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Spatial and seasonal variation of water quality in an impacted coastal lagoon (Óbidos Lagoon, Portugal)

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Abstract The spatial distribution of silicate, ammonium, nitrate, nitrite, phosphate, chlorophyll *a* and dissolved oxygen in Óbidos lagoon was obtained by surveying five sites in eight campaigns, between October 2004 and October 2006. A confined inner branch of the lagoon showed higher availability of ammonium (1.2–81 μmol l^{-1}), phosphate (1.9–17 μmol l^{-1}), silicate (0.85–86 μmol l^{-1}) and chlorophyll *a* (0.30–18 μg l^{-1}) than other sites (0.47–25 μmol l^{-1}, 0.10–3.9 μmol l^{-1}, 0.47–25 μmol l^{-1}, 0.25–11 μg l^{-1}, respectively). According to several trophic classification tools, that branch is considered eutrophic to polytrophic, emphasising its deteriorated conditions, while the rest of the lagoon is of better quality. In autumn/winter nutrients were inversely correlated to salinity ($r>0.93$) reflecting the freshwater inputs enriched in nitrogen and phosphorous compounds to the inner branch. In warmer periods, dissolved oxygen concentrations dropped during the night, and sediments of the branch become an important source of ammonium and phosphate. The low DIN:P ratio (median=10) obtained in the branch, which suggests an excess of phosphate, that increased in warmer periods and changed the limiting nutrient in the entire lagoon. These results emphasize the spatial heterogeneity of water quality in Óbidos lagoon, its seasonal variability, and the importance of recognising these distributions before defining homogenous water body on the scope of Water Framework Directive.

Keywords Coastal lagoon · Eutrophication · Nutrient dynamics · Sediment · Water Framework Directive

Introduction

Small rivers running towards the coast do not always reach the sea. Discharge to the ocean is often prevented by active beach-ridges, forcing water and suspended particulate matter to accumulate in small coastal lagoons. The ecology of the lagoons is determined to a large extent by freshwater inputs and the mixing and circulation processes with the adjacent sea (Postma 1981; Ittkoot et al. 2000). In lagoons with a permanent connection to the sea and strong tidal amplitudes, the circulation is highly influenced by semi-diurnal and fortnight tidal cycles, and only episodically freshwater discharges force the salinity gradient to move seaward near the inlet (Boynton et al. 1996). In densely populated regions, the discharge of nitrogen and phosphorous is augmented by domestic and industrial waste waters,

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urban drainage and agricultural effluents (Cabeçadas et al. 1999; Lillebø et al. 2005; Lopes et al. 2007). Additionally, most of the particulate organic matter that reaches the bottom is mineralised in top sediment layers, promoting a spatial variability in the nutrient exchange across the sediment–water interface (Lerat et al. 1990; Forja et al. 1994; Vidal and Morguí 1995).

Coastal lagoons with these vulnerabilities, exhibit frequently a temporary and progressive decline of water quality. The increasing number of ecosystems with these symptoms led environmental managers to identify eutrophication as a major worldwide problem (Cloern 2001; Hauxwell and Valiela 2004; Lillebø et al. 2007). Besides the high nutrient loading, primary producers may be limited to growth due to alterations of ratios between DIN, P and Si (Newton and Mudge 2005; Gikas et al. 2006; Lopes et al. 2007). Although the Redfield molar ratios for phytoplankton growth (Si/DIN/P=16:16:1) are merely used to define the resource availability (del Amo et al. 1997), a shift from these proportions may change the species dominance, composition, and results in loss of diversity (Tilman et al. 1982; Gikas et al. 2006; Lopes et al. 2007). Moreover, the limiting nutrient to primary production may vary seasonally (Falcão and Vale 1998). Since regeneration of nutrients in upper sediments depends on the supply of particulate organic matter, temperature and oxygen availability (Forja et al. 1994; Chapelle 1995; Asmus et al. 2000), fluxes to the overlying water are influenced by these environmental factors (Kristensen 1993; Wilson and Brennan 2004), and consequently also the succession of primary producers.

Within the framework of protecting the quality of surface water bodies, various ecological classification tools have been proposed to assess eutrophication (e.g. Bricker et al. 1999; Crouzet et al. 1999; Wasmund et al. 2001). However, the indexes are based on annual or winter means of nutrient levels, which may be insufficient in coastal lagoons impacted by organic loads.

This work presents the nutritional status of Óbidos coastal lagoon, an impacted ecosystem in Portugal, and discusses its spatial and seasonal variations. This study emphasises the importance of recognising the variability of water quality parameters, in order to define homogeneous water body within the Water Framework Directive (WFD).

