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HARBASINS Report:

# Comparison of the hydrodynamic regime of 1937 and 2005 in the Ems-Dollard estuary by applying mathematical modeling

Prepared by: Gerald Herrling and Hanz D. Niemeyer
**Lower Saxony Water Management,**
**Coastal Defence and Nature Conservation Agency**
**- Coastal Research Station -**

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Authors:
Gerald Herrling
Hanz Dieter Niemeyer

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# 1 Introduction

In coastal areas and particularly in estuaries or areas such as the Wadden Sea, there is a lack of straightforward procedures for the objective identification of 'Heavily Modified Water Bodies' (HMWB) according to the water framework directive (WFD) of the European Community. The aim of the investigation is to identify such areas using the application of hydrodynamical and morphodynamical models as basis for the evaluation of comparable assessment criteria.

The aim of work package 4 ("Hydro- and Morphological Pressures and Impacts") within the HARBASINS project is to generate process-based knowledge on these effects by high-resolution mathematical modelling in combination with the analysis of hydro- and morphodynamical parameters. Ultimately, it is intended to establish a modelling strategy to identify the spatial scale of potential HMWBs.

The Ems-Dollard estuary covering the area from the East Frisian Islands as far upstream as the tidal barrier at Herbrum in the Lower Ems is selected as the study area for this purpose.

To identify waterbodies that had experienced significant changes in their tidal regime due to human interferences, it seems reasonable to compare prevailing hydrodynamical parameters to those of historical states. But continuous current measurements of historical states hardly exist or are temporally and spatially delimited in most cases.

For this reason, the hydrodynamic regimes in the Ems-Dollard estuary respectively prior and after the main anthropogenic impacts, i.e. streamlining and deepening of the Lower Ems, are modelled by applying on the one hand the bathymetry of the year 2005 and on the other hand the reconstructed bathymetry due to data of the period between 1923 and 1952. The aim is to evaluate and compare the physical parameters, e.g. current velocities and tidal volumes. Significant changes between the mentioned states can then be assessed with respect to the ecological impact in further studies.

The preceding HARBASINS reports "Set-up of a hydrodynamic model of the Ems-Dollard Estuary" (HERRLING, NIEMEYER 2007b) and "Reconstruction of the historical hydrodynamic state of the Ems-Dollard estuary prior to significant anthropogenic changes by applying hydrodynamic modelling" (HERRLING, NIEMEYER 2007c) describe the set-up of the hydrodynamic model respectively for 2005 and 1937. This report focuses on the changes of tidal regime between those model states.

Both regimes are compared by applying mean hydrodynamic flow conditions. Differences in calculated flow conditions result from anthropogenic interferences in the system geometry superimposed by natural developments, i.e. the secular sea level rise. Changes in hydrodynamic regime are evaluated considering relevant physical parameters as the water levels, tidal discharges through cross-sections, duration of tidal current phases, current magnitudes and directions and tidal volumes.

## 2 Area of investigation

The investigated area covers the entire Ems-Dollard estuary and is situated on the Dutch-German North Sea coast. The seaward limit is at the 20 meter depth-line beyond the East Frisian Islands in the outer estuary (Fig. 1). The landward limit is at the tidal barrier at Herbrum in the Lower Ems. In the year 1898 this tidal barrage was built for navigational purposes at about 50 km upstream of the Dollard Bay.

The study area is marked by all geomorphological features characteristic for this type of coastline: deep tidal channels and inlets, intertidal flats and the inner estuarine environment.

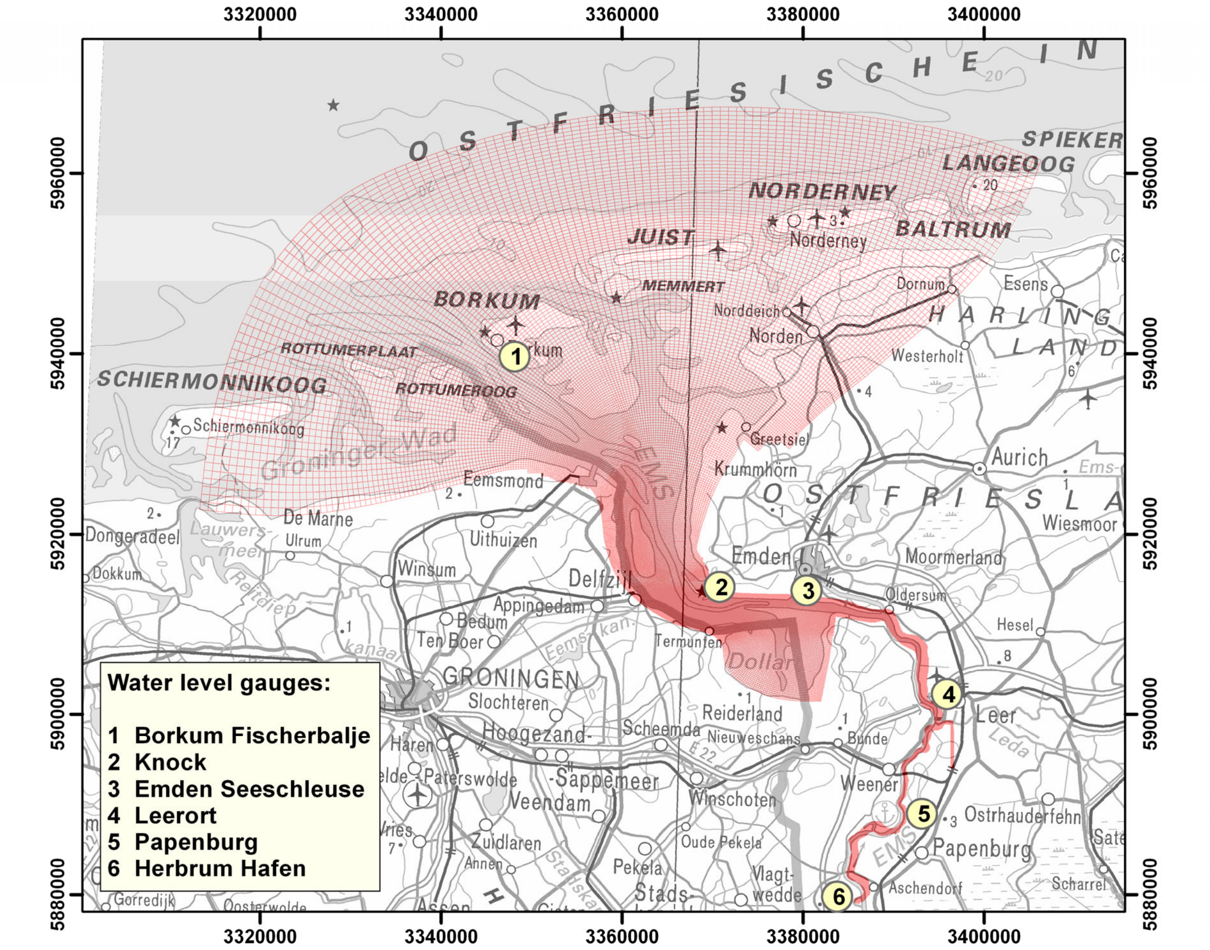

**Fig. 1: Area of investigation (numerical grid extent) and water level gauges**

# 3 Chronology of the main human impacts in the Ems-Dollard estuary

The Ems-Dollart estuary has been impacted by human alterations from the 16th century. The period between the 17th and the 20th century is marked by dykening and land reclamations in the Dollard Bay (Herrling & Niemeyer 2007). By end of the 19th century groins, harbours and other measures for the purpose of navigation were built in the Lower Ems and the Emder Fairway. Since the 1950s, the maintenance dredging of the navigational channel by suction dredging becomes common practice. Since the beginning of the 1980s, the waterway as far upstream as Papenburg, where the Meyer ship waft is located, was dredged frequently to allow the transfer of huge cruise ships to the open North Sea once their construction has been finished. For this event, the flood tidal barrier at Gandersum is closed in order to retain and raise the landward water level with the aim to improve the clearance of the cruise ships.

**Tab. 1: Chronology of the main measures in the Ems-Dollard estuary**

| Year | Measure or event | Source of information |
|---|---|---|
| 1583 to 1631 | Measures to redirect the flow of the Ems in a northern meander of the Nesserland to maintain the access to the harbour of Emden | BREUER, 1965 |
| 17th century until 1924 | Land reclamations by poldering and dykening in the Dollard Bay | HOMEIER, 1962 |
| 1860 | Start of canalization of the Lower Ems | BfG-1100, 1999 |
| 1870/ 1871 | Construction of 13 rubble mounted groynes on the Geise sand bank | BfG-1100, 1999 |
| 1876 | Sluice Nieuw Statenzijl | STEEN, 2003 |
| 1896 -1900 | Construction of a rubble mounted connection between the existing groynes on the Geise sand bank | BfG-1100, 1999 |
| 1892 - 1899 | Breakthrough of meandering river arms at Rhede and Tuxdorf (upstream of Papenburg) | Zeitschrift für Bauwesen (1902) |
| 1897 - 1899 | Construction of first weir at Herbrum | Zeitschrift für Bauwesen (1902) |
| 1898 | Dredging of the East Frisian tidal inlet | ALKYON, 2007 |
| 1907 | Watergate Nieuw Statenzijl | STEEN, 2003 |
| 1911 | Breakthrough at Mark | WSA Emden, 1990 |
| 1912 - 1924 | Claim of mudflats and the construction of the seadyke between Emden and Knock | SCHUBERT, 1970 |
| 1925 | Breakthrough of meandering river arm at Pottdeich | WSA Emden, 1990 |
| 1928 | Breakthrough of meandering river arm at Coldam | WSA Emden, 1990 |
| 1911 - 1929 | Waterway depth:<br>4.8 – 5.0 m below MTHW between Emden and Leerort | Historical maps of the Lower Ems with soundings (source: |

| | | |
|---|---|---|
| | 4,0 – 4.5 m below MTHW between Leerort and Papenburg | WSA Meppen) |
| 1930 - 1935 | Extention of the Geise training wall towards its western end (Geiseweststeert), construction of three groins on the opposite side of the channel | STEEN, 2003 |
| 1932 | Stabilization of the waterway by a bended training wall at Knock | SCHUBERT, 1970 |
| 1932 – 1939 | Channel maintenance between<br>a) Papenburg and Leerort at 4.10 m below MHWL<br>b) Leerort and Pogum at 5.50 m below MHWL | Historical maps of the Lower Ems with soundings (source: WSA Meppen) |
| 1958 - 1961 | Construction of 2.2 km long training dam “Seedeich” and 12 km Geise training wall from Pogum to Geisesteerwert and 17 new groynes | STEEN, 2003 |
| 1961 - 1962 | Narrowing of the river bed to the width between the heads of the former groins on the section between Herbrum and Papenburg | Personal communication, WSA Meppen |
| 1972 | Construction Sea harbour channel Delfzijl, end of dredging Bocht van Watum | ALKYON, 2007 |
| 1973 | Construction of deep-sea-port Eemshaven | |
| 1984 - 1990 | Streamlining of the river curve radius at the Bight of Weekeborg and the Bight of Stapelmoor by about 400m each | WSA Emden |
| 1985/1986 | Waterway depth in the Lower Ems of 5.7 m below MTHW | WSA Emden |
| 1992 | Waterway depth in the Lower Ems of 6.3 m to 6.8 m below MTHW | WSA Emden |
| 1991 | New sluice and watergate at Nieuve Statenzijl | STEEN, 2003 |
| 1994 | Waterway depth in the Lower Ems of 7.3 m below MTHW | WSA Emden |
| 2002 - 2003 | Construction of the storm surge barrier at Gandersum | |

# 4 Changes in tidal water levels

For at least 70 years there have been regular registrations of the tidal water levels along the Ems-Dollard estuary. Within this period the tidal range has significantly increased as an effect of anthropogenic interferences in the estuarine morphology and geometry.

