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ORIGINAL ARTICLE

Trophic state index (TSI) and physico-chemical characteristics of a shallow reservoir in southeast Brazil

Cristiano Cigagna[1] · **Daniel Marcos Bonotto**[1] · **Antonio F. Monteiro Camargo**[2] · **José Ricardo Sturaro**[1]

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Abstract This paper presents the trophic state index (TSI) and water physico-chemical characteristics of a shallow tropical reservoir located in southeast Brazil. It describes a study held over a hydrological and diurnal period, which enabled to map the variability of several physico-chemical variables due to regional climate and to compare the results with the TSI in winter and summer. The thermal behavior of the water column is typical of a polymictic reservoir. Low dissolved oxygen levels have been measured, reaching 0.07 mg L^{-1} in the deepest part of the reservoir as a direct consequence of the increased nutrient levels. The average pH was slightly acid (6.71) especially at the reservoir bottom and did not show significant changes during the monitoring period. The electrical conductivity varied according to seasons, i.e., it was higher in the rainy period compared to dry season, averaging 138 and 84.06 μS/cm, respectively. According to the TSI, the reservoir has been classified as mesotrophic and eutrophic in the dry and rainy season, respectively.

Keywords Hydrochemistry · Reservoirs · Eutrophication · Limnology

✉ Daniel Marcos Bonotto
danielbonotto@yahoo.com.br

[1] Instituto de Geociências e Ciências Exatas-IGCE, Universidade Estadual Paulista-UNESP, Av. 24-A No. 1515, P.O. Box 178, Rio Claro, São Paulo 13506-900, Brazil

[2] Instituto de Biociências-IB, Universidade Estadual Paulista-UNESP, Av. 24-A No. 1515, P.O. Box 178, Rio Claro, São Paulo 13506-900, Brazil

Introduction

Eutrophication of a water body is a process of nutrient enrichment, whether of anthropogenic or natural origin. In limnology, the study and classification of water bodies with respect to the degree of eutrophication began in 1919 with Naumann and in 1925 with Thienemann (Schäfer 1985). Trophic state categories have been proposed for the lakes, ranging from oligotrophic (low primary productivity) and mesotrophic to eutrophic (high primary productivity).

In general, under the geological timescale, the environments tend to pass from a natural oligotrophic condition to a mesotrophic one and finally to a eutrophic state that results in its siltation and disappearance (Welch 1952). Artificial (or anthropogenic) eutrophication can be observed in a shorter timescale, e.g., of decades. In many cases, it is associated with the supply of industrial and domestic effluents whose discharge occurs in water bodies (Rocha et al. 1997). Although anthropogenic impacts such as point (and non-point) source pollution are considered as the main determinants of eutrophication, some natural factors that reflect the water body buffer capacity to nutrient inputs can also play important roles in explaining the eutrophication status of lakes and reservoirs (Liu et al. 2010).

In several developing countries, most of the effluents are discharged in water bodies without any prior treatment. This causes large inputs of organic matter and pollutants that have been reported as the main factors responsible for the eutrophication of a wide variety of aquatic environments. Consequently, they have enhanced the concern about the pollution and contamination levels in lakes, rivers, reservoirs and other continental environments (Tundisi and Matsumura-Tundisi 2008).

The degradation of rivers and reservoirs in the last decades has been particularly important in Brazil, especially due to population growth and urbanization without proper sanitation. This phenomenon has considerably diminished the water quality, mainly due to nitrogen and phosphorus enrichment, harming this valuable natural resource especially for some types of uses (Esteves 2011).

The FEENA ("Edmundo Navarro de Andrade" State Forest) is located at Rio Claro city, São Paulo State, Brazil, consisting on an area protected by Federal Law No. 9985/2000 and administered by the Forestry Institute of the Environment Secretary, an agency of São Paulo State, Brazil. The well-known "Forest Lake" at Rio Claro city is a reservoir situated in the central part of FEENA that has been focused in this paper. It is a water body of significant historical and cultural heritage and local landscape enrichment. It receives daily local visitors and people from the region, for practicing sports and for leisure. Little research has been developed in this water body, existing is a lack of records focusing on its ecological quality. Therefore, it is difficult to assess the true extent of deterioration in this aquatic ecosystem, although it has been recognized that the degradation process has intensified in the last decades (Galvão and Raduan 1982; Zevallos 1986; Cunha 1997; Stradioto 2003; Hardt 2009).

Additionally, investigations of limnological processes are essential for understanding lentic ecosystems succession and for providing fundamental knowledge as an aid to interpret paleolimnological records (Wang et al. 2014). Thus, this study aimed to classify the trophic degree of the FEENA shallow tropical reservoir and to characterize its main physico-chemical parameters during a hydrological and diurnal period. Our purpose was to obtain basic information on the water quality and variability of several variables in a shallow tropical reservoir and to compare the results of the trophic state index (TSI) in the winter and summer. All the obtained information are very useful for decision makers engaged in environmental projects directed to conservation and management activities.

Study area

The FEENA reservoir is located in an important sustainable conservation unit of São Paulo State, southeastern Brazil, at the eastern edge of Rio Claro city (Fig. 1). The UTM (Universal Transverse Mercator) coordinates are 240258-240442 E and 7519137-7519380 S, 23 K zone, datum SIRGAS/2000. The authorization for the development of this research was provided by the Forestry Institute (SMA Case No. 260108-006744/2012). The reservoir is shallow (Table 1), heavily occupied by floating and submersed aquatic plants, and in an advanced and constant process of siltation, especially in the northern sector, next to the affluent stream.

