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Evaluation of Changes in the Tidal Regime of the Ems-Dollard and Lower Weser Estuaries by Mathematical Modelling

Gerald Herrling, Johanna Elsebach and Anne Ritzmann

Summary

Investigations for the Ems-Dollard and the Lower Weser estuaries have been done to compare the hydrodynamic regimes for historical and recent states. The research incorporates the identification of long-term spatial developments on the basis of historical and recent bathymetrical data and the application of process-based numerical modelling in order to hindcast the hydrodynamic regime. For the Ems-Dollard estuary the bathymetrical state of 1937 was reconstructed. This reference state represents the estuary prior to the main anthropogenic impacts of channel streamlining and deepening. A model bathymetry of the year 2005 was applied for comparison. For the Lower Weser estuary a historical state of 1887 was reconstructed and compared to the situation of the year 2000. Here, 1887 represents the situation prior to the "Weser correction" by Ludwig Franzius. Model results enable the comparison of hydrodynamic parameters and thus allow the quantification of changes in water levels, current velocities, tidal volumes, tidal discharges and the duration of tidal phases.

In the Lower Ems, the comparison of hydrodynamic parameters is assessed in the time domain at one specific location during one tidal cycle and for time-averaged values at 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 aforementioned 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 present 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 Ems-Dollard estuary and particularly the Lower Ems experienced a dramatic change of its tidal regime due to human interferences. The estuarine deepening and streamlining upstream of the Dollard Bay created long-term morphodynamical processes being still of importance. In the last centuries, natural and anthropogenic interferences in the Dollard Bay resulted in a strong reduction of tidal prism being responsible for changes to the tidal regime in the outer Ems-Dollard estuary.

For the Lower Weser estuary, the evaluation of hydrodynamic parameters along a longitudinal section between Bremen and Bremerhaven reveals a significant increase in mean tidal discharges and mean tidal volumes since 1887. Due to the shift of the natural flood current limit from Vegesack to Bremen, the duration of tidal phases nowadays feature a steep gradient in exactly this area, which means a sudden decrease in ebb duration and thus increase in flood duration. The spatial distribution of depth-averaged current velocities for the model states of 1887 and 2000 shows the enormous effect of streamlining the waterway and cutting-off of secondary channels since 1888. The strong anthropogenic impacts changed shallow water areas and secondary channels of relatively low current conditions into one straightened waterway characterized by high current magnitudes.

Keywords

Ems-Dollard-estuary, HARBASINS, Weser correction, waterway streamlining and deepening, Delft3D, process-based model, estuarine hydrodynamics, regime shift, comparison historical and present state

Zusammenfassung

In den Ästuaren von Ems-Dollart und Unterweser wurden Untersuchungen zum Vergleich der historischen und aktuellen Zustände des hydrodynamischen Regimes durchgeführt. Auf der Basis historischer und aktueller Topographien wurden für beide Ästuare numerische Modelle erstellt, um die räumliche und zeitliche hydrodynamische Entwicklung auszuwerten. Für das Ems-Dollart-Ästuar dient dafür als Referenzzustand das Jahr 1937, welches den Zustand vor den umfassenden anthropogenen Eingriffen wie Begradigung und Vertiefung darstellt. Den Vergleich mit dem aktuellen Zustand ermöglicht eine Modelltopographie des Jahres 2005. Der natürliche, historische Zustand der Unterweser wurde aus Topographiedaten des Jahres 1887 rekonstruiert, unmittelbar vor der Weserkorrektion nach Ludwig Franzius. Topographische Daten von 2000 repräsentieren den aktuellen Zustand. Die Modellergebnisse ermöglichen einen Vergleich hydrodynamischer Parameter und somit die Quantifizierung der Veränderungen von Wasserständen, Strömungsgeschwindigkeiten, Tidevolumen, Tidedurchfluss und Dauer der Tidephasen.

An der Unterems wurden hydrodynamische Parameter als Zeitreihen an einer Position für einen Tidezyklus ausgewertet und als zeitlich gemittelte Werte längs des Fahrwassers. Tidedurchfluss, Tidevolumen und Strömungsgeschwindigkeiten sind im Zeitraum 1937 bis 2005 signifikant angestiegen, während die Dauer der Tidephasen zumindest im Abschnitt zwischen Leerort und Pogum annähernd gleich geblieben ist. In Längsrichtung betrachtet hat die Differenz zwischen mittlerem Flut- und Ebbdurchfluss seit 1937 zugenommen. Für die Außenems zeigt ein räumlicher Vergleich der Tideströmungsgeschwindigkeiten die Unterschiede von Strömungsmuster und -intensität. Die Strömungsgeschwindigkeiten haben seit 1937 leicht zugenommen bei einer Konzentration auf die vertiefte Flussmündung und die tiefen Rinnen. Die räumliche Diversität der Strömungsgeschwindigkeiten und strömungsberuhigte Flachwasserbereiche im Mündungsbereich sind seit 1937 signifikant vermindert.

