Influence of the length of an estuary on tidal motion and sediment trapping

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Abstract

In this report, the influence of the location of the weir in the Ems estuary on the water motion and sediment dynamics has been investigated using an idealised analytical model. The water motion is described by the width–averaged shallow water equations, and the sediment dynamics by a width–averaged advection–diffusion equation with sinks and sources. For an extensive discussion of the model equations, see Chernetsky *et al.* (2010).

If the length of the estuary would be increased to 90 km, using parameter values representative for the Ems estuary in 2005, the model results suggest that

- the character of the tidal wave changes from a **standing** wave into a **travelling** wave.
- the **lowest low water level will increase** with approximately 60 cm and the highest water level will decrease with 70 cm, 60 km from Knock.
- the **ebb velocity will increase** to approximately 1 ms^{-1}, while the flood velocity will not change significantly (95 $\mathrm{cm\,s}^{-1}$).
- changes in tidal asymmetry **can not** be inferred from changes in the sea surface elevations, but can **only** be deduced from an analysis of the velocity components.
- an **increase of the length of the estuary** by approximately 10 km would result in **accumulation of fine sediment near Emden**, instead of close to the weir.

We would like to stress that the results of idealised models, state–of–the–art numerical models and observations should be used in an integrated way. The power of state–of–the–art numerical models is that, after calibrating the model to observations, very detailed calculations of water motion and sediment dynamics under those system conditions can be carried out. However, parameter sensitivity studies are difficult to perform both due to limitations of computational time and the absence of observations for those conditions, necessary to calibrate the model. The power of idealised analytical models is that they are specifically developed to describe the changes in general patterns under varying system boundary conditions and parameter settings. This means that the predicted effects by idealised model(s) need to be carefully tested by state–of–the–art numerical models, and numerical models should qualitatively show the behaviour suggested by the idealised model. Therefore, under the given situation with respect to models, a combination of both types of models will lead to a clear synergy and the best possible results.

Chapter 1

Introduction to the Ems River system and its estuary

The Ems estuary is part of the 600 km long European Wadden Sea. This shallow sea consists of a series of tidal basins protected from direct North Sea wave action by a string of barrier islands. The islands are separated by tidal inlets. A number of rivers drain into the Wadden Sea, the river Ems being one of them. The estuary is located at the border between the Netherlands and Germany (see Fig. 1.1) and is situated in an agricultural area. The estuary connects the northeastern part of the Netherlands and the northwestern part of Germany with the North Sea and forms an important navigation route for sea–going vessels and river ships. In this area there are three important harbours: Eemshaven, Delfzijl and Emden and a big shipyard in Papenburg.

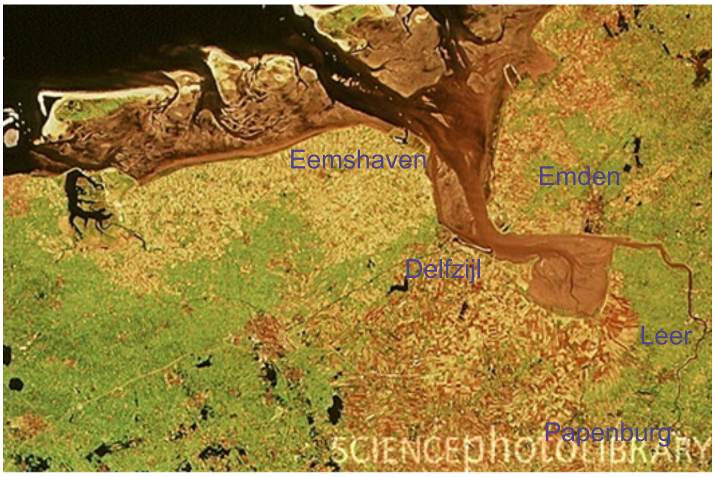


Figure 1.1: Map of the Ems estuary.

The river Ems has a length of 330 km. It drains an area of 12.650 km^2 and has a long-term average discharge of approximately 120 $m^3\,s^{-1}$ (near Pogum based on data by Hinrich (1974)). The weir near Herbrum, circa 100 km from the barrier islands

Borkum and Rottumeroog, separates the river Ems from marine influences and can be regarded as the head of the estuary.

The surface of the Ems estuary is 467 km^2, including a fresh water tidal area in the Ems until the weir at Herbrum (ca. 40 km^2). The upper part of the Ems estuary between Pogum and the inlet of the Dollard covers an area of circa 100 km^2. It consists of the upper estuary part (lower river Ems) and a shallow bay, the Dollard separated by a low guide dam, the Geisedamm. Water exchange is possible by a number of perforations in the dam. The main channel of the Ems is canalized and heavily dredged but it has tidal-flat embankments. Tidal flats also cover 85% of the Dollard area. Consequently, the mean water depth in the Dollard is low (1.2 m) and drift currents are important. The volume of water in the upper estuary at mean high water is approximately 220×10^6 m^3.

The middle part of the estuary, downstream of the Dollard has the classical estuarine funnel shape. This region extends to Eemshaven where the estuary joins the Wadden Sea. Most intertidal flats are situated along the main coastline, but a large tidal flat (Hond-Paap) divides the estuary longitudinally into two parts creating two channels. The main channel is on the east side. The other channel (Bocht van Watum) is silting up rapidly. The total surface of this section is 90 km^2 of which 45% comprises intertidal flats. The mean depth of this section increases gradually in a seaward direction, with the average water depth being 3.5 m. The water volume of this area at mean high water is approximately 460×10^6 m^3.

The most seaward region of the estuary is the Wadden Sea part of the estuary. This region is situated between Eemshaven and the islands Rottumeroog and Borkum. The boundary with the North Sea is formed by these two islands and the tidal inlet between them. The high elevated tidal flats between the islands and the mainland form the hydraulic boundaries between the estuary and the adjacent tidal basins. The area occupies 274 km^2 of which 44% consists of tidal flats. It has two channels separated by a series of shoals. The water volume of this region of the estuary at high water is approximately 1300×10^6 m^3.

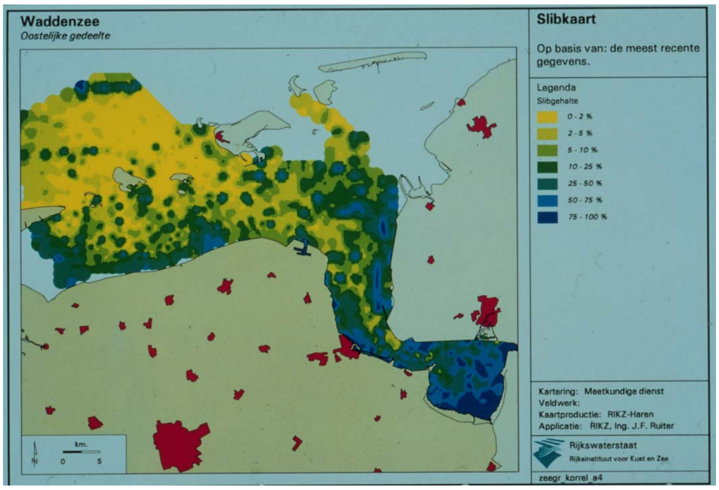


Figure 1.2: Map of the sediment distribution in the Ems estuary during the 1990s.

The morphology of the tidal flats, channels and gullies is complex, not only in their spatial distribution but also in their geometry. The morphology of the Ems estuary is not static. Slow changes are induced by natural processes such as sedimentation, meandering of channels and gullies, but they are also induced by human activities such as land reclamation, building of harbours, channel dredging and sand mining. An example of large scale natural morphological changes near the tidal inlet is described by Samu (1979). Samu concluded that the observed morphological changes in the outer estuary were cyclic and occurred with a periodicity of some 25 years. Comparably large morphological changes are also initiated by dredging activities and sand mining (in e.g. channel Randzelgat). The effects of these activities were noticeable within 1 year (de Jonge, 1983).

The distribution of the sediment composition is variable. The distribution in Fig. 1.2 indicates that the estuary contains areas varying from very muddy (near the coast and in the inner parts) to very sandy (main channels and outer parts).

The tidal prism between the barrier islands is approximately 10^9 m^3. The mean tidal range, an over-time-varying parameter, increases from roughly 2.3 m near the barrier islands to over 3.2 m at Emden. The complicated geomorphology and strong tidal currents result in complex water currents with a remarkable residual current pattern (de Jonge, 1992), steep average gradient in salinity and nutrients and characteristic, but historically changed, longitudinal distribution of suspended matter (see below).

