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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