Temporal and Spatial Variation of Thermal Profile and its Effect on the Chemical, Biological and Physical Parameters in the Subtropical Reservoir of Sal to Santiago-Paraná-Brazil

Nyamien Yahaut Sebastien[1], Gilmar Baumgartner[2], Daniella Ventura Nogueira[3]

[1]Professor, Dr. State University of Western of Paraná. Toledo Campus. Rua da Faculdade 645, Jardim Santa Maria. CEP: 85903-000 – Toledo

[2]Professor Dr. State University of Western of Paraná. Toledo Campus. Rua da Faculdade 645, Jardim Santa Maria. CEP: 85903-000 – Toledo

[3]Master in Environmental Sciences at State University of Paraná- UNIOESTE, Rua da Faculdade 645, Jardim Santa Maria. CEP 85903-000. Toledo Brazil

Abstract: ***The thermal profile of reservoirs is important in the distribution of chemical and biological compounds. The purpose of this study is to evaluate the spatial and temporal variation pattern of the thermal profile of the Salto Santiago reservoir during summer and winter in different points and to study the relationship between this structure and some physical, chemical and biological variables in four collection points. Temperature and oxygen sample collections were made onsite every meter from the surface to the bottom. Other variables such as pH, chlorophyll a, suspended matter, total phosphorus, orthophosphate and nitrate were evaluated in the laboratory according to the methodology recommended by the Standard Method for analysis. The analysis of the thermal profile showed two different periods such as a circulation in winter with low thermal resistance to circulation (TRC) values, and a stratification in summer with high TRC values. Statistical analyses of relations between this parameter indicated a spatial homogeneity in summer and winter and different between the two periods. Furthermore, correlations in the summer were significant, with negative values for the Total, orthophosphate and dissolved oxygen parameters and positive values for chlorophyll a, and nitrate in the winter.***

Keywords: Thermal profile, thermocline, circulation

1. Introduction

Water bodies are very complex and dynamic systems in their operation. According to Moss (1988), depending on their origin, bodies of water may be rich in organic derivatives, amino acid compounds, hydrocarbons, fluvial acids, and isoprenoids. Their distribution in the body of water depends on several factors such as the morphometric, morphological, and climatological characteristics and the process of thermal circulation and stratification. This stratification structure provides a stability originated by the transfer of heat in the different compartments from the solar radiations. The changes in the vertical structure of the reservoir are also caused by factors such as river discharges, rainfall precipitation in the winter, and wind incidence in the dry season (ChalarandTundisi, 1999; Tundisi, 2001). This dynamism together with chemistry parameters contributes to the alteration of the water quality. According to Esteves (2011) the distribution in a tropical limbic ecosystem is linked to the oxygen profile and the period of thermal stratification. The temperature variations influence in some ways the variations of the chemical compounds. According to Welch (2004), high temperatures accelerate the absorption of the phosphorus, with the rocks of the drainage basin being used as a source for continental aquatic ecosystems.

The stratification is a consequence of a temperature discontinuity in the water column (Cole (1975). Reservoirs that have a uniform temperature distribution from the surface to the bottom are consideredto be in a state of movement called circulation or instability, behaving as a single system with homogeneous distribution of chemical, physical and biological components. On the contrary, stability is characterized by high Thermal Resistance to Circulation (TRC) or thermocline.

The TRC or thermocline value enables a quantification of stratification, resistance to wind disruption, and the degree to which hypolimnion is isolated from superficial epilimnetic movements.

The stratified of water column structure provides much information among them the functioning, oxygenation, accumulation of methane and hydrogen sulfide gases (Tundisi, and Matsumura-Tundisi, 2008). It can vary daily, by season or by weather events as cold fronts. The permanence of the stratified structure of the water column may influence the behavior and physiology of various aquatic organisms.

Armengol et al. (1999) reported that the stability resulting from the reservoir profile is an important factor in the study of water quality and varies according to fluctuations in air temperature and weather conditions.

With the temperature fluctuations, rivers have a direct influence on the thermal profile of the reservoir due to their progressive inputs (Kennedy and Walker, 1990; Kimmel et al., 1990).