Material and methods

Study area

The Óbidos lagoon is a shallow coastal lagoon with a mean depth of 1 m and a wet area of 7 km^2, located on the west coast of Portugal (Fig. 1). The lagoon is permanently connected to the sea through a narrow inlet. The position of the inlet and the configuration of the channels in lower part of the lagoon have changed naturally during the last decades (Oliveira et al 2006). Three areas with different morphological and sedimentary characteristics have been identified (Quintino 1988; Oliveira et al. 2006): several sand banks, narrow channels and strong currents in the lower part, weaker velocity intensities in the broad middle lagoon, and muddy bottom sediments in the inner branches Barrosa and Bom-Sucesso. The freshwater tributaries, Cal, Vala do Ameal and Arnóia drain agricultural areas and enter the lagoon at Barrosa, Bom-Sucesso and between the two branches, respectively. The freshwater discharges are negligible in summer (<0.05 m^3 s^{-1}; IPIMAR 2006) and annually amount to an average of 3 m^3 s^{-1} (Oliveira et al. 2006). During the past decades domestic effluents from the town Caldas da Rainha had been discharged to the Cal river that ends into the Barrosa branch. Although, at the present time, this nutrient load enters directly the coastal zone adjacent to the lagoon through a submersed outfall, Cal river continued to have deteriorated quality conditions according to the Portuguese classification of freshwater systems (IST/IPIMAR 2008). In fact, monthly campaigns carried out in 2007 indicated flows varied from 0.1 and 0.5 m^3 s^{-1} with elevated levels of ammonium (2.9–9.4 mg l^{-1}), nitrite (0.17–1.2 mg l^{-1}) and phosphate (1.4–6.3 mg l^{-1}). Tide energy dissipates in the entire lagoon, and tides range between 1 and 2 m (Oliveira et al. 2006). The nutrient load and the longer resident time of water in inner branches (24–26 and 4–10 days in Bom-Sucesso and Barrosa, respectively) in comparison to the middle/lower lagoon (1–4 days; Santos, personal communication) favour the macroalgal cover (*Ulva* sp. and *Enteromorpha* sp.), as well as accumulation of organic matter in sediments (Loss of Ignition between 5.7 and 7.5%; IPIMAR 2006). Opportunist macroinvertebrate species found in Barrosa corroborates the eutrophic condition in the branches (Carvalho et al. 2005, 2006).

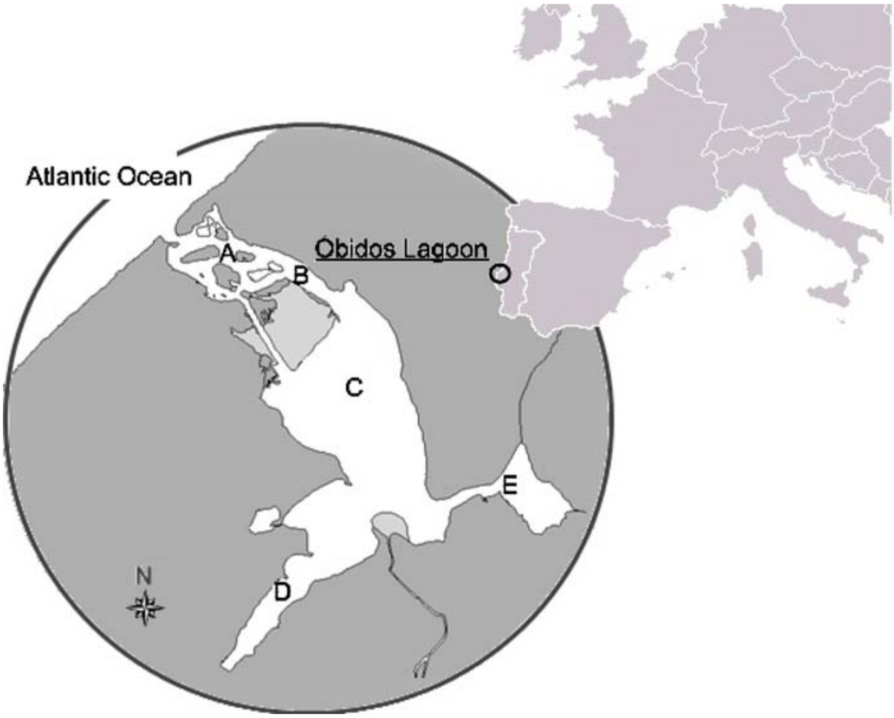


Fig. 1 Location of the sampling sites at the Óbidos lagoon: *A* inlet; *B* and *C* middle lagoon; *D* and *E* Bom Sucesso and Barrosa branches, respectively

Sampling and methodologies

Five sampling sites were selected to give an adequate representation of the various morphological conditions of the lagoon (Fig. 1): site A located near the inlet; B and C in the middle of the lagoon; D and E in Bom-Sucesso and Barrosa branches, respectively. The sites were visited in October 2004, February, June and October 2005 and February, May, August and October 2006.

Water (0.4-m depth) was sampled in high tide and low tide of the inlet channel. For logistic reasons, sampling started at the inlet and ended at inner branches. Each survey took less than two hours.

Only temperature was measured in situ using an YSI, 650 m. Water was sampled to various bottles according to the analytical specifications and transported to a field laboratory for filtration and preservation of the samples. Salinity was measured using an Autosal (Guildline Model 8400B Analyzer) analyzed against "IAPSO standard Sea Water" with accuracy of 0.003. Dissolved oxygen was determined by a modified Winkler method according to Carrit and Carpenter (1966). The coefficient of variation associated with this method was determined by analyzing replicates and was found to be less than 0.25%. Dissolved oxygen saturation was calculated according to OSPAR (2001). Suspended particulate matter (SPM) was obtained by filtering 250 ml of water through cellulose acetate membranes (0.45 µm) and determined gravimetrically (drying at 70°C). Samples for the determination of dissolved inorganic nutrients (nitrate, NO_3^-+NO_2^-; ammonia, NH_4^+; phosphate, PO_4^{3-} and silicate, $Si(OH)_4$) determinations were filtered through MSI Acetate Plus filters, and analysis carried out using an autoanalyser TRAACS 2000 (Bran + Luebbe). Certified standards (Wako, CSK Standard Solution) were used to ensure the accuracy of the procedures and precision was found to be ±1.0% for nitrate, ±2.0% for ammonia, ±1.9% for phosphate and ±1.1% for silicate. For chlorophyll *a* (Chl *a*) determinations, 250 ml of water was filtered through a Whatman GF/F (0.7 µm) filter that was immediately frozen at −20°C and later extracted in 90% acetone, for analysis in a Perkin-Elmer fluorometer using the modified protocol by Lorenzen (1966). Commercial solutions (Sigma Chemical Co.) of Chl *a* were used to calibrate the fluorometer. The coefficient of variation associated with this method was less than 1.8%.

