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Spatial and temporal dynamic of trophic relevant parameters in a subtropical coastal lagoon in Brazil

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Abstract Coastal lagoons are ecologically and economically important environments but a relative low number of studies were carried out in subtropical and permanently closed coastal lagoons. The present study aimed at assessing the temporal and spatial dynamic of trophic relevant water quality parameters in the small, deep and freshwater Peri coastal lagoon, South Brazil. During the 19 sampled months (March/2008–September/2009) spatial homogeneity (horizontal and vertical) was registered in all seasons for all variables, a condition related to the strong wind influence and low human occupation in the lagoon watershed. Seasonal variations of the water quality could be observed and they can be explained mainly by variation on temperature, wind forces and direction and rainfall, characteristic from the subtropical weather. Comparing this study with two others conducted in Peri lagoon in 1996 and 1998, no critical differences that evidence alteration in the water quality were found, but climate differences may have influenced in some small variations observed. The use of four trophic state indices indicated that indices designed for temperate lakes are inappropriate for the subtropical Peri lagoon. The lagoon was classified as oligotrophic for nutrients concentrations and meso-eutrophic for transparency and chlorophyll-a, which can be explained by the high densities and monodominance of the cyanobacterium *Cylindrospermopsis raciborskii* and the high recycling rates observed in warmer water bodies, when compared to the temperate ones.

Keywords Trophic state · Nutrients · Subtropical lake · Cyanobacteria · Florianópolis · Environmental protected area

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Introduction

Coastal lagoons are commonly shallow, marine-influenced water bodies, considered ecologically and economically important environments due to their high productivity rates and intense human use for aquaculture, recreation and waste disposal (Spaulding 1994). These ecosystems occupy around 13% of the coastal areas worldwide (Kjerve 1994) and are important contributors to groundwater reservoirs, local and regional weather stability, preservation of biodiversity and also as water suppliers (Esteves et al. 2008). In spite of their importance and multiple uses, urban development and the intense human use of

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coastal lagoons and their surroundings often have led to water contamination, eutrophication, introduction of invasive species, and habitat destruction (Ahmed et al. 2010; Gikas et al. 2006; Pereira et al. 2009; Specchiulli et al. 2010).

The distribution of coastal lagoons along the Brazilian coastline coincides with densely populated areas (Esteves et al. 2008). In this context, several Brazilian coastal lagoons are being subjected to several kinds of anthropogenic uses and influences, leading to degradation of their water quality (Branco et al. 1998; Esteves 1998; Konrath 1995; Petrucio 1998).

Coastal lagoons are underrepresented in the available literature (Panigrahi et al. 2009). Information on tropical and especially subtropical coastal lagoons is diffuse and fragmentary (i.e., published in non-indexed journals) and an even lower number of researches were carried out in small permanently or intermittently closed coastal lagoons, at which freshwater conditions predominate (Esteves et al. 2008).

Peri lagoon is a small coastal lagoon with some peculiar features. It is considered a shallow polymictic, soft water body, but in the context of coastal lagoons can be considered deep (Esteves 1998; Kjerve 1994; Schäfer 1988). It presents low nutrient concentrations and absence of direct marine influence (Laudares-Silva 1999; Simonassi 2001), which is also different from most coastal lagoons. In spite of the poor nutrient condition, Peri lagoon has high phytoplankton densities, with dominance of the potentially toxic cyanobacterium *Cylindrospermopsis raciborskii* most of the year (Grellmann 2006; Laudares-Silva 1999).

A few studies on this peculiar coastal lagoon were conducted concerning water quality features in the past two decades (Grellmann 2006; Laudares-Silva 1999; Simonassi 2001). For other Brazilian coastal lagoons, several important studies were made in the past three decades (e.g., Esteves 1998; Fonseca 1991; Huszar and Silva 1992; Konrath 1995; Schäfer 1988; Schwarzbold and Schäfer 1984; Schwarzbold et al. 1999). According to Esteves et al. (2008), the dynamic of abiotic factors is a central issue to the understanding of biological, chemical, and physical properties of coastal lagoons.

The trophic state classification of water bodies is an important management tool, since it allows comparisons between ecosystems within and among different ecoregions, besides offering an idea of the extent of cultural eutrophication suffered by the system (Dodds 2002). Trophic state indices are also useful to check relationships among several components of the ecosystem in study (Carlson 1977).

The present study aimed at assessing the temporal and spatial (vertical and horizontal) dynamic of trophic relevant water quality parameters in Peri coastal lagoon, by testing the following hypotheses:

(A) For the deep coastal Peri lagoon, significant variation between the sampling depths (an intermittently stratified water column) are expected but no differences between sampling stations, since coastal lagoons subjected to wind influences usually show horizontal homogeneity, and deep water columns show periods of stratification;

(B) In the subtropical context of Peri lagoon, four seasons can be distinguished concerning temperatures and rainfall: spring (mild temperatures, high rainfall), summer (high temperatures, high rainfall), fall (mild temperatures, low rainfall), and winter (low temperatures, low rainfall); in this sense, seasonal variations on water quality parameters are expected;

(C) No significant changes on trophic relevant water quality parameters (nutrients, chlorophyll, transparency, dissolved oxygen) are expected when compared to the studies carried out in the late 1990s in Peri lagoon, since no important changes in the surroundings of the lagoon occurred in the period;

(D) Different trophic classification are expected to be found among the four trophic state indices and parameters chosen to be compared in this study, because previous studies showed low nutrient concentrations, but a relatively high phytoplankton biomass in Peri lagoon, and other studies in tropical water bodies demonstrated that indices developed for temperate environments do not provide adequate trophic classifications.