The climate of the area is Cwa (Köppen classification), i.e., tropical with two distinct seasons. It is dry in winter and the hottest month reaches temperatures above 22 °C. The dry period is between April and September (average rainfall = 34.2–72.3 mm), whereas the rainy period is from October to March (average rainfall = 119.3–338.6 mm). The annual average rainfall is 1366 mm.

The study area is within the Ribeirão Claro sub-basin which, in turn, is part of the Corumbataí River watershed that is the main drainage system in the region, including its tributaries Ribeirão Claro, Cabeça and Passa Cinco streams. The source of these streams is on the *Cuesta* slopes and they flow south, discharging into Piracicaba River, which runs westwards reaching Tietê River (Cottas 1983). The main tributaries of Ribeirão Claro stream crossing FEENA are Lavapés, Santo Antônio and Ibitinga streams.

The reservoir is a result of the damming of the Ibitinga stream waters in the final portion of its course, within the boundaries of FEENA. This affluent feeds the reservoir at the north edge, and its fume is southwards, draining Santo Antônio stream, a left tributary of Ribeirão Claro stream that is responsible for part of the Rio Claro city water-supply system.

The main relief forms are linked to the regional geological context. In the area there are three main types of geological formations (Pirani et al. 2005): Corumbataí Formation (belonging to the Passa Dois Group), Serra Geral Formation (São Bento Group) and Rio Claro Formation (Cenozoic deposits). According to Zaine (1994), in the area predominate lithologies linked to basic intrusive rocks, represented by "diabase sills" lying in the E, NE and N sectors. There are lithologies related to Rio Claro Formation in the 630–656 m altitude, and to mudstones of Corumbataí Formation in the 568–650 m altitude. There is continued presence of Quaternary alluvial deposits consisting of sands, and clays are highlighted over the course of Ribeirão Claro channel.

Materials and methods

Data acquisition

The water samples were collected in the central part of the reservoir for chlorophyll a, total phosphorus and total nitrogen analysis in the dry (September 2012) and rainy (January 2013) seasons. A Wildco Model 1120 Van Dorn bottle, horizontal type, 2.2 L storage capacity, was used to collect them at different depths.

The samples were inserted in plastic bottles and stored in iced boxes. Then, they were transported to the limnology laboratory at the Ecology Department of the Biosciences

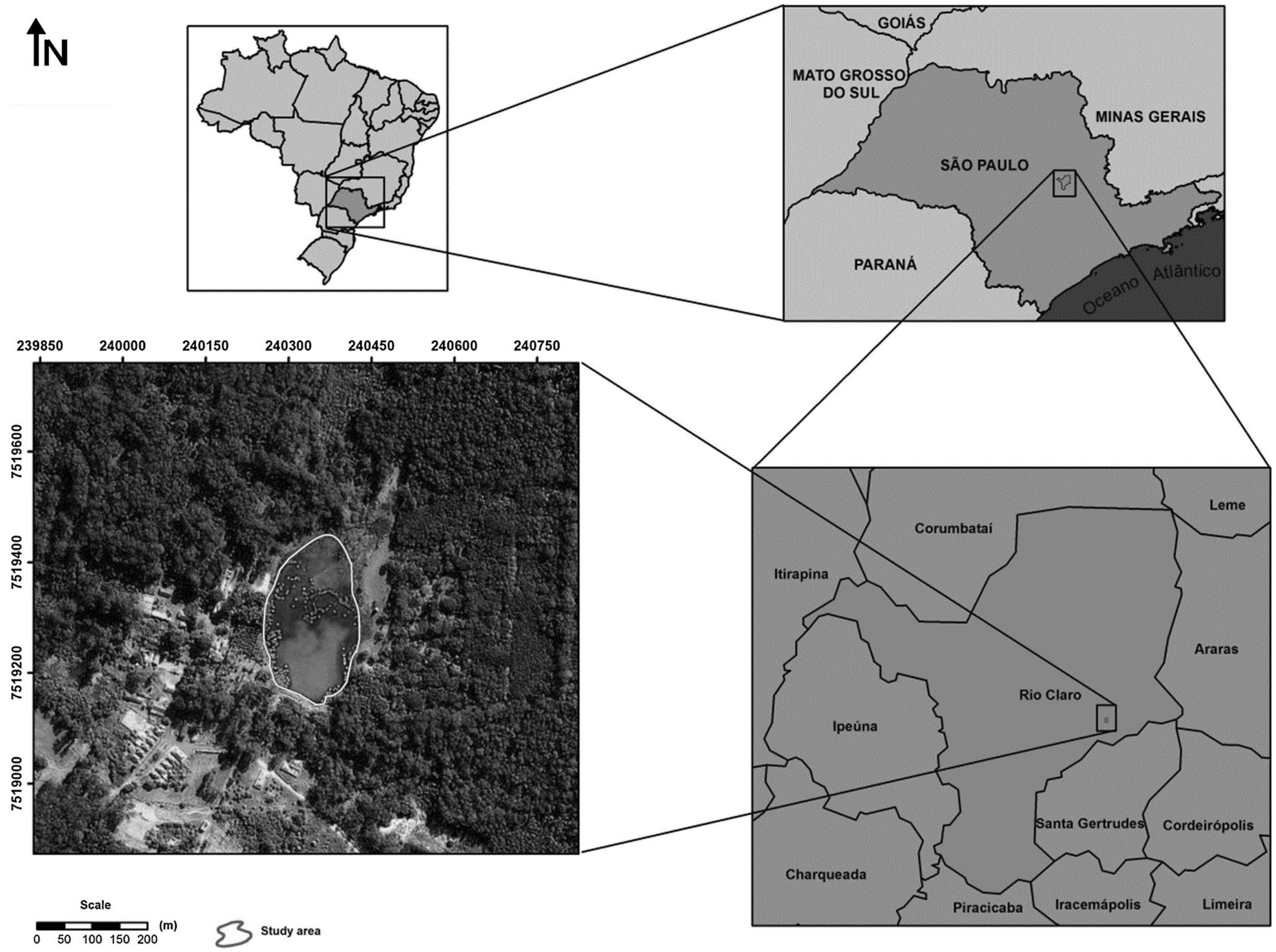


Fig. 1 Sketch map of the research region in Brazil

Table 1 Morphometric parameters of the FEENA reservoir

Parameter	Value
Area	25,866 m^2
Volume	22,251 m^3
Maximum depth	2.16 m
Perimeter	645 m
Maximum width	159 m
Maximum length	268 m
Average depth	0.86 m
Relative depth	1.19 %
Perimeter development	1.12
Volume development	1.19

