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The Weser Estuary

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Contents

1. Introduction

After the Elbe, the Weser is the second-largest river in Germany discharging into the North Sea. Its origin is the confluence of the rivers Werra and Fulda at Hannoversch-Münden. After cutting through low mountain ranges it flows in northerly direction through the Northern German lowlands. It can be subdivided into the sections Upper Weser (Oberweser: Hann. Münden – Minden), Middle Weser (Mittelweser: Minden – Bremen), Lower Weser (Unterweser: Bremen – Bremerhaven) and Outer Weser (Außenweser: Bremerhaven – open sea) (Fig. 1). The barrage in Bremen-Hemelingen defines the tidal boundary. While the bottom of the Upper Weser is characterized by rubble sediment of the overlying rock, the Middle Weser carries the gravel sediment of the lowlands. Bottom sediments of the Lower and Outer Weser consist mainly of medium and fine sands.

The entire length of the Weser is classified as a federal waterway (Bundeswasserstraße) for the transport of goods by barges and sea-going vessels. The 'Mittellandkanal', an artificial inland waterway intersecting the Weser near Minden, connects the waterway Weser in East-West-direction with the rivers Elbe, Ems and Rhine. Inland navigation vessels can directly go from the Lower Weser to the Ems, via the river Hunte and the 'Coastal Canal (Küstenkanal)'. Sea-going vessels can call on the Lower Weser ports Bremen and Bremerhaven (City of Bremen) as well as Nordenham and Brake (Lower Saxony).

Bremerhaven is the site of one of the most important Container terminals of the world. After completing construction works in 2008, the river-parallel container quay has an overall length of 5.4 km. Improvement and deepening of the navigation channel and the most modern quay equipment enable the currently largest container ships to call on Bremerhaven.

Turnover figures in **Bremen/Bremerhaven** had two-digit growth rates during the past few years and amounted to approximately 5,000,000 TEU in 2007. In addition to containers, cars are the most important cargo handled in Bremerhaven. In 2007, a turnover of 2,000,000 cars has been exceeded the first time.

The privately managed port of **Nordenham** excels in bulk goods. Mainly coal is transhipped here (import); iron and steel are growing factors. The growth rate of exported goods amounted to 8 % in the years 1998–2005.

The port of **Brake** is a hub for the import and export of animal feed and grain. A strong

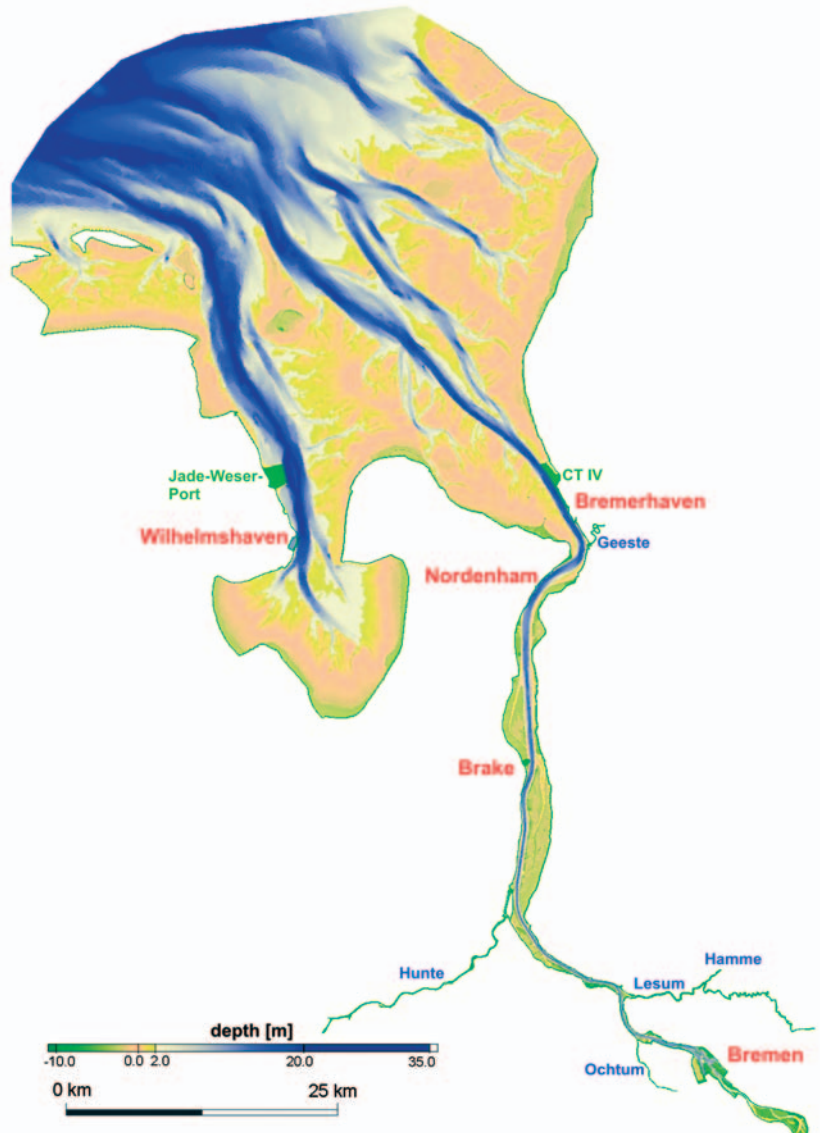

Fig. 1: General plan of the Weser estuary

increase can be noticed with lumber export and steel turnover. The growth rate for outgoing traffic was at approx. 6 % in the years from 1998 to 2005.

