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Research paper

The impact of channel deepening and dredging on estuarine sediment concentration

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ABSTRACT

Many estuaries worldwide are becoming more urbanised with heavier traffic in the waterways, requiring continuous channel deepening and larger ports, and increasing suspended sediment concentration (SSC). An example of a heavily impacted estuary where SSC levels are rising is the Ems Estuary, located between the Netherlands and Germany. In order to provide larger and larger ships access to three ports and a shipyard, the tidal channels in the Ems Estuary have been substantially deepened by dredging over the past decades. This has led to tidal amplification and hyper concentrated sediment conditions in the upstream tidal river. In the middle and outer reaches of the Ems Estuary, the tidal amplification is limited, and mechanisms responsible for increasing SSC are poorly understood. Most likely, channel and port deepening lead to larger SSC levels because of resulting enhanced siltation rates and therefore an increase in maintenance dredging. Additionally, channel deepening may increase up-estuary suspended sediment transport due to enhanced salinity-induced estuarine circulation.

The effect of channel deepening and port construction on SSC levels is investigated using a numerical model of suspended sediment transport forced by tides, waves and salinity. The model satisfactorily reproduces observed water levels, velocity, sediment concentration and port deposition in the estuary, and therefore is subsequently applied to test the impact of channel deepening, historical dredging strategy and port construction on SSCs in the Estuary. These model scenarios suggest that: (1) channel deepening appears to be a main factor for enhancing the transport of sediments up-estuary, due to increased salinity-driven estuarine circulation; (2) sediment extraction strategies from the ports have a large impact on estuarine SSC; and (3) maintenance dredging and disposal influences the spatial distribution of SSC but has a limited effect on average SSC levels.

1. Introduction

Many estuaries worldwide have been modified in the past decades to centuries, in order to reclaim land and to allow ever larger ship access to inland waterways. These interventions include channel deepening and straightening as well as reclamation of the intertidal area, frequently leading to a combination of tidal amplification, increasing estuarine circulation, and increasing flood-dominance of tidal asymmetry (Winterwerp and Wang, 2013; Winterwerp et al., 2013). All of these mechanisms lead to increased residual transport. Tidal amplification strengthens the ebb and the flood tide transports, and consequently also the difference between ebb and flood (in case of an asymmetric tide). For example, a flood-dominant estuary will then become more flood-dominant. An increase in the flood dominance of the tides strengthens the flood flow velocities and weakens ebb flow velocity. Sediment transport increases non-linearly with the flow, leading to larger flood tide transport. Estuarine circulation leads to up-estuary transport; any increase herein therefore enlarges the up-estuary sediment transport. Which of these mechanisms is more important is site-specific, depending on the tidal regime, fresh water supply and sediment type. As a result of larger up-estuary sediment transport, in most (if not all) estuarine systems, the suspended sediment concentration has strongly increased. Some examples are the Ems River (Winterwerp et al., 2013; de Jonge et al., 2014), the Elbe (Kerner, 2007; Winterwerp et al., 2013), the Weser (Schrottke et al., 2006), and the Loire (Walther et al., 2012; Winterwerp et al., 2013).

The response of estuarine suspended sediment concentrations caused by anthropogenic influences is still poorly known. Decadal time-series documenting long-term changes in suspended sediment concentrations are rare (Fabricius et al., 2013). Additionally, many of these anthropogenic measures took place gradually and

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concurrently, and the response of estuarine suspended sediment dynamics to these changes may be slow (Winterwerp et al., 2013) and difficult to separate. Lastly, estuarine suspended sediment dynamics are complex, with up-estuary transport usually dominated by a combination of different physical mechanisms. Up-estuary decreasing salinity gradients generate an up-estuary directed near-bed flow velocity and down-estuary directed surface flow (estuarine circulation: Hansen and Rattray, 1965) which, combined with typical higher near-bed sediment concentrations, generates up-estuary sediment transport. This type of vertical circulation is relevant for fine sediment transport when this mechanism maintains (partial) stratification; in well-mixed estuaries horizontal circulation tends to develop at the expense of vertical circulations (Dyer, 1994). Estuarine circulation may be strengthened by tidal straining (differential advection of salinity by a vertical velocity shear; Simpson et al., 1990), demonstrated by Burchard and Baumert (1998) to enhance up-estuary transport, as well as by tidal asymmetry in internal mixing (Jay and Musiak, 1994). An asymmetry in the tidal velocity field may also lead to up-estuary sediment transport when the duration of High Water (HW) slack exceeds the period of Low Water (LW) slack or when the duration of the flood is shorter than that of the ebb (Friedrichs and Aubrey, 1988). Spatial variations further contribute, with settling lag generating landward sediment transport in response to landward decreasing flow velocities (Postma, 1961) or water depth (van Straaten and Kuenen, 1957). A time-variation in sediment properties (mainly due to flocculation and consolidation) further adds to the complexity (Scully and Friedrichs, 2007; Winterwerp, 2011). The relative contribution of these mechanisms differs per estuary, but may also change in time as a response to human interventions (Winterwerp, 2011).

In addition to influencing hydrodynamics and thereby long-term sediment transport processes, deepening (and port construction) in turbid estuaries will also increase siltation rates and, as a result, maintenance dredging needs and disposal. On the short term, maintenance dredging leads to increasing concentration levels in the direct vicinity of the dredging vessel (e.g. Collins, 1995; Pennekamp et al., 1996; Mikkelsen and Pejrup, 2000; Smith and Friedrichs, 2011). In the long-term, the effects of dredging on SSC is dominated by more complex mechanisms related to the water–bed interaction such as buffering of fines in the sandy seabed (van Kessel et al., 2011a), which is more difficult to quantify (van Kessel and van Maren, 2013). Most studies related to the effect of dredging originate from coral reef and seagrass environments, where their impact is most detrimental; see reviews by Erftemeijer and Lewis, 2006 (seagrass) and Erftemeijer et al., 2012 (corals). However, the question remains, to what extent dredging influences a long-term increase in suspended sediment concentrations (apart from its short-term impact), for the Ems Estuary and other systems. Finally, deepening allows larger ship access and often also to more intense ship traffic. Therefore resuspension by ships is likely to enhance suspended sediment concentrations further (van Houtan and Pauly, 2007; Aarninkhof, 2008).

Given the scarcity of available data over sufficiently long timescales, the wide range of human impacts, and the non-linear behaviour associated with sediment transport processes, a quantitative assessment of changes in suspended sediment concentration in an estuary caused by human activities is challenging. In this paper we use a numerical model to systematically investigate the individual contributions of deepening and dredging on suspended sediment dynamics in a heavily influenced estuary (the Ems Estuary) for which a reasonably large amount of data (recent and historical) exists. Existing process studies focussed on the tidal river draining into the larger estuary (the lower Ems River), in which changes in tidal dynamics are dominant and the suspended sediment concentrations increased several orders of magnitude in the past 3 decades. The conclusions of these studies are based on (semi-) analytical idealised models, revealing the role of sediment-induced density currents (Talke et al., 2009) settling lag (Chernetsky et al., 2010), deepening and hydraulic roughness (Winterwerp et al., 2013) and the potential role of the length (Schuttelaars et al., 2013) and depth (de Jonge et al., 2014) of the tidal river. Observations by de Jonge (1983) in the Ems Estuary suggest an increase in SSC as a result of dredging activities, but available data is limited, and collected in a period when construction work simultaneously took place. Despite large amounts of dredging, knowledge on the effect of deepening in the outer estuary as well as the effect of dredging and subsequent release on long-term SSC remains limited. A model approach to simulate long-term sediment dynamics, recently developed by van Kessel et al. (2011a), provides a tool to obtain better insight in the relative importance of dredging and subsequent disposal (van Kessel and van Maren, 2013), in the short term as well as the long-term.

This paper aims to better understanding the relative role of deepening and dredging on the sediment dynamics in the Ems Estuary in quantitative terms. We will first introduce the Ems Estuary, and describe the historical changes in suspended sediment concentration during dredging and deepening of the estuary. In the following section, the model is introduced and calibrated (Section 3) with which the effect of dredging and deepening is further quantified and analysed (Section 4).

2. The EMS estuary

The Ems estuary, situated on the Dutch–German border (Fig. 1), is an estuary which has undergone large anthropogenic changes in the past decades to centuries. Land reclamations carried out in the past 500 years have greatly reduced the intertidal area. Since 1650, the size of the Ems Estuary (the subtidal, intertidal and intratidal area) up to Eemshaven (between km 35 and 70; see Fig. 1 for location) decreased by 40% from 435 to 258 km^2 (Herrling and Niemeyer, 2007). The combined intertidal and supratidal area decreased by 45% from 285 to 156 km^2. Infilling is mostly of marine origin (the Wadden Sea and/or North Sea); the sediment load carried by the Ems River or smaller local rivers is very small. Human interferences in the estuary have accelerated in the past 50 years, with the construction/extension of three ports (Eemshaven, Delfzijl and Emden) and a large shipyard (Papenburg). The present-day approximate maintenance depths of the approach channels to the ports are 12 m (Eemshaven), 10 m (Delfzijl) and 11 m (Emden), requiring regular maintenance dredging. The tidal channels in the Ems Estuary were historically organised as distinct ebb- and flood-channels (van Veen, 1950). Some of these channels have degenerated as a result of channel deepening, effectively transforming parts of the estuary (especially its middle reaches; see Fig. 1 for location) into a single-channel system. Channel deepening affects tidal propagation, typically increasing the tidal range; which in turn leads to higher turbidity levels (Uncles et al., 2002). Deepening, but especially port construction, leads to more maintenance dredging and subsequent sediment dispersal; de Jonge (1983, 2000) suggests that this has significantly influenced the average turbidity levels. In this section, we will illustrate changes in bathymetry, sediment concentrations, and dredging in more detail.

