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Limnology of the largest multi-use artificial reservoir in NE Brazil: The Castanhão Reservoir, Ceará State

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ABSTRACT

This work reviews the limnology of the largest multi-use reservoir in NE Brazil, the Castanhão Reservoir in Ceará State, during 5 years of an extended drought when the reservoir's volume decreased from 88% to about 30%. Major physical and chemical parameters of the water column, phytoplankton community, trophic state and sediment geochemistry were monitored, as well as the impact from extensive aquaculture. Water quality of the full reservoir was maintained due to hydrodynamics, which transport nutrients to the hypolimnion of a stratified water column, rendering an oligotrophic state to the reservoir, notwithstanding the large nutrient inputs from aquaculture and irrigated agriculture. However, with the extension of the drought period, the reservoir volume reduced, decreasing water depth leading to breaking of the thermocline due to wind forcing, and mixing the entire water column. This increased turbidity, nutrient availability and primary productivity, also changed phytoplankton functional groups. As a result, at the end of the monitoring period, when the reservoir attained its lowest volume, its trophic state became eutrophic. Under a scenario of climate change, where annual precipitation is decreasing, human uses of reservoirs in the semiarid should be very restricted to maintain water quality proper for human use.

Key words: Hydrochemistry, hydrodynamics, nutrients, water quality, sediments, aquaculture.

INTRODUCTION

The growing scarcity of water in the 21st century is considered a most serious global environmental problem. In semiarid areas, in particular, the irregularity and/or deficiency of rainfall and high evaporation, which frequently exceeds precipitation, usually result in loss of shallow water bodies and high variation of annual river flows, making the capture and storage of water extremely difficult. In the Brazilian semiarid, the most densely populated semiarid region in the world, long-term droughts result in severe negative impacts over the social and economic activities of the region and triggered a permanent process of river damming and building of artificial reservoirs to increase water storage capacity and minimize the adverse

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* Contribution to the centenary of the Brazilian Academy of Sciences.

effects of these extended drought periods (Alvala et al. in press).

Periodical extended droughts are also the primary cause of water quality deterioration due to increasing concentrations of dissolved salts and decreasing oxygen levels (Freire et al. 2009). Reduction of the reservoir volume results in nutrient accumulation and concentration, leading to increasing algal density and the frequency of cyanobacteria blooms, thus rendering these systems much more vulnerable to eutrophication (Molisani et al. 2010). The recent development of intensive fish cage aquaculture in many reservoirs in the Brazilian semiarid and the expansion of irrigated agriculture, additionally contribute to a further deterioration of water quality, in particular during extended drought periods (Oliveira et al. 2015). To a certain extent, however, once normal rainfall reestablishes, lakes and reservoirs may return to their typical trophic state, depending on the extension of the interval between two consecutive drought periods.

Superimposed onto this normally irregular climate conditions, global climate change has to be taken into consideration. Reduced rainfall and increased frequency of extended droughts result in the concentration of dissolved nutrients already present in water. On the other hand, increased frequency and intensity of extreme rainfall events augment nutrient inputs from the watershed. These, in the semiarid region, will intensify the drivers involved in the eutrophication process (Touhami et al. 2015). For example, in arid and semiarid regions in Australia, in the Colorado River Basin in the USA, and around the Mediterranean Sea, strengthening and increasing frequency of pluriannual drought periods have been recorded (Dawadi and Ahmad 2013). In the semiarid northeastern Brazil, where annual rainfall has been decreasing steadily over the past 50 years (Moncunill 2006), increasing frequency and duration of extended drought periods have also been recorded, highlighting the importance of including global climate change as a significant driver with sensitive impacts on the environmental and socio-economic conditions of the Brazilian semiarid (Krol and Bronstert 2007). Few studies, however, cover entire drought periods to allow the understanding of the different biogeochemical processes undertaking the eutrophication process. Moreover, although these reservoirs in the Brazilian NE are generally located far from large centers, testing new methodologies for remote assessing of water quality has become necessary. We present here a review of the results obtained during a long-term monitoring period (2010-2015) at the Castanhão Reservoir, the largest water storage and multiple use reservoir in the Northeastern semiarid region. During this limnological monitoring period, the reservoir volume dropped about 90% from its maximum capacity. Apart from the limnological data, an evaluation of the state of the principal area of this reservoir using images from the World View sensors (Digital Globe 2009) used here as a proposal for remote monitoring, is also discussed. The acquisition of the images, the atmospheric corrections and the classification process to generate the features were highlighted as a "synoptic chart" of the estimation of the spatial distribution of chlorophyll-*a*. To generate features of the resulting classification, a direct method of decision tree, a classification method, based on logical rules inference (Breiman et al. 1984) was used. The trees used were parameterized in bands of the electromagnetic spectrum associated with the absorbance and reflectance of chlorophyll-*a*.

ENVIRONMENTAL SETTING OF THE CASTANHÃO RESERVOIR

The Castanhão reservoir (Latitude 5.50°S; Longitude 38.47°W) in the Middle Jaguaribe River watershed is located entirely within the semiarid region in the State of Ceará, in Northeastern Brazil. The Castanhão reservoir flooded completely for the first time in 2004. Its total water storage capacity is 6.7 billion m³ whereas the normal operating capacity is 4.45 billion m³. The reservoir covers a flooded area of 325 km² and is 48 km in length, with a depth exceeding 50 m in some areas (DNOCS 2017). The classification of the World Commission on Dams (2000) includes the Castanhão as a large reservoir (Figure 1). Water level fluctuations are determined primarily by the dam system operation. However, during extended drought periods, there is a drastic reduction in the stored volume due to the prolonged absence of rain in the reservoir's basin and high evaporation.

The semiarid climate of Northeastern Brazil, which includes the Castanhão basin, features peculiarities associated with the behavior of its regulating weather systems marked by irregularities in rainfall across time and space. The climate is considered hot/semiarid (BSw'h', according to Köpper Classification) with temperatures higher than 26 °C. Average annual rainfall varies from 400 to 1,000 mm and a historical annual mean of 756.5 mm during the past 80 years is recorded (FUNCEME 2016). The Middle Jaguaribe Basin, where the reservoir is located, is the driest sub-basin of the river and shows a trend of decreasing annual precipitation in the past 90 years (Gondim et al. 2012, Campos 2014, Fernandes et al. 2017). Potential evaporation amounts for about 2,100 mm (SRH 2008). Low rainfall and high evaporation induce ephemeral conditions to the Jaguaribe River, dried during most of the dry season and with rainy season flows varying from 71 $m^3.s^{-1}$ to a maximum discharge of 3,485 $m^3.s^{-1}$ prior to dam construction (Dias et al. 2009). The rainy season extends from January to June while the dry season occurs from July to December. During the past 90 years extended drought occurred in three periods (1941-1950;

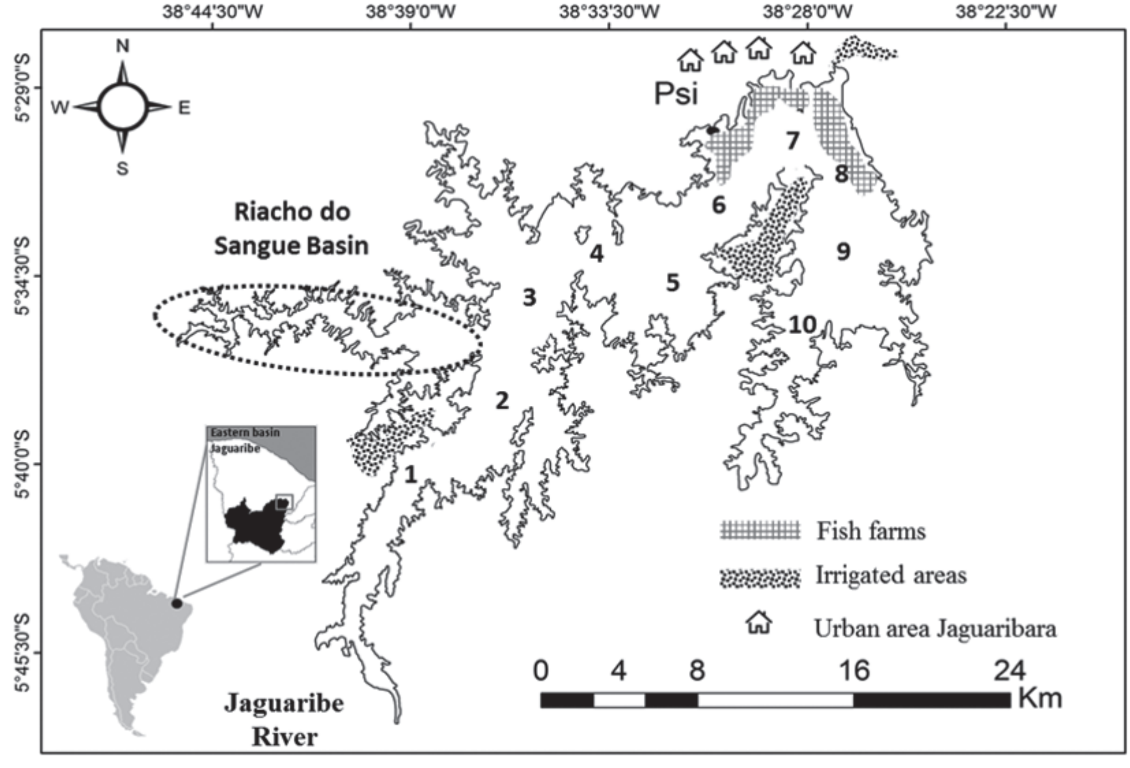

Figure 1 - The lake and basin of the Castanhão reservoir, Ceará State, NE Brazil, showing most significant anthropogenic activities. Psi refers to the location sample station in the aquaculture farm mentioned in Figure 11. Numbers within the reservoir refer to sampling stations listed in Figures 8 and 9. Adapted from Santos et al. (2017).

1976-1985; and the present one, which started in 2012 and is still occurring). During the driest years of these periods mean annual rainfall reached their minimum, significantly below the historical annual average: 302 mm (in 2012), 350 mm (in 1983), and 484 mm (1953), also suggesting strengthening of drought intensity in more recent years. Since these extended drought periods relate with strong El Niño events, whose tendency to increase due to global climate changes is expected, the Castanhão reservoir basin annual rainfall shows a forecast of at least 20% till during the next 40 years (Fernandes et al. 2017). Since increasing water necessity from major human activities, in particular agriculture, is also expected, this scenario will worsen (Krol and Bronstert 2007, Marengo et al. in press).

A very diverse relief dominates the region, a result of the large area covered by the Castanhão reservoir basin, including most of the different types of geological formations present in the State of Ceará. Most of its area is represented by the geomorphological units of the residual granitic outcrops and the inland depression, dominated by the savanna-like Caatinga Biome. Soil types of larger distribution are oxisols and ultisols, including quartz sands, halic planosols and podsols (IPECE 2011, COGERH 2011).

The Castanhão reservoir basin covers about 6,150 km^2 within the Middle Jaguaribe River watershed. The basin includes nine municipalities with very low urban and industrial development harboring a total population of 101,244 inhabitants, 57% of them inhabiting rural areas (IBGE 2010). The reservoir supplies water to 2.5 million inhabitants across the State of Ceará through a large-scale water diversion system and supports over 40,000 ha of irrigated agriculture. Dam operation is defined based on the water volume stored in the previous rainy season to attend the demands of the subsequent hydrological year (COGERH 2011, DNOCS 2017). Multiple water uses of the reservoir include tourism, fishing, and cage aquaculture. Cage fish farming have become the main activity of this reservoir with projected yield of 50,000 ton/year when the legal 1% limit of reservoir area will be used for aquaculture (Bezerra et al. 2014). Annual yield reached its maximum in 2011 (19,000 t) but has decreased to less than 10,000 t due to decreasing water quality following reduction of the reservoir volume (Oliveira et al. 2015).

