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The Elbe Estuary

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1. Introduction

The River Elbe has its source 1,386 m above sea level in the Giant Mountains and reaches the North Sea at Cuxhaven, after 1,094 km. The entire catchment basin of the Elbe (Fig. 1) covers 148,268 km², which makes it the fourth largest river in Central Europe after the Rivers Danube (817,000 km²), Vistula (194,112 km²) and Rhine (183,800 km²). The Elbe Estuary is comprised of the lower reaches between the weir at Geesthacht (Elbe-km 588) and the transition to the North Sea (Elbe-km 760). As long as no storm-tide conditions prevail, the tidal influence of the Elbe estuary is limited by the Geesthacht weir.

From the Geesthacht weir to Bunthaus, which is situated 20 km further downstream, the Elbe has a typical width of 300–500 m. This area is called the "Upper Tidal Elbe". At Bunthaus (Elbe-km 609), the River branches out into the Northern and Southern Elbe. Each of these branches is initially only 200 m wide. However, these widths increase continually, so that at the point where they merge again (Elbe-km 626), the Northern Elbe is around 400 m and the Southern Elbe around 300 m in width. The reunited Elbe continues as a river measuring around 500 m in total width. Seven kilometres further downstream (Elbe-km 633), the river abruptly widens to 2.5 km at the Elbe bay called Mühlenberger Loch.

From here, the navigation channel of the Elbe runs in a river bed that continuously alters its form and width with the islands of Hans-Kalb-Sand/Schweinsand/Neßsand, Lühesand, Drommel/Auberg/Bishorster Sand, Pagensand, Schwarztonnensand and Rhinplatte forming numerous side channels. At low tide, some sand bars such as the Brammer Bank, the Böschrücken and the Medem-Sand appear as visible elements. Downstream of Brunsbüttel (Elbe-km 695), the Elbe widens to become a funnel-shaped estuary mouth, with a maximum width of 17.5 km between Cuxhaven and the Trischen Dam. Only 1.5 km remain water-bearing at low tide, while the major part of the funnel-shaped Elbe estuary falls dry. The northern limit of the Outer Elbe seawards of Cuxhaven is not clearly defined in literature but, according to the authors, lies close to the great beacons A and Z north of the Scharhörnriff, where a lateral separation is formed by the drained sandbanks at low tide end.

Table 1: Tributaries of the Elbe Side channel (modified in accordance with IKSE, 2005)

Body of Water	Elbe-km	Catchment Basin area (CA) [km²]	Medial Stream Flow (MQ) [m³/s]
Ilmenau River	599.0	2 852.0	17.7
Seeve River	604.9	471.1	4.71
Bille River	615.3 Northern Elbe	506.4	3.99
Alster River	622.4 Northern Elbe	580.7	5.80
Este River	634.4	364.2	3.21
Lühe River	645.5	216.7	2.51
Schwinge	654.8	215.7	2.62
Pinnau River	659.7	367.0	3.46
Krückau River	664.9	275.7	2.42
Stör River	679.3	1 780.5	21.7
North-to-Baltic-Sea Canal (Nord-Ostsee-Kanal NOK)	696.0	1 536.7	19.1
Oste River	707.0	1 711.1	17.7
Medem and Hadelner Canal	712.6	482.8	7.81

The regional offices of the Federal Administration for Waterways and Navigation (Wasser- und Schifffahrtsverwaltung – WSV) at Cuxhaven, Hamburg and Lauenburg are responsible for the tidal river Elbe. Very uncommon is the delegation of maintenance of this federal waterway within the state boundaries of Hamburg by the Federal government to the Free and Hanseatic City of Hamburg.

The economic importance of the Elbe Estuary is mainly due to its role as the most important shipping route for international maritime traffic. In 2006, 12,400 seagoing ships (of which 7,560 were container ships) undertook the 70-sea-mile-long estuary journey up to the Port of Hamburg. Other seagoing vessels called at the ports of Cuxhaven, Brunsbüttel and Bützfleth, all situated at the Lower Elbe.

Cuxhaven is located in the immediate vicinity of the Elbe Mouth at the North Sea. Since 1997, the deep-sea port CuxPort (Elbe-km 724, Fig. 2) has been available for RoRo traffic. It is designed for container-cargo handling, storage and shipment of new vehicles, as well as general cargo handling. The Seaport of Brunsbüttel is the most important port in Schleswig-Holstein. It is comprised of the Elbe harbour, the oil harbour and the Ostermoor Harbour. The Glückstadt harbour is considered to be an outer harbour. The harbour at Stade/Bützfleth, Lower Saxony ranks among the 8 most important German seaports by turnover volume (data from 2006). Vessels of up to 150 m in length and 10.40 m draft can call at this harbour, which has been operating since 1972. Today, the Port of Hamburg is the largest Harbour in Germany, the third largest in Europe and ranks ninth among the container harbours world-wide. In 2007, the port handled a total of 140.4 million tons, of which 95.8 million were handled in 9.9 million Twenty-Foot Equivalent Units (TEU). Container-handling terminals and docks equipped to deal with general cargo, RoRo-traffic, suction goods, grab goods, foods and edibles, as well as liquids and chemicals are available. The continuously

Fig. 1: Position and catchment area of the Elbe (IKSE, 2005)

increasing container turnover is handled at four container terminals. The container terminal at Altenwerder, operating since 2002, is considered to be one of the world's most modern cargo handling facilities.

The Port of Hamburg is privileged mainly because of its eco-geographic location. It is the main hub for overseas traffic and the most important transhipment port for middle and eastern European countries as well as Baltic States in Northern Europe. It possesses an excellent infrastructure and the best interconnections to national and international transport networks.

The maritime waterway Elbe is connected to a well equipped network of mostly artificial waterways, which offers optimum conditions for an economically efficient and ecologically preferred further distribution of goods. The Kiel Canal *(Nord-Ostsee-Kanal)* connects the Elbe estuary between Brunsbüttel with the Baltic Sea near Kiel. It is the most navigated artificial maritime waterway of the world. Another link to the Baltic Sea is the 94-km long Elbe-Trave-Canal *(Elbe-Trave-Kanal)* between Lübeck and Lauenburg, linking the rivers

Fig. 2: Lower and Outer Elbe

Elbe and Trave. Today, this inland waterway is used mainly to transport bulk goods. The Elbe Side Canal *(Elbeseitenkanal)*, which is 115 km in length, connects the Elbe upstream from the Geesthacht weir between Artlenburg (Elbe-km 572) and Edesbüttel, near Wolfsburg to the Midland Canal *(Mittellandkanal)*, which is the East-West connection between the Ruhr and Berlin. The Elbe Side Canal, which has been in operation since 1976, provides a navigable link for inland vessels between Hamburg and the Elbe near Magdeburg at low water periods.

Next to its importance for commercial navigation, the Elbe is of economic relevance for other uses. Thus, various industrial facilities draw their process water – and power-station operators their cooling water – from the Elbe. Fishery plays an important role mainly in the area of the mouth of the Elbe and just outside of the Port of Hamburg. Because water quality has noticeably improved since the German reunification, commercial and sports fishing are being successfully practised again. There are a total of seven sewage treatment plants, which discharge into the Elbe estuary. Furthermore, seventeen industrial direct dischargers, ten of them in Greater Hamburg, are situated along the estuary.

Finally, the economic utilisation of the Elbe interacts with human habitat, animal and plant life. The Elbe River and its tributaries as well as the river floodplains, which are still left, influence the groundwater level of wide stretches of land and play an important role in the renewal of ground water and water extraction for drinking purposes. They guarantee drainage of most of the areas inland of the dike, which are used for agriculture and absorb smaller storm flood incidents until the storm-surge barriers are closed and cut off the retention areas. The flora and fauna along the Lower Elbe is of special importance, too. Some animals and plants occur exclusively in this catchment area, which makes them worthy of protection. The tidal influenced alluvial forest is a very characteristic form of vegetation with reeds and soft- and hardwood, which especially develops under the semi-diurnal flooding, thereby creating a habitat with a highly specialized fauna. With the integration of large parts of the Elbe Estuary and adjacent hinterland areas into the Natura 2000 Network (largest coherent EU-network of protected areas to safeguard biodiversity), important impulses are also given to tourism.