Material and methods

Study area

Peri lagoon is located in Southern Brazil, Santa Catarina State, in the southeastern portion of Santa Catarina island (27°44′S and 48°31′W), Florianópolis (Fig. 1). Its surface area of 5.7 km^2 is surrounded by mountains covered by Atlantic Rain Forest in the south, west, and north portions and by sandy Restingas in the east portion. Peri lagoon is considered a coastal lagoon due to the geographic location and geological origin, but presents some features that are quite different from other Brazilian coastal lagoons, such as a maximum depth of approximately 11.0 m in the central portion and average depth of 7.0 m (most coastal lagoons are very shallow water bodies), and no direct sea water influence (freshwater all over the year). The bottom of the lagoon is composed mainly by coarse clay (~70%), fine sand (~15%), and medium sand (~10%; Oliveira 2002). According to the available literature, it is a polymictic nutrient-poor water body and presents a relative spatial homogeneity concerning water quality features (Laudares-Silva 1999; Silva and Senna 1997; Simonassi 2001).

The lagoon and surroundings (including almost the entire drainage basin) are within an environmentally protected area ("Parque Municipal da Lagoa do Peri") with a restricted human occupation (traditional families) since 1981. Since 2000, the lagoon supplies potable water to a significant percentage of the inhabitants of Santa Catarina island. As for other uses, the only activity allowed is recreational swimming.

The climate in the area is characteristically subtropical, with rainfall (Fig. 2a) well distributed along the year, but concentrated in spring and summer months (October–March). Air tempera-

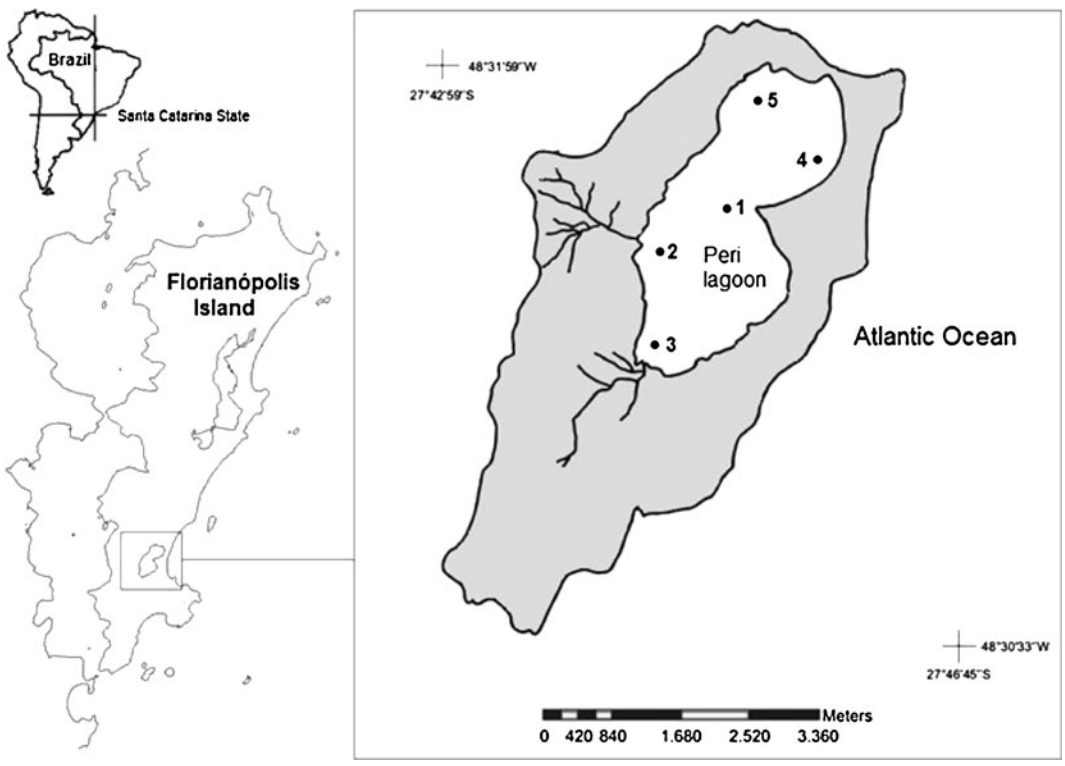

Fig. 1 Location of Peri lagoon and the sampled stations. The *gray area* delimitates the watershed and shows the two main rivers inflowing into the lagoon. *Numbers* indicate the sampling stations (coordinates for each station: 1–27°43′48.3″S / 48°31′16.7″W; 2–27°44′06.3″S / 48°31′59.4″W; 3–27°44′45.0″S / 48°31′58.5″W ; 4–27°43′31.9″S / 48°30′35.9″W ; 5–27°43′05.8″S / 48°30′41.7″W)

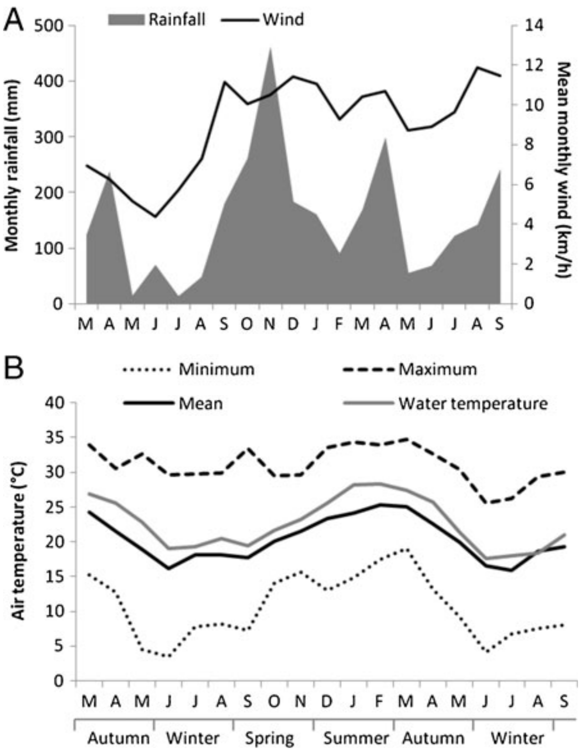

Fig. 2 **a** Monthly accumulated rainfall and monthly mean wind velocity. **b** Minimum, maximum and mean monthly air temperature in Florianópolis region during the study. Data gently provided by EPAGRI-CIRAM

ture varied between 3.5°C (June 2008) and 34.7°C (March 2009) during the study period (Fig. 2b), with a mean annual temperature around 21°C. Winds from the N-NE and S-SE quadrants are present all over the year, with increased intensities in spring and summer months.

