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Anthropogenic impacts on estuarine oxygen dynamics: A model based evaluation

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A B S T R A C T

Direct human interference has been shaping todays estuaries for centuries, and depletion of dissolved oxygen (DO) frequently occurs in such anthropogenically impacted estuaries. Whereas the role of nutrient input as a major human impact driving DO depletion is clear, the effect of bathymetric modifications as another human impact is less well-known.

Here, we aim at a better understanding of how DO dynamics are influenced by bathymetric modifications and changed nutrient input. Therefore, we introduce a coupled hydrodynamic-biogeochemical model (Untrim-Delwaq) and develop an idealized one-dimensional set-up of a vertically well-mixed, funnel-shaped estuary with strong human impact. The set-up dimensions are inspired by the Elbe Estuary (Germany) and model results show good agreement in comparison to observational hydrodynamic and water quality data. In particular, the model reproduces the dynamics of the summer oxygen minimum which regularly develops in the estuarine freshwater part.

Analysis of our model runs shows that the estuarine biogeochemistry is dominated by heterotrophic degradation processes rather than primary production because of severe light limitation. A scenario analysis indicates that a reduction in input load scales down all biogeochemical processes. In contrast, a bathymetric change affects the estuarine system and its DO in a more complex way. In particular, the interplay between surface-to-volume ratio and the degradability state of the organic material is the most important factor which determines the capacity to recover high DO mineralization losses by atmospheric input.

Thus, our study demonstrates the relevance of bathymetric factors during the assessment of human interference on DO dynamics and biogeochemical processes in estuaries.

1. Introduction

Constituting the interface between riverine and marine water bodies, estuaries are areas of intense biogeochemical activities. In the center of these activities, dissolved oxygen (DO) plays a prominent role: most of the transformation processes involve DO, and a lack of oxygen impacts the ecological functioning of an estuary, see Testa and Kemp (2011) and references therein.

Oxygen-depleted conditions are frequently reported for estuaries worldwide, like the Yangtze Estuary (Zhu et al., 2011), Chesapeake Bay (Hagy et al., 2004), the Scheldt Estuary (Meire et al., 2005) and the Elbe Estuary (Amann et al., 2012). The human influence on DO depletion ranges from globally acting anthropogenic climate change to local human interventions. Climate change impacts on estuarine ecosystems have been extensively studied during the past two decades (e.g. Najjar et al., 2000; Robins et al., 2016; Scavia et al., 2002), and an exacerbation of estuarine DO depletion due to large scale changes in e.g. water temperature and freshwater discharge is expected (Rabalais et al., 2009). In contrast, the effects of direct human interventions appear more regional and versatile (Wakelin et al., 2015). Such direct effects basically arise from, e.g., changing the input of substances like nutrients, trace metals and organic contaminants (Bianchi, 2007) or from modifying the estuarine geometry by e.g. land reclamation, realignment, barriers and channel deepening. Like climate change effects, the human-induced change of substance input has received much attention, especially the increased nutrient load of nitrogen and phosphorous, which was put on a level with the human-induced

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rise of carbon dioxide by Fulweiler et al. (2012). The increase in nutrient input, which fuels primary production and subsequent oxygen-consuming microbial respiration of its detritus, is commonly believed to be the predominant driver of exacerbated low oxygen conditions in estuarine and coastal areas worldwide (Diaz and Rosenberg, 2008; Howarth et al., 2011; Statham, 2012).

However, geometric influences on biogeochemical processes in estuaries have not been examined to the same extend, though the geometry fundamentally influences all processes in an estuarine water body. Generally, geometric changes interact with the biogeochemical system by several interrelations. Most basically, geometric changes induce changes in hydrodynamic characteristics. Furthermore, changes in hydrodynamics influence advective transport characteristics and biogeochemistry (Volta et al., 2014). Recent research explored the influences of differences in horizontal size and shape to control biogeochemical processes: whereas Jickells et al. (2014) focused on the area size of an estuary independent of its shape, Volta et al. (2016a) included different types of lateral shapes in their investigation. Yet, the influence of variations in depth, and thus the vertical dimension, is of special interest because in many estuaries worldwide human activities have altered the bathymetry to deepen the shipping channel for navigational purposes. Prominent examples are the Scheldt (Meire et al., 2005), the Yangtze (Wu et al., 2016), the Columbia River (Sherwood et al., 1990), the Seine (Marmin et al., 2014), the Ems (de Jonge et al., 2014; van Maren et al., 2015) and the Elbe (Boehlich and Strotmann, 2008). Nevertheless, scientific knowledge on the effect of changes in bathymetry to the biogeochemical system, and to DO dynamics in particular, is missing.