In addition to the utilization of river and estuary as a traffic artery, fisheries out of the small coastal harbours, energy production (wind power stations and cooling water for power stations) and an increasing tourism are other economical sectors. In spite of its high degree of improvement for navigation purposes, the Weser also represents a natural habitat for numerous species of animals and plants. Moreover, it is a region of recreation and repose for the population.

2. Geomorphology of the Weser Estuary

The bed material of the Lower Weser is mainly composed of fine and medium sands. Under the influence of changing water depths, tidal currents and fresh water discharge, pronounced bed forms (dunes superimposed by ripples) are created. They occur with average crest heights of 2 m at mean lengths of 60 m, while maximum heights of 4.5 m can be found. Seawards of Nordenham, the bedforms disappear. In this area the centre of the brackish water zone with high turbidity is located, leading to an accumulation of very fine sediments (silt and mud) on the bottom.

The funnel-shaped estuary of the Outer Weser, opening up towards the North Sea in north-westerly direction, is characterized by two main channels, several secondary channels, tidal gullies and extensive tidal flats. The topography and bathymetry of the system is subjected to continuous changes. Before the establishment of the main navigational channel in the inner estuary and its fortification by groynes and training walls at the beginning of the 20th century, cyclic variations led to an alternating preference of the western (Fedderwarder Arm) or eastern (Wurster Arm) channel. The sophisticated system of river training structures in combination with continuously necessary dredging keeps the main navigational channel in its present position. Fig. 2 shows the development of the cross-sectional underwater profiles.

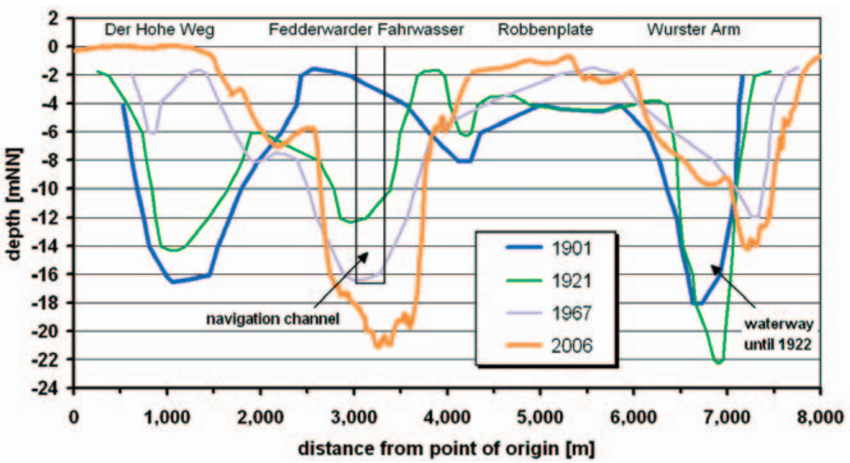

Fig. 2: Cross-sectional profiles at km 91 of the Weser estuary

The morphology of the surrounding wadden areas is still subjected to continuous changes. Tidal gullies and sand banks can move up to 100 m/a. Sediments of the channels of the Outer Weser are mainly fine and medium sands. Depending on the location, one can find sand, silt and all other sediment mixtures typical for tidal flats in the wadden areas and its gullies and streams (Fig. 3). The topology of the bottom of the navigation channel is shaped by extensive flat reaches interrupted by scoured areas or stretches with long dunes whose crest heights reach 5 m, interspaced at up to 480 m.

After the Weser estuary had attained its present shape in the Middle Ages, fortified embankments and dikes were the first man-made encroachments on the natural state (see

GRABEMANN et al., 1999). Purposeful regulation of the course of the river and its flow cross-sections began during the first correction of the Lower Weser (1. Unterweser-Korrektion) from 1887 to 1895. By damming up tributaries, straightening the river bed and establishing a defined navigation channel with a minimum depth for sea-going vessels with a draft of min. 5 m, a cross-section with a continuously decreasing area from open water up to Bremen, was aimed at. Now, the tidal wave could penetrate almost unimpeded till Bremen; the new depth of the navigational channel could be maintained with the aid of an improved flushing ability of the tidal currents. The island of Harriersand at the right-hand shore with its length of 16 km and a size of 6 km² is one of the longest river islands of Europe. Together with the 6 km-island of Strohauser Plate at the left-hand shore, it is a stabilizing factor in the river regime of the Lower Weser.

Offshore of Bremerhaven at the Outer Weser, the first river training measures for a sufficient water depth for the emerging trans-atlantic steam ship traffic were carried out. In order to adapt to increasing ship sizes and to the reaction of the estuary system to the man-made intervention, additional changes and improvements of Lower and Outer Weser were made in the 20th century. More training works and walls, jetties and groynes were built, to stabilize the course of the river and protect the embankments and shorelines (HOVERS, 1973).