Samplings and analysis

The study included monthly monitoring of several water quality parameters in five sampling stations (Fig. 1) during 19 months (March 2008 to September 2009) at Secchi disk depth using a 3 L van Dorn bottle. In the deepest station 1, four depths were sampled in order to evaluate vertical variations: surface, 10% light penetration (Secchi depth), 1% light penetration (three times Secchi depth), and aphotic zone (middle distance between lagoon bottom and three times Secchi depth). Light penetration in the water column (SD) was estimated by a 0.2-m white Secchi disk.

Water temperature (WT), conductivity (Cond), pH and dissolved oxygen (DO) were measured in situ with specific probes (WTW-Multi350i). Nitrite ($N\text{-}NO_2$—Golterman et al. 1978), nitrate ($N\text{-}NO_3$—Mackereth et al. 1978, ammonium ($N\text{-}NH_4$—Koroleff 1976), soluble reactive phosphorus (SRP—Strickland and Parsons 1960) and total phosphorus and nitrogen (TP and TN—Valderrama 1981) concentrations were determined in laboratory from filtered and unfiltered frozen water samples kept in polyethylene bottles at −20°C. Chlorophyll-a concentrations (Chl-a) were obtained by filtering 500-mL water samples through glass fiber filters Millipore AP40 using method and equations described by Lorenzen (1967).

Results were compared to previous studies developed in similar sampling stations in the late 1990s (Laudares-Silva 1999; Simonassi 2001).

Statistical analysis

Data were log (x + 1)-transformed in order to minimize the effect of different measurement units and obtain homogeneity of the variances. Seasonal and spatial variations were tested by one-way ANOVA (effects: seasons, stations, depths), followed by Tukey HSD post-hoc. Since no differences were found between sampling stations ($p = 1.000$), they were grouped in monthly means and also tested by one-way ANOVA, followed by Tukey HSD post-hoc. Cluster Analysis (Euclidean distances, single linkage) was performed to check which seasons were more similar considering all measured parameters. Relations between water quality parameters were tested by Pearson's correlation. Principal component analysis (PCA; correlation matrix) was performed to access the importance of each measured variable to explain the variance of the data. To compare our data and previous studies developed in the 1990s, Student t tests were performed. Statistical analyses were performed in the software Statistica 7 (StatSoft®), except for PCA (multivariate statistical package—MVSP, KCS©).

Results and discussion

Spatial variation of water quality parameters

No horizontal significant differences were found in Peri lagoon during the sampled period for all the parameters measured (one-way ANOVA, effect: station, $F = 0.437$, $p = 1.000$). Wind is probably the main cause of this lack of difference between sampling stations. N-NE and S-SE winds are present in the majority of the year in Santa Catarina island, and are particularly intense during spring and summer. Low human occupation and densely vegetated areas in the lagoon watershed as well as the small surface area are also contributing factors to the lagoon's homogeneity, since the water quality of lakes and lagoons may vary depending on the geological morphology, vegetation, and activities in the catchment basin (Gantidis et al. 2007).

Furthermore, Laudares-Silva (1999) and Simonassi (2001) also found no significant variation between sampled stations (three and seven stations, respectively) for all measured parameters in their studies, including phytoplankton community densities and richness.

Vertical samplings in four different depths in station 1 also did not show significant variations (one-way ANOVA, effect: depth, $F = 0.207$, $p = 1.000$) for all seasons. No thermal stratification was observed during the surveys. However, slight decreases in DO (maximum variation, 1.0 mg/L) and Chl-a (maximum variation, <5.0 μg/L) concentrations could be observed in a few months near the bottom of the lagoon.

Water column homogeneity is probably also related to the strong wind influence observed in the lagoon. The central position of the deep sampling station 1 with the lack of protection by the surrounding mountains is also an important factor contributing to the mixing conditions.

Laudares-Silva (1999) also investigated vertical samples in Peri lagoon in the central portion and found no significant differences between depths, even for the phytoplankton community. The author attributed the lack of spatial variation in the lagoon to the strong and constant presence of winds in the region as well.

Hydrodynamic processes are affected by the morphometry of the water body (Wetzel 2001), especially by its size and orientation in relation to the main winds, by the topography of the bottom and by the mean depth (Cardoso et al. 2003). In this sense, water bodies with small surface areas and not very deep water columns commonly present horizontal and vertical homogeneity as we found for Peri lagoon (e.g., Branco et al. 2000; Briand et al. 2002; Figueredo and Giani 2009; Nogueira and Ramirez 1998). Some authors studying coastal lagoons in Southern Brazil also found wind action as the main factor determining the water circulation and characterizing the lagoons as polymictic environments (Cardoso and Marques 2003; Fonseca 1991; Konrath 1995).

Seasonal variation of water quality parameters

Monthly variation of the in situ measured physicochemical and biological parameters can be visualized in Fig. 3.

Transparency of the water column varied relatively little, between 0.8 and 1.35 m. Low transparency of the water column seems to be a common feature for several coastal lagoons (e.g. Branco et al. 2000; Petrucio 1998) when compared to other water bodies, especially due to the high concentration of humic materials and/or the highly productive waters (Esteves 1998). However, in the coastal lagoons context, Peri lagoon can be considered a lagoon with relatively clear waters (Branco et al. 2000; Cardoso and Marques 2003; Gikas et al. 2006; Huszar and Silva 1992; Panigrahi et al. 2009). Secchi depth showed a weak but negative correlation with wind ($R = -0.28$), which may be related to sediment resuspension.

