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Nutrient dynamics in a back barrier tidal basin of the Southern North Sea: Time-series, model simulations, and budget estimates

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Abstract

In the tidal inlet of the back barrier area of Spiekeroog Island (Southern North Sea), nutrient concentrations (silica, phosphate, and nitrite plus nitrate) were determined hourly by an autonomously analysing system on a permanently installed time-series station from April 2006 to December 2008. Based on the high frequency of analyses we studied nutrient dynamics on annual, seasonal, and tidal time scales. By comparing the nutrient input to the tidal flat area via freshwater through a flood-gate and pore water discharge from tidal flat sediments, we conclude that nutrients are primarily supplied to the water column by pore water advection, while the freshwater contribution is negligible. To assess the annual nutrient contribution of our study area to the German Bight, we used a numerical Euler-Lagrangian model (EcoTiM) to calculate annual budgets of silica and phosphate. The model results indicate that the back barrier area of Spiekeroog Island exports inorganic silica ($128 * 10^6 \text{ mol a}^{-1}$), phosphate ($3 * 10^6 \text{ mol a}^{-1}$), and nitrite plus nitrate ($29 * 10^6 \text{ mol a}^{-1}$) to the North Sea. Extrapolation of these data to the entire Wadden Sea along the southern North Sea reveals that the back barrier areas export silica and phosphate in the same order of magnitude and nitrite plus nitrate one order of magnitude lower than the combined rivers Elbe, Weser, and Ems.

Keywords

Nutrients, Silica, Phosphate, Nitrite Plus Nitrate, NO_x , Wadden Sea, German Bight, North Sea, Modelling, Budgets

1 Introduction

The Wadden Sea as part of the Southern North Sea forms the transition zone between the terrestrial and open marine realm. This dynamic system is influenced by freshwater input via rivers and small coastal tributaries from the hinterland as well as by the exchange with offshore waters. Since eutrophication has been recognized as an international challenge (Nixon, 1990), many studies focus on sources and sinks of nutrients in coastal areas (de Jonge and Postma, 1974; van Raaphorst and Kloosterhuis, 1994; van Beusekom et al., 1999; van Beusekom and de Jonge, 2002; van Raaphorst and de Jonge, 2004; van Beusekom, 2005; Soetaert et al., 2006; Withers and Jarvie, 2008). Tidal systems, such as the Wadden Sea with its chain of barrier islands, are of special interest as they are characterised by intensive production and mineralization of organic matter.

High amounts of particulate organic matter are imported from the North Sea (van Beusekom and de Jonge, 2002) and after bacterial mineralization (Böttcher et al., 2000; Böttcher et al., 2004; Werner et al., 2006; Al-Raei et al., 2009) dissolved species are exported from the Wadden Sea, thus justifying the idea of the “bio-reactor Wadden Sea” (de Jonge and Postma, 1974; van Beusekom et al., 1999; van Beusekom et al., 2001; van Beusekom and de Jonge, 2002; van Beusekom, 2005; Beck et al., 2008a; Anschutz et al., 2009). Generally, about 70% of the coastal remineralisation of organic matter (OM) takes place in the water column (Smith and Hollibaugh, 1993). In contrast, in more shallow areas benthic processes gain in importance and can account for 50-60% of the total carbon mineralization (Heip et al., 1995).

Once nutrients are produced by OM degradation in surface sediments, their release to the open water column is governed by several factors, i.e. sediment permeability (Rusch and Huettel, 2000; Rusch et al., 2000), tidal pumping (Billerbeck et al., 2006a; Beck et al., 2008a,b; Deborde et al., 2008), bioturbation (Volkenborn et al., 2007), and nutrient assimilation by phytobenthos (Fong et al., 1993).

So far little is known about the importance of Wadden Sea areas for the nutrient budget of the Southern North Sea (Gätje and Reise, 1998; Brockmann et al., 1999; Sündermann et al., 1999; van Beusekom et al., 1999). In this contribution, we present nutrient dynamics in the surface waters of the back barrier tidal flat area of Spiekeroog Island (Southern North Sea) which were determined continuously by a time-series station between 2006 and 2008 (Grunwald et al., 2007). The numerical model “EcoTiM” (Kohlmeier and Ebenhöf, 2007) was used to simulate the nutrient variations and to estimate the outflow of nutrients from the Wadden Sea to the open North Sea. In order to assess potential nutrient sources in the Wadden Sea, we also analyzed small coastal tributaries and pore waters of surface tidal flat sediments.

2 Geographical setting

The Wadden Sea in the Southern North Sea (Fig. 1) stretches from Den Helder (The Netherlands) to Esbjerg (Denmark) and encompasses an area of about 9500 km². A chain of barrier islands forms the boundary between the Wadden Sea and the open North Sea. The entire Wadden Sea system is characterised by semidiurnal tides with a tidal range between 1.5 m in the most westerly part and 4 m in the estuaries of the rivers Weser and Elbe. The main study site of this contribution is the back barrier area of the Island of Spiekeroog, which covers about 74 km² (Walther, 1972). Depending on water level, freshwater contribution to the back barrier tidal flat occurs irregularly (i.e. not every day) about 2 h before low tide via a flood-gate in Neuharlingersiel (Fig. 1b). The catchment area of the flood-gate is about 125 km² and is composed of marsh soils in the north and fens as well as forests in the south.

Nutrient dynamics are studied at a time-series station (Grunwald et al., 2007; Reuter et al., 2009) located at $53^{\circ}45.02' \text{ N}$ and $7^{\circ} 40.27' \text{ E}$ in the tidal inlet between the Islands of Spiekeroog and Langeoog. Pore waters samples were obtained by using permanently installed lances located on the sandy tidal flat Janssand (site JS1, $53^{\circ} 44.18' \text{ N}$, $7^{\circ} 41.9' \text{ E}$; (Beck et al., 2007)). The tidal flat is covered by 1-2 m of water at high tide and emerges for a period of 6 hours during low tide.

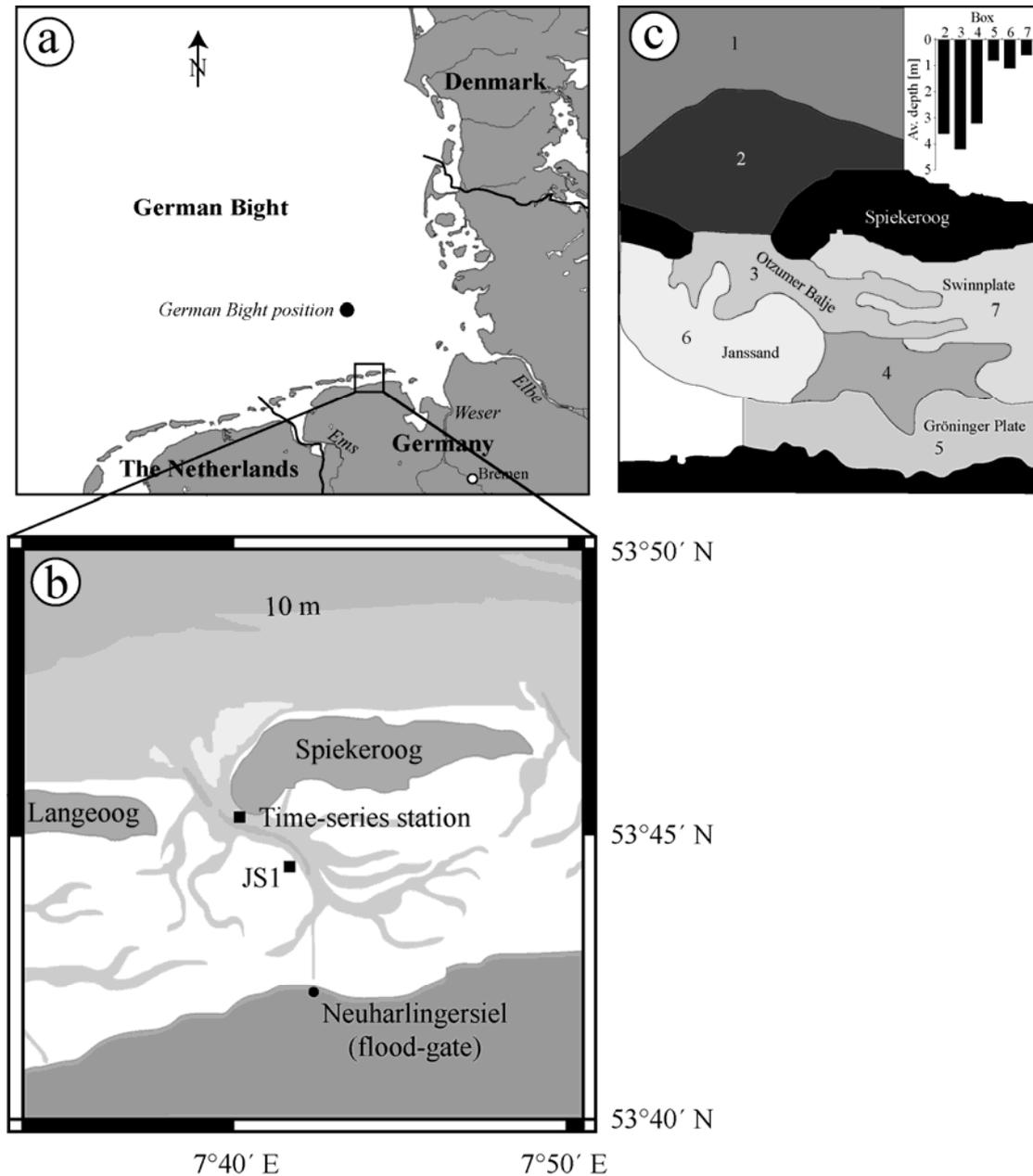


Fig. 1: Map of the study area. (a) At the German Bight position samples were analysed (MARNET, 2008) for the North Sea boundary conditions in the model setup. The close-up view (b) shows the sampling sites in the back barrier area of Spiekeroog Island: Time-series station, pore water sampling site JS1, and the flood-gate in Neuharlingersiel. (c) Classification of boxes used in the Euler-Lagrangian model simulations with corresponding average water depths.