In lakes, solar heating and the action of the winds on the surface create different horizontal and vertical currents in the liquid mass. In small bodies of water, with small depths, stratification occurs when the system is protected against the action of the wind (StraskrabaandTundisi, 2000).

According to Straškraba (1999), the change in the water quality of the reservoir can occur because of increased dwell time and decreased flow rate, causing strong stratification and development of an anoxic deep layer. According to Sperling (1999), the dynamics of circulation and stratification of the body of water are the main factors that regulate the distribution of substances and organisms in the net mass. According to SalençonandThebault (1997), the circulations created are linked to the temperature and density of the fluid, which depend on the hydrostatic pressure.

Most temperate and subtropical lakes, with the exception of the shallow ones, develop annually thermal stratification (Yoshimura, 1936; Hutchinson, 1957). The warm water column is clearly divided into epilimnium, metalimnium and hypolimnium by the difference in density produced by the heat of the surface of the lake as an energy source. In view of these varied alterations of the thermal structure of the bodies of water, it this study aims to analyze the spatial and temporal variation of the thermal profile of a subtropical reservoir in the Iguazu River, determining its circulation pattern and its influence on the variation of some chemical parameters.

Objectives

To determine the variation pattern of the thermal profile of the reservoir at different points along the summer and winter periods and establish a dependence relationship with some physical, chemical and biological variables.

Specific Objectives:

a) To visualize the temporal variation of the thermal pattern of the reservoir in summer and winter;
b) To determine the thermal resistance to circulation (TRC) or thermocline in summer and winter
c) To evaluate the variables COD, DO, orthophosphate, and nitrate and chlorophyll in different sample point;
d) To compare the spatial and temporal variation of the thermal pattern;
e) To evaluate the influence of TRC on the distribution of chemical parameters such as COD, DO, Orthophosphate, and nitrate and chlorophyll.

2. Material and Methods

The study was carried out in the reservoir of the Salto Santiago hydroelectric power plant on the Iguazu River. Four collection points were identified: Dam (DAM), near the plant; Porto Santana (POS), in the central body of the reservoir; near the Cavernoso river (CAV); and at the flood region (IAT). The samples were collected in the months of January (summer) and July (winter), from 2007 to 2011. At each point, the temperature and dissolved oxygen were determined onsite at each meter of the surface at the bottom with the aid of a WTW multiparameter coupled to a probe of 60 meters in length. The pH was determined in the samples collected with a Van Dorn bottle with capacity for 5 liters on the middle and bottom surface of each point, using an mPA-210 pH meter. The water samples were preserved in a 5-liter gallon on ice and taken to the limnology laboratory for the determination of Chlorophyll, COD, suspended matter, total phosphorus, orthophosphate and nitrate according to the recommended methods.

The orthophosphate was obtained according to the methodology described by Golterman (1978); the total dissolved phosphorus, according to methodology of Mackereth et al. (1978), through acid digestion in sulfuric acid; the COD was obtained according to the methods proposed by APHA (1998); nitrate was measured according to the method proposed by Mackereth et al. (1978), by reducing the nitrite in cadmium; and the chlorophyll a contents were obtained by 90% cold acetone extraction, according to Golterman et al. (1978). The profiles $T(x) = f(p)$ were obtained where T (°C) is the temperature and (p) is the depth in meters. Thermal Resistance to Circulation (TRC) was calculated according to the equation, TRC = $\frac{d_{t2} - d_{t1}}{d_{H2O(4)} - d_{H2O(5)}} (Joule)$ where d_{t2} is the water density at temperature t_2 in the top layer, d_{t1} is the water density at temperature t_1 in the bottom layer, $d_{H_2O(4)}$ the density of water at 4°C; and $d_{H_2O(5)}$ is the density of water at 5°C.

For the evaluation of the spatial and temporal circulation pattern, an analysis of variance (ANOVA) was performed at 5% significance. In order to evaluate the influence of TRC (thermal profile) on the distribution of chemical parameters and chlorophyll, a Pearson correlation test was performed at 5% of significance.