2. Geomorphology of the Elbe Estuary

Major geological alterations have occurred in The Lower Elbe, which has been subjected to major geological changes and, at a smaller time scale, to anthropogenic and natural alterations. The latest ice age formed the glacial valley, which is still visible today. The water from the melting ice cleared a glacial valley with an average width of 10 km, while at the same time the sea level rose. Areas of swamps, forests and moors were covered by marine sediments. Consequently, different horizontal and vertical layers of alluvial mud, sand and moor deposits can be found. Today, the Lower Elbe lies above Pleistocene sand deposits and the Holocene sediments of the river itself. Every now and then, glaciation relics in the form of large boulders surface along the lower stretch of the Lower Elbe.

The banks of the Elbe first formed a swampy, reedy landscape, which subsisted until the beginning of our era. During the Iron Age and its increasing demand for timber used for iron smelting, vast expanses of forest along the Middle and the Upper Elbe were deforested, triggering widespread soil erosion. The sediment load transported by the river attained such great quantities that the lower reaches of the Elbe virtually choked in mud. The river banks, which had been overgrown with common and giant reed, were covered with sediments, their surface level depending on the sediment amount available and the frequency of storm surges. This generated the typical marshlands of today. The course of the Elbe estuary has been constantly changing not only along the embankments which are visible to the human eye, but also under water. Apart from those obvious visible changes such as the erosion and sedimentation along the river banks the course of the channels beneath the water surface has always varied to different extents.

The development of the embankment has either been very slow as a result of erosion or sedimentation, or very abrupt, when for example large chunks from the edges broke off under the impact of high waves and strong currents. Natural alterations of the river bed morphology are still happening today depending on local currents and varying flow velocities. A rough morphological classification of the Lower and Outer Elbe can be made as follows:

From the Geesthacht Weir up to Bunthaus, where the Elbe splits into Northern and Southern Elbe, the estuary is restricted in its course. The bottom is made up of coarse sand and pebbles. In the Port of Hamburg itself, the river is enclosed by harbour installation, sheet pile walls and revetment slopes. Natural embankments are rather seldom. The river bed of the navigation channel is sandy, silt is more common in the port basins. From Blankenese to Glückstadt, several islands – some of them protected by revetments – divide the current into main and secondary channels. The river bed within the main channel is sandy, while the lateral zones are partially sandy but mainly muddy. From Glückstadt down to Brunsbüttel, the northern embankment is almost completely protected, while mudflats and salt marshes are typical features on the south side. From Brunsbüttel to Cuxhaven, the Lower Elbe considerably widens, and the deep channel runs mainly close to the southern embankment. To the North of the fairway, extensive mud-flats line the shore. They are part of the National Park "Schleswig-Holsteinisches Wattenmeer". Beyond Cuxhaven, the lateral boundary to the Outer Elbe is only visible around low tide. It is formed by the tidal flats of Duhnen, Neuwerk and Scharhörn to the South. To the North of the channel, a chain of connected sands existed 30 years ago. Since around 1990, the erosion of the "Großer Vogelsand" *(Great Bird Sandbank)* and losses of the western part of the "Gelbsand" *(Yellow Sand)* can be observed. Thus, no clearly recognisable northern limit of the Outer Elbe exists any more, today. The river bed, cutting through the shallow littoral zone, is mainly made up of middle and coarse sands. In deeper areas, alluvial mud also occurs.

3. Hydrological Key Parameters

The tidal wave propagates from the mouth of the river up to the tidal boundary; its progression speed depends mainly on the water depth. Unlike in the deep ocean, the water depth in the tidal river is at the same order of magnitude as the amplitude of the tidal wave. This means that the river flows in a significantly different bed at low tide than at high tide. This is particularly obvious beyond Elbe-km 715, where the cross-section is 75 % larger at high tide compared to low tide (see Fig. 3). As a result of these conditions, the crest of the tidal wave (high water) progresses faster than the trough (low tide). This leads to a deformation of the tidal curve with a relatively long period of tidal fall and a correspondingly shorter time of tidal rise.

The discharge measured at the gauge at Neu Darchau reaches the Tidal Elbe over the Geesthacht Weir (tidal) with a time delay of 1–2 days as fresh water inflow.

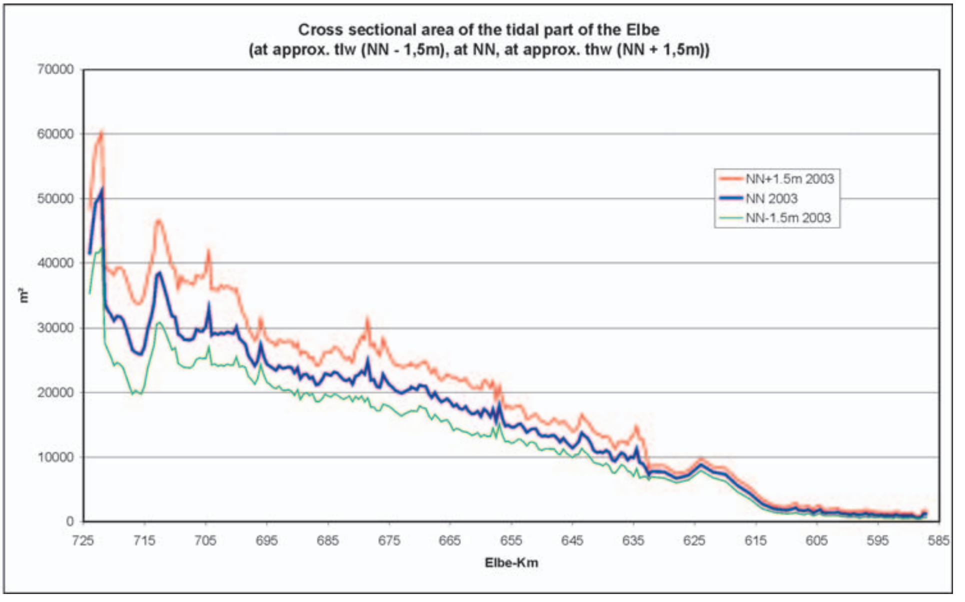

Fig. 3: Cross sectional area of the tidal part of the Elbe

Table 2: Freshwater discharge at gauge 'Neu Darchau' (source: HPA, 2007)

Lowest observed discharge	145 m^3/s
Lowest median discharge	278 m^3/s
Median discharge	713 m^3/s
Median highest discharge	1920 m^3/s
Highest observed discharge	3620 m^3/s

Coming from the sea, the mean low tide (MLW) rises by approximately 25 cm up to Glückstadt and then drops again towards Hamburg. During the past 30 years, the difference between MLW at Cuxhaven and Hamburg has continuously decreased to almost zero today. MHW along the tidal Elbe shows a different development: coming from the sea till Glückstadt, the MHW rises only insignificantly. From there a rise of approximately 0.5 m to Hamburg can now be observed (Fig. 4). This gradient has increased by approximately 0.25 m during the past 30 years as a consequence of changes of the river bed as described above.

