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Spatial-temporal evaluation of water quality in Brazilian semiarid reservoirs

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Abstract

Reservoirs are used in the Brazilian semiarid for human supply, power generation, irrigated agriculture and more recently, intensive fish farming, the Sobradinho reservoir being the largest of this region. In the last decade, the semiarid region has suffered a strong drought, in opposite direction to the increasing demand of multiple water uses. The present work aims to study the spatial-temporal variation of water quality in two reservoirs in the Brazilian semiarid region (Sobradinho and Itaparica reservoirs). For this, samples were collected in the dry and wet periods between 2011 and 2014, and the results were analyzed through boxplot charts and Principal Component Analysis (PCA). For both reservoirs, our results showed that the PCAs did not evidence a specific seasonal change in the water quality characteristics, distinguishing the wet and dry periods through the four years studied. A clear temporal pattern was detected in both reservoirs, with higher values of turbidity, dissolved oxygen and total phosphorus in the wet period and higher values of pH and alkalinity in the dry period. An upstream reduction of nutrients and turbidity was not found in this study, as is reported in literature for consecutive reservoirs, probably due to the irrigation and aquaculture activities, mainly in Itaparica reservoir.

Key words: drought region, seasonal variation, water diversion project, water management

INTRODUCTION

The water crisis is a current and global problem. Due to water consumption, it is estimated that 25% of the world's rivers will become intermittent in the near future before reaching the ocean (Pastor *et al.* 2014).

The scarcity of water resources is one of the main constraints for development of arid and semiarid regions in the Northeast of Brazil. In these regions, water distribution is not uniform, not in space nor in time, depending on climatic vulnerability and drought, which cause serious economic and social negative impacts on the local population. There are also water conflicts for multiple uses. The relationship between rainfall and evaporation presents a negative balance, which causes drought situations during most of the year. The high evaporation rates lead to a great loss of water in the reservoirs, dams and channels of the region (ANA 2015).

The rivers are mostly intermittent and conditioned to the wet season, when they actually present surface water, whereas in the dry season they seem to be extinct, being submerged in the alluviums of the valleys, or lowered, composing the water table already with little water reserve (Melo 2011).

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The main source of freshwater in the v semiarid region is the São Francisco river basin, supplying different water use demands, and contributing to the region's socioeconomic development (Rossiter *et al.* 2014). The basin is divided into four regions and the study area of this research is located in the submiddle region between Sobradinho and Itaparica reservoirs.

In addition to the reservoirs mentioned above, São Francisco River presents others reservoirs for multiple water uses, built primarily for electricity generation, where environmental problems are frequent (Koch *et al.* 2015).

The flow regime determined by São Francisco river regulation for power generation purposes, constitutes a potential source of conflict between public supply, irrigation and environmental flows (Martins *et al.* 2011). The planning and management of these reservoirs are critical to preventing and minimizing environmental problems in downstream waters.

Despite the low water availability in the semiarid region, the constant temperatures provide for the development of fish farming throughout the year in the reservoirs. The granting of water resources use is a management instrument mandatory in the regularization of fish farming. In water bodies of the Union domain, like the Itaparica reservoir, the grant is issued by the National Water Agency (ANA). In order to ensure the quantitative and qualitative control of water uses and the effective exercise of access to water resources, ANA analyzes the request according to the body's capacity to dilute the phosphorus load generated in fish farming enterprises (Silva 2019).

In order to minimize the great droughts in the Brazilian Northeast, in 2005 the Federal Government developed the Integration Project of the São Francisco River with the Hydrographic Basins of the Northern Northeast (PISF), with a proposal to transfer water to Pernambuco, Ceará, Paraíba and Rio Grande do Norte states through two channels: the North and East channels, whose water abstraction points are within the study area of this research. The East axis operates with $10\ m^3\ s^{-1}$ continuous flow and the North axis operates with $16.4\ m^3\ s^{-1}$ (MI 2014).

In this water diversion project, a program named Basic Environmental Program (PBA-22) was established, focusing on the monitoring of water quality and limnology (MI 2011). The water quality data used in this research are part of PBA 22, coordinated by a technical team from the Federal University of Pernambuco.

The quantitative and qualitative water aspects are coupled, once water quality is dependent on the substance concentration. The increase of these substances affects quality integrity, being stated by a higher input or by a water volume decrease that concentrates them. This study aimed to evaluate the spatial-temporal variation of water quality in two reservoirs of the Brazilian semiarid region, identifying differences and causes between dry and wet periods.

MATERIAL AND METHODS

Description of the study area

The São Francisco river basin extends to approximately 2,800 km, with an area of 640,000 km^2 that corresponds to almost 8% of the national territory. The research area is located in the submiddle region of the basin (see Online Resource 1, available in the online version of this paper). The area is characterized by a semiarid climate (according to Köppen classification), great irregularity of rainfall and high evaporation. The average temperatures range from 20 °C to 28 °C and its main rainy season is from January to April, resulting in a 7-month dry season. The historical annual precipitation in the central part of the submiddle region (the area of study) is between 300 mm and 600 mm (see Online Resource 2) (Bettencourt *et al.* 2015; Assis *et al.* 2018).

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In this research, the data corresponds to eight sampling points of the PBA 22 program, including the North and East axes abstraction points of the water diversion project (see Online Resource 1). The geographical coordinates of the sampling points are described in Table 1.