NUTRIENT EMISSIONS TO THE CASTANHÃO RESERVOIR

Nutrient emissions to the Castanhão reservoir result from natural and anthropogenic sources. Natural sources include atmospheric deposition and the denudation of soils; whereas major anthropogenic sources are irrigated agriculture, husbandry, fish aquaculture and urban runoff and solid waste disposal. Of those, only aquaculture released nutrient directly to the reservoir water column (Molisani et al. 2013, 2015, Avelino 2015, Santos et al. 2016). The comparison between estimates of the natural and anthropogenic nutrient loads to the watershed of the Castanhão reservoir indicates that anthropogenic sources correspond to almost all emissions of nitrogen and phosphorus to the reservoir (Table I). Therefore, changes of trophic state of the reservoir are directly associated with the occupation of its drainage basin and the type and intensity of activities carried out within the reservoir, in particular fish farming (Barbosa et al. 2012, Molisani et al. 2015).

A significant fraction of the total nutrients load to the basin is retained in soils prior to reaching the Castanhão Reservoir. Molisani et al. (2015) measured the Jaguaribe river nitrogen contribution to the reservoir during the rainy season. Although the results were extrapolated from this single rainy season (Molisani et al. 2013), they estimated a six-month nitrogen input of 733 tons. Using their daily river flow and phosphorus concentrations obtained from our group (Cajuí 2015), we estimated about

TABLE I
Comparison of natural and anthropogenic emissions of nitrogen (N) and phosphorus (P) ($t.ano^{-1}$), estimated using emission factors, to the Castanhão Reservoir Basin (Avelino 2015).

Emissions to the basin ($t.ano^{-1}$)	N	P
Natural emissions	292	39
Anthropogenic emissions	2,073	1,487
Total emission to the basin	2,365	1,524
% of the anthropogenic contribution to the basin	87.7	97.4
Direct emissions to the reservoir ($t.ano^{-1}$)	N	P
Fish aquaculture	518	163
Irrigated agriculture	116	80
Total direct anthropogenic emissions reservoir	634	243

212 tons, as a six-month flux for this element. It is very difficult to reach an annual contribution based on the rainy season river flow only, since a small, but significant contribution, still occurs during the dry season, directly from atmospheric deposition and intermittent rainfall. Most importantly, at least for nitrogen and phosphorus, loads from aquaculture and irrigated agriculture on the reservoir margin, enter the water column directly. Notwithstanding, comparing both estimates, retention of these two nutrients in the basin prior to reaching the reservoir would vary from 70% and 85% of the total emissions of nitrogen and phosphorus to the reservoir watershed, respectively. Therefore, highlighting the direct sources of nutrients to the water column, in particular intensive fish aquaculture and irrigated agriculture as the major responsible for any change in nutrient concentrations in the reservoir's water column.

Permanent and temporary agricultural crops occupy an area of 195.2 km^2 in the Castanhão reservoir watershed (IBGE 2010). There are three irrigated perimeters around the Castanhão (Figure 1); Curupati (4.47 km^2), Alagamar (3.12 km^2) and Mandacarú (3.90 km^2), whose effluents may reach directly the reservoir since, at least for the Curupati and Alagamar, these perimeters are located on the reservoir margins (Figure 1). The calculation of estimated discharges, obtained through emission factors and production figures (Paula Filho et al. 2015), indicates that agriculture contributes with about 116 $t.yr^{-1}$ and 80 $t.yr^{-1}$ of the total anthropogenic emissions of nitrogen and phosphorus to the reservoir, respectively, mostly including nutrients from excessive fertilizer use leached from soils and transported to the reservoir.

Another important source of nutrients directly released in the reservoir is fish aquaculture. The Castanhão reservoir has 600 concessions won by fish farmers. There are approximately 15,000 net-tanks, producing about 18,000 tons of Tilapia per year: around 60% of the total production in the State of Ceará. The water surface of the reservoir is 325 km² and the total area exploited with cage aquaculture is currently only 0.4%; i.e. only 40% of the production capacity is used for fish farming in reservoir. The potential for exploitation of Tilapia aquaculture can reach 1% of the water surface, increasing its production capacity to 40,000 $t.y^{-1}$. The estimated annual discharges of nitrogen and phosphorus to the reservoir from aquaculture reach 518 tons and 163 tons (Avelino 2015), respectively; representing the most important direct nutrient source to the reservoir and equivalent to 71% and 77% of the total fluvial input of nitrogen and phosphorus respectively, estimated by Molisani et al. (2013) and 30.6% and 16.3%, respectively, of the total anthropogenic emissions to the entire Castanhão watershed (Table I). Considering the large relative retention of nutrients in the basin soils prior to reaching the reservoir, aquaculture and local irrigated agriculture perimeters are the most important sources of nutrients to the reservoir water column and can efficiently trigger eutrophication.

HYDROLOGICAL SETTING

The river and basin runoff contributions of water to the reservoir influence the water circulation pattern in the lake. Also, basin discharges influence the average flow velocity, residence time and dilution of dissolved chemical species in the water column. The temporal variability of the rains results in the variability of the flows in the rivers and therefore reservoir volume and depth, which will eventually control the vertical stratification of the water column. Under high freshwater income and therefore high volume and depth, the water column remains mostly stratified. However, as water inflow decreases following drought conditions, lower volume and decreasing depth may facilitate the breaking of the water column stratification due to wind forcing. Changes in the reservoir volume during the monitored period due to the prolonged absence of rainfall in the region were reflected in the thermal structure of the water column (Figure 2). In water column profiles the highest average temperature differences below and above the thermocline were observed in November 2011 (1.3°C) and March 2012 (1.9°C) characterizing a well-established stratification pattern in the deeper, lacustrine sector of the reservoir. After, however, differences between surface and bottom water temperatures were well below 1.0°C.

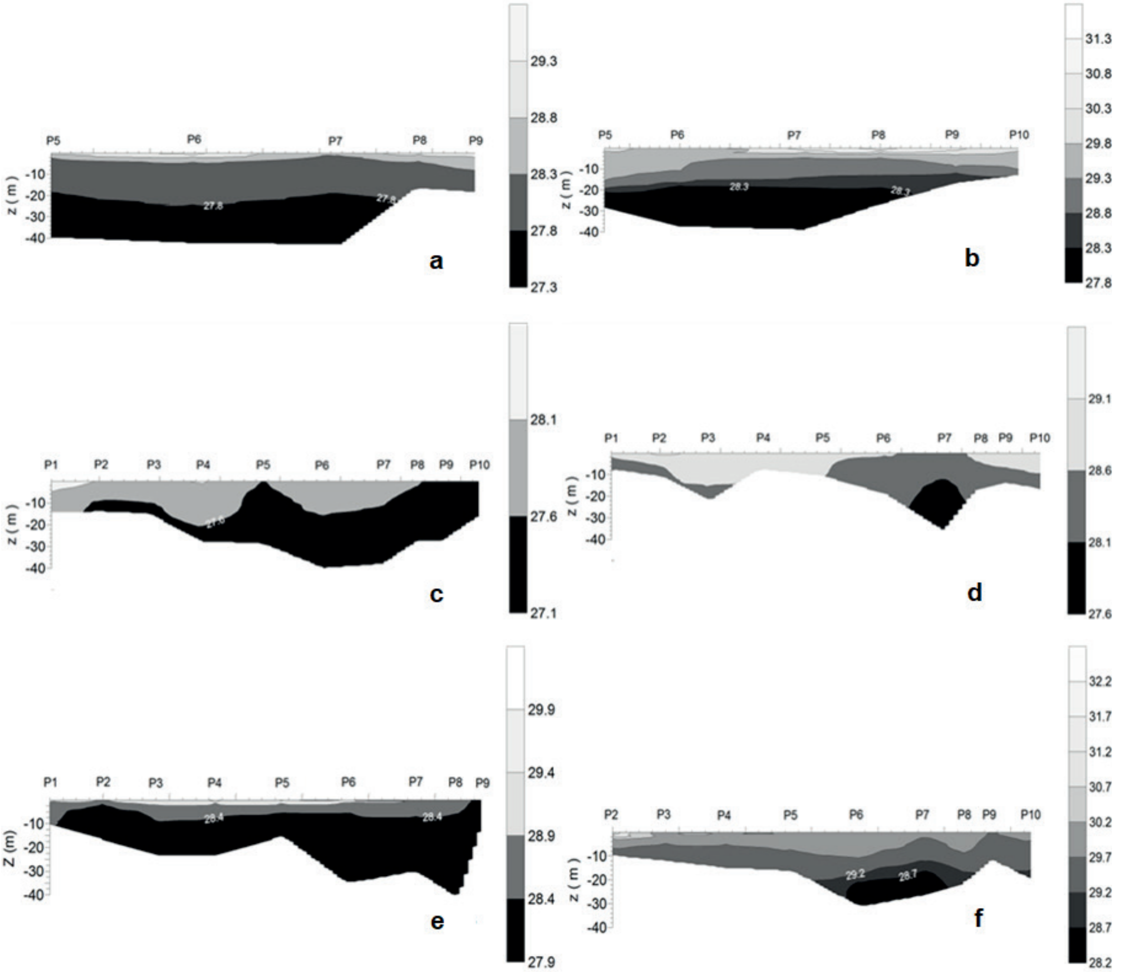

Figure 2 - Thermal structure of the water column: **a**) November 2011, **b**) March 2012, **c**) August 2012, **d**) January 2013, **e**) August 2013, **f**) May 2014, based on original data from Santos et al. (2017).

At the Castanhão reservoir, the monitoring of current velocities and directions obtained through the deployment of an ADCP (Santos et al. 2017; Oliveira et al. 2015) showed the highest current velocities at the surface and a decrease towards the reservoir bed. This supports the relatively small remobilization of bottom sediment and the permanence of the water column stratification. The observed water circulation pattern facilitates the renewal and dilution of incoming waters and its dissolved salts, including those from anthropogenic sources such as aquaculture and irrigated agriculture.

The processed images showed this water distribution trend taking into consideration the chlorophyll-*a* spectral signature. Figure 3 presents the pigmentation characteristics from the processed image, obtained in February 2012, over about 78 Km^2 of open water of the reservoir basin. This processed image provided the following estimative: a) High (red): 6.5%, b) Average (orange): 33.8% and c) Low (green): 59.7%. In March 2012, the maximum concentration of chlorophyll-*a* verified in the laboratory through the analysis of water samples obtained in situ varied from 2.3 to 5.3 µg.L^{-1}, with an average of 3.7 µg.L^{-1} (Table II, Table SI - Supplementary Material), while the level of the reservoir was approximately 80% of its total volume.

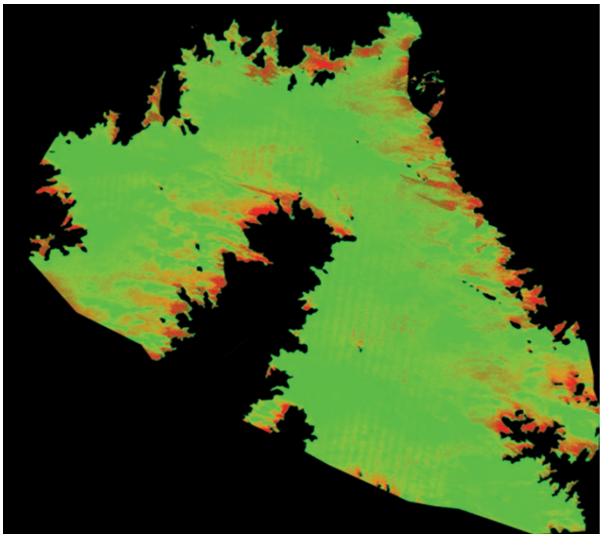

Figure 3 - The processed image of the principal open area of the Castanhão reservoir in 2012, showing chlorophyll content dispersed through the central area.

