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A Regime Shift From Low to High Sediment Concentrations in a Tide-Dominated Estuary

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Key Points:
- Using an idealized model of the Ems River, two coexisting regimes are found, representing low and very high sediment concentrations
- Assuming a low river discharge and increasing depth, a regime shift may occur from the low to the high sediment concentration regime
- Using observed tidal ranges, it is estimated that the change to high concentrations developed over a time scale of few years

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Abstract Many estuaries are strongly deepened to improve navigation, with sometimes large and poorly understood consequences to suspended sediment dynamics. To improve understanding of such large changes, we study the Ems River Estuary, where a *regime shift* from low to high sediment concentrations was observed after deepening. The aim of this study is to improve understanding of the development of the sediment concentration regime over time and estimate the associated time scale. Using the idealized width-averaged iFlow model, we identify the coexistence of two distinct stable equilibrium regimes representing low and high sediment concentrations, qualitatively matching the regimes observed in the Ems. Depending on the river discharge, a critical depth profile is identified at which the regime shifts. By combining the model results and long-term observations of the tidal range, first indications of the regime shift are observed around 1989, taking approximately 6–7 years to develop.

Plain Language Summary Many estuaries have been extensively deepened to accommodate large ships. In the Ems River Estuary, such deepening has resulted in a large increase of the amount of fine sediment suspended in the water, referred to as a *regime shift*. However, as historical observations of sediment concentrations in the Ems are scarce, it is unclear when the regime shift occurred and how long it took to develop. Using an idealized mathematical model, we investigate the depth and flow conditions that allow for this regime shift to occur. Depending on the discharge of the river, a critical depth is found at which a regime shift from low to high sediment concentrations occurs. Combining the model results and observations of the tidal range, it is estimated that the regime shift took approximately 6–7 years to develop, between approximately 1989 and 1995.

1. Introduction

Rapid changes in the long-term average suspended sediment concentration have been observed in several estuaries, including the Ems (Germany and Netherlands), Loire (France), and Yangtze (China) Rivers. These changes are probably driven in large part by human activity, including dam construction, removal or restoration of intertidal area, port development, and channel deepening. A sudden transition of a long-term average state or *regime* of a system, such as an estuary, is called a *regime shift* (e.g., Scheffer et al., 2001). Typically, a regime shift is accompanied by a shift in the dominant processes and occurs on a time scale that is much shorter than that of natural variability. This short time scale makes regime shifts a particularly challenging aspect in marine ecosystem management, because it leaves little time to develop measures to mitigate negative effects associated with a regime shift after the first adverse changes to the ecosystem have been observed (e.g., Biggs et al., 2009). Moreover, forecasting a regime shift using computational models is challenging, as it is unclear if process parametrizations and parameter values chosen in these models are sufficient to describe a regime shift. Therefore, to assess what systems are susceptible to a regime shift and if such a regime shift can be recognized in time to mitigate negative effects, it is necessary to systematically analyze examples of observed regime shifts and investigate the underlying physical processes and associated time scales.

In this study we focus on the lower Ems River, where the regime shifted from low to high suspended sediment concentrations following extensive channel deepening. Between the 1950s to 1960s and early 2000s, deepening of the estuary led to an increase in the suspended sediment concentration by at least one order of magnitude at the water surface, from 100–200 mg/L to 1–2 g/L (De Jonge et al., 2014) and at the bed from

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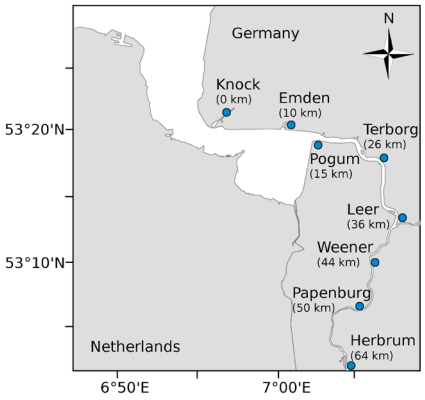

Figure 1. Map of the Lower Ems River (Germany) from Knock to the tidal weir at Herbrum. Figure copied from Dijkstra et al. (2019).