Institute from UNESP (São Paulo State University), Rio Claro city, in which chlorophyll a, total phosphorus and total nitrogen measurements were made following the descriptions by Lorenzen (1967), Golterman et al. (1978) and Mackereth et al. (1978). The settling and total suspended solids were analyzed at LABIDRO (Isotopes and Hydrochemistry Laboratory) of the Geosciences and Exacts Sciences Institute from UNESP, Rio Claro city, on using the volumetric and gravimetric methods (EPA Environmental Protection Agency 1997).

The deepest reservoir portion (limnological spot) was chosen to measure the water transparency (Secchi disk depth), whereas samples from the surface to the reservoir bottom at 30-cm intervals were collected to determine the temperature, dissolved oxygen, pH and electrical conductivity variations. Table 2 reports the equipments utilized for data acquisition. The sampling was held in 2012 (September and November) and 2013 (January, March, May and July) for covering a hydrological period. Additionally, nictemeral (daily) variation of the same parameters was evaluated in 01/24/2013 at 7:00 am, 10:00 am, 12:00 pm, 3:00 pm, 5:00 pm, and 7:00 pm.

Table 2 Equipments used in this study for determining the limnological variables

Variable	Equipment
Temperature (°C)	Digital immersion thermometer
Dissolved oxygen (mg/L)	Hanna oximeter model HI-9146
pH	Digimed pH meter model DM-LP
Conductivity (μS/cm)	Analion conductivity meter model C-702
Transparency (m)	Secchi disk

Trophic state index (TSI) for lentic water bodies

The TSI classifies the water bodies in different trophic degrees, evaluating the water quality cue to nutrient enrichment. However, this index does not distinguish the natural eutrophic environments from the artificial ones. In this study, the TSI adopted corresponded to that used by CETESB (Environmental Sanitation Technology Company of São Paulo State) for the classification of lentic environments. It was introduced by Carlson (1977) and modified by Toledo et al. (1983) who amended the original values to adapt them to subtropical environments (Table 3). CETESB usually does not consider the transparency in the TSI calculation as this parameter is affected by turbidity due to suspended material that is a common situation in reservoirs and rivers in São Paulo State.

Total phosphorus (PT) and chlorophyll a (Cl a) concentration (in mg L^{-1}) provides different TSI values that are used for estimating an average TSI according to the equations:

$$\mathrm{TSI}\ (\mathrm{PT}) = 10\{6 - [\ln(80.32/\mathrm{PT})/\ln 2]\}, \quad (1)$$

$$\mathrm{TSI}\ (\mathrm{Cl} - a) = 10\{6 - [(2.04{-}0.695\ln\ (\mathrm{Cl} - a)/\ln 2]\}. \quad (2)$$

A comparison of the TSI (Cl a) and TSI (PT) values allows determine the degree of phytoplankton productivity limitation. When the two indices rank the environment in the same trophic class, the degree of limitation is considered "normal". When the phosphorus index ranks the environment in a class higher than that obtained by the chlorophyll a concentrations, indicating that there is some limiting factor that reduces the phytoplankton productivity, the degree of limitation is considered "high". Conversely, when the chlorophyll a concentrations result in a higher ranking than obtained by the phosphorus index, the degree of limitation is considered "low", indicating the existence of favorable conditions for the primary productivity in the environment, considering the nutrient availability (Lamparelli 2004).

Results and discussion

Seasonal variations in the physico-chemical properties of water

The temperature in a lake is, apart from light, one important parameter affecting the seasonal development of the biological processes as phyto- and zooplankta grow according to their variation (Hutter and Johnk 2004). The temperature variation in the water column over a seasonal period is shown in Figs. 2, 3 and 4. The largest thermal amplitude in the reservoir surface during every monitoring month was 12 °C: the highest value (31.5 °C) was found in March 2013, while the lowest (19.5 °C) in July 2013. However, in the reservoir bottom, the greater temperature difference was 6.8 °C as the highest value was 24.2 °C (March 2013) and the minimum 17.4 °C (July 2013). In the same day, 7.3 °C (March 2013) was the highest temperature difference between the reservoir surface (31.5 °C) and bottom (24.2 °C). It happened when the whole water mass exhibited the highest temperature (Fig. 3).