The water circulation pattern results in the export of incoming elements to the open reservoir, where they can eventually settle in deeper and stratified areas of the reservoir and accumulate in the hypolimnion. Molisani et al. (2013) followed the fate of excess feed pellets used in local tilapia farms, they observed that the sedimentation time of these particles was long enough to have them transported to deeper areas of the reservoir, relatively far from their originating sites in local fish farms. However, once the volume decreases and wind forcing, acting upon the reservoir surface disrupts the thermal stratification, the accumulated elements and particles in the hypolimnion may be resuspended and redistributed through the oxic, surface waters, and therefore available for biological uptake, which eventually may trigger eutrophication.

The reduced seasonal variation typical of tropical lakes hampers the predictability of annual occurrence of thermal patterns and associated heat flows (Lewis 1983). The mixing patterns in these lakes are complex and daily water temperature and density variation might be more significant than the corresponding seasonal variation (Tundisi and Matsumura-Tundisi 2008). These variability patterns in thermal structure occur more frequently in lakes and reservoirs under semiarid climate (Bouvy et al. 2003, Souza Filho et al. 2006). For example, in the Pacajus reservoir, also in the northeastern semiarid region, wind forcing produces rapid water mixing during the dry season when wind velocities are maximum. During these events, sediment resuspension occurs changing water column properties (Freire et al. 2009). The prolonged low rainfall that characterized the study period renders this situation more frequent in the Castanhão reservoir, favoring changes in water chemistry and phytoplankton composition, specially

TABLE II
Average values for the limnological variables monitored in surface and bottom waters in the Castanhão reservoir, NE Brazil.

Variables	Depth	November 2011	March 2012	August 2012	January 2013	August 2013	May 2014
Temp. (°C)	**Surface**	28.9 ± 0.3^{a}	30.2 ± 0.6^{b}	27.8 ± 0.3^{c}	28.8 ± 0.3^{a}	29.1 ± 0.5^{a}	30.0 ± 1.0^{b}
	Bottom	27.6 ± 0.4^{ac}	28.3 ± 0.6^{ab}	27.4 ± 0.2^{c}	28.5 ± 0.3^{b}	28.3 ± 0.2^{ab}	29.4 ± 0.5^{d}
Secchi {Z}(m)	**Surface**	3.4 ± 0.6^{ac} {6 - 12}	2.3 ± 0.4^{b} {6 - 9}	3.4 ± 0.3^{c} {9 - 12}	2.8 ± 0.4^{ab} {6 - 10}	2.5 ± 0.4^{b} {6 - 10}	2.3 ± 0.8^{b} {5 - 9}
Turbidity (NTU)	**Surface**	1.3 ± 0.1^{ab}	1.1 ± 0.1^{a}	1.3 ± 0.2^{ab}	1.5 ± 0.3^{ab}	1.5 ± 0.6^{ab}	1.9 ± 1.0^{b}
	Bottom	1.0 ± 0.1^{a}	1.3 ± 0.9^{a}	1.5 ± 0.4^{a}	1.6 ± 0.4^{a}	1.7 ± 0.7^{a}	1.7 ± 0.9^{a}
Conduc. (µS.cm^{-1})	**Surface**	295 ± 2^{a}	313 ± 4^{ab}	315 ± 8^{b}	343 ± 7^{c}	347 ± 9^{c}	353 ± 20^{c}
	Bottom	289 ± 1^{a}	301 ± 4^{a}	313 ± 7^{a}	341 ± 7^{b}	340 ± 2^{b}	348 ± 31^{b}
DO (mg.L^{-1})	**Surface**	7.0 ± 0.1^{a}	6.6 ± 0.2^{a}	7.0 ± 0.3^{a}	6.8 ± 0.7^{a}	6.6 ± 0.4^{a}	7.7 ± 1.8^{a}
	Bottom	6.6 ± 0.3^{ab}	2.3 ± 2.6^{a}	6.3 ± 0.5^{b}	3.0 ± 2.6^{a}	4.5 ± 2.2^{ab}	2.6 ± 3.3^{a}
pH	**Surface**	8.1 ± 0.1^{abc}	8.1 ± 0.2^{abc}	7.7 ± 0.3^{ab}	7.5 ± 0.3^{a}	8.2 ± 0.4^{bc}	8.7 ± 0.7^{c}
	Bottom	7.4 ± 0.1^{ad}	8.1 ± 0.2^{abc}	7.8 ± 0.1^{ab}	7.2 ± 0.6^{d}	8.2 ± 0.5^{bc}	8.6 ± 0.5^{c}
Chlor-*a* (µg.L^{-1})	**Surface**	2.6 ± 1.2^{a}	3.7 ± 1.2^{ab}	4.0 ± 1.2^{ab}	4.1 ± 1.3^{ab}	5.2 ± 2.5^{ab}	14.8 ± 11.4^{b}
	Bottom	2.4 ± 1.7^{a}	1.3 ± 1.7^{a}	2.7 ± 1.4^{a}	2.4 ± 1.8^{a}	3.5 ± 0.8^{a}	10.5 ± 13.5^{a}
Tot-P (µg.L^{-1})	**Surface**	27.2 ± 8.9^{ab}	17.2 ± 7.1^{a}	22.3 ± 2.6^{a}	30.1 ± 10.7^{ab}	20.6 ± 8.7^{a}	49.1 ± 18.8^{b}
	Bottom*	39.5 ± 19.7^{ab}	32.2 ± 14.6^{a}	25.4 ± 4.3^{a}	43.8 ± 19.5^{ab}	19.2 ± 5.8^{a}	70.0 ± 40.0^{b}
Tot-N (µg.L^{-1})	**Surface**	510 ± 133^{a}	397 ± 167^{a}	489 ± 190^{a}	405 ± 170^{a}	481 ± 158^{a}	598 ± 312^{a}
	Bottom	559 ± 40^{ab}	432 ± 151^{ab}	457 ± 167^{ab}	452 ± 202^{ab}	345 ± 194^{a}	706 ± 322^{b}
Volume (m^{3})	-	5.0 x 10^{9}	4.8 x 10^{9}	4.2 x 10^{9}	3.6 x 10^{9}	3.2 x 10^{9}	2.6 x 10^{9}

Different superscript letters are significant different at $p \leq 0.05$. *Bottom depth for chlorophyll-*a* samples were considered the limit of the euphotic zone depth (Z).

providing optimum conditions to cyanobacteria blooms. Therefore, the hydrodynamics of the Castanhão reservoir and its response to wind and volume changes plays a key role in the water column chemistry and biology.

LIMNOLOGY

Nutrient inputs arriving in the reservoir from its basin or emitted directly into the water column, such as those present in aquaculture effluents, may be either retained within or exported from the reservoir, depending on the basin hydrological regime and dam operation characteristics (Friedl et al. 2004, Teodoru and Wehrli 2005, Cook et al. 2010). In the semi-arid region of northeastern Brazil, water is preferably used for human consumption and irrigation. Therefore, in these reservoirs, there is a strong regulation of water, which implies in the reduction of the discharge downstream and releasing controlled flows, defined operationally to supply the estimated water demand downstream of the dam. The tight water regulation of the Castanhão reservoir induces high retention of the incoming materials. As a result, water quality varies directly with reservoir volume and the magnitude of emissions. We review here the summary of a 5-year monitoring period, during which water volume decreased form about 100% to 30% of the total maximum volume, due to an extended drought period (Figure 4).

Table II shows a summary of the major physicochemical parameters monitored in the reservoir during the period between November 2011 and May 2014, obtained from 10 sampling stations covering the entire reservoir area (Figure 1). Detailed statistics are available in the supplementary material (Table SI). Surface water temperature varied little, roughly oscillating from summer to winter within 1 ºC. Bottom water temperature was 1-2 ºC lower than surface, which makes the stratification of the water column possible. Dissolved oxygen concentrations in surface waters were essentially equal throughout the monitoring period ($p > 0.05$) (Table II). Surface waters were well oxygenated and no values below those set by the Brazilian legislation (CONAMA 2005), a minimum of 5.0 mg.L^{-1}, were recorded (Santos et al. 2017). However, thermal stratification of the water column can lead to the formation of an oxycline, which results in a significant reduction in the dissolved oxygen in the hypolimnion.

During the monitoring period in November 2011 and August 2012, no oxycline was established in all the monitored sampling stations, notwithstanding the establishment of a thermocline in the deeper station. After these years, however, an oxycline was observed in all further campaigns, in particular in the deeper, open reservoir area, with dissolved oxygen concentrations as low as 0.07 mg.L^{-1} and with a maximum of 2.62 mg.L^{-1} (Santos et al. 2017). Water quality and management of the reservoir uses need to take into consideration the thermal and oxygen stratification pattern, since they influence ecologically important phenomena, such as eutrophication and algal blooms (Nogueira et al. 2007).

Following the reduction in the reservoir volume, the electrical conductivity of surface waters increased, as expected (Table II). Other drivers of increasing conductivity are the lack of water renewal by rainfall, the strong evaporation and the permanent influence of anthropogenic activities, which favor a rapid increase in the concentration of salts and in the accumulation of nutrients, as well as an augment of pH (Santos et al. 2017). Other studies in lakes and reservoirs in semiarid regions also observed high electrical conductivity, typically exceeding 300 µS.cm^{-1}, and generally exhibiting a negative correlation with the water level (Bouvy et al. 1999, Eskinazi-Sant'anna et al. 2007, Chellappa et al. 2008, Barbosa et al. 2012).

The concentrations of chlorophyll-*a* differ significantly ($p \leq 0.05$) between the sampling

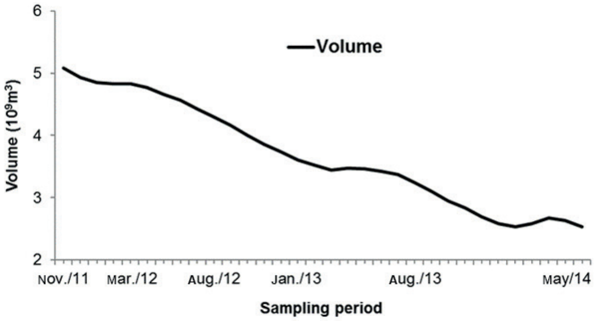

Figure 4 - Variation of the reservoir volume relative to its maximum safe operation capacity, between 2010 and 2015 in the Castanhão Reservoir (COGERH 2017).

campaigns and gradually increased with the reduction of the reservoir volume (Table II). Chlorophyll-*a* concentration is a good proxy of phytoplankton biomass and a valuable indicator of the trophic status of a water body. The majority of the observed Chlorophyll-*a* profiles (68%) showed highest concentrations between 2 and 10 m (Figure 5).

Salas and Martino (2001) used chlorophyll-*a* concentrations to classify the trophic status of tropical lakes and suggested concentrations of 5 to 10 $\mu g.L^{-1}$ as indicative of a mesotrophic state. Average chlorophyll-*a* concentrations in the Castanhão reservoir remained below 5 $\mu g.L^{-1}$ up to January 2013. Afterwards, concentrations in all stations exceeded 5 $\mu g.L^{-1}$, and exceeded 10 $\mu g.L^{-1}$, in May 2014 in large sections of the reservoir, suggesting a shift from mesotrophy to eutrophy during this period.

The processed images from 2013 also showed visually this variability of the trophic state (Figure 6), which increasing chlorophyll content mostly spread through shallower areas along the northern littoral, where major fish farms are located. This processed image provided the following estimative: Low (in green): 51.85%, Medium (in orange): 39.3% and High (in red): 8.85%. It should be noted that the maximum level of chlorophyll-*a* verified in the laboratory, through analyses of the *in situ* samples varied from 2.6 to 9.8 $\mu g.L^{-1}$, with an average of 5.2 $\mu g.L^{-1}$, nearly doubling the concentrations observed in February-March 2012 (Table II, Table SI).

