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The Jade

By AXEL GÖTSCHENBERG and ANDREAS KAHLFELD

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1. Introduction

The Jade stands out against other estuaries such as Ems, Weser, Elbe and Eider by its different geological development and the fact that it does not have a significant freshwater discharge.Therefore, it is considered a tidal bay rather than an estuary.

The geography of the Jade comprises the Outer Jade, Inner Jade and the Jade Bay (Fig. 1). The tidal flat area known as *Der Hohe Weg* separates the Jade from the Weser estuary.

The eponym Jade, a small, non-navigable river, enters the 'Jade Bay' (Jade Bay) through the sluice 'Wapeler Siel' into a system of tidal creeks and gullies at the southernmost point of the bay.

Wilhelmshaven, the main town of this region, lies at the south-western end of the Inner Jade. It was founded as a naval port in 1869 and still shelters a naval base of the Bundeswehr in its inner harbour separated from the Jade by a sea lock. This also houses transhipment facilities that are important for the region's economy. On the west bank of the Inner Jade, four transhipment piers located along the deep Jade fairway, and the industrial zones that stretch along the shore constitute the outer harbour. This is Germany's only deep water port with an access channel for very large sea-going vessels with an unrestricted draught of up to 16.5 metres. Tide-dependent access is possible for 250,000 TDW tankers with a maximum draught of 20 metres.

2. Geomorphology

Between the 11th and 15th century, the Jade Bay developed at the Frisian marsh coast as a result of storm tides in the North Sea and cuts deeply into the mainland. The fairway was developed and is being maintained as far as Wilhelmshaven. Upstream, it branches into several channels (Ahne, Vareler Fahrwasser and Stenkentief), which lead into the Jade Bay and, with diminishing cross-sections, merge into tidal creeks. They are used as fairways in the tidal flats.

The morphology of the Jade dates from the Ice Age with Holocene and Pleistocene sediments. Today, the spatial structure is dominated by the navigational and other deep channels, sandbanks and extended tidal flats. The regime is governed by natural forces (tidal currents and waves) as well as man-made activities (dyking, fairway maintenance and improvement and river training works).

Hydrological investigations (LANG, 2003; FRELS, 1995) indicate a positive material balance of sediment transport for the Jade. Due to various physical features, such as the dominance of flood tides, a residual flow via the 'Hohe Weg' tidal flats into the Weser estuary, lack of freshwater discharge and the shape of the Jade Bay, flood currents transport more sediment into the Jade Bay than ebb currents can take out again. This emphasizes the centuries-old