Für das Ems-Dollart-Ästuar und insbesondere die Unterems ist eine dramatische Veränderung des Tideregimes aufgrund anthropogener Faktoren festzustellen. Die Vertiefung und Begradigung des Ästuars stromauf des Dollarts hat langfristige morphodynamische Prozesse geschaffen, die noch immer von Bedeutung sind. Die natürlichen und anthropogenen Eingriffe der letzten Jahrhunderte im Dollart führten zu einer starken Reduzierung des Tideprismas, das für die Veränderungen des Tideregimes im äußeren Ems-Dollart-Ästuar verantwortlich ist.

Für das Weserästuar verdeutlicht die Auswertung hydrodynamischer Parameter in Längsrichtung zwischen Bremen und Bremerhaven einen signifikanten Anstieg des mittleren Tidedurchflusses und des mittleren Tidevolumens seit 1887. Aufgrund der Verlagerung der natürlichen Flutstromgrenze von

Vegesack nach Bremen zeigen die Tidephasendauern in diesem Bereich heutzutage einen steilen Gradienten, was eine plötzliche Verkürzung der Ebbdauer bzw. Verlängerung der Flutdauer bedeutet. Die Veränderung der Strömungsgeschwindigkeiten zwischen beiden Modellzuständen 1887 und 2000 zeigt die massiven Auswirkungen von Flussbegradigung und Abtrennung von Nebenarmen. Der starke anthropogene Einfluss hat Flachwasserbereiche und Rinnen mit geringer Strömung in ein begradigtes Fahrwasser mit hohen Strömungsgeschwindigkeiten verwandelt.

Schlagwörter

Ems-Dollart-Ästuar, HARBASINS, Korrektion Unterweser, Flussbegradigung und Fahrwasservertiefung, Delft3D, prozessbasiertes Modell, Ästuardynamik, Nachhersage (hindcast), Regime Veränderung, Vergleich historischer und aktueller Zustand

Contents

1 Introduction

In the course of the last centuries, many European estuaries and coastal waters experienced significant changes in their littoral environment not only due to natural processes but more and more due to human interference. Major anthropogenic pressures in estuaries and their habitats have been: land reclamation by establishing dykes on supratidal marshes and foreland, harbor extensions, implementation of groins and training walls, deepening and streamlining of waterways. These anthropogenic impacts change primarily both hydrodynamics and topography of estuaries.

In the framework of the European Interreg IIIb project HARBASINS ("Harmonised River Basins Strategies North Sea") the aim of the workpackage "Hydro- and Morphological Pressures and Impacts" was to generate process-based knowledge on these effects by high-resolution mathematical modelling. For this purpose, investigations have been carried out for the Ems-Dollard and Lower Weser estuaries. Objective was to compare the hydrodynamic regimes for recent and historical states and assess their long-term spatial developments. This paper is meant as a review on the formerly achieved research results (HERRLING and NIEMEYER 2007a, b, c; HERRLING and NIEMEYER 2008a, b, c; HERRLING and ELSEBACH 2008).

The study areas are located at the southern North Sea coast (Fig. 1) and marked by characteristic geomorphological features for this type of coastline: deep tidal channels and inlets, intertidal flats and the inner estuarine environment. The investigated estuaries are considered to be mesotidal with increasing tidal ranges further upstream. Their tidal limit is set by artificial tidal barriers located at 50 km and 70 km upstream of the estuarine mouth for the Ems-Dollard and the Lower Weser estuary, respectively.

Both estuaries have long histories of considerable anthropogenic interferences. The Dollard Bay already was marked by dykening and land reclamations in the period between the 17th and the 20th century (HERRLING and NIEMEYER 2007a). By the end of the 19th century groins, harbors and navigation measures were built in the Lower Ems and the Emden fairway. Since the 1950s, maintenance dredging of the navigational channel became common practice in the Lower Ems. In the Lower Weser estuary, streamlining the waterway and cutting-off of secondary channels from 1888 until 1895 were the strongest human impacts, nowadays known as "Weser correction", planned by Ludwig Franzius. Another significant anthropogenic intervention was the waterway deepening of 9 meters below the "nautical chart datum" (SKN) just after 1972.

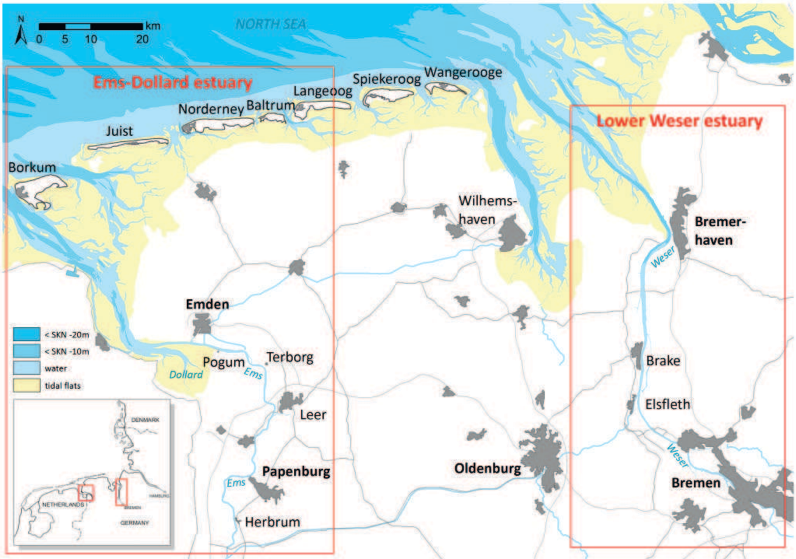

Figure 1: Areas of investigation: Ems-Dollard estuary and Lower Weser estuary.