This study aims at understanding estuarine DO dynamics in response to the direct human impacts of riverine nutrient load and depth change. Therefore, we developed an integrated hydrodynamic-biogeochemical model and an idealized model domain to provide an easier understanding of the processes under consideration. The model is a prototype of a vertically well-mixed, alluvial estuary that includes artificial modifications. The domain dimensions and proportions are inspired by the Elbe Estuary (Northern Germany) and the geometric idealization enables transferability of the results to other estuaries.

The Elbe Estuary extends between the tidal barrier in Geesthacht and the seaward end of the maintained shipping channel in the German Bight. The tidal limit, a weir, completely reflects the incoming tidal wave and constitutes a clear landward end of the estuary. The Port of Hamburg is located about 30 km downstream of the weir. There, the maintained marine shipping channel starts by a clear drop in bottom bathymetry to facilitate the navigation of large container ships between the port and the sea. Geometry and water quality of the Elbe Estuary were changed considerably compared to pristine conditions, making it a characteristic example of an anthropogenically influenced estuary.

In this study, we first develop our model and increase confidence in it by comparing model results to observational data. A subsequent parameter sensitivity study identifies the key processes of DO dynamics. After that we model different scenarios to investigate changes in DO dynamics due to changes in human impact. Besides a nutrient reduction scenario, we especially focus on a bathymetric change and thus provide deep insight into the interplay between bathymetry and estuarine DO dynamics.

2. Methods

We coupled the mathematical models Untrim (Casulli and Stelling, 2010) and Delwaq (Postma et al., 2003; Smits and van Beek, 2013). Details on both models can be found in e.g. Casulli (2008), Sehili et al. (2014) for Untrim, and in Blauw et al. (2009), Deltares (2014) for Delwaq. Untrim calculates hydrodynamic characteristics in tidal environments by solving the Reynolds-averaged Navier Stokes equations in a semi-implicit way. Based on these information, Delwaq simulates biogeochemical processes in the water column by solving the advection-diffusion-reaction equation for each state variable with a mass-conserving finite-volume method, but needs to be configured individually (see section 2.1 for our configuration) in terms of resolved processes and state variables. Our coupling of the mass-conserving models Untrim and Delwaq is realized by a coupling module that retrieves the exact water fluxes through the edges of each computational volume (Lang, 2012); the coupling itself is, thus, mass-conserving. In this study, we use the models in 1D mode and for water column processes only.

2.1. *Biogeochemical model*

Our configuration of the biogeochemical model Delwaq simulates the dynamics of nutrients, phytoplankton, particulate organic matter, dissolved organic matter and DO. In this section we summarize important interactions between the state variables (see Fig. 1). Appendix A lists the mathematical formulations of the biogeochemical model configuration in tabular form.

Our model resolves nitrogen, *ortho*-phosphate (PO4) and free silicate (Si) as inorganic nutrients. Dissolved inorganic nitrogen is further subdivided into ammonium (NH4) and nitrate (NO3).

The attenuation of light on its way through the water column is linked to suspended mineral and organic material. The model parameterization bases on the Beer-Lambert law and includes a general background attenuation, specific attenuation coefficients for inorganic suspended matter (SPMI) and particulate organic matter, and self-shading effects from phytoplankton.

Phytoplankton is in the model distinguished between freshwater diatoms (DIAT) and freshwater non-diatoms (NON-DIAT). Changes in their biomass arise from three processes: net primary production, mortality and settling – as also documented in detail in appendix A. Our approach ignores higher trophic levels but conceptually includes grazing in the pelagic zone through a higher mortality rate constant, and grazing by benthic filter feeders through settling.

Mortality of phytoplankton results in two shares: an autolysis share is directly remineralized into inorganic nutrients without any influence on the DO budget. The share fuels the detritus pool, which comprises carbonaceous, nitrogenous and phosphorous fractions. The degradation of detritus happens in several steps: the most easily degradable particulate organic matter for carbon (POC1), nitrogen (PON1) and phosphorous (POP1) is decomposed into inorganic nutrients, and in slowly degradable particulate organic matter with corresponding particulate nutrient fractions (POC2, PON2 and POP2), and dissolved organic matter (DOC, DON and DOP), respectively. The decomposition of the slowly degradable particulate matter also yields remineralized inorganic nutrients and dissolved organic matter. The dissolved organic matter pool is remineralized to inorganic nutrients.

The inorganic nitrogen cycling in our model configuration includes nitrification and denitrification, both dependent on the oxygen level. By remineralization, organic nitrogen is transformed into ammonium. In case of sufficient DO, ammonium is nitrified. In case of low DO condition, nitrate can be denitrified which effectively is a nitrate sink to the model. By mortality, the silicate that is incorporated into diatoms feeds an opal silicate pool (OPAL). This

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