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Stefan A. Talke

*Portland State University, talke@pdx.edu*

Huib E. de Swart

*Utrecht University*

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### **3. Circulation, sediment concentration and oxygen depletion in the tidal Ems River**

**Stefan A. Talke<sup>1</sup> and Huib E. de Swart<sup>2</sup>**

<sup>1</sup> Civil and Environmental Engineering Department, Portland State University, 202T Engineering Building, 1930 SW Fourth Avenue, Portland, OR, 97201, USA, e-mail: s.a.talke@pdx.edu

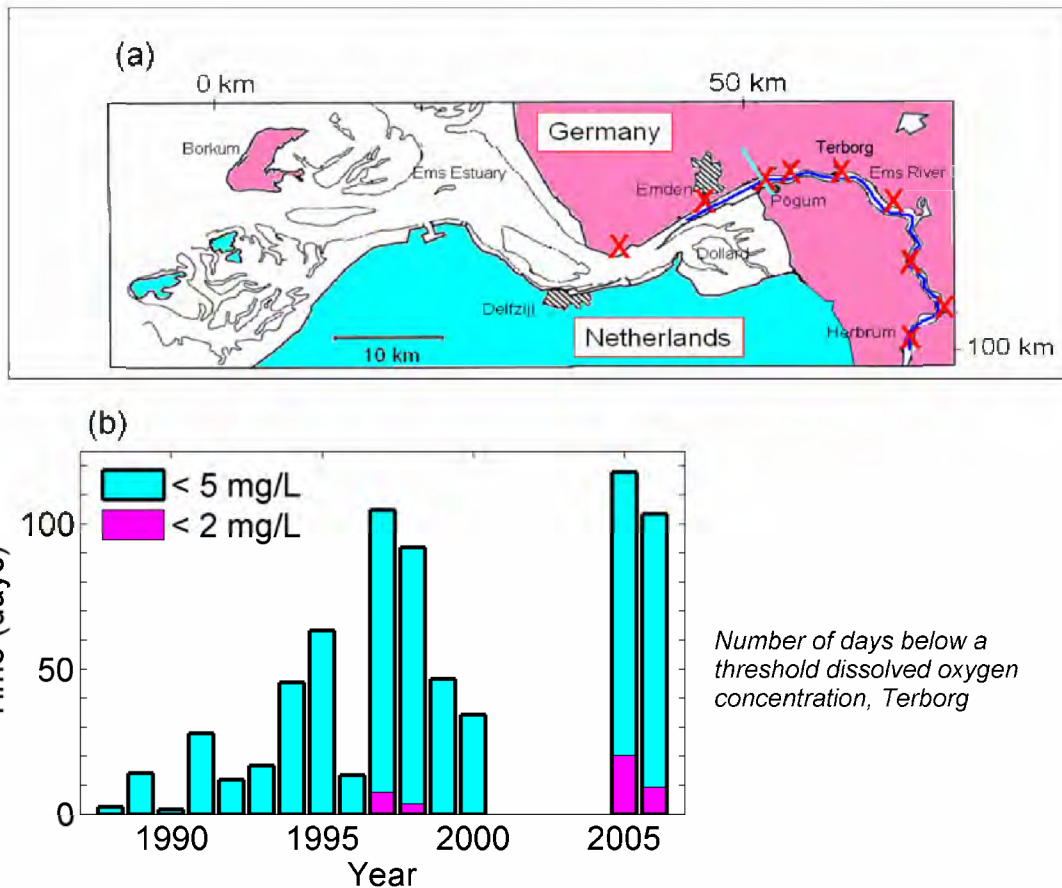
<sup>2</sup> Institute for Marine and Atmospheric Research, Utrecht University, Princetonplein 5, 3584 CC Utrecht, the Netherlands, e-mail: h.e.deswart@uu.nl

#### **Abstract**

We present measurements which show that the tidal Ems River in Germany is extremely muddy over a 30 km + turbid zone, with fluid mud of 1-2 m thickness covering the bed with suspended sediment concentrations (SSC) of greater than 50 kg.m<sup>-3</sup>. Moreover, we show that these elevated SSC contain large quantities of organic material which deplete dissolved oxygen (DO) and produce summertime hypoxic zones. Using mathematical modeling, we develop simplified representations of the estuary physics that reproduce the tidally-averaged circulation, SSC distribution, and oxygen depletion. These models show that SSC and oxygen concentrations are extremely sensitive to factors such as the mean depth, the mixing due to bottom friction (turbulence), and river flow. The observed increase in SSC and decrease in DO over the past 25 years is linked to the progressive deepening of the tidal Ems from 4-5 m to 7 m between 1985-1994, which moved the turbid zone upstream and decreased mixing. A review of scientific literature and data from the Ems suggests that human intervention (dyking, channel modification) combines with more gradual natural changes (sea level rise, climate variation) to continually modify sediment transport.