The lowest temperature difference (0.2 °C) between the reservoir surface (24.9 °C) and bottom (24.7 °C) occurred in the summer (January 2013), when a decrease of 1.9 °C was observed at ~60 cm depth; it was followed by a gradual temperature increase towards the bottom. The thermocline formation between 0.50 and 1 m depth has been identified, possibly related to the morphometric characteristics of the reservoir (Esteves 2011). The lowest temperature in the whole water column was found in July 2013 (mean = 18.1 °C), when probably occurred a full

Table 3 Limits for different trophic state levels according to the Carlson (1977) classification and modifications by Toledo (1990)

Criterion	Trophic State Index (TSI)	Transparency (m)	Total phosphorus (mg/L)	Chlorophyll (μg/L)
TSI ≤ 24	Ultraoligotrophic	≥7.8	≤0.006	≤0.51
24 < TSI ≤ 44	Oligotrophic	7.7–2.0	0.007–0.026	0.52–3.81
44 < TSI ≤ 54	Mesotrophic	1.9–1.0	0.027–0.052	3.82–10.34
54 < TSI ≤ 74	Eutrophic	0.9–0.3	0.053–0.211	10.35–76.06
TSI > 74	Hypereutrophic	<0.3	> 0.211	>76.06

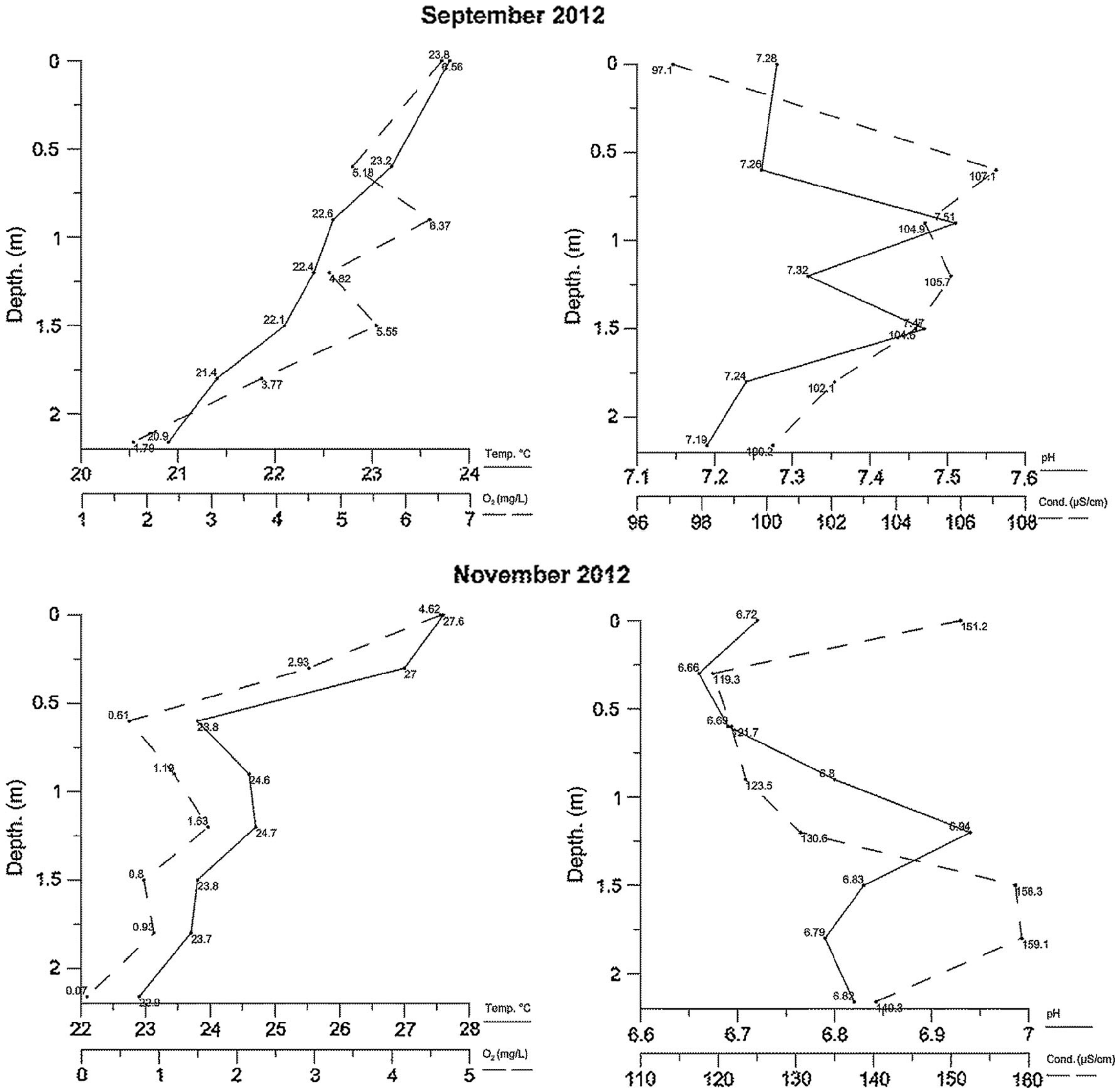


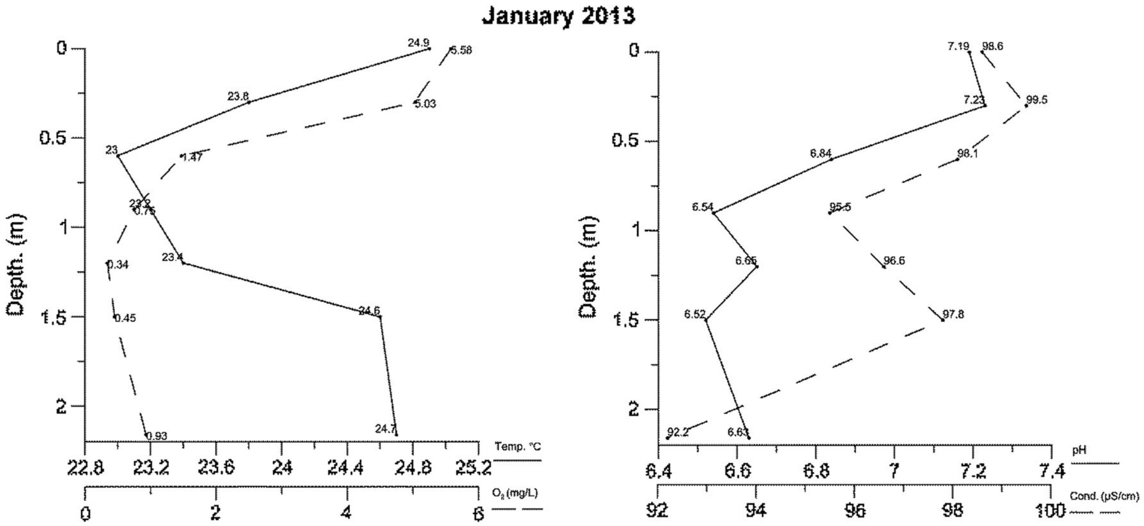
Fig. 2 Profiles of temperature, dissolved oxygen, conductivity and pH in the water column during the sampling in September 2012 and November 2012