Deepening the channels did not only result in a better penetration of the tidal wave and concentration of the currents. Due to the lower level of the LW and an improved discharge of freshwater from upstream the danger of lowering the ground water table upstream of Bremen arose. This was compensated by the construction of a tidal barrier and weir in Hemelingen between 1906 and 1911. Towards the end of the 1970s, the storm surge barriers

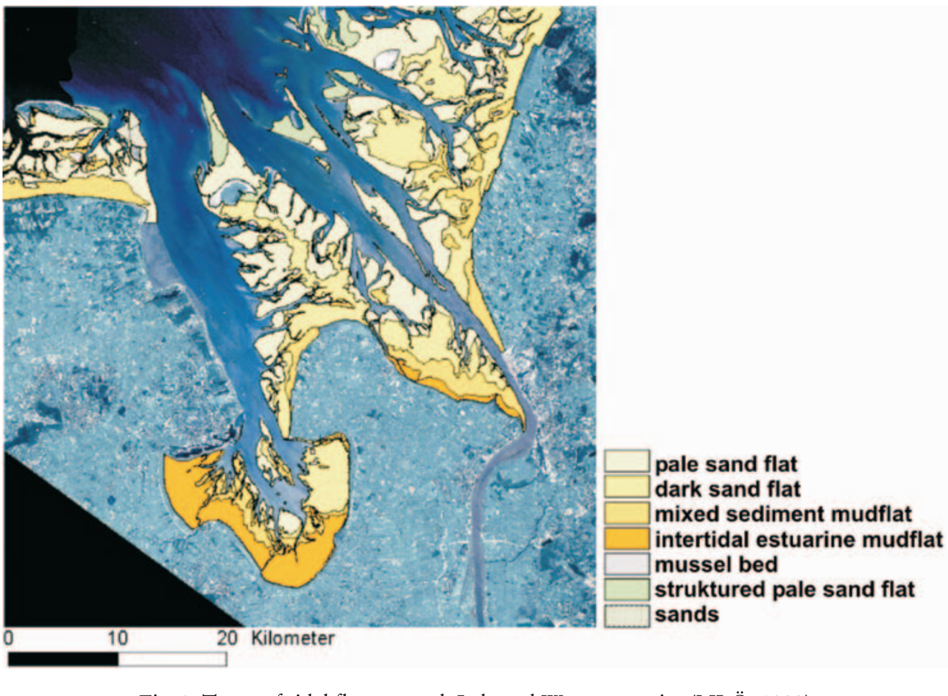

Fig. 3: Types of tidal flats around Jade and Weser estuaries (NLÖ, 1999)

at the mouth of the tributaries Hunte, Lesum und Ochtum were built. Additional man-made encroachments on the shape of the river bed and the embankments were the construction and further improvement of the harbours and quays at Bremen, Brake, Nordenham and Bremerhaven as well as the establishment of sluices and drainage canals. In the case of Lunesiel, this also led to the relocation of the mouth of the tributary Lune. For the compensation of construction measures, flood plains have been created along the foreshores of the Lower Weser.

Table 1: Compendium of river deepening and correction measures of Lower and Outer Weser (SKN = Seekartennull = nautical chart datum)

1887–1895	1. Unterweser-Korrektion for vessels with 5 m draft (5 m-correction) according to a plan of Ludwig Franzius
1913–1916	Upgrading of the Lower Weser for vessels of 7.0 m draft
1921–1924	Upgrading of the Lower Weser for vessels with a draft of 7.0 m when leaving Bremen (extended 7.0 m-correction of the UW)
1922–1926	Upgrading of ‚Fedderwarder Arm' in Outer Weser to SKN – 10 m
1925–1929	Upgrading of the Lower Weser for vessels with a draft of 8.0 m
1953–1958	Upgrading of the Lower Weser for vessels with a draft of 8.7 m, levelling of the bottom sill at Brake (Braker Buckel)
1969–1971	Upgrading of the Outer Weser to a depth of SKN – 12 m (dredging works for deepening)
1973–1978	Upgrading of the Lower Weser between Brake and Bremen to SKN – 9 m
1973–1974	Deepening of the Lower Weser between Bremerhaven and Nordenham to SKN – 11m and dredging of the turning circles
1998–1999	Upgrading of the Outer Weser to SKN – 14 m

Today, the river system of the Lower Weser is still governed by the principles of the 1st Weser correction (1. Weserkorrektion). The flow cross-sections below SKN have been designed to increase in size towards Bremerhaven and, thereby, match is the increasing water flow (Fig. 4).