1–2 g/L (Dechend, 1950) to 30–200 g/L (Becker et al., 2018; Papenmeier et al., 2013; Talke, De Swart, & Schuttelaars, 2009; Wang, 2010). Additionally, the estuarine turbidity maximum (ETM) has moved upstream and elongated, presently covering an area of over 40 km between Gandersum (km 20) and Herbrum (km 64), see Figure 1. We thus define the regime shift in the Ems as the transition from a single short ETM, where fluid mud may have been present only briefly and locally, to a long ETM, where fluid mud and high sediment concentrations are found during a large part of the year.

Due to a lack of historical observations of the sediment concentration, little is known about the moment the regime shifted and the time scale associated with this regime shift. Using a three-dimensional numerical model, Van Maren et al. (2015) reproduced some characteristics of the observed sediment concentration in the Ems in several years between 1945 and 2005 but only by recalibrating the model for each year, so that they could not dynamically model the sediment concentration over the course of the decades. Therefore, current knowledge about the regime shift in the Ems is based on more indirect and idealized models. Winterwerp et al. (2013) and De Jonge et al. (2014) inferred the time development of the sediment concentration by reconstructing the apparent friction in the estuary using observed water levels and a hydrodynamic model, reasoning that increasing sediment concentrations lead to a decreasing friction. In this way, Winterwerp et al. (2013) found a gradual decrease of the friction over time since 1960. De Jonge et al. (2014) also found a gradual decrease of friction over time since the 1960s but with the strongest reduction of friction between 1981 and 1992. However, as these idealized models did not resolve the effect of sediment on friction dynamically, they could only model individually calibrated states for different years, not the transition processes over time.

The aim of this study is to better identify how the sediment concentration regime in the Ems changed over time and thereby estimate the starting time and time scale of the regime shift. This is done by using the width-averaged idealized iFlow model (section 2). Recently, this model was used by Dijkstra et al. (2019) to reproduce the qualitative characteristics of the water motion and sediment concentration in the Ems in 1965 (before the regime shift) and 2005 (after the regime shift). This was done by only changing the channel depth, dynamically modeling the water motion, sediment concentration, and including the influence of the suspended sediment concentration on friction. Their study focused on the difference in dominant physical processes before and after the regime shift and did not look at the transition in time. Here the same model is used to compute dynamic equilibrium sediment concentrations, that is, the regime, as a function of the river discharge and channel depth, representing the conditions in the years between 1965 and 2005 (section 3) and for the first time demonstrating the existence of multiple coexisting sediment concentration regimes. By combining the modeled regimes with observations, it is estimated when the observations start to deviate from the low sediment concentration regime and move toward the high concentration regime, allowing the estimate of the starting time and time scale of the regime shift (section 4). The interpretation of these results for the Ems and for other estuaries is discussed in section 5. Finally, the main findings are summarized in section 6.

2. Model and Case Setup

2.1. The iFlow Model for the Ems

The iFlow model is a width-averaged model for tide-dominated estuaries that solves for an approximation of the nonlinear continuity, momentum, and suspended sediment equations using scaling and perturbation methods (Brouwer et al., 2018; Dijkstra et al., 2017). The model additionally resolves sediment-induced damping of turbulence and hindered settling, assuming that the eddy viscosity, eddy diffusivity, and sediment settling velocity are depth-uniform and time-independent (Dijkstra et al., 2019).

The geometry of the Ems River is represented by a smooth width and depth profile along the estuary, resolving estuary-scale geometric variations. The water motion is forced by an M_2 and M_4 tide at the seaward boundary based on the average of observations from 2005, with an amplitude of 1.4 and 0.21 m, respectively, and with a relative phase difference of −172°. These tidal conditions are representative for historic conditions as well (Chernetsky et al., 2010; Dijkstra et al., 2019). Fresh water enters at the landward boundary, with