water mass circulation (winter circulation). This was confirmed by the fact that it was found at the reservoir bottom, on the same day, a higher dissolved oxygen content than in the surface, as routinely verified along the whole monitoring period (Fig. 4).

The dissolved oxygen concentration decreases not only as a consequence of the temperature increase, but also as an effect of increased respiration, either as a direct response to increased temperature or due to increased nutrient levels (Battarbee et al. 2008). This effect has been confirmed in mesocosm studies (Moss et al. 2003, 2004). The effect will be larger where the water warms faster like at the shallower lake depths (Naumenko 2008) and with summer low-flow periods in streams (Cox and Whitehead 2009).

The greatest variation of the dissolved oxygen concentration at the reservoir surface was found between May 2013 (97.4 %) and July 2013 (65.3 %), whereas, at the bottom, the highest concentration was 77.6 % (July 2013) against the lowest value of 0.07 mg L^{-1} (1.2 %) in November 2012 (Fig. 2). This oxygen reduction is consistent with the reservoir trophic increase levels during the rainy period. The largest dissolved oxygen content difference between the reservoir surface (97.4 %) and bottom (17.7 %) was 79.7 % in May 2013, whereas the lowest was 12.3 % in the winter (July 2013). The monitoring held in 07/02/2013 indicated that the dissolved oxygen content was greater at the reservoir bottom (77.6 %) in comparison to the value in surface (65.3 %). A possible explanation could be related to the fact that the monitoring was carried

January 2013



March 2013

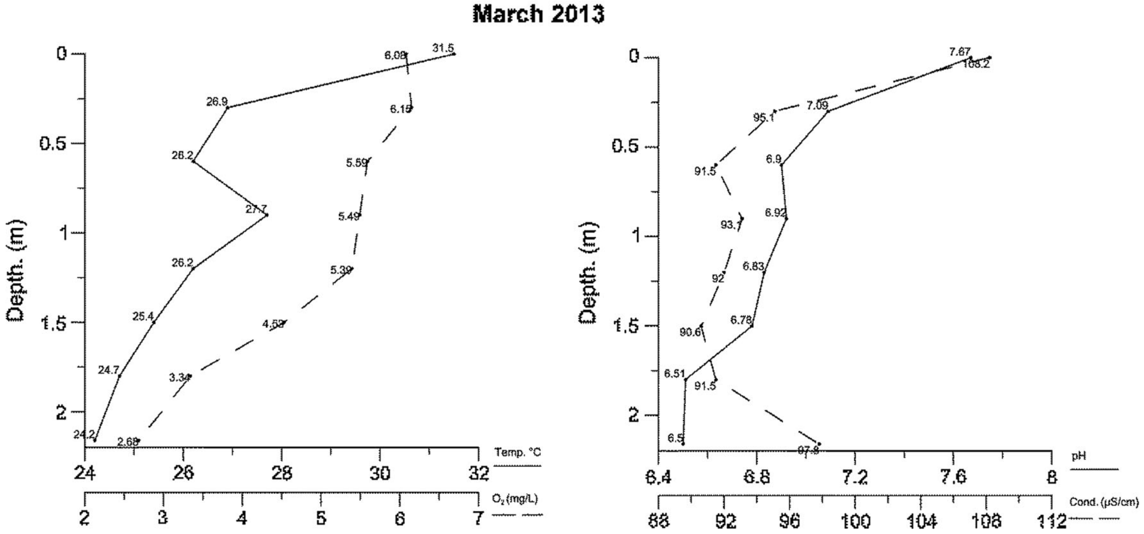


Fig. 3 Profiles of temperature, dissolved oxygen, conductivity and pH in the water column during the sampling in January 2013 and March 2013

out in a month characterized by low air temperatures, causing thermal instability in the water column and generating low resistance between the layers, thus, creating favorable conditions for the wind to circulate the entire water mass, oxygenating the deeper layers (Tundisi and Matsumura-Tundisi 2008).

The pH did not show large difference between the surface and bottom of the reservoir. The mean pH value of 6.71 indicated a slightly acid character. The most common natural acidification form is the humic acids production from organic decomposition. The pH is generally around 6.5 in sites dominated by the occurrence of these processes as a consequence of the water runoff in unacidified soils and forests with humic acid production (Hornstrom 2002).

The pH difference was 1.44 at the lake surface and 1.15 at the bottom. The highest pH value at the surface was 7.67 (March 2013) and the lowest 6.23 (July 2013), whereas the maximum was 7.19 (September 2012) and the minimum 6.04 (May 2013) at the reservoir bottom. The greatest pH difference was 1.17 (March 2013) when it was 7.67 and 6.50 at the reservoir surface and bottom, respectively. Generally speaking, the deepest part of the reservoir remained slightly more acidic than the surface layer. Additionally, the heterotrophic activity at the bottom tended to decrease the pH due to CO_2 production by respiration that also diminishes due to organic matter decomposition processes (Esteves 2011).