Water temperature ranged between 17.2°C and 29.7°C and varied in accordance with the subtropical climate along the year (Fig. 2). All seasons showed significantly different WT (one-way ANOVA, $p < 0.001$), which demonstrates the importance of this parameter on the lagoon dynamic. A PCA also demonstrates that WT is an important factor influencing the variation on the data (Fig. 4).

Our study found pH values ranging from 5.4 and 7.9, which shows that Peri lagoon presents

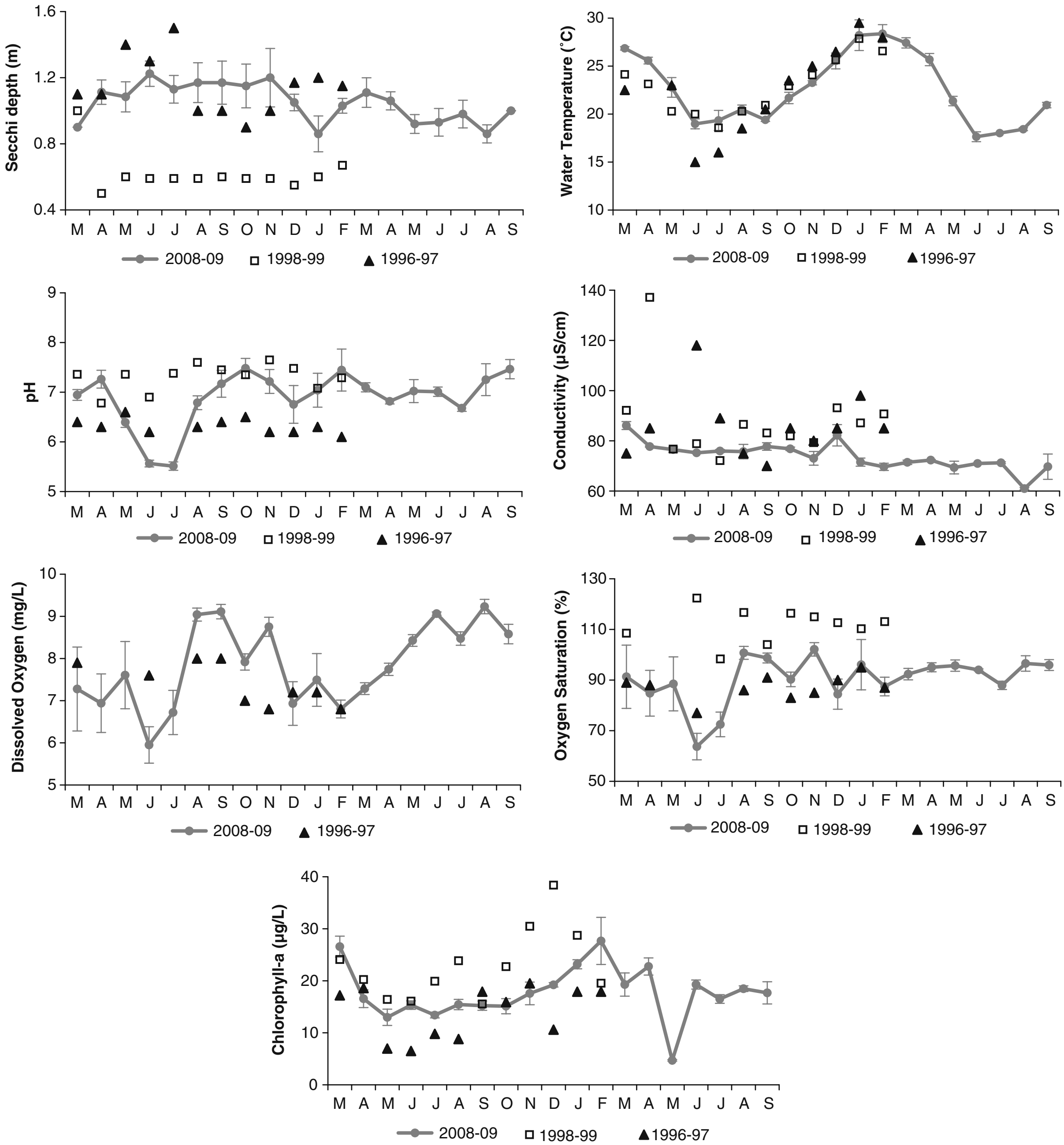

Fig. 3 Monthly means of the in situ physicochemical and biological parameters in Peri lagoon from March 2008–September 2009. Means obtained in previous studies are also shown (1996–97: Laudares-Silva 1999; 1998–99: Simonassi 2001)

water pH near to neutral most of the time, with periods of slightly acidity. pH in winter was significantly lower than in the other seasons (one-way ANOVA, $p < 0.001$) and had positive correlations with WT ($R = 0.33$), DO ($R = 0.48$), and Chl-a ($R = 0.20$), what may be explained by the fact that higher primary production rates in warmer periods consume CO_2, which leads to higher pH values, and increase DO in the water. Coastal lagoons usually present higher

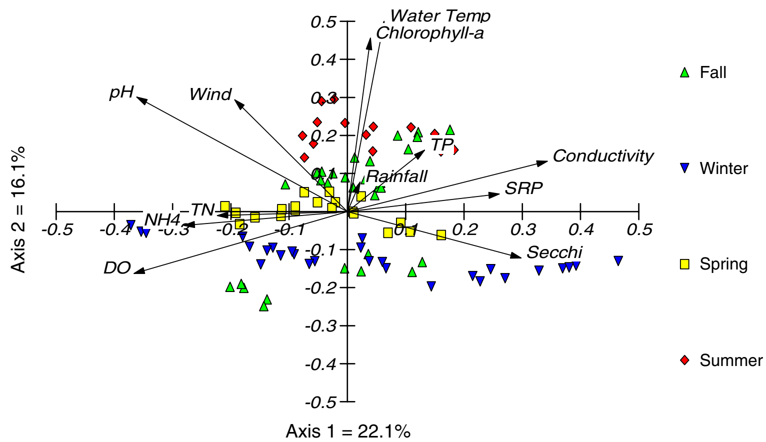

Fig. 4 Principal component analysis of the main water quality parameters for Peri lagoon during the studied period. Axis percentage of explanation: *axis 1* 22.14%; *axis 2* 16.13%

pH values especially because of the sea water influence (Chagas and Suzuki 2005; Coelho et al. 2007; Gikas et al. 2006; Lacerda and Gonçalves 2001; Macedo et al. 2001). The presence of humic materials, on the other hand, can acidify the waters (Branco et al. 2000).