Table 1 | Geographical coordinates of the sampling points

Sampling points	Locations	Geographical coordinates	
		Longitude W	Latitude S
A	Q01 - Sobradinho Reservoir	41°08′54,9″	08°25′42,86″
B	Q85 - SF River Orocó PE	39°43′04,00″	09°04′38,10″
C	Q03- SF River- North axis captation	39°27′19,86″	09°05′54,92″
D	Q86 - SF River – Ibó PE	39°05′50,00″	09°04′55,44″
E	Q54 - Itaparica Reservoir- East axis captation	38°24′23,62″	09°02′47,68″
F	Q84 - Itaparica Reservoir	38°01′38,00″	09°00′28,54″

For sample identification, a single-line sequence of points was used, denominated by the letters A through F corresponding to the sampling sites followed by the number of the sampling (see Online Resource 3). Eight samplings were carried out during the period between 2011 and 2014, one in the dry period and the others in the wet period, as reported in Table 2.

Table 2 | Sampling dates

Sampling	Year	Month	Period
1	2011	February	Wet
2	2011	October	Dry
3	2012	January	Wet
4	2012	July	Dry
5	2013	January	Wet
6	2013	September	Dry
7	2014	January	Wet
8	2014	September	Dry

The studied reservoirs have different operational characteristics (see Online Resource 4). Sobradinho reservoir flow regime is regularized by the operation of a hydroelectric complex and also by the previous Três Marias reservoir (Minas Gerais). The Sobradinho complex, located 748 km from São Francisco river mouth, is the fourth reservoir in installed capacity and the first in water accumulation capacity at the national level. Itaparica reservoir presents high evaporation rates and its water level regulation leads to operational amplitudes of up to 5 m (Melo 2011; Matta *et al.* 2018).

According to Silva (2019), there were 28 verified water grants issued by ANA for aquaculture in Itaparica reservoir, among the 45 active projects in the reservoir, in addition to 20 other related preventive grants. The municipality of Gloria (Bahia), located in the Itaparica reservoir, was the largest producer in 2017, with 11,644 tons of fish (see Online Resource 5).

Monitored parameters and data analysis

The water samples were collected on the surface, in 500 mL clean plastic or glass vials, previously washed with the water to be collected. Total alkalinity, Chlorophyll-a, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), nitrate, ammonia nitrogen and total suspended solids (TSS) were analyzed according to APHA (2005). Electrical conductivity

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(EC), turbidity, dissolved oxygen and hydrogen ion potential (pH) parameters were analyzed *in loco*, by a Horiba multiparameter probe, model B-213.

The sample analyses were done by an external accredited laboratory and both sampling and results were monitored by the UFPE technical team linked to the Chemical and Civil Engineering Departments. The author took part in this team in the period from 2012 to 2016.

Physicochemical results were evaluated according to CONAMA Resolution 357 (ME 2015) limits, which provides water bodies classification, taking as a parameter Class 2 water bodies, which is the current framework of the study area.

The historical reservoirs flow data and useful volumes were collected from São Francisco Hydroelectric Company (CHESF) and National Electric System Operator (ONS). Precipitation data were taken from the National Institute of Meteorology (INMET) in the rainfall station OMM 82979 (09° 62′56.93″ S and 042°07′72.14″ W), located in Remanso (Bahia), upstream of Sobradinho reservoir, in the submiddle São Francisco basin. Other operational data were obtained with the National Water Agency (ANA) and the São Francisco River Basin Committee (CBHSF).

From these data, comparative studies were carried out between Sobradinho and Itaparica reservoirs, relating inflow and effluent, percentage of useful volume and accumulated precipitation, to analyze how these variables influenced the physicochemical results of the water.

The physicochemical data were treated using boxplot charts and Principal Component Analysis (PCA), applied through the program Statistic for Windows (version 8 - Statsoft, 2010). Due to the high dispersion of the data, which is common in environmental conditions, the median was used as a parameter in the boxplot charts instead of the mean value of the results. In the PCA, principal components were chosen that represented more than 50% of the total variation and were considered as a significant correlation coefficient (>0.70) in the interpretation of the main component, since this value expresses a strong correlation between the limnological variables. The data were previously normalized through the Z-Score transformation.

RESULTS AND DISCUSSION

Sobradinho reservoir inflow had a higher variation in relation to its outflow (see Online Resource 6), the largest difference being recorded in January 2012 (2,530 $m^3 s^{-1}$). This stored volume can be justified to guarantee the reservoir's water safety, since 2012 was an extremely dry year, presenting rainfall indexes lower than the historical average. The Itaparica reservoir flows presented similar results.

As the Sobradinho outflow was very close to the Itaparica inflow, this difference would not be the cause for the detected differences in the physicochemical results, additionally there were no considerable consultative uses in this period.

Sobradinho flows did not present a profile dependent on accumulated precipitation, indicating: (i) the volume of water that reaches the reservoir is not directly influenced by the local rainfall regime; (ii) the operational management of the outflow regime is given primarily as a function of the water's multiple uses, including the demand for power generation by the electric system. During periods of high precipitation (December/2013 - 219.9 $mm \cdot m^{-1}$, April /2014- 173.7 $mm \cdot m^{-1}$), the outflow had low values (1,202 and 1,172 $m^3 \cdot s^{-1}$) in relation to the average value (1,660 $m^3 \cdot s^{-1}$).

Similar results were found in studies carried out by Lima & Severi (2014), where they concluded that the variation detected in the Sobradinho reservoir level is directly associated with precipitation events in the upper part of the basin and with the hydroelectric plant operation, thus its increase does not match with the highest precipitation period in the area of direct influence of the reservoir.