Data analysis

Statistical software (Statistica 6.1) was used for statistical analyses. ANOVA analysis was used to compare sampling sites and Tukey test was applied for post hoc comparison (Zar 1996). Differences between means were considered significant when $p < 0.05$. A Pearson correlation was performed to evaluate the degree of relationship between the analysed parameters.

Results

Temperature, salinity, dissolved oxygen and suspended particulate matter

Water temperature at the five sampling sites ranged within narrower intervals in winter surveys (e.g. 10–12°C in February 2005) than in summer (e.g. 18–25°C in August 2006). Elevated values were registered in the afternoon (low tide) at the inner branches. The median, the percentile 25% and 75%, maximum and minimum of salinity in each site are shown in Fig. 2. Outliers and extreme values marked in the figure were not taken into account for the median calculation. In most of the surveys salinity decreased landwards, from site A to E, reflecting the freshwater discharges to the inner branches. However, due to the small flows, the salinity gradient was located in the upper areas. Salinity in sites A and B ranged within narrow intervals centred at 36, the lower values being registered in low tide of February and October 2006 (extreme values in Fig. 2). In sites D and E, values ranged within broader intervals (29.1–37.1 and 25.9–37.1, respectively): the lower ones were registered in periods of higher freshwater discharges (autumn and winter); and values exceeding seawater salinity were found in May 2005 and August 2006, which indicates that freshwater discharges did not compensate evaporation. Considering all salinity data, values in site E were significantly ($p<0.05$) different from those observed in sites A, B and C.

The dissolved oxygen concentrations in sites A, B and C varied from 85% to 135% saturation. The broader interval in sites D and E (60–185%) indicated supersaturation that is attributed to both macroalgae and phytoplankton. Undersaturation was usually recorded in the morning of warmer periods, reflecting higher consumption during the night by respiration and organic matter oxidation, while supersaturation was observed in the afternoon, as result of intense photosynthesis.

The suspended particulate matter (SPM) concentration in the sites A, B and C varied from 1.9 to 77 mg l^{-1}, reaching 141 and 170 mg l^{-1} in sites D and E, respectively. Values were lower in autumn/winter (October 2004, October 2005 and February and October 2006) than in spring/summer (e.g., May and August 2006), and variation between low and high tide was not consistent. The strong wind intensity occurred in the afternoon of several sampling dates, may have caused bottom resuspension that could be responsible for small differences of SPM between sites and sampling periods.

Nutrients and chlorophyll *a*

Figure 2 shows the median, the percentile 25% and 75%, maximum and minimum concentrations of ammonium, nitrate, silicate, phosphate and chlorophyll *a* in each sampling site. Site E exhibited broader concentration ranges of all determinations than the other sites. Silicate, ammonium and phosphate in site E (0.9–56 µmol l^{-1}, 1.2–81 µmol l^{-1}, 1.90–17 µmol l^{-1}, respectively) were significantly ($p<0.05$) higher than in sites A, B and C (0.5–25 µmol l^{-1}, 0.5–25 µmol l^{-1}, 0.10–3.9 µmol l^{-1}, respectively). Nitrate plus nitrite concentrations amounted to values comparable to ammonium (maximum 74 µmol l^{-1}) and although sites D and E reached higher values, no significant ($p<0.05$) differences were obtained from sites A, B and C. Chlorophyll *a* was in general higher in site E (maximum 18 µg l^{-1}) and significantly ($p<0.05$) higher than in sites A and B.

Figure 3 shows the concentrations of silicate, ammonium, nitrate + nitrite, phosphate and chlorophyll *a* registered, in low and high tides, in sites A and E that represent the marine- and the river-end members of the lagoon, respectively. All the values of the two sites were considered, including those identified as outliers and extremes for the calculation of the median. In site A, nutrient concentrations in high tide were lower than in low tide, indicating that the incoming of seawater diluted the nutrient concentrations of the lagoon. The dilution effect was more accentuated in periods of elevated nutrient concentrations, although a seasonal pattern could not be identified for all nutrients. In site E, maximum nutrient values correspond always to low tide.