Conductivity varied very little and at very low level (61.0–88.0 μS/cm) along the study period and indicated (a) lack of direct marine influence in the lagoon all over the year; (b) soft water conditions; and (c) low dissolved nutrients concentration. Conductivity showed a negative correlation with DO ($R = -0.34$). A possible explanation for this correlation is the entrance of organic matter in the system, which increases conductivity, while the degradation of this organic matter consumes DO. Coastal lagoons are usually directly influenced by marine waters by permanent or intermittently connections to the sea, presenting higher conductivity levels and detectable salinity (Branco et al. 2000; Coelho et al. 2007; Chagas and Suzuki 2005; González et al. 2008; Lacerda and Gonçalves 2001; Pereira et al. 2009). Impacted water bodies usually show higher conductivity levels as well (e.g., Mãe-Bá coastal lagoon—Pereira et al. 2006; Marcelino coastal lake—Pedrozo and Rocha 2006). A few coastal lagoons however, especially the ones located a few meters above the sea level, do not receive direct marine influence, keeping freshwater and low conductivity values all over the year, as in the case of Peri lagoon and other minimally impacted coastal lagoons (Pedrozo and Rocha 2006; Pereira et al. 2006). Distance and influence of the sea, precipitation levels, geology of the catchment and the patterns of use and occupation of the watershed usually determine the conductivity in these water bodies.

Dissolved oxygen concentrations showed a negative correlation ($R = -0.39$) with WT, what was expected since higher temperatures diminish the oxygen solubility in the water, and generally followed a seasonal pattern, with higher concentrations during autumn and winter. An exception can be observed in June and July 2008, when a significant drop in DO was detected, accompanied by decreases in pH, what can be a result of a reduction in primary production and increase of community respiration, resulting in O_2 consumption and increased CO_2 concentrations in the water column. Values ranged from 5.6 to 9.4 mg/L and oxygen saturation remained around 90% during most of the sampled period, which demonstrates that oxygen is not a limiting factor for the biota in Peri lagoon. Similar oxygen concentrations are found in other coastal lagoons, such as Icaraí and Guanabara lagoons (SE Brazil—Pereira et al. 2006), Comprida lagoon (SE Brazil—Branco et al. 2000), and Foz de Almargem lagoon (Portugal—Coelho et al. 2007).

Peri lagoon presented high Chl-a values ranging between 4.5 and 32.3 μg/L (mean 17.7 μg/L). Values followed a seasonal pattern, with higher concentrations in the summer (ANOVA, $p < 0.05$) and a positive correlation with WT ($R = 0.41$) and a weak correlation with pH ($R = 0.20$). Higher temperatures increase primary production, which leads to higher Chl-a values, CO_2 consumption and consequently higher pH. High

Chl-a is usually associated to eutrophication problems but even coastal lagoons subjected to pollution show lower concentrations than Peri lagoon (Esteves et al. 1984; Lloret et al. 2008; Pereira et al. 2009; Panigrahi et al. 2009). Coastal lagoons from the near state of Rio Grande do Sul (similar weather conditions and freshwaters) also showed lower Chl-a values in spite of higher nutrients concentrations (Pedrozo and Rocha 2006). The dominance in high densities of *C. raciborskii* in Peri lagoon (biovolume 9.63–36.39 mm^3/L—Grellmann 2006) is probably the reason for such high Chl-a concentrations. In Peri lagoon, this species found an adequate environment and has been increasing its density and dominance in the last decade (Grellmann 2006; Laudares-Silva 1999).

C. raciborskii is known as an unusually capable competitor, which is spreading and invading water bodies in tropical, subtropical and, more recently, temperate areas (Briand et al. 2002; Padisák 1997; Wiedner et al. 2007). The success of this species is being attributed to several intrinsic competitive factors. The characteristics that are probably leading to *C. raciborskii* dominance in Peri lagoon are: high affinity for phosphorus and high P-storage capacity (Isvánovics et al. 2000), which can be very important in P-limited environments; superior shade tolerance (Briand et al. 2002), since light goes cannot penetrate the Peri lagoon at around 3 m in depth; high affinity for ammonium (Padisák 1997), which is very useful in an environment with higher ammonium concentrations relative to nitrate concentrations; and wide thermal tolerance (Briand et al. 2004), that allows the species to tolerate water temperatures varying between 15°C and 30°C in Peri lagoon.

Nutrient concentrations along the sampling period can be visualized in Fig. 5.

Dissolved nutrients showed very low concentrations. Nitrite and nitrate showed such low concentrations (even undetectable by the methods for some months) that were excluded from the results (nitrite, 0.5–0.8 μg/L; nitrate, non-detectable—11.0 μg/L).

Soluble reactive phosphorus was higher in June 2008 and December 2008 (one-way ANOVA, $p < 0.001$) and remained under 2.5 μg/L in the other sampled months. In both June and December 2008, high wind speeds in the days previous to the sampling campaigns may have caused SRP releases from the sediments, increasing the concentration of this nutrient in these 2 months. Despite the majority of the coastal lagoons have shown higher SRP concentrations than Peri lagoon (including non polluted lagoons), usually around 30 μg/L (Gikas et al. 2006; Pereira et al. 2006; Phlips et al. 2002), Comprida coastal lagoon in Rio de Janeiro state showed similar low concentrations (Branco et al. 2000).