Rossel & Fuente (2015) also concluded that the outflow control of Rapel reservoir, located in the central region of Chile, was mainly linked to the generation of electric energy. When the authors modeled the hydrodynamics and the water quality considering the restriction of ecological flow in the

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operation of the hydroelectric plant, the results showed that in the wet season there was no significant difference. In the dry season scenario, the chlorophyll concentration would increase in the reservoir.

When analyzing the useful volume rate of the reservoirs (see Online Resource 7), it was observed that for Sobradinho the decay profile of the useful volume began in May, rising again in November, a fact that occurred during the four year period studied. In 2012, the decrease percentage of Sobradinho was greater than in Itaparica reservoir, which remained very similar to 2011. In this year, the energy generated at Itaparica plant was reduced (mainly from July), due to the national distribution, which remained more stable and not needing large exports of energy from the Northeast to the other regions of the country (ONS 2017). In this scenario, the Itaparica reservoir volume remained high, evidencing the influence of the hydroelectric sector in the management of reservoirs.

Between 2013 and 2014, the useful volumes of both reservoirs were smaller than the previous years, with Itaparica reservoir decay more pronounced. This is explained by the actual reduction in the Sobradinho reservoir outflow since January 2013, which consequently decreased the flow that enters the Itaparica reservoir. In other words, the period from 2013 to 2014, when Sobradinho reservoir outflow was reduced, matched with a lower rate of useful volume in the reservoirs.

The oscillations of levels in Itaparica reservoir were also linked to the operational needs of Sobradinho Hydroelectric Power Plant, located about 200 km upstream, and the cascade reservoirs that receive water downstream (Moxotó, Paulo Afonso and Xingó Complex), as well as other consumption uses.

The results of a PCA applied to water quality data for the two first components (55.2% of the explanation of the total variation) is presented in Figures 1 and 2.

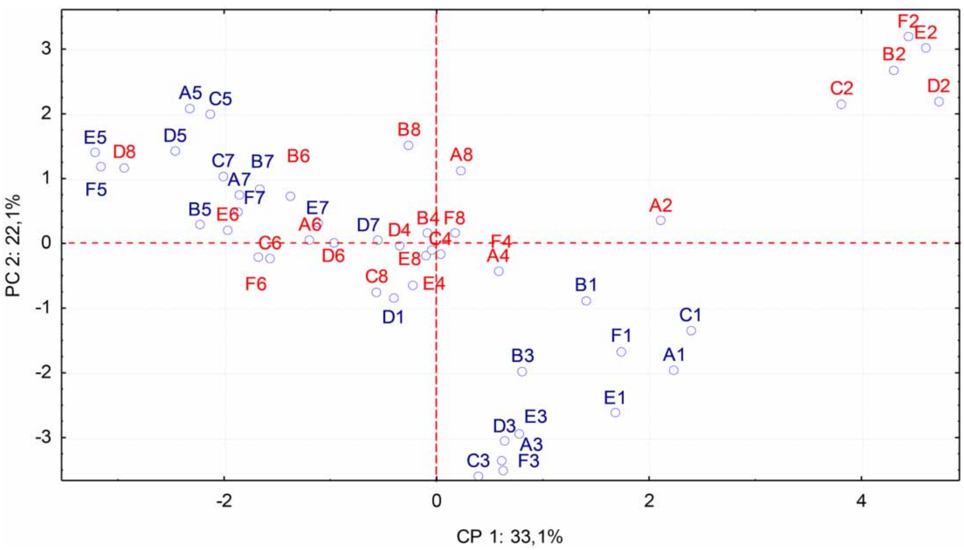

Figure 1 | Representation of temporal and spatial behavior of sampling network in the principal component space during dry (red) and wet (blue) period. The letters represent the sampling points and the numbers the sampling order.

As can be seen in Figure 1, there is no clear distinction between the samples by periods. That is, the sampling of wet and dry periods did not present many distinct characteristics, some specific groupings by sampling being observed.

Considering Figures 1 and 2, the first component (PC1) shows that the second sampling (October/2011, dry) presented values of nitrate (NO_3), total suspended solids (TSS) and total alkalinity (TA) higher than the other sampling dates. Most of the points of the fifth sampling (January/2013, wet) were characterized by higher electrical conductivity, turbidity, COD, BOD and total phosphorus (TP). The second component (PC2) characterized the third sampling (January/2012-wet) by higher