Simultaneously to the increase in chlorophyll-*a* content in the water column, total phosphorus concentrations exceeded 35 $\mu g.L^{-1}$, reaching nearly 50 $\mu g.L^{-1}$ in May 2014. These observed concentrations are within the range of values considered as the initial values at which the deleterious environmental effects of eutrophication begin to appear (Dodds et al. 1998, Salas and Martino 2001). Also, much higher total phosphorus concentrations were measured in the hypolimnion (> 70 $\mu g.L^{-1}$). Under such scenario, mixing of the water column affects the permanence of cyanobacterial blooms and favors the development of turbulence-tolerant organisms, such as diatoms, as well as species with high growth rates and nutritional requirements, such as phytoflagellates (Chalar et al. 2002, Barbosa and Padisák 2002).

The phytoplankton communities of the Castanhão Reservoir included six identified taxonomic classes (Cyanophyceae, Chlorophyceae, Bacillariophyceae, Zygnemaphyceae, Coscinodiscophyceae and Xanthophyceae) (Silva 2015), distributed in seven functional groups (MP, S1, SN, P, D, X1 and F) (Barroso et al. 2018), which responded to limnological conditions and also serve as indicators of trophic state. In March 2012, for example, cyanobacteria typical of turbid environments dominated, with *Planktolyngbya minor/limnetica* (S1), *Pseudanabaena limnetica* (S1) and *Pseudanabaena catenata* (MP) as major species. On the other hand, August 2012 and January 2013 were sampling campaigns characterized by *Pseudanabaena/Romeria* sp., *Pseudanabaena biceps*, *Planktolyngbya limnetica* (S1) and diatoms from functional groups D and P, well adapted to mixing conditions and a mesotrophic state. In August 2013, Cyanophyceae adapted to turbid waters of the S1 group and fast growing Chlorophyceae of functional groups X1 and F dominated the phytoplankton community

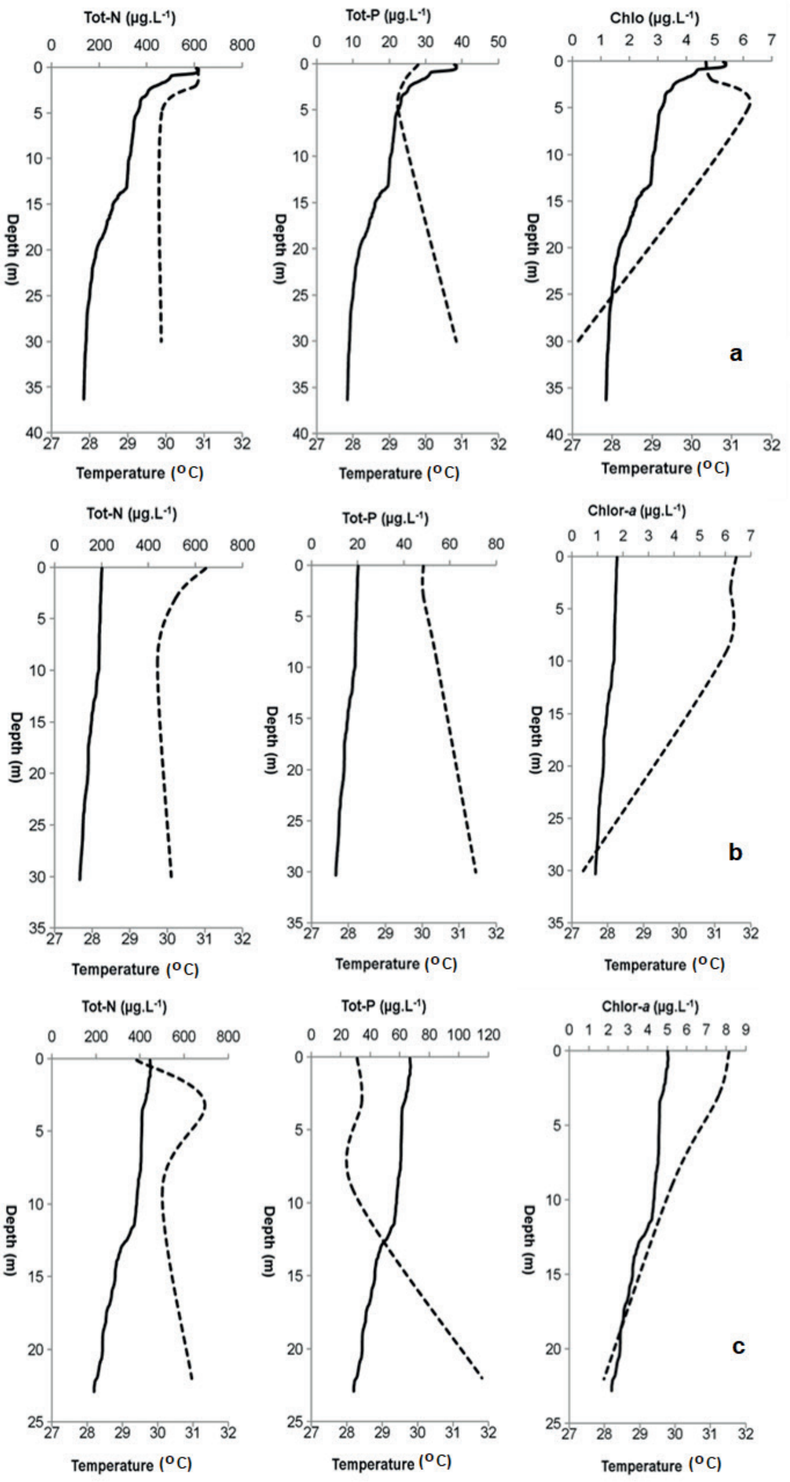

Figure 5 - Vertical profile of chlorophyll-*a*, phosphorus and nitrogen concentrations in station 7 (location in Figure 1) in the Castanhão reservoir, NE Brazil. **a**) March 2012; **b**) January 2013; **c**) May 2014. Bold line = Temperature; Dotted line = Variables. Since we have used a probe for chlorophyll quantification in the profile, values may include other pigments, in particular below 10-12 m of depth.

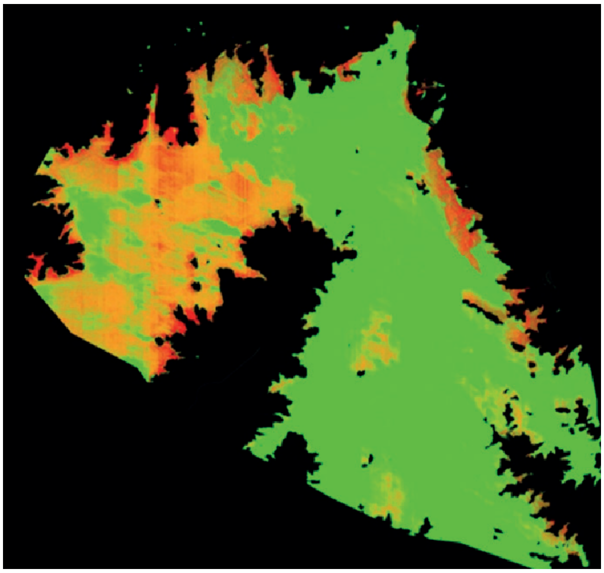

Figure 6 - The processed image from Castanhão reservoir in 2013 showing the increased eutrophication process.

(Silva 2015, Barroso et al. 2018). The dominance of these cyanobacteria from functional group S1 during most of the 2012-2013 period was an indicative of increasing water mixing. Stronger mixing conditions during drought years related to lower reservoir volume, was indicated by the replacement of small diatoms (MP and C) by large diatoms belonging to functional groups D and P (Barroso et al. 2018).

The increased concentration of organic detritus at the bottom of the water column and the subsequent decomposition of this material consume large amounts of oxygen and induce strong oxygen deficits and nutrient accumulation in the hypolimnion. Algal blooms on the reservoir surface constituted by *Microcystis* sp. (Silva et al. 2013), were observed in March 2012 along with the lowest Secchi disk measurements (Table II) and thermal stratification (Figure 2) and accompanied by chemical oxygen stratification (Santos et al. 2017). Both water stability and an increased residence time favor the predominance of *Microcystis* sp. (Costa et al. 2009). However, chemical oxygen stratification was observed in January 2013 despite the presence of thermal instability, yet no differences were observed in the water mass densities, suggesting the possibility that anoxic processes were already affecting the water column.

The total phosphorus concentrations differ significantly throughout the sampling period ($p \leq 0.05$) (Table I). Highest concentrations (> 45 $\mu g.L^{-1}$) occurred in the lacustrine zone in January 2013 and May 2014 and in the fluvial zone in May 2014. These concentrations are above the threshold established by the Brazilian legislation, maximum ≤ 30 $\mu g.L^{-1}$ for water bodies of Class 2 (CONAMA 2005). Soluble reactive phosphorus concentrations were below the detection limit (<1 $\mu g.L^{-1}$) in most parts of the surface reservoir (Santos et al. 2017). Detectable concentrations, in the profiles, occurred between 2.5 ± 0.8 $\mu g.L^{-1}$ and 114.5 ± 1.0 $\mu g.L^{-1}$). Phosphorus distribution within the water column showed that in about 70% of the sampling profiles, highest phosphorus concentrations were found in bottom waters (see Figure 5), which suggests an important role of bottom sediments in phosphorus availability. Also, there was a direct relationship of the temporal variation patterns between chlorophyll-*a* and total phosphorus, suggesting the role of phosphorus in phytoplankton biomass in the water column (Figure 7).

Average total nitrogen concentrations in surface reservoir did not differ significantly throughout the sampling period (397 - 598 μg L^{-1}) ($p > 0.05$) (Table II). In most sampling stations and campaigns, nitrate, ammonia nitrogen and nitrite concentrations were below the detection limit. The highest detected concentrations were 83.0 ± 3.5 $\mu g.L^{-1}$ (March 2012) for nitrate and 327.2 ± 1.0 $\mu g.L^{-1}$ (May 2014) for ammonia nitrogen. The availability of ammonia nitrogen in lacustrine zone in March 2012 might explain the algal blooms observed during that sampling campaign. Highest concentrations of ammonia nitrogen occurred in the deeper layers suggesting the favoring of ammonia formation under low oxygen. Detectable nitrite concentrations (2.5 ± 0.1 $\mu g.L^{-1}$) occurred only in

January 2013 and May 2014 (Santos et al. 2017), also suggesting the initiation of the eutrophication process.

The highest nutrient concentrations were measured in May 2014 and result from their accumulation in the hypolimnion due to hydrodynamics and the persistence of the thermocline. The hypolimnion is therefore a significant nutrient source to the reservoir, in particular of phosphorus and ammonia nitrogen. Molisani et al. (2013) suggested that over 97% of the fluvial input of phosphorus and nitrogen are retained in the reservoir hypolimnion, when volume is maximum and winds are unable of breaking the thermocline and mixing the entire water column. But this situation is reversed when volume decreases, and the hypolimnion changes from a sink to a source of nutrients to the water column, as have been observed in the Castanhão and other reservoirs in the Northeastern Brazil semiarid region, in particular during extended dry periods (Santos et al. 2017, Bouvy et al. 2003, Freire et al. 2009, Geraldes and Boavida 2005).

The primary productivity in the Castanhão reservoir is limited by phosphorus in most of the monitored period, as suggested by the high correlation between phosphorus and chlorophyll-*a* (Santos et al. 2017). However, in some stations it is possible a limitation by nitrogen and/or co-limitation by nitrogen and phosphorus. Eventually, variations in the reservoir water level can result in changes in the physical and chemical structure of the system and consequently the dynamics of plankton communities, including zooplankton abundance (Geraldes and George 2012), phytoplankton abundance (Chalar 2006), cyanobacteria blooms (Bouvy et al. 2003, Silva et al. 2013) and diversity (Costa et al. 2009). Naselli-Flores (2000) even suggested that water level fluctuations, influence phytoplankton composition more strongly than the nutrient levels. For example, a reduction in the reservoir volumes in Sicily during the spring, because of the high demand from summer usage, strongly affected the phytoplankton and nutrient dynamics, leading to eutrophication and the selection of cyanobacteria species that were harmful to human health (Naselli-Flores 2003). In the Castanhão reservoir however, since nutrient concentrations and distribution in the water column are strongly influenced by volume variation, through breaking of the thermocline and mixing of the water column, it is not possible to separate the effects of nutrients and volume as proposed by Naselli-Flores (2000).

