, indeed the opposite is true in that the contractor is properly rewarded for good work.

By retaining control of the operation rather than giving the contractor freedom to achieve the specified depths in any way he chooses HPA accepts a high degree of responsibility for the result. In other words the contractor is paid for the amount that he dredges, not for the result of that dredging. For this kind of arrangement to work well the responsibility is, and must remain in the hands of competent, experienced HPA management that understand the technology and practice of dredging works.

The recent dramatic increases in dredging quantities and therefore dredging costs are mainly due to factors outside of the control of those responsible for managing the dredging works. The possible reasons for the increase are discussed elsewhere in my report. The best hope for reducing costs lies in gaining a better understanding of the sediment transport processes in the whole estuarine system. At that time there may be scope for carefully considering for example:

- the use of silt traps;
- the order in which certain areas are dredged:
- the exact location and timing of "in estuary" disposal.

To embark on such strategies without a good understanding of the likely consequences could result in less efficient dredging.

7. IMPLICATIONS FOR SEDIMENT MANAGEMENT

In this Chapter the implications of the foregoing discussion are assessed with regard to future sediment management.

7.1 Contaminated sediment

This is a decreasing problem as water quality standards improve. However not all of these are under German control as the river catchment is believed to include discharges of contaminants in other countries. The long term solution is clearly to some extent political in that attempts should be made to control the pollution at source.

7.2 Uncontaminated or lightly contaminated sediment

I am reasonably satisfied that the very high rates of siltation will prove to be temporary and largely a result of the disturbance caused by the capital dredging operation itself.

Examining the estuary as a whole, without regard to political boundaries, the evidence suggests that what has taken place is more of a redistribution of siltation than a large increase. This is most marked in the interaction across the boundary between HPA and WSA Hamburg. If recirculation by the pumping mechanism is partly responsible for the increase then WSA's practice of disposing of $3Mm^3$ not far down estuary of the border is also implicated.

7.3 Relocation within the estuary

It would be premature to abandon altogether the idea of in-estuary disposal. Removal from the estuary altogether is not necessarily the best thing to do, especially as it is at very high cost because of the distance travelled by the dredger. Is it cheaper to dredge the same material twice a year (for example) than to dredge it once and remove it from the system for ever? That leads to the question of whether it is actually the same material or in fact only part of a much larger source either inside the estuary or outside of it in the coastal region. In other words the question needs to be studied "What will be the long term effect of continually removing sediment from the system over a long time scale?"

7.4 Estuary morphological engineering

A scheme is being suggested in the case of the Elbe to create sub-aquatic disposal sites near the mouth of the estuary for the excess sediment to reduce the tidal flow into and out of the estuary by, in effect, narrowing the entrance. The idea is to supplement this with opening up some areas presently excluded from tidal flow as close as possible to Hamburg. It is hoped that the combined effect will raise Low Water levels and reduce High Water levels.

The concept of re-introducing tidal volume is valid and should result in a greater lag in the ebb flow thus raising the low water level. In fact this is returning the estuary to a more natural state.

The concept of reducing the tidal flow is more difficult to assess. Engineering the mouths of estuaries has not always been successful. In the case of the River Ribble on the west coast of England canalisation of the shipping channel out into the outer estuary resulted in the build up of sediment on both sides of the channel and the formation of a bar not far beyond where the canalisation reached.

During studies of the Thames Estuary flood barrier it was found that to significantly dampen the tidal flow and reduce the tidal range in the order of one or two meters a blockage factor of more than 60% at a cross-section was needed. It follows logically that to create a change of this amount it would also give rise to a sharp hydraulic gradient that would generate locally high velocities. This is turn would cause erosion until the flow cross-section was more or less equal to the present one, at which point it would cease to effectively dampen the tide. A scheme of this nature was not implemented in the Thames: the Authorities preferred a moving barrier.