Ammonium was elevated in October 2005, February and October 2006 (maximum 32 and 81 µmol l^{-1} for

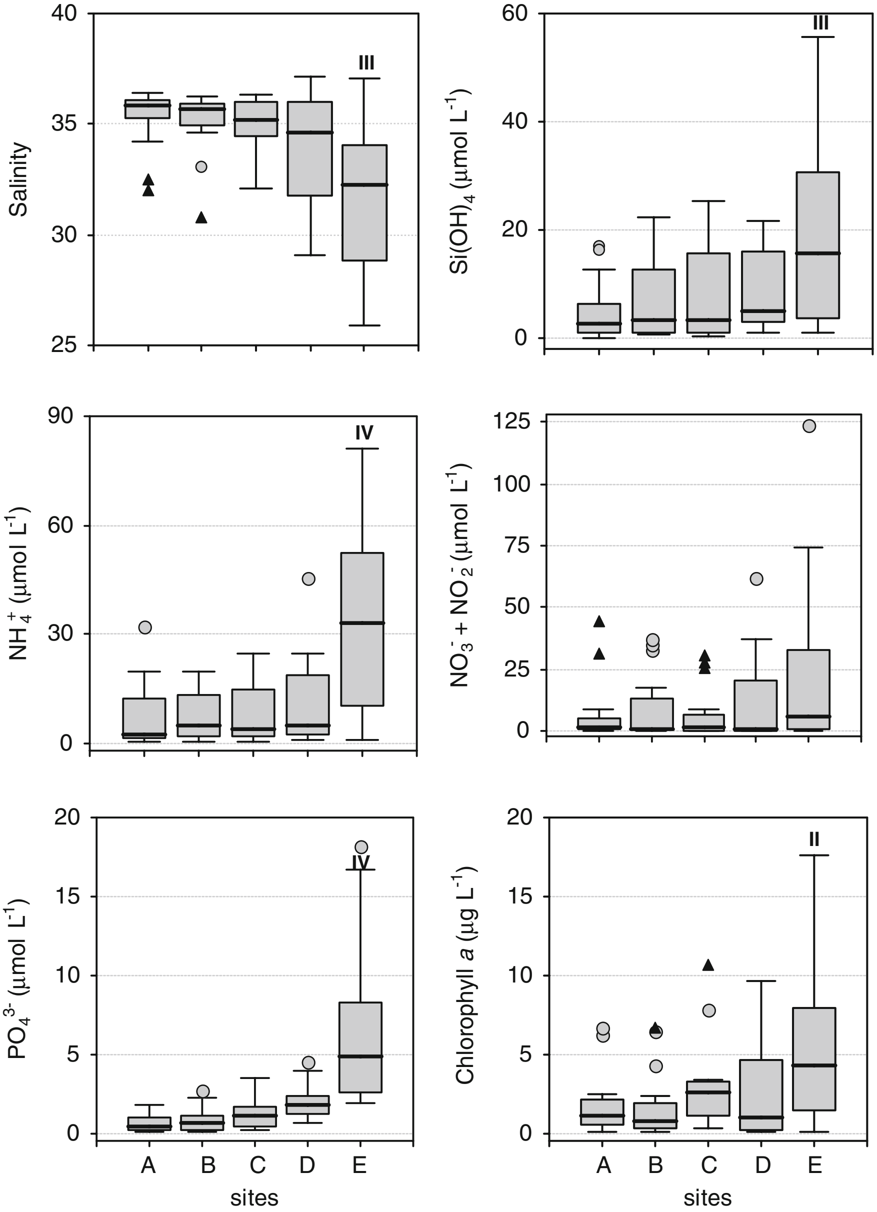
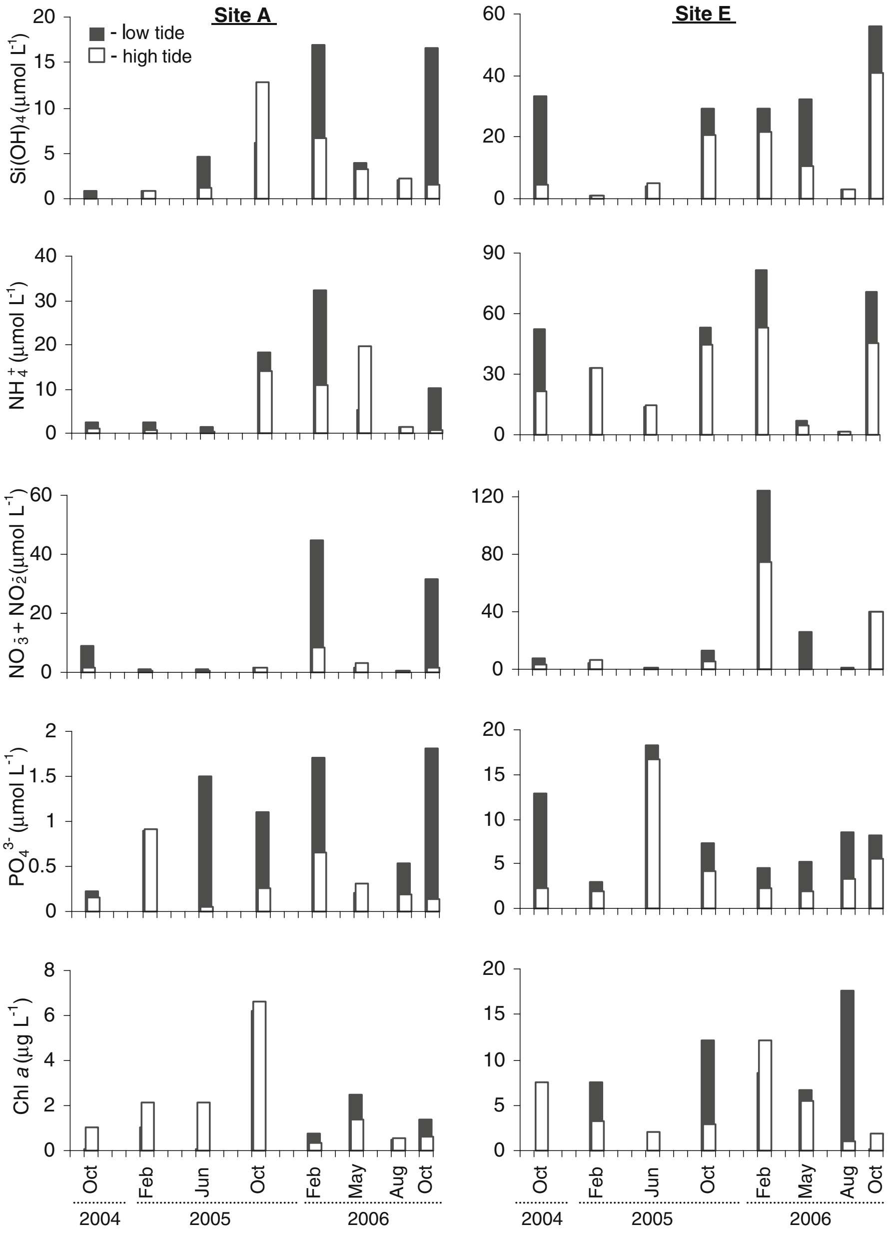