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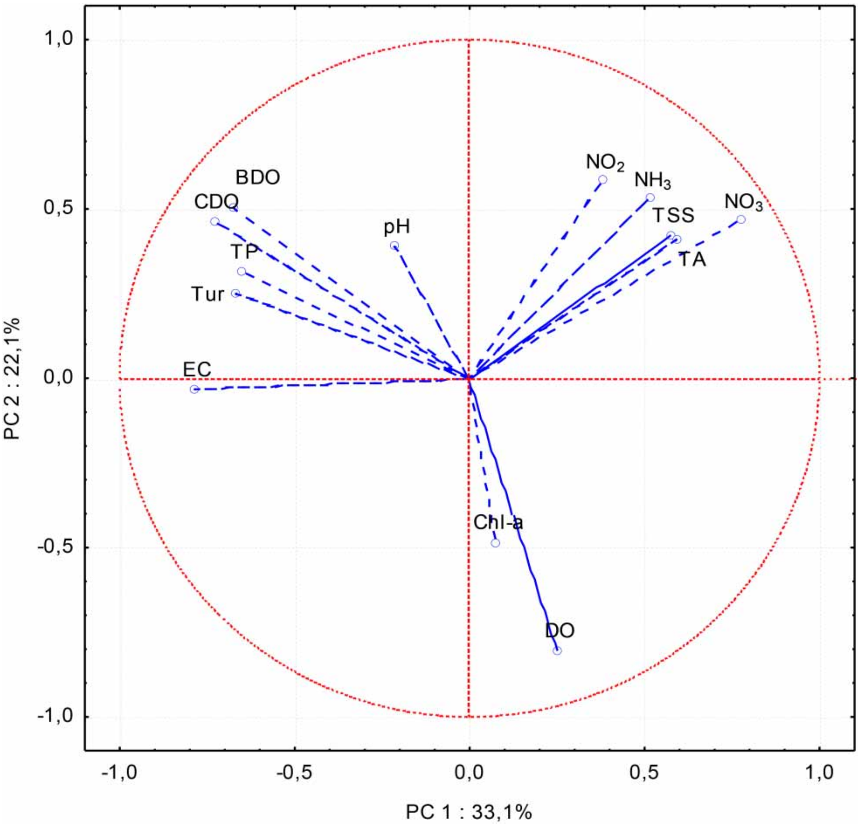

Figure 2 | PC1 and PC2 loading of water quality parameters.

values of dissolved oxygen (DO). As in the first component, there was no clear relationship between the parameters that characterize dry or wet periods.

However, in order to better evaluate how seasonality affects the physicochemical characteristics, boxplots were designed for wet and dry periods, as shown in Figure 3.

The turbidity presented higher median values in wet periods for the first four sampling points (A to D), as can be seen in Figure 3. The results of Itaparica reservoir (E and F) are similar and with the same order of magnitude as those recorded in the dry period for the previous sites. This may be related to the greater contribution of sediments carried to the water body by rainfall or transported through the main tributaries. This is greater in Sobradinho (point A) and in the lotic stretch of the São Francisco river (points B to D). The highest turbidity values were below the CONAMA Resolution 357/2005 limit, which is 100 NTU. Similar results were obtained by Lima *et al.* (2015) that reported a continuous reduction in water transparency observed during the drought period at the Pereira de Miranda reservoir, located in the state of Ceará.

Total suspended solids (TSS) presented very similar medians in dry and wet period. According to Lima & Severi (2014), in consecutive reservoirs the general tendency is that both the turbidity and the suspended material are smaller in the flows released downstream.

Comparing the Sobradinho (A) and the Itaparica reservoirs (points E and F), this spatial reduction was only evidenced for turbidity in the wet season, which indicates that Itaparica reservoir has its own sedimentation dynamics.

The electrical conductivity (EC) presented close values, with a small increase in the dry period. This can be related to the lower precipitation levels and higher evaporation, raising the concentration of salts and, consequently, the electrical conductivity.

In studies conducted by Rocha *et al.* (2016) at the São Pedro Dam in Juiz de Fora, Minas Gerais state, the turbidity and conductivity averages were also higher in the wet season, due to rainfall effect through surface runoff that carries sediments into the water body.

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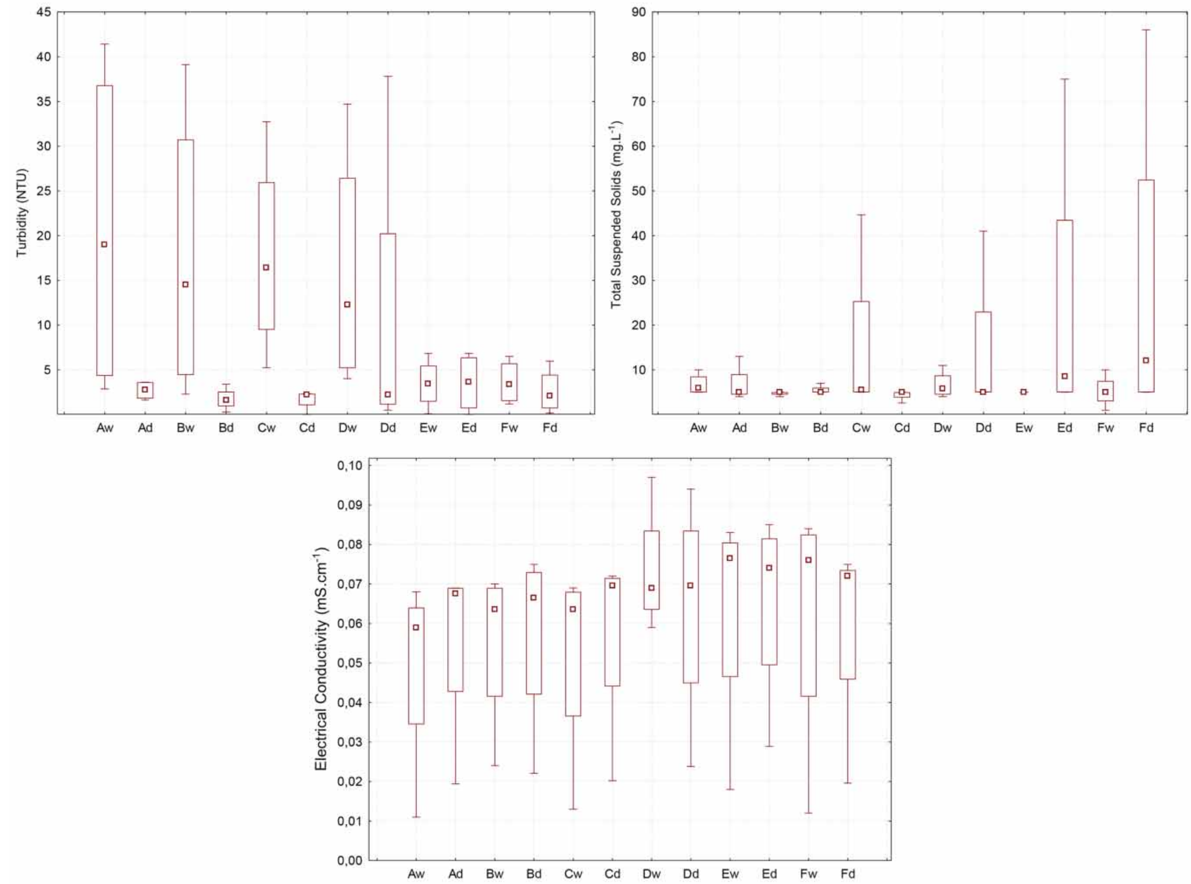