Computer model studies of the Loire Estuary in France have demonstrated that large-scale training works over a significant length of estuary (10's of km) may also be able to reduce upstream tidal range

Whilst this is a very interesting approach to the problem, one that I would not rule out, I would recommend very thorough computer modelling to generate an impact hypothesis before finally embarking on it. I would also recommend a cautious approach to the works, perhaps beginning with a small modification and monitoring the impact.

7.5 Comments on morphological aspects of disposal in the North Sea

The disposal at Buoy E3 has been studied before permission was given for a trial. Then measurements were made jointly by HPA and Dredging Research Ltd (UK) in September-October 2005. The objectives were to

- Measure the short-term transport of sediment released during disposal
- Obtain information about 'background' conditions
- Identify resuspension of disposed material

The short-term plume behaviour was as expected in that the majority of sediment reached the bed within seconds of opening the hopper doors. The upper part of water column away from the disposal area was not affected by sediment from the disposal operations. The plume remained "visible" in the lower part of water column until the tide started to turn. As current reduced so the sediment settled to the bed. The residual suspended solids concentrations were approximately 1-10 mg/L above 'background', though there was some doubt about what the normal background level was because the scarcity of long term data.
The study concluded that:

- Most of the sediment is transported to the near-bed zone very quickly
- After 1 - 1.5 hours plume decay is determined mainly by current speed (turbulence)
- As the tide turns sediment settles to bed
- As the current speed increases, some of the settled sediment is resuspended in the lower part of the water column

- The overall size of affected area may be slightly larger than the area affected in the short term (but at very low concentrations) due to repeated cycles of deposition & resuspension
- More research work of the type already carried out jointly by Dredging Research Ltd and HPA is required to investigate background conditions and long-term movement of material. Some background research into suspended matter in the German Bight is available in Puls et al (1997).

On this basis it was decided that it was possible to relocate the dredged material at this site at least for a limited period.

It is planned to place 800,000m^3 there beginning in March 2006 and a similar amount in the autumn. Permission is already given under satisfactory monitoring for more until 2008 but there are no guarantees beyond 2008. The total quantity agreed is for 4.5Mm^3.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 General

The trigger for this study was the recent large increase in the amount of maintenance dredging needed.

I have reviewed the available data and reports and have concluded that the increase up to 2005 is probably due not to one factor but to several at the same time, some of them interactive. The most significant are likely to have been:

- Temporary after effects of capital dredging works;
- Particularly low fresh water flow period;
- Increased use of recycling together with pumping mechanism;
- Increased trapping efficiency due to deepening, particularly in Koehlbrand area;

The latest evidence suggests that dredging rates in 2006 are decreasing again. Three possible reasons are suggested:

- This may be an immediate effect of removing the material to the North Sea instead of recycling within the estuary. Whether or not that is the most economical solution remains an open question.
- It could also simply be the result of the estuary "settling down" after a period of disturbance.
- A third possibility is the increase in freshwater flow in the Elbe River.

I would emphasise that this report is in the nature of a review of work done by others and information made available by HPA, interpreted in the light of my experience in other estuaries and of siltation and dredging generally. It is my considered view that before any final decisions are made about long term strategy further investigations should be carried out, indeed some are already underway.

8.2 Modelling

BAW are already well advanced in the technology of 3D computer modelling of complex systems and in particular of the Elbe estuary. I see this as an important tool in the decision making for major projects and sediment management. With further developments planned by WSA Hamburg, WSA Cuxhaven and HPA it is essential that these are studied in conjunction with each other and not in isolation.

The sediment transport system in the Elbe is very complex and to gain confidence in the model it is strongly recommended that some of the developments that have taken place are modelled so that the predictions can be compared to actual outturns. The in house study by BAW is addressing some of these issues and should be supported. Examples would be the changes at Glueckstadt. A significant problem with this will be that some of the developments overlap in time and the estuary has not had time to adapt to one change before another happened.