3 Materials and methods

3.1 Nutrient analysis at the time-series station

In surface waters of the back barrier area of Spiekeroog Island, the dissolved nutrients silica, phosphate, and nitrite plus nitrate (further referred to as NO_x) were determined since April 2006 by automated nutrient analyzers (Systea, $\mu\text{Mac}1000$) mounted on a permanent time-series station in the tidal inlet (Fig. 1). At the study site, the average water depth of 13.5 m (below mean sea level) varies due to semidiurnal tides with a range of 2.6 m (Flemming and Davis, 1994). Samples were taken from a through-flow tube within the time-series station at 9 m above seafloor. Nutrients were measured hourly after automated filtration by a belt filter (Metrohm, Series 01.12) of 7 – 12 μm pore size (Schleicher & Schuell, No. 1574). The time-series station and the analyzer setup are described in detail by Grunwald et al. (2007) and Reuter et al. (2009). Detection limits are 0.4 μM for silica, 0.01 μM for phosphate, and 0.2 μM for NO_x . The agreement of comparative measurements with analysers and laboratory spectrophotometers (Spekol 1100, Analytik Jena) according to methods described by Grasshoff et al. (1999) were 96% for phosphate, 89% for silica, and 94% for NO_x .

3.2. Total cell counts of algae

Samples for the analysis of total cell counts of algae (phytoplankton abundance of a size class $>3\mu\text{m}$) were collected at the position of the time-series station in 2008. Surface water was sampled during low tide in at least monthly intervals. Each sample of 100 mL was treated with 2 – 3 drops of Lugol's solution (aqueous iodine / potassium iodide solution) and stored at 4°C in brown glass bottles until analysis. Using the Utermöhl method (Utermöhl, 1958), a sample aliquot of 25 mL was counted under an inverted microscope (Zeiss Axiovert 25).

3.3. Salinity

Temperature (T) and conductivity (L) were determined by a Pt100 and an inductive type sensor (Kombisonde, -4H- Jena engineering) in the same flow-through tube of the time-series station where samples were taken for nutrient analysis. Additionally, hydrostatic pressure (Druck, PDCR901) was measured in the lowermost tube at 0.5 m above sea floor (Grunwald et al., 2007). Using these data, salinity was calculated every ten minutes according to standard procedures (UNESCO, 1985). In order to ensure data quality, reference measurements were conducted at the time-series station by a precisely calibrated CTD-probe (SeaBird, SeaCat 19plus) every fortnight. The accuracy of time-series salinity data in 2007 and 2008 exhibits a mean standard deviation of 0.012 (for details see Reuter et al., 2009). However, in 2006 only few reference measurements with a mean standard deviation of 0.02 are available.

3.4. Pore water

Pore waters were sampled during low tide at position JS1 (Fig.1) at monthly intervals from January – October 2008. Samples were taken using a permanently installed in-situ sampler (Beck et al., 2007). The samples were filtered through 0.45 μm SFCA syringe filters into pre-cleaned PE-bottles and acidified to 1 % (v/v) with HNO_3 (supra pure, Merck). For phosphate and silica analysis, a 5-fold diluted aliquot was measured using ICP-OES (iCAP 6300 Duo, Thermo Fisher). Accuracy and precision were controlled by a spiked seawater standard Cass-4 solution (National Research Council, Canada) containing 16 μM phosphate and 890 μM silica. Accuracy and precision were 3% and 7% for silica and 6% and 5% for phosphate, respectively. A comparison to concentrations determined using a spectrophotometer shows a deviation of +9% for silica and +10% for phosphate.

3.5 Freshwater

In freshwater, nutrients were analysed at monthly intervals from February 2002 to April 2004 at the flood-gate in Neuuharlingersiel. Nutrients were determined by a spectrophotometer according to Grasshoff et al. (1999).

3.6 Modelling nutrient dynamics in the back barrier area

The basis of the ecological tidal model (EcoTiM; Kohlmeier and Ebenhöf, 2007) is the European Regional Seas Ecosystem Model (ERSEM), which is a biomass based differential equation model describing the cycling of carbon and nutrients within a marine ecosystem (Baretta-Bekker and Baretta, 1997). EcoTiM is a semi-Lagrangian 2D-model describing water transport by water bodies moving along a velocity field provided by a general circulation model (Stanev et al., 2003). Diffusion is implemented as turbulent diffusion by a randomized offset of water bodies and by diffusive exchange between water bodies. North Sea boundary conditions are taken into account by (i) equating box 1 with the North Sea conditions and (ii) tracers entering box 1 become mixed with North Sea water to realize the import and export of nutrients and organic matter. Conditions at the North Sea boundary for state variables were taken from the COCOA-model, a Continental Coastal Application of ERSEM (Lenhart et al., 1997). For inorganic silica, phosphate, and NO_x the boundary conditions were derived from measurements in 2002 (MARNET, 2008) determined in the German Bight at 54.17°N and 7.45°E (Fig. 1a). Nutrient input via the flood-gate in Neuuharlingersiel is based on concentrations determined during this study and freshwater discharge rates published by Rupert et al. (2004).

The total exchange of a box (Fig. 1c) with the underlying sediment area is calculated by summing up the exchange of all single moving water bodies within the box at the actual time. The model is forced by temperature and irradiance (Photosynthetically Active Radiation, PAR) measured at the time-series station. The food web of functional groups is built with respect to trophic position, size, and function. The model describes the main metabolic processes as carbon assimilation, nutrient uptake and lysis of primary producers, grazing processes of secondary producers, and respiration, mortality excretion, and exudation of all organisms. As an extension to the original benthic food web of ERSEM (Ebenhöf et al., 1995), benthic silica dependent algae and non-silica dependent algae are added, following the description of Blackford (2002).

The benthic nutrient model (Ebenhöf et al., 1996; Kohlmeier, 2004) governs the nutrients nitrate, phosphate, and silica and their exchange with the pelagic system depending on the nutrient gradients at the sediment surface. As an additional process in model calculations transport of benthic organic particulate matter is included as exchange process between adjacent sediment areas (Ebenhöf et al., 2004).

The water movement is calculated with a fixed time step of 1/100 day. Ecological processes are calculated with a Runge-Kutta method with time step adaption and a maximum time step of 1/100 day. The number of Lagrangian tracers amounts to 200. Each tracer describes a volume of $2.22 \cdot 10^6 \text{ m}^3$. A more detailed description of the model is given in Kohlmeier and Ebenhöf (2007).

Calculations comprise the period of the first to the last low tide in 2007 (364.82 days). Different scenarios (run1 - run5) are used as a sensitivity analysis. The reference run (run1) is parameterised according to Kohlmeier and Ebenhöf (2007). In a second run (run2), the contribution via the flood-gate in Neuuharlingersiel is excluded to calculate the freshwater impact on nutrient budgets of the back barrier area. In runs 3 and 4 the influence of benthic organic particulate matter import is estimated. While in run3 the import of benthic particulate matter into the back barrier area is excluded, the amount is doubled in calculations of run4. The last (run5) gives a rough estimation on the impact of atmospheric intake. In comparison to run1, where atmospheric intake is neglected, an intake of $82 \text{ kg km}^{-2}\text{a}^{-1}$ phosphate according to Carlson (1986) and $1800 \text{ kg km}^{-2}\text{a}^{-1}$ nitrogen according to calculations by de Leeuw et al. (2003) are considered as rough estimations in run5.

4 Results and discussion

4.1 Seasonal dynamics in surface waters of the Wadden Sea

4.1.1 Silica

Silica shows a pronounced seasonal cycling in surface waters of the back barrier area of Spiekeroog Island (Fig. 2), with highest levels determined from late autumn to winter (November-March 2006/2007: 23 μM ; 2007/2008: 21 μM). Such pattern is predominantly caused by the distinctly decreasing assimilation by phytoplankton, which is also true for the adjoining larger rivers (Ems, Weser, Elbe) whose nutrient load is highest during the above mentioned seasons (Lenhart et al., 1997). Along with the input from westerly tidal systems these contributions lead to a general replenishment of the nutrient reservoir in the Southern North Sea. Single peak maxima, some are marked by black arrows in Figure 2, are paralleled by distinct drops in salinity, indicating a certain freshwater contribution. This assumption is strengthened by the fact that these nutrient maxima are observed during low tide, when a certain freshwater contribution via the flood-gate in Neuharlingersiel (Fig. 1b) appears more than likely.

Subsequent to elevated winter levels, a rapid decrease is seen in early spring due to the onset of the spring diatom bloom (Lewin, 1962; Antia et al., 1963; Grant, 1971; Ryther et al., 1971; Paasche, 1973). Generally, silica concentrations are lowest during spring and summer (April – September) with median values of 0.4 – 5.5 μM (Table 1). This level is below or at least close to the threshold of 2 μM where diatoms compete with dinoflagellates, which leads to a change in the phytoplankton community with increasing abundance of dinoflagellates in summer (Egge and Aksnes, 1992; Dippner, 1998; Egge, 1998). In 2006 and 2007, the diatom growth seems to be limited solely by silica availability. In contrast, phosphate as a further essential nutrient (Philippart et al., 2007) reaches a minimum in May 2008 as well (Fig. 2), which probably limited diatom growth and led to a decrease in silica uptake.