Based on water level records, the historical trends of yearly Mean High Water Levels (MHWL), Mean Low Water Levels (MLWL) and Mean Tidal Ranges (MTR) are evaluated for the gauge locations Borkum Suedstrand, Knock, Emden, Leerort, Papenburg and Herbrum (Fig. 2 to Fig. 4). The increase of MHWL and the decrease of MLWL is more pronounced in the Lower Ems (Leerort, Papenburg, Herbrum), where the fairway had been deepened for navigational purposes. The changes appear to be less significant in the outer estuary (Borkum, Knock, Emden), where both, MHWL and MLWL have slightly increased due to the superimposed effect of the secular sea level rise.

At the beginning of the water level registrations in the 1930s, the mean tidal range in the Ems-Dollard estuary had a bandwidth between 2.2 m at the island of Borkum increasing to its maximum of 3.0 m at Emden and decreases upstream to 1.0 m at the tidal border at Herbrum. The actual mean tidal range is at 2.3 m at Borkum increasing to the maximum of 3.5 m at Papenburg and decreases to 2.7 m at Herbrum. The total increase of the mean tidal range over the last 70 years is 0.09 m (4%) at Borkum, 0.22 m (7%) at Emden, 0.99 m (41%) at Leerort, 1.79 m (105%) at Papenburg and 1.73 m (175%) at Herbrum. The changes of respectively MHWL, MLWL and MTR are evaluated for a period of about 70 years from 1933/1937 (begin of observations) to 2001/2005 (actual situation) for several gauges along the estuary (Tab. 2).

In a non-modified estuarine system, the tidal range decreases gradually in the upper part due to the energy dissipation depending on the resistance of the morphology against the propagating tidal wave. During the last decades, the deepening and streamlining of the waterway in the upper estuary caused significant changes of the tidal regime. The cross-sectional extension and smoothing due to dredging activities in the waterway reduced the hydraulic resistance of the system and led to a concentration of the tidal energy on the navigational channel. As a consequence the tidal range increased.

**Tab. 2: Changes of MHWL, MLWL and MTR evaluated for a period of about 70 years**

| | MHWL [mNN] (1933-1937) | MHWL [mNN] (2001-2005) | Change of MHWL [m] |
|---|---|---|---|
| **Borkum S.** | 0.87 | 1.07 | +0.20 |
| **Emden** | 1.27 | 1.49 | +0.22 |
| **Leerort** | 1.40 | 1.76 | +0.36 |
| **Papenburg** | 1.41 | 1.88 | +0.47 |
| **Herbrum** | 1.70 | 1.98 | +0.14 |

| | MLWL [mNN] (1933-1937) | MLWL [mNN] (2001-2005) | Change of MLWL [m] |
|---|---|---|---|
| **Borkum S.** | -1.31 | -1.20 | +0.11 |
| **Emden** | -1.74 | -1.74 | +0.00 |
| **Leerort** | -1.03 | -1.66 | - 0.63 |
| **Papenburg** | -0.30 | -1.62 | - 1.32 |
| **Herbrum** | 0.71 | -0.74 | - 1.45 |

| | Mean tidal range [m] (1933-1937) | Mean tidal range [m] (2001-2005) | Change of mean tidal range [m] |
|---|---|---|---|
| **Borkum S.** | 2.18 | 2.27 | +0.09 |
| **Emden** | 3.01 | 3.23 | +0.22 |
| **Leerort** | 2.43 | 3.42 | +0.99 |
| **Papenburg** | 1.71 | 3.50 | +1.79 |
| **Herbrum** | 0.99 | 2.72 | +1.73 |

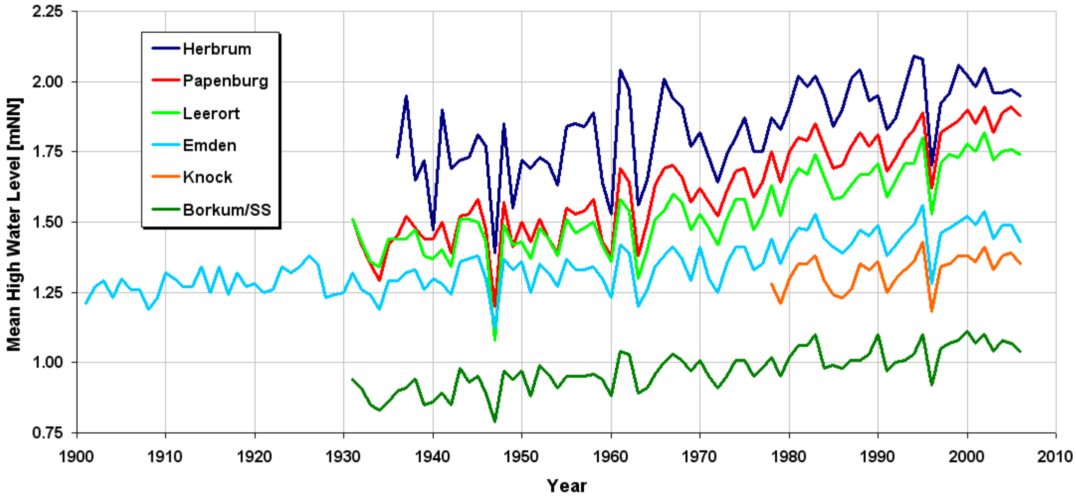

Fig. 2: Historical trend of yearly Mean High Water Levels (MHWL) at gauges along the Ems-Dollard estuary

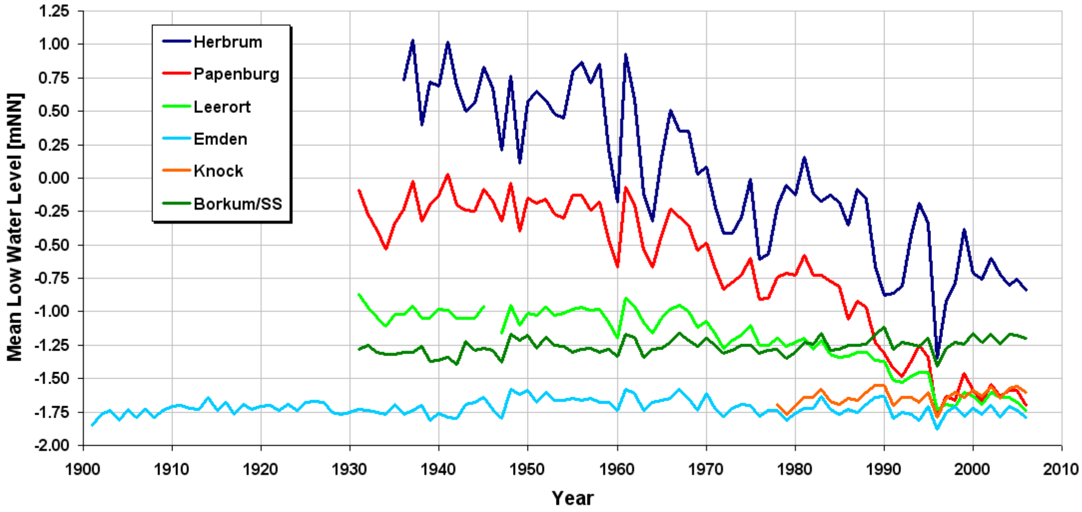

Fig. 3: Historical trend of yearly Mean Low Water Levels (MLWL) at gauges along the Ems-Dollard estuary

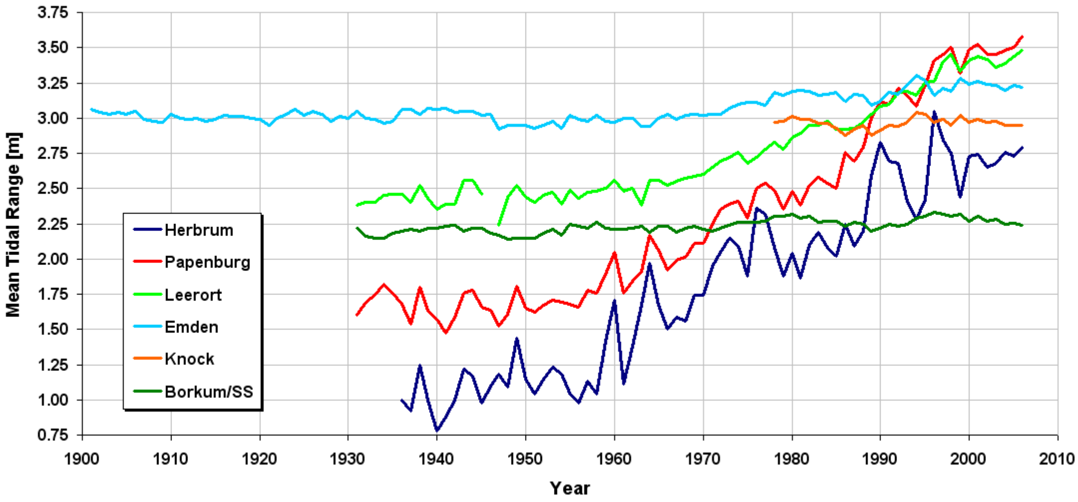

Fig. 4: Historical trend of yearly Mean Tidal Ranges (MTR) at gauges along the Ems-Dollard estuary

# 5 Comparison of model configurations for the state of 1937 and 2005

Information on the set-up, calibration and validation of each hydrodynamical model representing bathymetric configurations of 1937 and 2005 is found in the detailed reports with respect to the model set-up (Herrling & Niemeyer 2007b, 2007c). Hereafter, the model configurations, i.e. the model bathymetry, the offshore and riverine boundary conditions and the bottom roughness schematization are summarized and compared for the mentioned model states.

## 5.1 Comparison of model bathymetries

Bathymetries are interpolated on a numerical grid with curvilinear grid lines. The bathymetrical resolution is in the order of 800 meters offshore, 100 meters in the Dollard Bay and up to 15 meters in the Lower Ems. The bottom depth schematization of both states ranges from a maximum of about 25 meters below NN in the tidal inlets and offshore to an elevation of about 9 meters over NN along the main dyke (Fig. 5 and Fig. 6).

The river Leda, a tributary stream of the Ems is schematized in both bathymetrical states up to the tidal limit by a rectangular channel. Reason for this schematization was the exceedance of the maximal number of computational points. The extension and the total volume of the channel are approximated by considering the representative tidal prism of about 3 millions cubic meters.