Fig. 5 and Fig. 6 show tidal wave profiles at spring- and neap tide. They provide information on the water level situations as well as the rates of increase and decrease of the water level during regular tides. Tidal wave profiles which are close together reflect small increment and decrement rates; if they are further apart, these rates are high. Although the water-level gradients from sea to Hamburg are nearly equal during high and low tide, the maximum currents in the navigation channel from Hamburg towards the open sea continuously increase. Ebb currents become stronger compared to the flood currents. Due to the sudden change in width and depth of the cross-section at Bunthaus as well as at the tidal boundary at the Geesthacht weir, the tidal regime has been significantly transformed: While the tidal wave profiles downstream of Hamburg have nearly the same magnitude of inclination, the profiles

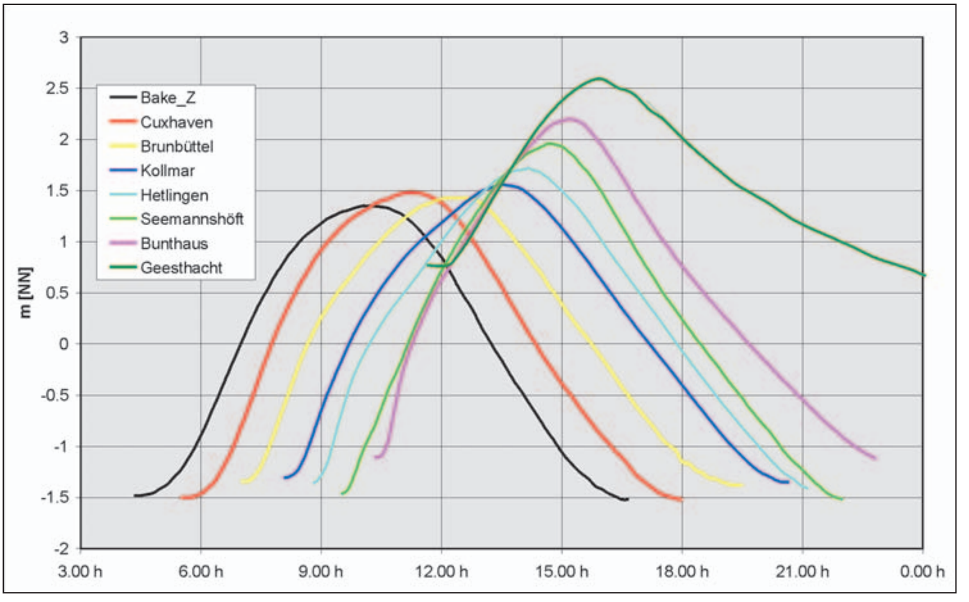

Fig. 4: Development of the tidal curve in the Elbe

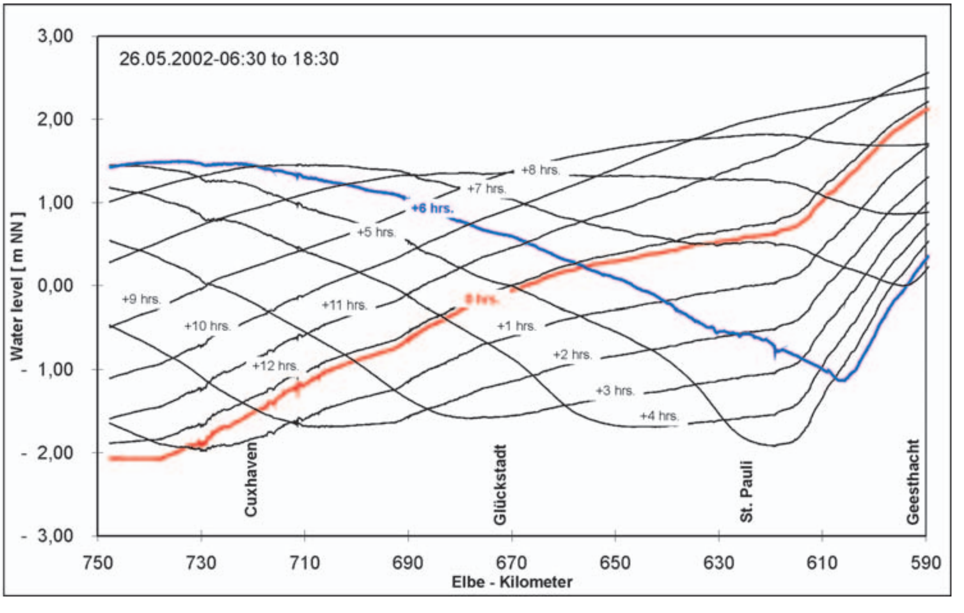

Fig 5: Tidal wave profile at spring tide

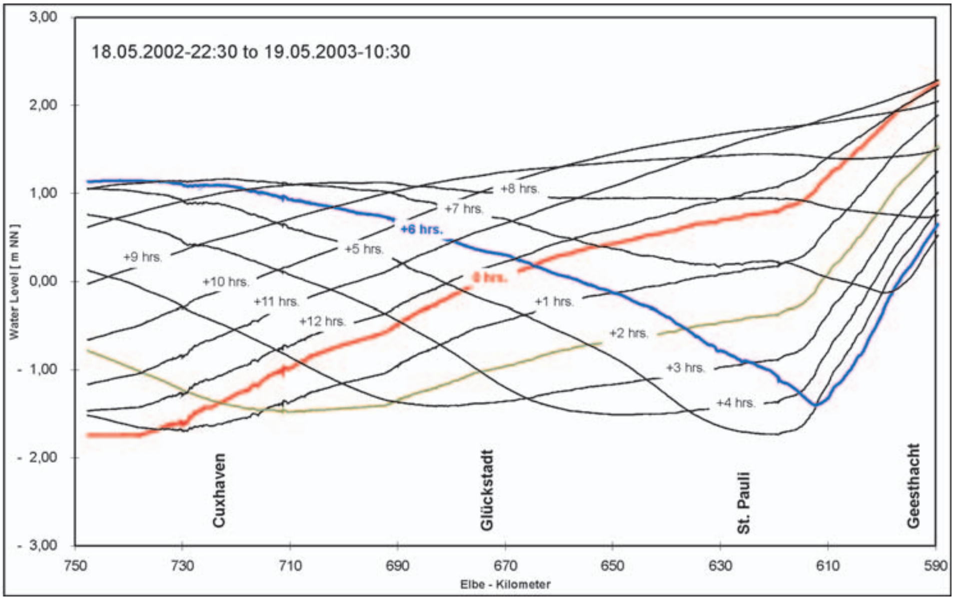

Fig. 6: Tidal wave profile at neap tide

upstream from Bunthaus show a much smaller gradient at high tide than at low tide, which is caused by the deformation of the tidal wave along this stretch.

Fig. 4 illustrates how the tidal wave is deformed on its way from the North Sea to further upstream. This originally almost sinusoidal wave is transformed due to the different propagation velocity of crest and trough. The flood gradient becomes steeper and the ebb gradient flattens. Both, the bed friction, which affects the currents, and the freshwater discharge contribute to this phenomenon. The following Tab. 3 clearly shows decreasing flood tide duration towards the upstream while the ebb-tide duration increases.