Chapter 2

Historical developments

2.1 System morphology

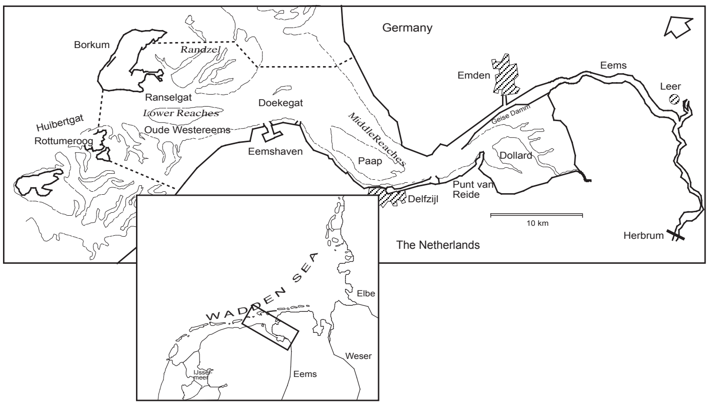


Figure 2.1: Map of the estuary with a subdivision in three main areas.

Originally the Ems estuary was clearly a two channel system. Before 1976 the navigation route in the outer reaches of the estuary followed the Oude Westereems along the Dutch side of the estuary (see Fig. 2.1). In 1976 the Ranselgat was chosen because the Oude Westereems showed strong sedimentation. Apparently this also happened with other channels. Later in time it became clear that the same happened with other channels like the Bocht van Watum, a channel along the Dutch side of the coast near Delfzijl. Also the Kerkeriet channel in the Dollard near 'Punt van Reide' showed strong siltation. There is thus clear evidence that the basic structure of the estuary has become undermined. A clear single cause for this phenomenon is not available but all the changes in land reclamation (Eemshaven, Rysumer Nacken, dike change in the Dollard) and engineering related activities (dumping of harbour spoil and dredged material in the Dollard and in the Bocht van Watum) have contributed to these morphological changes. These activities come on top of the natural variation in this dynamical system.

2.2 Tide related phenomena

Some remarkable tidal characteristic related changes have occurred in the estuary between Borkum and Emden and between Emden and Herbrum. First, the tidal range increased over the 1950-2000 period between Borkum and Herbrum. Near Borkum (Fig. 2.2) this increase is relatively modest and amplified at Emden, but upstream this town the changes are remarkable. From these graphs it is clear that the hydraulic situation on the tidal river Ems already started to change during the 1950s and not only during the 1970s (see below). When we consider the HW and LW levels over a period which includes the year 1937 (with very low estuarine dredging activities like $2-4\times10^6$ m^3 per annum (de Jonge, 1983, Fig. 3)) then we arrive at some conclusions about the tidal development. The estuarine system can be divided in a part upstream and another part downstream of Emden because this location seems to be a sort of 'hinge point' in the temporal developments of the tide in the entire system. Over time, and starting from a situation where at Emden the tidal range was maximal (1950) decreasing in both directions, the HW levels between Emden and Herbrum since then steadily increase while the LW levels show a major decrease in elevation. This LW decrease is important because it results in a much longer exposure time to air and light than before. In combination the figures 2.2 and 2.3 thus strongly suggest that also the early river adaptations (construction of the weir and sluice included) have led to tidal changes. The observed changes in sea surface elevation suggest changes in the tidal current velocities (and possibly changes in tidal asymmetry). However, conclusive information on changes in tidal asymmetry can only be obtained from tidal current velocities. It turns out that changes in tidal asymmetry are an important factor responsible for changes in mud accumulation (see below), hence especially the tidal currents should be studied in great detail, rather than sea surface elevations, if one is interested in the trapping of suspended sediment. Another point is that in the main estuary be-

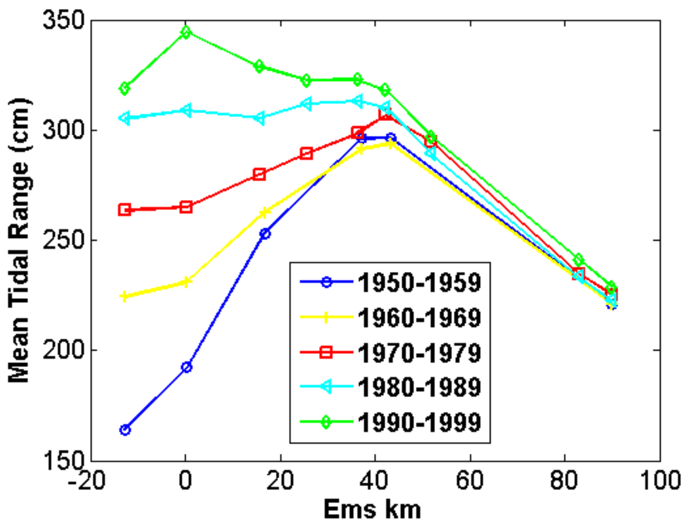


Figure 2.2: Longitudinal mean tidal range for 5 decades between 1950 and 2000. The 0 km point is the town Papenburg and -13 km the weir at Herbrum. The station at 87 km is Borkum, 46 is Knock and 40 km is Emden. Data obtained from NLWKN.

tween Borkum and Emden the tidal range also clearly increased (Fig. 2.2) and the time lag between HW and high water slack tide significantly decreased (de Jonge, 1983, Fig. 10). This suggests changed system roughness. The combination of decreased system roughness and increased SPM levels due to dredging (de Jonge, 1983, Figs. 9 and 14) may significantly stimulate further upstream (of Emden) SPM accumulation.

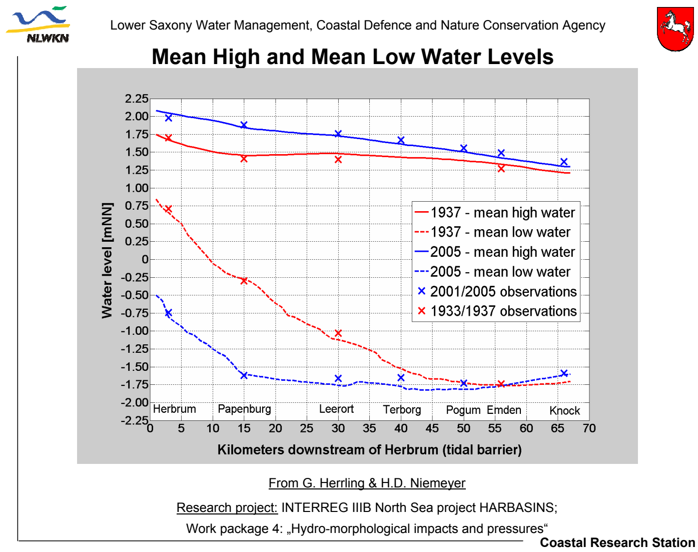


Figure 2.3: Observed and calculated mean high and mean low water levels between Knock and Herbrum for 1937 and 2005 (courtesy HARBASINS, G. Herrling NLWKN)

2.3 Environmental boundary conditions and organisms

Historically seen the river Ems has been a beautiful river bordered by green banks and even sandy beaches of interesting river flood plains. Between about Leer and the North Sea the river represented a normal (brackish) transition zone between river water and sea water (van der Welle & Meire, 1999). The estuary of the river Ems, between Emden and the North Sea island Borkum, nicely fitted the quality of the recent designated UNESCO World Heritage site Wadden Sea. That was due to the estuarine 'rest and drama' (cited from Geurt Busser, wadden painter) represented by the size of the area, the interplay between channels and intertidal flats, the continuously tide governed changes in landscape with changing waves, nice views and continuously changing colours of the water and the air and the absence of significant 'pollution of the sky-line' by big buildings or constructions.

Between the 1950s and the early 1980s the Ems estuary (area between Emden and the North Sea) has undergone varying human pressures due to the loading of immense quantities of organic material from the Netherlands (process water of the Dutch strawboard industry and potato flour industry), eutrophication (from Germany and The Netherlands), dredging (mainly from German activities), mercury and HCB's (from Delfzijl harbour). To our knowledge most of the contaminant related problems have been solved by The Netherlands authorities. The same holds for the strong loading of the estuary with organic material, a problem that has been solved completely. The eutrophication has been reduced due to European wide agreed measures, although the nutrient levels in the water are still too high. An existing problem that has only increased significantly over time is related to the maintenance of the navigation routes (fairways) in the estuary and up the river Ems until Papenburg.

2.3.1 Dredging

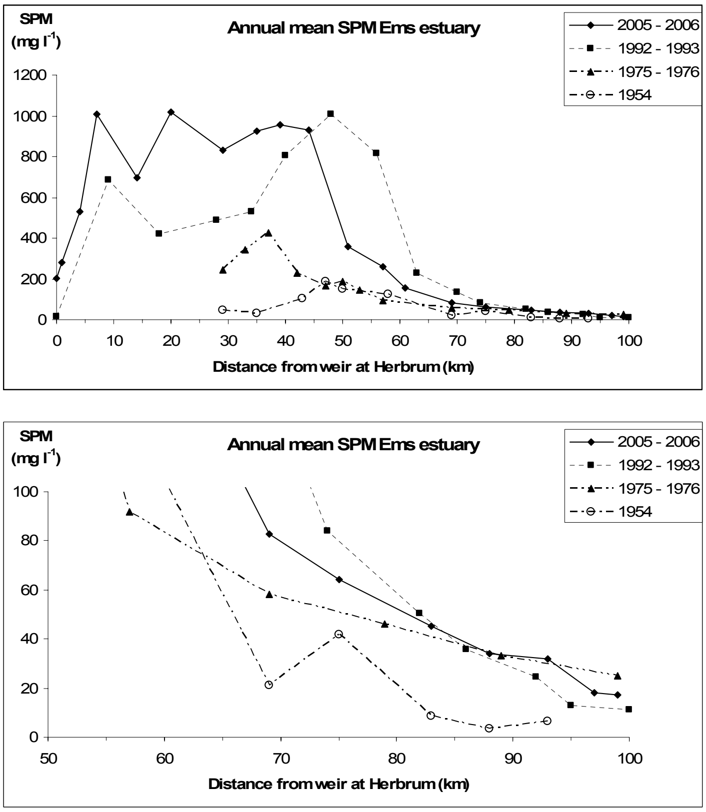


Figure 2.4: Mean annual suspended matter gradients for the years 1954, 1975–1976, 1992–1993 and 2005–2006 between Herbrum and Borkum (upper panel) and Emden and Borkum (lower panel).