Historical marine charts of the years 1923, 1926, 1941 and 1952 were used to reconstruct the historical model bathymetry in the outer estuary and the Dollard Bay. In the outer estuary, the spatial density of original depth information is rather low at the center of the intertidal flats and sand banks in comparison to a high density of data available at the margins of the tidal plains and the adjacent tidal channels. The interpolation of unequally distributed depth points on the numerical grid yields to a rather low elevation of the center of the tidal flats.
In the Lower Ems cross-sectional survey data at a distance of about 300 to 400 meters were available for 1927 and 1933. The area in between the cross-sections was reconstructed by interpolating linearly along the flow-directed grid lines.

Data of topographical surveys of the years 2004 and 2005 is used to establish the model bathymetry of the present state. Data of soundings were available for the sub- and intertidal areas in the outer estuary and the waterway, whereas airborne laser-scanning was used for the inter- and supratidal areas in the inner estuary.

Comparing the model bathymetry of 1937 and 2005 with the naked eye, it is not evident to identify morphological changes. In order to highlight morphological alterations between the mentioned states, the model bathymetries were subtracted from each other. The difference, plotted for the area of the transitional waters of the estuary between Eemshaven and Pogum, allows distinguishing areas that experienced a deepening (blue) or an accretion (red) relative to the historical state (Fig. 7). The main tidal inlet upstream of Eemshaven, the East Frisian Tidal Inlet, became predominantly deeper and more streamlined with respect to the tidal inlet of 1937. On the other hand, the Bight of Watum, the smaller, westerly tidal inlet that had still contributed to the exchange of the tidal prism in 1937, almost silted-up. Intertidal plains in the Dollard Bay accreted, whereas tidal channels and the Emder Fairway became deeper. The Deep-Sea-Harbor at Eemshaven was constructed in the beginning of the 1970s.

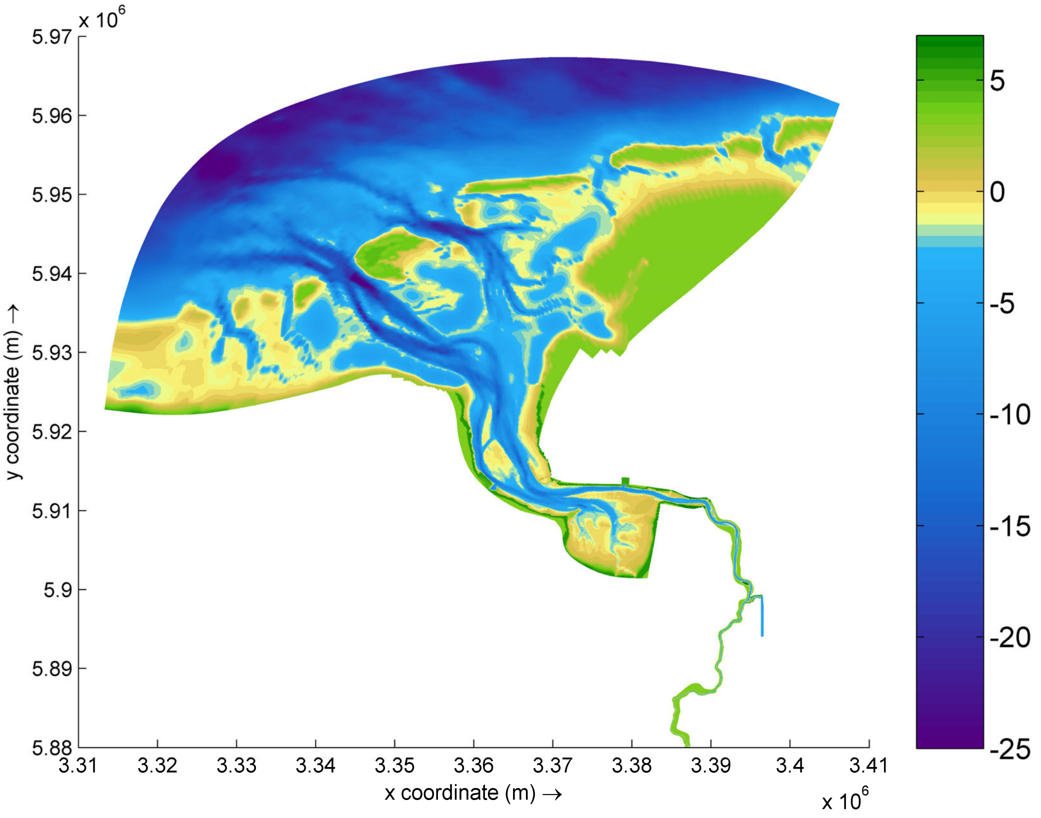

**Fig. 5: Reconstructed bathymetry applied for the model state of 1937 [m NN]**

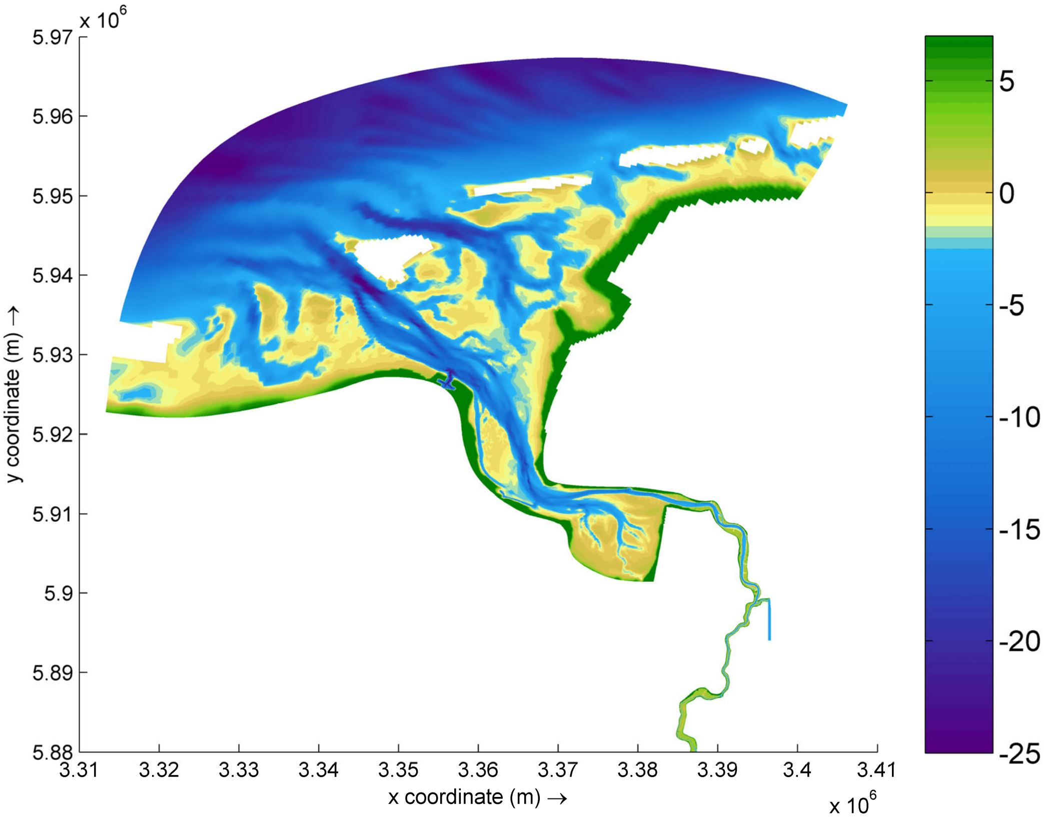

**Fig. 6: Bathymetry applied for the model state of 2005 [m NN]**

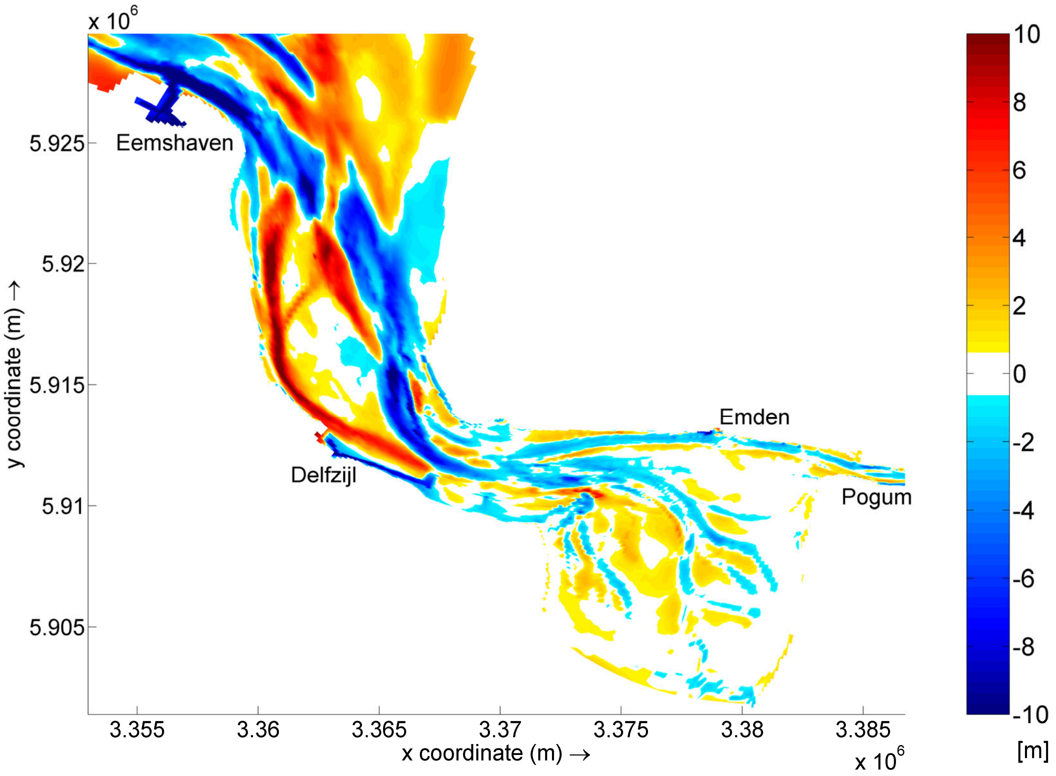

**Fig. 7: Net deepening (blue) and net accretion (red) between the bathymetrical states of 1937 and 2005 in the transitional waters between Pogum and Eemshaven**

## 5.2 Model boundary conditions

Hereafter the boundary conditions are selected that way to generate mean hydrodynamical flow conditions allowing the comparison of the computed tidal regimes of both mentioned model states. The aim is to reproduce an average tide, a tide with mean high water level (MHWL) and mean low water level (MLWL), which is in tune with mean water level observations, respectively of the situation in 1937 and 2005. Apart of the generation of a mean tide at the offshore boundary, the run-off at the upstream riverine boundary is tuned in order to match long-year mean discharges.