2 Methodology and Data

To identify significant changes in the tidal regime due to human impacts, it seems reasonable to compare prevailing hydrodynamic parameters to those of historical states. But continuous current measurements of historical states hardly exist or are temporally and spatially limited in most cases. Alternatively mathematical hydrodynamic modelling can compensate this lack of data if for a chosen reference status sufficient bathymetrical data is available. The historical model configuration is applied for hydrodynamic hindcasting, i.e. the reproduction of the hydrodynamic regime prior to the main human impacts like streamlining and deepening of the waterways. Aim is the comparison of hindcasted hydrodynamic parameters like current velocities and tidal volumes with the output of a current model state incorporating data of recent bathymetric surveys. Hydrodynamic models of the Ems-Dollard and the Lower Weser estuary were established by applying the vertically averaged version of the modelling system Delft3D (DELTARES 2006). The resolution of the numerical, curvilinear grids is in the order of 800 meters at the seaward boundaries and reaches up to 15 meters at the upstream river sections.

Historical marine charts and maps due to topographic surveys have been required from authorities and local waterway agencies. Marine charts of the years 1923, 1926, 1941 and 1952 are used to reconstruct the historical model bathymetry in the outer Ems-Dollard estuary and the Dollard Bay. At the riverine section of the Lower Ems cross-sectional survey data at a distance of about 300 to 400 meters is available for the years 1927 and 1933. The area in between the cross-sections is reconstructed by interpolating linearly along the flow-directed lines of the numerical grid. The data is found to be adequate to model the hydrodynamic state prior to the main human impacts. In the following, the historical configuration of the Ems-Dollard model is referred to the year 1937, since the oldest available water level observations being necessary for the model calibration go back to 1937. Recent data of bathymetric surveys based on echo-sounding (2004) and high-resolution airborne laser-scanning (2005) is used for the present model bathymetry.

For the Lower Weser bathymetrical data gathered from historical maps of the year 1887 represent the state prior to the correction of 1888. Data for the present state is based on airborne laser-scanning and echo-sounding surveys carried out between 1996 and 2000. Two digital elevation models have been created using GIS techniques. They were used as input for the model configurations of 1887 and 2000, covering the area of the Lower Weser from Bremerhaven (km 65) to Bremen (km 0).

The open model boundary conditions are selected in a manner to generate mean hydrodynamic flow conditions allowing the comparison of the computed tidal regimes of both mentioned model states. It is aimed 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 of the historical and the present state, respectively. The sea boundary conditions are generated by a nesting procedure with the overall German Bight Model (VERBOOM et al. 1992), except for the historical configuration of the Lower Weser model. Here, the record of a mean tide of 1887 (FRANZIUS 1888) was adapted and implemented at the sea boundary being located close to Bremerhaven at the mouth of the estuary. The selected type of boundary conditions only represents the astronomical tide without any meteorological effects. Apart from the generation of a mean tide at the sea boundary, the run-off at the upstream riverine boundary is set in order to match long-year mean discharges. The freshwater discharge has been assumed to be identical for the present and the historical model states, thus 82 m^3/s and 327 m^3/s for the Ems and Weser, respectively. The historical and current models of the Ems-Dollard and the Lower Weser estuary are calibrated by fine-tuning numerical and physical parameters, e.g. the bottom roughness. The quality of the models is verified by means of computed and observed water level comparison at gauge locations along the estuaries.

3 Results

The model results for the Ems-Dollard estuary with configurations of 1937 and 2005 enable a quantitative comparison of the hydrodynamic regimes. In the Lower Ems, the comparison of hydrodynamic parameters is assessed at one specific location 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. For the Lower Weser, hydrodynamic parameters are evaluated for the section between the tidal weir in Bremen and downstream as far as Bremerhaven. An example of significant changes in the hydraulic regime is given for a certain stretch between Brake and Elsfleth.

3.1 Results at one specific location in the Lower Ems

Modeled tidal discharges and volumes are monitored through cross-sections along the mentioned stretch at the distance of one kilometer each. Computed hydrodynamic parameters are evaluated exemplarily at kilometer 35 in the Lower Ems for the period of one tidal cycle, representing mean tidal conditions for 1937 and 2005. This comparison reveals the changes of the tidal regime in time. The observation point is located about 5 kilometers upstream of Terborg at a straight stretch in order to avoid fluctuations in current velocities due to secondary flows or sudden channel constrictions. Time series of water levels referenced to German datum [mNN], i.e. approx. mean sea level, and current velocities [m/s] are compared for mean flow conditions between 1937 and 2005 (Fig. 2).

Generally, the tidal range and the current velocities of the model state of 2005 have increased with respect to the situation in 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. At the given cross-section and generally in the Lower Ems, the overall tendency is towards a flood-dominated tidal flow.