Table 3: Tidal duration asymmetries

Tide Gauge	Mean High-Tide Duration (Min.)	Mean Low-Tide Duration (Min.)
Helgoland	341	404
Cuxhaven	337	408
Glückstadt	327	418
Schulau	322	423
Blankenese	314	431
St. Pauli	303	442
Zollenspieker	265	480

Furthermore, the tidal curve is also considerably modified by the amount of freshwater discharge. This is illustrated by Fig. 7, which shows the duration of flood and ebb periods of the Elbe estuary as a function of discharges of 300 m^3/s and 2000 m^3/s. The higher the fresh-

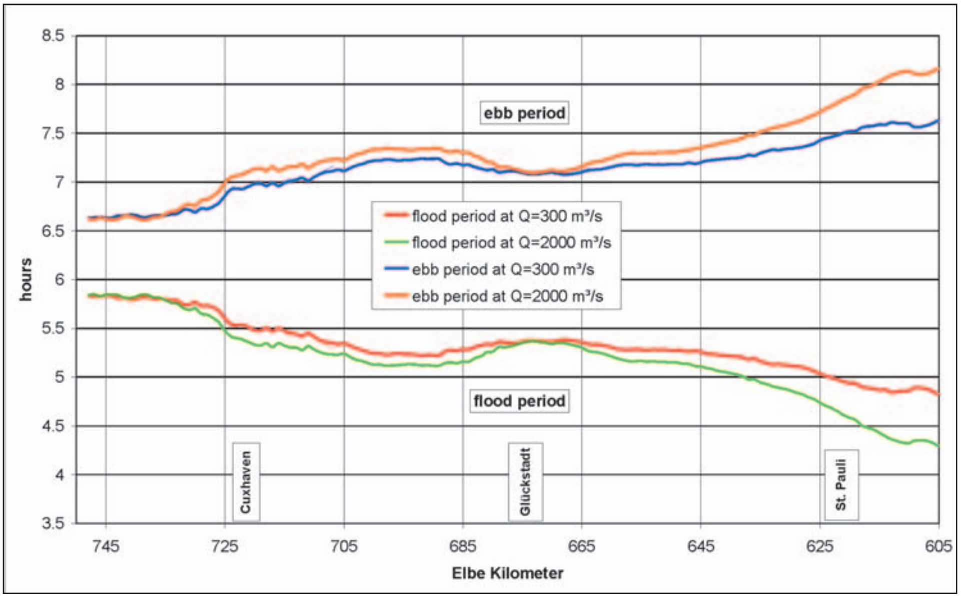

Fig. 7: Dependency of flood and ebb periods on the fresh water discharge

water discharge, the longer is the duration of the ebb tide while the flood tide duration becomes even shorter. This effect subsides towards downstream. That this phenomenon cannot simply be explained by the total volume of water, since it also linked to resonance and reflection, shows its minimum effect at Glückstadt: there is nearly no change in the duration of the ebb- and flood periods as a function of the freshwater discharge.

Similar to an inland river, the freshwater discharge affects the mean water level dependent on the river width. Moreover, upstream of St. Pauli, an increase of the discharge leads to a reduced tidal range. In this area, the reduction can reach 2 m if the discharge increases from 300 m^3/s up to 2000 m^3/s at the Geesthacht weir.

The influence of wind during a storm event with winds from a north-westerly direction leads to considerable increases in the tidal high water level along the Elbe, often even to storm surges. The fact that gale force winds and storms from the east also lead to significant changes in the water levels is not considered alarming for the population but, for navigation purposes, it is an unwelcome aggravation. Fig. 8 shows what moderate gale force winds at force 7, blowing from easterly directions for several days, can achieve: Compared to the normal water levels, the tidal high water level drops by up to 1 m, and the tidal low water level also decreases by around 0.5 m. This wind-generated effect appears, just as it is the case during a storm surge, virtually without any time lag and quickly abates.

Fig. 9 shows the development of the monthly averages of MHW and MLW at the tidal gauges Cuxhaven Steubenhöft and St. Pauli. While values obtained from gauge Cuxhaven only show a slight positive trend in the development of MHW and no significant trend regarding MLW, the gauge at St. Pauli shows a different water level development. During the past 50 years, MLW has decreased by nearly 1 m, while MHW has increased by around 0.5 m. Dependent on the type of deepening the fairway, past upgrades of the navigational channel have certainly influenced this development. For example, a reaction to the end-to-end fair-

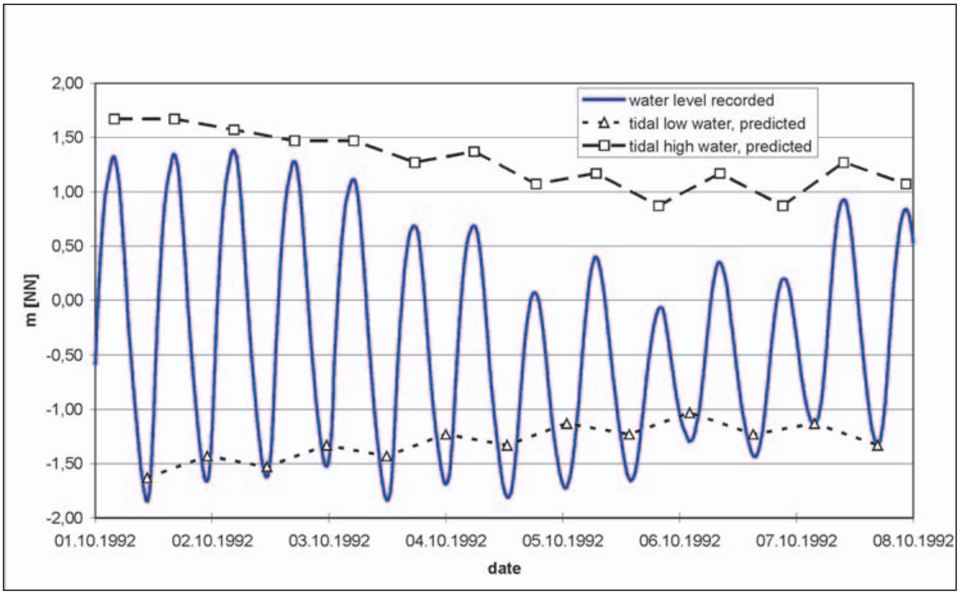

Fig. 8: Water level at Cuxhaven, predicted and recorded

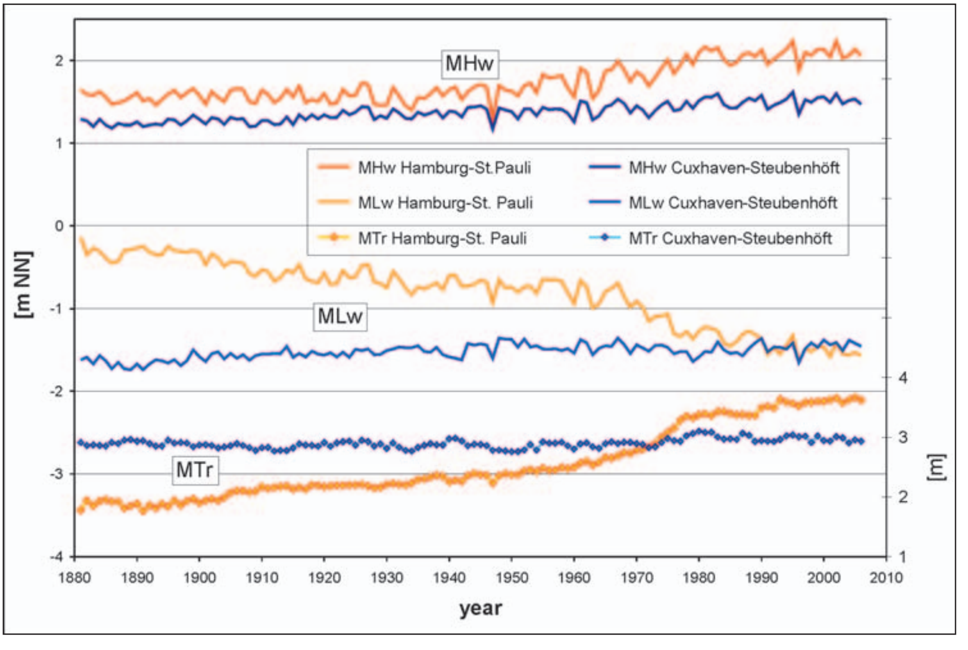

Fig. 9: Development of the mean high water, low water and the tidal range since 1880

way improvement to a depth of 13.5 m Chart Datum (*Karten Null* KN) in 1976 can be clearly seen in the MHW and MLW-levels. A similar effect to the deepening works in 1999 has not been observed, yet. Also the loss of water volume within the tidal prism due to the change of harbour basins into footprints for containers in the port of Hamburg has an influence on the tidal range in the same direction. Investigations carried out by the Federal Waterways Engineering and Research Institute *(Bundesanstalt für Wasserbau Dienststelle Hamburg – BAW)* have indicated that major naturally caused sediment movements in the Outer and Lower Elbe have generated equally strong effects on the water level, comparable to those induced by deepening measures. Examples are the shifting of the Medem Channel *(Medemrinne)* and the breakthrough at the "Lüchter Loch" during the past 20 years.