### 5.2.1 Offshore boundary

To allow a comparison of mean hydrodynamical flow conditions in the estuary, the model is forced with a representative mean tide at the offshore boundary. The tidal peaks of the representative mean tide of the model state of 1937 are supposed to match with MHWLs and MLWLs that were observed over the years 1933 to 1937, whereas the representative mean tide of the model state of 2005 is selected matching with MHWLs and MLWLs of the period of 2001 to 2005.

From a time series of two month of modeled water levels, the one tide was selected to be the representative mean tide fitting best at its peaks with MHWL and MLWL. The model simulation of mean flow conditions based on that mean tide is then evaluated with respect to the relevant hydrodynamic parameters, i.e. mean tidal volume.

The selected representative mean tides are from June 25th 1937 at 09:00 p.m. to June 26th 1937 at 09:11 a.m. and from July 7th 2005 at 08:00 p.m. to July 8th 2005 at 08:12 a.m., respectively for the model state of 1937 and 2005. As one could expect, both selected tides fall in the time period between spring and neap tide.

### 5.2.2 Upstream riverine boundary

The quantity of the freshwater discharge has a significant influence on the water levels and flow velocities in the Ems, especially in the upper part of the Lower Ems between Herbrum and Papenburg, where the cross-sectional area of the stream is still relatively small. In order to compare mean flow conditions of both mentioned model states the imposed discharges have to match with long-year mean discharges. Data show that yearly mean discharges of the Ems tend to be very similar over the last century. Thus, the mean discharges are set to be identical for the model state of 1937 and 2005.

Long-year mean discharges of Ems, Leda and Westerwoldsche Aa are respectively 81, 25 and 6 m³/s. These are arithmetic averages of flow discharges. But in case of the Ems, discharges can vary between mean minima of 16 m³/s and mean maxima of 376 m³/s according to the analysis of long time series (German Yearbook of Hydrology, 2002). Considering arithmetic averages, few events of high discharge might raise the mean value significantly.

Considering the 50 percent non-exceedence-probability (or median) based on a time series from 1941 to 2002 (German Yearbook of Hydrology, 2002), the discharges in the Ems are smaller than 55.7 m³/s at 183 days of a year. In contrast to the arithmetic average, the median is less sensitive to outlier criterions, i.e. extreme values. For this reason, it is assumed that the 50 percent non-exceedence-probability (median) is more suitable for this analysis.

But the long-term median discharge is not available for the discharges of Leda and Westerwoldsche Aa. It is assumed that the ratio of the median discharge to the arithmetic average discharge of the Ems (55.7 / 81 = 0.69), is applicable for the Leda and the Westerwoldsche Aa. The outcomes are median discharges of 17 and 4 m³/s, respectively for Leda and Westerwoldsche Aa.

The discharges of the Ems are recorded at Versen in the Upper Ems, which is located about 40 km upstream of the tidal barrier at Herbrum. Hence, discharge contributions of run-offs between Versen and Herbrum are not included. The Waterway Agency in Meppen (WSA Meppen) estimates the additional discharge contributions of about 10 percent of the recorded quantity of discharge at Versen. Taking these contributed quantities into account, the median discharge at the tidal barrier at Herbrum is about 61 m³/s (55.7 m³/s x 1.10 = 61.3 m³/s).

## 5.3 Comparison of the bottom roughness schematization

In the framework of the set-up of the historical and the actual model state, the bottom roughness has been adapted and calibrated separately for each state in order to achieve global agreement between modeled and observed water levels along the estuary.

Comparing the spatially varying bottom roughness values between the model states, it turned out that both bottom roughness schematizations are generally similar in the outer estuary and on the intertidal flats, whereas in the Emder Fairway and along the Lower Ems the bottom roughness of the actual state is to some extent reduced. For the section from Herbrum to the Knock, the overall mean differences between the bottom roughness schematizations of 1937 and 2005 are in the order of 0.005 with respect to the Manning formulation, accordingly by a value of 30 referred to the formulation after Chézy.

# 6 Comparison of hydrodynamical parameters between the state of 1937 and 2005

This chapter is dedicated to the results gained from hydrodynamical models with bathymetric configurations of respectively 1937 and 2005. The model results enable a quantitative comparison of the hydrodynamic regimes and thus of the changes occurred.

In the Lower Ems, the comparison of hydrodynamical parameters is assessed at one specific location (km 35) and at a longitudinal section from the tidal barrier at Herbrum to the Dollard Bay. In the outer Ems, a spatial comparison of current velocities shows the differences in flow regime.

## 6.1 Comparison of hydrodynamical parameters at one specific location in the Lower Ems

Computed hydrodynamical parameters are compared at kilometer 35 (counted downstream from the tidal barrier) in the Lower Ems for the period of one tidal cycle, representing mean tidal conditions respectively for 1937 and 2005. The purpose of this comparison is to highlight the changes of tidal regime in the time domain. The observation point is located about 5 kilometers upstream of Terborg on a straight stretch in order to avoid fluctuations in current velocities due to secondary flows or sudden channel constrictions.

Time series of water levels [m NN] and current velocities [m/s] are compared for mean flow conditions, respectively for 1937 and 2005 (Fig. 8). Generally, the tidal range and the current velocities of the model state of 2005 have increased with respect to the situation of 1937. Nowadays, the tidal curve is significantly broader at high tide with a steepened flood and ebb phase section. Flood current velocities have significantly increased for the first part of the flood phase. In the given cross-section and generally in the Lower Ems, the overall tendency is towards a flood-dominated tidal flow (see also 6.2.2).

The time series of the momentary tidal discharges and related hydrodynamical parameters are respectively computed for 1937 and 2005 due to the cross-sectional flow at kilometer 35 for one mean tidal cycle (Fig. 9 and Fig. 10).

The mean tidal volume or tidal prism [m³] is determined as the mathematical product of the mean tidal discharge [m³/s] and the mean current phase duration [h], respectively for ebb and flood tides:

$V_e = Q_e * T_e$ ( → flood tidal volume $V_f$ is determined analogously)

with: $V_e$ = ebb tidal volume [m³]
$Q_e$ = ebb tidal discharge [m³/s]
$T_e$ = ebb current phase duration [h]

Both, momentary mean discharges and mean tidal volumes have increased from 1937 to 2005, whereas the mean tidal phases have remained almost constant in time, respectively for ebb and flood tides. The mean tidal discharge computed as the arithmetical averages over one tidal phase has increased of 811 to 1394 m³/s (72%) for flood tide and of 717 to 1114 m³/s (55%) for ebb tide. The mean flood tidal volume $V_f$ has increased by about 73% of

14.8 to 25.6 Mill. m³, whereas the mean ebb tidal volume $V_e$ has increased by approximately 55% of 18.4 to 28.5 Mill. m³.

The before mentioned hydrodynamical parameters being highlighted exemplarily for one single cross-section are evaluated in the following chapter along a longitudinal-section in the Lower Ems.

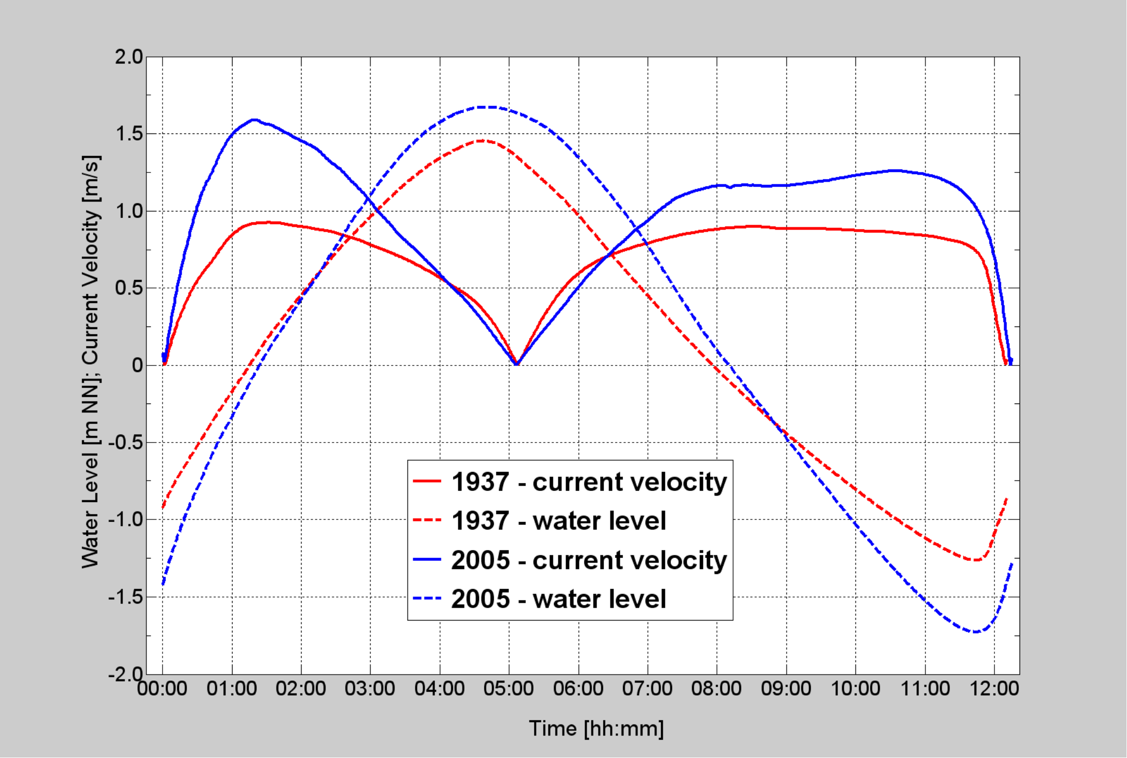

**Fig. 8: Water levels and current velocities at kilometre 35 downstream of the tidal barrier at Herbrum in the Lower Ems for the model state of 1937 and 2005**