The impact of human activities is most pronounced in the lower Ems River, a tidal river draining into the Ems estuary (see Fig. 1). The water depth increased from 4 m below MHW (circa 1960) up to 7.5 m below MHW (present day), leading to a strong tidal amplification and increasing suspended sediment concentrations. While suspended sediment concentrations were typically 10s to 100s of mg/l in the 1950's (Postma, 1961) and 1970s

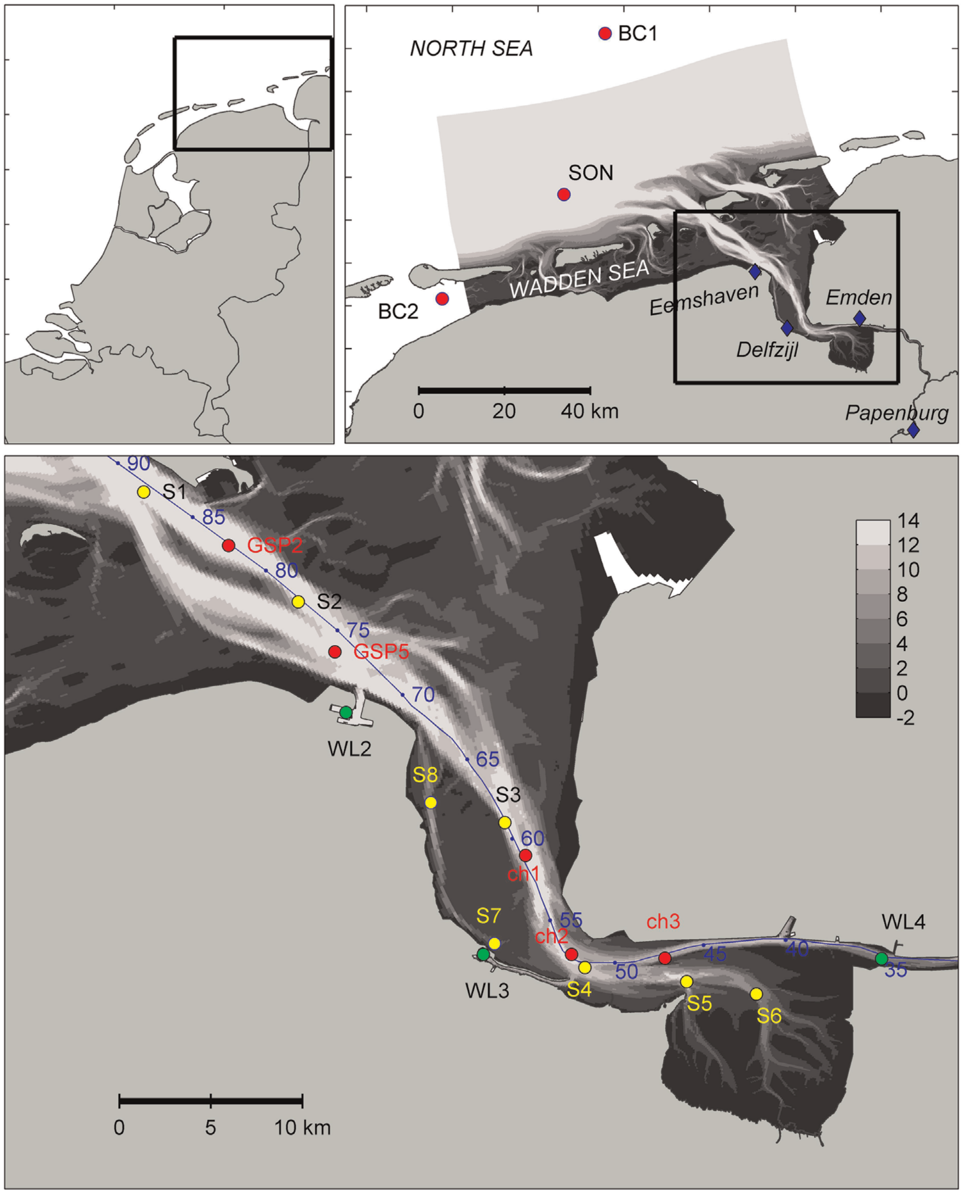

Fig. 1. Top right: map of the Ems estuary and model domain with the ports of Emden, Delfzijl, and Eemshavenand observation stations for waves (SON) and salinity (BC1 and BC2). Lower panel: more detailed map with observation stations Yellow dots stations indicate suspended sediment concentration observation points, green dots are water level observation points, and red dots represent flow velocity observations and model output. The blue markers and numbers are Ems kilometres, a standard reference in the estuary. Only the bed level between −2 and 14 m is shown to highlight the difference in tidal flats and channels, but the channels and offshore sea may be up to 30 m deep. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(de Jonge et al., 2014), the present-day lower Ems River is characterized by thick fluid mud deposits with concentrations in the order of 10s to 100s of g/l (Talke et al., 2009; Wang, 2010; Papenmeier et al., 2013). Large quantities of fine sediment are transported from the Ems estuary into the lower Ems River by a combination of density-driven flow (Talke et al., 2009, Donker and de Swart, 2013), lag effects (Chernetsky et al., 2010) and various types of tidal asymmetry (Winterwerp, 2011), possibly strengthened by tidal resonance after construction of an up-estuary weir (Schuttelaars et al., 2013). However, it remains unclear to what extent changes in the lower Ems River affect the Ems estuary. The high turbidity zone of the lower Ems River may be partly flushed into the Ems estuary during large winter discharge events (Postma, 1981, de Jonge et al., 2014). On the other hand over 1 million tons of fine sediment are extracted annually from the lower Ems River (Krebs and Weilbeer, 2008) potentially reducing the suspended sediment concentration in the Ems estuary.

Four standardized measurement locations exist in the Ems estuary, which are regularly sampled as part of the standard Dutch Monitoring Programme (hereafter called MWTL, see locations in Fig. 1). Measurements started in the early 1970s, but before 1990 the sampling strategies and methods regularly changed. Since 1990, the suspended matter is clearly increasing (Fig. 2) – statistical analyses reveal that this increase is statistically significant at the 95% confidence level (Vroom et al., 2012).

The most dramatic changes that took place in the estuary itself (excluding the lower Ems River) were deepening of the tidal channels and changes in dredging volumes and strategy. North of km 610 (Fig. 3), the morphological change is mainly reflected in laterally migrating channels. However, in the narrow section (between km 595 and 605), the main navigation channel became consistently deeper, whereas a degenerated tidal channel west of the main channel continually filled up with sediment (both with several metres).

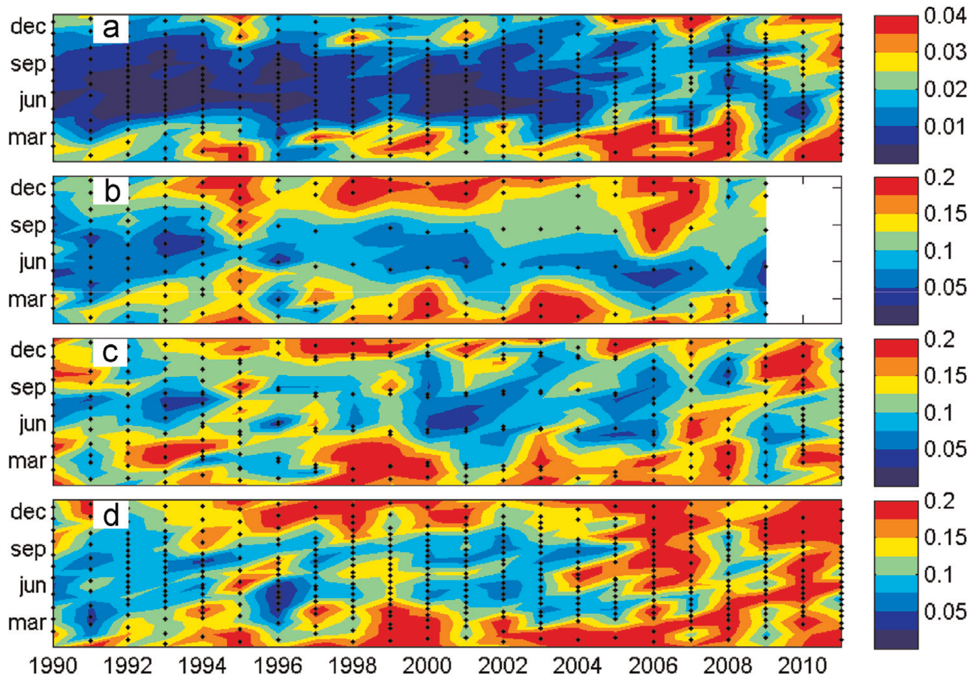

Fig. 2. Timestack plot of suspended sediment concentration in kg/m^3 in S1 (a; most seaward station), S8 (b), S7 (c), and S6 (d; most landward station); see Fig. 1 for locations. Observations at S8 were discontinued in 2010.

Since the 1960s the dredging activities in the Ems estuary have increased significantly (Fig. 4). The dredging volume is the amount of sediment that is removed from the seabed. This sediment can be extracted (when sediment is brought on land) or dispersed (when the sediment is disposed on dumping grounds elsewhere in the estuary). Sediment can be extracted for navigational purposes or for sand mining; the latter by definition meaning extraction. There have also been several changes in dredging strategies over the past decades. Most of the dredged sediment is muddy (Mulder, 2013).