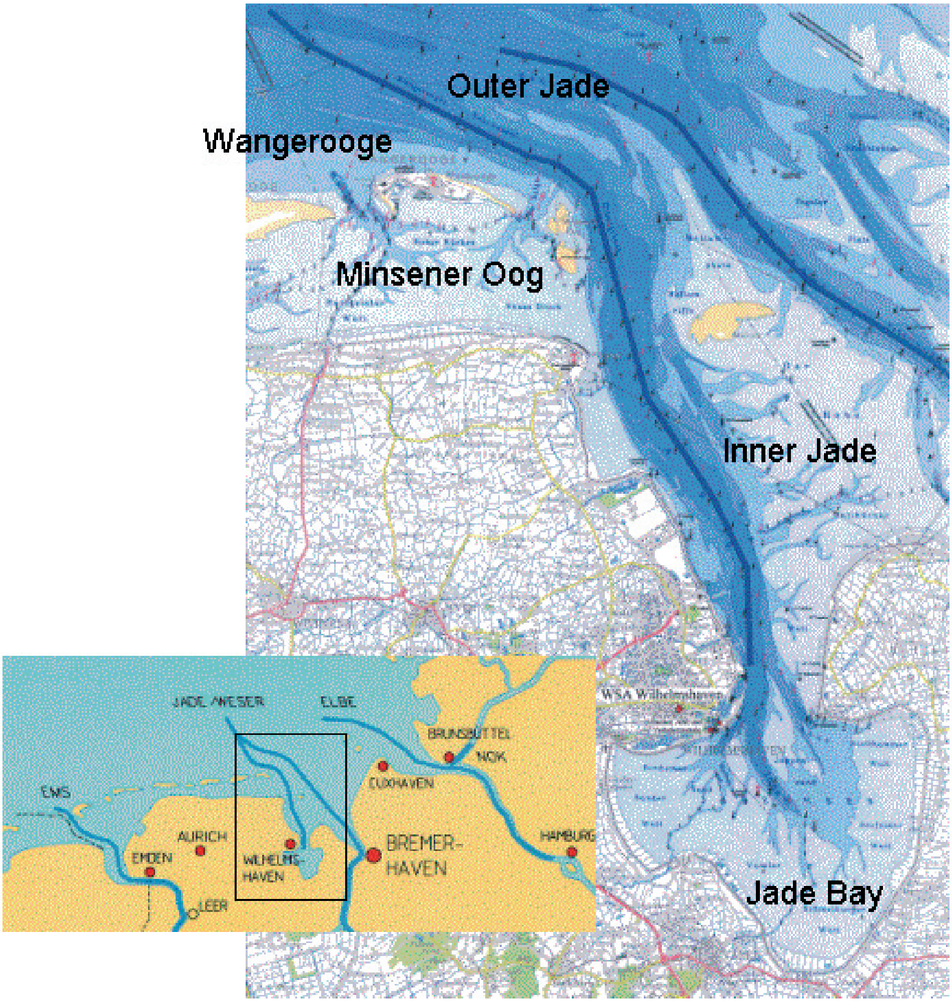

Fig. 1: General plan of the Jade

significance of the self-maintaining character of the main Jade channel. According to the investigations of LANG (2003) the reason for this behaviour is to be found in reflection properties of the tidal wave in the Jade Bay with a low dissipation of energy and an increase in the tidal range caused by resonance.

In the Jade, the tidal current moves in weak meanders. In the Inner Jade and in the Jade Bay, the incoming and outgoing tides sometimes follow different tracks. As a result, in these regions modifications of varying intensity to the morphology are caused above all at the undercut and slip-off slopes and in the areas of divergence (cf. chapter 5). Various river engineering structures, such as the groyne system on Minsener Oog and the training wall on the Schweinsrücken (cf. Figs. 1 and 5), guide and bundle the flow to prevent local sedimentation in the fairway and to facilitate maintenance.

3. Hydrological Parameters

3.1 Fresh Water Discharge

A unique feature of the Jade is its expansive tidal bay character with almost no fresh water discharge. The drainage sluices in the Jade Bay make an almost imperceptible contribution to the total volume of around 400 million cubic metres that flow in and out of the Jade Bay with every tide. The freshwater discharge has also little influence on the salinity in the Jade. This varies between 2.9 and 3.2 % and a brackish water zone does not develop.

3.2 Water Levels

Measurements of hydrological parameters can be traced back to the founding of Wilhelmshaven as a naval port. Water levels were recorded at the gauge station 'Alter Vorhafen' starting in 1853. At the harbour of the island of Wangerooge, records have been kept (with some interruptions) for about 100 years. Additional tidal gauges were installed after the storm surge of February 1962. However, due to dike construction (gauge station Voslapp) or sedimentation (gauge station Schillig) they were frequently moved in the early years. Long-term time series of water levels are therefore only available from the gauge stations 'Alter Vorhafen' and at the Mellumplate lighthouse (beginning in 1943). These stations were additionally used to collect data for the preservation of evidence after improvement measures in the Jade carried out between 1960 and 1976.

An overview of the mean high water levels along the navigation channel for the hydrological year 2007 is depicted in Fig. 2.

The increase of 44 cm in MHW from the sea to the Inner Jade can be clearly recognized. The opposite effect can be observed for MLW: from Wangerooge to the entrance of the Jade Bay, the low water level decreases by 56 cm. The data from the 10-year time series from 1998 to 2007 (see Tab. 1) confirm the mean conditions of the year 2007.

In the Jade Bay, the mean high water levels are a little higher than at the gauge station 'Alter Vorhafen', as the tidal wave spreads out into and is partially reflected in the Jade Bay. The mean low water levels in the Jade Bay show little difference in comparison with those of 'Alter Vorhafen'.