Figure 3 | Boxplots of turbidity, total suspended solids (TSS) and electrical conductivity in the sampling points (A, B,C, D, E,F)* for the dry (d) and wet (w) periods. * sampling points in order (see Table 1).

Medeiros & Magalhães (2015), studying the influence of flow and precipitation on turbidity and suspended material concentration in a stretch of the Lower São Francisco basin in the 2001, 2004 and 2007 periods, reported that the rainfall on the São Francisco river basin was determinant to the high concentrations of suspended material and turbidity, being more important than the total precipitation intensity. The absence of correlation between suspended material and turbidity with the flow demonstrated the influence of maximizing the hydroelectric energy production in flow management.

For most of sampling points the median pH (shown in Figure 4) were similar, but tendentiously higher in the dry period. The exception was detected for the Northern axis (C) abstraction point, where the difference between the dry and wet periods was higher. Only points C and D in the wet period presented results outside the range established by CONAMA 357/2005, which is 6 to 9.

As the total alkalinity of a solution is a measure of its capacity to neutralize acids, the higher the pH, the higher the basic concentration and its alkalinity. The results of total alkalinity were consistent with pH, also showing higher values in the dry period. According to Sabino *et al.* (2015), the increase in pH is strongly influenced by primary production (macrophytes or algae), which increases during the day, being more pronounced in the dry period due to evaporation. However, through Figure 7, it is evident that this would not be the reason, since there was no significant increase in chlorophyll-a in the dry period. Therefore, this pH increase must be linked to a higher precipitation of carbonates, also reflected in the alkalinity increase.

The median values of dissolved oxygen (DO) were lower in the dry period (Figure 5). However, all values were higher than the minimum established by CONAMA Resolution 357/2005, 5 mg·L^{-1} O_2 for Class 2 water bodies. This result may be related to the increase in water stratification and the

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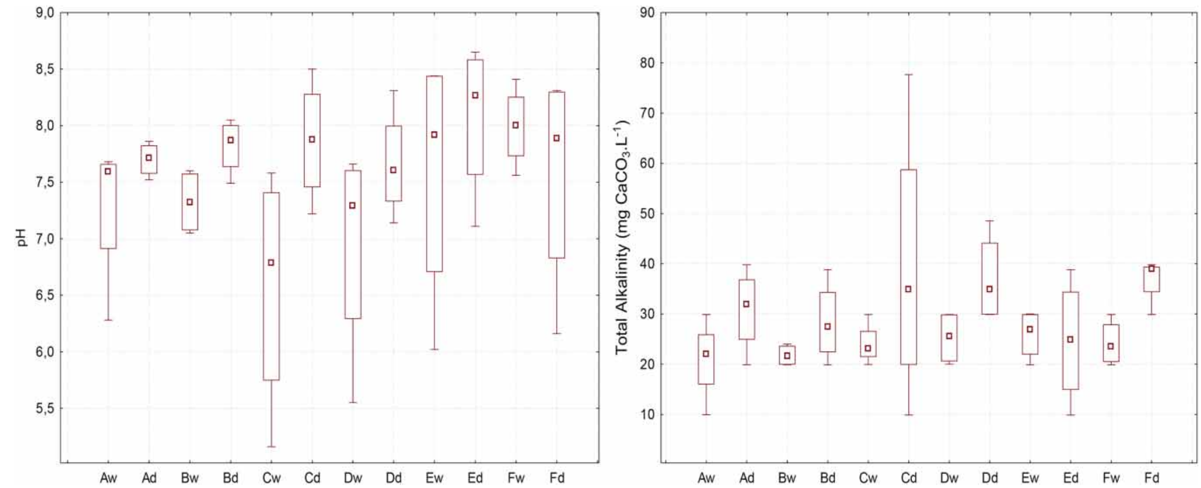

Figure 4 | Boxplots of pH and total alkalinity in the sampling points (A,B,C,D, E, F)* for the dry (d) and wet (w) periods. * sampling points in order (see Table 1).