An important observation is that the total dredging volume was at its peak in the 1970s and 1980s (~18 million m^3), but has decreased since then to ~10 million m^3. Surprisingly, the amount of dispersed sediment has remained fairly constant (at ~8 million m^3). The main change is related to sediment extraction. Between 1960 and 1994, 5.1 million m^3/year on average was extracted from the port of Emden (1.5 million m^3/year) and fairway (3.6 million m^3/year). Since 1994, sediment is no longer dredged from the port of Emden, but instead regularly re-aerated, thereby preventing consolidation. The resulting poorly consolidated bed remains navigable, and consequently the port no longer requires maintenance dredging (Wurpts and Torn, 2005). Sediment is still extracted from the lower Ems River. Since the early 1980s, the yearly dredged volume in the lower Ems River is disposed on land and has been steadily increasing from around 200,000 m^3/yr (Krebs and Weilbeer, 2008) to 1.5–2 million m^3/yr since 1993 (Weilbeer and Uliczka, 2012). Initially, the dredged sediment was sandy but is now predominantly muddy (Krebs and Weilbeer, 2008).

Sediment originating from the Emden fairway and the ports of Delfzijl and Eemshaven are dispersed in the Ems Estuary. Six million m^3/yr is dredged from the Emden fairway (Ems-km 40–53), and disposed seaward of Ems-km 64 (see Fig. 1 for the Ems km, but Section 4 for the location of the disposal grounds). An additional 2.8 million m^3/yr is dredged from the ports of Delfzijl and Eemshaven (Mulder, 2013), half of which is locally re-suspended through water injection dredging (Port of Delfzijl). About 1 million m^3/yr is dredged from the Eemshaven and disposed locally, whereas 0.3 million m^3/yr is dredged from the port of Delfzijl and disposed in the Dollard basin.

The rapid rise in required dredging volumes in the lower Ems River (around 1993) coincided with deepening of the lower Ems River from 5.7 to 7.3 m (1991–1994). However, in the same period the port of Emden ended its annual extraction of ~5 million m^3/yr, increasing the amount of sediment available for transport into the lower Ems River. The increase in dredging requirements may therefore be the result of deepening, but also of the changing dredging strategies.

The main human interventions can be summarised as follows. Over centuries, the size of the intertidal areas has been gradually reduced, resulting in increasingly less natural sediment sinks. In the past decades, several ports have been constructed and extended, requiring deepening of the approach channels and dredging and disposal of sediment. In the port of Emden, sediment was not disposed of, but ~5 million m^3 of sediment was annually extracted. This extraction strategy ended in 1994, simultaneously with a substantial deepening of the lower Ems River. The effect of tidal channel deepening in the Ems Estuary and sediment extraction from the port of Emden will be investigated in more detail in the next section.

3. Numerical model setup and calibration

3.1. Hydrodynamics

In order to quantify the individual impacts of dredging and deepening on the suspended sediment dynamics, a 3D numerical model was setup using the Delft3D software. The 8 vertical σ-layers increase logarithmically in thickness from the bed to the surface (2, 3, 5, 8, 13, 19, 25 and 25% respectively). The model bathymetry is based on surveys by the Dutch Ministry of Public Works in 2005 (Fig. 1). The model is forced at the seaward boundaries by water levels, salinity and temperature. The water level time series were derived from a larger operational model available online (http://opendap-matroos.deltares.nl/thredds/catalog/maps/normal/hmcn_kustfijn/catalog.html), in which tidal and storm-induced water level variations are modelled. The salinity is

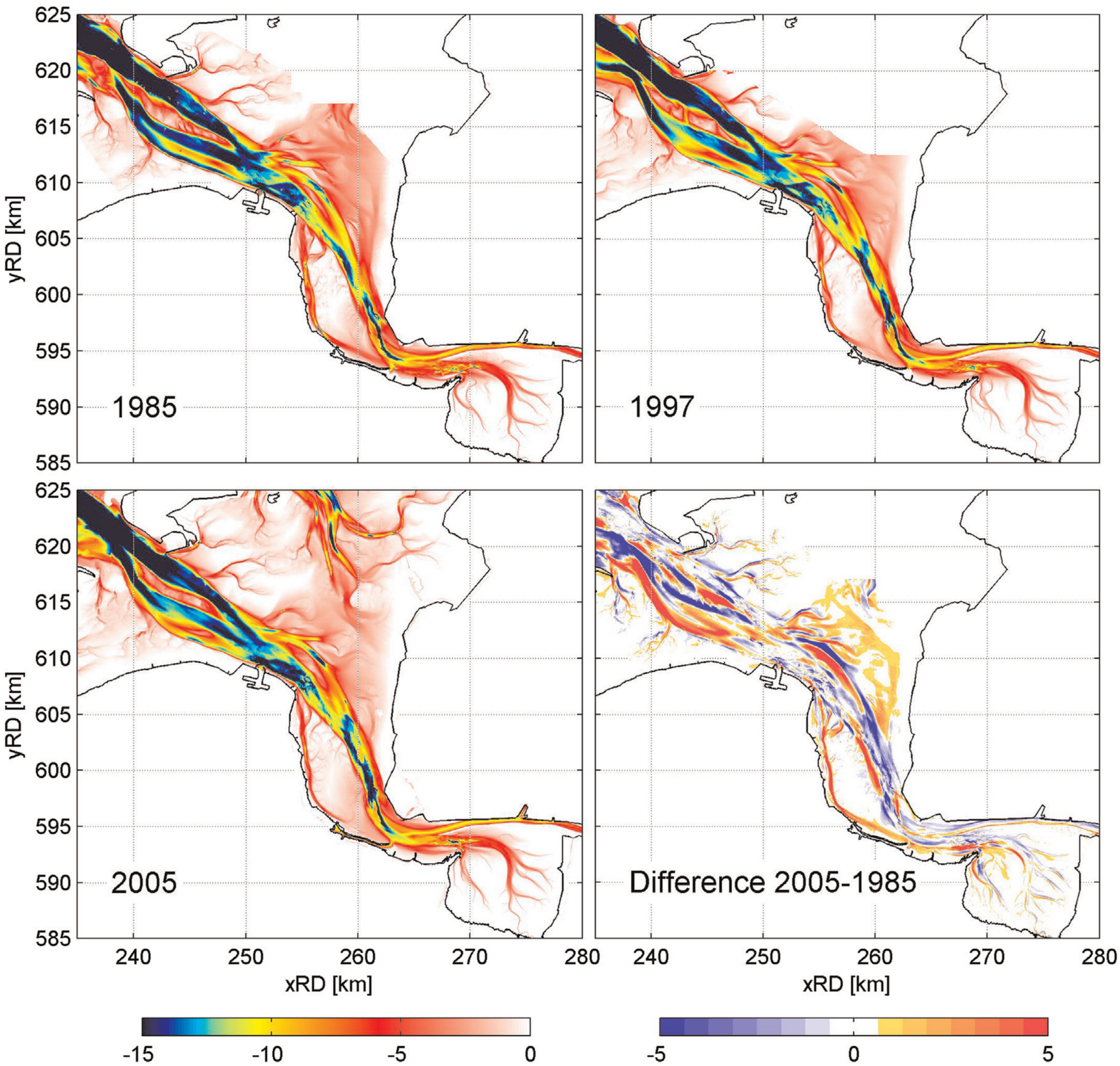

Fig. 3. Bathymetry in the Ems estuary in 1985, 1997, and 2005 (in metres relative to Dutch ordnance datum, based on soundings by the Dutch ministry of public works), and the difference between 1985 and 2005 (in metres).

derived from a nearby observation station measured every 4 weeks (live.waterbase.nl). Six rivers drain into the model of which the discharge of the largest (the Ems River) varies between 30 and 300 m^3/s (Fig. 5). The other rivers are typically an order of magnitude smaller, but also prescribed in the model. The effect of waves is computed with a SWAN wave model (Booij et al., 1999) run in online mode to include wave–current interaction. The wave model is forced by wave parameters (significant wave height, direction and the representative wave period) observed at an offshore wave buoy (Fig. 5) assuming a JONSWAP-spectrum (Hasselmann et al., 1973), and a spatially varying wind field (HIRLAM).

The computed water levels are compared with one-year observations in the frequency domain (using harmonic analysis; Pawlowicz et al., 2002) at 4 selected water level stations covering the estuary (Table 1). Typically, the error in computed water level amplitudes A_h and phases ϕ_h of the individual constituents is less than 5%, with even higher accuracy in the outer reaches of the estuary. From the most seaward station (S1) to the most up-estuary station shown here (WL3) the tides (observed as well as computed) are amplified by ~50%. Flow velocity has been observed for a period of 5 months at two stations (GSP2 and GSP 5) located in the estuary mouth. The amplitudes and phases of the modelled flow velocity (Table 2) are within 20% of observations at the most seaward station (GSP2) and in slightly better agreement deeper into the estuary (GSP5).

The type of asymmetry is determined by the flow velocity phase inclination θ_u of M_4 with M_2, given by $\theta_u = 2\phi_{u,M2} - \phi_{u,M4}$. The modelled and observed θ_u is 279 and 298° respectively using results from Table 2 at station GSP 5 (GSP 2 is not used to compute θ_u because of the small flow velocity amplitude $A_{u,M4}$). Tides with θ_u between 225° and 315° have equal ebb and flood flow velocities, but a longer duration of high water (HW) slack than low water (LW) slack. Such a slack tide asymmetry generates landward sediment transport by the settling lag (Postma, 1961); especially fine sediment is sensitive to local asymmetries in the duration of slack tide (Friedrichs, 2011). For short tidal basins, a phaselag θ_u of 270° corresponds to a phaselag in water levels θ_h of 180° (Friedrichs and Aubrey, 1988). The phaselag θ_h (with $\theta_h = 2\phi_{h,M2} - \phi_{h,M4}$) is typically between 160 and 180° in the four selected water level stations (Table 1, for both observations and model results), therefore in line with the velocity asymmetry. Both the water levels and the velocity data therefore show that the duration of HW slack exceeds the duration of LW slack (promoting tide-driven up-estuary sediment transport) which is reproduced by the model.