In 2007, silica concentrations decreased within 25 days from a value of 29 μM (18th March) to 0.4 μM (11th April) resulting in an average loss of 1.1 $\mu\text{M d}^{-1}$. In 2008, concentrations decreased from 30 μM to 1.7 μM (2nd March - 15th April) with a gradient of 0.6 $\mu\text{M d}^{-1}$ within 45 days. Thus, the spring diatom bloom started later in 2007 but was more intense when compared to 2008. Typically, the spring bloom starts in the shallow waters of the German Bight between week 6 and 14 (Wiltshire et al., 2008). Wiltshire and Manly (2004) postulated that a delay of the early spring bloom may be related to a longer persistence of zooplankton grazers in autumn and early winter (Beare et al., 2002). A further reason for a delay in spring bloom is insufficient insolation under disadvantageous weather conditions (cloudiness, wave action), which is especially important in the turbid waters of the study area (Smetacek and Passow, 1990; Townsend et al., 1994; Tillmann et al., 2000; Colijn and Cadee, 2003; Billerbeck et al., 2007; Loebel et al., 2009).

The silica pattern during the winter period reveals distinct differences for the investigated years (Fig. 2). While in winter 2006/2007 (December - March) the silica pattern has a plateau-like shape, data from winter 2007/2008 are characterized by a steeper slope with maximum values being reached in January 2008 (Table 1). Differences in the shape of winter concentrations are likely caused by different onsets of spring diatom blooms and the intensity of autumn blooms, respectively. The pattern and concentration levels found in our study area are comparable to data from the Belgian coastal area (south-western North Sea) in 1993 and 1994 (Schoemann et al., 1998) and in 2002 (van der Zee and Chou, 2005) as well as from the List tidal basin (northern Wadden Sea, German Bight) in 2004 and 2005 (Loebel et al., 2007; van Beusekom et al., 2009). The authors determined highest silica concentrations in February with up to 30 μM for the Belgian coast and 35 μM for the List tidal basin. A subsequent strong decrease in March due to assimilation by diatoms is observed at all study sites. Low concentrations during summer with similar levels when compared to the back barrier area of

Spiekeroog Island as well as increasing levels towards autumn also have been reported for both, the Belgian coast (Schoemann et al., 1998; van der Zee and Chou, 2005) and the northern part of the Wadden Sea (Loebl et al., 2007; van Beusekom et al., 2009).

4.1.2 Phosphate

The concentration of dissolved phosphate in marine environments is strongly affected by primary production. In the water column of the back barrier area, phosphate shows a seasonal cycle, however the annual pattern is different when compared with silica (Fig. 2) as maximum levels are observed in late summer and early autumn. The phosphate level increases to a maximum value of on average 1 μM in September/October, whereas minima below 0.2 μM are reached between April and May (Table 1). This seasonal pattern is in good agreement with the behaviour of phosphate reported for the Southern North Sea and the adjacent Wadden Sea areas (Postma, 1954; de Jonge and Postma, 1974; Brockmann et al., 1990; Hickel et al., 1993).

As described for the silica cycle, maximum phosphate concentrations are seen at a different time in the years 2006 – 2008. The autumn maxima change from a plateau-like shape in 2006 to a more peak-like profile in 2008. Although phosphate is assimilated by phytoplankton, decomposition of produced biomass prevails over consumption from early summer onwards, thereby replenishing the pelagic phosphate pool (van Beusekom et al., 2009). The predominance of decomposition over consumption occurs until September/October, when the annual maximum concentrations are reached. Afterwards, the phosphate level decreases in autumn and winter, which can be hardly attributed to phytoplankton activity, as supported by decreasing total cell counts of algae (Fig. 2). As the phosphorus cycle is not only governed by bioproductivity and organic matter decomposition, adsorption and desorption processes by ferric oxyhydroxides in the sediments have to be considered as well (Einsele, 1938; Berner, 1973; Slomp et al., 1996; van Beusekom and de Jonge, 1998). The connection between dissolved phosphate and the sedimentary iron cycle probably causes differences in the shape of autumn patterns as well as lower average winter concentrations when compared to autumn values.

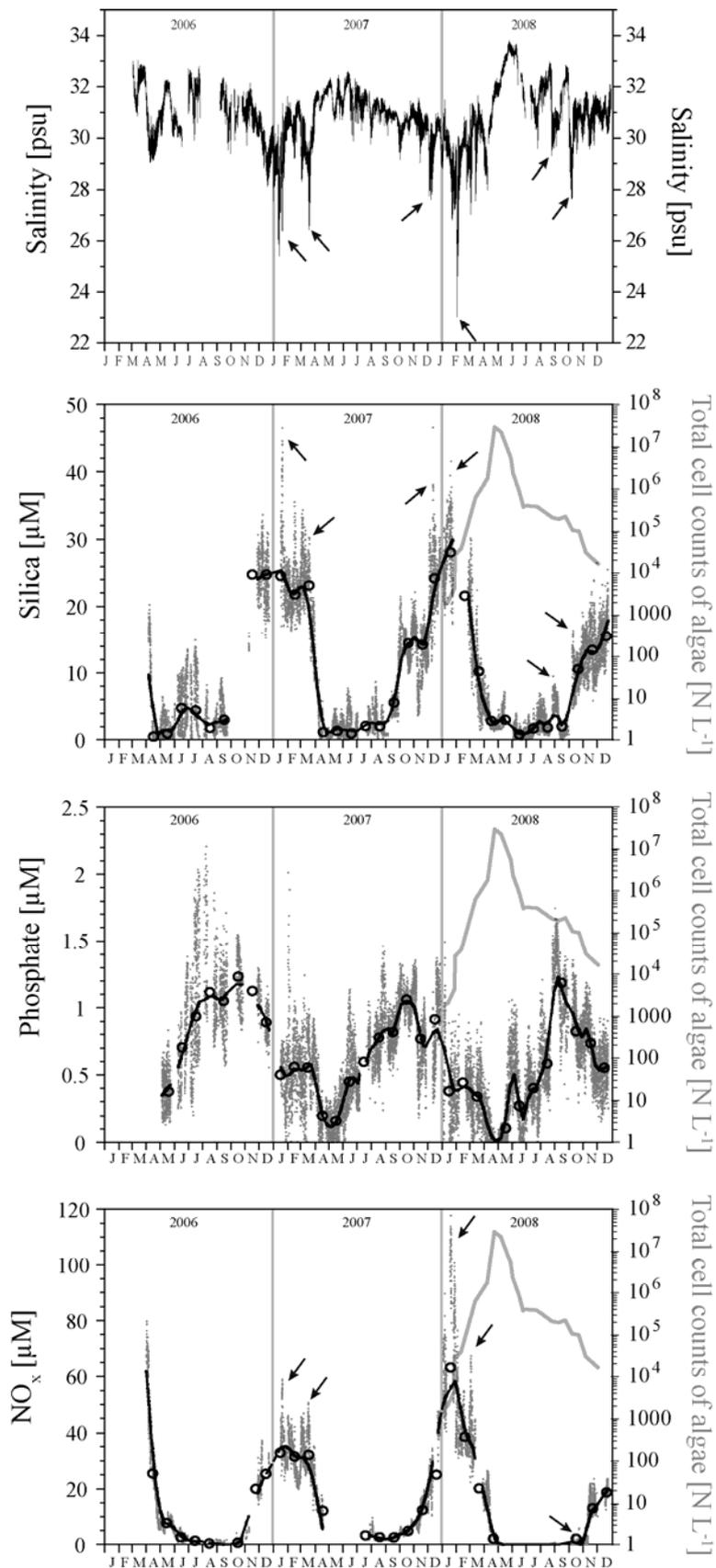


Fig.2: Salinity, silica, phosphate, and nitrite plus nitrate in the years 2006-2008 determined at the time-series station in the tidal inlet of the Island of Spiekeroog. Single nutrient measurements are shown as grey dots. The black line represents running average concentrations and open circles indicate monthly averages. Total cell counts of algae in 2008 (grey line) are given on a logarithmic scale. Black arrows mark nutrient peak maxima of silica and NO_x accompanied by drops in salinity.

4.1.3 Nitrite plus nitrate (NO_x)

The seasonal pattern of NO_x in 2006 - 2008 is comparable to that of silica (Fig. 2) with highest values in winter and the lowest level during spring and summer. However, the inter-annual variability in winter is much more pronounced for NO_x when compared with silica and phosphate. From January to March 2007, we determined almost uniform plateau-like average concentrations of about 32 μM, whereas in the same period in 2008 monthly average concentrations varied from about 63 μM (January) to 17 μM in March (Table 1). Although, there is a small data gap, Figure 2 indicates that NO_x winter concentrations in 2005/2006 were similar to those in 2008. The inter-annual variation of winter NO_x levels in the study area is likely governed by both: varying supply by large rivers, as indicated by lower salinities in figure 2, and sediment denitrification, as described van Beusekom et al. (2008) for the northern Wadden Sea of the German Bight. This assumption is supported by findings of Lacroix et al. (2007) and Johannsen et al. (2008) who reported highest NO_x river loads in winter, which may vary by a factor of 2 in succeeding years (e.g. Lacroix et al., (2007)). Low concentrations in spring and summer denote the direct coupling to primary production, which is supported by the almost coincident decrease of NO_x and silica during spring bloom in 2007 and 2008. The pattern as well as concentration levels of NO_x observed in the study area are in good agreement with data for the Dutch Wadden Sea (van Beusekom et al., 2001) and the List tidal basin of the northern Wadden Sea (Loebl et al., 2007; van Beusekom et al., 2009). However, the seasonality in NO_x is not only affected by phytoplankton assimilation but by nitrogen recycling processes as well, which occur in the water column (Caperon et al., 1979; Glibert, 1982; Christensen, 1994; Soetaert et al., 2006; Pätsch and Kühn, 2008) and in the sediments (Nixon et al., 1976; Lohse et al., 1993; van Beusekom et al., 1999; Ehrenhauss et al., 2004; Murray et al., 2006). Especially during spring and summer decomposition of organic material leads to enhanced oxygen consumption in sediments and thus to elevated denitrification (Christensen, 1994; Jensen et al., 1996; Seitzinger and Giblin, 1996; van Beusekom et al., 2008). Low NO_x concentrations during spring and summer presumably result from enhanced assimilation and denitrification. Unfortunately, both parameters are not available for our study area yet. Thus, knowledge about assimilation rates and nitrification/denitrification rates would be desirable to estimate the impact of these processes on NO_x cycles on a tidal and seasonal scale.