#### **i. Overview**

The tidal Ems River is part of the Ems-Dollard estuary, which is located at the border of Germany and the Netherlands (Fig. A-3.1). The estuary extends approximately 100 km from the barrier island of Borkum (km 0) to a tidal weir (gate) in Herbrum (km 100). Tidal forcing is significant, and the mean tidal range of up to 3.5 m produces currents of 1-2 m.s<sup>-1</sup> during peak flood, with smaller currents occurring during the ebb.



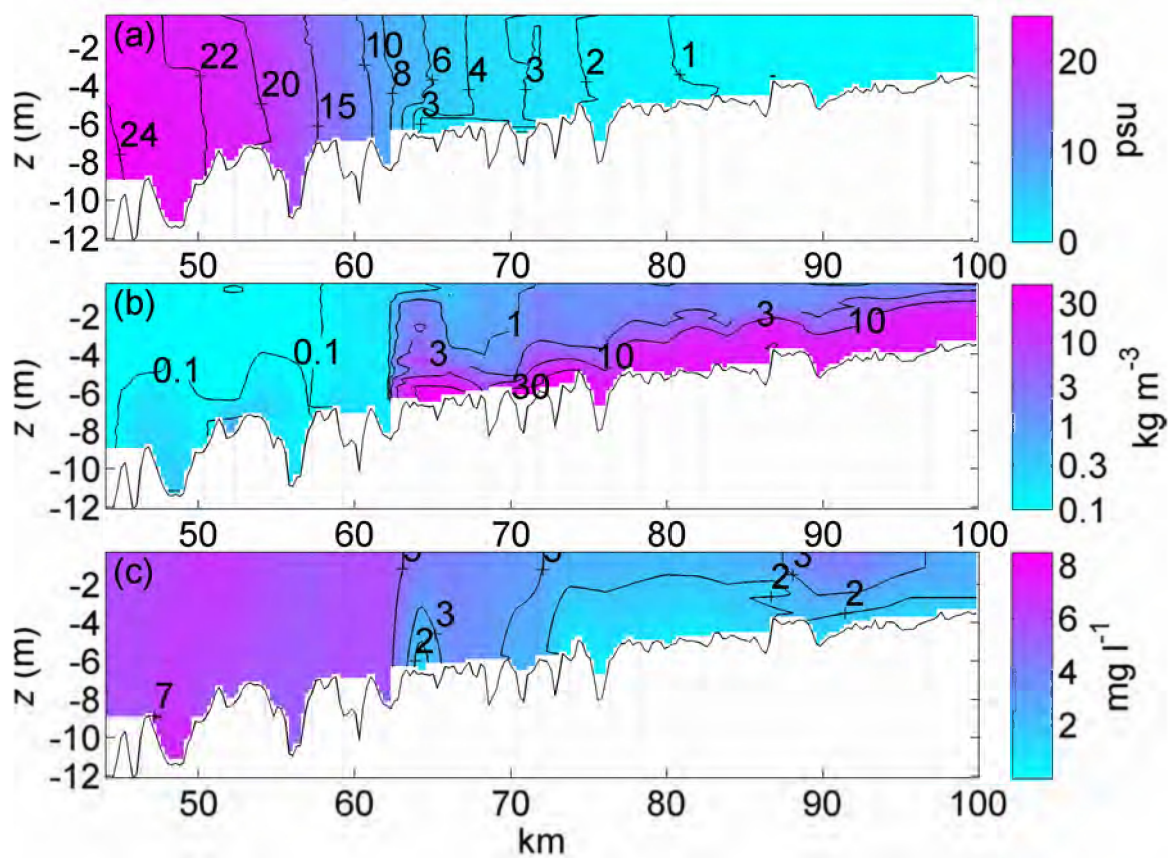
**Fig. A-3.1:** Location of Ems Estuary (a), and increasing oxygen depletion over time (b); the crosses (X) denote location of monitoring stations, solid line denotes location of experimental transects.