There are only few observations on the suspended matter concentrations (SPM) in the Ems estuary before 1970. Available data from 1954 suggest (see also de Jonge (1983)) that the gradient was as given in figure Fig. 2.4.

During the 1970s the dredging activities in the estuary between Emden and the North Sea were extended up the coastal zone and were significantly intensified. All together this resulted (depending on the annual dredging activities) in a steeper gradient of suspended matter (SPM) between Borkum and the estuarine turbidity maximum (originally situated between Emden and Leer), the time lag between high water level and the turn of the flow at high water slack tide and the tidal range (de Jonge, 1983). Depending on the dredging activities the mean SPM concentrations between Borkum and the turbidity maximum varied between circa 40 and 90 mgl^{-1} (annual average values for the estuary between the turbidity maximum and Borkum) and thus over two-fold (Fig. 2.5). The 1954 value (circa 40 mg l^{-1}) represents the situation with minor annual

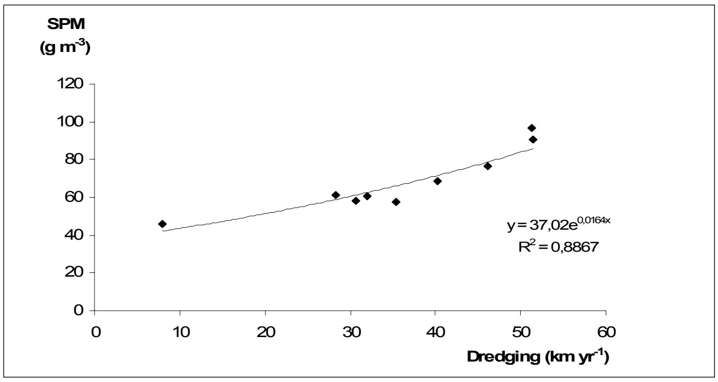


Figure 2.5: Relation between total length of bars removed and channels widened and deepened and mean annual concentrations of suspended matter (de Jonge, 1983)

dredging activities. Important to note is further that during the period 1970–1979 the mean annual SPM concentrations of the estuarine turbidity maximum were rather stable and circa 200 mg l^{-1}suspended particles (de Jonge, 1983, 2000). The observations by de Jonge (1983, Figs. 9 and 14), however, mean that more dredging means an increased mean SPM in the estuary and thus also a higher SPM concentrations in that part of the system which positively influence local as well as upstream mud accumulation.

Since the 1990s the SPM values in the estuary between Emden and Borkum (Fig. 2.4 lower panel) are two- to three-fold the values obtained for 1954. The situation thus has strongly deteriorated compared to the 1950s because of a higher turbidity which directly impacts the irradiation negatively. A decrease in the irradiation will lead to a proportional decrease in algal growth and thus a decrease in the food production for the ecosystem (see below).

The situation on the tidal river Ems between Emden and Herbrum also changed significantly. Since 1954 the mean SPM values of the estuarine turbidity maximum have increased nine-fold while the turbidity zone has moved up the river. Moreover, the turbidity maximum has significantly increased in length.

The two problems (the changes in the main estuary between Borkum and Emden and those on the tidal river between Emden and Herbrum) are created independently from each other but their effects cumulate. The effect of both problems thus contribute to the present SPM gradient. When the curves in Fig. 2.4 are fitted (exponentially) then it appears that the 1992/93 and the 2005/06 mean annual curves follow about the same function. Based on this it is hypothesised that the present SPM concentrations in the water column are in 'equilibrium' with the mud storage near the bottom as 'fluid mud'. Based on this hypothesis it is also hypothesised here that the present situation will continue to exist because all new mud that enters this part of the system from the seaward direction will be stored on the tidal river as fluid mud near the river bed because there is no other escape.

2.3.2 Organisms

The main estuary and the tidal river together represent the transition zone between the fresh water systems and the marine system. The changed situation since the 1950s has, however, led to some important changes in the ecological functioning of the system. The outer reaches of this estuary cover 275 km^2 (Fig. 2.1) of relatively clear water. This area is basically the 'granary' for the rest of the system. Here the production of 'green stuff' (the micro algae) takes place which is required for the rest of the system as food. This is so important because in upstream direction the water turbidity rapidly increases while at the same time the surface area declines from 275 to 90 km^2.

Calculations and measurements show that the algal food production in the water and on the intertidal flats in the outer reaches is over 80% of the total while the surface area is only 50% of the total area (Fig.2.6). This difference is caused by the differences in turbidity and the differences in surface area between channels and intertidal flats. Fact is that the outer reaches are of pivotal importance in feeding the rest of the system.

ALGAL GROWTH **Primary production (%)**	**LOWER REACHES**	**MIDDLE REACHES**	**DOLLARD**	**TOTAL ESTUARY**
Reference conditions (no dredging)	82 (100%)	12 (100%)	6 (100%)	100 (100%)
Measured 1975-1980 (35 km estuarine dredging)	49 (60%)	8 (67%)	5 (83%)	62 (62%)
Situation 2005-2006 (~35 km estuarine dredging + river improvements)	28 (34%)	5 (42%)	5 (83%)	38 (38%)

Figure 2.6: Deterioration in algal growth over time compared to a situation without any dredging. The present total algal growth is estimated to be lower than 40% of what it should have been.

A second problem is related to the turbidity maximum on the river. During the summer season the water of the river near the surface is hypoxic over a distance of circa 15 km. Deeper in the water the situation is even worse. Due to this no organism can migrate between fresh and marine waters. Another problem is related to the very high SPM concentrations due to which water filtering organisms can not live here. A third problem is related to seagrass (eelgrass, Zostera marina) which has developed on the Paap intertidal flat since in 1973 the first eelgrass plant was found there (by the second author). After a successful development between 1988 and the early 2000s (up to over 300 ha) a decline in the eelgrass beds occurred of which the cause is uncertain but must be related to developments within the system.

Thus, the total algal food production (Fig. 2.6) has, due to the increase in turbidity, decreased in steps which were ~ 60% of its maximum in the 1970s further down to less than 40% at present.

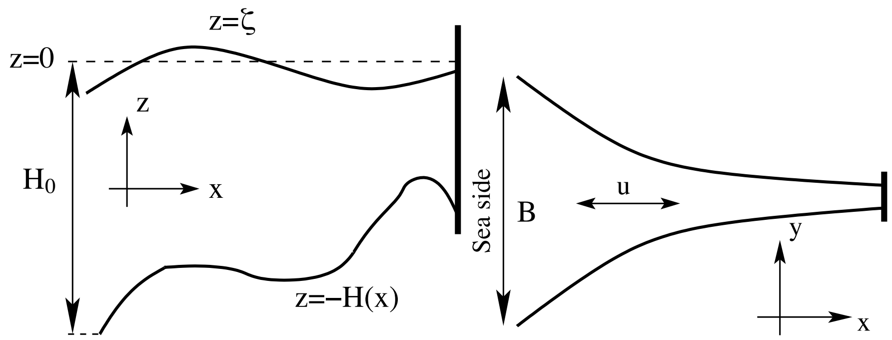
The main ecological conclusion thus is that due to the increase in SPM in the outer reaches the total estuarine system is suffering from a shortage in high quality basic food while due to the deterioration of the situation on the Ems river aquatic life there is strongly hindered and all migration during the summer season is impossible.

Chapter 3

Methods

To investigate the sensitivity of the water motion and the sediment trapping to the length of the estuary, results obtained with the model developed by Chernetsky *et al.* (2010) will be analysed. Below, a short description of this model will be given. For details, we refer the interested reader to the original article. The model of Chernetsky *et al.* (2010) is a so–called *idealised* model: the model is based on physical first principles, geared to gain knowledge of specific phenomena. To this end, the equations are approximated in an appropriate way, retaining only processes that appear to be important. Furthermore, the geometry is often simplified. One of the main advantages of this approach is that the results obtained with this type of model can be analysed in depth, using standard mathematical tools.