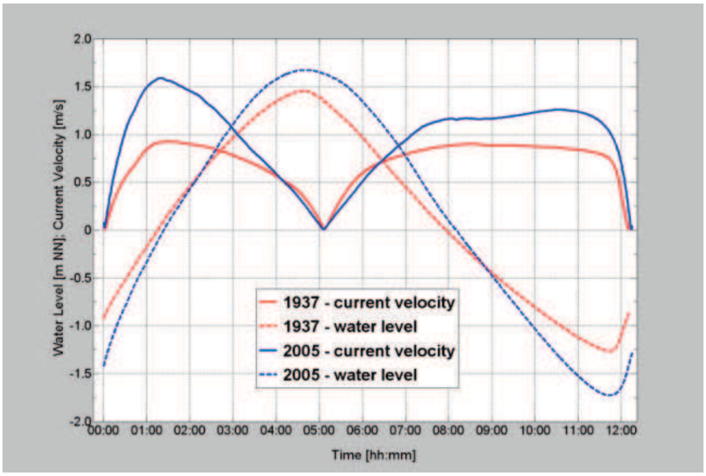

Figure 2: Modelled mean tidal water level and mean current velocity in the cross-section at kilometer 35 downstream of the tidal barrier at Herbrum in the Lower Ems.

The time series of the momentary tidal discharges and related hydrodynamic parameters are computed for 1937 and 2005 due to the cross-sectional flow at kilometer 35 for one mean tidal cycle (Fig. 3). Mean tidal fluxes and mean tidal volumes have increased from 1937 to 2005, whereas the mean tidal phases have remained almost constant in time for ebb and flood tides. The mean tidal flux computed as the arithmetical average over one tidal phase increased from 811 to 1394 m^3/s (72 %) for flood tide and from 717 to 1114 m^3/s (55 %) for ebb tide. The mean flood tidal volume V_f increased by about 73 % from 14.8 to 25.6 Mill. m^3, whereas the mean ebb tidal volume V_e increased by approximately 55 % from 18.4 to 28.5 Mill. m^3.

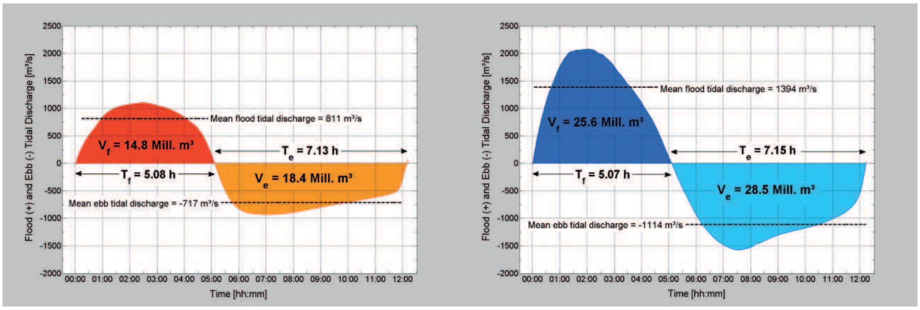

Figure 3: Mean tidal flux, mean tidal volume V and mean tidal period T in the cross-section at kilometer 35 downstream of the tidal barrier in the Lower Ems for the model state of 1937 (left) and 2005 (right).

3.2 Results along a longitudinal section in the Lower Ems

Computed results for the states of 1937 and 2005 at the longitudinal section from the tidal barrier at Herbrum downstream to the Dollard Bay highlight differences in hydrodynamic parameters such as mean water levels, mean and maximum tidal discharges, mean tidal volumes, mean tidal current phases as well as means and maximum current velocities.

Modelled 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 fairway 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 the tidal discharges and the tidal volumes at Leerort, which can be assigned to the freshwater discharge contributed by the Leda tributary.

Mean water levels

Observed and computed mean water levels (MHWL and MLWL) are compared at the longitudinal section from the tidal barrier at Herbrum to the location Knock at about

67 kilometers downstream (Fig. 4). MHWL and MLWL for the state of 1937 (red) are plotted against those of 2005 (blue). Computed values are due to the simulation of one representative mean tide for 1937 and 2005. Observations are based on 5-year-period time series: for 1933 to 1937 and 2001 to 2005, with an exception of the historical observations at Herbrum being available only for the period 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.

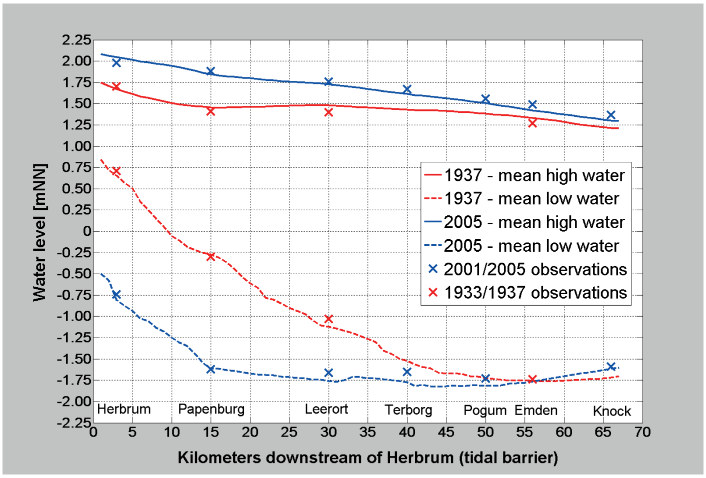

Figure 4: Modeled and observed MHWL and MLWL along a longitudinal section between Herbrum and Knock for the model states of 1937 and 2005.