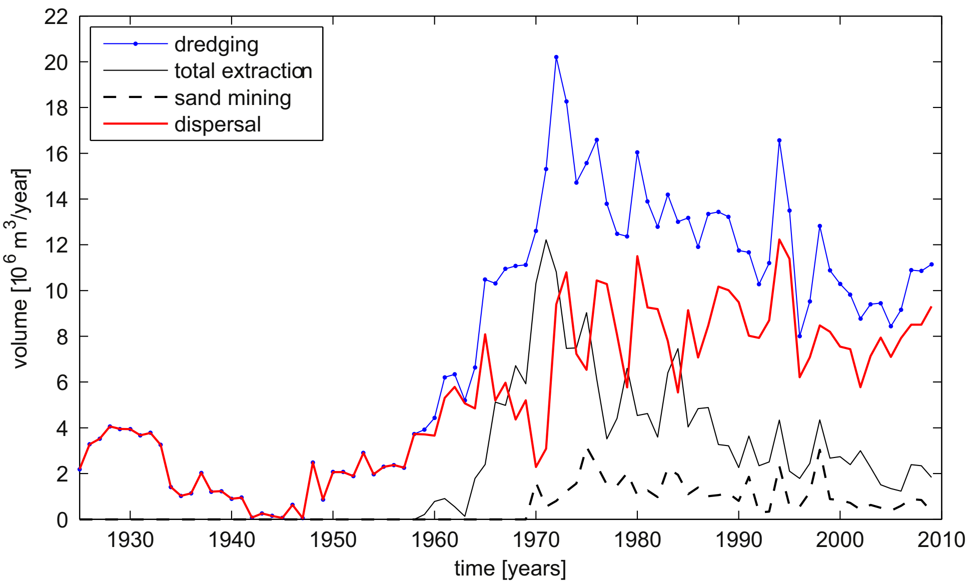

Fig. 4. Dredging volumes for the Ems estuary since 1925. Dredging volumes before 1960 are from de Jonge (1983) and exclude sand mining. Dredging volumes after 1960 is from Mulder (2013) for the Ems estuary (including sand mining) and from Krebs (2006) in the lower Ems River (until 2006; after 2006 a constant value of 1.5 million m^3 is assumed). Total extraction includes sand mining and dredge spill. Before 1994, this sediment was mainly from the port of Emden and approach channel (Mulder, 2013), averaging 5 million m^3/yr. After 1994, mostly sediment dredged in the lower Ems River is brought on land (~1.5 million m^3; Weilbeer and Uliczka, 2012). Sediment dispersal is the difference between dredging and total extraction.

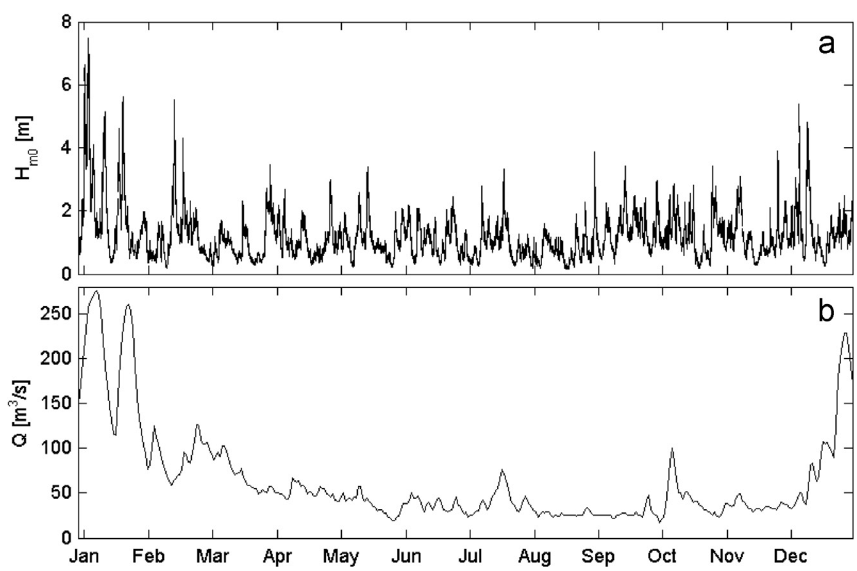

Fig. 5. Wave height (a) observed in an offshore wave station (SON, see Fig. 1 for location), and daily discharge (b) of the main river draining into the Ems Estuary (the Ems river at Herbrum), in 2012.

Table 1
Observed/modelled water level amplitudes (A_h) and phases (ϕ_h) of the 4 largest tidal constituents at stations S1 and WL1 – WL3. See Fig. 1 for the location of stations.

Constituent	Parameter	Station			
		S1	WL2	WL3	WL4
M_2	A_h [cm]	104/102	124/122	141/138	156/147
	ϕ_h [°]	248/247	281/275	300/295	313/313
S_2	A_h [cm]	31/30	35/35	40/39	42/44
	ϕ_h [°]	327/325	5/359	234/272	43/45
N_2	A_h [cm]	13/13	17/16	20/18	23/20
	ϕ_h [°]	236/235	275/269	298/294	312/314
M_4	A_h [cm]	9/9	10/10	18/17	18/13
	ϕ_h [°]	336/334	39/34	70/74	114/96

Table 2
Observed/modeled major flow velocity amplitudes (A_u) and phases (ϕ_u) of the 4 largest tidal constituents at stations GSP2 and GSP5. See Fig. 1 for the location of stations. Observed flow velocity amplitudes of 5 cm/s or less are shaded grey.

Constituent	Parameter	Station	
		GSP2	GSP5
M_2	A_u [cm/s]	80/96	87/99
	ϕ_u [°]	13/23	32/32
S_2	A_u [cm/s]	22/26	22/26
	ϕ_u [°]	85/96	103/103
N_2	A_u [cm/s]	17/17	17/18
	ϕ_u [°]	351/6	10/14
M_4	A_u [cm/s]	2/6	11/13
	ϕ_u [°]	325/327	126/145

3.2. Sediment transport

Next, a sediment transport model has been setup incorporating the effect of the buffering of fine sediments in the seabed (applying the algorithms developed by van Kessel et al., 2011a) and accounting for deposition in, and dredging and dispersal of sediments from the three estuarine ports. These algorithms are coupled offline with the hydrodynamics, and have been applied previously in the North Sea (van Kessel et al., 2011a), the Western Scheldt (van Kessel et al., 2011b), and Singapore (van Maren et al., 2014). This model distinguishes two bed layers: an upper layer (S_1) which rapidly accumulates and erodes, and a deeper layer (S_2) in which sediment accumulates gradually and from which it is only eroded during energetic conditions (spring tides or storms). This S_2 layer represents a sandy layer in which fine sediment accumulates during calm conditions. When the bed shear stress exceeds a critical value the sandy layer becomes mobile, and fine sediment that infiltrated earlier into this layer is slowly released. However, the transport of the sand layer itself is not modelled, but prescribed as a layer of a constant, and user-defined, thickness. Most sediment is stored (buffered) in this S_2 layer; S_1 represents the typically thin fluff layer consisting of mud, which rapidly erodes.

The erosion rate E_1 of S_1 depends linearly on the amount of available sediment below a user-defined threshold M_0/M_1:

$$E_1 = mM_1\left(\frac{\tau}{\tau_{cr,1}} - 1\right), \quad m < \frac{M_0}{M_1}$$

$$E_1 = M_0\left(\frac{\tau}{\tau_{cr,1}} - 1\right), \quad m > \frac{M_0}{M_1}$$

Here m is the mass of sediment in layer S_1 (in kg/m^2). This has the important consequence that also in dynamic environments the equilibrium sediment mass on the bed is non-zero, contrary to standard Krone-Partheniades (KP) models. Typically, this results in smoother and more realistic model behaviour in mixed sand–mud environments ($m < M_0/M_1$). For completely muddy areas ($m > M_0/M_1$), the buffer model switches to standard KP formulations for erosion of bed layer S_1. Hence, M_0 is the standard zero-order erosion parameter (kg/m^2/s) whereas M_1 (1/s) is the erosion parameter for limited sediment availability.

The erosion E_2 of S_2 scales with the excess shear stress to the power 1.5, in line with empirical sand transport pick up functions, assuming that fines trapped within the sandy bed are released when sand is mobilised:

$$E_2 = p_2M_2\left(\frac{\tau}{\tau_{cr,2}} - 1\right)^{1.5}$$

Here, p_2 is the fines fraction in S_2 (computed by the model) and M_2 is the resuspension parameter for S_2 (kg/m^2/s).

The deposition flux D is the settling velocity w_s times the near-bed sediment concentration C:

$$D = w_sC$$

The deposition flux D is divided between layers S_1 and S_2 with a burial parameter α:

$$D_1 = (1 - \alpha)w_sC$$

$$D_2 = \alpha w_sC$$

The value for α is based on calibration (van Kessel and van Maren, 2013), and is typically 0.05–0.2. A low value for α implies a slow exchange with buffer layer S_2. In combination with settings for M_2 and $\tau_{cr,2}$ it also determines the residence time of fines in the buffer layer.

We use two sediment fractions, IM1 with a large settling velocity (1.2 mm/s) and IM2 with a small (0.25 mm/s) settling velocity. The settling velocity of IM1, representing fairly large and rapidly settling flocs, is based on observed settling velocities of flocs in the Ems estuary typically between 1 and 2 mm/s (van Leussen and Cornelisse, 1996). The IM2 settling velocity corresponds to the minimum settling velocity observed by van Leussen and Cornelisse (1996). The spatial distribution of IM1 and IM2 is determined by the model: all sediment in the model domain entered through the open boundaries, where IM1 and IM2 were prescribed at equal sediment concentrations.