3.1 Model description



(a) (b)

Figure 3.1: Sketch of the model geometry. The panel at the left hand side depicts the side view of the estuary and the other panel presents the top view. A Cartesian coordinate system is used, with x the along-channel coordinate directed landwards, y the transverse coordinate and z the vertical coordinate pointing upwards. Other variables are introduced in the text.

For the research question we want to answer, a width-averaged idealised model for an estuary that is constrained by a weir at the landward side is constructed. The seaward boundary of the estuary is located at $x = 0$, the weir is found at $x = L$ (see Fig. 3.1). The estuary is assumed to be exponentially converging, i.e., the width $B(x)$ of the estuary is given by

$$B(x) = B_0 e^{-x/L_b}, \tag{3.1}$$

with B_0 the width of the estuary at the seaward side and L_b the exponential convergence length. The bed profile is described by $z = -H(x)$, $z = 0$ denotes the undisturbed water level and $z = \zeta(t, x)$ denotes the water surface.

The water motion in the longitudinal direction is modelled by the width-averaged shallow water equations:

$$u_x + w_z - \frac{u}{L_b} = 0, \tag{3.2a}$$

$$u_t + uu_x + wu_z + g\zeta_x - \frac{g\rho_x}{\rho_0}(z - \zeta) - (A_v u_z)_z = 0. \tag{3.2b}$$

Here, $x(u)$ and $z(w)$ denote the along-channel and vertical coordinate (velocity), respectively. Time is denoted by t, $g \sim 10$ m/s^2 is the gravitational acceleration, $\rho_0 \sim 1020$ kg m^{-3} is the reference water density and A_v is the vertical eddy viscosity coefficient. The along-channel density of the estuarine water is denoted by $\rho(x)$. At the free surface $z = \zeta$ the no stress condition and the kinematic boundary condition are prescribed, at the bottom we assume the bed to be impermeable and a partial slip condition is prescribed.

The water motion is forced by a prescribed tidal elevation at the seaward side of the estuary that consists of a semi-diurnal (M_2) constituent and its first overtide (M_4). The frequency of the M_4 tide is twice that of the M_2 tide (i.e., this tidal constituent results in four times high water per day, whereas the M_2 is a tidal component with twice–daily high water). This overtide is generated due to nonlinear interactions of the M_2 tidal component and bottom frictional effects in for example the North Sea. Hence at the boundary both tidal components are present, resulting in the following boundary condition:

$$\zeta(t, x) = A_{M_2} \cos \sigma t + A_{M_4} \cos(2\sigma t - \phi),$$

where $\sigma = 1.4 \cdot 10^{-4}$ s^{-1} is the tidal frequency of the M_2 semi-diurnal tidal constituent, and A_{M_2} and A_{M_4} are the amplitude of the externally forced M_2 and M_4 tidal constituent at the seaward boundary of the estuary. The relative phase ϕ is the phase difference between the M_4 and M_2 tidal components, defined by $\phi = \phi_{\zeta_{M_4}} - 2\phi_{\zeta_{M_2}}$, where $\phi_{\zeta_{M_2}}$ ($\phi_{\zeta_{M_4}}$) denotes the phase of the M_2 (M_4) tidal constituent. Apart from the externally prescribed M_4 overtide, overtides are also generated internally by nonlinear interactions and bottom roughness. The combination of the M_2 and M_4 velocity constituents results in so-called **tidal asymmetry**: an estuary is called flood (ebb) dominant if flood currents are stronger (weaker) than ebb currents.

At the riverine side a constant river discharge Q is prescribed and the tidal discharge is required to vanish

$$B(x) \int_{-H}^{\zeta} u dz = Q \quad \text{at} \quad x = L. \tag{3.3}$$

Sediment is assumed to consist of noncohesive (no capacity for forming aggregates) fine particles that have a uniform grain size (constant settling velocity) and are transported primarily as suspended load. The governing equation for the sediment dynamics is the width-averaged sediment mass balance equation

$$c_t + uc_x + wc_z = w_s c_z + (K_h c_x)_x + (K_v c_z)_z - \frac{1}{L_b} K_h c_x, \tag{3.4}$$

where c denotes the width-averaged sediment concentration and $w_s \sim 0.2 - 5$ mm s^{-1} the settling velocity. The turbulent vertical eddy diffusivity coefficient K_v is assumed to be equal to A_v. The horizontal diffusivity coefficient is denoted by K_h. Suspended sediment is transported due to diffusive contributions, temporal (or local) settling lag effects (related to tidal asymmetry and local inertia, see Groen (1967)), and spatial settling lag effects (which are related to the finite time for sediment particles to settle, see Postma (1954); de Swart *et al.* (2009)). At the surface, we require that no sediment particles enter or leave the system and that the normal component of the sediment flux at the bottom due to erosion is related to bed shear stress and the erosion coefficient $a(t, x)$.

If we assume that the tidally averaged erosion and deposition are locally in equilibrium, a condition for morphodynamic equilibrium is obtained that reads

$$\left\langle \int_{-H}^{\zeta} (uc - K_h c_x) dz \right\rangle = 0, \tag{3.5}$$

where we assume that there is no residual sediment flux at the weir (since the tidal velocities have to vanish at this location as well). Using this morphodynamic equilibrium condition, the unknown erosion coefficient $a(x)$ can be calculated for the estuary as defined above. This results in the spatial and temporal distribution of suspended sediment in the estuary under morphodynamic equilibrium conditions.

3.2 Solution Method

To get insight in the main balances described by the system of equations of section 3.1, the physical parameters and variables are scaled by their typical values. By analysing the scaled equations, it follows that not all terms are of equal importance as some contributions are multiplied by a small parameter (in this case the ratio of the amplitude of the M_2 sea surface elevation and the water depth at the entrance). This allows the construction of a so–called asymptotic solution, in which the physical variables are expanded in this small parameter. By this method, (quasi–)analytical solutions can be obtained at any order.

To get the dominant contribution to the water motion and sediment trapping, it suffices to construct the residual, M_2 and M_4 solution of the sea surface elevation, velocities and concentrations. Details about the solution procedure can be obtained from Chernetsky *et al.* (2010).

Chapter 4

Results

In this chapter, model results will be presented for parameter values and bathymetries that are representative for the Ems estuary between Knock and the weir at Herbrum in 1981 and 2005. Most of the parameter values, given in Table 4.1, are directly obtained from the observations, only the vertical eddy viscosity and the stress parameter are obtained from least–square fitting the model results to observed. Note that the length of the Ems estuary estuary between Knock and the weir at Herbrum (~ 63.7 km) is not given in the table, since this parameter will be varied in the experiments. The bathymetry from Knock to the weir at Hebrum is inferred from actual measurements of water depths in the years 1981 and 2005 (for the smoothing procedure, see Chernetsky *et al.* (2010)). To be able to vary the length of the estuary by moving the weir upstream of Hebrum, the water depth has been extended in this region with a water depth of

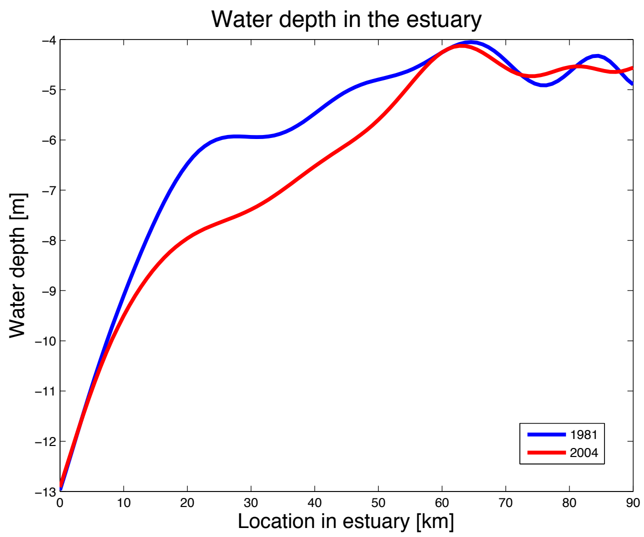


Figure 4.1: The bathymetry used in the experiments for the years 1981 and 2005.

approximately 4.5 m (see Fig. 4.1). The results are not very sensitive to this choice of extension of the bathymetry.