Fig. 2 Salinity, Si(OH)$_4$, NH$_4^+$, NO$_3^-$+NO$_2^-$, PO$_4^{3-}$ (µmol l^{-1}) and chlorophyll *a* (µg l^{-1}) in the sampling sites (*A–E*) for the surveyed period: median, percentile 25% and 75%, maximum and minimum, outliers (*circle*) and extreme (*triangle*) values. *II* Significant different from sites *A* and *B*; *III* significant different from sites *A*, *B* and *C*; *IV* significant different from sites *A*, *B*, *C* and *D*

sites A and E, respectively) and was low in June 2005 and August 2006 (minimum 0.5 and 1.2 µmol l^{-1} for sites A and E, respectively). A similar trend was observed for silicates that had also a peak in the same sampling periods (maximum 17 and 56 µmol l^{-1}) and minimum values in February 2005 (min. 0.9 µmol l^{-1} in both sites). The nitrate variation in the two sites was dominated by a pronounced peak in February 2006 (45 and 124 µmol l^{-1}). Phosphate in sites A and E showed elevated levels in June 2005 (1.5 and 18 µmol l^{-1}, respectively). In site A other maximum values were observed in February and October 2006, with considerable differences between low and high tide. The semi-diurnal differences of Chl *a*, superimposed the seasonal variation in site E particularly in October 2004, October 2005 and August 2006. In site A emerged the high values in low and high tide of October 2005.

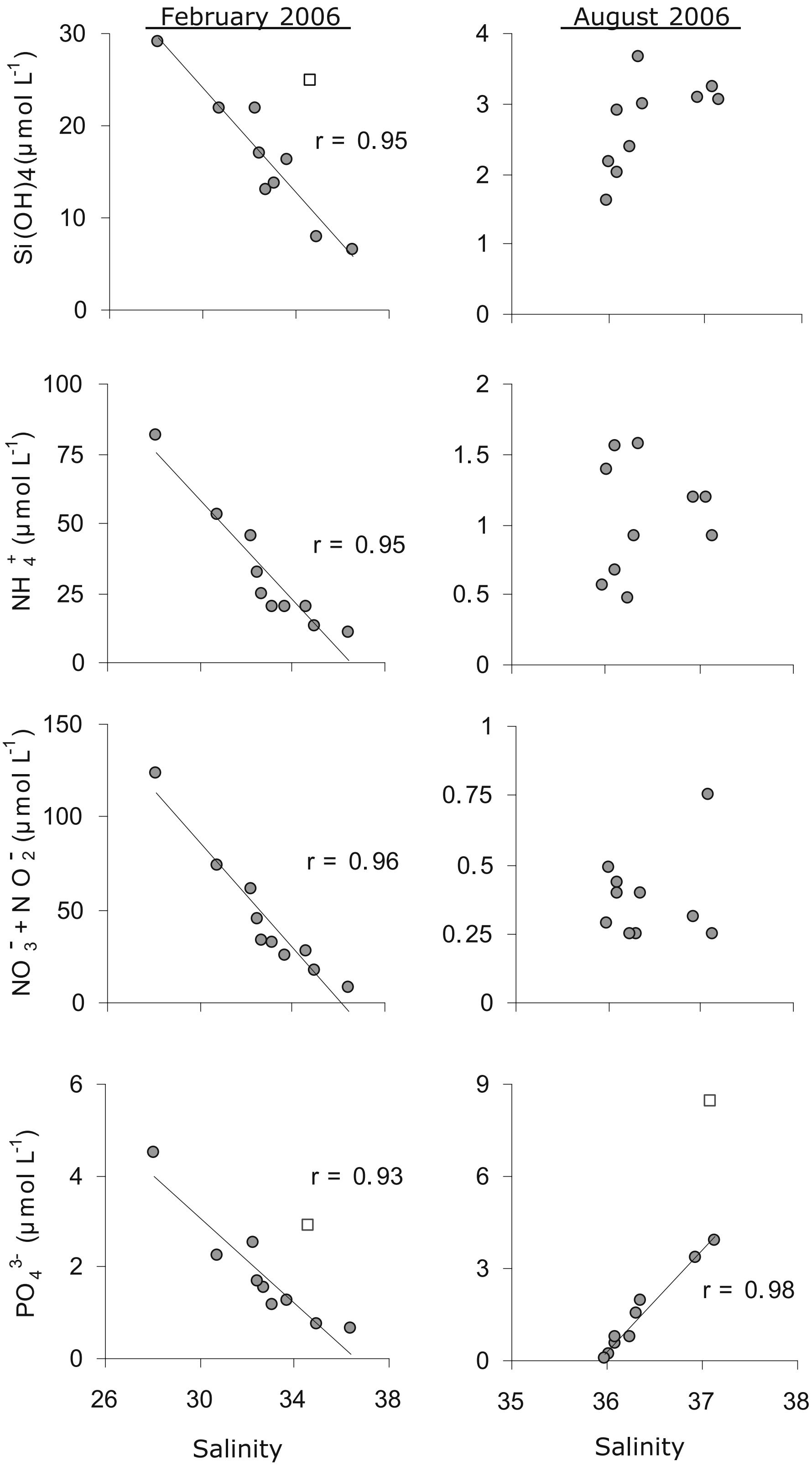
Fig. 3 Seasonal variation of $Si(OH)_4$, NH_4^+, NO_3^-+NO_2^-, PO_4^{3-} (µmol l^{-1}) and chlorophyll *a* (µg l^{-1}) in sites *A* and *E*, in low and high tides