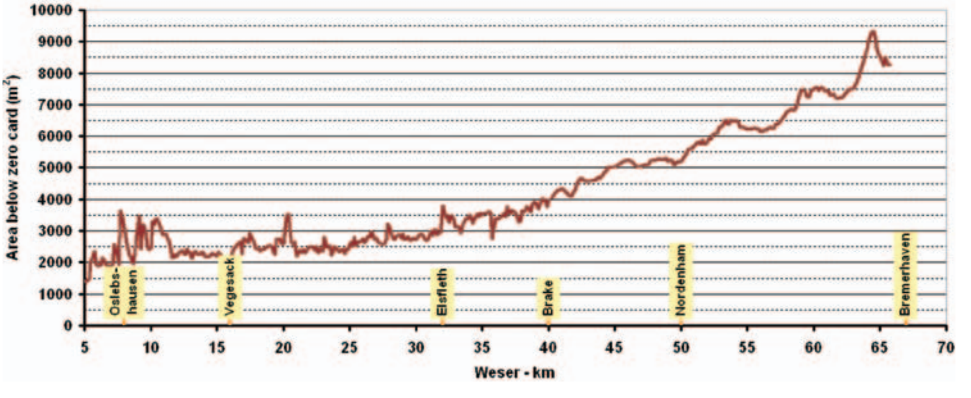

Fig. 4: Cross-sectional area below reference datum along the Lower Weser

The evolution of depths of the navigation channel of the Lower Weser as a consequence of river improvement measures is shown in Fig. 5. Channel widths were increased from 80 m (5 m-correction) to 150–200 m today.

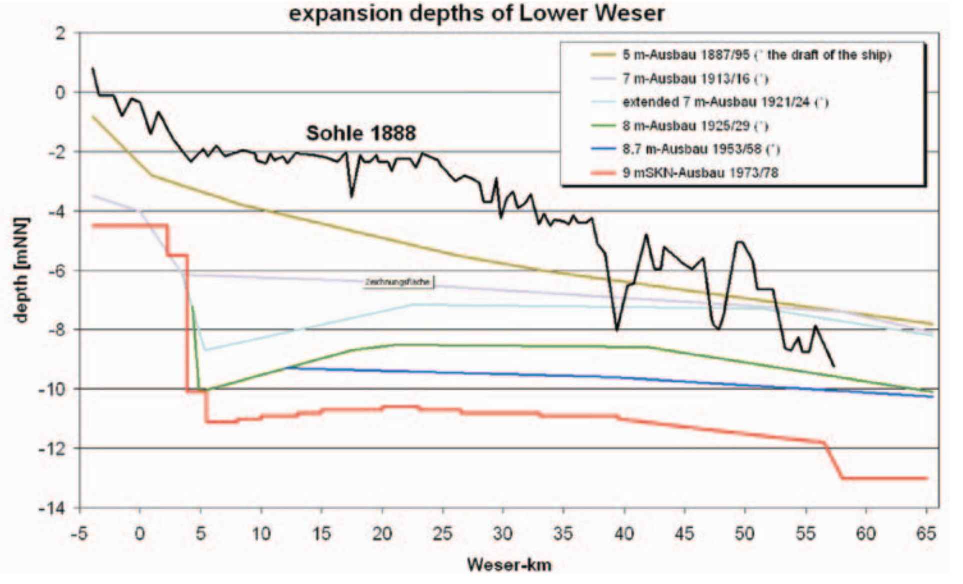

Fig. 5: Development of the navigational channel of the Lower Weser

3. Hydrological Parameters

The entire catchment area of the Lower Weser – a composition of those of the source rivers Werra and Fulda and of the Weser itself – adds up to Bremerhaven to be approx. 46,000 km^2. The catchment area of the Outer Weser is difficult to define, because of the surrounding flat landscape with some areas below NN.

In the following Table 2, the hydrological discharge values of the Lower Weser have been compiled (source: Gewässerkundliches Jahrbuch, 2004). These data were collected at the gauge Intschede, which is located at Middle Weser km 331.1, some 30 km upstream of the tidal barrier in Bremen-Hemelingen.

The wide range of discharge values between approx. 60 and 3,500 m^3/s places a high demand on water management of the Upper and Middle Weser. For once, navigability has to be guaranteed for low discharges; and high discharges have to be dissipated without causing damage. Fig. 6 shows the time series of discharge between 1985 and 2005. One can see that values of more than 1,000 m^3/s occur only for short periods during winter months. During summer months, lower discharge values between 100 and 200 m^3/s prevail.

High fresh water discharge values have no significant influence on the dike safety along the Lower Weser. Here, a real threat is presented by increased water levels during storm surges, combined with strong winds from westerly directions.

Tidal elevations in the Weser estuary are influenced by the distribution and spreading of

Table 2: Discharge values of the Middle Weser at gauge Intschede

	Abbr.	unit	year 2004	Period 1941/2004
Lowest discharge	NQ	m^3/s	119	59,7
Mean lowest discharge	MNQ	m^3/s		124
Mean discharge	MQ	m^3/s	280	326
Mean highest discharge	MHQ	m^3/s		1270
Highest discharge	HQ	m^3/s	831	3500
Annual peak	HQ_1	m^3/s		963
Mean five-year peak	HQ_5	m^3/s		1640

the tidal wave in the North Sea (cf. Tide Tables for European Waters, BSH, 2008) and its modification by partial reflexion and shoaling effects etc. in the estuary. This results in a semi-diurnal tide with a tidal range of 2.8 m in the northern part of the Outer Weser. On the way towards Bremerhaven the mean tidal range increases to 3.8 m to attain 4.1 m in Bremen (5-year average 2003/2007). Running time from the gauge Alte Weser at the mouth till Bremen (115 km) is approx. 3 hours. Due to the various upgrading and construction measures with deeper channels and more regular cross-sections, carried out since the end of the 19th century, friction losses were reduced, and the influence of the tide is greatly enhanced.