Table 4.1: Model input parameters representing 1980 and 2005 measurements carried out along the Ems/Dollard estuary, respectively

Parameter	Symbol	Dimension	1980	2005
Semi-diurnal tidal frequency	σ	s^{-1}	1.4×10^{-4}	
Gravitational acceleration	g	$m\ s^{-2}$	9.8	
β	β	psu^{-1}	7.6×10^{-4}	
Ref. density	ρ_0	$kg\ m^{-3}$	1020	
Sediment density	ρ_s	$kg\ m^{-3}$	2650	
Convergence length	L_b	km	30	
Water depth at the entrance	H_0	m	12.2	
M_2 tidal amplitude at the entrance	A_{M_2}	m	1.43	1.35
M_4 tidal amplitude at the entrance	A_{M_4}	m	0.25	0.19
Relative phase at the entrance	ϕ	degrees	−170.9	−174.6
Vertical eddy viscosity coefficient	A_{v0}	$m^2\ s^{-1}$	0.019	0.012
Stress parameter	s_0	$m\ s^{-1}$	0.098	0.049
River discharge	Q	m^3/s	60	
Along-estuary residual salinity gradient	$< s >_x$	$psu\ m^{-1}$	0.5×10^{-3}	
Settling velocity	w_s	$m\ s^{-1}$	0.002	
Horizontal diffusivity	K_h	$m^2\ s^{-1}$	100	

4.1 Water Motion

4.1.1 1981

In this section, the influence of the length of the estuary on the amplitude of the M_2 sea surface elevation is investigated, using the parameter values representative for the Ems in 1981. In Fig. 4.2, left panel, the colours indicate the M_2 amplitude in the estuary (x–axis) as a function of the length of the estuary (y–axis). Warmer (cooler) colours indicate larger (smaller) amplitudes.

To clarify the figure, consider an embayment with a length of 30 km, i.e., take the value of 30 on the y–axis (indicated by the yellow line in Fig. 4.2, left panel). The colours between 0 and 30 km (location of the systems upstream end) in x–direction indicate the M_2 amplitude of the sea surface elevation between the entrance (0 km) and the end (30 km) of the estuary. For clarity, these amplitudes are plotted again in the right hand panel (yellow line). Hence for an estuary of 30 km the amplitude increases from the seaward side of the modelled estuary part (Knock) from approximately 1.43 m to a maximum of 1.5 m at the point where the weir has been positioned in the model. Next, an estuary with a length of approximately 60 km (the length of the Ems right now) is considered (blue line). For this length the amplitude of the M_2 sea surface elevation decreases from the seaward side (Knock) to approximately 1.1 m at the location of the weir. Making the estuary even longer (for example 90 km, represented by the red line), this decrease in amplitude is even larger.

In a similar way, the amplitude can be inferred from this figure for estuaries with a different length. It is seen that an estuary with a length of ~ 35 km is in resonance: for this length the amplitude of the sea surface elevation is maximum at the landward side for all possible lengths of the estuary (see Appendix A for a discussion of tidal resonance). It is interesting to see that the character of the tidal wave is very different

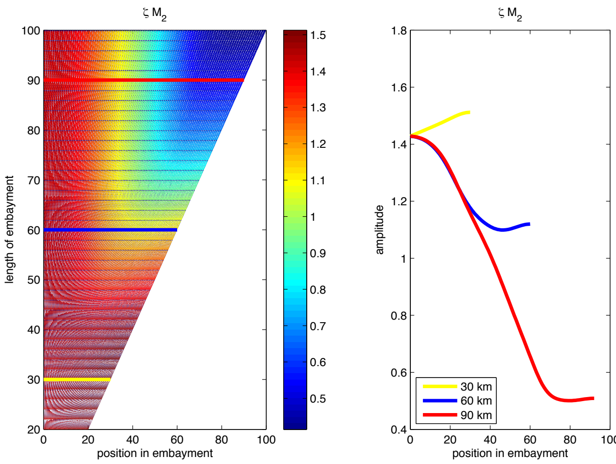


Figure 4.2: Colour plot of the M_2 sea surface elevation in the estuary as a function of the embayment length.

for an embayment with a length smaller than the resonance length, compared to the character for longer embayments. This is illustrated in Fig. 4.3. For short embayments (i.e, $L \leq 35$ km), the tidal wave has mainly the character of a standing wave, i.e., the phases are almost constant and the sea surface lags the velocity field by 90 deg (the relative phase difference between the M_2 tidal velocity and the M_2 sea surface elevation is approximately 90 deg, which means that the moment of maximum flood is a quarter tidal period earlier than the moment that the maximal sea surface elevation is reached). For long embayments (i.e. embayments longer than the resonance length of 35 km), the tidal wave behaves in a large part of the estuary as a travelling wave, i.e., the phase increases with distance and the relative phase is less than 90 deg.

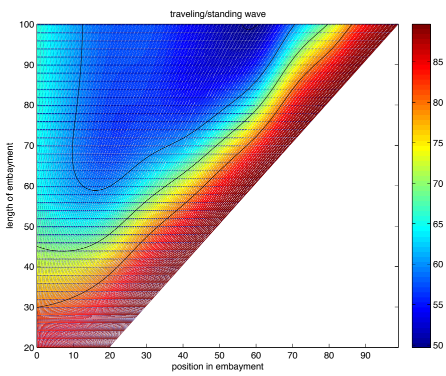
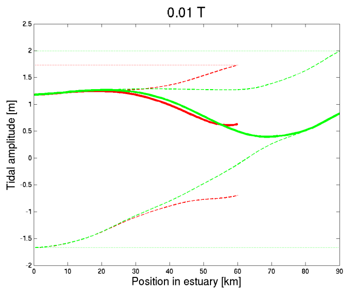


Figure 4.3: Colour plot of the M_2 relative phase in the estuary as a function of the embayment length.

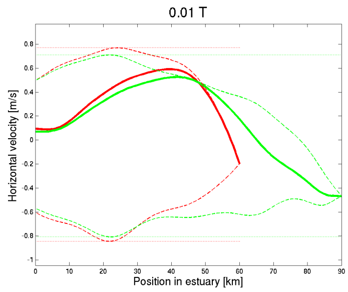
CONCLUSION I, 1981

In 1981 the Ems estuary has a length much larger than the M_2 resonance length. The tidal wave has a travelling wave character whose amplitude decreases with distance.

In Fig. 4.4, left panel, the sea surface elevations is shown at the beginning of a tidal cycle for an embayment with a length of 60 km (red line) and 90 km (green line). The dashed lines indicate the maximum positive and negative tidal elevations for an estuary with a length of 60 km (dashed red line) and 90 km (dashed green line). In the same figure, right panel, the horizontal velocity at the free surface is shown. The different lines have the same meaning as for the plot showing the sea surface elevation. From these figures, the following conclusions can be drawn:



(a) sea surface elevation



(b) surface velocity

Figure 4.4: Snapshot of the sea surface elevation (left panel) and surface velocity (right panel) at the beginning of the tidal cycle (solid lines) for an embayment with a length of 60 km (red) and 90 km (green). The dashed lines give the maximum/minimum values reached at that specific location in the estuary.

CONCLUSION II, 1981

Considering the estuary with a length of 60 km, the lowest water level at the landward side of the Ems was ~ -0.8 m, and the highest water level ~ 1.75 m (see Fig. 4.4). The maximum (minimum) surface velocity was of the order of 80 (-80) cm/s, reached approximately 20 km from Knock.

CONCLUSION III, 1981

When increasing the length of the estuary to 90 km, both the lowest and highest water level at 60 km from Knock have increased with ~ 0.5 m. The maximum (minimum) surface velocity are still of the order of 80 (-80) cm/s, reached approximately 20 km from Knock.

4.1.2 2005

Next, using the parameter values of the Ems of 2005, similar experiments have been performed as for the 1981 case. In Fig. 4.5 the amplitude of the M_2 component of the sea surface elevation is shown for different lengths of the estuary. The amplitude of the sea surface elevation reaches a maximum at the landward side for an estuary with a length of approximately 55 km. This implies that in 2005 the Ems estuary has a length

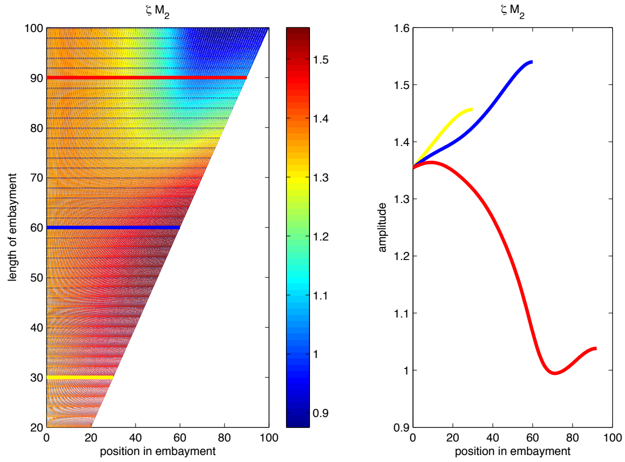


Figure 4.5: Colour plot of the M_2 sea surface elevation in the estuary as a function of the embayment length.

that is very close to its resonance length. The change in tidal characteristics is due to the deepening of the estuary *and* the decrease of bottom friction and vertical mixing due to the formation of a fluid mud layer (see Appendix A for a discussion of these two effects). As the system is much closer to resonance, the character of the tidal wave changed from mainly a travelling wave in 1981 to a wave with a more pronounced standing wave character in 2005. This can be seen by comparing the relative phase for an embayment of 60 km in 1981 (see Fig. 4.3) and 2005 (see Fig. 4.6).