The difference of the electrical conductivity at the reservoir surface was 62.9 μS/cm, i.e., the highest value was 151.2 μS/cm in the rainy season (November 2012), while the minimum was 88.3 μS/cm (May 2013) (Fig. 2). The difference was 64.6 μS/cm at the reservoir bottom during the same monitoring period as the highest value was 140.3 μS/cm (November 2012) and the minimum 75.7 μS/

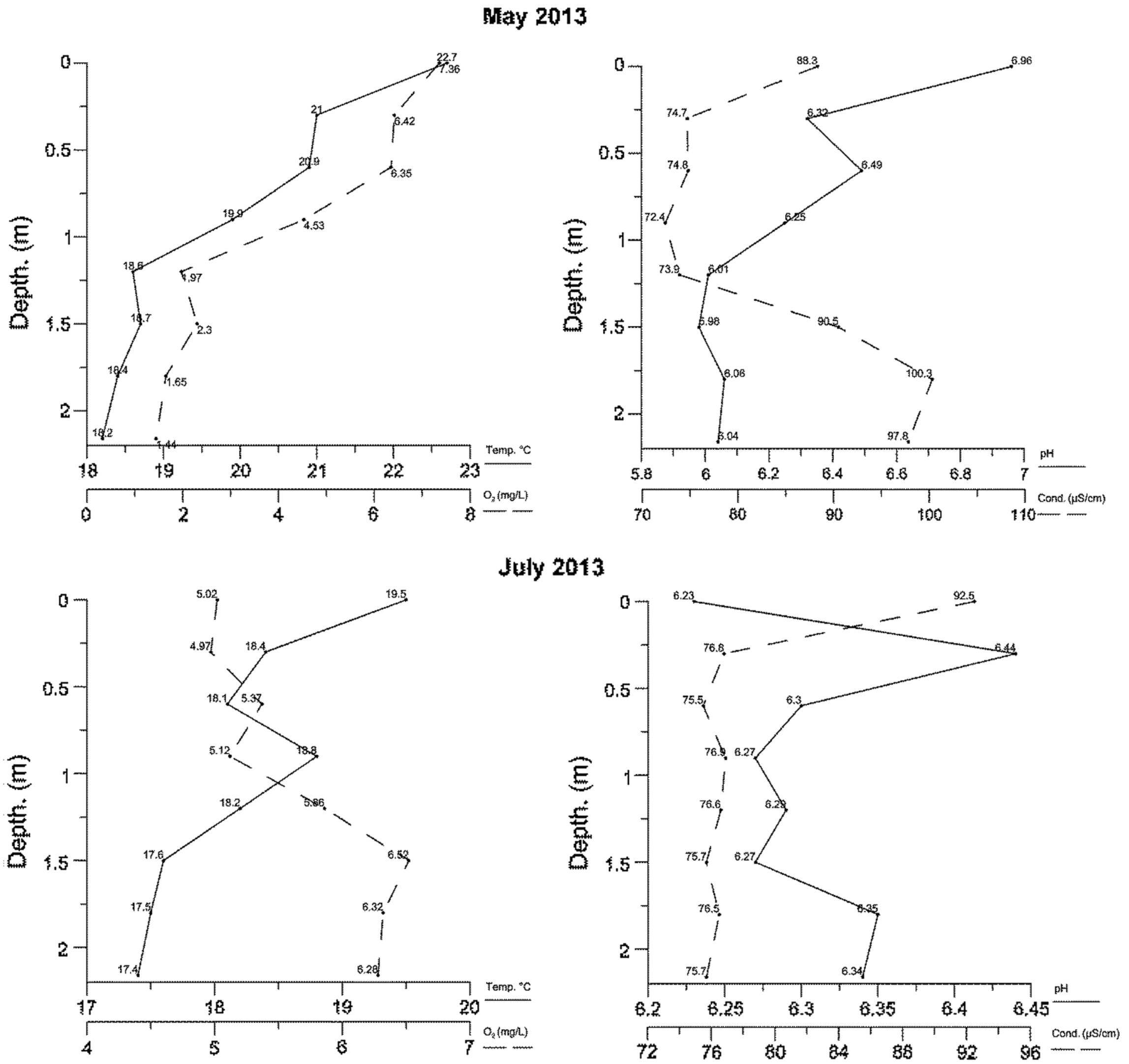


Fig. 4 Profiles of temperature, dissolved oxygen, conductivity and pH in the water column during the sampling in May 2013 and July 2013

cm (July 2013). The highest difference between the reservoir surface and bottom was 16.8 µS/cm and the lowest 3.1 µS/cm.

Secchi disk transparency observations have become an integral component of large lake surveillance strategies. These measurements form the only major "optical history" for water bodies on a global scale (Naumenko 2008). The Secchi disk depth was higher in the dry season than in the rainy season due to the greater amount of suspended material, which considerably decreased the water transparency (Fig. 5). The Secchi depth reached ~1 m in September 2012, decreasing following the seasonality. The extent of the photic zone can reach the sediments at the reservoir bottom during this period of increased water clarity due to its lower depth (mean = 0.86 m). The sun rays reaching the water body bottom may result in a total primary productivity quite high in relation to the reservoir volume (Sperling 1999). The average depth in each environment has a strong influence on the annual variation of phytoplankton productivity in tropical reservoirs (Esteves 2011). The lowest transparency values were observed during the months of greatest rainfall, reaching a minimum of 28 cm in January 2013.