Table 1: Summary of monthly averaged concentrations for silica, phosphate, and nitrite plus nitrate for the years 2006 – 2008. Corresponding ranges (min – max) are given in brackets. ‘n’ denote the number of measurements used for averaging. Values indicated by ‘*’ are below detection limit.

	2006		2007		2008	
	Median	(min - max; n)	Median	(min - max; n)	Median	(min - max; n)
Silica [μM]						
January	n.d.	(- ; 0)	24	(17 - 47; 267)	28	(17 - 42; 405)
February	n.d.	(- ; 0)	22	(16 - 36; 503)	22	(14 - 27; 72)
March	n.d.	(- ; 0)	23	(8.8 - 34; 524)	10	(1.5 - 30; 636)
April	0.4	(<0.4* - 20; 521)	1.1	(<0.4* - 12; 445)	2.8	(1.3 - 9.7; 572)
May	0.9	(<0.4* - 6.4; 590)	1.3	(<0.4* - 4.7; 648)	2.9	(1.6 - 7.2; 284)
June	4.7	(<0.4* - 14; 465)	0.9	(<0.4* - 7.7; 592)	0.8	(<0.4* - 4.0; 619)
July	4.4	(<0.4* - 15; 358)	2.0	(<0.4* - 5.1; 145)	1.6	(<0.4* - 7.0; 589)
August	1.7	(<0.4* - 8.2; 278)	2.0	(<0.4* - 8.7; 363)	2.2	(0.6 - 9.5; 526)
September	2.9	(0.6 - 9.3; 328)	5.5	(0.7 - 17; 429)	2.0	(<0.4* - 7.8; 515)
October	n.d.	(- ; 0)	14	(9.9 - 22; 615)	11	(4.7 - 19; 540)
November	25	(13 - 31; 83)	14	(3.6 - 22; 592)	13	(5.9 - 27; 695)
December	25	(15 - 34; 345)	24	(11 - 47; 572)	15	(9.7 - 26; 527)
Phosphate [μM]						
January	n.d.	(- ; 0)	0.5	(0.01 - 0.8; 261)	0.4	(0.01 - 1.5; 389)
February	n.d.	(- ; 0)	0.6	(0.01 - 2.0; 476)	0.4	(0.05 - 1.0; 295)
March	n.d.	(- ; 0)	0.6	(0.01 - 1.2; 520)	0.3	(<0.01* - 0.9; 590)
April	n.d.	(- ; 0)	0.2	(<0.01* - 0.7; 408)	<0.01*	(<0.01* - 0.5; 643)
May	0.4	(0.1 - 0.8; 438)	0.2	(<0.01* - 0.6; 588)	0.1	(<0.01* - 1.1; 662)
June	0.7	(0.3 - 1.4; 311)	0.4	(0.01 - 1.1; 612)	0.3	(<0.01* - 1.0; 566)
July	0.9	(0.2 - 2.0; 405)	0.6	(0.2 - 1.1; 224)	0.4	(0.01 - 1.0; 591)
August	1.1	(0.7 - 2.2; 269)	0.8	(0.2 - 1.5; 504)	0.6	(0.2 - 2.2; 523)
September	1.0	(0.6 - 1.7; 316)	0.8	(0.5 - 1.2; 609)	1.2	(0.3 - 1.8; 518)
October	1.2	(0.8 - 1.6; 237)	1.1	(0.8 - 1.3; 611)	0.8	(<0.01* - 1.4; 539)
November	1.1	(0.7 - 1.3; 74)	0.8	(0.2 - 1.4; 544)	0.7	(0.3 - 1.2; 691)
December	0.9	(0.6 - 1.3; 207)	0.9	(0.3 - 1.4; 347)	0.6	(0.2 - 0.9; 527)
NO_x [μM]						
January	n.d.	(- ; 0)	33	(23 - 59; 260)	63	(16 - 118; 396)
February	n.d.	(- ; 0)	31	(20 - 46; 500)	38	(21 - 77; 584)
March	n.d.	(- ; 0)	32	(12 - 51; 547)	17	(<0.2* - 67; 623)
April	25	(5.3 - 80; 584)	12	(5.9 - 21; 299)	1.9	(<0.2* - 27; 651)
May	7.4	(4.1 - 12; 557)	n.d.	(- ; 0)	<0.2*	(<0.2* ; 668)
June	2.4	(0.6 - 6.2; 508)	n.d.	(- ; 0)	<0.2*	(<0.2* ; 504)
July	1.2	(<0.2* - 2.3; 402)	3.1	(1.8 - 7.3; 69)	<0.2*	(<0.2* ; 592)
August	0.2	(<0.2* - 1.9; 129)	2.4	(1.8 - 9.6; 316)	<0.2*	(<0.2* - 0.9; 421)
September	0.6	(<0.2* - 1.8; 162)	2.3	(1.5 - 4.4; 580)	n.d.	(- ; 0)
October	0.5	(<0.2* - 4.3; 173)	4.6	(2.7 - 9.1; 520)	0.9	(<0.2* - 12; 212)
November	20	(2.1 - 31; 100)	12	(4.3 - 20; 621)	13	(<0.2* - 24; 565)
December	25	(17 - 37; 106)	25	(5.8 - 47; 337)	18	(0.5 - 24; 180)

4.2 Tidal dynamics in the Wadden Sea

The tidal patterns of silica, phosphate, and NO_x are exemplarily discussed using data determined at the time-series station in 2007 (Fig. 3).

4.2.1 Silica

Silica shows a uniform tidal pattern in every season, reaching maximum values at low tide. Additionally, differences in amplitude, i.e. concentration range between low and high tide, and concentration level are observed throughout the year. For instance, the winter amplitude in February 2007 of almost $6 \mu\text{M}$ at a median concentration level of $22 \mu\text{M}$ (compare Table 1) decreases towards spring (May) to an amplitude and concentration level of below $1 \mu\text{M}$, respectively. Although, high tide silica is still depleted in June 2007, low tide concentrations increase to values of up to $7.7 \mu\text{M}$. This indicates that the supply rate of dissolved silica exceeds its removal by diatom uptake in the back barrier area during that time period. The reduced levels at high tide, which reach the lowest values of on average $<0.4 \mu\text{M}$ in June 2007, are due to dilution with nutrient-poor waters from the German Bight. In the following time period, decreasing silica assimilation in the offshore waters results in slightly elevated high tide concentrations of about $2 \mu\text{M}$ in August 2007. This gain in silica continues during autumn, finally reaching the highest level in winter.

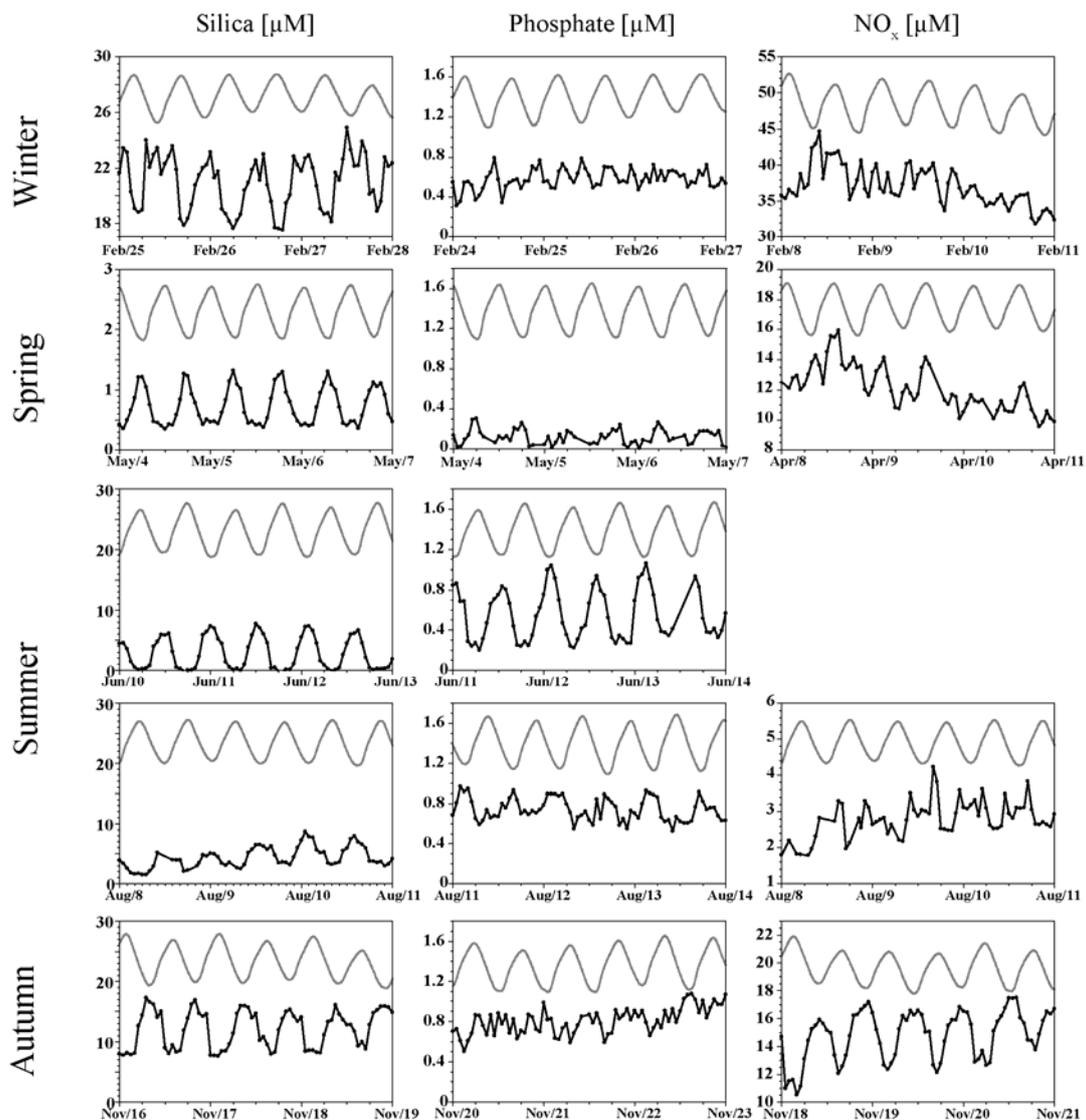


Fig. 3: Tidal dynamics of silica, phosphate, and nitrite plus nitrate in winter, spring, summer, and autumn 2007. Note the different scales for silica (winter) and nitrite plus nitrate. Grey lines indicate the tidal state.