Spatially uniform values for the critical shear stress for erosion τ_{cr} are prescribed for the S_1 layer and the S_2 layer. Sediment which does not or only marginally consolidates has a critical shear stress for erosion τ_{cr} of several 0.01 to ~0.1 Pa (e.g. Widdows et al., 2007). Therefore the critical shear stress for the fluff layer is very low ($\tau_{cr,1} = 0.05$ Pa), implying that sediment in the top layer is easily resuspended. Sediment in S_2 is assumed to erode during more energetic conditions only, when a substantial amount of sand is brought in suspension and the mud trapped in the sand layer is released. This occurs at larger shear stresses than the initiation of motion of sand particles; earlier studies (van Kessel et al., 2011a) suggested a value around 1 Pa. In this study, $\tau_{cr,2}$ is set to 0.9 Pa. The thickness of the sand bed (layer S_2) is set to 10 cm, representing the zone where active mixing by biological activity and (bedform-related) sediment transport takes place. The erosion parameters M_0, M_1, and M_2 (see Table 3) are obtained through calibration (van Kessel and van Maren, 2013). Flocculation and consolidation are not modelled. The use of 2 bed layers represents model behaviour similar to consolidation: during low energy conditions sediment is progressively buried in layer 2 (and is therefore no longer regularly resuspended). Also the effect of biology (influencing the erodibility of the intertidal mud deposits) is not accounted for in the model.

The boundary conditions at the North Sea and Wadden Sea are set at 10 mg/l and 100 mg/l for IM1 and IM2 respectively, based on long-term observation stations (similar to the observations in Fig. 2). A sediment concentration of 10 mg/l is also prescribed to all fresh water sources. An equilibrium bed condition (the amount of sediment in S_1, S_2, and in suspension) is obtained by: running the model with a thin S_2 bed layer (for faster adaptation time) for a number of years; then increasing the thickness of the S_2 layer to 10 cm (a typical active layer depth); and finally running the model repetitively with cyclic hydrodynamic forcing until dynamic equilibrium is achieved (where the suspended sediment concentration and sediment availability vary with tidal and seasonal timescales, but not over the years). Depending on the settings of the model, a dynamic equilibrium for both the distribution of mud on the bed and suspended in the water column is achieved within several years (Five years using the settings in Table 3). The bed level in the sediment transport model is kept constant, so it is not a morphological model: erosion and deposition influences the available mass of sediment below a bed level which is constant in time.

Nine areas are defined from which sediment is dredged once

Table 3
Sediment transport model settings.

Parameter	Description	IM1	IM2
$w_{s,0}$ [mm/s]	Settling velocity	1.2	0.25
M_0 [kg/m^2/s]	Erosion parameter	2.5×10^{-3}	2.5×10^{-3}
M_1 [/s]	Erosion parameter	1.2×10^{-4}	1.2×10^{-4}
M_2 [kg/m^2/s]	Erosion parameter	1.2×10^{-3}	1.2×10^{-3}
$\tau_{cr,1}$ [Pa]	Critical bed shear stress	0.05	0.05
$\tau_{cr,2}$ [Pa]	Critical bed shear stress	0.9	0.9
α [−]	Burial rate	0.1	0.1
Thickness S_2 [m]	Thickness of sand bed	0.1	

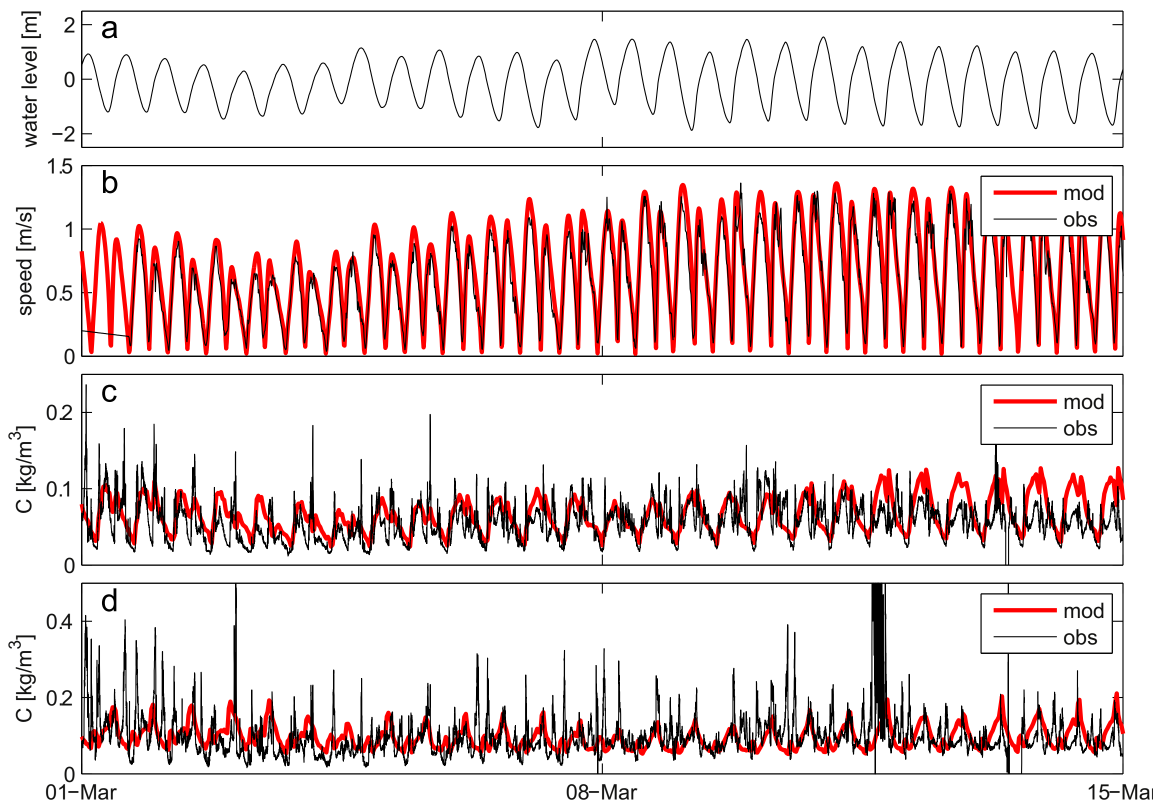

Fig. 6. Computed water level (a); observed (black) and computed (red) depth-averaged flow velocity (b); near-surface sediment concentration 4 m below the water surface, (c); and near-bed sediment concentration (d) at location GSP5, from 1 to 15 March 2012. See Fig. 1for the location. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

every week (from layer S_1 and layer S_2), and disposed in the dumping locations designated to the dredging sites. Dredging is instantaneous, but disposal is distributed over 3 days to avoid unrealistic peaks in the suspended sediment concentrations. Given the large dredging volumes in the area, discretization of dredging and dumping in different areas provides a more realistic description of sediment transport in the estuary. Additionally, the computed deposition rates in the ports can be compared with observed dredging volumes, providing validation of the sediment transport model. An added value of such a dredging module is that it allows for a quantitative insight in the long-term effects on dredge spoil dispersal.

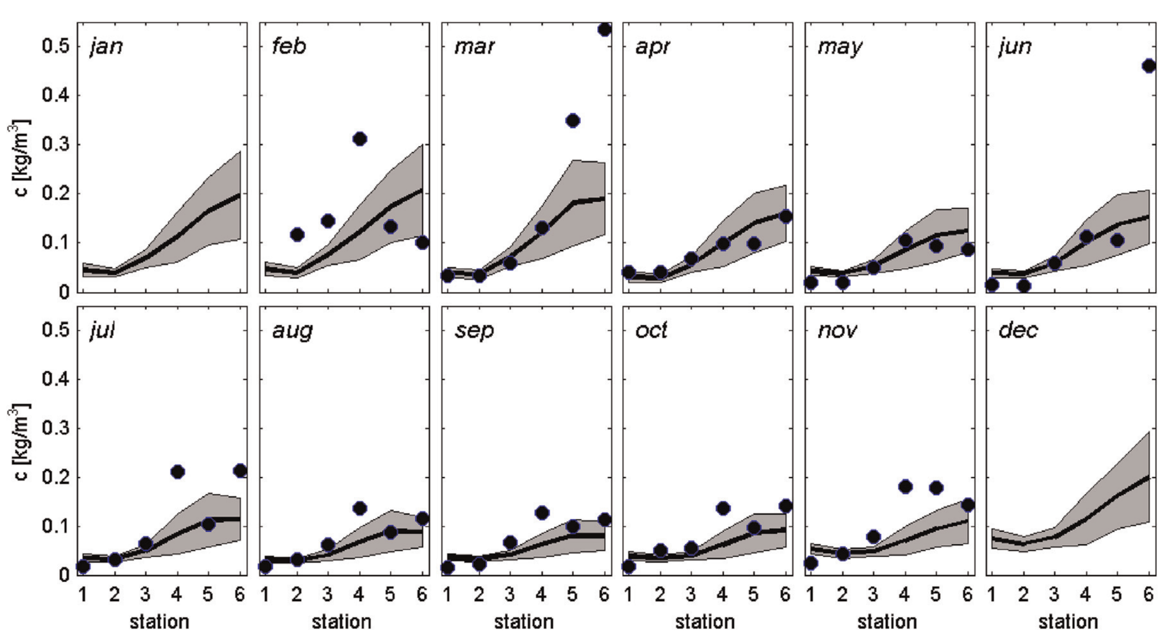

Fig. 7. Monthly averaged computed surface sediment concentration (black line, with grey shading indicating the standard deviation) and observed surface sediment concentration (black dots, February through November) in 2012 at stations S1–S6 (in kg/m^3). See Fig. 1 for the location of stations.