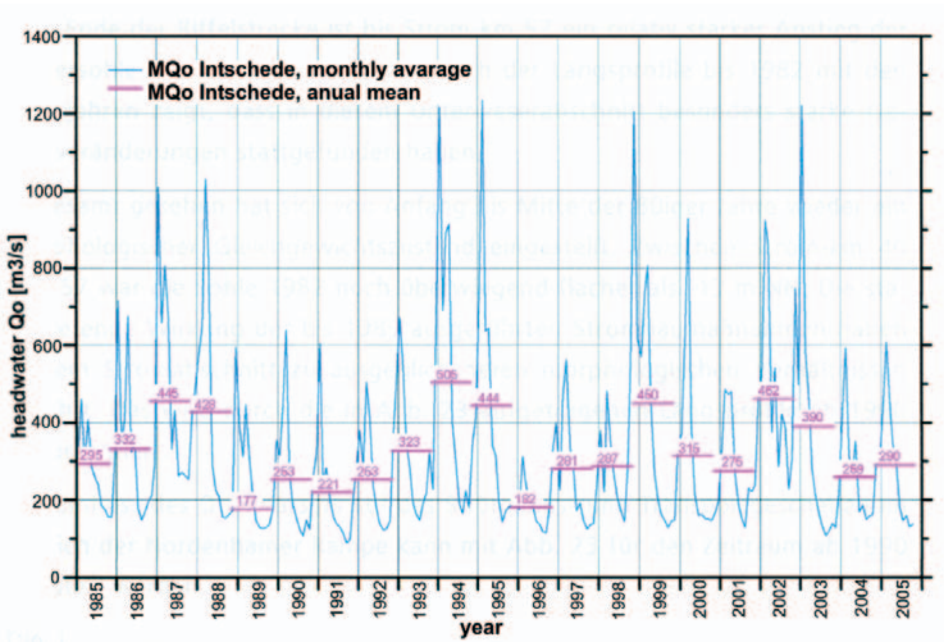

Fig. 6: Weser freshwater discharge at gauge Intschede from 1985 to 2005
(HOCHSCHULE BREMEN, 2006)

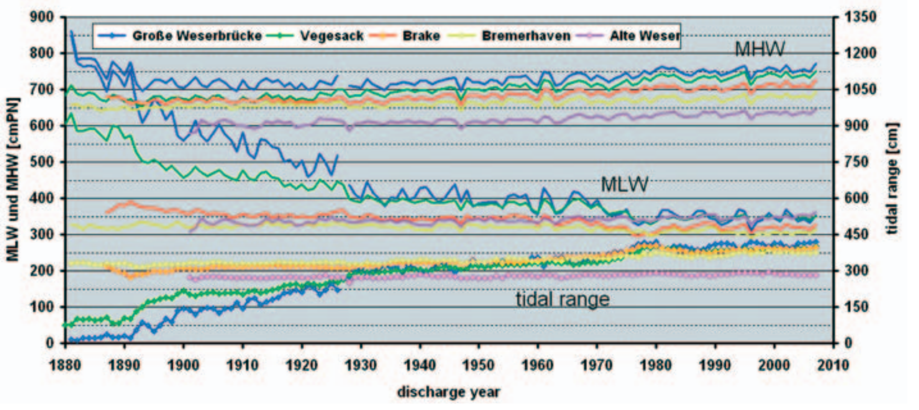

Fig. 7: Development of mean high water (MHW) and mean low water (MLW) between 1880 and 2007 (WSA Bremerhaven, 2008)

The increase of the tidal range is the most obvious indication of changes: the initial 20 cm in Bremen grew to a range of more than 4 m, mostly attributed to a drop of the mean low water (MLW) (Fig. 7). Upgrading and deepening are reflected more or less strongly in changes of the running time as well as in the flood and ebb duration.

Fig. 8 illustrates a time series of salinity values at high slack water (max. salinity) and at low slack water (min. salinity) obtained from measurements in the years of 1998 to 2005. As a consequence of discharging caustic potash solution coming from mining activities, the Lower Weser has an initial level of **salinity** of 0.5 to 1 ‰. With a classification of the brackish water zone as the region with salinity values between 2 and 20 ‰, it extends from km 45 to 70 at high slack water and from km 60 to 92 at low slack water on a long-standing average. Even though the location of the brackish water zone is also influenced by the freshwater

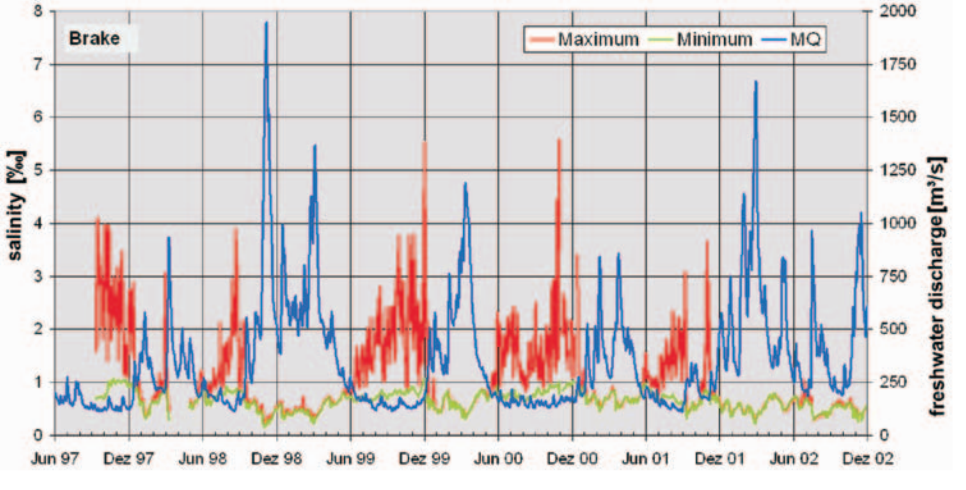

Fig. 8: Long-term time series of salinity and discharge at gauge Brake (WSA Bremerhaven, 2004)