summer, winter, and yearly average values of 40, 150, and 80 m^3/s, respectively, based on 1987–2006 average measurements at Versen. At the seaward boundary at Knock (Figure 1), a tide-averaged, depth-averaged sediment concentration of 0.1 kg/m^3 is imposed. This is representative of historic conditions but is a conservative estimate for recent conditions (BfG, 2017; De Jonge et al., 2014). However, since little is known about the time development of the sediment concentration at Knock, we choose to use a value of 0.1 kg/m^3 for all years. It is assumed that no sediment enters the estuary from the watershed, because the average sediment concentration in the nontidal river is only 20–40 mg/L (NLWKN, 2008). Sediment is represented as a single fraction with an erosion coefficient of 0.02 s/m, a gelling concentration of 100 kg/m^3, and a clear-water settling velocity of 1 mm/s. The settling velocity only varies due to the effects of hindered settling. Salinity is included in the model as a concentration that varies in the along-channel direction and is dependent on the river discharge but is uniform in depth and constant in time (Talke, De Swart, & De Jonge, 2009). The model resolves the M_2, M_4, and subtidal water motion (horizontal velocity u, vertical velocity w, and surface elevation ζ) and sediment concentration c in the vertical and along-channel dimension in dynamic equilibrium. Here dynamic equilibrium is defined as a state in which the water motion and sediment concentration vary on the tidal time scale but not on the subtidal time scale. To reach such an equilibrium, the model computes the amount of sediment in the model domain, based on the boundary conditions, flow, and sediment transport.

2.2. Schematization of the Depth

Between 1965 and 1995, the estuary between Emden and Papenburg has been deepened sequentially from 5 m below mean high water (MHW) (1961–1962), to 5.7 m (1984–1985), 6.3 m (1991), 6.8 m (1993), and finally to 7.3 m below MHW (1994–1995; Krebs & Weilbeer, 2008; Lange, 2007). Observations of the thalweg depth in 1965, 1981, 1990, 1992, and 2005 are reported by De Jonge et al. (2014). Notably, the channel is up to 1.5 m deeper in 1981 than in 1965, even though there was no official deepening campaign within this period. This was possibly a response to engineering works in the outer estuary and building of dikes and dams. We use these observations as a motivation to approximate the deepening of the Ems as a gradual process, rather than a sequential process.

The continuous depth development between 1965 and 2005 is approximated by taking smooth depth profiles fitted to the observations in 1965 and 2005, $d_{1965}(x)$ and $d_{2005}(x)$, used by Dijkstra et al. (2019). The depth in the intermediate years, d_{yr}, is defined as a linear combination of the depth in 1965 and 2005, that is,

$$d_{yr}(x;\alpha) = (1-\alpha)d_{1965}(x) + \alpha d_{2005}(x), \tag{1}$$

where α is a bed profile parameter that follows from fitting the observed depth of 1981, 1990, and 1992 to equation (1) in a least-squares sense. This yields a different value of α for each year. The value of α increases monotonically over time but not at a constant rate in each time interval, see Figure 2 (top left). The depth observations and fits per year are plotted in Figure 2. The fitted profiles do not capture the strong scatter in depth observations related to large dunes and troughs but qualitatively capture the estuary-scale characteristics of the depth.

2.3. Setup of the Model Experiments

The model is only calibrated to observed tidal amplitudes in 1965 ($\alpha = 0$) and is not recalibrated when used for other years. Model experiments are conducted by varying the bed profile parameter α between 0 and 1 and taking a fixed river discharge Q that is varied between 30 and 150 m^3/s, keeping all other model parameters the same. The result of each model experiment consists of a spatially and tidally varying water motion and sediment concentration in dynamic equilibrium. The stable dynamic equilibria are obtained by continuation in α. This procedure is repeated two times: for increasing and decreasing α.