When all data from the 5-year monitoring period are analyzed together, three spatially separated compartments are easily observed at the end of the monitoring period in May 2014 (Figure 8). These compartments respond differently to changes in volume, with the shallower section close to the Jaguaribe river mouth (stations 1 and 2, in Figure 8), reaching super-eutrophic conditions, whereas the deepest stations (5 to 9) remain mesotrophic.

The calculate trophic state index (TSI) indicated a change in the trophic status of the Castanhão reservoir from oligotrophic to eutrophic during this extended drought period (Figure 9). In a short monitoring study between November 2006 and July 2007, Molisani et al. (2010) classified this reservoir as mesotrophic and detected anoxic events as well as the presence of cyanobacteria typical of mesotrophic/eutrophic environments, just after a two-year drought period. It is a strong evidence that hydrodynamics is a very important factor for the operation of the Castanhão reservoir, in order to maintain the reservoirs water quality. The potential capacity to monitoring this system using satellite image with resolution similar to World View 2, proved able to classify the trophic state and evaluate the chlorophyll-*a* dispersion along the reservoir, as demonstrated in this period. The remote monitoring stands as an alternative, minimizing the high costs of *in situ* monitoring of distant areas, where analytical

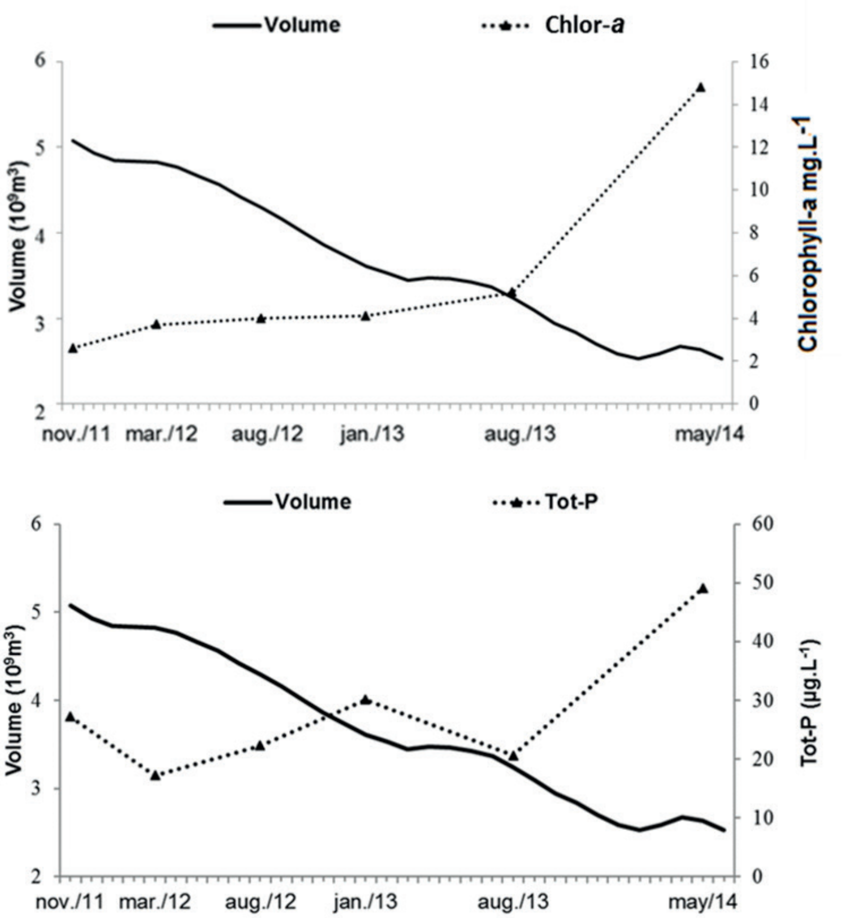

Figure 7 - Variation in total phosphorus concentrations and chlorophyll-*a* content relative to the total volume in the Castanhão Reservoir during the monitoring period.

laboratories are located and of the logistics of people and equipment transport. In many semi-arid reservoirs, it is observed that the trophic state is related to the seasonal fluctuations in the system's hydrology controlled by rainfall (Naselli-Flores 2000, Chaves et al. 2013, Batista et al. 2014) and this points to the intensification of the monitoring efforts in the future.

The observed deterioration of the TSI suggests that the first process to occur is the concentration and accumulation of nutrients from anthropogenic activities, following the decrease in the reservoir volume, breaking thermal stratification, mixing of the water column, and, at least in the shallowest stations, sediment resuspension.

The eutrophic section in May 2014 also receives an important contribution from the Rio do Sangue sub-basin, which is responsible for about 37.5% of N and 36.8% of P entering the Castanhão Reservoir basin. Close to the Rio do Sangue outfall at the reservoir, the highest concentrations of chlorophyll-*a* (33.0 ± 1.0 μg.L^{-1}), phosphorus (55.1 ± 3.8 μg.L^{-1}) and nitrogen (926.7 ± 114.7 μg.L^{-1}) were observed by Cajuí (2015), thus contributing to the super-eutrophic conditions of this section of the reservoir in May 2014.

SEDIMENTS

Lakes and reservoirs sediments interact with the water column either as a sink or source of nutrients and contaminants, depending of their physical and chemical conditions. Among the major elements, whose availability strongly depends on sediments, is phosphorus (Ding et al. 2015, Ni and Wang 2015, Tang et al. 2014, Sen et al. 2007), a limiting nutrient to productivity but also the key element involved in the eutrophication process, as in the case of the Castanhão reservoir, where phosphorus is strongly linked to primary productivity and the eutrophication state of the reservoir, as discussed above. Therefore, to understand the eutrophication process in the Castanhão reservoir towards its management, the complex nature of the P fate in the reservoir's sediments needs to be addressed.

Sediments of the Castanhão Reservoir has been reported enriched with total phosphorus relative to those from affluent rivers, such as the two major contributors to the reservoir, the Jaguaribe River proper and the Riacho do Sangue. Molisani et al. (2013) estimated, based on inflow-outflow balance of soluble reactive phosphorus, total phosphorus and suspended solids, that the Castanhão Reservoir can retain over 95% of these incoming materials. Also, a positive correlation was observed between suspended solids and total phosphorus, suggesting the joint deposition of suspended solids and nutrients and further accumulation in bottom sediments Molisani et al. (2010). During their studies, the Castanhão reservoir displayed nearly 70% of its full water storage capacity and was considered oligotrophic, with fully stratified waters and still incipient aquaculture as a direct source of nutrients to the reservoir.

Cajuí (2015) reported a 4-fold increase in total phosphorus content in reservoir sediments adjacent to the confluence of the Riacho do Sangue relative to the concentrations found in sediments sampled upstream from the discharge point at the reservoir (0.38 and 0.04 to 0.10 mg.g^{-1}, respectively). Total nitrogen (4.5 and 0.3 to 0.9 mg.g^{-1} respectively) and organic matter content (16.4 and 3.9 to 5.4%, respectively) showed the same pattern. The results confirm previous balances of the high capacity of the reservoir in retaining incoming nutrients and particles from the watershed. The Jaguaribe River downstream from the dam showed increasing total phosphorus concentrations during the past decade (Marins et al. 2007) associated with increasing phosphorus emissions to the lower basin, mostly from increasing untreated urban discharges and aquaculture; but also presented lower concentrations than those observed in the reservoir.

Total phosphorus concentrations in bottom sediments of the Castanhão reservoir varied little from 170 µg.g^{-1} to 250 µg.g^{-1}, and were relatively lower than values found in recently flooded reservoirs, such as the three Gorges in China, where total phosphorus concentrations 911 ± 99 µg.g^{-1} (Wu et al. 2016) are much lower than older reservoirs, as expected, where values can reach up to 10 times higher, due to continuous natural and anthropogenic inputs from watersheds (Zhang et al. 2010).

Spatial distribution of total inorganic and organic phosphorus showed decreasing concentrations from the fluvial zone to dam zone in January 2013, when water flow from the upstream basin was still significant, suggesting a

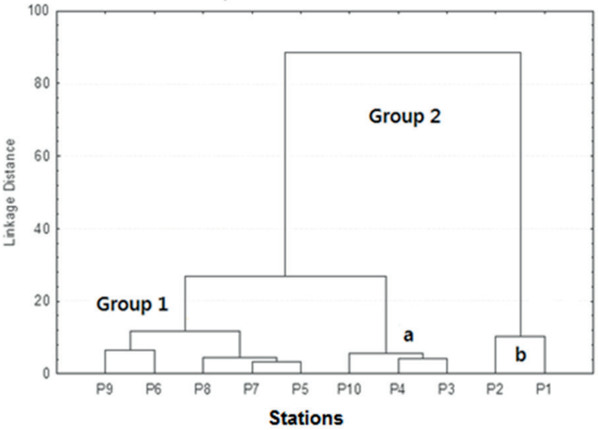

Figure 8 - Total (TP), organic (TOP) and inorganic (TIP) phosphorus (µg.g^{-1}) distribution in bottom sediments of the Castanhão Reservoir. Station 1 is the most influenced by the upstream watershed; stations 7 and 10 are located at the dam area. Location of stations as in Figure 1.

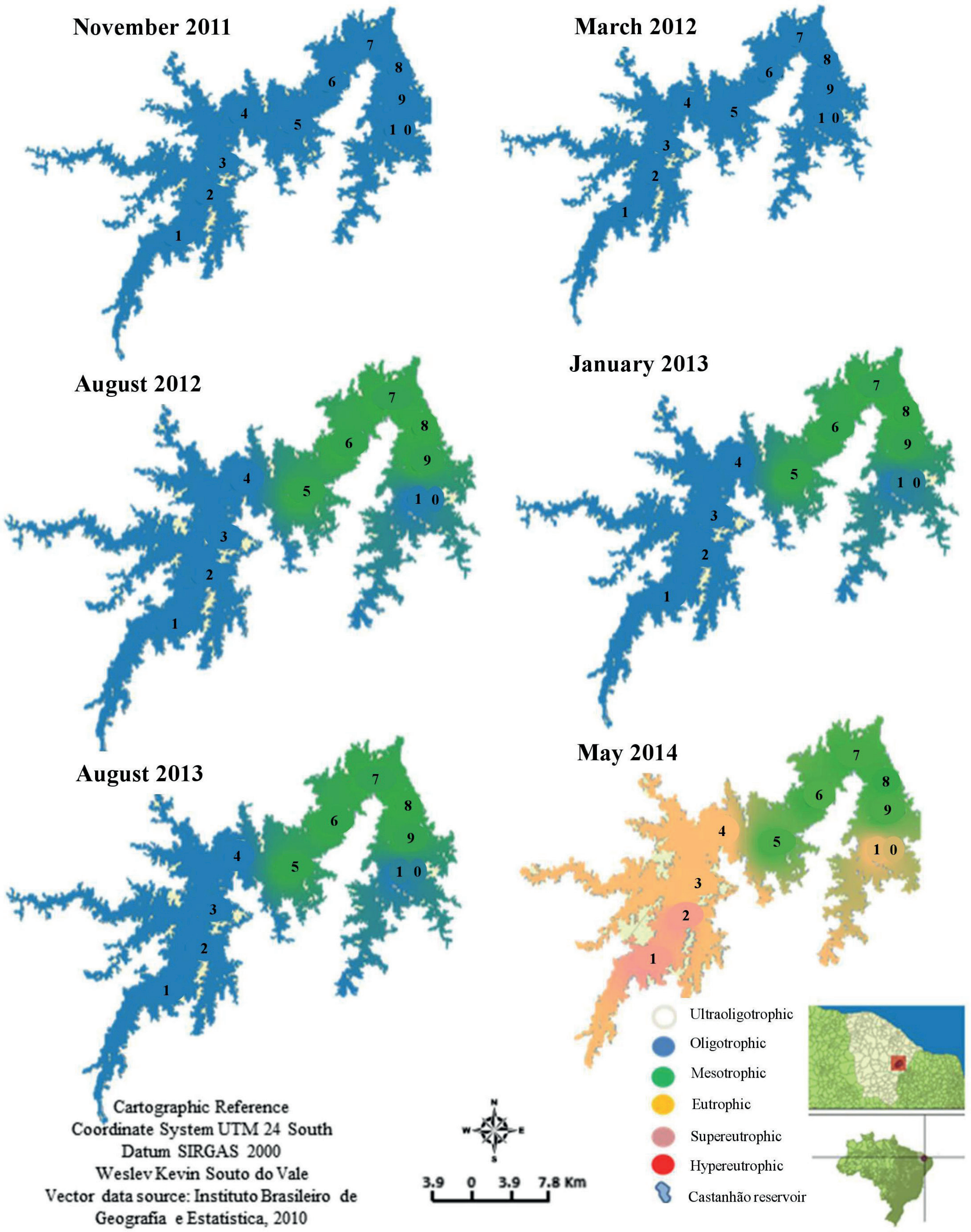

Figure 9 - Trophic state index changes in the Castanhão reservoir in NE Brazil, along the monitoring period.