The settling and total suspended solids did not show significant variations, except in January 2013, due to the rainy period (Fig. 5). The average settling solids level was 0.1 mL L^{-1} during the entire monitoring period and its highest value was 0.3 mL L^{-1} (January 2013). The mean total suspended solids' level was 0.026 mg L^{-1} and its highest value was 0.08 mg L^{-1} (January 2013). The lowest Secchi disk depth (28 cm) was also found in January 2013.

The electrical conductivity varied according to seasonality during the research period, i.e., it was lower in the dry season and higher in the rainy season (hottest period).

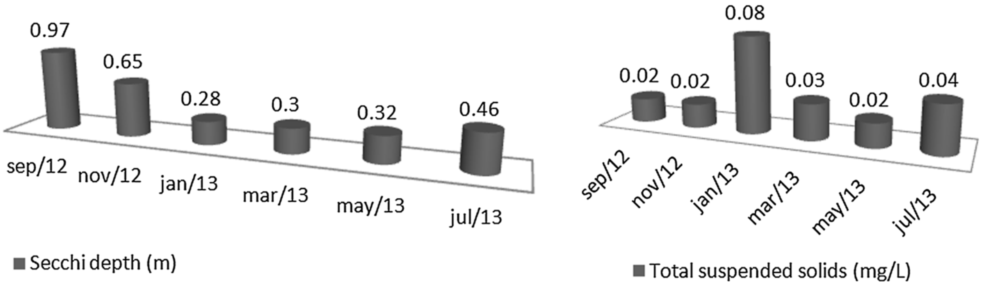


Fig. 5 Variation of the Secchi disk depth and total suspended solids during the dry and rainy seasons

These results are consistent with lower Secchi disk depths and higher total suspended solids measured in January 2013 (Fig. 5). The data reported by Matsuzaki et al. (2004) for fish ponds were similar and attributed to the resuspension of the tank bottom material that increases the decomposition rate of the organic matter, releasing larger ions amounts to the water column. Therefore, the electrical conductivity is a useful indicator of the total dissolved solids content, confirming the relationship between these parameters because the electrical conductivity in an electrolyte solution is primarily dependent of the ionic species concentration (see, for instance, Hayashi 2004).

Diurnal variations in the physico-chemical properties of water

The monitoring of the physico-chemical variables during 12 h of a summer day (01/24/2013) revealed the dynamics of these variables at different depths (Fig. 6). A light reverse stratification of the water column was observed at 7:00 pm. The water temperature at the reservoir surface was 22.6 °C, while at the bottom was 23.8 °C. An isotherm (average = 23.9 °C) of the water mass was detected at 10:00 am when the water temperature was 24.9 and 24.7 °C at the reservoir surface and bottom, respectively. This was the lowest temperature difference (0.2 °C) recorded throughout the day between the inferior and superior layers. The water column stratified progressively after noon, with the water temperature at surface reaching a maximum of 28.2 °C at 5:00 pm, when the temperature difference between the reservoir surface and bottom was 3.3 °C. A cooling process of the water column upper layer began from 7:00 pm due to heat loss to the atmosphere. The largest temperature difference of the upper surface layer throughout the day was 5.6 °C, whereas a lower value (1.5 °C) was found at the reservoir bottom.

The dissolved oxygen concentration varied significantly throughout the day. The highest percentage of saturation in the surface layer occurred at 5:00 pm, when the concentration was 99.4 %. The oxygen concentration at the reservoir bottom was only 1.9 % at the same time, exactly when the thermal stratification of the water column reached the maximum level (temperature difference between the reservoir surface and bottom = 3.3 °C). In general, low levels of dissolved oxygen saturation at the reservoir bottom were found throughout the day, ranging from 1.5 % (7:00 am) to 15 % (3:00 pm) (Fig. 6).

The pH and electrical conductivity values showed little variation during the hourly monitoring period. The average pH was 6.74 and the deepest reservoir part remained slightly more acidic than the surface throughout the day. The conductivity varied between 98.6 and 115.1 µS/cm at the reservoir surface and from 92.0 to 104.5 µS/cm at the bottom. The higher difference between the surface and bottom layers occurred at 12:00 pm (21.5 µS/cm), when the conductivity was 115.1 and 93.6 µS/cm at the reservoir surface and bottom, respectively.

Trophic state index (TSI)

The reservoir has been classified as mesotrophic in the dry season (Table 4). In winter, the lack of rainfall increases the water transparency and reduces the nutrients supply into the reservoir, improving the water quality. This is confirmed by the dissolved oxygen concentration values that were higher throughout the profile in this season. The TSI (PT) calculation ranked the environment in the mesotrophic class, while the TSI (Cl *a*) ranked it in a higher class, i.e., eutrophic. Thus, the degree of limitation is considered “low”, indicating possible favorable conditions for primary productivity according to the available nutrients (Lamparelli 2004).

The nitrogen and phosphorus concentration was higher in the rainy season due to the nutrients leaching processes occurring at the drainage basin of the reservoir area. This probably happened because the source of Ibitinga stream, a tributary of the reservoir, is located outside the FEENA limits in areas where the monoculture cropping predominates, particularly sugarcane and some farms that use fertilizers. Cunha (1997) found high soil loss rates that are above those considering the natural dynamics as a