3. Model Results

Figure 3 shows the maximum near-bed tidally averaged sediment concentration (Figure 3, top left) and the total amount of sediment suspended in the estuary, that is, the *suspended sediment stock* (Figure 3, top right), as a function of α for various Q. When keeping $Q < 60$ m^3/s and for increasing α, the near-bed sediment concentration and stock gradually increase up to a critical value of α. For α larger than this critical value, the near-bed concentration and stock jump to much larger values; the solution jumps to a different branch. The existence of two branches and the abrupt jump is related to a strong positive feedback between sediment-induced turbulence damping and sediment import by the $M_2 - M_4$ tidal asymmetry, elaborated

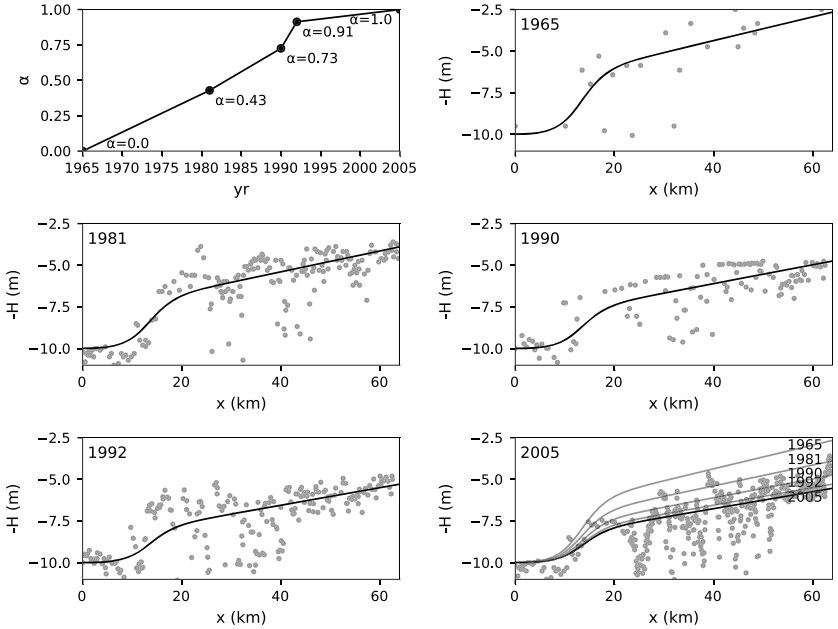

Figure 2. Evolution of the bed profile in the Ems, with in the top-left panel, the development of the bed profile parameter α (equation (1)) over time, obtained by fitting to observed depths in 1965, 1981, 1990, 1992, and 2005 (De Jonge et al., 2014). The other panels show the resulting smooth fitted depth profiles (solid lines) in these years, together with observed thalweg depth (dots). The bottom-right panel for 2005 additionally shows the smooth fitted profiles of the other years for comparison.