To establish the differences in water quality between the seasons (Summer and winter) and the samplings in the physical and chemical variables were subjected to principal component analysis (PCA), and the retained axes were analyzed by the criterion of Broken-Stick (Peres-Netoetal.,2005). The procedures for performing and interpreting the results follow the recommendations of McCune and Grace (2002).

3. Results and Discussion

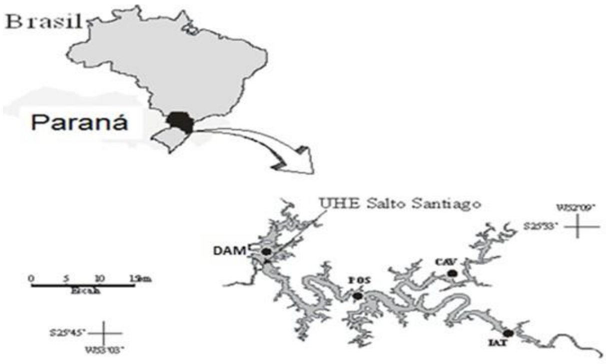


Fig. 1: Map of the different collection points in the Salto Santiago reservoir – Paraná, Brazil

The thermal profiles at the different collection points and different periods are shown in Figures 2. The rectilinear line structure of the temperature in the months of July, characterizing a uniform temperature in almost the entire body of water, except for slight changes in the surface. This was the opposite as seen in the months of January, in which the profile showed many nonlinear changes, indicating the formations of stratifications. This is due to presence of thermocline, whose location in the different depths is caused by the action of the winds, as observed by Henry and Barbosa (1989) in Vale do Rio Doce Lake.

Winter in the figure 3 characterizes a circulation defined by the absence of thermoclines or a weak presence, when they exist. In this case, the reservoir is subject to Kelvin-Helmholtz instabilities, Langmuir circulations and turbulent flows, as opposed to wind actions. In summer, solar heating and wind action are the main factors that gave rise to horizontal and vertical differences in the water mass (StraškrabaandTundisi, 2000). The instability observed in winter is due to the period of the year, which is rainier and colder with stronger winds compared to summer, the pressures and low temperatures cause a mixture even when there is no wind action, due to the process of transfer and diffusion of the temperature, replacing the body of water, i.e., the colder water moves to the bottom. This movement of replacement causes the mass circulation of water. Subsequently, layer mixtures and homogenization of the compartment result in the uniformity of the temperatures.

Figure 3 shows the value of Thermal Resistance to Circulation (TRC) at the different points and collection period with mean values for summer and winter.