Relationships between nutrients and salinity

Pearson correlations (r) between each nutrient and salinity were applied to all data (n=80). Silicate, ammonium and nitrate + nitrite exhibited significant (p<0.05) inverse linear relationships with salinity: −0.77, −0.62 and −0.60, respectively. Despite the narrow interval of salinity in most of the surveys, the obtained correlation coefficients suggest that nutrients were relatively well explained by conservative mixing between the nutrient-rich freshwater and seawater. The decrease of silicate, ammonium, nitrate + nitrite and phosphate with salinity (Fig. 4) was better observed in February 2006 (−0.95, −0.95, −0.96 and −0.93 respectively). The low chlorophyll *a* in the lagoon (except in site E) favours the observed conservative behaviour of nutrients during this rainy period (59 mm of monthly average rainfall; SNIRH 2008). Rainfall decreased in May and August 2006 (1.2 and 4.5 mm, respectively) and increased in October (189 mm). In August 2006, salinity ranged within the interval 36.0 to 37.1, increasing landwards.

Fig. 4 Relationships between salinity and nutrients (µmol l^{-1}) at all sites in February 2006 and August 2006. (*square* value not considered in the relationship)



The higher nutrient levels in samples where salinity exceeded the seawater value and under negligible freshwater discharge conditions should result from evaporation of the lagoon water in summer. Phosphate presented a positive correlation with salinity ($r = 0.98$).

Molar ratios

The molar ratios of dissolved inorganic nitrogen ($\mathrm{DIN} = \mathrm{NH}_4^+ + \mathrm{NO}_3^- + \mathrm{NO}_2^-$)/P and DIN/Si were calculated for all data. Figure 5 shows the median of these ratios, the percentile 25% and 75%, maximum and minimum in each site. The identified outliers and one extreme value were not taken into account for the median calculation. The two plots present broader ranges of values in site A decreasing towards the site E. Ratios in this site were significantly ($p<0.05$) lower than in site A. Most of the DIN/P ratios in sites C, D and E were lower than the Redfield ratio (16), while the median in A and B were 19 and 18, respectively. Almost all the Si/P ratios in the five sites were below the respective Redfield ratio (16), and the median of DIN/Si ratios for the five sites were above the respective Redfield ratio (1).

Figure 6 shows DIN/P and Si/P ratios in sites A and E, in low and high tides, at each sampling periods. Site A exhibited broader differences of the ratios between low and high tide, resulting from the exchange with adjacent seawater that masked an eventual seasonal signal of the ratios. Otherwise, a seasonal variation was observed in site E. The ratios DIN/P were lower than 16 (Redfield ratio) in all surveys, except in February 2005 and February 2006. The ratios Si/P were always lower than 16, with lowest values recorded in February 2005 (0.3) and June 2005 (0.2) and August 2006 (0.4) and maximum ones in February 2006 (10).

Discussion

The availability of nutrients in the water column of Óbidos lagoon varied between autumn/winter and spring/summer, although concentrations in northern inner branch (site E) exceeded always those found in other areas (except for nitrate). Compared to other temperate estuarine systems the mean concentrations of DIN, phosphate and silicate fell within the range of values described for the Mondego estuary (Lillebø et al. 2005) and Ria de Aveiro, located in western Atlantic coast of Portugal (Lopes et al. 2007). As in Óbidos lagoon, tributaries receiving domestic and agriculture effluents discharge into confined areas of those systems, which exchange water with the rest of the system through narrow channels. Otherwise, nutrients in northern inner branch of Óbidos lagoon are frequently more abundant than in Ria Formosa, a shallow coastal lagoon in south-western Iberia exchanging 70% of its water volume in spring tides (Falcão and Vale 2003).

