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Long-term trends in nutrient budgets of the western Dutch Wadden Sea (1976–2012)

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ABSTRACT

Long-term field observations of nitrogen [N] and phosphorus [P] concentrations were used to construct nutrient budgets for the western Dutch Wadden Sea between 1976 and 2012. Nutrients come into the western Dutch Wadden Sea via river runoff, through exchange with the coastal zone of the North Sea, neighbouring tidal basins and through atmospheric deposition (for N). The highest concentrations in phosphorus and nitrogen were observed in the mid-1980s. Improved phosphorus removal at waste water treatment plants, management of fertilization in agriculture and removal of phosphates from detergents led to reduced riverine nutrient inputs and, consequently, reduced nutrient concentrations in the Wadden Sea. The budgets suggest that the period of the initial net import of phosphorus and nitrogen switched to a net export in 1981 for nitrogen and in 1992 for phosphorus. Such different behaviour in nutrient budgets during the rise and fall of external nutrient concentrations may be the result of different sediment-water exchange dynamics for P and N. It is hypothesized that during the period of increasing eutrophication (1976–1981) P, and to a lesser degree N, were stored in sediments as organic and inorganic nutrients. In the following period (1981–1992) external nutrient concentrations (especially in the North Sea) decreased, but P concentrations in the Wadden Sea remained high due to prolonged sediment release, whilst denitrification removed substantial amounts of N.

From 1992 onwards, P and N budgets were closed by net loss, most probably because P stores were then depleted and denitrification continued. Under the present conditions (lower rates of sediment import and depleted P stores), nutrient concentrations in this area are expected to be more strongly influenced by wind-driven exchange with the North Sea and precipitation-driven discharge from Lake IJssel. This implies that the consequences of climate change will be more important, than during the 1970s and 1980s.

1. Introduction

Estuaries are highly productive ecosystems, mainly because they receive large inputs of nutrients and organic matter from both river runoff and the open sea (Cloern et al., 2013; Nixon, 1995). Since the 1960s, there has been much environmental concern about the effects of increased riverine nutrient supply on the structure and functioning of estuarine ecosystems in Europe (Rosenberg, 1985) and the United States (Cloern et al., 2013). Particularly, increased inputs of nutrients had major consequences for the coastal ecosystems, such as an increase of biomass of primary producers leading to oxygen depletion, changing species compositions and biodiversity and shifts to bloom-forming algae species, some of which are toxic (e.g. Cloern, 2001). Eutrophication is, amongst others, referred to as the excessive increase in nutrient inputs (Golterman, 1975) and the increase of organic matter due to an increased nutrient supply (Nixon, 1995). Here, we use the first definition. Worldwide measures in the 1980s following conventions, legislative instruments and other laws on eutrophication (Ferreira et al., 2011) were successful in reducing nutrient loads in the North Sea and Baltic Sea, but less effective in other European and US coastal waters, in particular for nitrogen (Grizzetti et al., 2012; Scavia and Bricker, 2006).

The Wadden Sea, located in the south-eastern part of the North Sea bordering Denmark, Germany and The Netherlands is a shallow, intertidal sea consisting of intertidal flats, shallow subtidal flats, drainage gullies and deeper inlets and channels. Due to its outstanding universal values, it became a UNESCO world heritage site in 2009 (www.waddensea-worldheritage.org). The western part of the Dutch Wadden Sea is a highly dynamic estuarine environment with nutrient inputs from two main sources, i.e. from Lake IJssel, receiving water from the river Rhine, and from the coastal waters of the North Sea connected to the tidal basins via tidal inlets between the barrier islands (Duran-Matute et al., 2014; Postma, 1950; Ridderinkhof et al., 1990).

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Field measurements and information from reflectance images retrieved by means of remote sensing suggest the presence of a coastal zone seaward of the barrier islands in which such an exchange of water, nutrients and organic matter between the Wadden Sea and the North Sea takes place (Jung et al., 2016; Postma, 1981; Postma, 1984; van Raaphorst et al., 1998; Visser et al., 1991).

Loadings of nitrogen and phosphorus into the coastal waters of the North Sea, including the western Wadden Sea, strongly increased from the early 1950s until the early 1980s and decreased since the mid-1980s (e.g. Philippart et al., 2007; Prins et al., 2012; van Raaphorst and de Jonge, 2004; van Raaphorst et al., 2000; Vermaat et al., 2008). Between 1978 and 1987, the main nutrient source in the western Wadden Sea was Lake IJssel (approximately 50% for phosphorus and 75% for nitrogen; Philippart et al., 2000). Consequently, during the early 1980s, the relative contribution of loading from the coastal North Sea was low; the loading of phosphorus was <25% and that of nitrogen <5% of the total loading (Philippart et al., 2000; van Raaphorst and van der Veer, 1990). Reduction of nutrients that started in the late 1970s was uneven in that P loadings were more effectively reduced than N loadings. This led to a large imbalance in the N:P stoichiometry in the Wadden Sea (Philippart et al., 2007) and the North Sea (Burson et al., 2016) and has affected the phytoplankton communities and productivity (Burson et al., 2016; Philippart et al., 2007). In particular during the spring bloom, phytoplankton in general is now mainly P-limited, whereas a Si–P-co-limitation is likely for the diatom populations, when present (Ly et al., 2014).