A time-series comparison of the computed and observed suspended sediment concentration at station GSP5 (Fig. 6) reveals that the intra tidal and spring neap variation in SSC are well reproduced. The computed near-bed sediment concentration is typically two times larger than the near-surface sediment concentration, which is in line with field observations, suggesting that the vertical sediment concentration gradients are reproduced. The along-estuary gradient in SSC is evaluated by comparing the model against snapshot surface samples collected every 2–4 weeks at 6 stations (S1–S6, see Fig. 1 for location). The model reproduces the observed up-estuary increase in the surface sediment concentration, and the seasonal variation of the sediment concentration with larger sediment concentrations during the winter months (Fig. 7). The largest deviations between observations and model results occur in February and November. An explanation for this could be that sediment flushed from the lower Ems River is underestimated by the model: the largest deviations occur at stations halfway the estuary. This flushing is underestimated because the sediment transport processes in the Ems River are very complex – see the end of this section. Nevertheless, even though two-weekly snapshot measurements only provide an indicative value for comparison with a sediment transport model, the reasonable correspondence suggests the model reproduces the actual estuarine suspended sediment concentration gradient.

The model also reproduces the pronounced up-estuary increase in mud content in the bed (Fig. 8). The highest mud content is observed and computed in the Dollard bay and the approaches to the port of Delfzijl. In line with observations, the computed mud content increases in the landward direction of the Wadden Sea (the coastal lagoon adjacent to the Ems Estuary) as well. The computed siltation in the three ports in the estuary is typically around 0.5–0.8 million tons/yr. The computed deposition in the ports of Eemshaven and Delfzijl are within 10% of the long-term observed deposition rates (Table 4). However, deposition in the port of Emden and its approach channel is strongly underestimated. This is probably related to the hyper turbid conditions in the lower Ems River, which drains into the Ems estuary close to the port of Emden.

The sedimentary conditions in this reach of the river require a different modelling approach with more complex formulations to account for flocculation, sediment-induced density effects, and consolidation. These processes demand for more detailed and short time scale simulations which conflict with the multi-year objectives of this study. Therefore a more accurate description of the sediment dynamics in the lower Ems River is beyond the scope of this paper.

Table 4
Estimated and computed deposition rates.

Port/area	Estimated deposition (million tons/yr)	Computed deposition (million tons/yr)
Eemshaven	0.5	0.44
Delfzijl	0.8	0.76
Emden port and fairway	1.6	0.55

4. Effect of sediment extraction sediment disposal and deepening

The developed model is subsequently used to experiment with historic scenarios. This reference model reflects the present-day conditions (i.e. the 2005 bathymetry and no extraction of sediment). It was hypothesised earlier in this paper that discontinuing sediment extraction (dredging the ports and bringing sediment on land) has led to a pronounced increase in SSC. Therefore the reference model with dredging is re-run with extraction (instead of dredging and dumping) of all sediment depositing in the port of Emden and its approach channel. With respect to this scenario with extraction, the reference model (with dredging from Emden) leads to an increase of 0–50 mg/l in SSC in the outer reaches, but up to 100 mg/l within the estuary (Fig. 9a). The typical concentrations in these up-estuary sections are 100–300 mg/l (Fig. 7), implying the impact of dredging strategy is substantial. However, it was also concluded that the model strongly underestimates deposition rates in the port of Emden and its approach channel (Table 4). Therefore, although historically as much as 2.5 million tons were extracted on an annual basis, only 0.5 million tons/yr is extracted in the model. To better approximate the effect of extracting such a large sediment mass, the model is also run with extraction from all ports (totalling a mass of 1.75 million tons, see Table 4). This leads to a two-fold larger suspended sediment concentration change (Fig. 9b).

The most realistic way to evaluate the effect of the presence of ports (excluding their approach channels) is by comparing the model including ports and subsequent dredging and disposal activities (the reference model), with a scenario without ports (and therefore also without deposition in ports nor related dredging and disposal activities). Including ports raises the suspended sediment concentration in the vicinity of disposal sites, but decreases the sediment concentration further away from the disposal sites (Fig. 9c). This follows from the large sediment accumulation rates in the ports, extracting sediment from the estuary and hence lowering the ambient suspended sediment concentration.

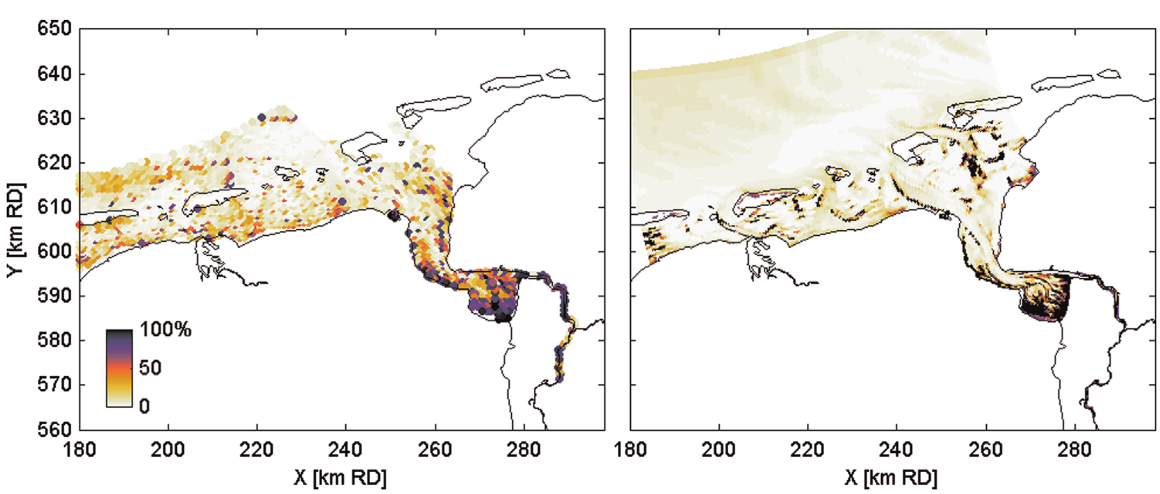

Fig. 8. Observed (left, based on surveys from 1989) and computed (right, S1 and S2) mud content in the bed (in %).

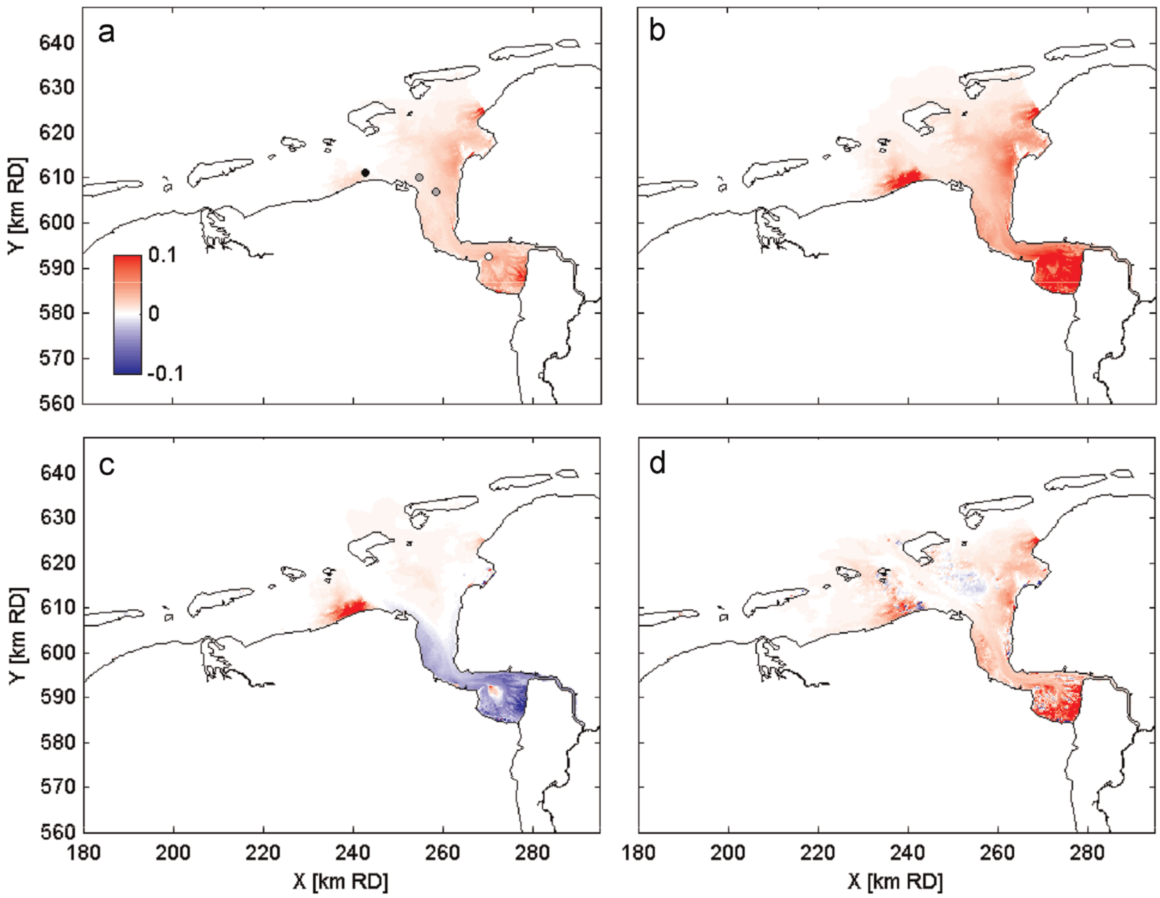

Fig. 9. Computed increase of yearly averaged surface suspended sediment concentration (in kg/m^3) for 4 scenarios. The increase is defined as the difference of the annual means, computed for Scenario (a): dredging and dumping of all ports, compared with extracting from Emden; Scenario (b): dredging and dumping from all ports, compared with extraction from all ports; Scenario (c) construction of ports and resulting dredging and disposal of sediment, compared with no ports nor dredging activities; Scenarios (d) extraction from Emden with the 1985 bathymetry compared to dumping from Emden and 2005 bathymetry. The disposal grounds are visualised in panel (a) with circles, with a colour depending on the origin of the disposed sediment (black for Eemshaven, grey for Emden, and white for Delfzijl).