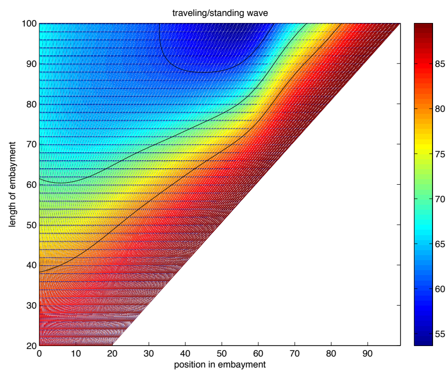
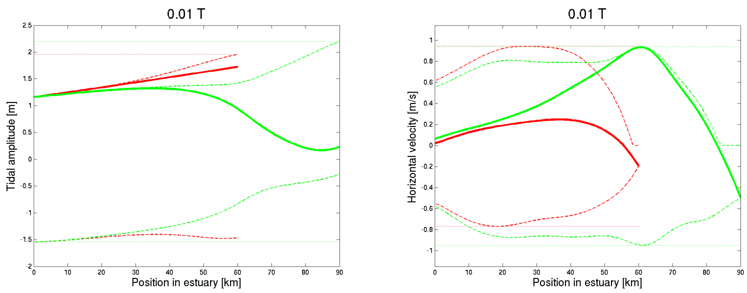


Figure 4.6: Colour plot of the M_2 relative phase in the estuary as a function of the embayment length.

CONCLUSION I, 2005

In 2005 the Ems estuary has a length that is close to the M_2 resonance length. The tidal wave has a standing wave character whose amplitude increases with distance.

In Fig. 4.7, left panel, the sea surface elevations is shown at the beginning of a tidal cycle for an embayment with a length of 60 km (red line) and 90 km (green line). The dashed lines indicate the maximum positive and negative tidal elevations for an estuary with a length of 60 km (dashed red line) and 90 km (dashed green line). In the same figure, right panel, the horizontal velocity at the free surface is shown. The different lines have the same meaning as for the plot showing the sea surface elevation. From these figures, the following conclusions can be drawn:



(a) sea surface elevation

(b) surface velocity

Figure 4.7: Snapshot of the sea surface elevation (left panel) and surface velocity (right panel) at the beginning of the tidal cycle (solid lines) for an embayment with a length of 60 km (red) and 90 km (green). The dashed lines give the maximum/minimum values reached at that specific location in the estuary.

CONCLUSION II, 2005

Considering the estuary with a length of 60 km, the lowest water level at the landward side of the Ems was ~ -1.5 m, and the highest water level ~ 2.0 m (see Fig. 4.7). The maximum (minimum) surface velocity was of the order of 95 (-80) cm/s, reached approximately $20 - 30$ km from Knock.

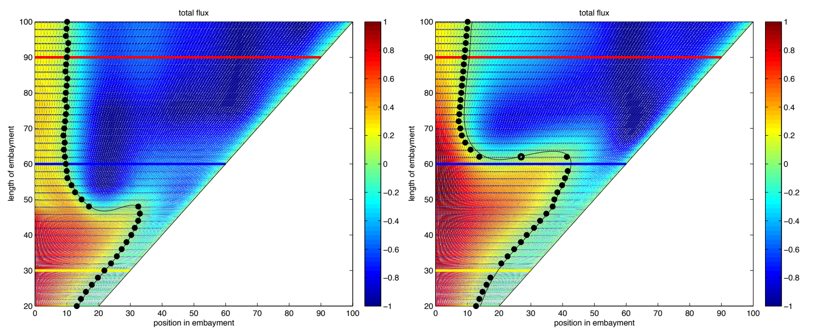
CONCLUSION III, 2005

Increase of the length of the estuary to 90 km, the lowest water level 60 km from Knock increased with approximately 60 cm and the highest water level decreased with $\sim$ 70 cm. The maximum surface velocity is still of the order of 95 cm/s, reached approximately 60 km from Knock. The minimum surface velocity is now ~ -1 m/s, reached at the same location.
Hence increasing the length of the estuary results in shorter exposure time of the river flood plains, which can strongly influence the ecological development of this habitat.

4.2 Sediment Trapping

Using the velocity fields (presented in the previous section), the spatial and temporal distribution of the suspended matter in the idealised estuary is calculated using the method, outlined in Chernetsky *et al.* (2010). Using this method, we are able to calculate the spatial pattern of the unknown sediment availability function $a(x)$ (and thus the suspended sediment concentrations) under morphodynamic equilibrium conditions (i.e. assuming that there is no tidally averaged transport of sediment). We are not able to predict the amount of sediment in the estuary, this means that only the *patterns* can be interpreted.

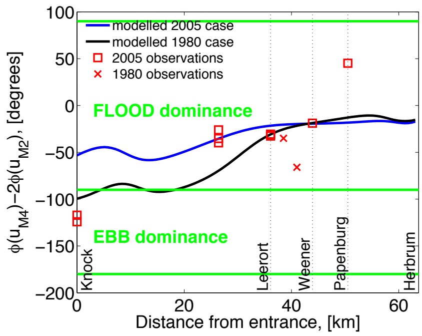
In Fig. 4.8 the location where the sediment is trapped is shown as a function of the length of the estuary. The trapping locations are indicated by the black solid–dotted line. The trapping locations are the locations where the highest concentration of suspended sediments will be found under the assumption that the system is in morphodynamic equilibrium. Of course, one can assume that the sediment availability is uniform in the estuary. This is *not* an morphodynamic equilibrium, and hence tidally averaged transport of suspended sediment is to be expected. This (scaled) transport is depicted in Fig. 4.8 by the colour plot: warm (cold) colours in this plot indicate the up–estuary (down–estuary) scaled transport of suspended sediment. When comparing the



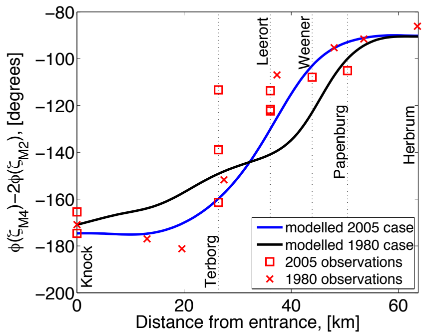
(a) Trapping locations in 1981 (b) Trapping locations in 2005

Figure 4.8: Trapping locations of suspended sediment (indicated by the black–dotted line) as a function of estuarine length. Warm (cold) colours in this plot indicate the up–estuary (down–estuary) scaled transport of suspended sediment if the availability function is taken constant in the estuary.

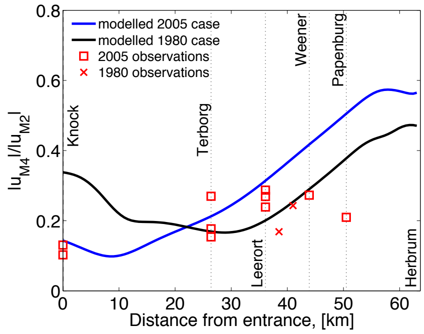
trapping location of sediment for 1981 (left panel) and 2005 (right panel) for an estuary with a length of approximately 60 km, it is clear that there is a dramatic shift: in 1981, sediment was trapped close to Emden (here around km 10), in 2005 the sediment was trapped much farther upstream (approx. 40 km from Knock). Since the different contributions to the total suspended sediment flux can be analysed in great detail, changes in trapping location can be associated with specific physical mechanisms. From a detailed analysis, it follows that this change in trapping location is mainly due to a strong increase of the tidal asymmetry between 1981 and 2005. This increase is mainly due to the fact that the character of the tidal wave has changed from a travelling tidal wave in 1981 to a standing wave in 2005. This resulted not only in a different sea surface elevation (see Fig.4.9b), but also in different velocity profiles (see Fig.4.9a and 4.9c). Note that the changes in tidal asymmetry, shown in Fig.4.9a, cannot be directly inferred from changes in the sea surface elevations (see Fig.4.9b). Since the changes in



(a)



(b)



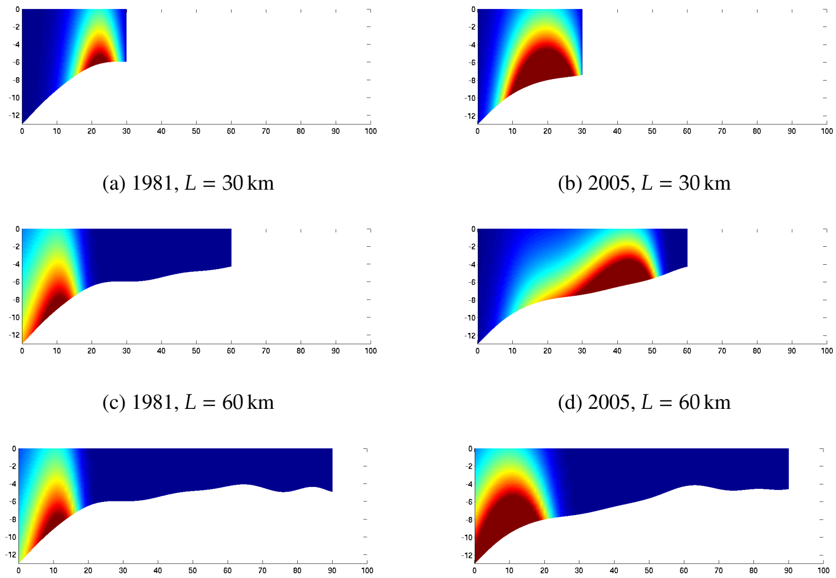
(c)

Figure 4.9: The water motion model results, taken from Chernetsky *et al.* (2010). The blue curves represent model predictions; the red marks show measured data at various locations. Scattered data at the same location means that measurements were done at various times. The dotted lines show locations at which the measurements were made in 2005. The upper left panel depicts the relative phase of the horizontal velocity at the surface and the upper right one represents the relative phase of the sea surface elevation. The lower panel shows the ratio of the M_4 over M_2 horizontal velocity at the surface. Changes from parameter regions with ebb and flood dominance are indicated by the green solid lines.

sediment transport are related to changes in the *velocities*, it is essential to look into changes in the velocities.