discharge, the decisive factor for peak values are the tides. If during a succession of several tides LW increases, i.e.storm tides push seawater into the estuary, an increase of salinity intrusion into Lower Weser can be noted. During such extreme situations, the brackish water influence can be felt up to Brake and beyond.

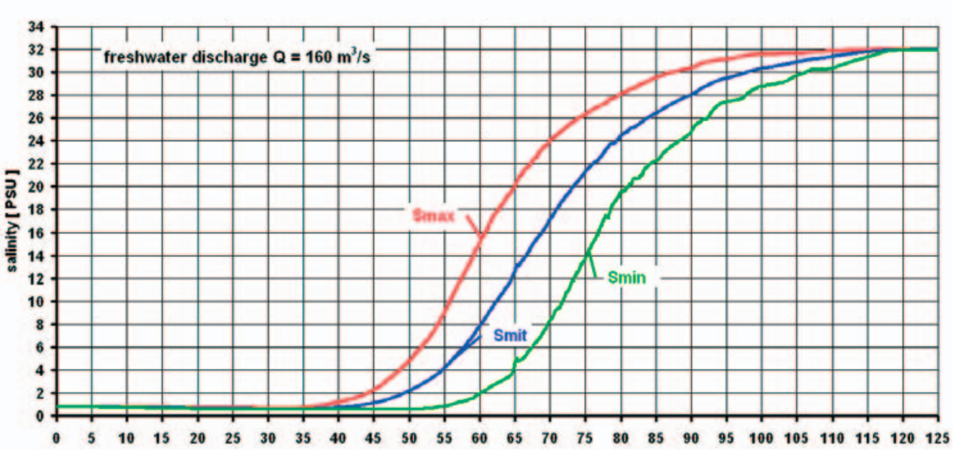

Fig. 9: Location of the brackish water zone at a discharge of 160 m³/s
(num. model investigations BAW)

For further clarification of the local salinity variations during one tide, Fig. 9 depicts the extreme salinity values along the longitudinal section of the Weser estuary (Q_o = 160 m³/s) obtained from a numerical tide model.

The local and time-dependent horizontal and vertical distribution of current velocities and directions in the tidal Weser is dependent on many factors. Apart from tidal and discharge conditions, especially the bathymetry of the river bed and water density play an important role. Fig. 10 shows the vertically averaged ebb and flood current velocities in the centre of the navigation channel of Lower and Outer Weser. Values have been obtained from a three-dimensional numerical model for a spring-neap tidal cycle. Moreover, residual currents and the ratio of flood-to-ebb current have been calculated for the evaluation of the current regime. Field investigations as well as the model results indicate that in most stretches of the navigation channel of Lower and Outer Weser vertically averaged ebb currents are stronger than flood currents. There are, however, typical stretches, such as the reach between km 80 and 95, where the flood stream prevails due to strongly diverging currents in the centre channel. Due to these ‘current discontinuities’, shoals develop in the navigation channel requiring a high maintenance effort.

During the 1980s, measurements in the turbidity zone of the Weser (projects MASEX ’83 and MASEX ’85) were carried out. The results of the analysis have been published in various articles (see FANGER et al., 1985 and NEUMANN et al., 1985). Only recently, in a pilot project of the Federal Institute of Research and Coastal Engineering (BAW), new measurement methods were deployed to obtain a cross-sectional image of suspended matter at Nordenham for the duration of one tide.