The salinity in the tidal Elbe ranges from pure fresh water to sea water with a salinity of around 32 PSU at the point where the Outer Elbe meets the German Bight. The location and extent of the brackish-water zone is considerably determined by the volume of the freshwater discharge, by the mean water level of the North Sea and by the tidal range. Under average conditions, the brackish water zone extends to Elbe-km 660 until flood slack water (K_f) and to Elbe-km 680 at ebb slack water (K_e) (Fig. 10). If minor freshwater discharges last for several days, the upper limit of the brackish-water zone can, according to BERGEMANN (1995), move upstream to Elbe-km 645. Furthermore, higher water levels in the North Sea due to meteorological circumstances can generate higher salinity levels compared to the mean values of the Lower Elbe.

The effects of high freshwater discharge values at the position LZ4 at Elbe-km 731.1 are represented in Fig. 11. In August 2002, the discharge at Neu Darchau increased from 500 m³/s to nearly 3,500 m³/s. As a result, the salinity which had oscillated between 14 and 26 PSU in rhythm with the tides, now varied between 3 and 26 PSU. The brackish-water zone not only

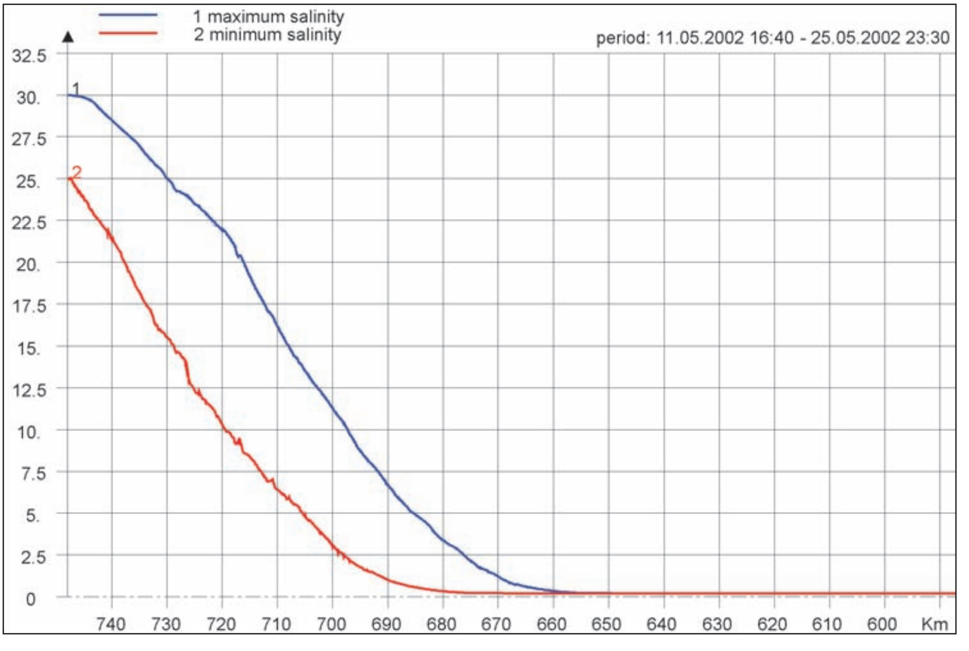

Fig. 10: Minimum and maximum salinity in the Elbe

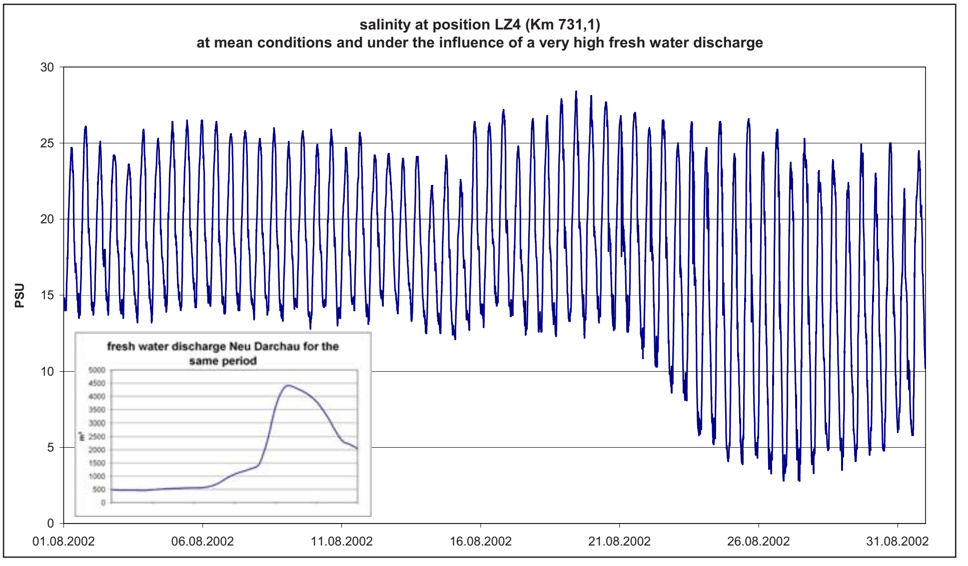

Fig. 11: Salinity at position LZ4 at Elbe-km 731.1

shifts towards the sea in such an incident, but it becomes much shorter, while the amplitude of the salinity can considerably increase at one location.

While the water level and the salinity in an estuary have a uniform large-scale distribution, the current velocity is a parameter, which varies strongly with space and time. This is what Fig. 12 and Fig. 13 clearly shows: it depicts maximum flood- and ebb velocities in the middle of the navigation channel of the Lower and the Outer Elbe. Furthermore, distinctive flood dominance from upstream of Glückstadt to Hamburg can be seen. This condition existed already around 1970, but only in a reduced form upstream of Lühesand and not as significant as today. This factor leads to the "Tidal Pumping" of sediments from the lower reaches of the Elbe to areas further upstream, resulting in insufficient water depths in the navigation channel and the harbour basins.

An overview of the concentrations of suspended matter and the behaviour of the turbidity zone in the Elbe Estuary has to be composed of single measurements carried out by various authorities and institutions (KAPPENBERG, 1996; ARGE ELBE, 2000). The shape and location of the turbidity zone change, depending on the freshwater discharge. The maximum concentration of suspended solids during periods of higher fresh-water discharge (Q > 900 m³/s) can reach around 0.35 kg/m³. The maximum is then found at Elbe-km 690, and the turbidity zone is more compressed than during an average discharge of 500 m³/s. In this case, the maximum concentration is at approx. 0.6 kg/m³ and lies about 10 km further upstream at Elbe-km 680 (FHH, 1997).

Results of the 3D-Elbe Model of the BAW-DH are substantiated in Fig. 14. Here the calculated cross-sectionally averaged results are represented, which were computed for a constant freshwater discharge of 350 m³/s (red lines) and a variable freshwater discharge of around 800 m³/s (black lines). The model shows not only the seaward shift of the turbidity zone at higher discharges but also flood-tide induced transportation (net transport > 0) upstream of the turbidity zone depending on the freshwater discharge.