A gradual transition between salt water ( $S = 30$ ) and freshwater ( $S < 1$ ) occurs in the middle of the estuary, with a peak gradient on the order of  $S = 1 \text{ km}^{-1}$ . Channel depths are maintained at a depth of 8 m in the outer estuary (maximum is 30 m), and are approximately 7 m from Emden (km 47) to Papenburg (km 87). River discharge is primarily from the Ems River, and varies from an average of  $35 \text{ m}^3 \cdot \text{s}^{-1}$  during the warm summer months to peak flows of up to  $600 \text{ m}^3 \cdot \text{s}^{-1}$  during winter months. The yearly average flow is  $80 \text{ m}^3 \cdot \text{s}^{-1}$ , with a median flow of  $\sim 65 \text{ m}^3 \cdot \text{s}^{-1}$ . Over the past 25 years, the number of days with severe oxygen depletion has greatly increased (Fig. A-3.1). During the same period, the river between Emden and Papenburg was deepened from 4-5 m to 7 m (1985-1994), and an increase in tidal range of up to 1.5 m was observed near the tidal weir (Talke & de Swart, 2006).

We undertook extensive hydrodynamic and water quality measurements in monthly increments from Feb. 2005 to Dec. 2007 along the longitudinal axis of the Ems estuary. Selected cross-sectional and fixed channel measurements occurred over a tidal period in March 2005, February 2006, and September 2006 in the area near Pogum (km 53) and Terborg (km 63). As explained in more detail in Talke et al. (2009a), all these experiments included measurements of water quality parameters such as nutrient concentrations, SSC, and chlorophyll. Additionally, many of these field experiments included measurements of flow velocity, salinity, temperature, dissolved oxygen (DO) concentration, and optical backscatter (for turbidity and SSC). We focus here on these latter measurements.

## ii. Field Measurements

During low river discharge conditions during the summer, salinity is well mixed vertically and transitions from marine conditions ( $S > 20$ ) to freshwater conditions ( $S < 1$ ) over nearly 30 km (Fig. A-3.2a). As occurs in many estuaries, SSCs vary spatially and collect in the so-called estuary turbidity maximum (ETM; Fig. A-3.2b). Unlike most other estuaries, this ETM extends outside of the brackish water region ( $S = 1-2$ ) and covers the entire freshwater zone up to the tidal weir at km 100. SSCs in the ETM are enormous and form a fluid mud layer ( $SSC > 10 \text{ kg.m}^{-3}$ ) of 1-2 m depth over a 35 km region. The density gradient in the vertical suppresses mixing. The SSC varies sharply in the brackish water region, and produces a longitudinal density gradient that is up to an order of magnitude larger than the longitudinal salinity gradient (on the order of  $10 \text{ kg.m}^{-3}$  near the bed).



**Fig. A-3.2:** Measurements of salinity (a), suspended sediment concentration (b), and dissolved oxygen concentration (c) along the axis of the Ems River Estuary on August 2nd, 2006 (Reprinted from Talke et al., 2009b).

At the water surface, turbidity at  $S = 4$  salinity attenuates light intensity by 3 orders of magnitude within the first 15 cm of the water column (not shown). Under these conditions, phytoplankton cannot grow. The effect of turbidity on the onset of phytoplankton blooms was theoretically investigated by De Swart et al. (2009), and shows that much lower SSC concentrations than measured in the Ems ETM either move the phytoplankton bloom seaward or prevent one from occurring.

The oxygen demand from organic material (approximately 10 % of SSC as organic carbon) in the ETM is sufficient to produce a large zone of hypoxia ( $< 2 \text{ mg.l}^{-1}$ ) over much of the freshwater/brackish water region (Fig. A-3.2c; see Talke et al., 2009b). To first order, we find that oxygen demand is proportional to SSC, with the smallest Dissolved Oxygen (DO) occurring in the region of largest SSC (Talke et al., 2009b). Fish populations are stressed and cannot live at  $\text{DO} < 5 \text{ mg.l}^{-1}$  and  $\text{DO} < 2 \text{ mg.l}^{-1}$ , respectively. Hence, understanding the physical conditions and processes that produce large SSC, fluid mud, and low DO are essential to devising solutions for the stressed ecology of the Ems.