The particular way the model is run is very time consuming. Ways of reducing the run times are being considered to make it a more flexible tool. Other models, at a lower level of detail, can be used to study general sediment transport behaviour and improve knowledge of the sediment transport processes in the whole estuary.

8.3 Measurement campaign

In order to set up and calibrate the model, particularly with regard to sediment transport, it is necessary to collect good data. Consideration should be given to setting up a team with the responsibility to gather and collate a wide range of data.

A number of suspended solids concentration monitoring stations recording say every 15 minutes at a number of depths, including near-bed for a minimum period of a year would yield very valuable results.

An ADCP sediment flux measurement campaign could be undertaken to characterise the sediment transport under a number of flow conditions. A similar exercise is currently in progress on the Thames estuary in the UK.

Regular bathymetric surveys should observe bed levels using dual frequency echo-sounders to investigate the conditions under which fluid mud forms. Use of this equipment during the next dredging campaign in Koehlbrand would be particularly useful. This will observe the extent to which fluid mud is a factor in the siltation process and assist in deciding how best to manage it.

It is worth noting that in the Thames Estuary while fluid mud is not a factor with regard to navigable depth it does form a part of the natural sediment transport in the estuary. There are certain areas, such as in eddy zones in the lee of bends and in dock entrances where sediment settles from suspension and forms a high concentration layer during certain phases of the tide. In the case of bends it is resuspended by the reverse tide. In the case of dock entrances it is more likely to accumulate and eventually consolidate, requiring removal by dredging.

Acknowledging the useful work that has already been done addition work is required to verify and quantify the importance of the pumping mechanism. ADCP measurements would be helpful in observing the mechanism in the field. Such measurements have given great insights into the sediment transport in the Thames, in the context of the London Gateway Project.

It would be worth considering holding a workshop involving interested parties such as WSA Hamburg, WSA Cuxhaven, BAW and HPA to discuss how an investigative monitoring programme should be set up and what data would be required. There may be opportunities for cost sharing.

8.4 Sediment management

It is very clear that any sediment management strategy must take into account the activities of the three political regions affected.

The very high rate of siltation in 2004 - 2005 is thought to be temporary and should not be used as a basis for long term planning unless verified by several years of similarly high values.

Nevertheless the dredging rates in the HPA area are likely to be higher than the historic ones. This is attributed to a number of factors including development and deepening of the port area and the recycling of dredged material.

Relocation of dredged material in the estuary should not be abandoned but reduced to the level that it was before the large increase took place. Further investigation should be carried out to identify if there is a better location for doing so. This may need co-operation with WSA Hamburg.

Together with the North Sea option and management of relatively small quantities of contaminated sediment this may provide enough capacity to cope with the rate when it settles down. While further investigation goes on regarding the morphological estuary engineering it would be contingent to seek an extension in time to the use of the E3 site.

8.5 Dredging management

The dredging works are well planned, well monitored and well controlled in financial terms. There are a number of things to think about in the future:

If fluid mud transpires to be a significant factor in the siltation process (as I suspect it may be) then rewarding the contractor for high density cargoes may not be the best solution.

Taking account of the near certainty of the formation of high concentration near-bed layers it would be sensible in future capital and maintenance dredging works to attempt to reduce the amount of spillage and continue the present practice of not allowing dredge hopper overflow.

There may be a case for more selective use of the water injection technique.

There may also be scope for further matching the dredging management contracts to the sediment management objectives.

8.6 Long term strategy

In developing a long term strategy consideration should be given to overall sediment budget of the whole estuary system. If the rate of removal exceeds the rate of supply of new sediment then eventually there will be some impact on the morphology of the estuary. Sediment transport is part of the balance of nature so when sediment is managed in an estuary it needs to be done carefully. For this reason studies should be carried out over the next few years using modelling tools and field monitoring. This applies both to dredging strategy and any proposals for morphological estuary engineering.

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