The water level dynamics vary due to astronomical and meteorological influences. The highest high water level was observed at 'Alter Vorhafen' to be NN + 1022 cm on 16.2.1962.

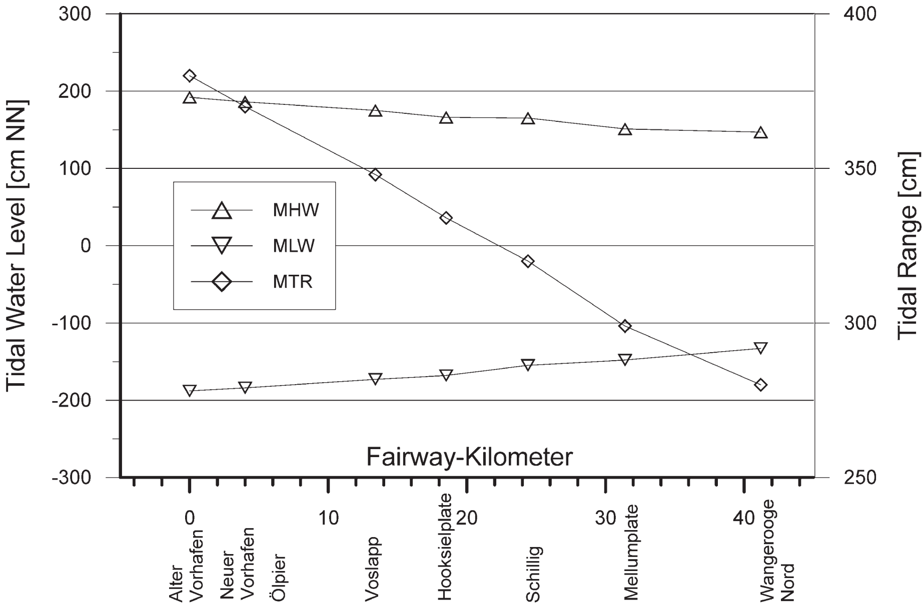

Fig. 2: Mean high and low water levels (MHW, MLW) and mean tidal range along the navigational channel of the Jade in the hydrological year 2007

In contrast, the lowest recorded low water level was NN + 59 cm on 16.02.1900. Water levels measured at the seaward gauge stations show the same relation (see Table 1).

Table 1: Mean and extreme water levels in the Jade

Gauge station	Gauge datum cm below NN	MHW 1998–2007	MHW 2008	MLW 1998–2007	MLW 2008	Mean Tidal Range	Mean Tidal Range 2008	Highest HW		Lowest LW	
Wilhelmshaven Alter Vorhafen	502	686	684	305	302	381	382	1022	16.02.1962	59	16.02.1900
Wilhelmshaven Neuer Vorhafen	500	678	677	307	304	371	371	965	01.11.2006	103	02.03.1987
Ölpier (Oil pier)	500	676	677	302	298	374	375	961	10.01.1995	154	14.02.1994
Voslapp	502	671	670	322	318	349	352	950	21.01.1976	161	14.02.1994
Hooksielplate	502	662	661	327	325	335	336	925	28.01.1994	167	14.02.1994
Schillig	500	655	654	335	330	320	324	913	01.11.2006	180	14.02.1994
Mellumplate	502	646	645	345	342	301	303	930	16.02.1962	124	02.03.1987
Wangerooge Nord	503	643	642	361	358	282	284	907	03.01.1976	134	02.03.1987
Wangerooge West	503	647	647	361	358	286	289	915	21.01.1976	144	02.03.1987

Fig. 3 shows a time series of MHW and MLW at 'Alter Vorhafen' since 1905. The slope of the regression line over a period of 100 years yields a mean increase of MHW of 37 cm while MLW is almost unchanged. Consequently, the tidal range has increased by 33 cm during the last 100 years. An influence of the deepening of the Jade fairway (cf. chapter 4) cannot be discerned in this almost linear development. However, channel improvement resulted in an increase in the velocity of the tidal wave progression (Fig. 4). This was due to deepening the navigation channel with a concentration of the currents, an increased hydraulic radius and a correspondingly reduced frictional resistance of the bed.