4.2.2 Phosphate

During winter (February 2007, Fig. 3), phosphate shows no tidal pattern and scatters around an average value of 0.6 μM . During spring (May 2007), the phosphate level generally decreases by a factor of about 2 and a slight tidal dependence develops. Again, maximum concentrations are seen at low tide (about 0.3 μM) whereas extremely low values occur at high tide resulting in a faint tidal pattern (amplitude 0.3 μM). Similar to silica, the low high tide level is due to elevated phosphate assimilation in the German Bight. Towards June 2007 the tidal cyclicity is much more pronounced with amplitudes of 0.6 μM . This points towards a higher phosphate release within the back barrier area in June, which is in accordance with other tidal flats systems and estuaries in the Southern North Sea (Rutgers van der Loeff et al., 1981; Jensen et al., 1995; Dick et al., 1999). Such clear tidal dependency is much less pronounced in August 2007 (amplitude 0.4 μM) and disappears almost completely in autumn.

4.2.3 NO_x (Nitrite plus nitrate)

The tidal pattern of NO_x is different from those of silica and phosphate. In winter, NO_x in general does not reveal tidally-driven dynamics, but during certain days higher concentrations may be observed at low tide. This tidal dependence only lasts for up to 4 days and seems to be caused by random contribution of freshwater via the flood-gate. In spring, concentrations are slightly higher at high tide compared to low tide. The lower concentrations at low tide may reflect higher assimilation rates in the back barrier area compared to the German Bight. Enhanced denitrification in tidal flat sediments may further lead to depleted concentrations at low tide. As phytoplankton is able to store nitrate in its vacuoles (Dortch, 1982; Stolte et al., 1994), the deposition of intact cells may result in nitrate accumulation in the sediment (Cadée, 1996). After decomposition of deposited cells nitrate is released (Philippart et al., 2000) thereby enhancing denitrification rates (Lomstein et al., 1990).

In summer (August 2007, Fig. 3), a coupling to the tidal signal can be seen which is inverse to the pattern observed in April 2007. Higher NO_x concentrations tend to appear during low tide with an amplitude of 1.2 μM thus pointing towards remineralisation within in the back barrier area. This is in accordance with investigations in the Dutch Wadden Sea (Helder, 1974), where decomposition of organic matter dominates over assimilation in late summer and autumn. The slight consent with the tidal state observed in summer (August 2007) becomes most pronounced in autumn (November 2007), when an amplitude of about 4 μM is observed.

4.3 Nutrient sources in the back barrier area

For the back barrier area of Spiekeroog Island several potential sources for dissolved inorganic nutrients have to be considered. These sources are freshwater discharge via the flood-gate in Neuharlingersiel, pore waters draining out of the tidal flat sediments, and precipitation as a source for atmospheric nitrogen input. Here we focus on the contributions via freshwater and pore water, due to lack of information about the amount of atmospheric deposition. Additionally, in view of the data shown before, the offshore waters from the open North Sea act in almost all cases only as a diluent.

4.3.1 Freshwater

In the study area, freshwater discharge via the flood-gate in Neuharlingersiel to the back barrier area changes seasonally due to rainfall and vegetation periods in the hinterland. For the calculation of the freshwater contribution averaged water discharge rates from the years 1996 to 2006 (Rupert et al., 2004) and nutrient concentrations determined at the flood-gate in 2002 – 2004 (Fig. 4) were used. High water discharge rates from November to March are directly coupled to precipitation. In contrast, during the vegetation period the freshwater contribution is distinctly lower and not related to precipitation. The inter-monthly variation of

averaged water discharge ranges from $0.4 \cdot 10^6 \text{ m}^3 \text{ month}^{-1}$ in June to $3.4 \cdot 10^6 \text{ m}^3 \text{ month}^{-1}$ in January (Rupert et al., 2004).

Monthly amounts of nutrient discharge by freshwater to the tidal flat area reveal different patterns for silica, phosphate, and NO_x (Fig. 4). While silica and NO_x follow roughly the freshwater discharge, phosphate seems to be decoupled, which is likely due to different sources and geochemical behaviour (see section 4.1).

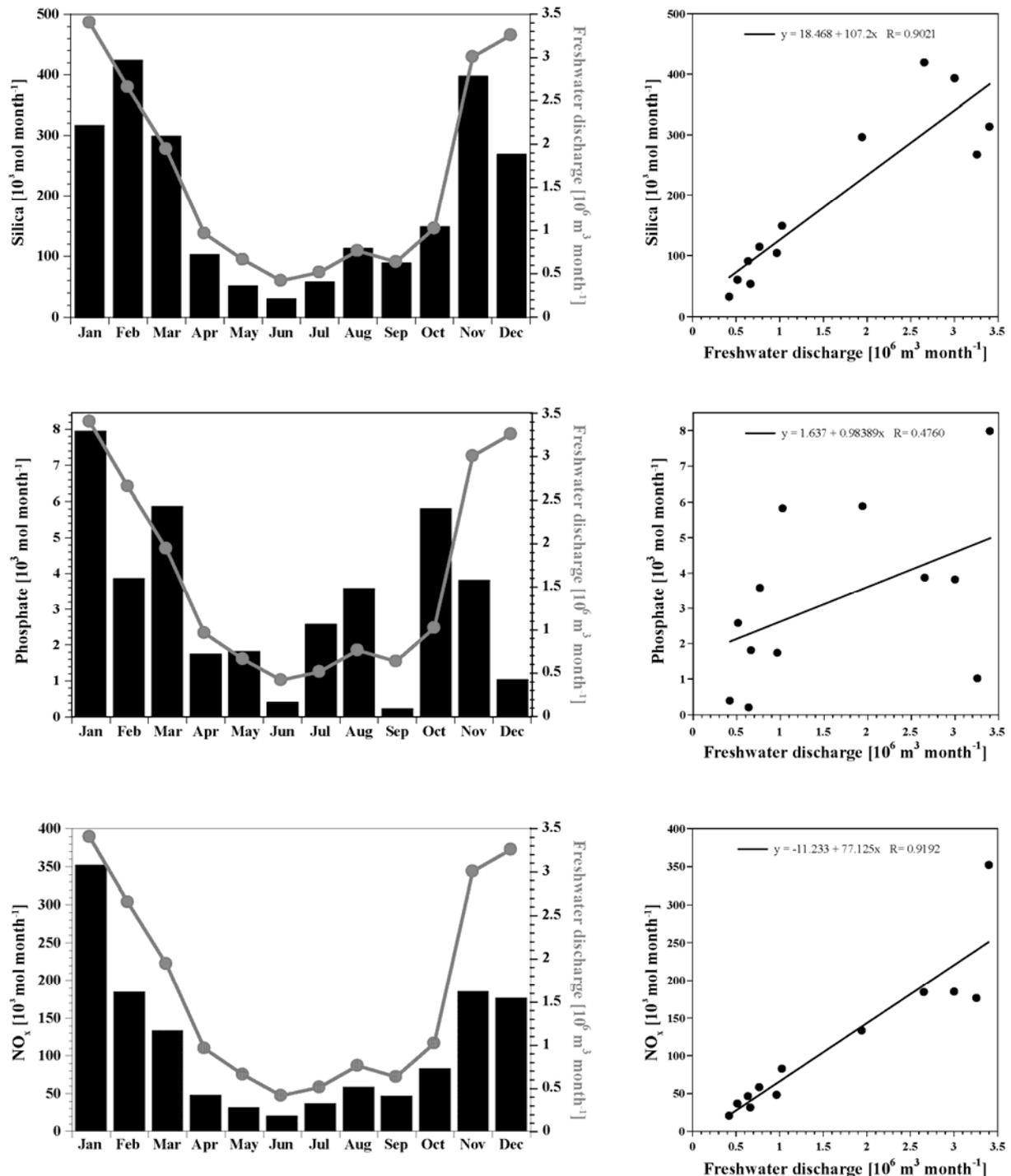


Fig. 4: Monthly freshwater contribution of silica, phosphate, and nitrite plus nitrate via the flood-gate in Neuuharlingersiel to the tidal flat area of Spiekeroog (columns). Data are averaged for the years 2002-2004. For comparison, averaged freshwater discharge rates (Rupert et al., 2004) via the flood-gate are given (circles). Plots on the right side present the relation between freshwater discharge volume and nutrient load.

The annual variability of silica and NO_x discharge via freshwater is comparable to the patterns observed at the time-series station (compare to Fig. 2). In contrast, such similarities are less pronounced for phosphate. However, this relation does not evidence the freshwater as the dominating nutrient source since both systems are governed by the same seasonal processes. Thus, nutrient concentrations in freshwater are also subject to phytoplankton dynamics. The higher precipitation during autumn and winter enhances the freshwater discharge which in turn leads to the pattern observed at the flood-gate in Neuaharlingersiel. Both silica and NO_x contribution is directly coupled to the amount of discharged water volume (Fig. 4) and varies between $0.3 \cdot 10^5$ (June) to $4.2 \cdot 10^5$ mol per month (February) and $0.2 \cdot 10^5$ (June) to $3.5 \cdot 10^5$ (January), respectively. For phosphate, no seasonal pattern is found and the contribution via freshwater is irregular ranging between 0.2 and $8 \cdot 10^3$ mol per month.