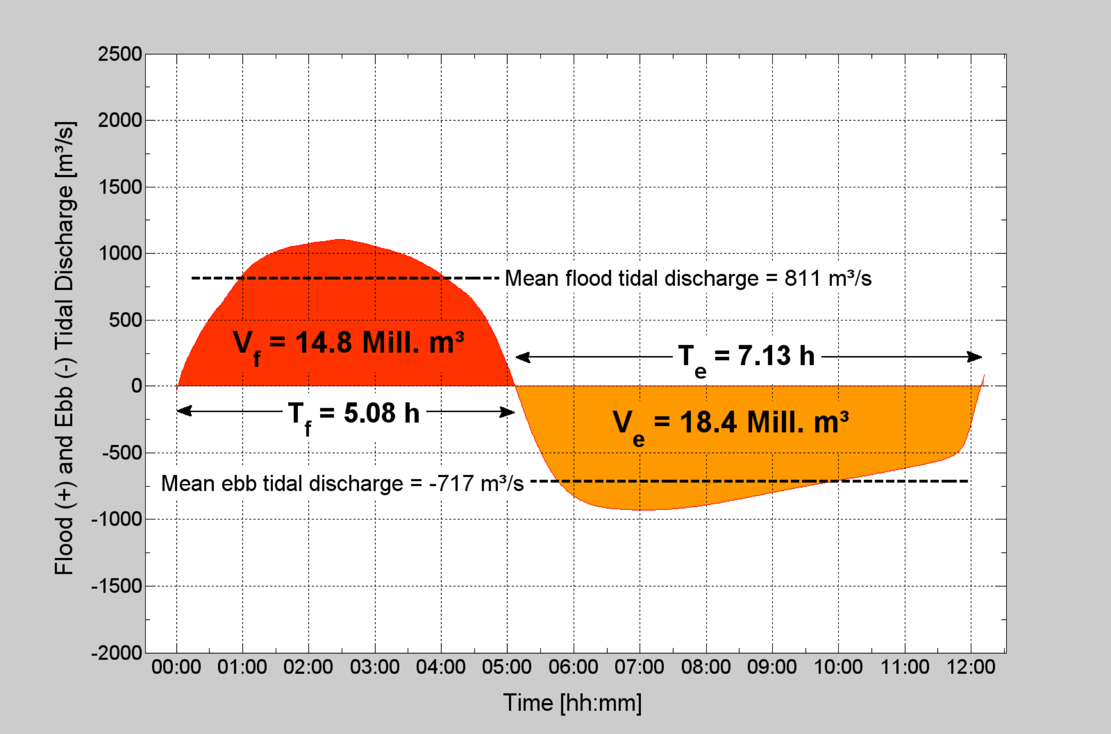

**Fig. 9: Mean tidal volume and tidal discharge computed for the cross-section at kilometre 35 downstream of Herbrum applying the model state of 1937**

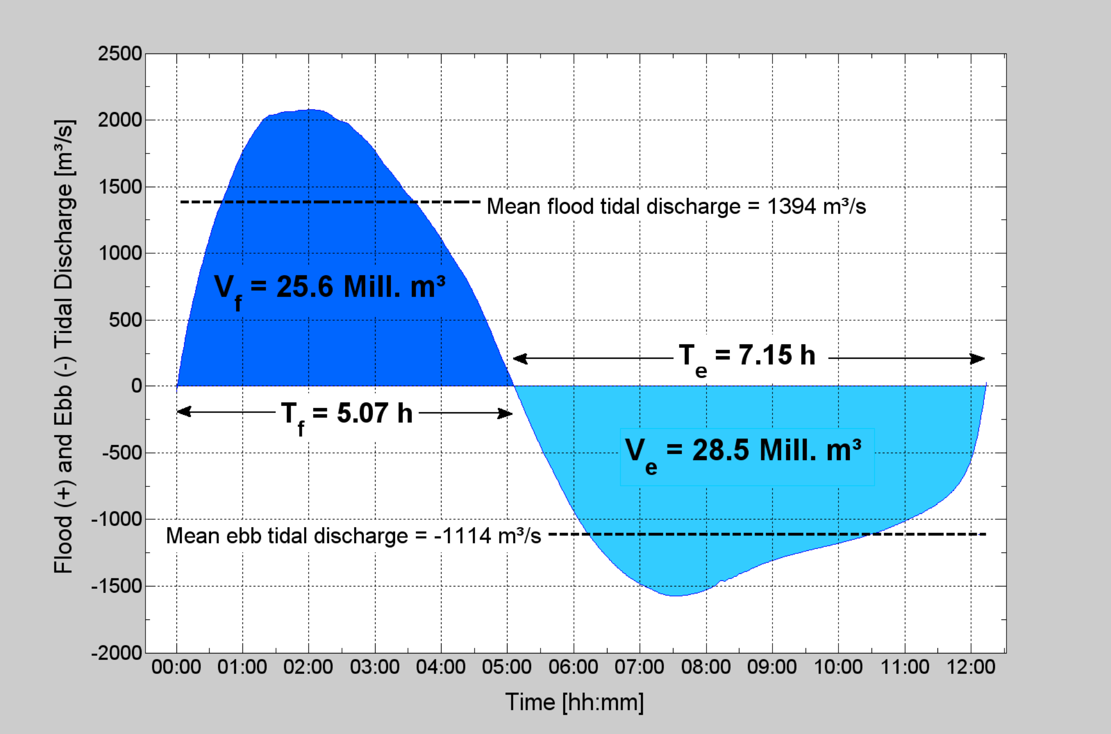

**Fig. 10: Mean tidal volume and tidal discharge computed for the cross-section at kilometre 35 downstream of Herbrum applying the model state of 2005**

## 6.2 Comparison of hydrodynamical parameters at a longitudinal section in the Lower Ems

Hereafter, the computed results of hydrodynamic models for the state of 1937 and 2005 are compared at the longitudinal section from the tidal barrier at Herbrum downstream to the Dollard Bay. Differences of hydrodynamical parameters as mean water levels, mean and maximal tidal discharges, mean tidal current phases and the mean tidal volume are evaluated and quantified.

Modeled tidal discharges and volumes are monitored through cross-sections along the mentioned stretch at the distance of one kilometer each. Water levels and depth averaged current velocities are computed at observation points every kilometer along the centerline of the waterway, thus at about the deepest part of each previously mentioned cross-section.

Tidal discharges and volumes can only be properly determined as far downstream as Pogum. Further downstream, where the Lower Ems discharges in the Dollard Bay, it is not evident to set the width of the cross-section, because water masses are flooding sideways over the Geise training wall into the Emder waterway and vice-versa. This almost circular flow pattern is different from the directed flow in a channel and thus not comparable with the parameters evaluated in the Lower Ems.

There is a significant increase of respectively the tidal discharges and the tidal volumes at Leerort, which can be ascribed to the freshwater discharge that is contributed of the river Leda.

### 6.2.1 Mean water levels

Observed and computed mean water levels (MHWL and MLWL) are compared on the longitudinal section from the tidal barrier at Herbrum to the location Knock at about 67 kilometers downstream (Fig. 11). MHWL and MLWL of the state of 1937 (red) are plotted against those of 2005 (blue). Computed values are due to the simulation of one representative mean tide, respectively for 1937 and 2005. Observations are based on time series of a 5-year-period, respectively of 1933 to 1937 and 2001 to 2005, with an exception of the historical observations at Herbrum being available only for the period starting from 1936 until 1940.

The differences between the modeled and the observed values are in the order of 5 to 10 centimeters. Thus the amplitude of the tidal wave propagating upstream is reproduced satisfactorily for both model states.

At Emden, the observed MLWLs, both for the present and the historical situation, are exactly at the level of -1.74 m NN (the red cross is exactly on top of the blue cross). There is evidence to suggest that Emden is the location where the decrease of the MLWL, as the effect of the waterway deepening and streamlining, is leveled out against the increase of the MLWL due to the secular sea level rise. This implication is very well reproduced by the models; the MLWL-lines of both model states intersect exactly at Emden.

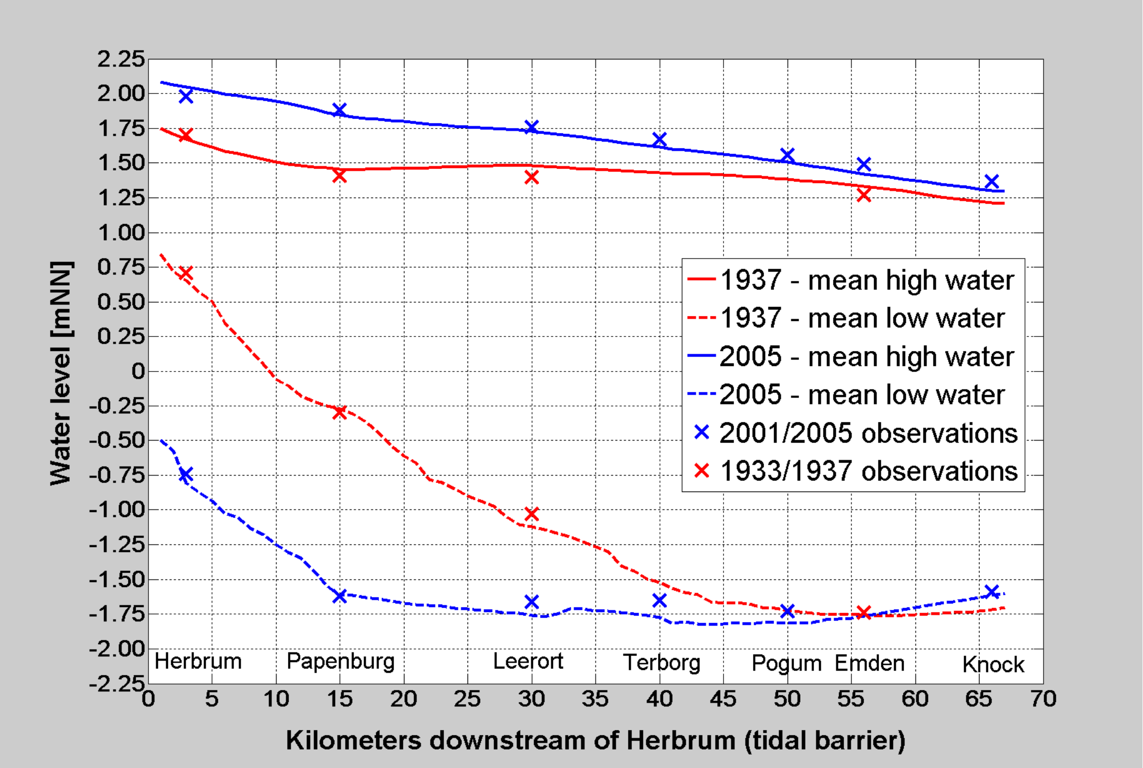

**Fig. 11: Modeled and observed MHWL and MLWL along a longitudinal section between Herbrum and Knock respectively for the model state of 1937 and 2005**

### 6.2.2 Mean and maximal tidal discharges

The tidal discharge is determined as the momentary flow [m³/s] recorded with an interval of one minute through cross-sections at every kilometer on the section between Herbrum and Pogum. The mean tidal discharge is the arithmetical average of the recorded momentary flows over the period between two subsequent slack-tides, respectively for ebb- and flood-directed currents (Fig. 12). The maximal tidal discharge is evaluated as the peak flow during respectively ebb and flood tidal current phases (Fig. 13).

Both, ebb and flood tidal discharges have significantly increased since 1937 for the whole section.

Although the freshwater discharge counteracts the flood tidal flow, the mean flood tidal discharge is higher than the mean ebb tidal discharge respectively at the section between Leerort and Pogum for the historical state and between kilometer 17 and Pogum for the state of 2005. In this context one has to bear in mind that the flood current phase is significantly shorter than the ebb current phase and thus the equilibrium of the estuarine in- and outflow is maintained (see 6.2.3).

Considering the section between Leerort and Pogum, the net difference between mean ebb and mean flood discharge is in the order of 100 m³/s for the state of 1937 compared to 300 m³/s for 2005, whereas the duration of the tidal phases did not change significantly between both model states. This circumstance is to be regarded as an evidence for the increase of the tidal asymmetry with respect to the state of 1937.

