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Substrate origin and morphology differentially determine oxygen dynamics in two major European estuaries, the Elbe and the Schelde

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The expansion of oxygen minimum zones (OMZ's) in estuaries can be harmful for ecology and economy, prompting the demand for expensive measures. Here we look at the oxygen dynamics in two northern temperate European estuaries, the Schelde (The Netherlands/Belgium) and the Elbe (Germany) and analysed data from the period of 2004–2009. The Schelde is characterized by two zones of increased oxygen consumption; the Elbe shows one zone of increased oxygen consumption. Despite reduction in biochemical oxygen demand in both estuaries, oxygen conditions improved in the Schelde estuary, while the oxygen minimum zone persisted in the Elbe estuary. To understand these different oxygen dynamics, we applied a one-dimensional reactive transport model to both estuaries. In the Schelde we found low oxygen concentrations to be related to organic matter and ammonium input from the major tributaries. In the Elbe, additionally to a high input of organic matter from upstream, oxygen dynamics were influenced by abrupt changes in estuarine morphology. Next, the origin of the organic matter substrate differs between the two estuaries. In the Elbe, the organic matter imported is mostly composed of algal die-off produced in the Elbe River upstream. In the Schelde the organic matter and ammonium input is mostly related to sewage input of anthropogenic origin. This implies that waste water treatment will be more effective to remediate hypoxia related problems in the Schelde than in the Elbe.

1. Introduction

Decreasing oxygen concentrations are considered the most serious threat related to eutrophication (Carpenter et al., 1998; Diaz and Rosenberg, 2008; Kemp et al., 2009; Rabalais et al., 2010). The threshold value for hypoxia is usually set at 2 mg O_2 L^{-1} (63 O_2 mmol m^{-3}) (Diaz, 2001; Diaz and Rosenberg, 2008; Conley et al., 2009), although there is evidence for a broader range of oxygen concentration thresholds at which ecological stress is caused (Vaquer-Sunyer and Duarte, 2008). In this study a threshold value of 5 mg L^{-1} (156 O_2 mmol m^{-3}) is adopted, corresponding to the level below which fish may experience sub-lethal effects (Best et al., 2007; Vaquer-Sunyer and Duarte, 2008). When low oxygen concentrations are reached, invertebrate and fish communities can collapse (Gazeau et al., 2005; Maes et al., 2008; Vaquer-Sunyer and Duarte, 2008; Mialet et al., 2010) and biogeochemical changes in water column and sediment are induced (Gunnars and Blomqvist, 1997). Furthermore, ecological damage is accompanied by economical loss of fishery resources (Helly and Levin, 2004; Diaz and Rosenberg, 2008; Vaquer-Sunyer and Duarte, 2008). Although hypoxia existed through geological time, its occurrence in marine, coastal and estuarine areas increased significantly (Diaz, 2001), doubling every ten years since 1960 (Diaz and Rosenberg, 2008). Currently hypoxia is a worldwide phenomenon (Conley et al., 2009), particularly severe in many North-American and European countries (Howarth et al., 2011).

Estuaries are naturally eutrophic and productive systems as they concentrate water from large drainage areas in relatively small water bodies (Van Damme et al., 2005). However, excess in nutrients and organic matter input, following from increased human activity (industry, agriculture, sewage disposal), on top of the naturally eutrophic conditions, can lead to severe oxygen

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deficiencies (Rabalais et al., 2010). Examples of oxygen deficiencies in estuaries in Europe can be found amongst others in the Seine (France; Garnier et al. (2001)), Schelde (Belgium – the Netherlands; Soetaert et al., 2006; Van Damme et al., 2005), Elbe (Germany; Bergemann et al., 1996; Schroeder, 1997; Kerner, 2007; Amann et al., 2012), Gironde (France; Lanoux et al., 2013), the estuary of Bilbao (Spain; Villate et al., 2013), the Ems estuary (the Netherlands-Germany; Talke et al., 2009), and the Tamar and Tweed estuary (UK; Uncles et al., 2002).

Hypoxia or oxygen deficiency develops when aerobic respiration and (bio)chemical oxidation of reduced substances cannot be compensated by oxygen supply (primary production, air-water exchange, transport) (Schroeder, 1997; Rabalais et al., 2010). There are many biological, chemical and physical regulating factors that influence the strength, timing, frequency and location of low oxygen zones (Rabalais et al., 2010). Temperature and salinity affect oxygen concentrations directly and indirectly, i.e. by their control on solubility, and for temperature also by the rate at which biochemically mediated oxygen demanding and producing processes proceed (Testa and Kemp, 2011). The duration and intensity of oxygen deficiencies depends on the availability and degradability of the dissolved or particulate organic carbon (Abril et al., 2002), on the presence of primary producers and on the availability of ammonium which may create a large oxygen demand when being nitrified (Kemp et al., 2009). In the 90s in the Schelde for instance, nitrification contributed to more than half of the oxygen consumption (e.g. in Soetaert et al., 2006). Residence time of the water is another crucial factor that determines the degree of mineralization (Rabalais et al., 2010) and hence oxygen consumption. Furthermore, the relationship between the euphotic zone and the total water depth is of importance, as it will influence the amount of oxygen supplied due to primary production (Wolfstein and Kies, 1999).