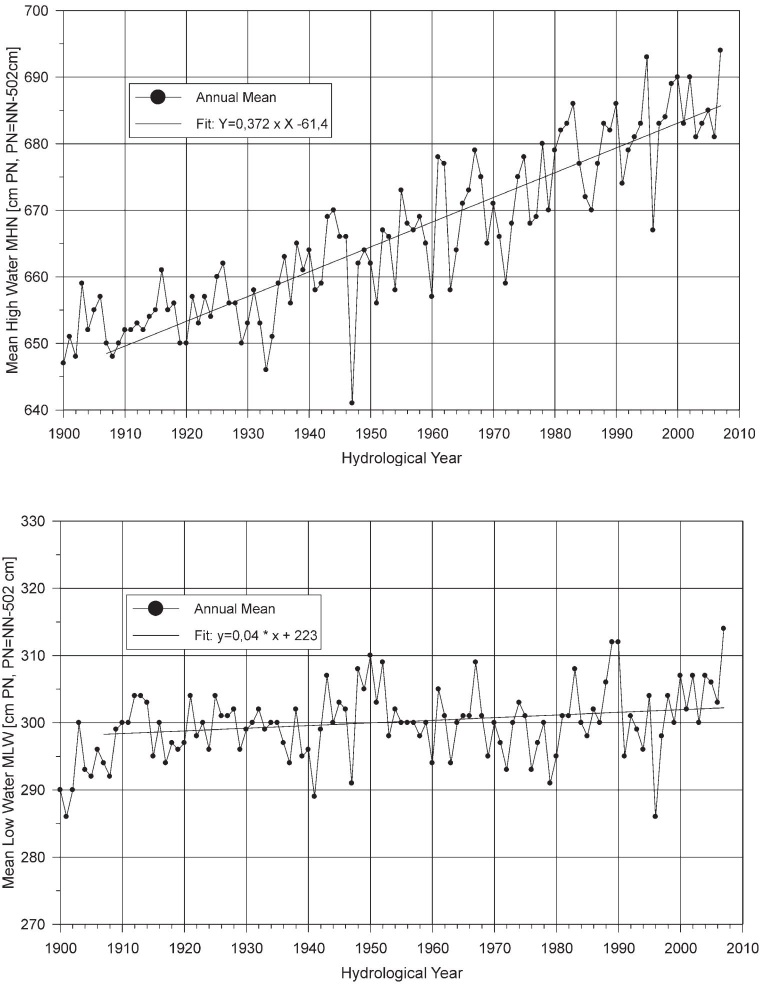

Fig. 3: Tidal peaks (MHW, MLW) at the gauge station Wilhelmshaven Alter Vorhafen since 1905

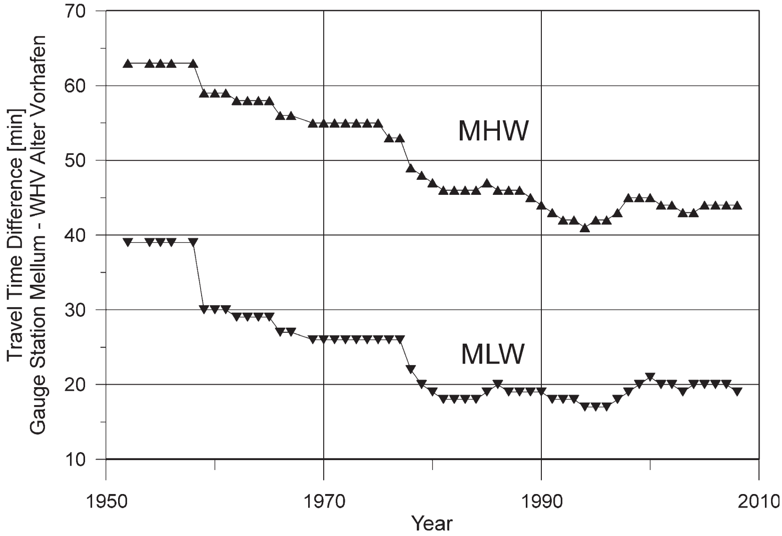

Fig. 4: Development of the travel times of the tidal peaks MHW and MLW between Mellumplate and Wilhelmshaven Alter Vorhafen