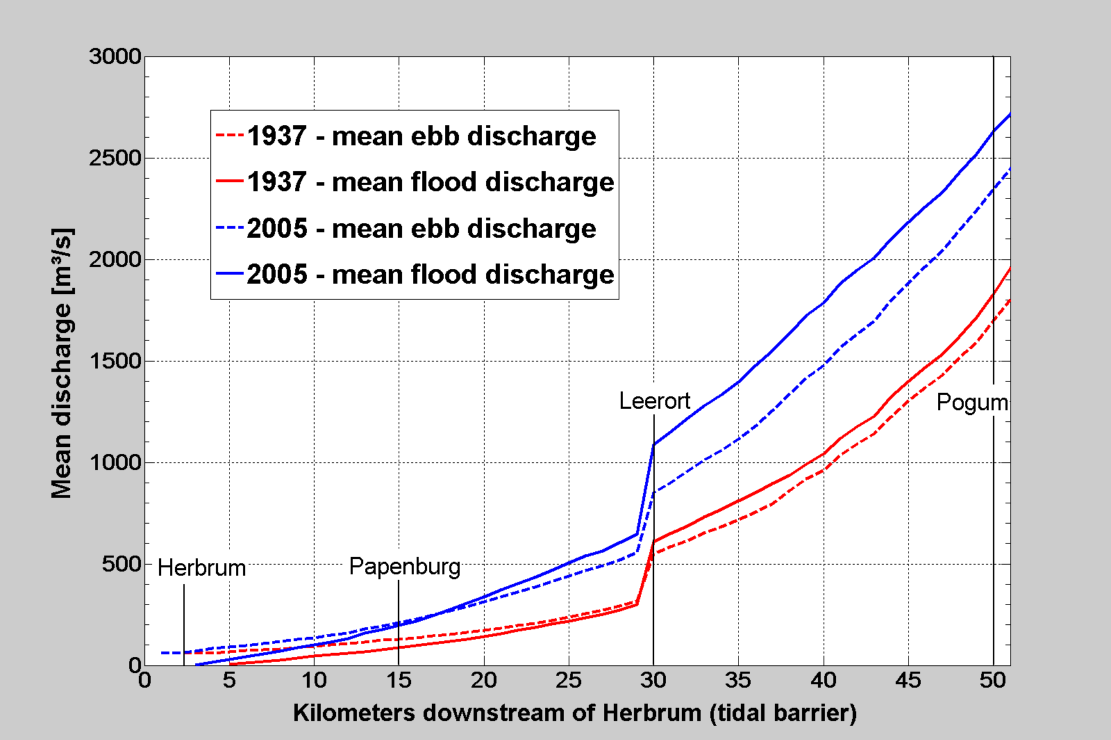

Fig. 12: Comparison of mean tidal discharges in the Lower Ems between the model state of 1937 and 2005, respectively for flood and ebb tide

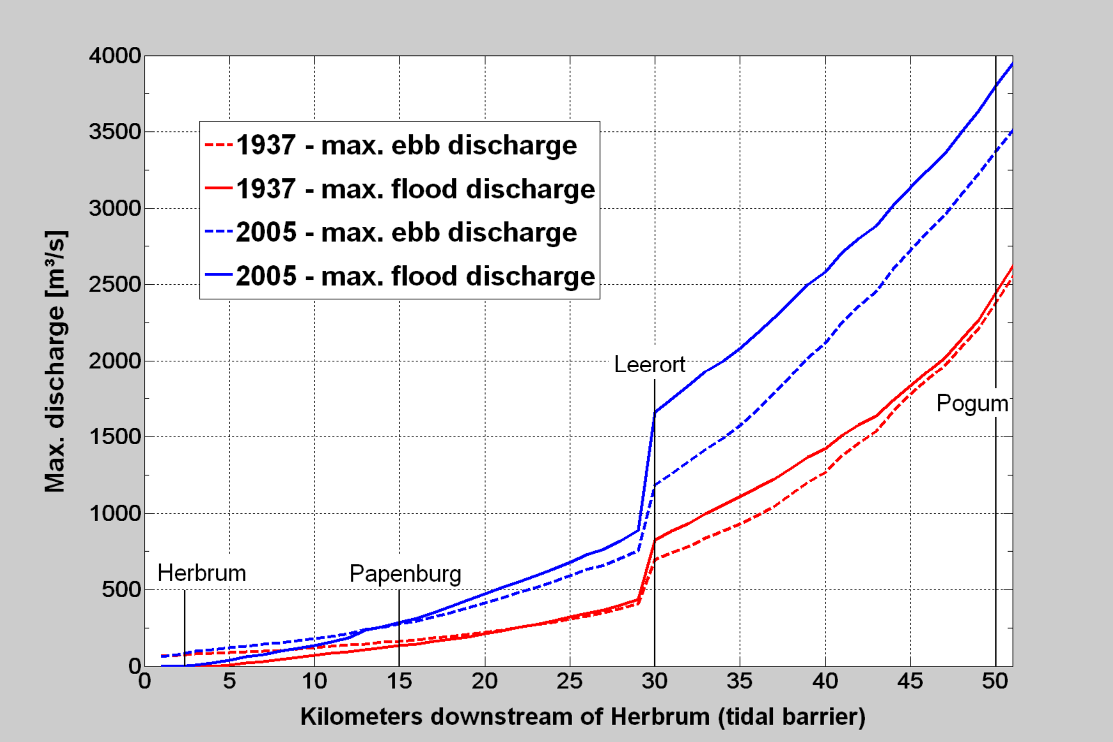

Fig. 13: Comparison of maximal tidal discharges in the Lower Ems between the model state of 1937 and 2005, respectively for flood and ebb tide

### 6.2.3 Mean tidal current phases

The mean tidal current phases are determined as the duration [h] between two slack-tides, respectively for ebb and flood tide (Fig.14).

The mean flood current phase is generally shorter than the mean ebb current phase with decreasing trend towards the upper part of the estuary. At the tidal limit close to Herbrum, the duration of the flood current phase is zero, whereas the duration of the ebb current phase is about 12.4 hours – one complete tidal cycle.

On the section between Herbrum and Leerort, the duration of the mean flood current phase is significant longer for the present situation compared to 1937 (e.g. about 45 min at Papenburg). As the duration of one complete tide is fixed to 12.4 hours, consequently the mean ebb current phase has to be shorter by the same extent nowadays.

Downstream of Leerort almost no differences occur in the duration of the mean current phases between the present and the historical state.

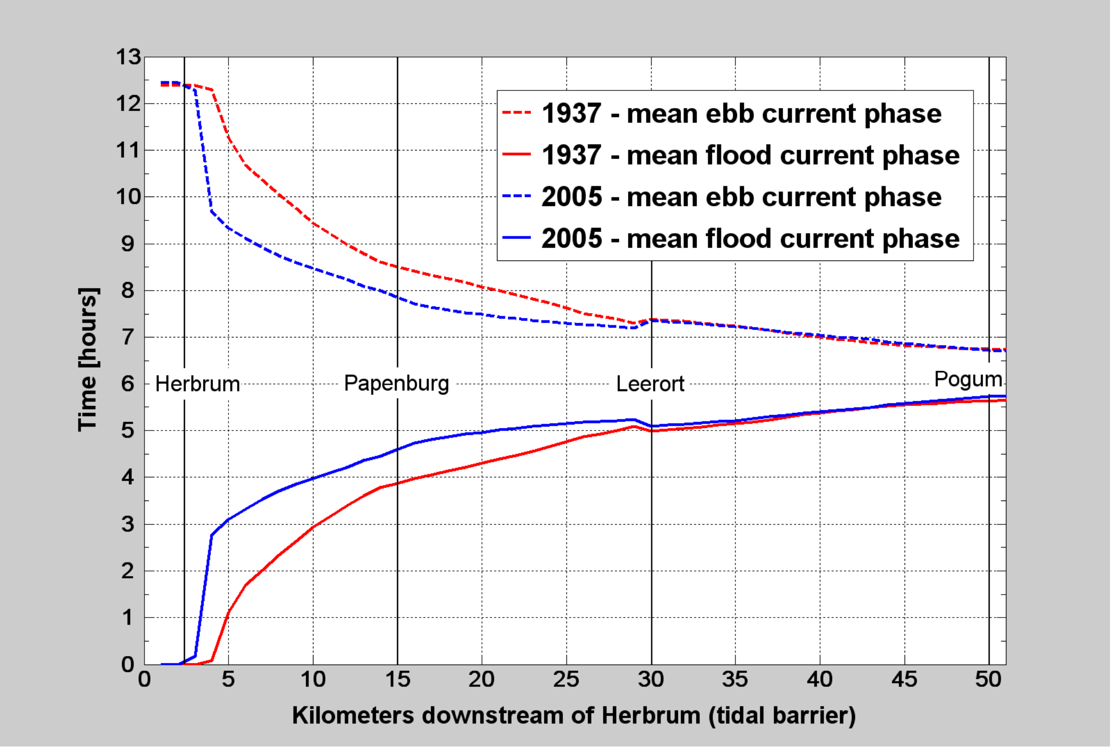

**Fig. 14: Comparison of mean tidal current phases in the Lower Ems between the model state of 1937 and 2005, respectively for flood and ebb tide**

### 6.2.4 Mean tidal volume

The mean tidal volume or tidal prism [m³] is determined as the mathematical product of the mean tidal discharge [m³/s] and the mean current phase duration [h], respectively for ebb and flood tide.

The difference between ebb and flood tidal volume is equal to the volume of freshwater that is discharged during one tidal cycle:

$$V_e - V_f = Q_0 * (T_e + T_f)$$

with:
$V_e$ = ebb tidal volume [m³]
$V_f$ = flood tidal volume [m³]
$Q_0$ = freshwater discharge [m³/s]
$T_e$ = ebb current phase duration [h]
$T_f$ = flood current phase duration [h]

The freshwater discharge (see 5.2.2) and hence the difference between mean ebb and flood tidal volume is identical for both model states (Fig. 15). Generally, the mean tidal volume computed for today's mean hydrodynamical conditions is significantly higher compared to the equivalent of 1937 as a result of the anthropogenic streamlining and deepening of the channel-cross-sections leading to a smaller hydraulic resistance.

The percentage increase of the mean tidal volume is expressed relative to the mean tidal volume of 1937 (Fig. 16). The relative increase ranges from 100 percent at Papenburg to up to 600 percent at Herbrum. In 1937, the hydraulic resistance of the channel bed was higher than today preventing the tidal wave to propagate as far in the upper estuary as today. As a consequence the tidal range used to be much smaller in the upper section explaining that the relative increase of tidal volume turns out to be very high. Further downstream the relative increase of flood tidal volume since 1937 is in the order of 70 percent at Leerort decreasing gradually to about 40 percent at Pogum.

The relative increase of the mean ebb tidal volume with about 75 % is highest on the section between Papenburg and Leerort. At Pogum the increase is almost 40 %, thus similar to the increase of the mean flood tidal volume.