Ammonium presented the highest concentration, range and monthly variation among the dissolved nutrients, but no clear pattern could be inferred from the data. Monthly means remained around 15.0 μg/L in most sampled months, which is also lower when compared to data registered for other coastal lagoons (Branco et al. 2000; Gikas et al. 2006; González et al. 2008; Pedrozo and Rocha 2006).

The low dissolved nutrients concentration could be related to high recycling rates, the well-oxygenated water column and high assimilation by the phytoplankton and bacterial communities, which result specially in low nitrate and SRP concentrations in the lagoon.

Total phosphorus concentrations ranged from 9.9 to 26.5 μg/L (mean, 14.8 μg/L). These values are also considered low in the coastal lagoons context and may reflect the effect of the environmental protection of the area. Total phosphorus showed significantly higher concentrations in summer (one-way ANOVA, $p < 0.01$), which may be explained by higher wind influences during this season and higher sediment resuspension. Higher TP concentrations are commonly found in other coastal lagoons in Brazil (Chagas and Suzuki 2005; Esteves et al. 1984; Pedrozo and Rocha 2006) and worldwide (Badylak and Phlips 2004; Gikas et al. 2006; Panigrahi et al. 2009). Comprida lagoon showed similar low concentrations (mean 12.3 μg/L) once more, indicating phosphorus limitation in this environment as in Peri lagoon.

Total nitrogen was registered in lower concentrations in spring (one-way ANOVA, $p < 0.001$), what could be related to higher dilution due to more intense precipitation during September, October and November 2008. Total nitrogen concentrations ranged between 262 and 1,096 μg/L

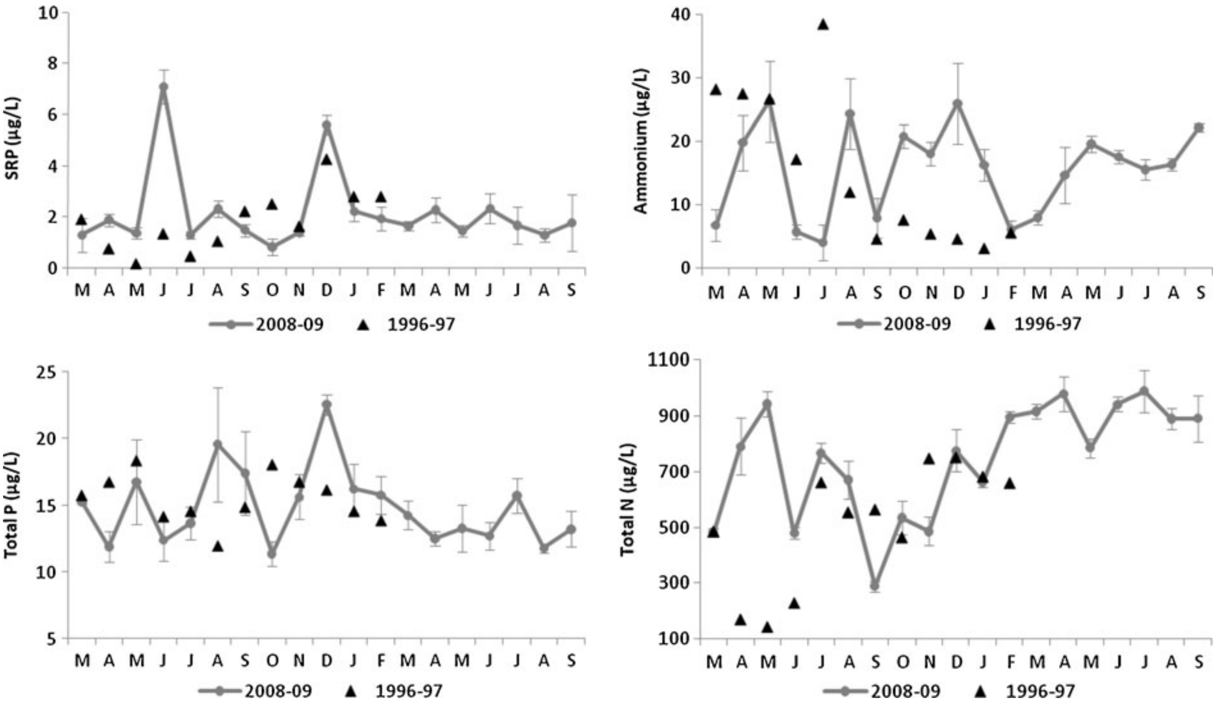

Fig. 5 Monthly means of the main nutrients in Peri lagoon from March 2008–September 2009. Means obtained in a previous study are also shown (1996–97: Laudares-Silva 1999)

(mean, 746 μg/L), what is in accordance or even slightly higher than other coastal lagoons (Badylak and Phlips 2004; Branco et al. 2000; Chagas and Suzuki 2005; Panigrahi et al. 2009), except those subjected to high anthropogenic impacts (e.g., Marcelino coastal lagoon—Pedrozo and Rocha 2006).

Peri lagoon showed a wide range in the TN:TP ratio and no seasonal clear pattern, however, P-limitation was in course during all the study period (Fig. 6) according to the Redfield mass ratio (TN:TP = 7.2:1). Guildford and Hecky (2000) proposed TN:TP molar ratios to determine if lakes and oceans are N-limited (TN:TP < 20) or P-limited (TN:TP > 50). Converting these values into mass ratios, we find that TN:TP mass ratios >22.5 indicate P-limited environments and that Peri lagoon was strongly limited by P during all sampled months, except for September 2008. The relative absence of P-rich sewage inputs, as well as a well-oxygenated water column, keeping phosphorus attached to the sediments, is possible explanations for this situation in the lagoon.