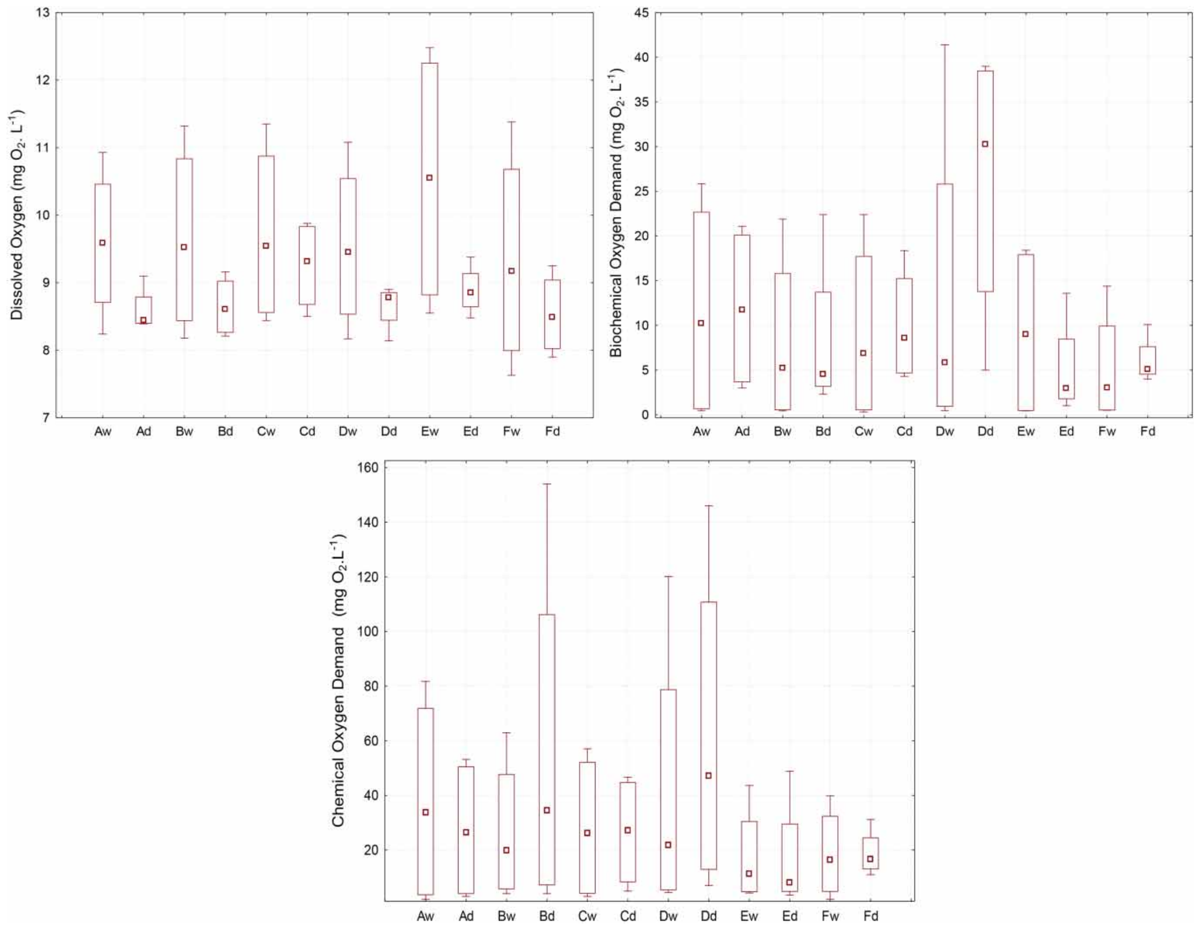

Figure 5 | Boxplots of dissolved oxygen, biochemical oxygen demand and chemical oxygen demand in the sampling points (A, B, C, D, E, F)* for the dry (d) and wet (w) periods. * sampling points in order (see Table 1).

decomposition and fixation processes of organic matter in the system during drought, which results in very low DO concentrations in the hypolimnium, which also ascends to surface waters.

The biochemical oxygen demand (BOD) medians were similar in all the points during the wet and dry periods, except for point D (São Francisco River/ Ibó). However, most of the results were higher

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than the maximum limit established in CONAMA 357/2005, which is 5 mg·L^{-1} O_2, indicating a high degree of biodegradable organic matter at all points.

Like the BOD, the COD showed similar values between dry and wet periods, with the exception of point D. This similarity at point D (São Francisco River/city of Ibó-PE) indicates a possible anthropic point source pollution, detected in the dry period (with consequent lower water level) by an increase of concentration due to the reduction capacity of water dilution.

The nitrate median (NO_3) shown in Figure 6 were similar in terms of points and sampling periods. On the other hand, nitrite (NO_2) presented a higher seasonal and spatial variability. The ammonia (NH_3) remained practically constant between the periods and the points. For all nitrogen compounds the obtained values were below the maximum limits established for Class 2 water bodies by CONAMA 357/2005, which are 10.0 mg·N·L^{-1}(nitrate), 1.0 mg·N·L^{-1} (nitrite) and 1.0 mg·N·L^{-1} (ammonia). It was not evidenced a spatial reduction of nitrogen between the Sobradinho and Itaparica reservoirs.