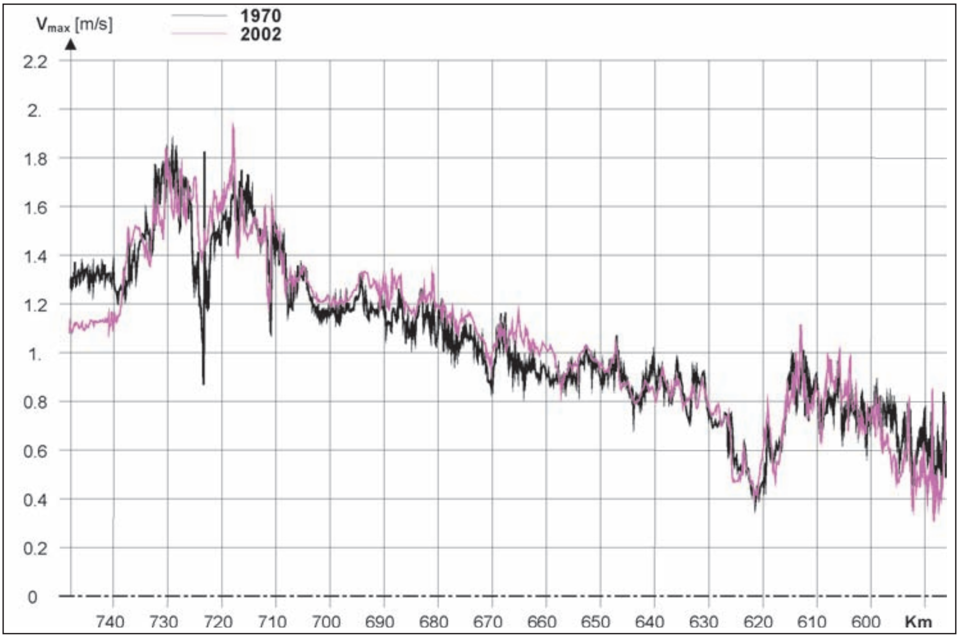

Fig. 12: Maximum current of the ebb tide 1970 and 2002 in the Elbe river

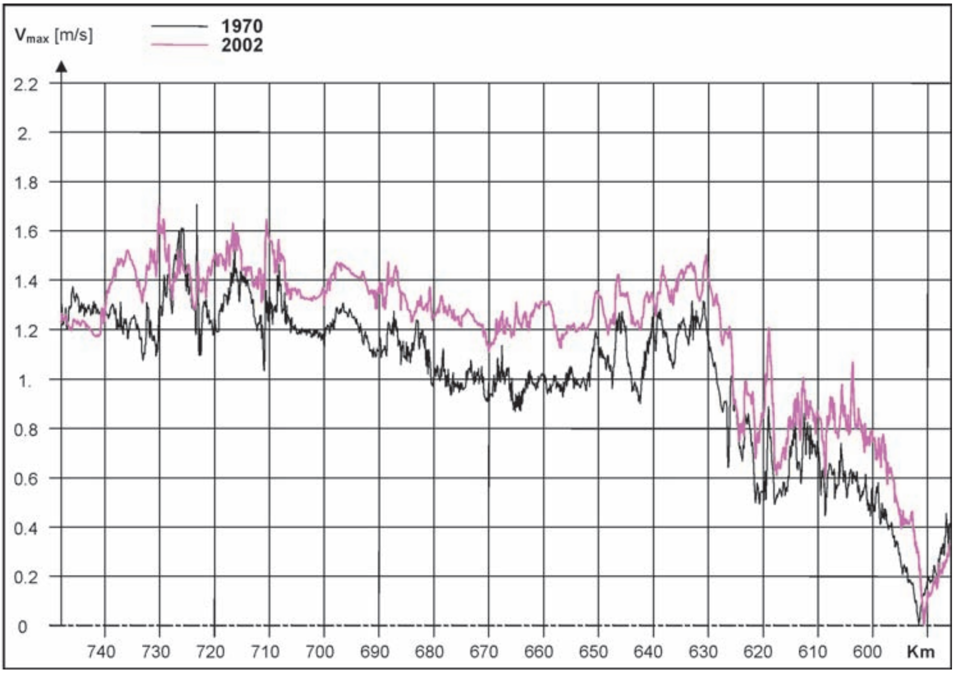

Fig. 13: Maximum current of the flood tide 1970 and 2002 in the Elbe river

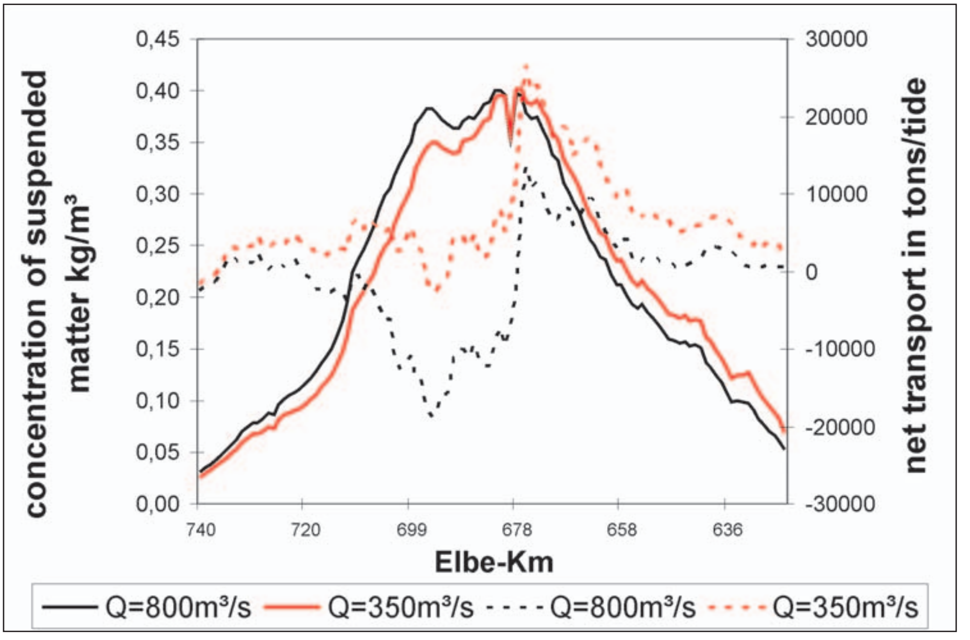

Fig. 14: Characteristics of the transport of suspended matter

The suspended load concentration varies considerably within a cross-section and during a tidal cycle. Current calculations of this concentration from the back-scatter signal by ADCP measurements (Fig. 15) give a first insight into these dynamics (MAUSHAKE and AARDOM, 2007). Near bed suspended load concentrations of an order of magnitude of O >> 1 kg/m³ occur not only in the turbidity zone, but also in the Hamburg port area.

4. Construction Measures in the Elbe Estuary

Since approximately the 13th century, uninterrupted dikes lined both embankments of the Tidal Elbe. Drainage of the hinterland areas lead to soil subsidence. Furthermore, sedimentation taking place during storm surges does not reach the hinterland, the elevation of which always remains below the mean water level. Today, large-scale areas are still below mean sea level (MSL).

As a result of the severe storm surges of 1962 and 1976, extensive dike realignments took place. By impoldering, additional areas were cut off from the tidal influence and storm surge events. Between 1900 and today, the foreshore areas of Schleswig-Holstein and Lower Saxony have decreased by 50 % and 74 %, respectively.