PCA has been a widely used tool to identify relevant groups of water and the most important factors affecting water quality variation (Liou et al. 2004). In that sense, a PCA (Fig. 4) was performed to evaluate the main parameters influencing water quality in Peri lagoon. The first two components explained only 38.27% of the variation of the dataset. The first axis accounted for 22.14% of

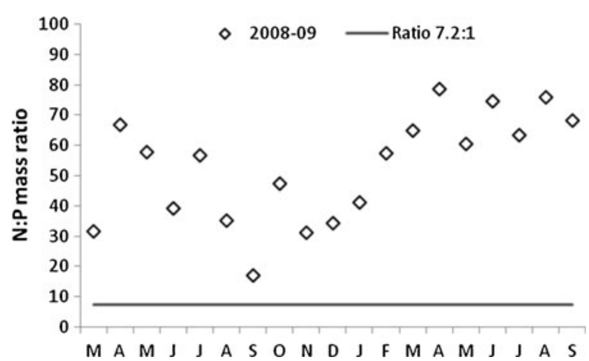

Fig. 6 N:P mass ratio for Peri lagoon between March 2008 and September 2009, compared to the Redfield mass ratio (7.2:1)

total variance and DO, Cond, and pH were the main factors contributing to it. The second axis explained only 16.13% of the data variation and was highly correlated with WT and Chl-a. High seasonal variation of most water quality parameters probably resulted in similar importance values to several variables, leading to low explanation of the first two axes.

Cluster analysis for seasons sampled (Fig. 7) showed differences (high Euclidean distances) between summer/spring and the colder seasons fall/winter. Besides warmer temperatures, higher rainfall and increased wind velocities (especially in S-SE winds) are other common features during summer and spring. The PCA (Fig. 4) also shows a clear separation between summer and winter samples related to temperature and chlorophyll-a, with spring and fall in the middle. Important seasonal variations on water quality are observed in several studies and are also related to temperature, wind, and rainfall regimes. Phlips et al. (2002) found that nutrient dynamic is affected by seasonal patterns of rainfall in a subtropical coastal lagoon in the USA. Dry and wet seasonality strongly influence key variables in a temperate coastal lagoon in Greece (Gikas et al. 2006) as well. Seasonal patterns on wind velocity and direction are an important factor affecting phytoplankton community and water quality in a temperate coastal lagoon in Portugal (Macedo et al. 2001) and in a subtropical coastal lake in South Brazil (Cardoso and Marques 2003). Seasonal temperature variations are key factors determining water quality dynamic in several aquatic environments (Gikas et al. 2009; Specchiulli et al. 2010; Yang et al. 2010).

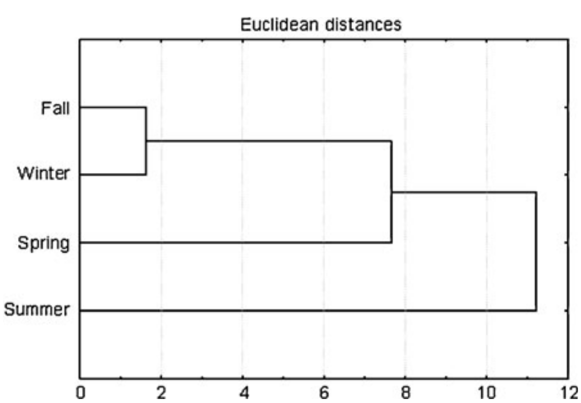

Fig. 7 Cluster analysis (Euclidean distance) for the seasons sampled in the studied period (March 2008–September 2009) in Peri lagoon

The effectiveness of a protected watershed in relation to water quality parameters

In this section, a comparison between the results found by the present study and two previous studies conducted in Peri lagoon between March/1996–February/1997 (Laudares-Silva 1999) and March/1998-February/1999 (Simonassi 2001) was made in order to evaluate if any water quality alterations occurred in the period that could affect the water supplying and explain the increasing dominance of *C. raciborskii* observed in the lagoon. Results from the two studies can be visualized as black triangles (1996–97) and white squares (1998–99) in Figs. 3 and 5.

Secchi depth values in 1996–97 were very similar to our study, but Simonassi (2001) measured lower transparencies (t test, $t = 4.10$, $df = 59$, $p < 0.001$) in 1998–99 (mean, 0.62 m). Similar values of WT were found by both previous studies, except in winter 1996, when Laudares-Silva (1999) detected lower WT (around 15°C). The lower temperatures during winter months may have caused the lower pH and Chl-a values (June–September, t test, $p < 0.05$) found in 1996–97, since lower primary production rates are expected in lower temperatures. The 1998–99 study detected higher pH (winter, t test, $p < 0.005$), Cond ($t = -2.66$, $df = 59$, $p < 0.01$), oxygen saturation ($t = -2.06$, $df = 59$, $p < 0.05$) and Chl-a (winter, spring, and summer, t test, $p < 0.05$, except for June and September 1999). Laudares-Silva (1999) found Cond and DO concentrations similar to our study.

Oversaturation and higher pH and Chl-a indicate a more net autotrophic environment in 1998–99, while the undersaturation and lower Chl-a and pH observed in the present study and in 1996–97 showed a net heterotrophic and possibly an allochthony situation in the lagoon. According to these observations, apparently Peri lagoon alternates between periods of carbon sources predominating from algae and microbial breakdown of particulate organic carbon (autochthony) and periods of carbon sources predominantly coming from outside the aquatic system, such as plant and soil materials (allochthony). However, additional studies are necessary to better understand this situation.

The El Niño Southern Oscillation phenomenon was particularly intense in 1998 (NOAA—National Oceanic and Atmospheric Administration, available in http://www.noaa.gov). Increased rainfall is a common feature during El Niño periods, which may have caused the lower transparencies and influenced the slightly higher pH, Cond, oxygen saturation and Chl-a values observed in 1998–99.