Compared to 1981, the system is much more flood dominated in 2005 (with flood dominance inferred from the velocities, *not* from the sea surface elevations) and the ratio of the amplitude of the M_4 and M_2 tidal velocities increased in a large region of the estuary. These changes in the velocities resulted in a more efficient transport of suspended sediment into the estuary.

From the previous section it follows that by increasing the length of the estuary, the tidal wave behaves more and more as a travelling wave. In this case, the import of sediment due to tidal asymmetry decreases and the sediment is trapped more towards the seaward entrance of the estuary. This is illustrated in Fig. 4.10, where the concentration profiles are plotted for an estuary with lengths of 30, 60 and 90 km, for the years 1981 and 2005. If we consider 1981 first (the left column of Fig. 4.10), we see that only for a very short embayment L = 30 km) the sediment is trapped at the weir. Increasing



(a) 1981, L = 30 km

(b) 2005, L = 30 km

(c) 1981, L = 60 km

(d) 2005, L = 60 km

(e) 1981, L = 90 km

(f) 2005, L = 90 km

Figure 4.10: Concentration profiles for specific lengths of the estuary. In the top row, the weir is placed 30 km upstream of Knock, in the middle row 60 km and in the bottom row 90 km. The left (right) column shows the results for 1981 (2005).

the length, high concentrations are found near the entrance of the estuary. This shift of high concentrations from the landward side of the estuary towards the entrance occurs if the embayment length is larger than the resonance length (see section 4.1). A similar behaviour is observed for the 2005 case: for estuaries that are short compared to the resonance length (i.e. L = 30 km) or have a length close to this resonance length (i.e. L = 60 km), high concentrations are mainly found near the weir. When the length of the estuary is significantly larger than the resonance length (i.e. L = 90 km), high sediment concentrations are only found near the entrance. From Fig. 4.8 it follows that if one would increase the length of the estuary to 70 km in 2005, the model predicts that the sediment will be trapped close to Emden. However, this result should be treated with care (as we are using an idealised model, in which many assumptions were made) and has to be compared with results obtained with state–of–the–art numerical models.

CONCLUSION IV

To assess changes in tidal asymmetry, it is not enough to consider sea surface elevations, one has to use the associated velocity fields to calculate this quantity.

CONCLUSION V

The upstream displacement of the trapping location from 1981 to 2005 is the result of an increase of tidal asymmetry. Note that the exact location of trapping depends, amongst others, on the magnitude of the river discharge and the grain size (cf. Fig.17 in Chernetsky *et al.* (2010)).

CONCLUSION V

Considering the conditions of 2005, but locating the weir 70 km upstream of Knock, results in trapping of sediment close to Emden. This is a result of the decrease of sediment import due to a decrease of transport resulting from tidal asymmetry.

Chapter 5

Conclusions

In this report, the influence of the location of the weir in the Ems estuary on the water motion and sediment dynamics has been investigated using an idealised model. The water motion is described by the width–averaged shallow water equations, and the sediment dynamics by a width–averaged advection–diffusion equation with sinks and sources. For an extensive discussion of the model equations, see Chernetsky *et al.* (2010). Here we would like to stress the following points:

- The model is not meant to be a *predictive* tool, it is developed to clarify which physical mechanisms are important and how they result in tidal amplification, sediment trapping, etc. Hence the aim of this model is not to get a comparison of model results and data that is as accurate as possible (by calibrating/validating the idealised model parameters), but to capture the behaviour of the system qualitatively and explain this behaviour from first physical principles.

  The 'predictions' made by the idealised model should be qualitatively compared and checked with results obtained from state–of–the–art complex numerical models, *and vice versa (this model intercomparison should be a two–way process).*

- In deriving these equations, simplifying parameterisations have been used (for example, the vertical eddy viscosity and diffusivity are assumed to be constant in time and space), the presence of fluid mud has been taken into account only parametrically (by varying the bottom stress parameter between different years) and the geometry has been simplified (i.e. a exponentially converging estuary is considered). This should be kept in mind when interpreting the results of the idealised model.

For an estuary with a length of 60 km, the water motion was non–resonant for the parameter values, representative for the Ems estuary in 1981. The amplitude of the M_2 sea surface elevation **decreased** when moving from the entrance of the estuary towards the weir, and the M_2 tidal wave behaved as a **travelling wave**.

Using parameter values representative for 2005, the water motion was resonant. The amplitude of the sea surface elevation **increased** from the seaward entrance towards the weir and the tidal wave had the characteristics of a **standing** wave. Both the **deepening of the estuary** and the **accumulation of fluid mud** (decreasing vertical mixing and bottom friction) contributed to in this amplification in the estuary.

This change in tidal dynamics resulted in a change of low and high water levels near the weir in Hebrum between 1981 and 2005. In 1981, the lowest water level at the landward side of the Ems was ~ -80 cm, and the highest water level ~ 1.75 m (see Fig. 4.4). The maximum (minimum) surface velocity was of the order of 80 (-80) cm/s, reached approximately 20 km from Knock. In 2005, the lowest water level at the landward side of the Ems decreased dramatically to ~ -1.5 m, and the highest water level increased to ~ 2.0 m (see Fig. 4.7). The maximum (minimum) surface velocity was of the order of 95 (-80) cm/s, reached approximately $20 - 30$ km from Knock.

Considering the 2005 situation, **increasing the length** of the estuary to 90 km will result in an **increase of the lowest water level** 60 km from Knock with approximately 60 cm and the highest water level decreases with $\sim$ 70 cm. The maximum surface velocity is still of the order of 95 cm/s, reached approximately 60 km from Knock. The minimum **surface velocity has increased** to ~ -1 m/s, and is reached at the same location.

Considering an estuary with a length of 60 km and using the parameter values representative for the Ems in 1981, it was found that the sediment would be trapped approximately 10 km upstream of Knock. Using parameter values, representative for 2005, the sediment was trapped in a much larger region starting approximately 20 km upstream of Knock up till 50 km upstream of Knock. This difference in sediment trapping was traced back to an **increase of the tidal asymmetry**: in 2005 the tidal asymmetry resulted in a strong import of sediment into the estuary, while this contribution was much weaker in 1981. This **increase in tidal asymmetry could *not* be inferred from changes in the sea surface elevations**, but could only be deduced from an analysis of the velocity components. This **change in transport due to tidal asymmetry** was shown to be closely related to **changes in the resonance characteristics of the estuary**. The trapping location does (of course), depend on grain size, river discharge, etc (Chernetsky *et al.*, 2010).

This change in suspended sediment distribution has resulted in **deteriorated light conditions** in the Ems estuary (between Borkum and Herbrum). This led to a situation where the primary production of organic material is estimated to have decreased by 60% compared to a natural situation without any dredging. The total food production is at present thus only 40% of what it could have been.

By **increasing the length of the estuary**, using the parameter values representative for the Ems estuary in 2005, the trapping location shifts from the end of the estuary to a location approximately 10 km upstream of Knock. According to the model results, **an increase of the length of the estuary by approximately** 10 **km would result in accumulation of fine sediment near Emden, instead of close to the weir**. We would like to stress again that these idealised model results have to be carefully tested using state–of–the–art numerical models (see above), as idealised models cannot be use as predictive tools but rather as tools that suggest the qualitatively behaviour of the system under consideration.

Appendix A

Tidal Resonance

In this appendix, the concept of tidal resonance is clarified by considering the cross–sectionally averaged shallow water equations for a homogeneous fluid in a tidal embayment with uniform depth H:

$$\zeta_t + [Hu]_x = 0, \tag{A.1}$$

$$u_t + +g\zeta_x + \frac{\hat{r}}{H} = 0. \tag{A.2}$$

Here the subscript defines differentiation with respect to that variable unless stated otherwise. The water motion is forced at the seaward entrance by a prescribed sea surface variation $\zeta = \hat{Z}\cos(\sigma t)$, with $\sigma \sim 1.4{\cdot}10^{-4}\,\mathrm{s}^{-1}$ the M_2 tidal frequency and $\hat{Z}$ the prescribed tidal amplitude. At the boundary on the landward side the depth–averaged velocity is required to vanish. Furthermore, $\hat{r} = 8UC_D/3\pi$, where U is a characteristic velocity scale and $C_D \sim 0.001$ is the drag coefficient. The bottom friction in the momentum equation (A.2) is linearised according to the energy dissipation condition discussed by Zimmerman (1992).