stronger influence from the upstream watershed, in agreement with the nutrient mass balance proposed by Molisani et al. (2010, 2013), also derived under high river contribution. This trend has been also observed in other subtropical reservoirs (Wu et al. 2016). However, as the reservoir volume decreases, both phosphorus species concentrations increased downstream from zone fluvial reaching maximum values in the dam area, suggesting the augmenting importance of local phosphorus sources, in particular fish farms and irrigated agriculture, preferentially located around the dam area and the continuous decrease in the phosphorus contribution from the watershed due to decreasing rainfall (Figure 10).

The eventual release of P to the water column will depend, therefore, on inorganic speciation of phosphorus in sediments and the redox conditions of overlying bottom waters and porewaters, which may affect phosphorus-iron complexes (Boström et al. 1988, Mhamdi et al. 1994, Pettersson 1998, Chalar and Tundisi 2001, Søndergaard et al. 2003, Fonseca et al. 2011).

Iron oxides are the major carrier of phosphorus to bottom sediments, in particular in tropical climate and under oxic conditions in the water column. In the Jaguaribe River sediments, iron phosphates are the major form of sedimentary phosphorus. This fraction will easily dissolve and release its phosphorus burden, responding to the lowering of the redox potential of waters (Marins et al. 2007). Although phosphorus speciation in the Castanhão sediments were not performed simultaneously to the limnological analysis discussed above, unpublished data from our group (Teles et al. 2015) showed that reduced iron Fe^{2+} is the dominant fraction in the reservoir sediments, suggesting that reduction of ferric species due to low redox potential is already taking place. Our monitoring of dissolved oxygen concentrations in bottom waters is in agreement with the release of phosphorus to the water column from the sediment environment, particularly as the reservoir volume is reduced (Santos et al. 2017).

THE IMPACT OF FISH FARMING

Fish farming is considered a sustainable major source of protein to humans and a feasible option to capture fisheries, which is reported as decreasing worldwide (FAO 2012). The activity has developed technologies that allow for intensive farming practices with high and increasing productivity, which resulted in decreasing prices and an increasing participation of aquaculture products in the human diet. However, the dependence of modern aquaculture practices on large inputs of artificial feed, fertilizers and of other chemical additives have raised concern on the impact of these substances on aquatic environments and eventually to food security and public health.

The most widespread fish species presently farmed around the world are a few species of tilapia, in particular the Nile tilapia (*Oreochromis niloticus*). Brazil holds the 5th largest tilapia production in the world (FAO 2014) and Ceará State is the second in Brazil (IBGE/SIDRA 2015). In the Northeastern semiarid, tilapia production is carried out in artificial reservoir, whose major use is to supply good quality water for human consumption. Therefore, fish aquaculture may pose a threat to water quality due to poor management or under extreme climate conditions. Reservoir management regulation accepts up to 1% of the surface area to harbor intensive cage aquaculture. However, if reservoir volume decreases significantly, the activity can prove unsustainable.

During the 2010-2014 period, total tilapia production from the Castanhão reservoir averaged 18,000 tons per year, but considering the total potentially available area on the reservoir legally able to harbor fish cages, production figures could reach 40,000 tons per year. A major environmental aspect of intensive fish aquaculture practiced in

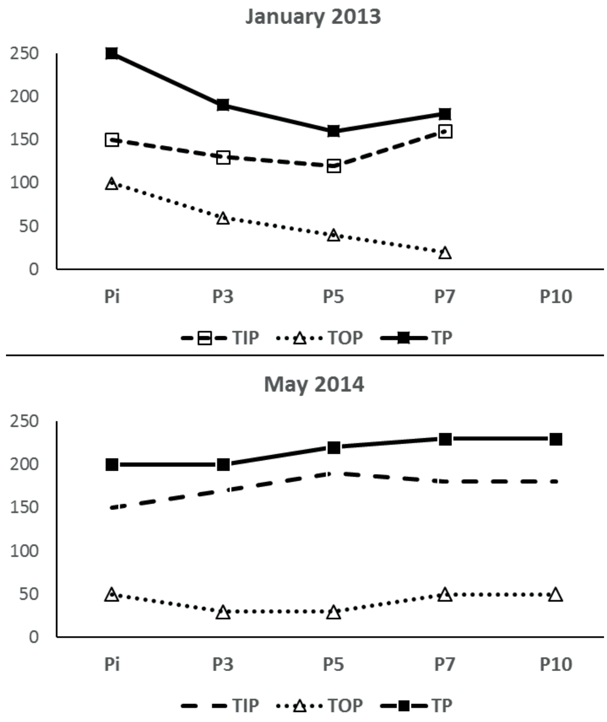

Figure 10 - Total (TP), organic (TOP) and inorganic (TIP) phosphorus (µg.g-1) distribution in bottom sediments of the Castanhão Reservoir. Station 1 most influence by upstream watershed; stations 7 and 10 at the dam area. Location of stations as in Figure 1.

the Castanhão reservoir is the intensive use of aquafeed to sustain high production figures of about 150 t.ha^{-1}.yr^{-1}; to reach such a production, with a conversion rate of 1.7, about 258 t.ha^{-1}.yr^{-1} of aquafeeds are necessary (Oliveira et al. 2015). Excess aquafeeds and fish excreta result in this activity displaying the largest emission factors for nitrogen and mercury and the second largest for phosphorus, among all anthropogenic sources emitting these substances to the Castanhão reservoir (Table III). At present, due to the relatively small area used by fish farms, the activity contributes little to the total annual load of nutrients and metals to the reservoir, but already respond with 25% and 9% of the total nitrogen and phosphorus loads, respectively. In addition, fish cage aquaculture is the only activity whose emission is directly released into the reservoir waters, which increases its environmental significance.

The influence of the intensive fish farming upon the reservoir is clearly shown in Figure 11, that depicts a similarity analysis of areas under the influence of fish cages and in the open reservoir, based on sediment characteristics. The analysis shows three distinct and separated groups; one including only the station within the farm area (Psi), another group (stations 1, 3 and 5), located along the major axis of the reservoir, roughly following the previous Jaguaribe River bed and a third group (stations 7 and 10), in the open reservoir area. Sediments, rather than the water column, integrate through time discharges of pollutants and therefore are better compartments to understand the cumulative impact of anthropogenic emissions (Salomons and Förstner 2010) even those from the fish farms to the environment. Oliveira et al. (2015) have also detected significant differences between organic carbon and Hg concentrations in sediments below fish cages and sediments sampled outside the area of influence of the fish farm. Analysis of sediment cores clearly showed increasing concentrations of both variables at the onset of fish farming in the Castanhão reservoir.

When integrating the observed distribution of nutrients in water and sediments and the reservoir hydrodynamics, a model of the evolution of eutrophication and its triggering processes can be detailed integrating the role of aquaculture and the changing volume of the reservoir (Figure 12). The model explains why the water column surrounding fish farms are relatively oligotrophic and how the decreasing water volume affect hydrochemistry.

When normal rainfall conditions prevail, the reservoir reaches such high volume and depth that stratification of the water column occurs. Under the prevailing eastern winds typical of the region, surface currents push surface waters to the NW coast of the reservoir, where major fish farms are located. Upon reaching the shore, currents loop back into

TABLE III
Comparison of nitrogen, phosphorus, copper and mercury emission factors (Cu, N, and P; kg.ha^{-1}.yr^{-1}) (Hg; g.ha^{-1}.yr^{-1}) and average total annual loads from different anthropogenic activities (Cu and Hg; kg) (N and P tons) after (Lacerda et al. 2011, Avelino 2015, Oliveira et al. 2017) occurring in the Jaguaribe River Basin and Castanhão Reservoir fish farm, NE Brazil.

Activity	**Emission factors**				**Annual input**			
Element	Hg	Cu	N	P	Hg	Cu	N	P
Agriculture and Husbandry	<0.003	47.2	6.0	4.2	<0.01	7,600	1,348	1,215
Wastewaters discharge	0.2	2.7	4.9	1.3	10	700	227	55.8
Solid wastes disposal	0.4	3.2	-	-	9	200	-	-
Fish farm	1.24	2.0	7.0	2.2	0.15	148	518	163

the reservoir, washing out through the bottom and export effluents from fish cages to depths below the thermocline, accumulating nutrients in the hypolimnion and keeping most of the water column oligotrophic. Details on this hydrodynamic pattern can be seen in Oliveira et al. (2015, 2017). This is facilitated by the dynamic of aquafeed pellets, which floats long enough to be transported prior to sedimentation, as demonstrated by Molisani et al. (2015). This process explains why the water column, even surrounding fish farms, are relatively oligotrophic as demonstrated in many previous surveys (Molisani et al. 2010, 2013, 2015, Barroso et al. 2018, Santos et al. 2017).

During extended drought periods such as the present one that started in 2012, abnormally small contribution from rivers and the watershed runoff reduces the reservoir volume, breaking the stratification of the water column and mixing bottom waters with surface. Nutrients and organic matter that were accumulated in the hypolimnion, below the thermocline, during high water conditions, are upwelled to the photic zone triggering eutrophication and reducing water quality that also affects fish farming.

CONCLUSIONS

The accumulating knowledge on the limnology of reservoirs located in the semiarid NE Brazil, already allows to understand the chain of events that may eventually result in eutrophication, compromising their multiple uses and posing a threat to water consumers and other economic activities, in particular aquaculture, which depends not only on a large water availability, but mostly on water quality.

Extended periods of drought result in a dramatic fall of reservoir volume, which in turn provokes shifts in the structure of the water column, breaking the thermocline and triggering eutrophication. However, the establishment of compartments characterized by distinct physical and chemical parameters in the different regions of the reservoir, suggests that the changing of the trophic state is unevenly distributed in the reservoir area.

The long-term limnological scenario described for the Castanhão reservoir points to a revision of management regulation of this reservoir, and is probably valid for other reservoirs in the semiarid arid NE region, to secure a sustainable utilization of their water resources. The large variability of climate, in particular the rainfall regime, presently further enhanced as an impact from global climate change, has to be taken into consideration when establishing sustainable uses, especially aquaculture permits and land use surrounding the reservoir, since these two activities are the major contributors with nutrients and pollutants to reservoir and are, therefore, directly linked to water quality.