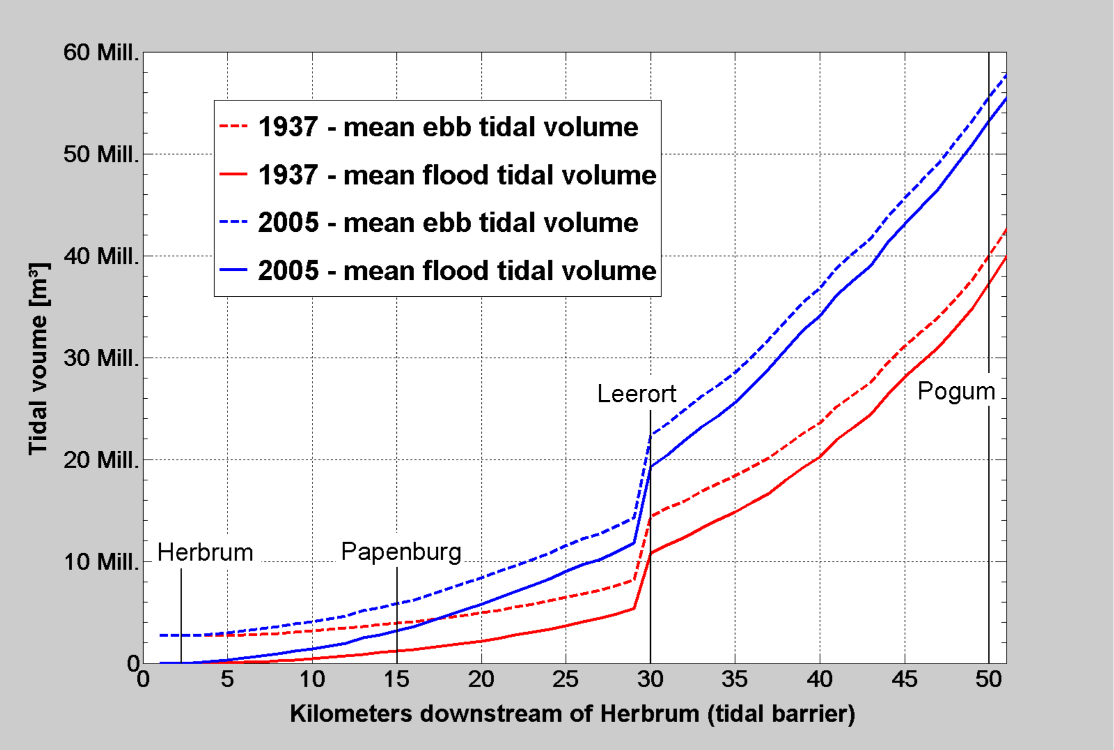

Fig. 15: Comparison of mean tidal volume in the Lower Ems between the model state of 1937 and 2005, respectively for flood and ebb tide

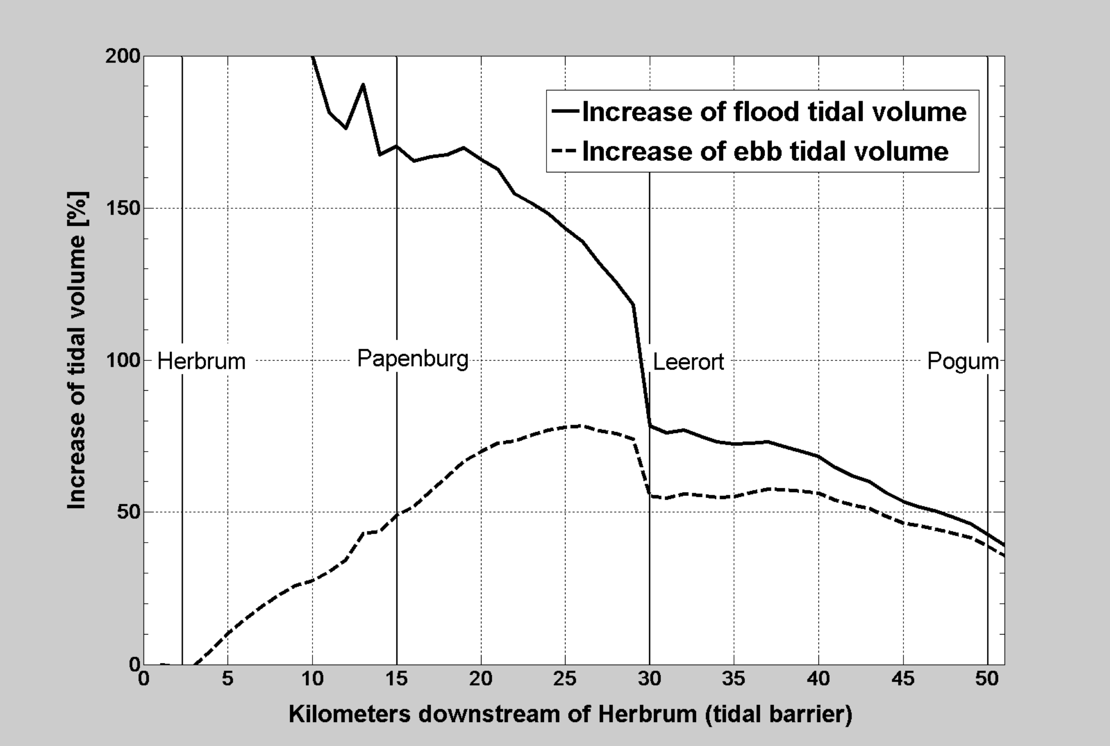

Fig. 16: Relative increase [%] of the mean flood and ebb tidal volume in the Lower Ems between 1937 and 2005 in respect to the mean tidal volume of 1937

### 6.2.5 Mean and maximal current velocities

The mean and maximal current velocities are determined for mean hydrodynamical flow conditions on the longitudinal section between Herbrum and Knock (Fig. 17 and 18). The current velocities are monitored every kilometer at about the deepest part of the waterway’s cross-section. High fluctuations in magnitudes between subsequent monitoring points are due to changes in bottom depth, sudden flow constrictions or the effect of secondary flows in river bends.

Hereafter it is focused to point out a qualitative trend in the relation between current velocities. The determination of the current velocities at the middle of the waterway is considered to be a relevant parameter that can be used to evaluate the qualitative sediment load, because high shear stresses in the middle of the cross-section initialize the sediment transport.

Generally, maximal and mean current velocities are higher for the actual than for the historical model state during both ebb and flood phases. Upstream of Leerort (km 30), the difference of current velocities between ebb and flood on the one hand and between the model state of 1937 and 2005 on the other tend to increase.

Considering the actual model state on the stretch between kilometer 25 and 40, the maximal current velocities are significantly higher for flood tide compared to ebb tide. The maximal current velocities as regards the historical state for the same section are similar for ebb and flood tide.

Downstream of Terborg (km 40), the mean current velocities are higher for ebb than flood tide, whereas the maximal current velocities of ebb and flood tide are generally more similar, respectively for both model states.

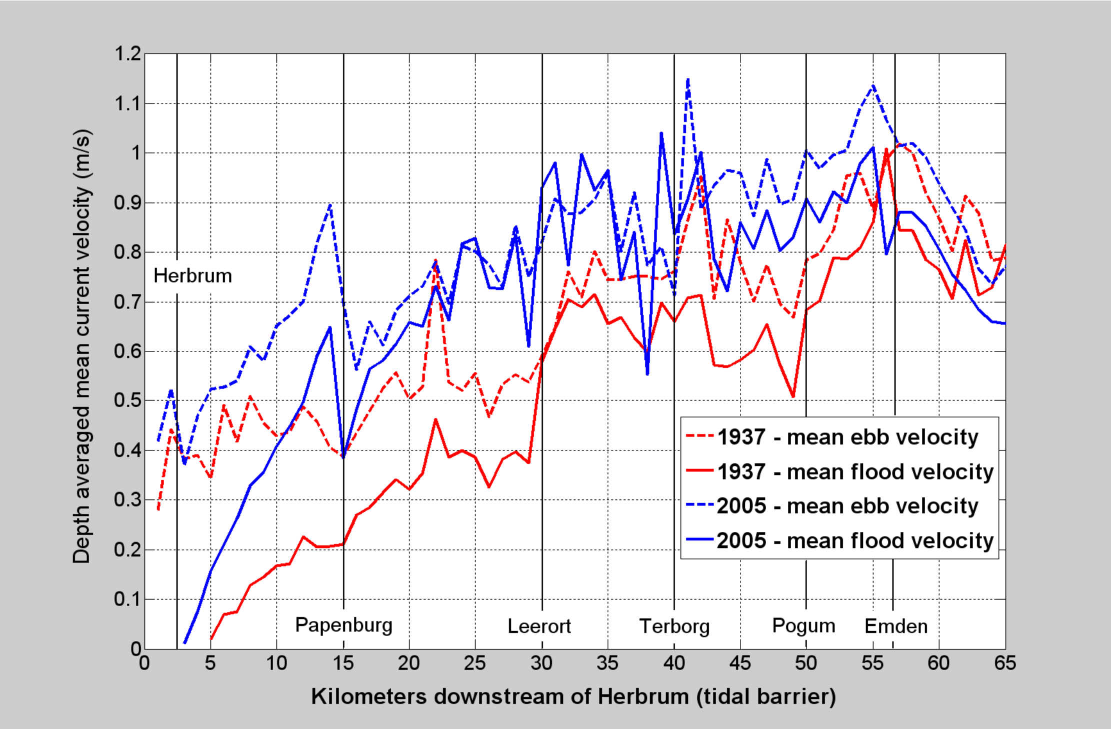

**Fig. 17: Comparison of the mean current velocities in the Lower Ems between the model state of 1937 and 2005, respectively for flood and ebb tide**

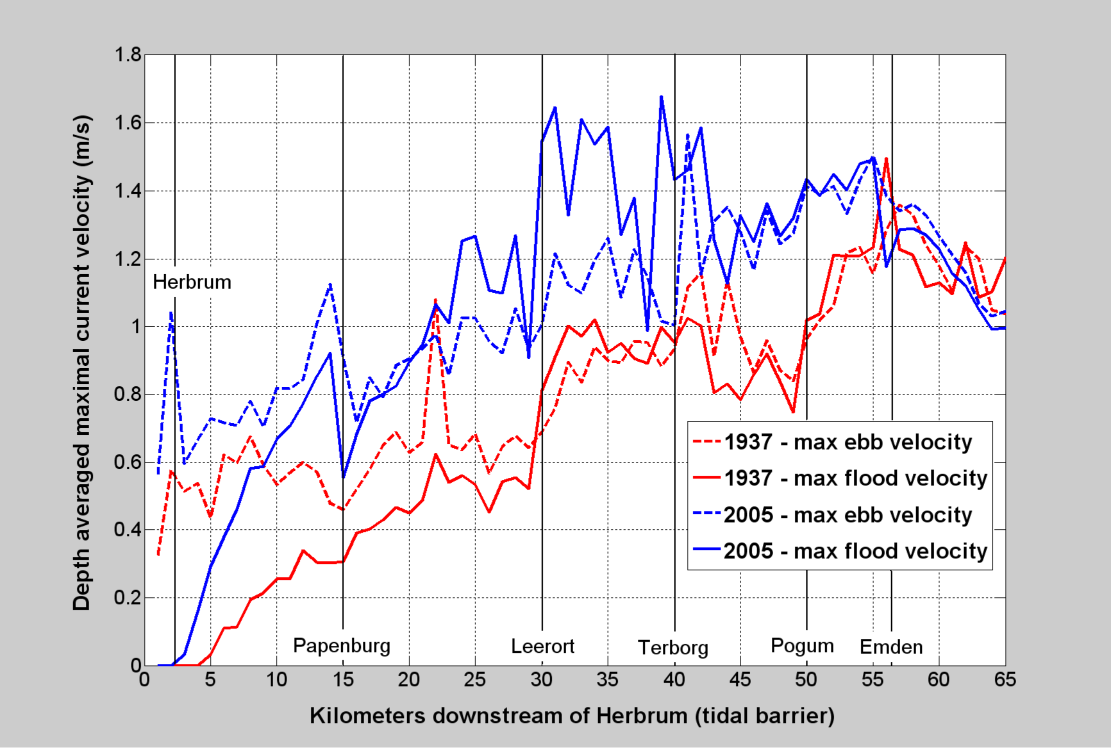

**Fig. 18: Comparison of the maximal current velocities in the Lower Ems between the model state of 1937 and 2005, respectively for flood and ebb tide**

## 6.3 Spatial comparison of current velocities

The application of mathematical models not only allows the evaluation of hydrodynamical parameters in predefined points or cross-sections, but also at a spatially broader scope. The migration of tidal channels and tide dominated current pattern can be highlighted.