In order to allow ships to enter the ports, tidal channels are frequently deepened. The tidal channels in the Ems estuary have been deepened with several metres (Fig. 3). As a consequence, a model with the 1985 bathymetry was setup. The closest approximation of the change from the 1980s to the 2000s is by comparing the reference model with a scenario including the 1985 bathymetry model and extraction from the port of Emden (Fig. 9d). Compared to extraction only (Fig. 9a), the increase in suspended sediment concentration is larger. Therefore the impact of deepening alone is evaluated in more detail.

The model is run with the 1985 and 2005 bathymetry (with all other settings equal). The year 2005 is simulated with a baroclinic model (including density-induced effects due salinity) and a barotropic model (without density effects) in order to separate the change in SSC due to estuarine circulation. Deepening of the estuarine channels alone leads to an increase of more than 50 mg/l

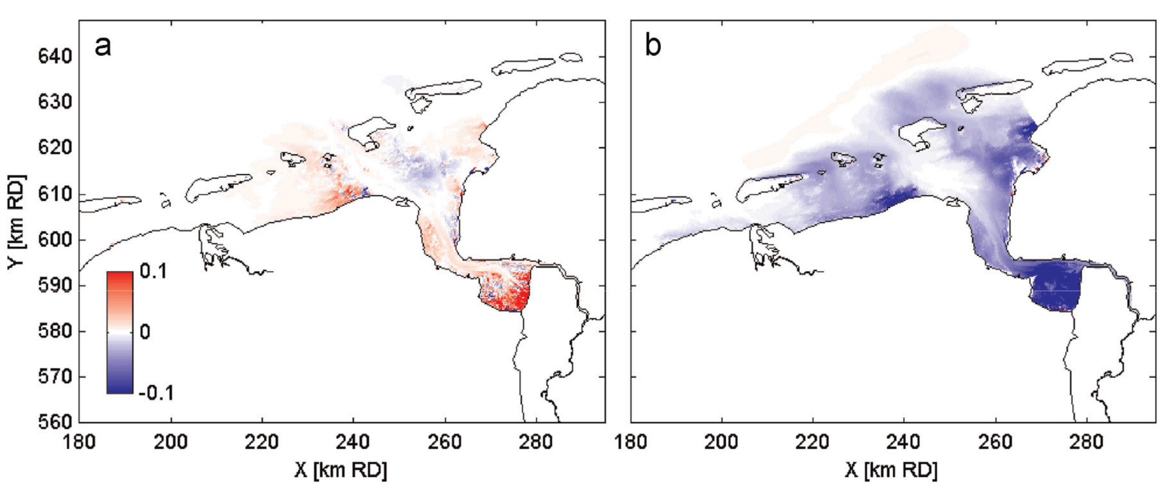

Fig. 10. Computed increase in surface sediment concentration (in kg/m^3) due to deepening from 1985 to 2005 (a) and a reduction in surface sediment concentration by running the model without density effects (b).

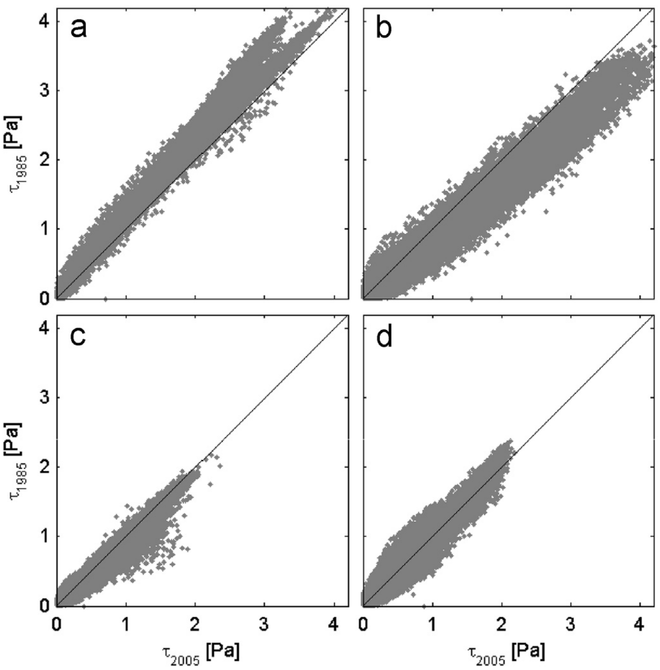

Fig. 11. Bed shear stress computed every 10 minutes at GSP2 (a), ch1 (b), ch2 (c), and ch3 (d) for 2005 (*x*-axis) and 1985 (*y*-axis): plotted values cover the full year. See Fig. 1 for the location of stations.

in the up-estuary parts (Fig. 10a). The tide-induced bed shear stresses differ slightly between 1985 and 2005 (Fig. 11) because of small phase shifts in the propagation of the tides, but there is no overall trend. At station GSP2, the bed shear stress was slightly larger in 1985 whereas the bed shear stress at ch1 was slightly larger in 2005. Such relatively small changes do not have an effect on turbidity as large as in Fig. 10a.

A more realistic mechanism for this change therefore is estuarine circulation. Estuarine circulation is a residual flow component (superimposed on the oscillating tidal currents) which develops in the presence of a horizontal salinity gradient, and increases in strength with larger water depth. The surface flow velocity is directed towards the area of higher salinity, the near-bed velocity is directed towards the freshwater source. Since the near-bed sediment concentration is higher than the near-surface sediment concentration (see also Fig. 6), estuarine circulation generates up-estuary sediment transport. For the 2005 bathymetry, estuarine circulation is a key mechanism for up-estuary transport, which is demonstrated with a model excluding density effects. The suspended sediment concentration in this barotropic model is much lower than the reference model (Fig. 10b), demonstrating the importance of estuarine circulation.

The effect of salinity is therefore further explored with residual flow velocity profiles at 4 stations throughout the main channel of the Ems estuary (Fig. 12, see Fig. 1 for the location). Without density effects, the residual flow velocity is low and displays a logarithmic vertical profile. In contrast, for both 1985 and 2005 (with density effects) the residual near-bed flow velocity is typically directed up-estuary. However, the magnitude of the near-bed flow velocity is typically two times larger in 2005, compared to 1985. It is therefore concluded that the deepening of the tidal channels in the estuary in the period 1985 to 2005 has strengthened density-induced estuarine circulation patterns, which subsequently substantially raised the suspended sediment concentration.

5. Discussion

5.1. Long-term effects of dredging on SSC

With a few exceptions such as de Jonge (1983), the long-term impact of dredging on suspended sediment concentrations has received fairly limited attention in scientific literature. The long-term morphological effects of dredging are fairly well known due to the relatively large amount of (historic) topographic data in heavily modified estuaries (e.g. Jeuken and Wang, 2010; Monge-Ganuzas et al., 2013). Most commonly, studies related to dredging-induced turbidity focus on the sediment dynamics in the direct vicinity of the dredger (Pennekamp et al., 1996; Mikkelsen and Pejrup, 2000; Spearman et al., 2011; Smith and Friedrichs, 2011), on the fate or deposition of dredged sediment (e.g. Bai et al., 2003; Van den Eynde, 2004; Cronin et al., 2011; Hayter et al., 2012; Alba et al., 2014), or on the impact on sensitive ecosystems (Erftemeijer

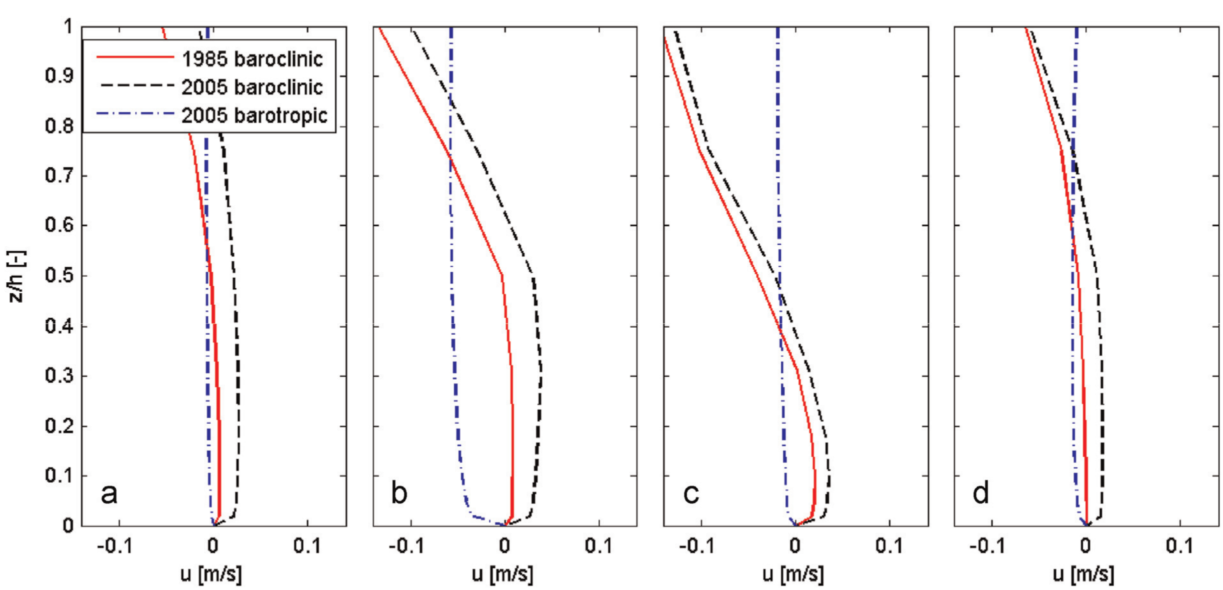

Fig. 12. Residual flow velocity profiles, with positive values directed up-estuary, computed at GSP2 (a), ch1 (b), ch2 (c), and ch3 (d) for 1985 and 2005 (baroclinic mode) and 2005 (barotropic mode, i.e. no density effects). The averaging period is January through March, the period during which the fresh water discharge is largest. See Fig. 1 for the location of stations.