On the other hand, the La Niña phenomenon was in process in 1996 (NOAA), which is characterized by decreases in temperatures, particularly in winter and spring. The lower WT, pH, and Chl-a values found in 1996–97 by Laudares-Silva (1999) could be related to the La Niña influence in the sampling period.

In spite of the La Niña effect, Laudares-Silva (1999) observed in 1996–1997 very similar mean concentrations for both dissolved and total nutrients (annual mean SRP = 2.2 μg/L, N-NH_4^+ = 15.4 μg/L, TP = 17.2 μg/L, TN = 546.8 μg/L; t test, $p > 0.5$).

The similar results found by the two studies may be reflecting the maintenance of the water quality and the effectiveness of the protection of the lagoon surroundings.

Similar comparisons were made by Gikas et al. (2006) for Vistonis coastal lagoon in Greece, between 1984 and 1998, where they found that the implementation of protective measures in order to eliminate or reduce pollution is not improving the poor water quality of the lagoon. Also in Greece, water quality parameters in Polyphytos reservoir were compared between the years of 1987–1988, 1991–1993, and 2004–2005 and Gikas et al. (2009) concluded that the trophic state of the water body has become worse (mesotrophic to eutrophic, in 15 years).

Results found by Gikas et al. (2006, 2009) suggest that once degraded, the improvement of the water quality is a very complicated and slow process (Dodds 2002), and that protective measures after pollution are not always effective to solve the problem. Protecting and monitoring the water body surroundings before degradation of the water quality seems to be working for the maintenance of the water quality in Peri lagoon throughout the years.

Trophic state indices in Peri coastal lagoon

Several methodologies have been developed in the last decades in order to evaluate the state of eutrophication of inland waters, based on several parameters, especially SD, Chl-a, and TP concentrations. The most commonly used trophic indices are the trophic state index (TSI) of Carlson (1977) and the OECD (1982) index, both designed for temperate water bodies and well accepted as indicators of their eutrophication condition. However, several authors affirm that those indices are not suitable for warmer water bodies and have been generating inappropriate results and classifications for tropical and subtropical lakes and lagoons (Esteves 1988; Salas and Martino 1991). In this sense, two trophic state indices were developed for warmer water bodies and have been used for some authors: Salas and Martino (1991) and the TSI of Toledo et al. (1983), based on OECD and Carlson's TSI, respectively.

Table 1 shows the results for the four above mentioned trophic indices for Peri lagoon. Comparing the four indices we can notice that for SD and TP, the indices designed for temperate lakes exacerbate the classification when compared to the results obtained with the tropical designed

Table 1 Trophic state indices for Peri lagoon during the studied period (March 2008–September 2009) according to different parameters

	Secchi depth	Chlorophyll-a	Total phosphorus	Total nitrogen
TSI Carlson (1977)	Eutrophic	Eutrophic	Mesotrophic	–
TSI Toledo et al. (1983)	Mesotrophic	Eutrophic	Oligotrophic	–
Salas and Martino (1991)	–	–	Oligotrophic	–
OECD (1982)	Hypertrophic	Eutrophic	Mesotrophic	Mesotrophic

indices. According to the results showed in the previous sections of this paper and the fact that Peri lagoon is a potable water supplier after simple treatment, the classifications provided by the Salas and Martino (1991) and Toledo et al. (1983) indices seem more suitable to the studied lagoon.

Another interesting aspect emerges when comparing the results obtained by the same index but for different parameters (SD, Chl-a, TP, and TN). The Toledo TSI, for example, shows three possible classifications (oligo, meso, and eutrophic) for Peri lagoon depending on the chosen parameter. This emphasizes the importance of a careful choice of which trophic index to use and which parameters to measure in order to minimize errors when determining the state of eutrophication of a water body, especially for management purposes.

Other studies have also found divergent results from different trophic classification methods and different water quality parameters (Coelho et al. 2007; Fia et al. 2009; González et al. 2008; Mercante and Tucci-Moura 1999).

Based on Table 1 and the discussion above, Peri lagoon is classified as oligotrophic for nutrient concentrations and meso-eutrophic for SD and Chl-a. A plausible explanation for such contrasting classifications is the presence in high densities of *C. raciborskii*, which in spite of the low nutrient contents, can take advantage of several factors and be a successful competitor in Peri lagoon (as discussed earlier). The high density of this cyanobacterium is probably the main factor leading to low transparency and high Chl-a values.

Moreover, Esteves (1988) affirms that most tropical lakes are classified as oligotrophic for nutrients, while the high recycling rates in annual terms lead to high phytoplanktonic productivity rates, similar to those found for eutrophic temperate lakes. This can also be the case for Peri lagoon and may be leading to the contrasting classifications obtained by different trophic indices and parameters.

Conclusions

1. Peri lagoon showed spatial homogeneity (horizontal and vertical) in all seasons, despite its relative deep water column. This is a consequence of the constant and strong influence of N-NE and S-SE winds in the coastal region of Santa Catarina state and the low human occupation and influence (low potential waste water inputs) in most of the lagoon watershed.
2. Seasonal variations of the water quality were observed in Peri lagoon. Seasonal trends can be explained mainly by the changes in temperature, wind and rainfall regimes, characteristic from the subtropical weather.
3. No strong differences that evidence alteration in trophic relevant water quality parameters in Peri lagoon were found when comparing this study with previous researches conducted in 1996 and 1998. This can be a reflection of the effectiveness of the environmentally protected area in which the lagoon and most of its watershed are inserted and the low human influence and occupation in the lagoon surroundings.
4. When tropical indices were used, Peri lagoon was classified as oligotrophic for nutrients concentrations and meso-eutrophic for transparency and chlorophyll-a, which can be explained by the high densities of the cyanobacterium *C. raciborskii* and by the high recycling rates observed in tropical and subtropical water bodies.

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