The Lower and Outer Elbe have been considerably altered by river-engineering measures. Already during the 15th century, the 'Hamburg Düpe Gentlemen' and later the 'Düpe Commission' (a committee in charge of ensuring an appropriate navigable depth towards Hamburg) had the responsibility of monitoring the fairway depth of the Lower Elbe. If somewhere within the fairway the water depth was too shallow for the ships of that

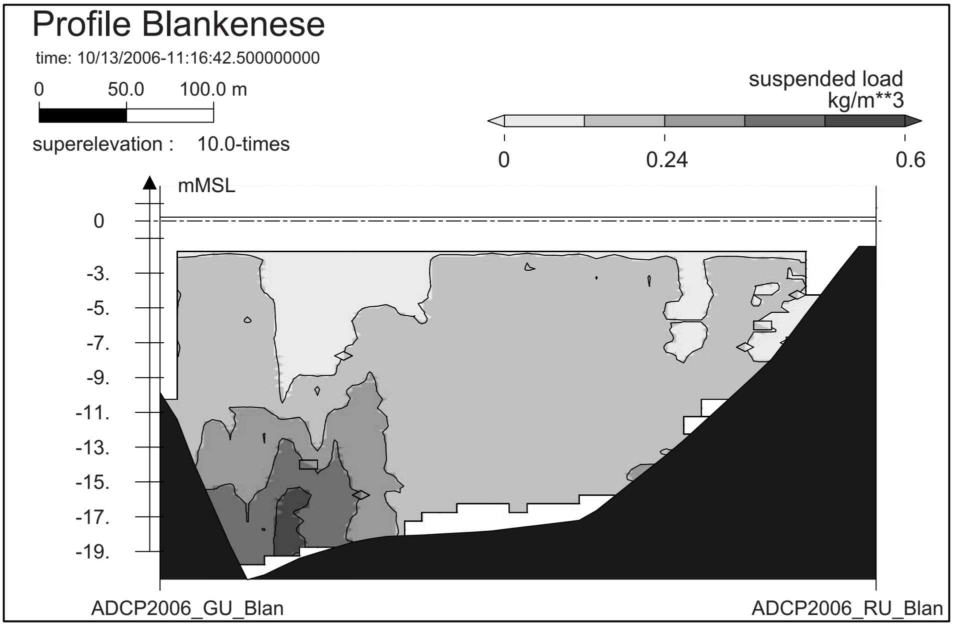

Fig. 15: Suspended matter at a cross section at Blankenese

generation, there were limited means to remove these shoals. Only since 1834, effective devices (for example steam powered excavators) were available to undertake major changes to the navigation channel. Consequently, until 1868, the channel depth of 5.30 m in the Lower Elbe could be established by only removing single sand bars and ripples. After this, several deepening campaigns were carried out to follow the rapid development of maritime traffic:

– 10.0 m depth upgrade from 1936 to 1956
– 11.0 m depth upgrade from 1957 to 1962
– 12.0 m depth upgrade from 1964 to 1969
– 13.5 m depth upgrade from 1974 to 1978
– 14.5 m depth upgrade from 1999 to 2000

The depths mentioned above refer to the chart datum which until then had been the mean low water spring tide. Fig. 16 illustrates the fact that the existing longitudinal profiles in the fairway were quite complex.

Previous upgrades of the fairway always included deepening as well as widening the navigational channel with the effect that tidal dynamics were considerably altered. Another considerable factor of influence was the change of the surface water areas. Until the middle of the 19th century, the Port of Hamburg was located along the northern embankment of the Elbe. Starting around 1880, construction works creating harbour basins on the south side of the Elbe were carried out. By around 1970, the water surface areas exposed to the tidal dynamics had increased by nearly 1000 ha. Between 1970 and 2005, 187 ha of these areas were converted back into land in the course of various projects.

By comparison, the construction of the storm- surge barriers at the tributaries of the Elbe, which have been carried out since 1968, as well as the dike constructions along the

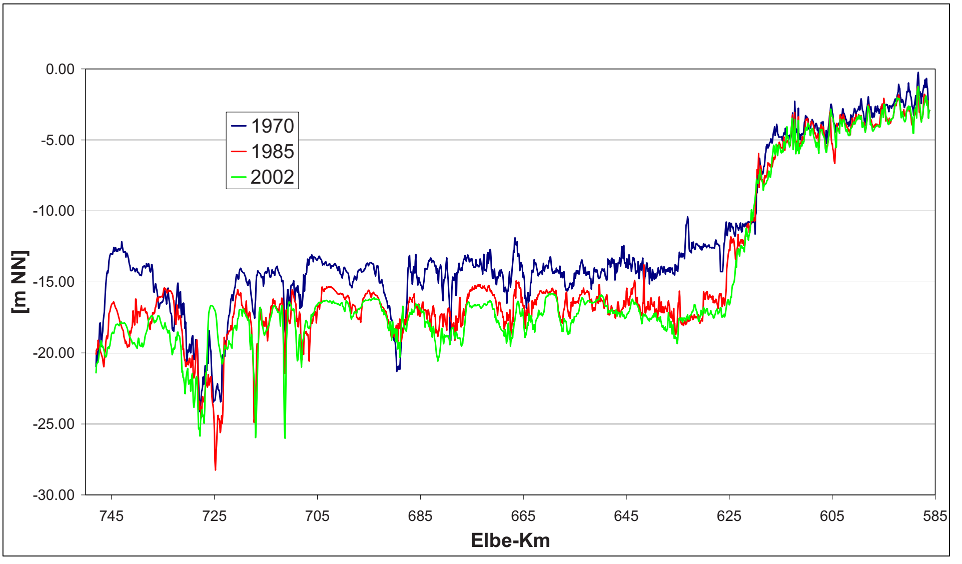

Fig. 16: Depth of the fairway of the Elbe since 1970

Lower Elbe have had only little effect on the average tidal dynamics. Their influence on storm surge elevations in the Elbe estuary, however, must be described as significant. Thus, in Lower Saxony 10,600 ha of the former 13,900 ha of foreshore areas and 14.800 ha of a total of 19,700 ha of former flood planes in Schleswig-Holstein were impoldered, which is equivalent to three thirds of the previously existing hinterland areas (Fig. 17).

Between 1840 and 1850, first considerations regarding the improvement of the fairway conditions, particularly in the stream divide area of Hamburg by systematic river training measures were taken. Initially, the dredgers deployed in the port area, ensured the necessary water depths, until larger construction and regulation projects were made possible. The Hanseatic City of Hamburg secured its right to upgrade the Norderelbe and the Köhlbrand. Additionally, a breakthrough at Kaltehofe and the construction of the training wall at Bunthäuser Spitze ensured a larger flow passage through the Northern Elbe. Further measures to regulate the Elbe from the Seeve to Brunshausen laid down the fundamentals for today's Elbe course. This marked the beginning of the human interference in the tidal regime of the Elbe. By constructing a 7.5 km long training wall between the islands of Schweinsand and Hans-Kalb-Sand, the natural cross-drift of sands into the navigation channel was prevented. Already in 1911, the dumping of sand to an elevation of the main water level at the southern side of the training wall formed the basis for the island's shape as it is today. In the course of further fairway upgrades, the island has been gradually raised up to its present elevation. On the western side of the island of Schweinsand, the new island of Nesssand emerged in 1968. In the course of the upgrade of the navigational channel in 1969, the islands of Hans-Kalb-Sand, Neßsand and Schweinsand were linked together and now form a single island between the main and the secondary channel of 'Hahnöfer Nebenelbe'.