In the area of the transitional waters between Pogum and Dukegat, the maximal flood and ebb current velocities are determined for the moment when the respective flood and ebb peak velocities are reached at the location “Knock”, situated in the center of the mentioned area (Fig. 19 a, b and Fig. 20 a, b).

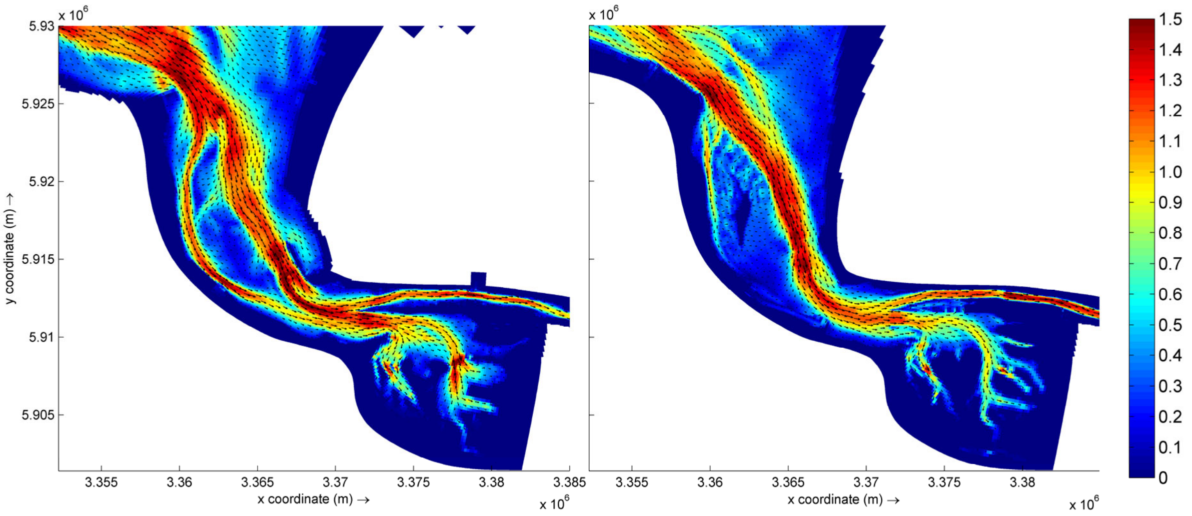

**Fig. 19: Comparison of maximal food current velocities [m/s] with respect to the location Knock for the model state of 1937 (a) and 2005 (b) in the transitional waters**

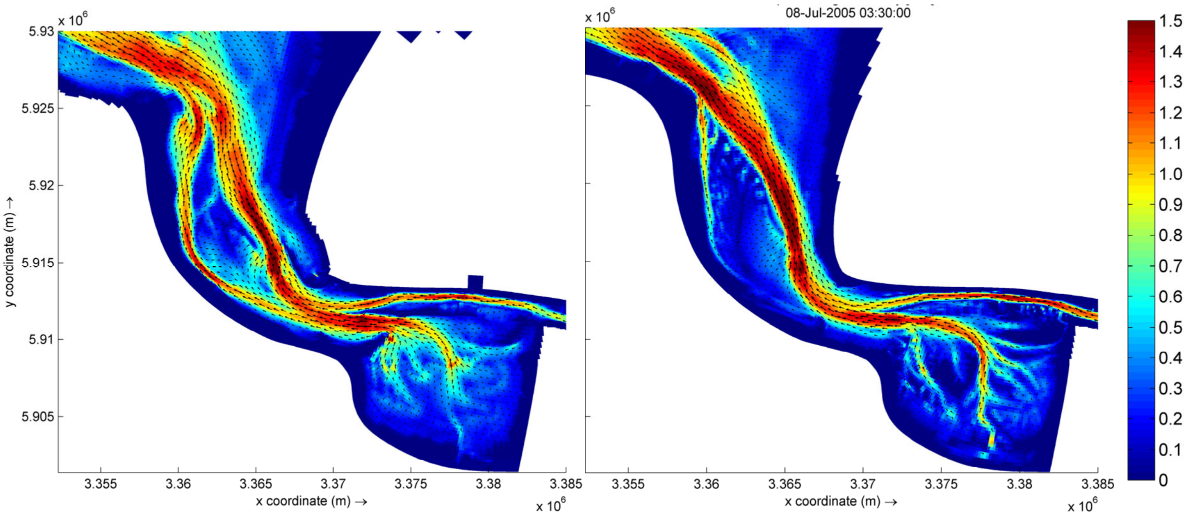

**Fig. 20: Comparison of maximal ebb current velocities [m/s] with respect to the location Knock for the model state of 1937 (a) and 2005 (b) in the transitional waters**

At the tidal inlet and at the seaward area, as regards the state of 1937, the current pattern is broadly extended with spatially varying current magnitudes, whereas the current pattern is significantly concentrated on the deepened waterway for the state of 2005.

For the state of 1937, a significant part of the tidal volume is exchanged through the Bocht van Watum which is the smaller tidal channel at the estuarine inlet. Nowadays this tidal channel is almost silted-up and the tidal currents concentrate on the main inlet and thus have increased in magnitude.

In the Lower Ems, the maximal flood current velocities are highlighted at the stretch between Terborg and Oldersum (Fig. 21).

A general increase of maximal flood current velocities can be determined from 1937 to 2005, especially in the river bends.

For the historical state, secondary channels exist on the straight sections upstream of Terborg and downstream of Oldersum, whereas the tidal currents in 2005 are focused on one single channel.

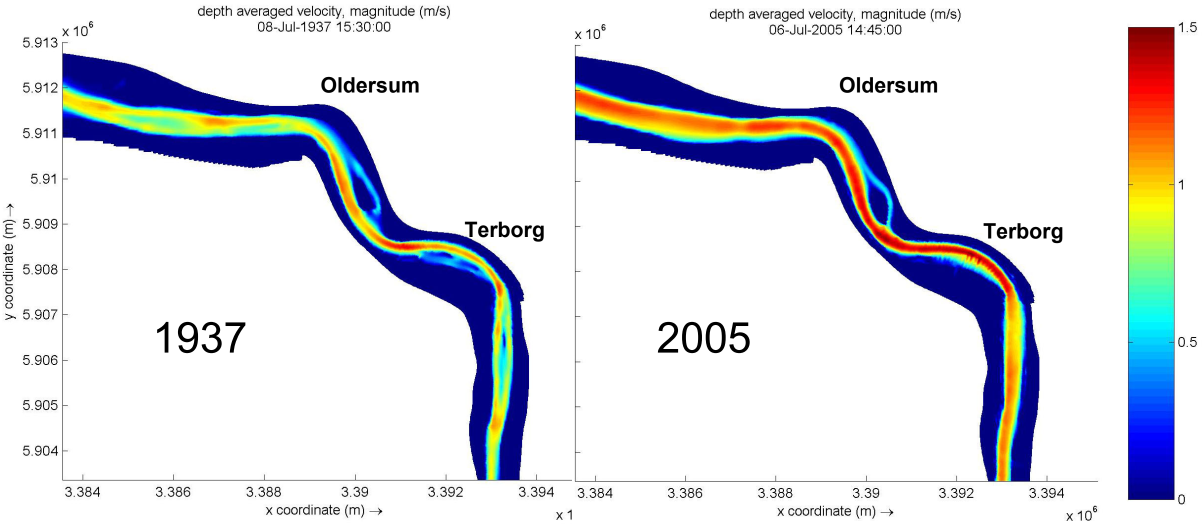

**Fig. 21: Comparison of maximal flood current velocities [m/s] in the Lower Ems at the section between Terborg and Oldersum for the model state of 1937 (a) and 2005 (b) with respect to the location Terborg**

# 7 Summary

The changes in tidal regime between the 1930s and today are evaluated by the use of water level observations and by the application of mathematical hydrodynamic models. In order to relate the encountered changes in tidal regime to possible anthropogenic impacts, a number of the main anthropogenic measures in the estuary are listed chronologically.

Water level observations of the last 70 years have been evaluated and the increase of the tidal range in the order of 4 % (0.09 m) at Borkum, located at the seaward limit of the estuary, to 175 % (1.73 m) at Herbrum close to the tidal barrier has been determined.

Hydrodynamical parameters computed by the application of mathematical models with bathymetric configurations of respectively 1937 and 2005 are compared for mean hydrodynamical conditions. The model results enable a quantitative comparison of the hydrodynamic regimes.

In the Lower Ems, the comparison of hydrodynamical parameters is assessed at one specific location and along a longitudinal section. Tidal discharges, volumes and current velocities have significantly increased between 1937 and 2005, whereas the duration of the tidal phases has remained almost constant in time for at least the section between Leerort and Pogum. For the mentioned longitudinal section, the difference between mean flood and mean ebb discharges has increased from 1937 until now.

In the outer Ems, a spatial comparison of tidal current velocities shows the differences in flow pattern and magnitudes. Comparing the actual to the historical model state, tidal current velocities have slightly increased and the current patterns are more concentrated on the deepened tidal inlet and channels. The diversification of current magnitudes on a spatial scale has been significantly reduced with respect to 1937. Shallow water areas with reduced current velocities have almost disappeared in the tidal inlet.

The comparison of computed hydrodynamical parameters of the state prior and after human interferences in the system can be successfully used as assessment criteria for the objective identification of Heavily Modified Water Bodies (HMWB). The area-wide evaluation of the changes in the tidal regime is essentially in particular for the determination of changes in the physical environment needed for the further assessment study of the ecological impact and the ecological potential. Model outcomes, e.g. changes in current magnitudes, can be transferred in a Geographical Information System (GIS) and can then be used for related ecological studies.

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