At Emden, the observed MLWLs, both for the present and the historical situation, are exactly at the level of -1.74 mNN (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 at Emden.

Mean and maximum tidal discharges

The tidal discharge is determined as the momentary flow [m^3/s] recorded with an interval of one minute through cross-sections at every kilometer at 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, for ebb- and flood-directed currents, respectively (Fig. 5a).

The maximum tidal discharge is evaluated at the peak flow for ebb and flood current phases (Fig. 5b). Both, ebb and flood tidal discharges have significantly increased since 1937 for the whole section. Although the freshwater discharge counteracts the tidal flow during flood tide, the mean tidal flood discharge is higher than the mean tidal ebb discharge in 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.

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 the year 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.

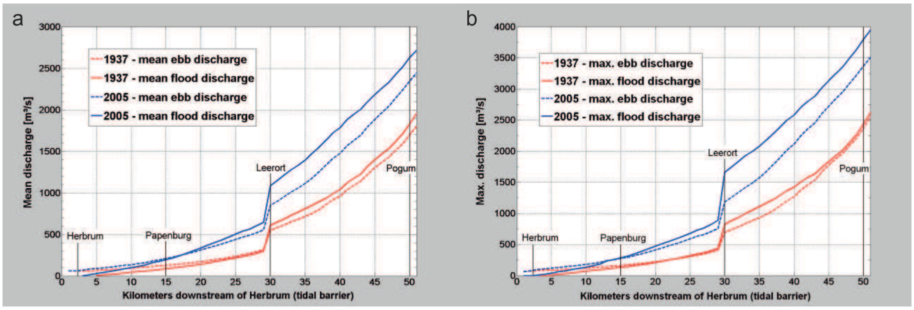

Figure 5: Comparison of mean (a) and maximum (b) tidal discharges in the Lower Ems between the model states of 1937 and 2005 for flood and ebb tide.

Mean tidal volume

The freshwater discharge and hence the difference between mean ebb and flood tidal volume is identical for both model states (Fig. 6a). Generally, the mean tidal volume computed for today's mean hydrodynamic 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.

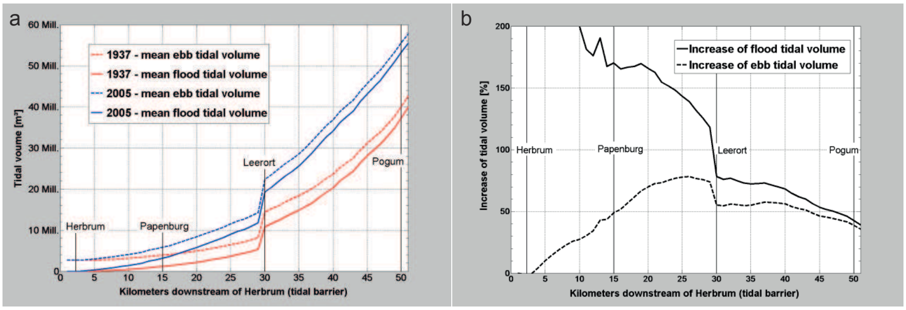

Figure 6: Comparison of mean tidal volumes at a longitudinal section in the Lower Ems for the model states of 1937 and 2005 (a); relative increase [%] in mean flood and ebb tidal volume between 1937 and 2005 in relation to the mean tidal volume of 1937 (b).

The percentage increase of the mean tidal volume is expressed relative to the mean tidal volume of 1937 (Fig. 6b). 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 the relative very high increase in tidal volume. Further downstream the relative increase in flood tidal volume since 1937 is in the order of 70 % at Leerort decreasing gradually to about 40 % at Pogum. The relative increase in the mean ebb tidal volume with about 75 % is highest in the section between Papenburg and Leerort. At Pogum the increase is almost 40 %, thus similar to the increase in mean flood tidal volume.

Mean tidal current phase

The mean tidal current phases are determined as the duration [h] between two slack-tides for ebb and flood tide, respectively (Fig.7). 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. In the section between Herbrum and Leerort, the duration of the mean flood current phase is significantly 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.