These measurements confirm that in the brackish water region of the Lower Weser

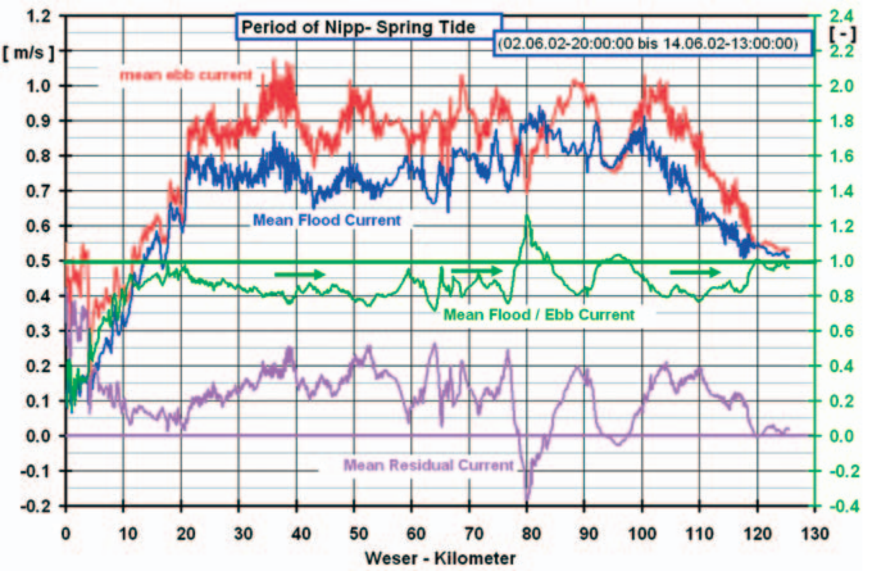

Fig. 10: Longitudinal section of vertically averaged flood and ebb currents during a spring-neap-cycle, of residual currents and of the ratio of flood and ebb current velocity (num. model investigations BAW)

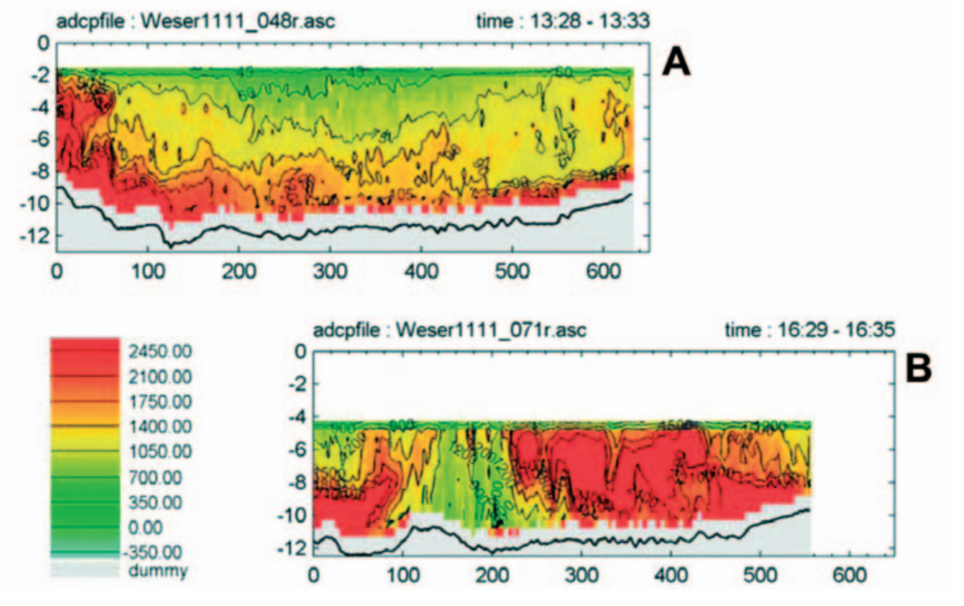

Fig. 11: Concentrations of suspended matter in the Lower Weser at ebb currents (A – beginning ebb currents, B – full ebb currents) (AQUA VISION, 2004)

concentrations of suspended matter between 300 and 600 mg/l in the water column can occur. At particular tidal phases, these values can go up to 2000 mg/l close to the bottom.

Fig. 11 shows these concentrations of suspended matter at the beginning and during full ebb currents. It is obvious that concentrations are stronger close to the embankments as compared to the centre channel.

4. Measures for the Improvement of the Weser Estuary

Past improvement and deepening measures in Lower and Outer Weser (Tab. 1) have been accompanied by river training works such as training walls and groynes, in order to stabilize projected water depths in the fairways and secure the embankments and shores. Today, the managed and maintained river training system extends from km 90 in the Outer Weser till km 42 near Brake. Upstream of Brake, the embankments of some river stretches are being secured by heavy revetments.

Presently, the projects '*adaptation of the navigation channel of the Outer Weser to the development of marine traffic and depth adaptation of the port-related turning circle*' as well as '*adaptation of the navigation channel of the Lower Weser to the developing marine traffic*' are being prepared in working groups. The public can follow the procedure at http://www.weseranpassung.de.

The access channel from the open sea (Outer Weser) to the Container terminal Bremerhaven is to be adapted to the foreseeable development of sizes of modern container vessels. The tide-independent accessibility of CT Bremerhaven for large container vessels with a maximum draft of 13.50 m – this is equivalent to a future-oriented degree of a lading draft of 93 % of the construction draft of vessels of the S-class – is supposed to maintain and strengthen the medium and long-term competitive position of the Container terminal Bremerhaven.

To secure and improve the competitive position of those ports along the Lower Weser and to avoid disadvantages because of an insufficient depth of the navigation channel, the adaptation of the Lower Weser between Nordenham and the ports of Brake und Bremen is scheduled. This was done considering new requirements of port enterprises and shipping companies. Deepening the Lower Weser for vessels to reach the port of Brake tide-dependent with a lading draft of max. 12.80 m would secure the future competitiveness of the port for the bulk goods animal feed and grain. A future accessibility of the port of Bremen for vessels with a lading draft of max. 11.10 m particularly ensures and improves the economical transport of iron ore and coal.