Despite the small quantity of freshwater discharged annually into the inner parts of the lagoon (Oliveira et al. 2006), a longitudinal trend of nutrients was observed, as in many other estuarine systems with an important freshwater input (Cabeçadas et al. 1999; Lopes et al. 2007). The inverse relationships between nutrients and salinity in autumn/winter indicate the input of silicate, ammonium, nitrate and phosphate derived from the drainage of the catchment area that

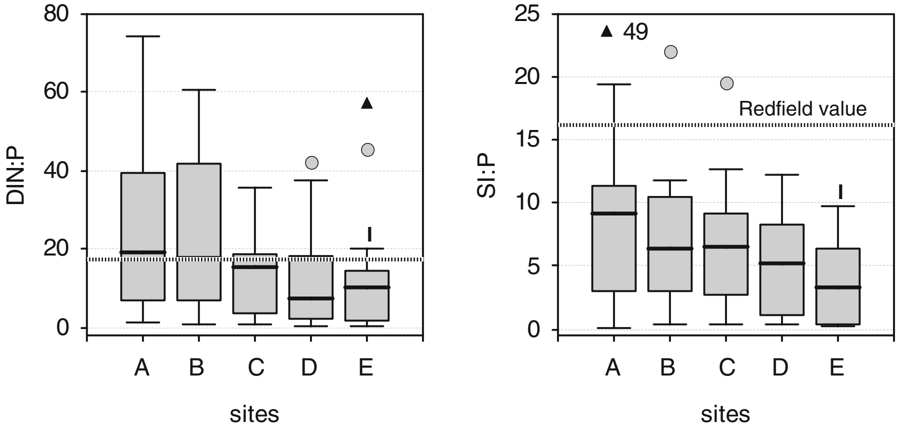


Fig. 5 DIN/P and SI/P ratios in the sampling sites for the surveyed period; median, percentile 25% and 75%, maximum and minimum, outliers (*circle*) and extreme (*triangle*) values. *I* Significant different from site *A*

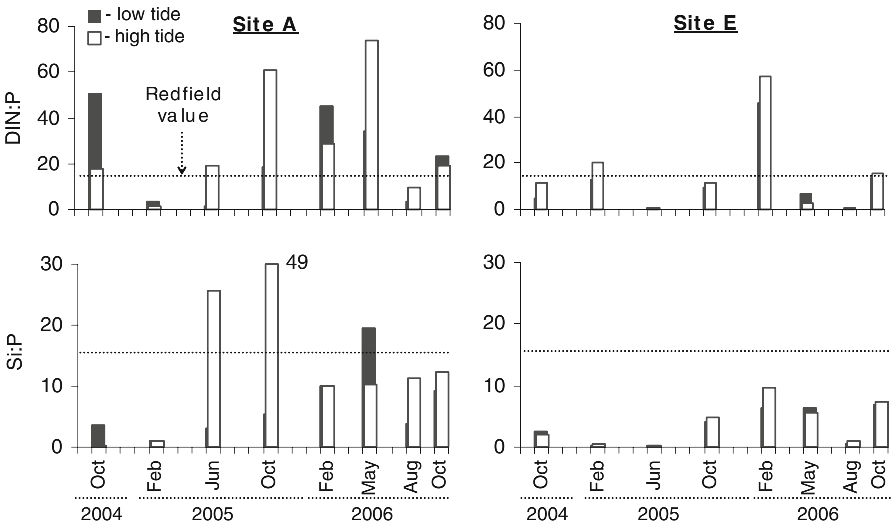


Fig. 6 Seasonal variation DIN/P and SI/P ratios in sites *A* and *E*, in low and high tides

consists of agriculture fields and small villages. In other surveyed periods, with small salinity intervals, correlations were not obtained. However, the availability of nutrients appears to favour the high biological production, as evidenced by the high chlorophyll *a* and macroalgae (*Ulva* sp. and *Enteromorpha* sp.) that covers almost the entire sediment (Carvalho et al. 2006).

The specificity of that branch was confirmed by the application of three methods for trophic classification (Table 1). On the basis of the EU–Crouzet et al. (1999) method, which considers the annual means of nitrate + nitrite and phosphate, sites E, D and C were classified as "bad" (based on phosphate), while only site E was "bad" using the nitrate + nitrite. The status of other sites was between "poor" to "fair". The Carlson's Trophic State Indices (TSI; 1977) uses annual means of phosphate and Chl *a* as metrics. The TSI values (Chl *a*) point site E as "mesotrophic", while according to phosphate was "hypereutrophic". The method proposed by Wasmund et al. (2001) is based on the annual means of Chl *a*, and winter means of phosphate and DIN concentrations. According to Chl *a* only site E was "eutrophic", but using DIN and phosphate this site was "polytrophic". The others sites were classified as "mesotrophic" (Chl *a*) to "eutrophic" (DIN and phosphate). All these tools pointed to an extreme deterioration conditions in the northern inner branch (site E) and better quality status in other areas of the Óbidos lagoon, although having a less coherent classification. These classifications agree with the results obtained from the use of the

Table 1 Trophic status of Óbidos lagoon according to indexes proposed by Crouzet et al. (1999), Carlson (1977) and Wasmund et al. (2001)

Parameters	Sites	Classification method				
		Annual mean	Crouzet et al. 1999	Carlson 1977	Winter mean	Wasmund et al. 2001
NO_3^-+NO_2^- (μmol l^{-1})	A, B, C, D	6.7–12	Fair–poor	–	–	–
	E	22	Bad			
PO_4^{3-} (μmol l^{-1})	A, B	0.67–0.80	Fair–poor	Mesotrophy	1.0–1.7	Eutrophic
	C, D	1.4–1.6	Bad	Eutrophy		
	E	6.4		Hypereutrophy	3.0	Polytrophic
DIN (μmol l^{-1})	A, B, C, D	–	–	–	25–47	Eutrophic
	E				102	Polytrophic
Chorophyll *a* (μg l^{-1})	A, B, C, D	1.7–2.6	–	Hypolimnia	1.7–2.6[a]	Mesotrophic
	E	5.6		Mesotrophy	5.6[a]	Eutrophic

[a] Annual mean

marine biotic index AMBI in the assessment of the ecological status of the Óbidos lagoon (Carvalho et al. 2006). The increase in organic matter content of sediments from down to upstream areas was associated with the dominance of opportunistic benthic species, while sensitive species to organic enrichment were mainly associated with the clean sandy area in the middle and lower lagoon. Regardless the low levels of chemical contaminants, the AMBI index allowed identifying the northern branch as an impacted area.