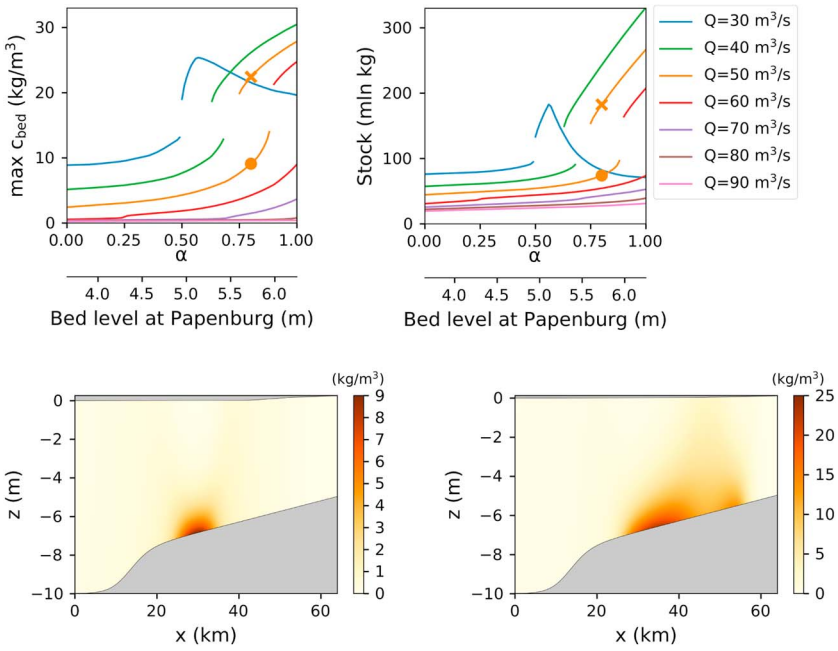

Figure 3. Modeled dynamic equilibrium solution for the maximum near-bed concentration (top left) and total amount of suspended sediment (top right) as a function of the bed profile parameter α and river discharge Q. For $Q < 70$ m^3/s, two branches of solutions are found characterizing low and high sediment concentration regimes. The branches overlap for specific α and Q, and the transition between the two branches is discontinuous. Two distributions of the subtidal sediment concentration are plotted in the bottom panels for $Q = 50$ m^3/s and $\alpha = 0.8$, corresponding to the lower branch (bottom-left panel, corresponds to the orange circle in the top panels) and upper branch (bottom-right panel, corresponds to the orange cross in the top panels).

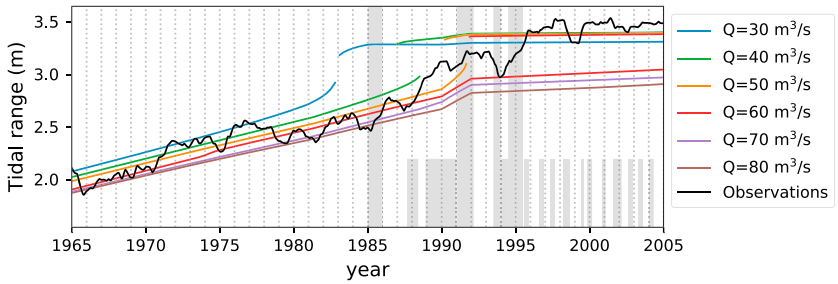

Figure 4. The observed 28-day-averaged tidal range in Papenburg (black line) and modeled equilibrium solutions for the tidal range (approximated as twice the M_2 tidal amplitude) in Papenburg as a function of time and Q. The model results are obtained by varying the bed profile parameter α and then relating α to the year using the top-left panel of Figure 2. The model results shows two branches of solutions corresponding to the branches of low and high sediment concentrations in Figure 3. The tall gray bands in the figure indicate the times of the official deepening campaigns. The smaller gray bands indicate the times of maintenance dredging since 1985 according to Lange (2007).

on by Dijkstra et al. (2019): If the suspended sediment concentration is sufficiently low (lower branch), this feedback is weak. For sufficiently high sediment concentrations (upper branch), however, this feedback dominates the sediment dynamics. On the upper branch, the sediment concentration and stock keep increasing when further increasing α. Only for very low discharges ($Q \sim 30\ \mathrm{m}^3/\mathrm{s}$) does a further increase of α leads to a decrease in the suspended sediment concentration and stock. This is because sediment is pushed closer to the upstream boundary, where it deposits on the bed and cannot be kept in suspension due to the low flow velocities.

Examples of the spatial distribution of sediment corresponding to the branches are plotted in the bottom panels of Figure 3. The lower branch of equilibrium solutions corresponds to a single short ETM located around km 20–30 (bottom-left panel), characteristic of historical conditions in the Ems. The upper branch of solutions corresponds to a double ETM near km 30 and 60 (bottom-right panel), with high concentrations in the entire zone between the two ETM, characteristic for current conditions. We thus define the two branches as different regimes and the transition between the branches as a regime shift (cf. definition in section 1).

The two branches can overlap for specific α and Q, for example, for $Q = 50\ \mathrm{m}^3/\mathrm{s}$, they overlap for α between 0.75 and 0.9. Thus, there is a range of values of α and Q for which multiple equilibrium solutions exist. Therefore if, given a constant Q, the equilibrium state of the estuary evolves from the lower to the upper branch, the depth needs to be decreased in order to evolve back to the lower branch again, thus creating hysteresis in the model behavior for increasing and decreasing depth. Mathematically, such behavior is known as a double saddle-node bifurcation.