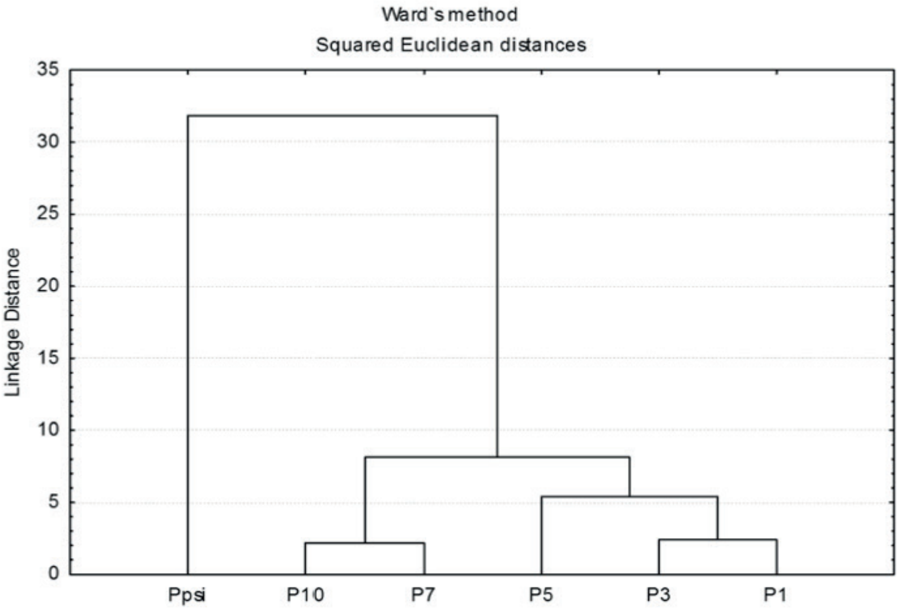

Figure 11 - Dendrogram based on sedimentary characteristic separating those under the influence of fish cages and other stations in the reservoir.

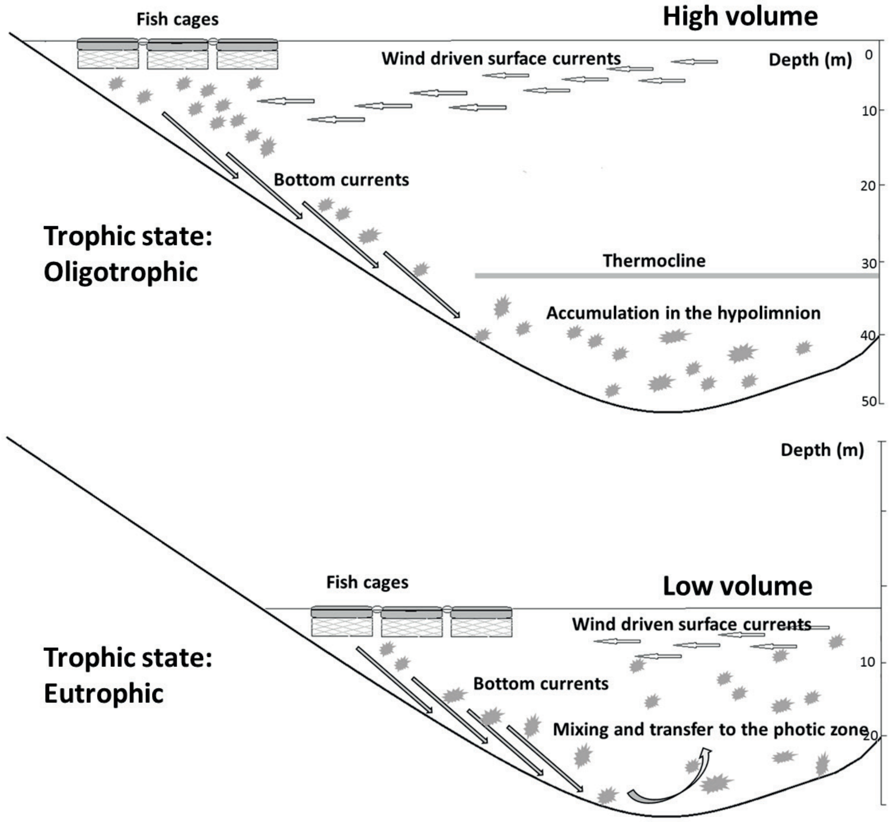

Figure 12 - Limnology and hydrodynamics of the Castanhão reservoir during normal rainfall regime and after an extended drought period showing the processes involved with triggering eutrophication.

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REFERENCES

ALVALA RCS, CUNHA AP, BRITO S, SELUCHI ME, MARENGO JA, MORAES OLL AND CARVALHO MA. IN PRESS. Drought monitoring in the Brazilian Semiarid region. An Acad Bras Cienc.

AVELINO IIF. 2015. Avaliação ambiental do Reservatório Castanhão (CE) utilizando o método DPSIR, 51 p. Trabalho de Conclusão de Curso. Instituto de Ciências do Mar, Universidade Federal do Ceará, Fortaleza. (Unpublished).

BARBOSA FAR AND PADISÁK J. 2002. The forgotten lake stratifications pattern: atelomixis, and its ecological importance. Verh Internat Verein Limnol 28: 1385-1395.

BARBOSA JEL, MEDEIROS ESF, BRASIL J, CORDEIRO RS, CRISPIM MCB AND SILVA GHG. 2012. Aquatic Systems in Semi-arid Brazil: limnology and management. Acta Limnol Bras 24: 103-118.

BARROSO HS, SANTOS JA, MARINS RV AND LACERDA LD. 2018. Assessing temporal and spatial variability of phytoplankton composition in a large reservoir in the Brazilian northeastern region under intense drought conditions. J Limnol 77: 130-146.

BATISTA AA, MEIRELES ACM, ANDRADE EM, IZIDIO NSC AND LOPES FB. 2014. Sazonalidade e variação espacial do índice de estado trófico do açude Orós, Ceará, Brasil. Rev Agroambiente 8: 39-48.

BEZERRA LAV, PAULINO WD, GARCEZ DS, BECKER H AND SÁNCHEZ-BOTERO JI. 2014. Características limnológicas em um reservatório do semiárido brasileiro com cultivo intensivo de *Orechromis niloticus* (Linnaeus, 1758). Acta Limnol Bras 26: 47-59.

BOSTRÖM B, ANDERSEN JM, FLEISCHER S AND JANSSON M. 1988. Exchange of phosphorus across the sediment-water interface. Hydrobiologia 170: 229-244.

BOUVY M, ARFI R, OLIVEIRA S, MARINHO M AND BEKER B. 1999. Dynamics of a toxic cyanobacterial bloom (*Cylindrospermopsis raciborskii*) in a shallow reservoir in the semi-arid region of Northeast Brazil. Aquat Microb Ecol 20: 285-297.

BOUVY M, NASCIMENTO SM, MOLICA RJR, FERREIRA A, HUSZAR V AND AZEVEDO SMFO. 2003. Limnological features in Tapacurá reservoir (northeastern Brazil) during a severe drought. Hydrobiologia 493: 115-130.

BREIMAN L, FRIEDMAN JH, OLSHEN RA AND STONE CJ. 1984. Classification and Regression Trees, Chapman and Hall/CRC, Boca Raton, FL, 358 p.

CAJUÍ KNS. 2015. Estimativas de cargas de nitrogênio e fósforo e hidroquímica de uma microbacia do semiárido cearense, 102 p. Trabalho de Conclusão de Curso. Instituto de Ciências do Mar, Universidade Federal do Ceará, Fortaleza. (Unpublished).

CAMPOS JNB, SOUZA FILHO FA AND LIMA HVC. 2014. Risks and uncertainties in reservoir yield in highly variable intermittent rivers: case of the Castanhão reservoir in semi-arid Brazil. Hydrol Sci J 59: 1184-1195.

CHALAR G. 2006. Eutrophication's dynamics on different temporary scales: Salto Grande Reservoir (Argentina-Uruguay). In: Tundisi JG, Matsumura-Tundisi T and Galli CS (Eds), Causas, consequências e tecnologias de gerenciamento e controle. Instituto Internacional de Ecologia, São Carlos, p. 87-101.

CHALAR G, DE LEON L, BRUGNOLI E, CLEMENTE J AND PARADISO M. 2002. Antecedentes y nuevos aportes al conocimiento de la estructura y dinâmica del Embalse Salto Grande. In: Fernandez-Cirelli A and Chalar G (Eds), El Agua en Sudamérica: de la Limnología a la Gestión en Sudamérica. CYTED Aprovechamiento y Gestión de los Recursos Hídricos, Montevideo, p. 123-142.

CHALAR G AND TUNDISI JG. 2001. Phosphorus fractions and fluxes in the water column and sediments of a tropical reservoir (Lobo-Broa – SP). Internat Rev Hydrobiol 86: 183-194.

CHAVES FIB, LIMA PF, LEITÃO RC, PAULINO WD AND SANTAELLA ST. 2013. Influence of rainfall on the trophic status of a Brazilian semiarid reservoir. Acta Scientiarum 35: 505-511.

CHELLAPPA NT, BORBA JM AND ROCHA O. 2008. Phytoplankton community and physical-chemical characteristics of water in the public reservoir of Cruzeta, RN, Brazil. Brazil J Biol 68: 477-494.

COGERH - COMPANHIA DE GESTÃO DOS RECURSOS HÍDRICOS. 2011. Inventário Ambiental Açude Castanhão.

Geosolos Consultoria, Projetos e Serviços Ltda, Fortaleza, 142 p.

COGERH - COMPANHIA DE GESTÃO DOS RECURSOS HÍDRICOS. 2017. Portal Hidrológico do Ceará. http://www.hidro.ce.gov.br/. (Accessed in May 20, 2017).

CONAMA - CONSELHO NACIONAL DE MEIO AMBIENTE. 2005. Resolução no. 357 de 17 de Março de 2005. Ministério do Meio Ambiente e da Amazônia Legal, Brasília, http://www.mma.gov.br/port/conama/res/res05/res35705.pdf. (Accessed May 20, 2017).

COOK PLM, ALDRIDGE KT, LAMONTAGNE S AND BROOKES JD. 2010. Retention of nitrogen, phosphorus and silicon in a large semi-arid riverine lake system. Biogeochemistry 99: 49-63.

COSTA IAS, CUNHA SRS, PANOSSO RF, ARAÚJO MF, MELO JLS AND ESKINAZI-SANT'ANNA EM. 2009. Dinâmica de cianobactérias em reservatórios eutróficos do semiárido do Rio Grande do Norte. Oecol Brasil 13: 382-401.

DAWADI S AND AHMAD S. 2013. Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population. J Environ Manag 114: 261-275.

DIAS FJS, MARINS RV AND MAIA LP. 2009. Hydrology of a well-mixed estuary at the semi-arid northeastern Brazilian coast. Acta Liminol Brasil 21: 377-385.

DIGITAL GLOBE. 2009. White Paper 06.03.13: The benefits of the eight spectral bands of WorldView-2. London, https://dg-cms-uploads-production.s3.amazonaws.com/uploads/document/file/35/DG-8SPECTRAL-WP_0.pdf. (Accessed November 30, 2017).

DING S, HAN C, WANG Y, YAO L, WANG Y, XU D, SUN Q, WILLIAMS PN AND ZHANG C. 2015. *In situ*, high-resolution imaging of labile phosphorus in sediments of a large eutrophic lake. Wat Res 74: 100-109.

DNOCS - DEPARTAMENTO NACIONAL DE OBRAS CONTRA AS SECAS. 2017. Açude Castanhão. http://www.dnocs.gov.br. (Accessed June 10, 2017).

DODDS WK, JONES JR AND WELCH EB. 1998. Suggested classification of stream trophic state, distributions of temperate of stream trophic state: chlorophyll, total nitrogen, and phosphorus. Wat Res 32: 1455-1462.

ESKINAZI-SANT'ANNA EM, MENEZES R, COSTA IS, PANOSSO RF, ARAÚJO MF AND ATTAYDE JL. 2007. Composição da comunidade zooplanctônica em reservatórios eutróficos do semiárido do Rio Grande do Norte. Oecol Brasil 11: 410-421.