and Lewis, 2006; Erftemeijer et al., 2012). When carefully executed, the impact of dredged sediment disposal on turbidity may be limited to the short-term and near-field (Fredette and French, 2004). Often the dispersion of individual plumes is considered, whereas it is the long term cumulative effect of a large number of individual plumes that determines the impact. Over longer timescales resuspension of dredged material from the seabed may become the dominant factor contributing to turbidity (van Kessel and van Maren, 2013). Fettweis et al. (2011) observed a long-term increase in the suspended sediment concentration and formation of fluid mud. Fluid mud formation is not included in our model, even though fluid mud forms in the entrance of the Emden navigation channel. Regular resuspension of this fluid mud layer contributes to elevated sediment concentration levels. As indicated earlier, the underestimated sediment concentrations in February and November are possibly related to the complex suspended sediment dynamics in the navigation channel, which are not captured by the model. If any long-term increase in SSC is related to fluid mud formation, this will not be properly accounted for in the model applied here.

In our simulations, the effect of dredging and disposal is large when comparing the present-day situation (a scenario in which dredged sediment is disposed) to a scenario in which sediment is not disposed but sediment is still allowed to settle in ports (equivalent to extraction, see Fig. 9b). However, a more appropriate scenario to estimate the effect of dredging and disposal is to compare the present-day situation to a scenario without ports (and hence no dredging and disposal). This reveals a much more limited effect of dredging and disposal: the sediment concentration increases near the disposal sites but slightly decreases elsewhere (Fig. 10c). Our results are difficult to compare with de Jonge (1983), who concluded that the suspended sediment concentrations in the Ems Estuary in a specific year depended on the distance dredged during that year. This relationship was strongly influenced by capital dredging for construction of the Eemshaven, and it remains unclear how much of the dredged sediment in the analyses is extracted or disposed. Moreover, although the distance dredged and sediment concentration is correlated in de Jonge's data, both also increase in time: hence the increase may also be the result of channel deepening.

5.2. Effects of deepening on SSC

It is well known that salinity-induced density currents lead to up-estuary transport of sediment (e.g. Meade, 1969; Uncles et al., 1985). In our model, this effect of salinity-induced residual currents is demonstrated by the pronounced difference between the computed sediment concentration in barotropic (excluding salinity-induced residual currents) and baroclinic (including salinity-induced residual currents) simulations (Fig. 11b). The magnitude of the residual flow velocity u in the tidal channel scales with the cubed water depth h as in Hansen and Rattray (1965):

$$u_z \equiv h^3\left(1 - 9\left(\frac{z}{h}\right)^2 + 8\left(\frac{z}{h}\right)^3\right)$$

As a result of this strong depth-dependence, deepening of tidal channels leads to strengthening of the residual current. For a 10 m deep channel, deepening by 2–4 m leads to a 1.7–2.7-fold increase in salinity-induced residual flow (assuming the horizontal salinity gradient is unaffected by deepening). In very few (if any) estuaries worldwide, observational evidence exists for the impact of deepening on estuarine circulation. The reason for this is that the residual flow velocity is very sensitive to the observational technique and exact location. Channel deepening is often accomplished over many years or even decades. Identical data collection programs before and after channel deepening are therefore few or non-existent. A reliable alternative to assess the impact of deepening on residual currents is a scenario analysis using a well-calibrated process-based numerical model.

Our model strongly suggests that baroclinic processes influence the estuarine suspended sediment dynamics, and that the magnitude of estuarine circulation increased as a result of deepening. As a result, the modelled response to channel deepening is an up-estuary increase in SSC. It should be realised that the computed effect of different scenarios (dumping/extraction, 1985/2005, barotropic/baroclinic) is influenced by the parameter settings and process formulations of the numerical sediment transport model. Therefore, while the trends remain valid, the absolute values or details in the spatial patterns of changes in suspended sediment concentration computed with process-based numerical models as used here should be interpreted carefully.

5.3. Other impacts

The change in dredging strategy and deepening is likely not the only contributor to increased suspended sediment concentration. In the Ems Estuary, and the lower Ems River, the loss of tidal flats may influence long-term changes in the suspended sediment dynamics. Deepening of the lower Ems River (the main river draining into the Ems Estuary) has strongly amplified the tides and increased the suspended sediment concentrations within the tidal river (e.g. de Jonge et al., 2014). One million tons of sediment is annually extracted from the lower Ems River (Krebs and Weilbeer, 2008), and on the long term the tidal river may therefore reduce the sediment concentration in the estuary. However, regular flushing of the tidal river during high discharge events (Spingat and Oumeraci, 2000) transports sediments from the river into the estuary, and the long-term effect of the tidal river on the estuary remains poorly known. Additionally, many of the intertidal areas that existed in the Ems estuary have been reclaimed in the past centuries. These intertidal areas provided a natural sink for sediment to accumulate.

Since 1650, the size of the Ems Estuary has decreased by 40% (177 km,see Section 2) due to infilling with fine sediments. Most of this accumulation took place in the Dollard, which used to be much larger: the present-day intertidal area used to be tidal channels. In some areas, deposition must therefore have been many metres. These sediment deposits are well consolidated, and therefore have a dry density of $\sim$1500 kg/m^3. Assuming an average thickness in deposition of 3 m yields an average annual accumulation rate of 2.3 million tons (partly consisting of sand), between 1650 and present. This number is a very crude estimate for the yearly siltation rates, and more research is needed to further quantify it. Nevertheless, the long-term loss of sediments by deposition is probably comparable to the extraction rates from the port of Emden ($\sim$2.5 million tons/yr). With a constant supply of sediments, removal of this natural sink inevitably leads to a rise in suspended sediment concentrations. It therefore seems likely that apart from deepening and port construction, the suspended sediment concentration has already been slowly increasing for centuries. Compared to the large dredging volumes, and especially the impact of extraction, the impact of changing ship traffic (hypothesized in Section 1) is probably a minor effect

This leads to the following hypothesis for the increasing suspended sediment concentrations in the Ems Estuary:

1. The potential sediment supply to the Ems estuary by the North Sea and Wadden Sea has always been large.
2. The large-scale reclamation of intertidal areas increased the suspended sediment concentrations in the past centuries.

3. Large-scale port construction but especially deepening of the tidal channels in the 1960s increased the up-estuary sediment transport; however.
4. The increase in suspended sediment concentration remained limited because of large-scale sediment extraction (on average ~2.5 million tons/yr) in and near the port of Emden until the early 1990s.
5. After 1990, sediment was no longer extracted, and as a result the suspended sediment concentrations increased substantially.

5.4. Relevance for other estuaries

Many estuaries worldwide are heavily modified. Channels are deepened to accommodate larger ships, and intertidal areas are reclaimed to for need of land. These changes have led to tidal amplification and to increasing suspended sediment concentrations (Winterwerp and Wang, 2013; Winterwerp et al., 2013). The role of dredging on the suspended sediment concentration and the impact of deepening on turbidity through enhanced estuarine circulation (both addressed in this paper), have so far received little scientific attention. This is probably because (1) many of these human interventions occur concurrently, and therefore it is difficult to distinguish individual contributions, and (2) long-term data documenting changes in suspended sediment concentration are rare (Fabricius et al., 2013). Although the impact of dredging is often monitored and modelled on short timescales (especially during capital dredging works), long-term effects have so far only been established to a limited degree (van Kessel and van Maren, 2013).

Some aspects of the results presented here on the Ems Estuary are very site-specific, such as the sediment extraction. However, most other aspects are probably typical for estuaries in populated areas: (1) intertidal areas are reclaimed, leading to a loss of sediment sinks, (2) channels are deepened, resulting in more up-estuary transport of sediment. We therefore believe that the results presented here apply to a wide range of turbid estuaries in which tidal channels have been deepened for port construction, and tidal flats reclaimed for land use.

6. Conclusions

A calibrated suspended sediment transport model has been setup to simulate suspended sediment dynamics in the Ems Estuary. This model suggests that the observed increase in the suspended sediment concentration can be mainly related to the increase in up-estuary transport of sediment due to estuarine circulation caused by deepening of tidal channels. It is also possible that the large-scale reclamation of intertidal areas increased the suspended sediment concentrations in the past centuries. Discontinuing the large-scale sediment extraction from the port of Emden produced an additional pronounced increase in SSC because the imported sediment was not further removed from the system. The effect of the ports themselves, including dredging and dumping, is lower than deepening and consequent extraction. Compared to an estuary without ports, the sediment concentration in the present-day estuary is higher near disposal sites, but lower elsewhere in the estuary (because the ports act as sinks). The Ems estuary provides an example of a heavily impacted estuary for which a relatively large amount of data is available, but may be representative for many estuaries worldwide.

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