3.3 Current Velocities

The tidal current conditions in the fairway are being monitored all year round by means of measuring campaigns at various locations. The centre channel is exempted because of shipping traffic. Since 1998, four permanent measurement stations with another two added in 2006, have monitored the current regime in the Inner Jade. At present, the chain of measurement points stretches from the Varel fairway (Vareler Fahrwasser) to a point on a level with Horumersiel.

Table 2: Mean current velocities in the Jade

Station	Flood tide v_{mean} [cm/s]	Flood tide v_{max} [cm/s]	Ebb tide v_{mean} [cm/s]	Ebb tide v_{max} [cm/s]
D0 Jade Bay	46	96	53	113
D1 Steenkentief	46	97	49	95
D2 Neuer Vorhafen	52	97	47	88
D3 Niedersachsen-Brücke	50	94	48	104
D4 Hooksiel	58	106	63	115
D5 Horumersiel	58	109	58	110

Characteristic parameters can be seen in Table 2. In addition, Fig. 5 shows the distribution of the surface current velocities as calculated by the mathematical tidal model for the Jade-Weser Estuary operated by the German Federal Waterways Engineering and Research Institute (Bundesanstalt für Wasserbau – BAW).

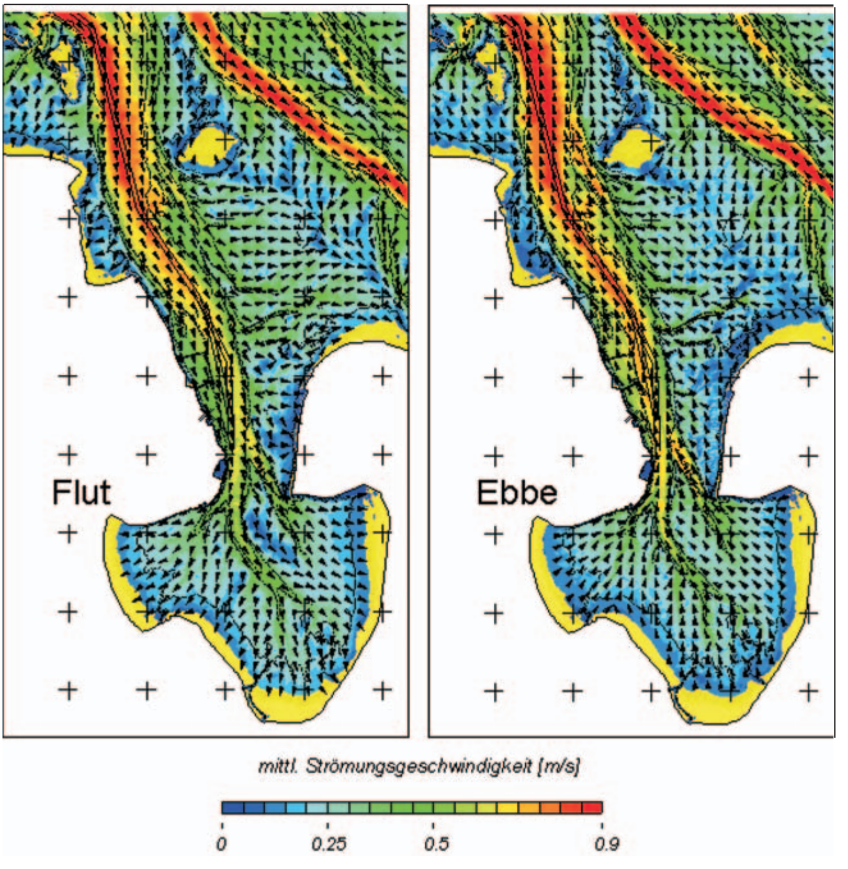

Fig. 5: Flood (right) and ebb (left) current velocities averaged over a neap-spring cycle obtained from a 3D-HN simulation with the model UnTRIM3D (BAW, 2003a)

3.4 Waves

Only sporadic information is available on the sea state in the Jade. The only wave information is based on measurements carried out for the planning and design of port facilities in the Inner Jade and as input values for various modeling and measuring techniques (IM+P, 2003). The following wave phenomena were deduced from the bathymetric and topographical conditions (BAW, 2003b):

- As a result of the large flow cross sections and very deep water of the Jade, swell can penetrate far into the Inner Jade, depending on the phase of the tide. It may be generated far away in the North Sea and arrives from a northerly to north-westerly direction.