### iii. Modelling

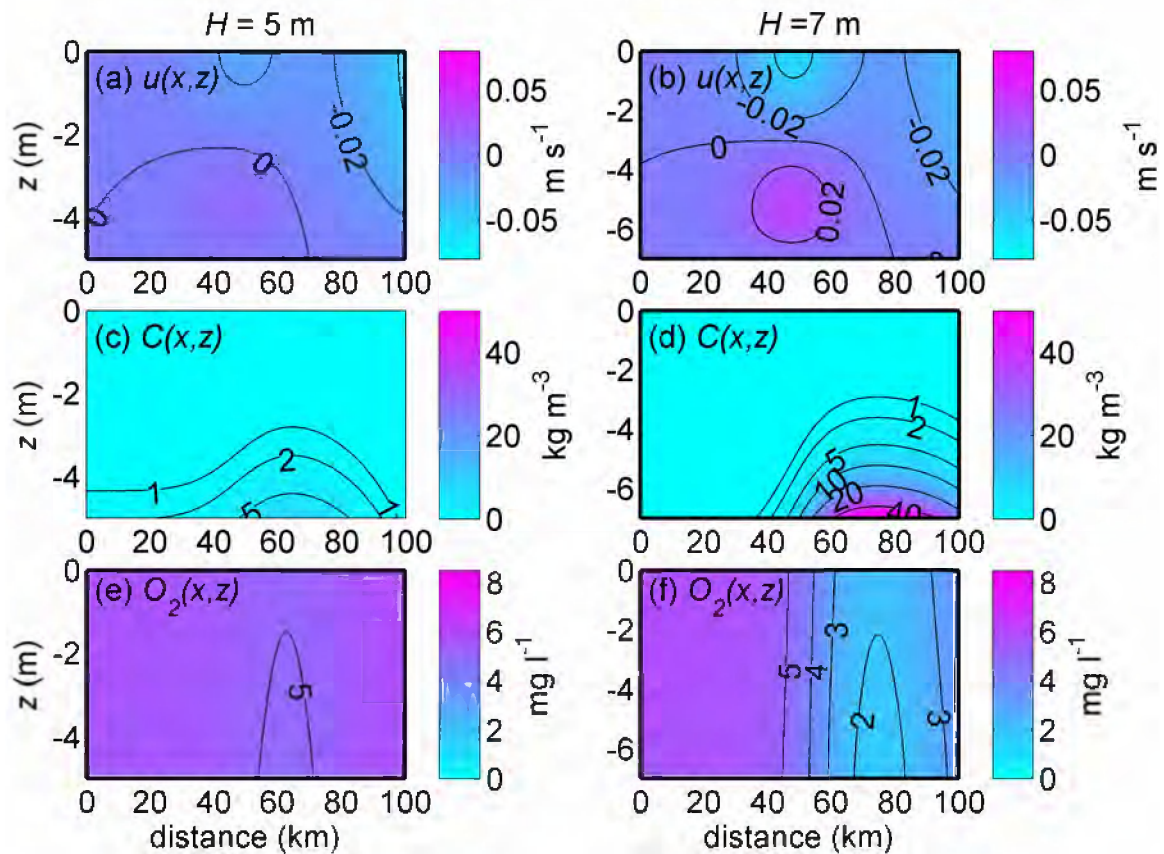
To understand why SSC is elevated and oxygen is depleted, we developed mathematical (analytical) models that identify important controlling parameters in a simplified, idealized domain. While such models necessarily exclude detail such as complex bathymetry, its simplicity allows for parameter sensitivity studies that provide insight into the effect of changing conditions. The equations can be found in Talke et al. (2008, 2009a,b); here, we qualitatively describe our methodology.

As a first step, we assume that the distribution of SSC and depleted oxygen is determined primarily by tidally averaged circulation and by mixing, which can be captured by constant vertical and horizontal mixing coefficients. Moreover, we assume a constant depth and an exponentially decreasing width (funnel shape), with an e-folding scale that is based on the natural environment. We assume a rigid lid and make the Boussinesq assumption, following standard practice. River discharge is assumed to be constant. Salinity is observed to be well mixed vertically and varies like a hyperbolic tangent in the longitudinal direction (see Fig. A-3.2).

The assumptions listed above were classically applied by Hansen & Rattray (1965) to the tidally averaged shallow water equations, which describe how pressure—either from a surface slope or from a horizontal density gradient—produces circulation. We modify the classical relationship by recognizing that dynamically significant density gradients occur not only due to salinity, but also due to the longitudinal distribution of SSC (Fig. A-3.2). Moreover, we note that SSC is distributed approximately exponentially in the vertical, with the largest concentrations near the bed (Talke et al., 2009a). This is modelled by assuming a balance vertically between diffusion and a constant settling velocity. These insights are then mathematically incorporated into the shallow water equations. The resulting novel expression describes circulation patterns that arise due the salt field, river discharge, and the distribution of SSC. As shown in Figure A-3.3a and A-3.3b, surface flow is seaward everywhere. Near the bed, a cell of upstream circulation occurs due the salinity gradient. Turbidity induced circulation downstream of the ETM opposes, but does not reverse, this upstream flow. A large dependence on depth is observed; increasing the depth from 5 m to 7 m, which occurred in the Ems between 1985 and 1994, results in a factor of nearly 3x greater circulation.