Since the implementation of the European Water Framework Directive in national legislation, nutrient and organic load reduction have been widely applied to reverse eutrophication and associated hypoxia events (Kemp et al., 2009). Despite waste water treatment in both the Schelde and Elbe estuary, oxygen concentrations increased in the Schelde estuary (Van Damme et al., 2005; Soetaert et al., 2006), while oxygen deficiency situations persist in the Elbe estuary (Amann et al., 2012). The reasons why these estuaries respond differently to measures of nutrient reduction are not known. In the Elbe the sudden increase in depth, in and downstream of the Hamburg port area has been associated with the oxygen minimum zone observed here, as the increase in depth reduces the euphotic depth/mixing depth ratio (Bergemann et al., 1996; Wolfstein and Kies, 1999; Kerner, 2000). Estuaries experience high pressure due the harbour large populations and economic importance, resulting in anthropogenic changes in morphology (embankments, rectifications, channel deepening and widening), biogeochemistry (eutrophication, inputs of contaminants) and food webs (Meire et al., 2005). Therefore, it is important to elucidate the underlying mechanisms that may lead to oxygen depletion or hypoxia. Only then the effectiveness of current management strategies can be assessed and adjusted if necessary.

We hypothesize that in contrast to the Schelde, in the Elbe not only water quality, but also the current morphological situation, e.g. the sudden increase of average depth in the port area, causes the recurrence of oxygen deficiency situations in summer. To elucidate how water quality improvement and morphological changes differentially affect the oxygen dynamics in the Schelde and Elbe estuaries we use a one-dimensional reactive transport model and perform two types of scenarios: a reduction by half of the input of oxygen consuming substances at the boundary and tributaries, and a change in estuarine morphology, by adapting depth or width.

2. Material and methods

2.1. Study area

The Schelde estuary (Fig. 1D, The Netherlands/Belgium) has a length of approximately 160 km from the weir and sluices near Gent (51.00214° N; 3.722781 E – 0 km) to the mouth near Vlissingen (51.412110 N; 3.566041 E – 160 km) (Meire et al., 2005). The border is located at 102 km from the weir. The Elbe estuary (Fig. 1E, Germany) has a length of about 150 km reaching from the weir at Geesthacht (53.423279 °N; 10.3347464 °E – 0 km) to the mouth at Cuxhaven (53.897798 °N; 8.6954743 °E – 150 km) (Amann et al., 2012). Both estuaries discharge in the North Sea, and both include a large port of international importance, the Port of Antwerp at 82 km, and the Hamburg Port area at 39 km from the weir. The river catchment area of the Schelde is about 21 500 km^2, while that of the Elbe is approximately 7 times larger (148 300 km^2). About ten million people live in the river basin in the Schelde (465 inhabitants km^{-2}), 24.5 million people live in the river basin of the Elbe (165 inhabitants km^{-2}) (Meire et al., 2005; Amann et al., 2012).

2.2. Data sources

Schelde water quality data from the monitoring programs in Flanders (Maris and Meire, 2016) and the Netherlands (Knuijt and Soetaert, 2012) were combined. In total about 30 stations (Fig. 1D) were sampled monthly. Water quality data from the Elbe estuary were obtained from the FGG Elbe data portal (FGG, 2015). In total about 25 stations (Fig. 1E) were sampled six times a year, among which monthly in summer and once every other season. Oxygen concentrations and biochemical oxygen demand data were taken for the study period extending from 2004 till 2009, for which a consistent data set was available collected in the framework of the European Interreg IVb project TIDE (Tidal River Development, 2017). Unfortunately, biochemical oxygen demand was not measured in the Dutch part of the Schelde estuary. Biochemical oxygen demand defines the oxygen consumed over 5 days (Schelde) or 7 days (Elbe) for water incubated at 20 °C; it comprises oxygen needed for both mineralization and nitrification, since no inhibition for nitrification was applied prior to measurement. Spearman rank correlations of biochemical oxygen demand (BOD), particulate organic carbon (POC), dissolved organic carbon (DOC), chlorophyll *a* (chl *a*) and ammonium (NH4); and POC/chl *a* ratios were calculated using the R-package Performance Analytics to discuss the origin of the substrate in the Schelde and Elbe estuary.

Morphology data of the Schelde and Elbe, also collected in the framework of the European Interreg IVb project TIDE (Tidal River Development, 2017), was obtained from the Flanders Hydraulics Research Centre and Hamburg Port Authority, respectively (Vandenbruwaene et al., 2012). Bathymetry for the Schelde and Elbe was based on data from the year 2009 and 2006, respectively. The Schelde grid has a resolution varying from 5 × 5 m to 20 × 20 m. The Elbe grid has a resolution of 10 × 10 m. Bathymetrical depth is expressed with respect to the local sea level reference (Fig. 1D–E), in the Schelde in m TAW (Tweede Algemene Waterpassing), in the Elbe in m NN (Normalnull). Geometry data of the Schelde (width, depth and area) were calculated based on mean high and mean low water levels from the year 1991–2000. Geometry data of the Elbe were calculated based on data of the year 2006.

Freshwater discharge data for the Schelde was provided by Flanders Hydraulics Research Centre (Waterinfo, 2016); freshwater discharge data for the Elbe was brought by the Wasser-und Schifffahrtsamt Lauenburg (Pegel Online 2017).