- As a result of long fetches and deep water, locally generated waves in the Inner Jade will be intensified and can – dependent on the tidal phase – have a particular impact on the higher eastern tidal flats and coastal sections.
- The Jade Bay is characterized by extensive tidal flat areas. Waves entering through the 'Vareler Fahrwasser' and the 'Ahne' from the Inner Jade are transformed in shallower water by processes such as shoaling, refraction, diffraction and breaking. In addition, local wind effects modify the sea state depending on the tidal phase.

The results of a numerical spectral wave model for the rare extreme event "storm tide with ebb current" (BAW, 2003b) indicate that incoming offshore waves with a significant wave height $H_S = 6$ m and a peak period of $T_P = 15$ s will be already reduced to a $H_{Smax} = 3.5$ m at the level of Schilling by the influence of shallower water. Further south, in the Inner Jade towards Wilhelmshaven, significant wave heights decrease to values of 2 to 3 metres. The spatial distribution of the wave heights depends on the topography. Depending on the location of the deep channels, the larger wave heights are concentrated in the western part of the Inner Jade. In the southern channels with a greater water depth (Stenkentief, Vareler Fahrwasser, Ahne), waves with a height $H_S = 1 – 2.5$ m can penetrate more easily into the Jade Bay. In the shallow regions of and on the tidal flats of the Jade Bay and on 'Hohe Weg Watt' only waves with heights of $H_S < 1.5$ m occur.

3.5 Turbidity and Suspended Matter

As it requires considerable effort, the direct measurement of suspended load is only carried out in exceptional cases for the calibration of turbidity measurements. Annual turbidity measurement series are available from the permanent measuring points along the Inner Jade. The mean values range from 50 NTU in the region of Hooksiel to 80 NTU in the Jade Bay. The high values in the Jade Bay are caused by turbulent flow action and resuspension of fine matter on the tidal flats. In the Inner Jade region, ebb currents from the wadden area at 'Hohe Weg' occasionally cause turbidity peaks. Otherwise, the transportation of fine sand in the form of large dunes at the bottom is dominant here. Suspended load concentrations of between 200 and 2,000 mg/litre have been measured.

4. Construction Measures – Review and Outlook

With the last dyking in 1854, the Jade Bay was largely given its present shape. In the early 20th century, the inner harbour at Wilhelmshaven was extended southwards. The first interference with the dynamics of the Jade through construction activities, namely the building of the approx. 5.8 kilometre-long training wall on 'Schweinsrücken in the Jade Bay', started from 1893 to 1897. This structure regulates the tidal flow along the entrances to the Innenhafen (inner harbour) at Wilhelmshaven and in this form has ensured their accessibility until today.

In the transition zone between the Outer Jade and the Inner Jade, the littoral drift from West to East interferes with the maintenance of the Jade fairway. With the construction of the approx. 10.5 kilometre-long groyne system of 'Minsener Oog' between 1909 and 1936, an important contribution to stabilising the fairway was made. Migrating sandbanks and bars (so-called Platen) were kept away from the fairway.