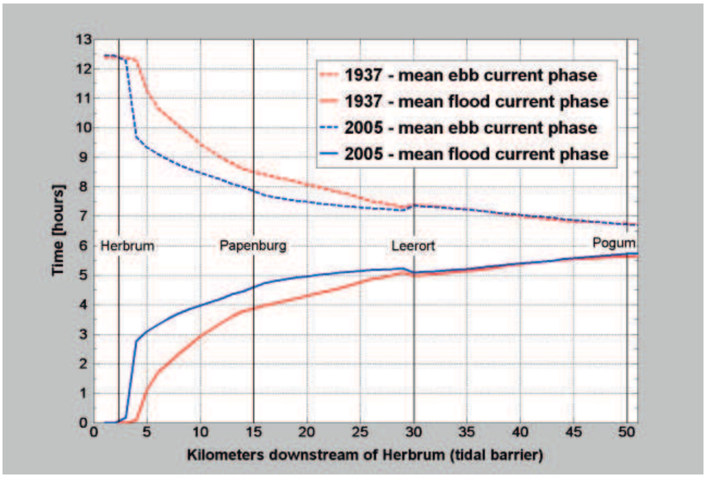

Figure 7: Comparison of mean tidal current phases in the Lower Ems between the model states of 1937 and 2005 for flood and ebb tide.

Mean and maximum current velocities

The mean and maximum current velocities are determined for mean hydrodynamic flow conditions at the longitudinal section between Herbrum and Knock (Fig. 8). 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 to evaluate the qualitative sediment load, because high shear stresses in the middle of the cross-section initialize the sediment transport.

Generally, mean and maximum current velocities are higher for the present 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 present model state at the stretch between kilometer 25 and 40, the maximum current velocities are significantly higher for flood tide compared to ebb tide. The maximum 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 maximum current velocities of ebb and flood tide are generally more in agreement for both model states.

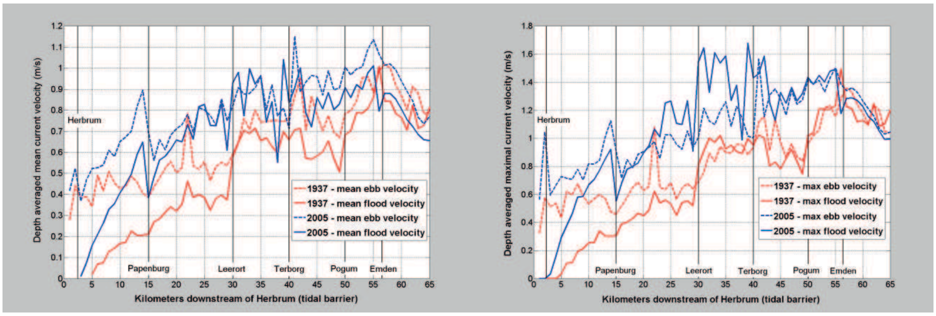

Figure 8: Comparison of mean (a) and maximum (b) current velocities in the Lower Ems between the model states of 1937 and 2005 for flood and ebb tide.

3.3 Spatial results in the Outer Ems

The application of mathematical models does not only allow the evaluation of hydrodynamic 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.

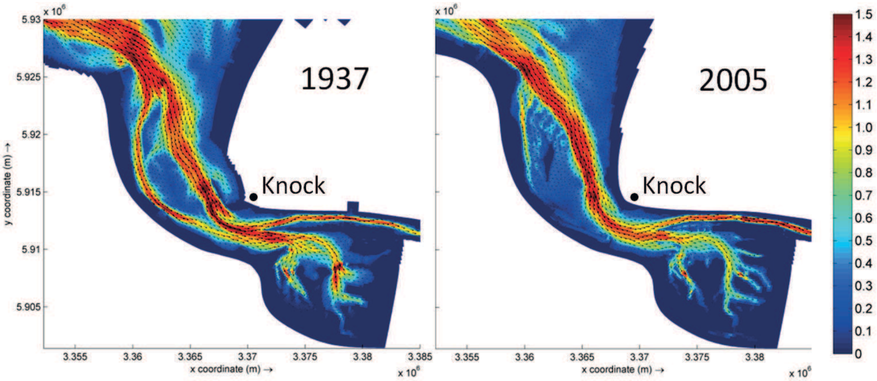

Figure 9: Comparison of maximum flood current velocities [m/s] in the transitional waters with respect to the location Knock for the model states of 1937 (a) and 2005 (b).

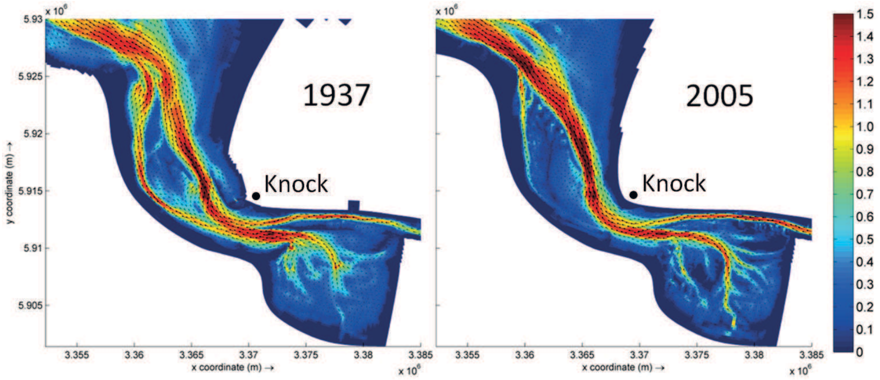

Figure 10: Comparison of maximum ebb current velocities [m/s] in the transitional waters with respect to the location Knock for the model states of 1937 (a) and 2005 (b).