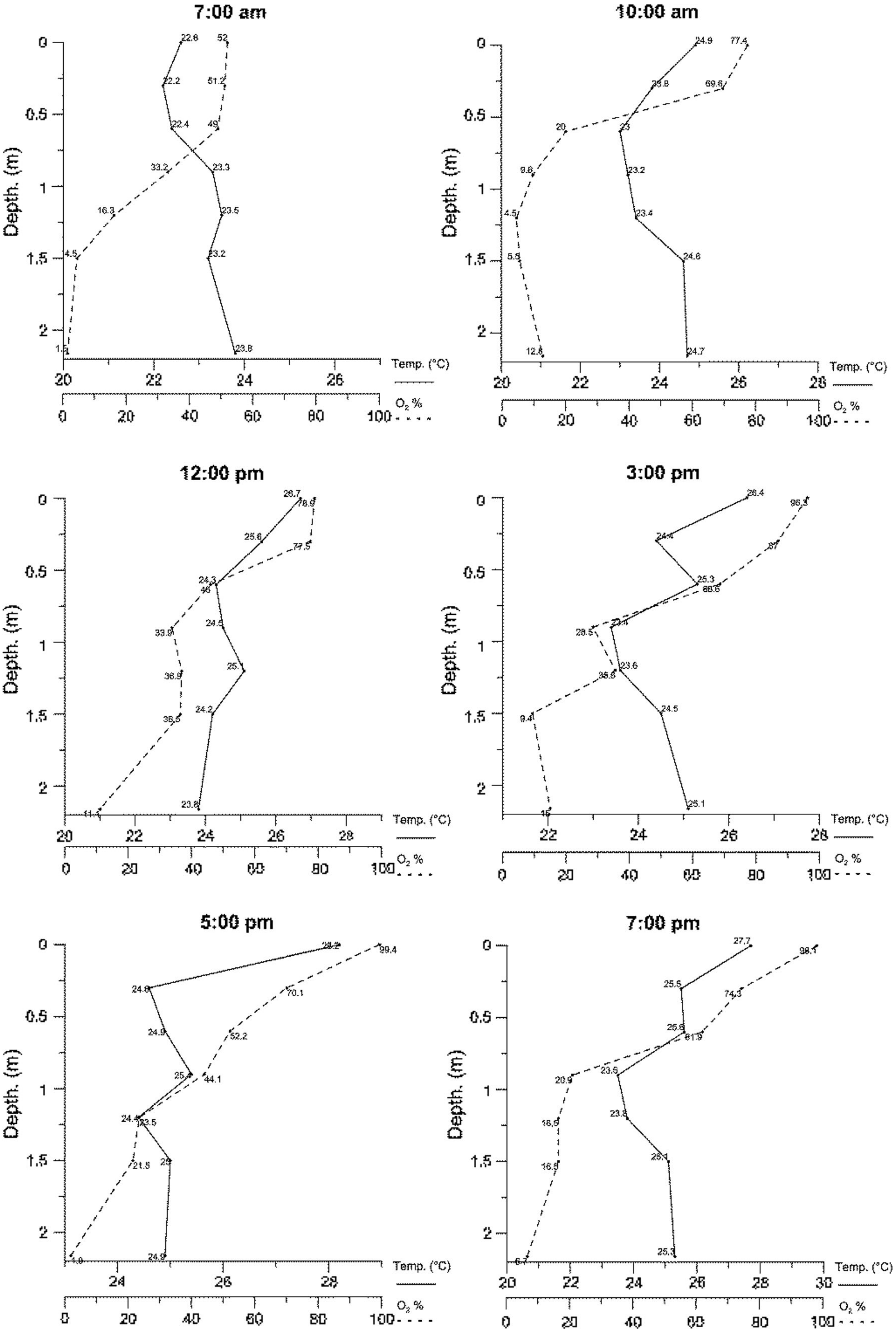


Fig. 6 Profiles of temperature and dissolved oxygen in the water column during 12 h of a summer day (01/24/2013)

Table 4 Trophic state index (TSI) calculated during the dry and rainy seasons by the phosphorus (P) and chlorophyll (Cl *a*) concentrations

Dry season		Rainy season	
TSI (P)	46.70	TSI (P)	62.29
TSI (Cl *a*)	45.55	TSI (Cl *a*)	58.64
TSI	46.12	TSI	60.46
Classification	Mesotrophic	Classification	Eutrophic

consequence of the presence of exposed soils, inappropriate soil management techniques, and removal of riparian vegetation from the banks and headwaters of the Ibitinga stream. This trophic level increase has dramatically diminished the water quality in the reservoir, especially the transparency and dissolved oxygen, which reached levels close to zero. The reservoir can be classified as eutrophic (Table 4) due to the increased supply of nutrients during the rainy season. Therefore, in this case, the TSI (PT) and TSI (Cl *a*) indicated the same trophic classification, i.e., eutrophic. Thus, the degree of limitation is considered "normal".

Therefore, the results reported here are consistent with those given by Liu et al. (2010) who applied correlation and multiple regression analysis to their dataset and found that the Secchi disk depths and TSI were mainly linked to the annual precipitation and annual maximum air temperature.

Conclusion

The trophic level and physico-chemical characteristics of FEENA reservoir, Rio Claro city, São Paulo State, Brazil, have been characterized in this paper. The temperature variations observed in seasonal and diurnal monitoring are typical of a tropical polymictic reservoir type with frequent periods of circulation and stratification of the water column. The dissolved oxygen concentration decreased as a consequence of the increased nutrient levels. Although the reservoir is shallow, significant variations in the dissolved oxygen content were detected, where low concentrations such as 0.07 mg L^{-1} were found at the bottom. The pH did not present significant variations (average = 6.71), always remaining slightly acidic, especially at the reservoir bottom. The electrical conductivity varied due to seasonality, reaching an average value of 84.06 μS/cm in the dry season and 138 μS/cm in the rainy season, certainly caused by the higher amount of ions flowing into the reservoir. The TSI also varied due to seasonality, allowing to classify the reservoir as mesotrophic during the dry season and eutrophic during the rainy season. The results obtained are an important tool for further evolution studies focusing the eutrophication process and water quality in the reservoir. All information obtained becomes very useful for decision makers and people engaged in environmental projects developed in the study area, addressing better conservation practices and management activities.

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