The distribution of SSC presented in Figure A-3.3c and A-3.3d is solved for by assuming equilibrium conditions. Mathematically, we assume that the local deposition of sediment equals local erosion and that the quantity of suspended sediment in the model domain is fixed. Consequently, the total sediment flux through a cross-section vanishes, i.e., the area-integrated sediment fluxes due to a combination of advection and diffusion are zero.





**Fig. A-3.3:** Modeled circulation, SSC, and dissolved oxygen for different depths (Reprinted from Talke et al., 2009b).

The result is an analytical expression for SSC that depends on the salinity field, the freshwater discharge, depth, the horizontal and vertical mixing coefficient, the settling velocity of sediment, and the prescribed total amount of suspended sediment in the system. Comparing Figures A-3.2b and A-3.3d, we observe that the modelled turbidity zone (Fig. A-3.3d) qualitatively captures the features of the measured distribution of SSC (Fig. A-3.2b). Elevated SSC of greater than  $10 \text{ kg}\cdot\text{m}^{-3}$  extends over the freshwater and brackish water zone and covers the bed by 1-2 m in both the measurement and model. Moreover, the SSC gradient in the brackish water transition zone is steep in both cases.

Interestingly, increasing the depth from 5 m (Fig. A-3.3c) to 7 m (Fig. A-3.3d) results in a larger turbidity zone with nearly an order of magnitude greater SSC that is centered farther upstream. Similar changes have been observed in the Ems River, in which channel deepening from 4-5 m to 7 m between 1985 and 1994 resulted in an upstream movement of the ETM and greatly increased SSC (e.g., Talke & de Swart, 2006). Our model suggests that contributors to the historically observed variation include: (1) decreased river flow (because of greater cross-sectional area), (2) increased gravitational circulation (cubic dependence on depth), and (3) a changed vertical distribution of SSC (which is now proportionally lower in the water column). Other factors include decreased mixing and increased sediment supply (not shown). More recent models also point out the importance of tidal asymmetries, increased tidal range, settling lag

effects, reduced bottom friction, and flocculation processes in producing an upstream movement of SSC (Chernetsky et al., 2010; Winterwerp 2010).

The distribution of circulation and SSC is next used to model oxygen depletion. A mass-balance approach to dissolved oxygen (DO) yields an advection-diffusion equation with a sink term that is proportional to organic material, and hence SSC. Reaeration at the surface is held proportional to the local oxygen deficit, while sediment oxygen demand at the bed produces an additional source of oxygen depletion. Additional details and model verification are given in Talke et al. (2009b). As shown in Figure A-3.3e and A-3.3f, the modeled oxygen depletion is closely related to the distribution of SSC. The changes described earlier for SSC between the H=5 m case and the H=7 m case cause a switch from well aerated conditions ( $DO > 5 \text{ mg.l}^{-1}$ ) to conditions that are hypoxic ( $DO < 2 \text{ mg.l}^{-1}$ ) over a large section of the estuary. From these simulations we conclude that it is the dynamics of turbidity maxima—rather than the residence time of water or the input of nutrients—that determines the depletion of oxygen in highly turbid estuaries such as the Ems.

A review of scientific literature and data from the Ems suggests that human intervention and natural variation continually modify sediment transport (Talke & de Swart, 2006). Until approximately 1950, the largest change to estuarine physics (as measured for example by tidal range) occurred due to land reclamation. Since 1950, channel modification and deepening has amplified tidal range, increased the tidal asymmetry in currents, magnified SSC and turbidity, and produced hypoxia. Other sources of variation include rising sea level and increasing tidal range in the North Sea, as well as variations to wind, waves, and river discharge caused by the Northern Atlantic Oscillation cycle (Talke & de Swart, 2006). Although natural changes are occurring more gradually than anthropogenic modifications, both factors alter depth, flow and mixing characteristics (Talke & de Swart, 2006). The models and measurements presented here suggest how these factors affect estuarine sediment transport patterns and water quality.

#### **iv. Conclusions**

In this paper we summarize recent measurements and models which show that the Ems estuary is a highly stressed environment marked by extremely turbid conditions, fluid mud, and hypoxia. A tidally-averaged circulation model is used to solve for the distribution of suspended sediment concentrations and dissolved oxygen. The model results suggest that deepening of the Ems River is responsible for the increased SSC and degraded water quality over the past 25 years.

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