The development of the Jade, which had formerly been characterised by river bifurcations, began in 1957 and lasted, in various phases, until 1974. Natural channel depths of between 10 and 12 m below sea chart datum were developed into a navigation channel for deep-drawing vessels with a guaranteed depth of 17.60 m below SKN_{LAT} and a width of 300 m. At the same time, the embankment of wadden and marsh areas (Groden = polders) on the west shore of the Inner Jade and their development for the establishment of harbour facilities for mineral oil and chemical industries, as well as for power generation was carried out. It started with 'Heppenser Groden' in 1940, followed by 'Rüstersieler Groden' in 1960 and 'Voslapper Groden' in 1970. In addition, four transhipment piers were constructed on the west shore of the Inner Jade, the first being completed in 1958 and the last in 1980. Since the completion of the engineering works for the relocation of the Jade fairway near Hooksiel in the year 1987, no major encroachment on the Jade has taken place. Dredged spoils from the construction works of approx. 500 million m^3 were removed from the hydraulic regime of the Jade and dumped or washed into marginal areas outside the main tidal flow (cf. chapter 5).

After construction works were completed, a natural adaptation of the morphodynamic conditions in the Jade followed, continued even until after completion and required extensive maintenance dredging until the mid 1990s. As the western Inner Jade is partially obstructed with the transhipment piers resting on a trestle structure, the tidal currents have lost some of their strength in this zone. The main current moved eastwards, resulting in a shallower western shore. At the eastern embankment slope, the depth contours are fairly stable. This stability applies also to the tidal creek system east of the fairway. Following the completion of the major interventions in the mid 1980s, a slow-down in the sediment relocation process has been observed since the early 1990s. Consequently, a modified dredging strategy and management by the regional authority (WSA Wilhelmshaven) of the Federal Administration of Waterways and Navigation (WSV) could be introduced, resulting in a decline of dredged volumes in the Jade fairway.

The deepwater container terminal JadeWeserPort, which is currently under construction, and the partial relocation of the fairway between km 6 and km 14 will affect the transport regime of the Inner Jade again and are expected to trigger sedimentation in the shallow water areas at the western shore up- and downstream of the JadeWeserPort for a period of years.

5. Maintenance of the Navigation Channels

One of the two main dredging areas is located between kms 41 and 49 of the Outer Jade. Here, a guaranteed water depth of 17.60 m below SKN_{LAT} is provided. In the zone close to the fairway, extensive sedimentation has become apparent at the northern edge of 'Langes Riff'. Compensation of this progressing sedimentation emanating from the southern edge of the navigation channel can be seen in the erosion by tidal currents along the northern edge of the undercut slope. Apart from the need to occasionally remove sediment around groyne A at 'Minsener Oog' (Km 35–36), which was transported by sand bars migrating through 'Blaue Balje', the remaining fairway section is practically maintenance-free.

The second major dredging area is located in the Inner Jade between kms 6 and 13. The cause for the sedimentation of primarily silt material in this zone is the dominance of the flood currents. The weaker ebb currents are not able to completely remove all solids deposited by the incoming tide. Another reason is the ebb current from the 'Ahne' obliquely crossing the navigational channel and thereby dropping material. Only a very small proportion of the sediments that are carried in twice each day with the flood tide remains in the fairway (and in the deeper mooring basins provided in front of the piers) in the Inner Jade zone. In total, however, there are considerable volumes that must be removed from the system.

According to the guidelines of the German Navy (Bundesmarine), in the entrance of 'Neuer Vorhafen' a water depth of SKN_{LAT} –9.60 m[1] and in the remaining areas SKN_{LAT} -8.00 m has to be provided by means of maintenance dredging. The three deep channels 'Steenkentief', 'Vareler Fahrwasser' and 'Ahne' in the Jade Bay are not part of the Jade federal waterway, but form the southern end of the Jade Bay. For this reason, no fairway maintenance work is carried out here.

Fig. 6 shows the annual maintenance dredging volumes since 1905. Since 1997, the majority of this volume of dredged spoils has been processed by the WSV-operated own hopper suction dredger "NORDSEE" (capacity: 5,650 m³).