With the same motivation of preventing uncontrolled shifting of channels, a training wall at Pagensand was built in 1922–1930. This was to prevent further shifting of the quicksand bar "Hungriger Wolf". Between 1928 and 1936, this was followed by the training wall to the

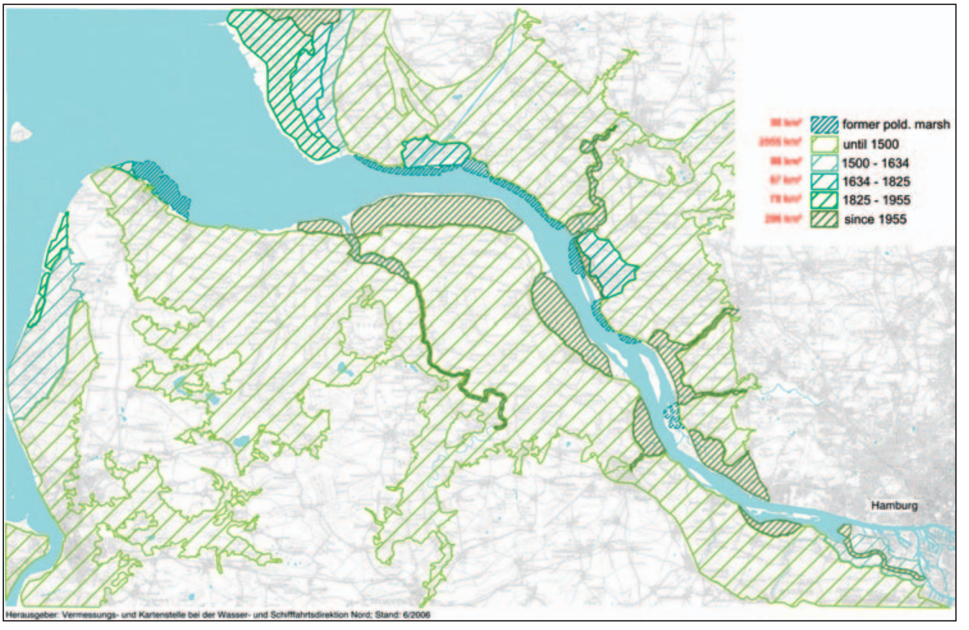

Fig. 17: Loss of flood prone areas

north of Pagensand in connection with several dredging campaign to remove sand from Schwarztonnensand. Between 1971 and 1977, substantial parts of the island of Schwarztonnensand were finally raised above MHW level. The islands of Lühesand and Rhinplatte, artificial in their present shape, serve as training walls to control and concentrate currents. The cross sections of the river should be in an equilibrium to enable the current energy to clear both channels.

Between 1922 and 1937, the building of the groynes along the Osteriff, the removal of material from the Ostebank and the construction of the training wall at Hermannshof near the mud flats at Neufeld were carried out. These measures also served to generate and maintain sufficient water depths as well as to stabilize the navigation channel. They also aimed at reducing the amount of dredged sediment at the Ostebank, a goal which has not been achieved till today. In the highly dynamic region of the mouth, a three-channel system had developed. The construction of the training wall 'Kugelbake' reduced this to two channels and stabilized its location. Construction works on the training wall were carried out in several stages between 1939 and 1962. In the beginning, the training wall was 9 km long. Between 1975 and 1977, it was extended to approx. 10 km.

The most recent river engineering measures are the under-water deposit areas at Krautsand and Twielenfleth which were constructed during the last fairway adaptation in 1999. They were meant to reduce the amount of dredging with increased current velocities keeping sediments in motion in these areas.

For the protection of river banks and in order to stabilize the course of the Elbe, extensive groyne systems were built. Some of the groynes are large enough and built with such a small slope to trigger the evolution of calm foreshores and embankments where even the growth of reeds might be possible. This could create a habitat said to have existed in earlier times.

The diversity of the morphological structure of the Elbe Estuary is significantly influenced by the tides, and its natural state is characterised by an intensive drift of solid particles, linked to a constant transformation of the river bed and foreshore. It features bifurcations, shifting, alternating widths of the water body, scours and aggradations in the form of mud flats, sands and islands, the formation of side channels and embankment collapse. In addition to the internal sediment sources, coarser sandy material is carried into the Elbe Estuary from the North Sea. In contrast, rather fine solids are carried down from the upper course of the Elbe. In spite of a qualitative improvement since the German Reunification, they are still contaminated. In the estuary, these sediments are mixed up and can settle for a short period of time or permanently. Preferred sedimentation areas are shallow water regions, such as side channels and harbour basins where weaker current conditions exist.

In order to guarantee safety and ease of navigation on the Elbe and in the Port of Hamburg all year round, maintenance dredging has to be carried out by hopper suction dredgers, bucket dredgers and water-injection devices. For economical reasons, a minimisation of the sediment volumes to be dredged is aimed at. Moreover, the impact on the benthos, the characteristics of the river bed (grain size and texture), the concentration of suspended sediments and the oxygen concentration all demand environmentally friendly dredging operations.

Dredged material is being treated in different ways according to the particular intention and the sediment quality. Either the material is extracted from the water body or it is relocated within the estuary itself. The relocation within the estuary is done by dumping the material in areas where there are sufficient depths and where it does not cause any disturbance. However, this procedure has certain limitations concerning the contamination level of the sediments. Contaminated material is removed from the water body and treated ashore. According to the degree of contamination, it can either be used for construction measures or is dumped in containment areas.

In order to maintain the required water depths in the Port of Hamburg, 3–5 million m³ of sediments are dredged, of which around 1.4 million m³ are brought ashore. Except for a smaller proportion that is used for drainage and construction purposes most of it is deposited. From September to March, the larger amount is relocated at the Isle of Neßsand at the state border. In order to avoid or minimise the effects of relocation, mandatory instructions were formulated and agreed on by the responsible ministries of the Hanseatic City of Hamburg. These involve temporal, spatial and technical mitigation measures. Another such instruction concerning the handling of contaminated dredged spoils was decided upon by the Environment Ministries of the states bordering the Elbe in 1996.

But also throughout the rest of the estuary all the way up to the mouth, there is a need for maintenance of the waterway at regular intervals. The Federal Administration for Waterways and Navigation (WSV) has to relocate up to 12 million m³/a. Around the entrance to the Kiel Canal, the regional office of WSV, WSA Brunsbüttel, commissions dredging of approx. 7 million m³/a. In the secondary channels of the Elbe and its tributaries, maintenance dredging of around 0.6 million m³ is necessary in order to maintain the navigable water depths.

To avoid or minimise any negative effects due to the maintenance measures, the Federal Ministry for Transport, Building and Urban Affairs issued the *'Instructions for Dealing with Dredged Material in inland areas'* (Handlungsanweisung für den Umgang mit Baggergut im Binnenland – HABAB-WSV) (BMVBW and BfG, 2000). Further downstream beyond Elbe-km 683 (Freiburg Haven Creek) the *'Instructions for dealing with Dredged Material in Coastal Areas'* (Handlungsanweisung für den Umgang mit Baggergut im Küstenbereich – HABAK – WSV) (BfG, 1999) have to be applied accordingly.

5. On–going Monitoring and Analysis

The first regular tidal observations at the German coastal region already took place upon orders by the Hamburg Navigation and Port Deputation in 1841. For this, measurement stations were installed at Hamburg St. Pauli and Cuxhaven. Ever since, high and low tidal peaks have been registered (STEHR, 1964). Today, water levels are recorded by 29 tidal gauges in the Tidal Elbe between Geesthacht and the former lighthouse "Großer Vogelsand". Since 1997/98, current velocities have been measured at 13 stations (partly at two different water depths); some of these measuring devices are equipped with a supplementary sensor for measuring the turbidity. On five selected profiles, single point current measurements are made in cross sections. Conductivity and salinity have also been continuously measured in some parts of the Elbe since 1987.

Along with the upgrade to a 13.5 m depth, a working group on 'Preservation of evidence' consisting of members from federal and state authorities (Bund-Länder-Arbeitsgruppe 'Beweissicherung') was established. This group has submitted in a two-part final technical report data concerning the changes in water level, current velocities, salinity and bank development. Conversely, during the Planning Approval Procedure for the 14.5 m deepening, a considerably more comprehensive monitoring programme was imposed with a main focus on biotic parameters. The reports and data published so far can be loaded down from www.portal-tideeelbe.de.

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