Similar results were obtained by Freitas *et al.* (2011) in studies carried out in the Cruzeta reservoir located in the Seridó river basin, in the semiarid region of Rio Grande do Norte state. There the total

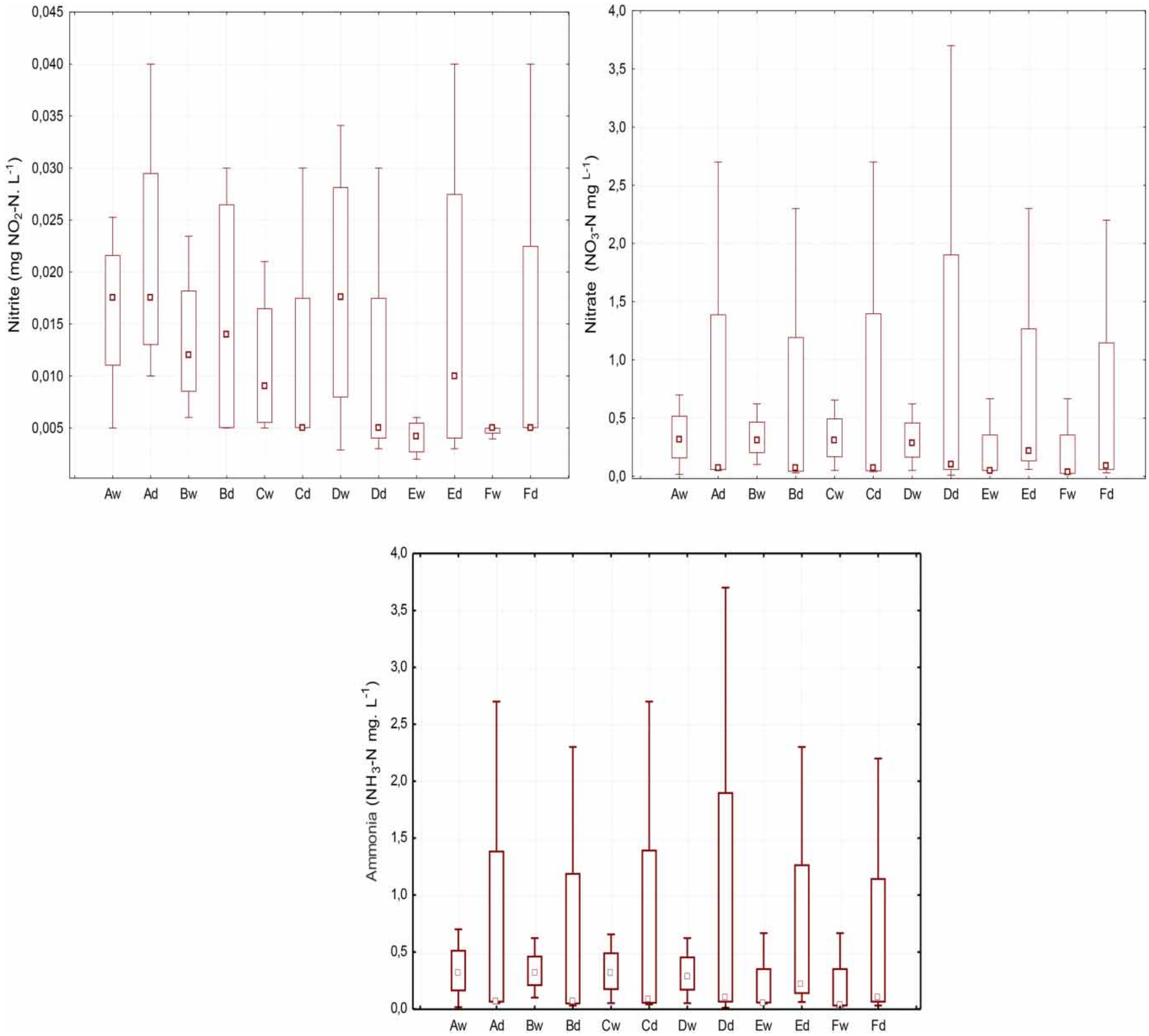

Figure 6 | Boxplots of nitrate, nitrite and ammonia in the sampling points (A, B, C, D, E, F)* for the dry (d) and wet (w) periods. * sampling points in order (see Table 1).

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organic nitrogen concentration was relatively constant between dry and wet periods between 2007 and 2008.

Total phosphorus (PT) presented higher median values in the wet period for all points, this difference being less accentuated in the Itaparica reservoir (points E and F) (Figure 7).

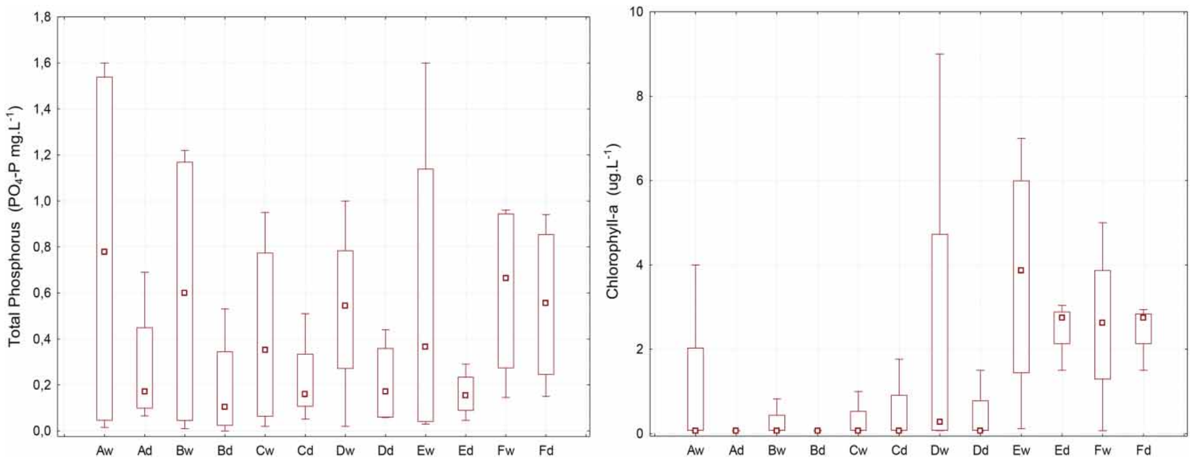

Figure 7 | Boxplots of total phosphorus and chlorophyll-a in the sampling points (A, B, C, D, E, F)* during the dry (d) and wet (w) periods. * sampling points in order (see Table 1).