As the freshwater is discharged irregularly (i.e. not every day) to the back barrier area, the tidal nutrient patterns determined at the time-series station, can only be hardly explained by freshwater contribution. Furthermore, the highest discharge volume of $3.4 \cdot 10^6 \text{ m}^3$ per month is one order of magnitude smaller than the smallest water volume of the back barrier area of about $39 \cdot 10^6 \text{ m}^3$ occurring at spring tide low water (Stanev et al., 2003). Although, both silica and phosphate are highly enriched in the freshwater (silica: factor 35, range: 3-94; phosphate: factor 22, range: 0.3-180) when compared to the water column of the back barrier area, the volume of freshwater released to the back barrier area is too small to account for the generally increasing level in autumn and winter. For instance, in January 2008 when the highest freshwater discharge occurred, the phosphate contribution was on average $1.3 \cdot 10^2$ mol per tide whereas the phosphate inventory of the entire water column of the back barrier area amounts up to $400 \cdot 10^2$ mol. Consequently, the nutrient discharge via the flood-gate in Neuaharlingersiel is most likely of minor importance, which is also supported by results of the model simulations shown in Section 4.4.

4.3.2 Pore water

A further nutrient source form pore waters draining out of the tidal flat sediments during low tide. Numerous studies dealing with nutrient and organic carbon dynamics (e.g. (Howes and Goehring, 1994; Böttcher et al., 1998; Böttcher et al., 2000; Böttcher et al., 2004; de Beer et al., 2005; Billerbeck et al., 2006b; Beck et al., 2008a,b; Kowalski et al., 2009) have identified intertidal sediments as the loci of enhanced degradation of organic matter. After subsequent release of dissolved nutrients to the pore waters these nutrients enter the overlying water column (Billerbeck et al., 2006a). Jansen et al. (2009) studied pore water dynamics in the upper few centimetres at site Janssand. They emphasized the high variability in solute exchange in this layer.

In the upper 10 cm sediment at site JS1, pore water concentrations of silica and phosphate change seasonally as seen in Figure 5. Silica pore water concentrations are highest during the growth season (March – September), while during autumn and winter concentrations are lower. The level ranges between 25 μM in winter (January) and up to 250 μM in early summer (June). The pattern of pore water silica seems to be influenced directly by the diatom succession in the water column. After the onset of the annual diatom spring bloom in February, silica concentrations in pore water increase. Earlier studies report the formation of diatom-dominated aggregates during diatom blooms (Riebesell, 1991a; Riebesell, 1991b). After deposition and subsequent incorporation of the aggregates into the surface sediment (Huettel and Rusch, 2000) the degradation of the aggregates leads to a release of biogenic silica. Dissolution rates of diatom walls depend on temperature as well as pH, i.e. dissolution increases at higher temperatures or at higher pH (Lewin, 1961; Kamatani and Riley, 1979; Kamatani, 1982; Nelson et al., 1995; Cheng et al., 2009). Although, water temperatures are highest in both the water column and the sediment (Beck et al., 2008b) in July and August silica concentrations already decrease in the pore waters. This pattern is directly coupled to the total cell counts of diatoms (Fig. 5). In spring (March-May) diatom cell counts

dramatically increase resulting in elevated pore water concentrations due to dissolution of diatom frustules. However, from end of May the diatom cell counts distinctly decrease which leads to a strong decrease of pore water silica concentration with a time delay of about one month. This phenomenon may be enhanced by increasing diatom aggregation caused by elevated TEP (transparent exopolymer particles) release during the breakdown of diatom blooms (Alldredge and Gotschalk, 1989; Bhaskar et al., 2005; Kowalski et al., 2009). Such aggregation is known to preserve diatom frustules against dissolution (Passow et al., 2003) and thus to inhibit the release of dissolved silica to the surrounding pore water.

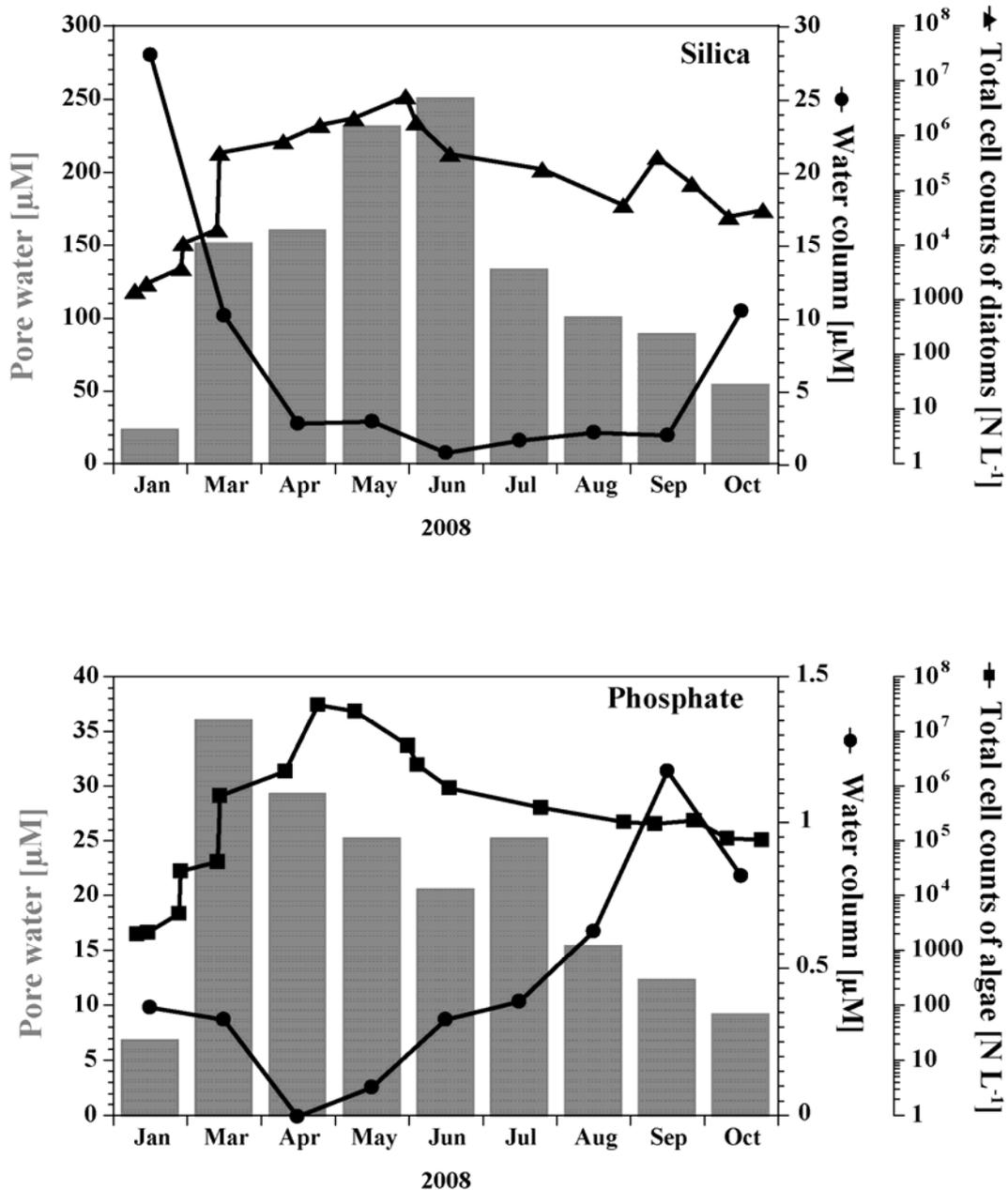


Fig. 5: Pore water concentrations of silica and phosphate in 2008 at site Janssand JS1 (columns). For comparison, monthly averages of water column concentrations (circles) are shown. Total cell counts of diatoms (triangles, upper plot) and algae (squares, lower plot) are indicated on a logarithmic scale.

At our study site the temperature of pore water in the upper decimetres of the sediment follows directly the temperature of the overlying water column (Beck et al., 2008b). For instance, from January to March 2008 the monthly average temperature of the water column varies only little from January (4.5°C) to February (4.9°C), and March (5.8°C). Thus, the strong increase in pore water silica concentrations in March is likely not only due to an increase in temperature, but a consequence of enhanced import of fresh diatom frustules to the sediment surface during the onset of the spring bloom. Additionally, the decrease of pore water silica is weakened from August to September 2008 by a diatom summer bloom (Fig. 5) supplying new diatom frustules to the sediment.

For phosphate, the seasonal pattern in pore water differs from that of silica. Similar to silica, highest phosphate concentrations are observed in March. However, concentrations decrease towards autumn and winter. Besides the direct coupling to biological assimilation and degradation of organic matter, phosphate underlies a further source/sink process. Phosphate from both organic matter decomposition in the sediment and the open water column can be trapped during precipitation of ferric oxyhydroxides in oxic surface sediments. This process is most pronounced in autumn and winter when decreasing microbial activity due to lower temperatures (Vosjan, 1974) results in an expansion of the oxic surface layer. In contrast, high rates of organic matter mineralization in spring and summer reduce the redox potential in surface sediments, promoting the reduction of ferric iron and a coupled release of phosphate (van Beusekom et al., 2001). This is particularly true in March, when high amounts of organic matter produced during the spring bloom are incorporated into the upper sediment layers. As a result of the consequently resulting increase in microbial activity a large quantity of dissolved phosphate is released leading to rising pore water concentrations (Fig. 5). On the other hand, formation of ferrous iron phosphate (vivianite) is rather unlikely as in such sulfidic systems iron monosulfides are the preferred phase. Thus, during spring and summer the pore waters are highly enriched in phosphate, which may escape to the overlying water across a thin layer of oxidised sediment. Phosphate released from the sediment is rapidly assimilated by phytoplankton as indicated by low concentrations in the water column (0.3 μM) and high values in pore water (36 μM). Increasing concentrations in the water column accompanied with a decrease of pore water phosphate towards late summer is due to diminished assimilation by phytoplankton and a proceeding exhaustion of pore water phosphate, respectively.