Although this study was not designed to investigate the role of sediments as internal source of nutrients to the water column, their influence in the regeneration of nutrients was apparent. The increase of phosphate in inner branches of Óbidos lagoon in summer surveys suggests its release from sediments as oxidation of organic matter increases under high temperatures. Salinity by exceeding the seawater value (Fig. 2) rules out the hypothesis of the input of freshwater enriched in phosphate. It has been demonstrated the relevance of nutrient regeneration in sediments to the ecology of various shallow ecosystems. For example, studies developed in Ria Formosa showed that inter-tidal areas are apparently capable of supplying most of the daily N and P requirements of phytoplankton in the overlying water (Falcão and Vale 1998).

Temperature is a key factor influencing the benthic fluxes of nutrients (Van Raaphorst et al. 1992; Kristensen 1993; Wilson and Brennan 2004) and promotes a temporal variability in sediment-water nutrient exchanges in coastal environments with marked seasons (Forja et al. 1994; Vidal and Morguí 1995). Nevertheless, only phosphate concentrations were positively correlated with temperature in summer (August 2006; r=0.95, p<0.05), indicating the release of phosphate from sediments of the inner areas of the lagoon where higher temperature was registered. Significant correlation was not obtained considering all data from June 2005, May and August 2006 (periods of negligible rainfall), suggesting influences of other variables besides temperature. No correlations were also found for ammonium and nitrate, reflecting complex processes associated with the cycle of nitrogen. Ammonium may differ from steady-state conditions reflecting the balance between production through organic matter mineralization (Bally et al. 2004), nitrification/denitrification (Vidal and Morguí 1995) and consumption by the abundant primary producers living near the sediment-water interface (*Ulva* sp. and *Enteromorpha* sp.), corroborated by the increase in chlorophyll *a* in summer. The undersaturation levels of dissolved oxygen observed in the inner branches of Óbidos lagoon suggest insufficient oxygen diffusion across the water-sediment interfaces during the night. The decrease of nitrification rates explains the high variation of nitrate concentrations. Nitrification/denitrification processes are also temperature-dependent. Thus, during the period of higher temperature (maximum of 25°C), denitrification of nitrate to the gaseous forms of nitrogen N_2 and N_2O (Cartaxana et al. 1999) may contribute to drop nitrate levels in sediment porewater of the extensive inter-tidal areas exposed to the atmosphere around low tide.

The positive linear relationship between phosphate and salinity emphasises two important aspects: sediment becomes a relevant internal source of P when temperature increases, and its consumption by the abundant primary producers does not cause a negative deviation on its correlation with salinity. These conclusions are supported by the positive relationship between phosphate and temperature in August 2006. It is well documented that phosphorus reacts with a wide variety of surfaces, being taken up and released from biogenic and abiogenic particles (Van Raaphorst and Kloosterhuis 1994). The retention/release of phosphate in marine systems is controlled by temperature and dissolved oxygen as referred in several studies (Slomp et al. 1998; Asmus et al. 2000). Phosphorus accumulated in solid phase during winter, partially due to P-sorption onto iron oxides, is released to sediment porewater and transferred to the overlying water in periods of elevated temperature due to reducing sediment conditions (Ohtake et al. 1984; Van Raaphorst and Kloosterhuis 1994). Low dissolved oxygen in water column of the Óbidos inner branches registered during the morning, points to reducing conditions in the sediment during the night.

Presumably, the phosphate released from the sediments was not consumed in the inner branches as ammonium, since DIN/P ratio was low (median of 7 to 10). Although Redfield molar ratio (DIN/P=16) are merely indicative of resource availability (del Amo et al. 1997), the obtained values fall into a region in which P excess is most likely to occur. The excess was more noticed in warmer periods presumably due to the increase of phosphate released from the sediments. Furthermore, DIN/P ratios was also low in other sites of the lagoon, suggesting the dispersion of phosphate by the tide and supporting the hypothesis of phosphate being in excess in the entire lagoon during spring/summer. The two illustrative conditions presented in Fig. 6 indicate that only when substantial amounts of freshwater are discharged into the lagoon (e.g. February 2006), the DIN/P ratios in the northern inner branch, became higher than the Redfield ratio (16:1), meaning that external input of fresh nitrogen compensates the excess of phosphate and inverses the nutrient limiting situation.

The low Si/N and Si/P ratios point to a limitation in silicate, more accentuated in the upper part of the lagoon. These conditions seem to favour the non-siliceous-based phytoplankton food webs and it has been compared to a loss of environmental quality status (Rocha et al. 2002; Domingues et al. 2005).

Given the implementation of the Water Framework Directive in a large number of impacted coastal lagoons in Europe, it is important to assess the seasonal fluctuation of quality status before the designing of the monitoring programmes. A particular relevant challenge is to establish scenarios, eventually supported by models, in order to predict changes and spatial variability on nutrient availability and its implications on phytoplankton, macroalgae and benthic macroinvertebrates, which are key biological elements to define the quality of coastal and transitional waters.

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