This can be explained by the intense agricultural activity (mainly in the irrigated perimeters near the Itaparica reservoir) and by fish farming, which enlarges in a constant level the supply of phosphorus. The most used technique in Itaparica reservoir fish farming is the net cage, which has a low operational cost; however, it generates large nutrient emissions in the water.

The median results were above the limit established by CONAMA Resolution 357/2005 (0.030 mg·L^{-1} for lentic environments and 0.050 mg·L^{-1} for lotic environments), evidencing a high eutrophication risk at all points. The contribution of domestic effluents, fertilizers and aquaculture are the main sources of phosphorus in the area. This was confirmed by Arruda (2015) for Itaparica reservoir, reporting that the practices adopted for soil fertilization, fish farming developed in net cages and the discharge of sanitary sewers increase the reservoir's eutrophication risk by their contribution of phosphorus in the water and bottom sediments.

According to Silva *et al.* (2010), for consecutive reservoirs each dam eliminates part of the nutrients, progressively decreasing the phosphorus and nitrogen concentrations in the water. This was not the behavior between Sobradinho and Itaparica reservoirs, which is explained in part by the aquaculture activities that take place in the region and carry nutrients to Itaparica reservoir.

A study done by Melo (2011) indicated that in many parts of Itaparica reservoir the range of 100 meters from a permanent preservation area as specified in Resolution CONAMA No. 04/85, being observed around deforestation and irregular constructions, is not respected. This is another important cause of the increasing eutrophication.

The chlorophyll-a (chl*a*) medians were similar between the wet and dry periods, the values of Itaparica reservoir (points E and F) being higher than the other points, indicating a higher biomass of algae. This result is consistent with the high phosphorus (nutrient) values in the Itaparica reservoir.

From the 13 physicochemical parameters studied, five presented distinct characteristics between the wet and the dry periods: turbidity, dissolved oxygen and total phosphorus were higher in the wet season and pH and alkalinity were higher in the dry period. This corroborates the initial observation stated by the 'variability of the physicochemical parameters was not strongly dependent on the annual seasonality (wet or dry period), but on the characteristics of each sampling.

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Silva *et al.* (2017) studied the spatio-temporal variability of sodium, chloride, nitrate, pH and electrical conductivity in the Trussu river, located in a semiarid region, from 2013 to 2015. They concluded that there were no large variations between dry and wet periods for these parameters. These conclusions corroborate our findings.

However, other studies carried out in other areas evidenced a greater differentiation between the dry and wet periods, reflecting the influence of local characteristics on the water quality results.

Silva (2015) obtained a seasonal pattern with small spatial variation for physicochemical characteristics of water in Bita and Utinga reservoirs located in Ipojuca, in the state of Pernambuco. Rocha *et al.* (2016), for São Pedro reservoir in the Paraiba do Sul basin, showed that color, turbidity, iron, hardness, conductivity and BOD presented a seasonal pattern, with an increase in the wet period. The explanation for these findings is related to the runoff, carring sediments with nutrients and organic matter into the water body.

Rossiter *et al.* (2015) studied the water quality of the Sertão Alagoano Channel, also located in the semiarid region, during the dry period of 2014. This channel is 80 km from Itaparica reservoir. By means of the Mann-Whitney non-parametric test, it was found that there were significant differences for all studied parameters: temperature, pH, turbidity, conductivity, hardness, sulfates, chlorides, total nitrogen and total phosphorus. Although reservoir and channel are different systems, this study reinforces the obtained results about temporal variability of the semiarid region.

CONCLUSIONS

Sobradinho reservoir outflow is controlled mainly by the electrical generation demand, being not so influenced by local precipitation. In the area between Sobradinho and Itaparica reservoirs, there was no standard of distinct characteristics between the wet and dry periods that characterized the samples. A temporal variation could be observed where the results of the sampling points showed similarity by sampling. Regarding seasonality, the parameters that presented different characteristics were: turbidity, dissolved oxygen and total phosphorus, which were higher in the wet period, and pH and alkalinity in the dry period.

Although literary sources report that for consecutive reservoirs there is an upstream reduction of nutrients and turbidity, this spatial behavior was not evidenced between the reservoirs of Sobradinho and Itaparica, mainly due to the irrigation and aquaculture activities close to Itaparica reservoir that contribute to great nutrient inputs. All total phosphorus values were higher than the limits of CONAMA 357/2005 (ME 2015), leading to higher eutrophication. This result reinforces how the anthropic activities developed in the surroundings can affect water characteristics.

Our data indicate that for São Francisco submiddle region (semiarid of Brazil) there is no specific standard for water quality during wet or dry periods. As this area corresponds to the captation water point of São Francisco water diversion project, this information could help the local government to determinate their monitoring programs.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/wpt.2020.001.

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