Jensen et al. (1995) figured out a low molar Fe/P ratio of 2 in the sediments of Aarhus Bay during late summer. At this level the buffer capacity of the sediment for P adsorption by ferric iron seems to be exhausted. By contrast, the authors found maximum molar Fe/P-ratios of about 10 in winter and early spring (February and May), when the sediments are well oxygenated and thus still possess capacity for phosphate fixation. Therefore, sediments act as phosphate sinks during winter (van Beusekom et al., 2001) whereas adsorbed P is released during summer. Especially in the Wadden Sea, iron-bound phosphate is of the same importance as particulate organic phosphorus (van Beusekom and de Jonge, 1997; van Beusekom and Brockmann, 1998), which emphasises the significance of sediments as an intermediate sink in the phosphorus cycle of tidal flat systems.

4.4 Nutrient budgets

The Euler-Lagrangian model EcoTiM describes the cycling of silica, phosphate and NO_x in the back barrier area of Spiekeroog Island. In this study we focus on the export budgets in the tidal inlet at the boundary between model boxes 2 and 3 (Fig. 1c). An estimation of dissolved inorganic nutrient export as well as the impact of nutrient supply via freshwater and atmospheric intake is summarized in table 2.

The comparison of reference run (run1) and data determined at the time-series station in 2007 shows that the seasonal pattern is reproduced by the model (Fig. 6). However, calculated winter concentrations of silica and NO_x are too low compared to the time-series data. This may be due to the applied boundary conditions, which were not available for 2007 but have

been derived from data in 2002. Thus, winter values at the North Sea boundary as well as assumed particulate matter import into the back barrier area in autumn and winter might be underestimated in the model study. Nevertheless, the strong concentration decrease due to the annual spring bloom is reproduced very well. The annual simulated phosphate pattern reproduces the measured values, with the exception that from June to October, the model results are too low. This may be caused by an underrated contribution of phosphate-rich pore waters to the pelagic system or by overestimated assimilation by phytoplankton. In agreement with the measurements, model results of run2 reveal that nutrient contribution via the flood-gate is of minor importance and accounts for only 2% (silica), 1% (phosphate), and 6% (NO_x) of the total nutrient budget of the study area, respectively.

Table 2: Results of Euler-Lagrangian model simulations. Export of dissolved inorganic silica, phosphate and nitrite plus nitrate from the back barrier area are given for different runs of model calculations (see text). Import variables of model calculations are given by ‘organic import water’ and ‘organic from sediment’ as well as the impact of freshwater contribution via the flood-gate. Values in brackets indicate the percentage in comparison to the reference run (run1).

	run1	run2	run3	run4	run5
Silica [10⁶ mol a⁻¹]					
Dissolved export	127.7	125.2 (98 %)	38.0 (30 %)	206.4 (162 %)	127.6 (100 %)
Organic Import water	31.9	32.1 (101 %)	35.9 (112 %)	29.0 (91 %)	31.8 (100 %)
Organic from sediment	93.7	93.6 (100 %)	0.0 (0 %)	175.6 (187 %)	93.8 (100 %)
Freshwater input	2.6	0.0 (0 %)	2.6 (100 %)	2.6 (100 %)	2.6 (100 %)
Phosphate [10⁶ mol a⁻¹]					
Dissolved export	3.06	3.02 (99 %)	2.73 (89 %)	3.50 (114 %)	3.22 (105 %)
Organic Import water	2.50	2.51 (100 %)	2.70 (108 %)	2.35 (94 %)	2.47 (99 %)
Organic from sediment	0.53	0.53 (100 %)	0.0 (0 %)	1.13 (213 %)	0.53 (100 %)
Freshwater input	0.05	0.00 (0 %)	0.05 (100 %)	0.05 (100 %)	0.05 (100 %)
NO_x [10⁶ mol a⁻¹]					
Dissolved export	28.9	27.2 (94 %)	33.9 (117 %)	26.5 (92 %)	34.5 (119 %)
Organic Import water	37.0	37.2 (101 %)	41.8 (113 %)	33.3 (90 %)	36.2 (98 %)
Organic from sediment	8.4	8.4 (100 %)	0.0 (0 %)	18.1 (215 %)	8.4 (100 %)
Freshwater input	1.9	0.0 (0 %)	1.9 (100 %)	1.9 (100 %)	1.9 (100 %)

Dynamics of particulate organic matter (POM) is probably the least studied parameter which is included in the model. According to van Beusekom and de Jonge (2002) who emphasise the import of POM into the Wadden Sea, this is implemented in the model calculations. Nutrient gradients occurring within back barrier areas (Ebenhöh et al., 2004) can only be reproduced by the model if an additional sedimentary import of organic matter is implemented (Postma, 1961). To analyse the importance of sedimentary import of organic matter, this import is omitted in run3, whereas in a further scenario (run4) the import is doubled.

While phosphate and NO_x budgets are quite similar for all scenarios, silica concentrations show significant differences (Fig. 7). Without import of additional sedimentary organic matter, the model underestimates silica winter values within the back barrier area. The scenario with doubled import (run4) is in good agreement with measured data in winter, whereas summer values are overestimated.

The influence of atmospheric import is investigated in run5. This can only be a rough estimation because the import of nitrogen used in EcoTiM bases on model calculations. However, atmospheric intake increases the export of dissolved phosphate by 5% and 19% for NO_x .

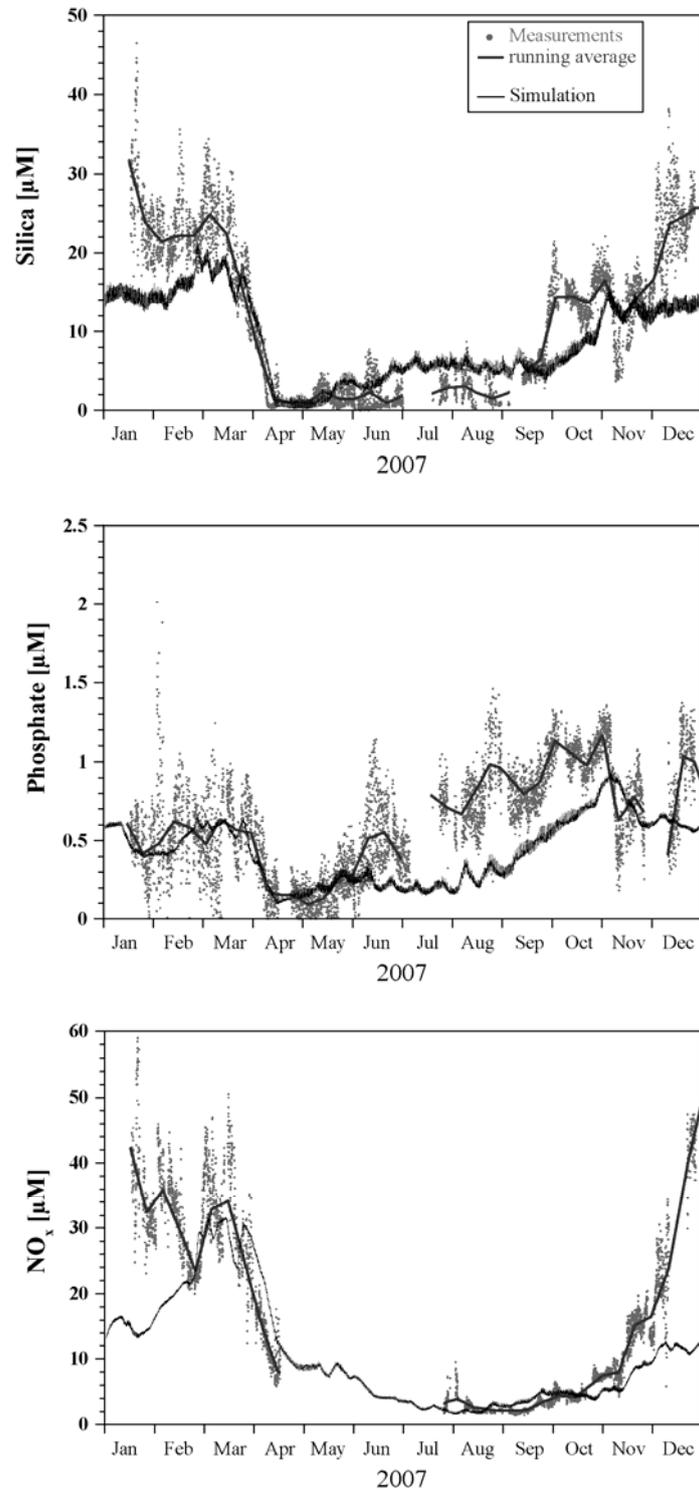


Fig. 6: Model simulation (run1) for silica, phosphate, and NO_x (black line) compared with data determined at the time-series station (grey circles) in 2007. The running average of the measurements is given by grey lines.

Overall, the model calculations indicate that dissolved inorganic silica, phosphate, and NO_x are exported from the back barrier area of Spiekeroog Island towards coastal waters of the North Sea. The given sensitivity analysis show that amounts between $125 * 10^6 \text{ mol a}^{-1}$ and $206 * 10^6 \text{ mol a}^{-1}$ for dissolved inorganic silica, $2.7\text{--}3.5 * 10^6 \text{ mol a}^{-1}$ dissolved inorganic phosphate, and $26\text{--}34 * 10^6 \text{ mol a}^{-1}$ dissolved inorganic NO_x are supplied to the North Sea. Here the maximum values for silica and phosphate occur due to a high estimation of organic import to the back barrier area. The maximum value for NO_x is due to atmospheric intake.