The solution to the coupled system of equations (A.1–A.2) reads

$$\zeta = \Re\left\{\frac{\hat{Z}}{\cos(k_\star L)}\left[\frac{1}{2}e^{k_i(L-x)}e^{i(k_r*x-\sigma t-k_r L)} + \frac{1}{2}e^{k_i(L-x)}e^{i(k_r*x-\sigma t-k_r L)}\right]\right\}, \tag{A.3}$$

with $\Re\{\cdot\}$ the real part of the expression, L the length of the estuary and $k_\star = k_r + ik_i$, with

$$k_r = \frac{\sigma}{\sqrt{gH}}\left\{\frac{1}{2}+\frac{1}{2}\left[1+\left(\frac{\hat{r}}{\sigma H}\right)^2\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}}, \qquad \text{and} \quad k_i = \frac{\sigma}{\sqrt{gH}}\left\{-\frac{1}{2}+\frac{1}{2}\left[1+\left(\frac{\hat{r}}{\sigma H}\right)^2\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}}.$$

Resonance of the estuary is characterised by an amplification of the sea surface elevation near $x = L$, i.e., the closed boundary. To this end, the ratio of the amplitude of the sea surface elevation $\hat{Z}/\cos(k_\star L)$ and the amplitude at the entrance of the embayment $\hat{Z}$ is shown in figure A as a function of the scaled embayment length. The embayment length is scaled with a quarter of the frictionless tidal wavelength L_g (with $L_g = 2\pi\sqrt{gH}/\sigma$).

When the frictionless case is considered ($\hat{r} = 0$, resulting in $\lambda = \hat{r}/\sigma H = 0$), we see that the amplitude of the sea surface at the coast goes to infinity for $L = \frac{1}{4}L_g, \frac{3}{4}L_g, \ldots$ (remember that the length L is scaled with $\frac{1}{4}L_g$). Hence we can conclude the following:

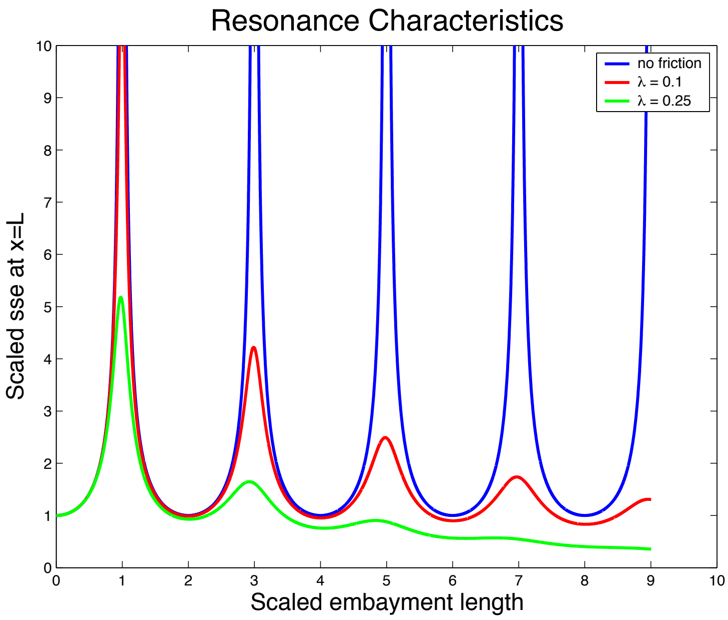
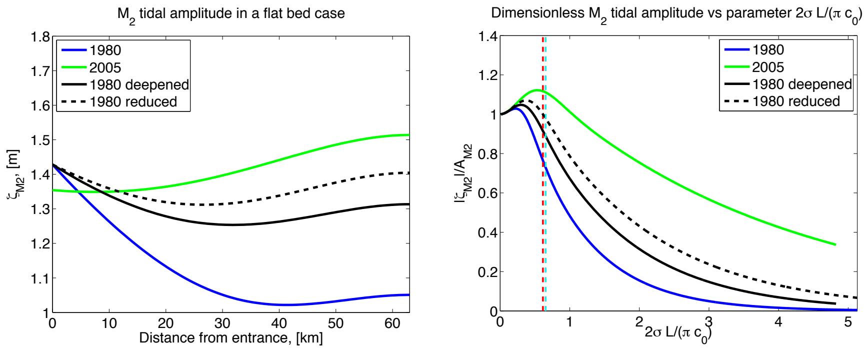


Figure A.1: Dimensionless sea surface amplitude at the coast versus scaled embayment length. The parameter $\lambda = \hat{r}/\sigma H$.

> If the estuary has a length of a quarter wavelength of the frictionless tidal wave (or three quarters, etc) the estuary is in *resonance*.
> This resonance length depends on the *water depth* H. This implies that by changing the water depth, a system that was not resonant can become resonant.

Bottom friction causes the resonance peaks to become finite. The decrease is larger as the ratio embayment length/free wavelength increases. With increasing values of bottom friction the resonance peaks shift towards smaller values of the scaled length and become wider.

In the main text, the model used is not integrated over the water depth. However, we can investigate the resonance of the estuary in this model in a similar way. As a first step, we consider an estuary with a flat bed constrained by a weir. We choose a representative water depth of $7.7m$ and $8.7m$) for 1980 and 2005, respectively. With these choices, the tidal character for the M_2 water motion is well-reproduced in the simplified model (see Chernetsky *et al.* (2010) for a detailed comparison). Again, the dimensionless M_2 tidal amplitude at the weir is plotted as a function of the embayment length scaled with a quarter wavelength of the frictionless tidal wave $L_g = \sqrt{gH/\sigma}$ in Fig. A.2b. The vertical red dashed line represents the length of the embayment of $L = 63.7\ km$, which is the length of the Ems estuary, with depth $8.7m$ and the cyan dashed line $7.7m$. In 1980 the estuary is far from resonance, by either deepening or reducing the bottom friction and vertical eddy viscosity the embayment becomes more resonant. Decreasing the vertical eddy viscosity and friction parameter is slightly more efficient in pushing the embayment towards resonance than deepening. As shown already in Chernetsky *et al.* (2010), both deepening and decrease of the vertical eddy



(a) (b)

Figure A.2: Flat bed model output. The left panel represent the M_2 tidal amplitude along the estuary and the right one depict the effect of bottom friction and deepening on the resonance characteristics.

viscosity and stress parameter are necessary to reproduce the 2005 amplification.

For completeness, the M_2 tidal amplitude is given as a function of position in the estuary for the different cases discussed above in Fig. A.2a.

Bibliography

CHERNETSKY, A., SCHUTTELAARS, H.M., & TALKE, S.A. 2010. The effect of tidal asymmetry and temporal settling lag on sediment trapping in tidal estuaries. *Ocean Dynamics*, **60**, 1219–1241.

DE JONGE, V.N. 1983. Relations between annual dredging activities, suspended matter concentrations and the development of the tidal regime in the Ems estuary. *Can. J. Fish. Aquat. Sci*, **40**, 289–300.

DE JONGE, V.N. 1992. Tidal flow and residual flow in the Ems estuary. *Estuarine, Coastal and Shelf Science*, **34**, 1–22.

DE JONGE, V.N. 2000. Importance of temporal and spatial scales in applying biological and physical process knowledge in coastal managemant, an example for the Ems estuary. *Cont. Shelf Res.*, **20**, 1655–1686.

DE SWART, H.E., SCHUTTELAARS, H.M., & TALKE, S.A. 2009. Initial growth of phytoplankton in turbid estuaries: a simple model. *Cont. Shelf Res.*, **29**, 136–147.

GROEN, P. 1967. On the residual transport of suspended matter by an alternating tidal current. *Neth. J. Sea Res.*, **3**, 564–575.

HINRICH, H. 1974. Schwebstoffgehalt, Gebietsniederschlag, Abflu und Schwebstofffracht der Ems bei Rheine und Versen in den Jahren 1965 bis 1971. *Dtsch. Gewsserk. Mitt.*, **18**, 85–95.

POSTMA, H. 1954. Hydrography of the Dutch Wadden Sea. *Arch. Neerl. Zool.*, **10**, 405–511.

SAMU, G. 1979. *Die morphologische Entwicklung der Aussen–Ems von Dukegat bis zur See*. Tech. rept. Bundesanstalt für Wasserbau, Hamburg.

VAN DER WELLE, J., & MEIRE, P. 1999. *Levende Eems. Herstelplan voor Eems en Dollard*. Tech. rept. Waddenvereniging.

ZIMMERMAN, J. T. F. 1992. On the Lorentz linearization of a nonlinearly damped tidal Helmholtz oscillator. *Proc. Kon. Ned. Akad. v. Wetensch.*, **95**, 127–145.