4. The Transition Process in Time

While the equilibrium state makes sudden transitions between the two identified regimes as a function of the river discharge and depth, the actual state of the estuary constantly adapts to this equilibrium by gradually importing or exporting sediment. This adaptation takes time, and the time scale of this process cannot be identified from model. Therefore, information about the adaptation time scale is obtained by comparing the modeled equilibrium state to observations. Since there are too few observations of the historical evolution of the sediment concentration, we cannot infer information about adaptation time scales directly from sediment concentration measurements. However, an increasing sediment concentration leads to sediment-induced damping of turbulence, which can be observed as an increasing tidal range. As high time-resolution measurements of the tidal range are available since the 1950s, we use the tidal range to estimate the adaptation time scale.

The observed 28-day-averaged tidal range in Papenburg (km 50) between 1965 and 2005 is shown by the black line in Figure 4. The modeled equilibrium tidal range in Papenburg, approximated as twice the M_2 tidal amplitude, is shown by the colored lines for various values of the river discharge. The model results show a lower branch, which corresponds to the low concentration regime (section 3), characterized by a single short ETM, and an upper branch, which corresponds to the high concentration regime, characterized by two ETM and a long highly turbid zone.

The observations indicate that the tidal range increased gradually between 1965 and 1989, even though there is a significant year-to-year fluctuation. These fluctuations remain roughly within the range of modeled tidal ranges on the lower branch using Q between 30 and 150 m^3/s. As stated above, this lower branch corresponds to the lower branch of sediment concentrations with gradually increasing concentration in one short ETM around km 20–30. This is supported by observations of the sediment concentration in the 1970s (De Jonge et al., 2014), which place the ETM around this location, and records of the bed material composition along the estuary in 1989 (BfG, 2017), which show mostly small amounts of fines (<63 μm) in the bed, except around km 20–30.

Between 1989 and 1994, the observed tidal range diverges from the modeled tidal range on the lower branch, marking the onset of the regime shift. Observational evidence seems to support 1989 as the starting year of the regime shift. Lange (2007) and references therein report a sevenfold increase in the dredging volume near Herbrum, comprising higher ratios of mud following the spring of 1989. Furthermore, De Jonge et al. (2014) report observed surface concentrations in 1992–1993, which are similar to those in 2005. Nevertheless, water quality between 1990 and 1993 was still assessed as "moderately critically burdened" (German: *mäßig-kritisch belasted*), indicating good biodiversity and oxygen conditions, better than any other German tidal river at the time (Lange, 2007).

The observed tidal range first attains levels matching the modeled tidal range on the upper equilibrium branch in 1994–1995, and observations remain close to this branch after 1995. This implies that the high sediment concentration regime prevails throughout these years. After 1995, hypoxic conditions were measured over prolonged times (Talke, De Swart, & De Jonge, 2009), the water quality in 2004 was described as "strongly excessively polluted" (German: *stark-übermäßig verschmutzt*; Lange, 2007), and sediment concentrations measured since 2006 show levels of 30–200 g/L (Becker et al., 2018; Papenmeier et al., 2013; Talke, De Swart, & Schuttelaars, 2009; Wang, 2010).

The development of the observed tidal range in the transition years 1989–1995 gives an indication about the typical time scales required to adapt to changing regimes. In these years, the equilibrium associated with high sediment concentrations only exists for low discharges ($Q < 50$–$70\ m^3/s$), while the equilibrium associated with low sediment concentrations is the only equilibrium for larger discharges. The observed tidal range is between the two equilibrium branches and does not show large seasonal oscillations between these two branches, known as *flickering* (e.g., Scheffer et al., 2009), related to seasonal variations in the river discharge. This indicates that the time scale to adapt to new equilibrium conditions is considerably larger than a season. In other words, both sediment import and flushing of accumulated sediment happen on a time scale that is longer than the few months of consistently low and high river discharge that occur each year. Furthermore, the figure indicates that regime shift occurs between 1989 and 1995, meaning that adaptation time scale is less than 7 years. This is much shorter than the time scale of decades hypothesized by Winterwerp et al. (2013). As the deepening operations followed each other within the time scale of the regime shift, one could argue that the time scale of the regime shift changed while it was unfolding but remained of the order of several years.