Nutrient dynamics are not only influenced by the loadings of dissolved phosphorus and nitrogen, but also by sedimentary processes (storage, burial, remineralization, and denitrification) and sediment-water exchange of their particulate and dissolved forms. A recent study on sediment budgets showed that sedimentation rates in the western Wadden Sea are under the long-term influence of the closure of the southern part of the former Zuiderzee in 1932 (Elias et al., 2012). The closure has formed the present Lake IJssel and has resulted in an increased net inward transport of sediment and its associated organic matter, as tidal channels had to adjust to lower tidal volumes. Apart from these long-term morphological adjustments, sedimentary processes also interact with eutrophication trends. At the onset of eutrophication, local phosphorus concentrations might be buffered by net storage of P in the sediment, followed by gradual release after reduction of nutrient loads (Prastka et al., 1998). In the western Wadden Sea, remineralization plays an important role in the P cycle (Leote et al., 2015). Here, phosphorus might be stored over a longer time in the sediment and therefore serve as a buffer between the freshwater source of Lake IJssel and the North Sea (Kuipers and van Noort, 2008; Tappin, 2002). Local nitrogen concentrations will be influenced by denitrification, i.e. the reduction of nitrate to dinitrogen gas. Because denitrification rates in coastal sediments are related to the amount and quality of sedimentary organic matter and the concentrations of nitrate in waters overlying the sediment, changes in loads of sediments, organic matter and nutrients influence the magnitude of this flux (Deek et al., 2012).

In this study, we present phosphorus and nitrogen budgets of the western Dutch Wadden Sea for the period 1976–2012 to analyse changes in the relative importance of import of nutrients from the North Sea coastal zone compared to that of other sources (Philippart et al., 2000; van Raaphorst and van der Veer, 1990). Previous budgets assumed that closing residuals of the budgets were related to the import of organic matter (N, P) and denitrification (N). For the present budgets, the possible contribution of changes in sedimentation and pelagic-benthic fluxes to the closing residuals of the budgets are also considered.

2. Materials and methods

2.1. Study area

The Wadden Sea is a seaward barrier of sandy islands and shoals, stretching for 600 km from Denmark in the northeast to The Netherlands in the southwest. In this study, we focus on the Marsdiep and Vlie tidal basin in the westernmost part of the Dutch Wadden Sea. These basins are connected to the North Sea by two tidal inlets, i.e. the Marsdiep and the Vlie (Fig. 1A). Marsdiep and Vlie are the tidal basins with the main tidal inlets of the western Dutch Wadden Sea with tidal prisms of about 1050×10^6 and $1070–1150 \times 10^6$ m^3, respectively (Duran-Matute et al., 2014; Philippart, 1988; Postma, 1982). The smaller Eierlandse Gat, located north of the Marsdiep and south-west of the Vlie tidal basin, has a tidal prism of $160–200 \times 10^6$ m^3 and its water exchange with the Marsdiep and Vlie basins is relatively low (Duran-Matute et al., 2014; Postma, 1982). It was, therefore, decided to exclude this basin from the nutrient budget analyses (c.f. Philippart et al., 2000). On average, the temperature of the Marsdiep tidal basin varies between 3 °C in February and 18 °C in August (van Aken, 2008b). Freshwater enters the Marsdiep tidal basin directly from discharges of Lake IJssel and indirectly from river runoffs in the south via the coastal zone (Fig. 1A). The salinity shows high variability and depends strongly on the amount of fresh water entering the system (van Aken, 2008a).

2.2. Nutrient data

Time series on nutrient concentrations were obtained from the water quality monitoring database (DONAR, http://www.watergegevens.rws.nl) of the Dutch Ministry of Transport and Public Works. Details about the locations of the used stations and sampling methods can be found in Philippart et al. (2000) and van Raaphorst and van der Veer (1990). Total phosphorus (TP) includes dissolved inorganic phosphate (DIP), dissolved organic phosphorus (DOP) and particulate compounds of phosphorus (POP). Total nitrogen (TN) is the sum of ammonium (NH_4^+), nitrate plus nitrite (NO_x), dissolved organic nitrogen (DON) and particulate compounds of nitrogen (PON). For all stations which were used to construct the nutrient budgets (Fig. 1A), TP and TN concentrations were estimated from irregular measurements (see below) for every month from January 1976 to December 2012 ($n = 444$).

For Stations b and c (Fig. 1A), nutrient concentrations were measured during the full study period but sampling occurred at irregular intervals. To construct a regular data set with monthly values for all stations, generalized additive models (GAM) were fitted for nitrogen and phosphorus separately. We used GAM because of its ability to fit the non-linear seasonal and long-term trends.

The nutrient concentrations were modelled as a function of "Station" and as a function of the smoother f_1 for "Year" (for the long-term trend) and as a function of the smoother f_2 for "DayInYear" (for the seasonal trend). To smooth the seasonal trend, a penalized cyclic cubic spline was used to ensure that the ends of the fitted seasonal splines match up. The statistical model for nutrient concentrations ([TP] and [TN]; mol m^{-3}) at different stations (S), years (Y) and day in the year (D) reads:

$$[\mathrm{Nutrient}]_{SYD} \sim \alpha + \beta \times S + f_1(Y \times S) + f_2(D \times S) + \varepsilon \qquad (1)$$

Measurements at stations a, d and e were, however, terminated in 1988 (a) and 1993 (d and e) (Fig. 1A). We estimated the nutrient concentrations at these locations by using measurements at other locations. We used the generated monthly values from the GAM (Eq. (1)) for Station f in Dutch coastal waters to obtain values for a, and of Station g in Lake IJssel for e and d. In both cases the relationships between the concentrations of the respective stations were obtained by fitting a linear model through the data where both stations were sampled on the same day in the following form:

$$\mathrm{Nut}_{\mathrm{Station}\ 2} \sim \alpha + \beta \times \mathrm{Nut}_{\mathrm{Station}\ 1}] + \gamma \times \mathrm{Month} + \varepsilon \qquad (2)$$

where $\mathrm{Nut}_{\mathrm{Station}\ 2}$ is the nutrient concentration (mol m^{-3}) at a station

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