FAO - FOOD AND AGRICULTURE ORGANIZATION. 2012. The State of World Fisheries and Aquaculture 2012. FAO Fisheries and Aquaculture Department, Rome.

FAO - FOOD AND AGRICULTURE ORGANIZATION. 2014. Fishstat 2014, Rome, http://www.fao.org/fishery/statistics/software/fishstatj/en. (Accessed March 10, 2017).

FERNANDES RO, SILVEIRA CS, STUDART TMC AND SOUZA FILHO FA. 2017. Reservoir yield intercomparison of large dams in Jaguaribe Basin-CE in climate change scenarios. RBRH 22: 201.

FONSECA R, CANÁRIO T, MORAIS M AND BARRIGA FJAS. 2011. Phosphorus sequestration in Fe-rich sediments from two Brazilian tropical reservoirs. Appl Geochem 26: 1607-1622.

FREIRE RHF, CALIJURI MC AND SANTAELLA ST. 2009. Longitudinal patterns and variations in water quality in a reservoir in the semiarid region of NE Brazil: responses to hydrological and climatic changes. Acta Limnol Bras 21: 251-262.

FRIEDL G, TEODORU C AND WEHRLI B. 2004. Is the Iron Gate I reservoir on the Danube River a sink for dissolved silica? Biogeochemistry 68: 21-32.

FUNCEME - FUNDAÇÃO CEARENSE DE METEOROLOGIA E RECURSOS HÍDRICOS. 2016. Calendário de Chuvas no Ceará. Séries Históricas. http://www.funceme.br/index.php/areas/23-monitoramento/meteorol%C3%B3gico/633-calend%C3%A1rio-das-chuvas (Accessed October 17, 2016).

GERALDES AM AND BOAVIDA MJ. 2005. Seasonal water level fluctuations: Implications for reservoirs limnology and management. Lakes Reservoirs Res Manegt 10: 59-69.

GERALDES AM AND GEORGE C. 2012. Limnological variations of a deep reservoir in periods with distinct rainfall patterns. Acta Limnol Bras 24: 417-426.

GONDIM RS, CASTRO MAH, MAIA AHN, EVANGELISTA SRM AND FUCK SCF. 2012. Climate change impacts on irrigation water needs in the Jaguaribe River Basin. J Am Water Resour Assoc 48: 355-365.

IBGE - INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. 2010. Censo 2010. Disponível em: http://www.censo2010.ibge.gov.br/pt/. (Accessed June 12, 2015).

IBGE/SIDRA - INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA/SISTEMA IBGE DE RECUPERAÇÃO AUTOMÁTICA. 2015. Produção Pecuária Municipal - 2015. https://sidra.ibge.gov.br/Tabela/3940. (Accessed in June, 2017).

IPECE - INSTITUTO DE PESQUISA E ESTATISTICA ECONOMICA DO CEARA. 2011. Ceará em números 2011. http://www2.ipece.ce.gov.br/publicacoes/ceara_em_numeros/2011/infra/index.htm. (Accessed June 8, 2017).

KROL MS AND BRONSTERT A. 2007. Regional integrated modeling of climate change impacts on natural resources and resources usage in semi-arid Northeast Brazil. Environ Model Software 22: 259-268.

LACERDA LD, SOARES TM, COSTA BGB AND GODOY MDP. 2011. Mercury Emission Factors from Intensive Shrimp Aquaculture and its relative importance to the Jaguaribe River Estuary, NE Brazil. Bull Environ Contam Toxicol 87: 657-661.

LEWIS WM. 1983. Temperature, heat and mixing in Lake Valencia, Venezuela. Limnol Oceanogr 28: 273-286.

MARENGO JA, ALVES LM, ALVALA RCS, CUNHA AP, BRITO S AND MORAES OLL. IN PRESS. Climatic characteristics of the 2010-2016 drought in the semiarid Northeast Brazil region. An Acad Bras Cienc.

MARINS RV, PAULA FILHO FJ AND ROCHA CAS. 2007. Geoquímica de fósforo como indicadora da qualidade ambiental e dos processos estuarinos do rio Jaguaribe – Costa Nordeste Oriental Brasileira. Quím Nova 30: 1208-1214.

MHAMDI MA, ALEYA L AND DEVAUX J. 1994. Phosphorus exchanges between sediment and water in trophically different reservoirs. Wat Res 28: 1971-1980.

MOLISANI MM, BARROSO HS, BECKER H, MOREIRA MOP, HIJO CAG, MONTE TM AND VASCONCELLOS GH. 2010. Trophic state, phytoplankton assemblages and limnological diagnosis of the Castanhão Reservoir, CE, Brazil. Acta Limnol Brasil 22: 1-12.

MOLISANI MM, BECKER H, BARROSO HS, HIJO CAG, MONTE TM, VASCONCELLOS GH AND LACERDA LD. 2013. The influence of Castanhão reservoir on nutrient and suspended matter transport during rainy season in the ephemeral Jaguaribe River (CE, Brazil). Brazil J Biol 73: 115-123.

MOLISANI MM, MONTE TM, VASCONCELLOS GH, BARROSO HS, MOREIRA MOP, BECKER H, REZENDE CE, FRANCO MAL, FARIAS EGG AND CAMARGO PB. 2015. Relative effects of nutrient emission from intensive cage aquaculture on the semiarid reservoir water quality. Environ Monitor Assess 187: 707-721.

MONCUNILL DF. 2006. The rainfall trend over Ceará and its implications. Proceeding of 8 ICSHMO. Foz Iguaçu, Brazil - INPE, p. 315-323.

NASELLI-FLORES L. 2000. Phytoplankton assemblages in twenty-one Sicilian reservoirs: relationship between species composition and environmental factors. Hydrobiology 424: 1-11.

NASELLI-FLORES L. 2003. Man-made lakes in Mediterranean semi-arid climate: the strange case of Dr. Deep Lake and Mr. Shallow Lake. Hydrobiologia 506: 13-21.

NI Z AND WANG S. 2015. Historical accumulation and environmental risk of nitrogen and phosphorus in sediments of Erhai Lake, Southwest China. Ecol Enginer 79: 42-53.

NOGUEIRA MG, JORCIN A, VIANNA NC AND BRITTO YCT. 2007. Reservatórios em cascata e os efeitos na limnologia e organização das comunidades bióticas (fitoplâncton, zooplâncton e zoobentos) – Um estudo de caso no Rio Paranapanema (SP/PR). In: Nogueira MG, Henry R and Jorcin A (Eds), Ecologia de reservatórios: impactos potenciais, ações de manejo e sistemas em cascata. Rima, São Carlos, p. 83-125.

OLIVEIRA KF, LACERDA LD, PERES TF, BEZERRA MF AND DIAS FJS. 2015. Emission factor and balance of mercury in fish farms in an artificial reservoir in NE-Brazil. Environ Sci Pollut Res 22: 18278-18287.

OLIVEIRA KF, LACERDA LD, PERES TF, MARINS RV AND SANTOS JA. 2017. The Fate of Cu, Zn and Mn in an Intensive Fish Aquaculture (Tilapia - *Oreochromis niloticus*) in an Artificial Reservoir in Northeastern Brazil. Environ Process 4: 107-121.

PAULA FILHO FJ, MARINS RV AND LACERDA LD. 2015. Natural and anthropogenic emissions of N and P to the Parnaíba River Delta in NE Brazil. Estuar Coast Shelf Sci 166: 34-44.

PETTERSSON K. 1998. Mechanisms for internal loading of phosphorus in lakes. Hydrobiologia 373: 21-25.

SALAS HJ AND MARTINO P. 2001. Metodologías simplificadas para La evaluación de eutroficacion em lagos cálidos tropicales. Organización Panamericana de La Salud (OPS) – División de Salud y Ambiente. Centro Panamericano de Ingenieria Sanitaria y Ciências Del Ambiente (CEPIS), Lima, 60 p.

SALOMONS W AND FÖRSTNER U. 2010. Sediments and the “System”: from site-specific to regional-scale research. J Soils Sediments 10: 1436-1439.

SANTOS JA, MARINS RV, AGUIAR JE, CHALAR G, SILVA FATF AND LACERDA LD. 2017. Hydrochemistry and trophic state change in a large reservoir in the Brazilian northeast region under intense drought conditions. J Limnol 76: 41-51.

SANTOS JA, OLIVEIRA KF, ARAÚJO ICS, AVELINO IIF, CAJUÍ KNS, LACERDA LD AND MARINS RV. 2016. Phosphorus partitioning in sediments from a tropical reservoir during a strong period of drought. Environ Sci Pollut Res 23: 24237-24247.

SEN S, HAGGARD BE, CHAUBEY I, BRYE KR, COSTELLO TA AND MATLOCK MD. 2007. Sediment phosphorus release at Beaver Reservoir, northwest Arkansas, USA, 2002-2003: A preliminary investigation. Water Air Soil Pollut 179: 67-77.

SILVA LP. 2015. Comunidade Fitoplanctônica do Reservatório Padre Cícero (Castanhão), Ceará, 120 p. Dissertação de Mestrado, Instituto de Ciências do Mar, Universidade Federal do Ceará, Fortaleza. (Unpublished).

SILVA LP, SANTOS JA, COSTA BGB, BEZERRA MB, SILVA ATF AND MARINS RV. 2013. Caracterização da comunidade fitoplanctônica no açude padre Cícero (Castanhão), CE. An XIV Congr Bras Limnol. Associação Brasileira de Limnologia, Bonito, Mato Grosso do Sul, p. 123.

SØNDERGAARD M, JENSEN JP AND JEPPESEN E. 2003. Role of sediment and internal loading of phosphorus in shallow lakes. Hydrobiologia 506: 135-145.

SOUZA FILHO FA, MARTINS ESPR AND PORTO M. 2006. O processo de mistura em reservatórios do semiárido e sua implicação na qualidade da água. Rev Bras Rec Hídr 11: 109-119.

SRH - SECRETARIA DE RECURSOS HÍDRICOS DO ESTADO DO CEARÁ. 2008. Programa de Açudes Estratégicos. Available at: http://www.srh.ce.gov.br. (Accessed May 17, 2017).

TANG X, WU M, DAI X AND CHAI P. 2014. Phosphorus storage dynamics and adsorption characteristics for sediment from a drinking water source reservoir and its relation with sediment compositions. Ecol Enginer 64: 276-284.

TELES SO, CARVALHO JLL, ARAÚJO ICS AND MARINS RV. 2015. Determinação de ferro e seu fracionamento geoquímico em águas naturais e marinhas do semiárido. XXXIV Encontro de Iniciação Científica, Universidade Federal do Ceará, Fortaleza, abstract. (Unpublished).

TEODORU C AND WEHRLI B. 2005. Retention of sediment and nutrients in the Iron Gate reservoir on the Danube River. Biogeochemistry 76: 539-565.

TOUHAMI I, CHIRINO E, ANDREU JM, SÁNCHEZ JR, MOUTAHIR H AND BELLOT J. 2015. Assessment of climate change impacts on soil water balance and aquifer recharge in a semiarid region in south east Spain. J Hydrol 527: 619-629.

TUNDISI JG AND MATSUMURA-TUNDISI T. 2008. Limnologia. São Paulo, Oficina de Textos, 631 p.

WORLD COMMISSION ON DAMS. 2000. Dams and Development: A new framework for decision-making. Earthscam Publications Ltd, London and Sterling, VA, 356 p.

WU Y, WANG X, ZHOU J, BING H, SUN H AND WANG J. 2016. The fate of phosphorus in sediments after the full operation of the Three Gorges Reservoir, China. Environ Pollut 214: 282-289.

ZHANG E, LIU E, JONES R, LANGDON P, YANG X AND SHEN J. 2010. A 150-year record of recent changes in human activity and eutrophication of Lake Wushan from the middle reach of the Yangze River, China. J Limnol 69: 235-241.

SUPPLEMENTARY MATERIAL

Table SI - Mean, maximum and minimum values for the variables monitored in surface and bottom waters in the Castanhão reservoir, NE Brazil.