In the area of the transitional waters of the Ems-Dollard estuary, the maximum flood and ebb current velocities are determined for the instant of time when flood and ebb peak velocities are reached at the location Knock (Fig. 9 and 10). At the tidal inlet and in 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 to the West in 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 maximum flood current velocities are highest at the stretch between Terborg and Oldersum (Fig. 11). A general increase of maximum flood current velocities can be determined from 1937 to 2005, especially in the river bends. For the historical state, secondary channels exist in the straight sections upstream of Terborg and downstream of Oldersum, whereas the tidal currents in 2005 are focused on one single channel.

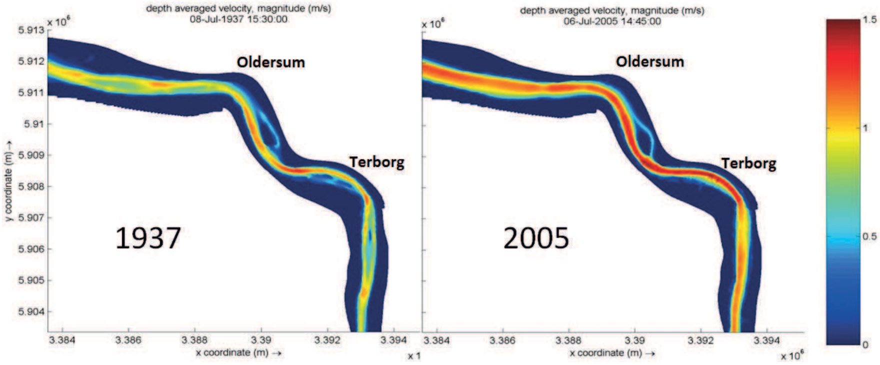

Figure 11: Comparison of maximum flood current velocities [m/s] in the Lower Ems at the section between Terborg and Oldersum for the model states of 1937 (a) and 2005 (b).

3.4 Results along a longitudinal section in the Lower Weser estuary

Results for the model states of 1887 and 2000 at the longitudinal section beginning at the artificial weir in Bremen downstream to Bremerhaven highlight differences in hydrodynamic parameters such as mean tidal discharges, mean tidal volumes and mean tidal current phases.

Mean tidal discharge

The mean tidal discharge in the section between Bremen and Bremerhaven is evaluated for mean ebb and mean flood current phases (Fig. 12). Both, ebb and flood tidal discharges have significantly increased since 1887 for the whole section. Considering the present state, the zone between Bremerhaven and Vegesack shows almost no difference in mean ebb and mean flood tidal discharges, whereas upstream, the river is determined by higher mean ebb than mean flood discharges due to the counteracting of river and tidal flow and smoothing of the river bed due to anthropogenic changes (Lecher et al. 2001). In 1887, the mean flood discharge was higher downstream of Elsfleth compared to a contrary pattern for the upstream section up to the natural flood current limit at Vegesack.

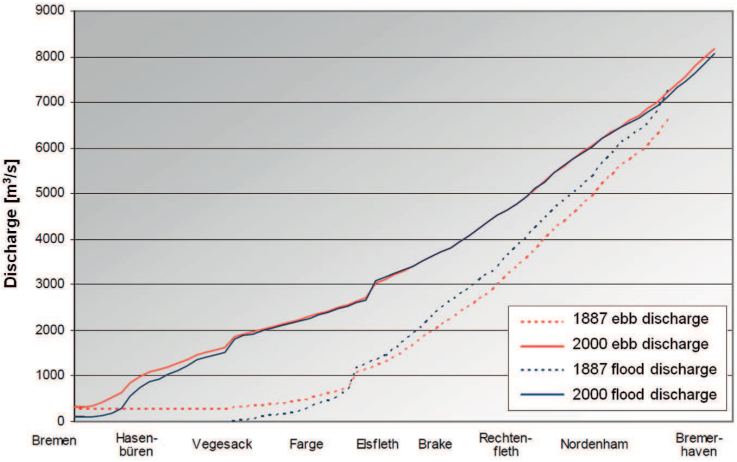

Figure 12: Mean ebb and mean flood tidal discharges of the Lower Weser estuary for the model states of 1887 and 2000.

Mean tidal volume

The freshwater discharge and hence the difference between mean ebb and mean flood tidal volume is assumed to be identical for both model states. The mean tidal volume for the current state is significantly higher compared to the computed equivalent of 1887 (Fig. 13), presumed to be a result of the Weser corrections. The present mean tidal volume shows a linear trend for the whole section, whereas the 1887 state shows two certain trends: a steep increase for the section Elsfleth to Bremerhaven and an almost constant mean tidal volume for the upstream stretch, associated to the former natural flood current limit at Vegesack up to the tidal limit at Bremen (Zanke 2002).