Table 3: Nutrient export from back barrier areas (without estuaries) of the Wadden Sea into the German Bight based on model calculations of run1 compared with riverine nutrient load. Values in brackets give the range of exports based on runs 1-5.

		Σ Wadden Sea back barrier areas	Σ rivers (Elbe, Weser, Ems)*	Elbe*	Weser*	Ems*
Silica	$[10^8 \text{ mol a}^{-1}]$	30 (29-47)	20	7	10	3
Phosphate	$[10^6 \text{ mol a}^{-1}]$	70 (62-81)	25	17	7	1
NO_x	$[10^8 \text{ mol a}^{-1}]$	7 (6-8)	23	13	7	3

*: Lenhart and Pätsch (2001)

Furthermore, the model results indicate that particulate nutrients are imported from the North Sea to tidal flat areas. The organic silica import by water transport ranges between 29 and $36 * 10^6 \text{ mol a}^{-1}$ for the different runs (Table 2), depending on the assumed amount of benthic imported material ($0\text{--}176 * 10^6 \text{ mol a}^{-1}$). Values for organic phosphate by water transport are $2.4\text{--}2.7 * 10^6 \text{ mol a}^{-1}$ (organic benthic import: $0\text{--}1.1 * 10^6 \text{ mol a}^{-1}$) and for nitrogen $33\text{--}42 * 10^6 \text{ mol a}^{-1}$ (organic benthic import: $0\text{--}18 * 10^6 \text{ mol a}^{-1}$). All scenarios show the same pattern, with inorganic material being exported while organic matter is imported. This is caused by the topography of the region, since sedimentation and efflux out of the sediment have a stronger impact on nutrient concentrations in shallow water than in deeper water (Ebenhöh et al., 2004). Additionally, in the semi-enclosed tidal flat areas settling and degradation of imported OM is likely faster than in the open North Sea. The tidal flat ‘bioreactor’ accelerates remineralisation processes within permeable sediments thereby releasing dissolved inorganic nutrients, which are partly exported to the coastal waters of the North Sea.

The entire tidal flat area without estuaries of the Wadden Sea comprises about 1688 km^2 (Grunwald et al., 2009), which is about 23 times larger than the back barrier area of Spiekeroog Island. An extrapolation of the export values of run1 from our study area to the entire back barrier area of the German Bight denotes the significance of tidal flat areas in the line of nutrient contribution to the German Bight (Table 3). A comparison of nutrient concentration patterns and levels of our study area with data from the northern Wadden Sea (van Beusekom et al., 2009) exhibits similarities and thus allows the extrapolation to the entire area of tidal flat systems of the German Bight. The sum of net dissolved export of silica and phosphate is in the same order of magnitude like the combined major German rivers Elbe, Weser, and Ems (Lenhart and Pätsch, 2001) discharging into the German Bight, while NO_x export is one order of magnitude lower than riverine contribution. Although the riverine nutrient contribution to the Southern North Sea underlies seasonal variation with highest values during winter (Lenhart and Pätsch, 2001) the rivers exhibit a net export of nutrients. Generally, riverine supplied nutrients sustain the concentration level in the North Sea especially during winter, thereby forming the basis for phytoplankton growth in spring. Nutrients assimilated by phytoplankton enter the tidal flat areas as particulate organic matter,

where it is mineralized and again supplied to the southern North Sea. Therefore, nutrient recycling in the tidal flat areas has to be taken into account when budget calculations for the North Sea are performed.

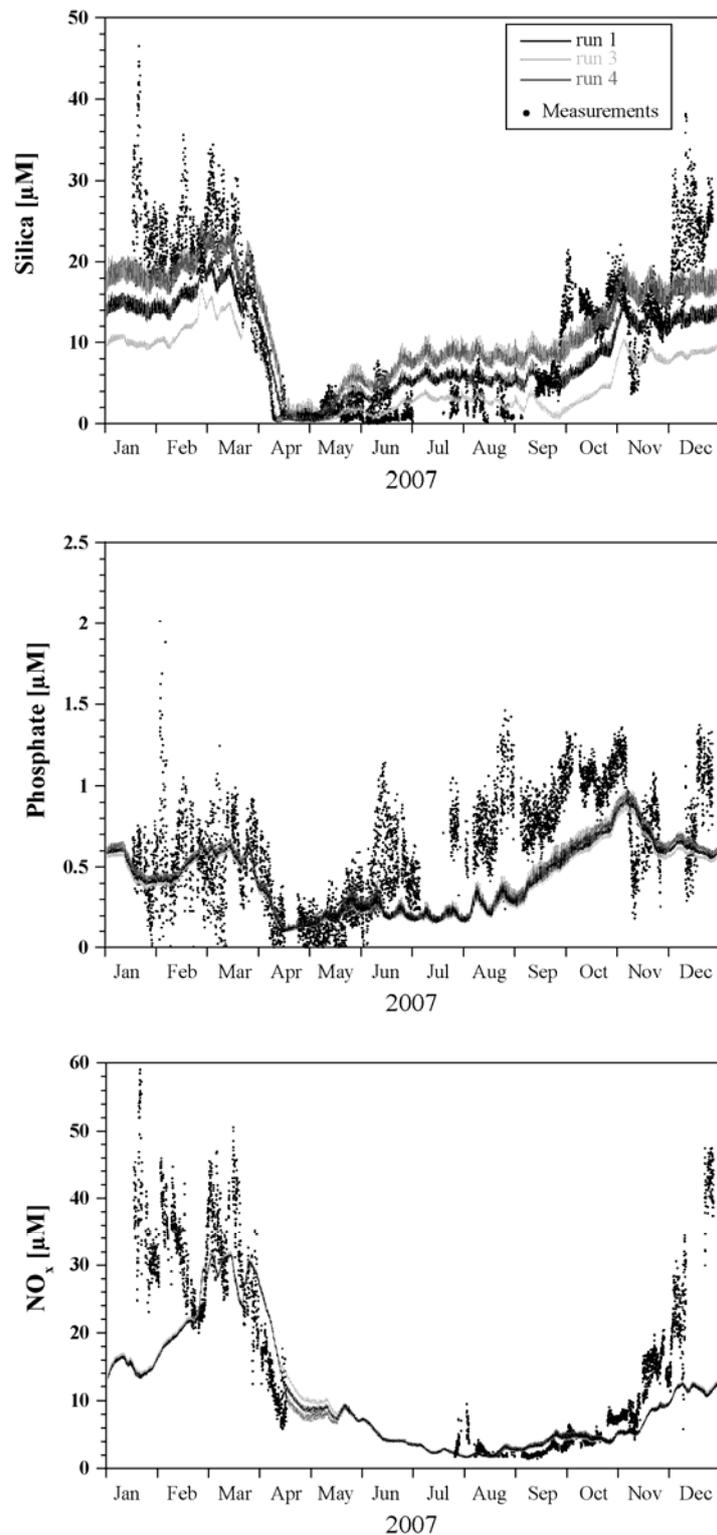


Fig. 7: Annual pattern of silica, phosphate, and nitrite plus nitrate in 2007 as simulated by the reference run (run1, black line), the run without additional import of POM (run3, light grey line), and enhanced import of POM (run4, dark grey line) compared to measured data from the time-series station (black dots).

5 Summary and conclusions

Silica, phosphate, and nitrite plus nitrate (NO_x) concentrations of surface water were determined hourly since April 2006 by automated nutrient analysers mounted on a time-series station in the tidal inlet of the back barrier area of Spiekeroog Island. The high frequency of measurements provides the opportunity to identify dynamics on annual, seasonal, and tidal scales. Silica concentrations are governed by diatom assimilation leading to low concentrations in spring and summer. Due to the subsequent remineralisation of diatom frustules within the sediments, silica concentrations increase towards autumn reaching highest values in winter. Phosphate is affected by both physiological processes and the iron cycle in the tidal flat sediments. While elevated amounts of phosphate are trapped by ferric iron oxides in winter, phosphate is released from the sediments in summer due to more pronounced reducing conditions. NO_x concentrations are highest in winter months, mainly controlled by discharge of large rivers. Interannual variation in concentration levels are governed by fluctuating river loads as well as denitrification processes within the sediments.

Nutrient patterns on a tidal resolution reveal a different behaviour for silica, phosphate, and NO_x . Silica shows a consistent relation to the tidal state with higher concentrations at low tide throughout the year. Contrasting, the tidally driven pattern of phosphate is only seen in summer and less pronounced during the remaining seasons. For NO_x a clear tidal pattern can be observed only in autumn.

Time-series data are used to verify model simulations and to calculate nutrient export budgets. The freshwater contribution to the back barrier area from the hinterland via the flood-gate is negligible for the annual nutrient budget, whereas pore waters form the main source at least for silica and phosphate.

Overall, the back barrier tidal flat ecosystem forms a 'bio-reactor' where nutrients are assimilated and remineralized. Assuming an import of particulate organic matter from the North Sea into the Wadden Sea model results indicate export of dissolved inorganic nutrients from the tidal flats. Thus, tidal flat systems play a major role in supplying nutrients to the German Bight and have to be considered in budget calculations besides riverine nutrient discharge, since they export in the same order of magnitude as the combined rivers Elbe, Weser, and Ems discharging to the Southern North Sea.

Finally, this study emphasises that continuous measurements are required to understand tidal and seasonal dynamics associated with the transformation of organic matter and export of dissolved nutrients. In previous studies (Gätje and Reise, 1998; Sündermann et al., 1999) tidal dynamics and associated exports were less successfully considered.

Acknowledgements

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