5. Maintenance of the Fairways

To guarantee the ease and safety of marine traffic, a sufficient water depth has to be established and maintained. Dredging works in the estuary are contracted out in close cooperation between the regional water and shipping authorities (Wasser- und Schifffahrtsämter) Bremen and Bremerhaven. In the Lower Weser, maintenance dredging in the sandy reaches between Bremen and Nordenham is carried out by water injection dredgers; between Nordenham and Bremerhaven, the prevailing silt is dredged by hopper dredgers which are also mostly deployed in the Outer Weser.

The dredged spoils transported by hopper dredgers is generally dumped on sites in or close to the navigation channel. Sometimes, suitable dredged material is also used for beach nourishment to secure the embankments of the Lower Weser and for construction measures of third parties.

In the fairways of Lower and Outer Weser and in the turning circles, the water and shipping authorities and third parties dredge approx. 4–8 Mio. m^3 of sand and silt, annually. The development of quantities of dredged material in various reaches of Lower and Outer Weser can bee seen in Fig. 12. The capital investment of the Federal Administration of Waterways and Navigation (Wasser- und Schifffahrtsverwaltung, WSV) for maintenance dredging in the Lower and Outer Weser has amounted to approx. 8–18 Mio. €/a since 1999.

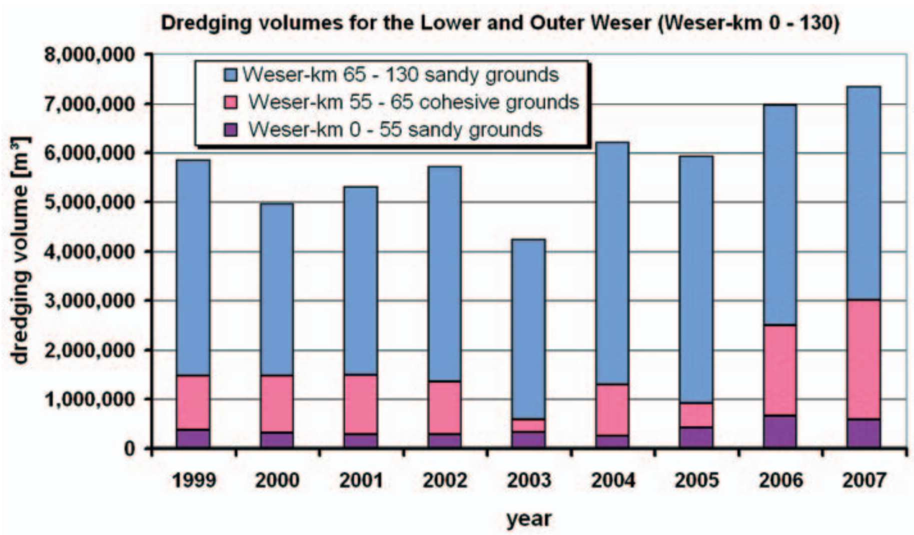

Fig. 12: Quantities of dredged spoils at the Weser estuary (WSA Bremerhaven)

6. Monitoring and Analysis of the Weser Estuary

Due to the complex dynamics of the Weser estuary, continuous maintenance of the navigation channel and river training works as well a new improvement projects always trigger new questions. These have to be answered based on general water engineering expertise, local knowledge and long-term experience of the estuary. Consequently, the spectrum of tasks in water engineering at the water and shipping authorities (WSÄ) of Bremen and Bremerhaven is fairly broad.

Recording and analyzing water level data is a focal point of hydrological tasks. Its importance is underlined by more than 30 water level gauges along the Lower and Outer Weser and their tributaries. These gauges are continuously maintained by WSV or provincial authorities. Abiotic parameters such as conductivity, temperature and partly turbidity are recorded by WSV on 13 locations along the Outer and northern Lower Weser.

Data are used among others for preservation of evidence. This is done with the intention to determine – from time series of various parameters – modifications induced or triggered by improvement or upgrading projects. Long-term measurements are required from before (status-quo) as well as from after construction works have been finished.

The extension of the present preservation of evidence is anchored in the 'plan approval order' for the '*improvement of the Federal Waterway Weser between km 65 and 130 to establish a minimum water depth of 14 m below SKN*', Jan. 30, 1998, paragraph A.II.3. Preservation of evidence investigations for water levels, conductivity, morphology and ship-induced waves have been identified to be carried out. The entire extent and contents of the programme and first results can be inspected at the given internet address: http://www.wsv.de/wsa-bhv/weserausbauten/14m_Ausbau/beweissicherung/index.html.

In various institutes, hydrodynamic-numerical models representing partial areas or the entire investigation area of the Weser estuary are deployed and maintained for the investigation of water engineering and ecological questions. Provincial authorities run their own numerical models in order to simulate natural conditions and investigate dike safety und storm surge conditions. Commissioned by WSV, university institutes are investigating questions concerning currents and sediment transport. BAW is looking at matters of the adaptation of the Weser to the requirements of marine traffic using numerical models with a locally increased grid resolution. These are to simulate the effect of deepening fairways etc. on currents, sediment transport and morphology. Modelling methods are permanently being improved to include morphodynamic simulations of dredging and dumping as well as long-term development of the bathymetry.

Another challenge is the simulation of the historical development of the estuary to also permit the analysis of improvement measures of the last decades. This requires an intimate knowledge of the estuary, of water engineering methods and the cooperation of all persons and institutions involved.

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