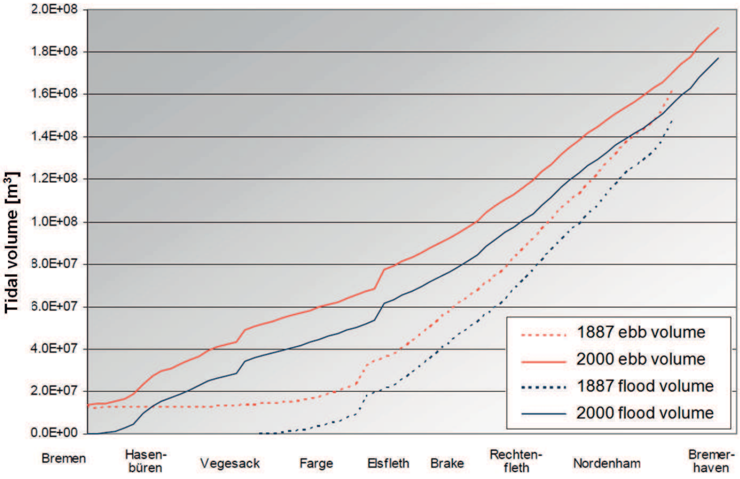

Figure 13: Tidal volume along a longitudinal section in the Lower Weser estuary for the model states of 1887 and 2000.

Mean tidal current phase

Concerning both model states, the mean flood current phase is generally shorter than the mean ebb current phase with a decreasing trend towards the downstream section. Along the whole section the duration of the mean flood current phase is significantly longer for the present situation compared to 1887, consequently the mean ebb current phase is shorter by the same extent. At the tidal weir in Bremen, the duration of the flood current phase is almost zero, whereas the duration of the ebb current phase is about 12.4 hours – one complete tidal cycle (Fig. 14). The steep decrease in ebb duration between Bremen and location Hasenbüren (and hence the increased flood duration) is attributed to the reflection at the artificial weir as well as the changed roughness of the river bed due to the Weser corrections. The historical state shows a smooth continuous decline in downstream direction of the former natural flood flow current limit at Vegesack. Concerning the present state, the difference between ebb and flood tide is decreasing very quickly for the short section Bremen to Hasenbüren followed by almost constant phase lengths downstream.

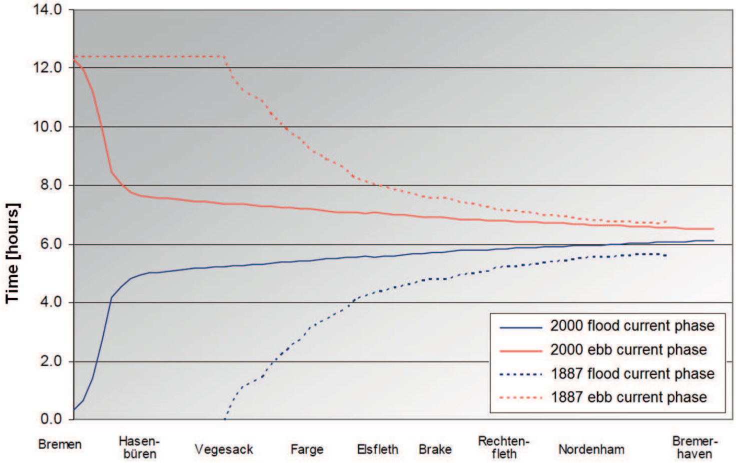

Figure 14: Mean tidal current phases in the Lower Weser estuary for the model states of 1887 and 2000.

3.5 Spatial results for the Lower Weser estuary

Another example of significant changes in the hydraulic regime is given for the Lower Weser estuary in the area of Brake (Fig. 15). The state of 1887 is considered as the natural reference state prior to the correction, starting in 1888. The current state is represented by the year 2000.

The spatial distribution of depth-averaged current velocities for the model states of 1887 and 2000 shows the enormous effect of streamlining the waterway and cutting-off of secondary channels. The strong anthropogenic impacts have changed shallow water areas and secondary channels of relatively low current conditions into one straightened waterway characterized by high current magnitudes. Maximum flood current velocities increased from about 0.7 m/s to 0.9 m/s (approximately 30 %) in the primary channel near Brake. In addition, the spatial variation of current magnitudes over the river width has disappeared due to the channel deepening and fixation.

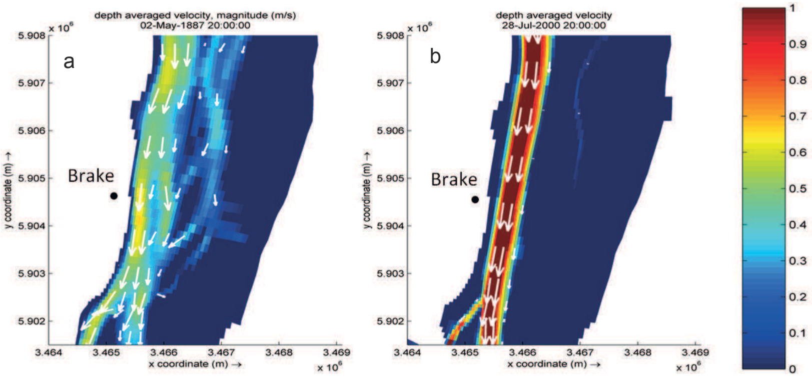

Figure 15: Comparison of maximum flood current velocities [m/s] in the Lower Weser in the area of Brake for the model states of 1887 (a) and 2000 (b).

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