5. Discussion

5.1. Model Interpretation and Limitations

The state of the Ems since the regime shift is characterized by a thick layer of fluid mud with concentrations of up to several tens to hundreds grams per liter. Due to the model simplifications, including the assumption of a depth uniform, time-independent eddy viscosity, and eddy diffusivity, the iFlow model cannot reproduce the specific behavior associated with such a strongly layered system. As a result, the model disregards some potentially essential sediment processes in this highly turbid regime (e.g., Becker et al., 2018; Winterwerp et al., 2017). However, the model is expected to capture the essential sediment transport processes in the low-concentration regime. The model results should therefore be interpreted as a model extrapolation of the processes essential in the low-concentration regime to a larger depth. The results show under what conditions these processes allow for the onset of a regime shift. After the regime shift, the model results cannot be expected to represent all the essential processes.

The conclusion that transitional behavior took place over a time scale of several years strongly motivates study into the seasonal behavior during the transition period. Such a study is necessary to get a better under-

standing of the dynamic processes causing the sediment to remain in the estuary during times of high discharges, which cannot be captured in our equilibrium model.

5.2. Implications for Other Estuaries

While channel deepening has led to highly increased sediment concentrations in the Ems, we stress that it is not generally true that channel deepening implies sediment import and higher sediment concentrations as was hypothesized by Winterwerp et al. (2013). As shown by Dijkstra et al. (2019), the effect of channel deepening on the sediment concentration in an estuary strongly depends on the physical mechanisms that dominate the sediment dynamics and the effect of deepening on each of these mechanisms. The Loire River is thought to have become hyperturbid over time as a consequence of deepening, but this is yet to be proven (Winterwerp et al., 2013). On the other hand, examples where models have shown that deepening does not lead to large increase of the sediment concentrations are provided by, for example, van Maanen and Sottolichio (2018) for the Gironde Estuary and by Dijkstra (2019) for the Scheldt Estuary. In the case of the Scheldt, it was derived that some physical processes respond to deepening by importing more sediment, while other mechanisms respond by importing less sediment. This suggests that it may not even be possible to make an a priori estimate of the effect of deepening based on directly observable indicators, and system specific modeling of individual estuaries is essential to determine the effect of deepening on the sediment concentration.

6. Conclusions

Using the idealized width-averaged iFlow model representing the lower Ems River, we investigated the development of the dynamic equilibrium sediment concentration as a function of the channel depth and river discharge. For sufficiently low river discharge ($Q < 70\,\mathrm{m}^3/\mathrm{s}$, approximately 60% of the time), we found two types of dynamic equilibria or regimes. The first regime is characterized by one short ETM around km 20–30 and generally moderate sediment concentrations. The second regime is characterized by two ETM, which together form a long ETM zone between roughly km 30 and 60, with high sediment concentrations in the entire zone. The dynamics in this regime are dominated by sediment-induced reduction of turbulence, which is also expressed in amplification of the tidal range. This study is the first to show that both regimes coexist for certain depth profiles. The regime shifts from the low to the high concentration regime when the estuary becomes deeper than a discharge-dependent critical channel depth.

From a comparison between the model results and long-term observations of the tidal range in Papenburg, the time scale of the regime shift was found to be much shorter than thought earlier, taking a few years since 1989 instead of decades. The observed tidal range is close to the modeled tidal range corresponding to the high concentration regime since approximately 1995. Hence, we estimated the time scale associated with the regime shift to be a few years. The available historical observations of sediment concentrations support this time scale estimate.

Acknowledgments
Data of the tidal elevation at Papenburg were provided by the Federal Waterways and Shipping Administration (WSV). The iFlow model used for this study is available from version 2.6.2 on GitHub (doi: 10.5281/zenodo.822394) under LGPL license. Here you can also find input files to reproduce the simulations in this study. When using iFlow, you are kindly requested to refer to Dijkstra et al. (2017). We thank Maarten Kleinhans, Carl Friedrichs, and an anonymous reviewer for reviews of this work.

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