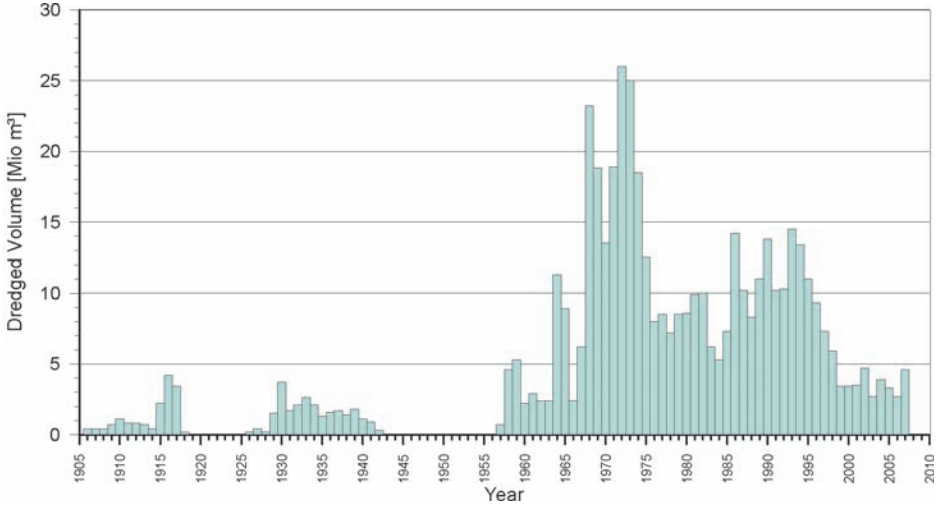

Fig. 6: Annual dredged volumes in the Inner Jade and Outer Jade
(without dredging of the outer harbour)

The total volume of material dredged from the Jade fairway is dumped on five offshore sites.

Dumpsite	Location
"01"	north of the Outer Weser fairway
"Jade-Weser"	between the fairways of the Outer Jade and Outer Weser
"Mellumplate"	near Mellumplate lighthouse
"Südreede"	at the southern end of the Inner Jade
"Vareler Fahrwasser"	in the Jade Bay

[1] SKN = sea chart zero

6. Monitoring and System Analysis

6.1 Hydrological Measurements

Nine gauge stations and six permanent measuring points form the basic monitoring network. They serve to improve the dredging and dumping strategy and the general information on the prevailing hydrological parameters of the system.

The dredging and dumping activities are assessed regularly. The first study of this kind was completed in 2003 (BfG and WSA Wilhelmshaven, 2003). Since then, more detailed studies have been carried out at selected dumpsites, and in the year 2008, a comprehensive examination of the statements of the initial study will be commissioned by the responsible regional authority, i. e. WSA Wilhelmshaven.

In the context of the construction of the JadeWeserPort, extensive measures for the preservation of evidence have been agreed on with the project manager. They include all hydrological parameters (water levels, currents, turbidity etc.) and the observation of morphological changes through regular surveys based on echo-soundings.

At present, preliminary investigations are taking place regarding the distribution of heat in cooling water from planned power station enlargements or new constructions on 'Voslapper Groden'.

6.2 Model Studies

In addition to and in support of field investigations, various mathematical models for the simulation of the physical processes in issues of water quality, concerning the ease and safety of maritime traffic and water engineering problems, are being used. The German Federal Waterways Engineering and Research Institute (BAW) in Hamburg, the advisory federal authority of WSV, is participating in the development of these state-of-the-art hydrodynamic and morphodynamic numerical tools for the simulation of tidal dynamics, waves, transport of sediments (bed and suspended load), dissolved substances (salt) and heat. The BAW operates a model for the Jade-Weser-Estuary with a high spatial and time resolution on its own compute servers based on the following methods:

- UnTRIM3D for tidal dynamics, sediment (suspension, salt) transport and heat transport
- SediMorph for bed load transport and morphodynamics
- K-model for wave transformation

In addition, a model using the Delft3D method is operated. The model was used for the environmental impact assessment studies in the approval procedure for the construction of the JadeWeserPort, for the fairway adaptations of the Outer and Lower Weser and for the expansion of the Wilhelmshaven power plant capacities. The validation of the model was done on the basis of comprehensive field measurements. With the BAW software for post-processing, further parameters (e.g. duration of flooding, tidal range, mean and maximum ebb and flood tide velocity, residual flow etc.) were generated in a so-called tidal parameter analysis and permit a substantiated description of the behaviour of and/or any changes within the hydrodynamic and morphodynamic system. This also includes visualization and animation of results (e.g. water level and flow velocity in the tidal dynamics).

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