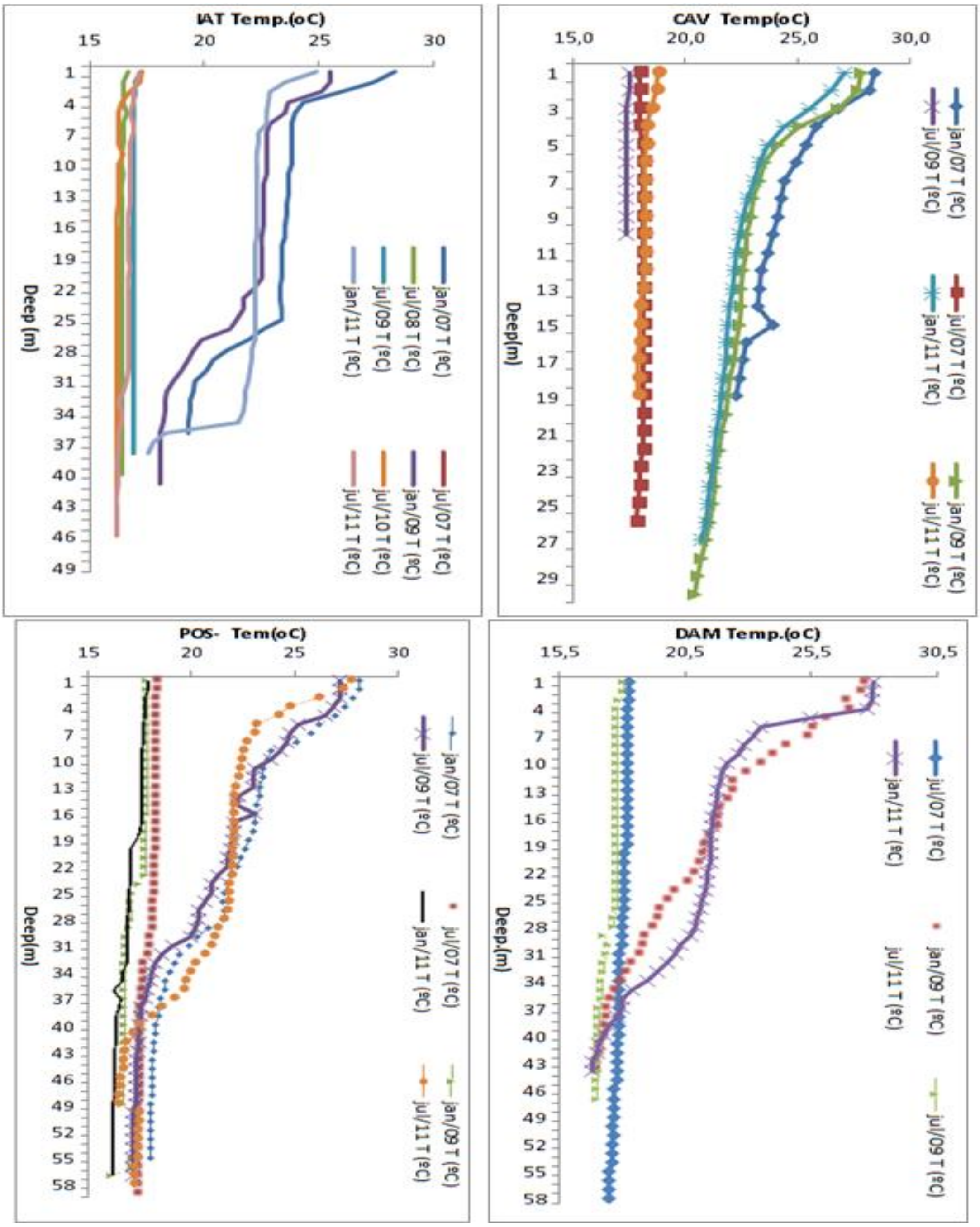


Figure 2: Temporal and spatial variation of the thermal profile in Salto Santiago reservoir at the different sample points

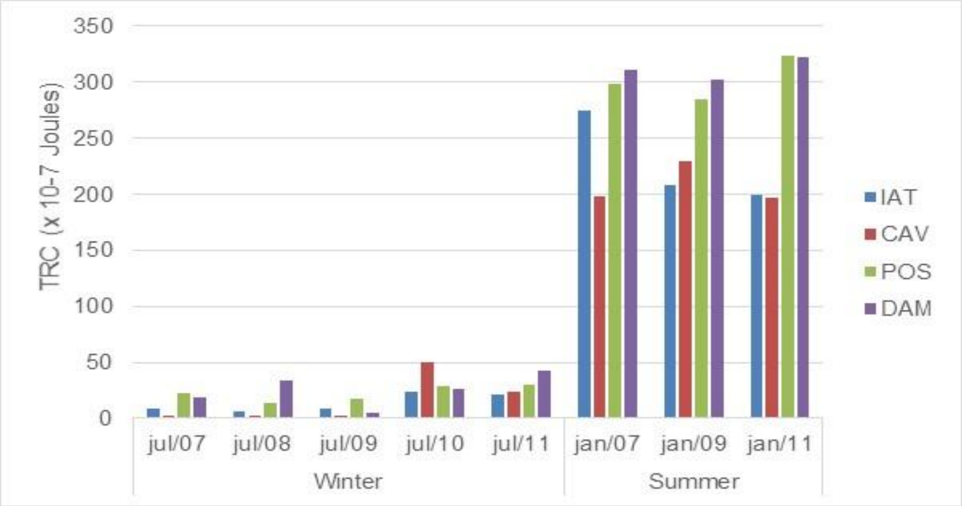


Figure 3: Temporal and spatial variation of the Thermal Resistance to Circulation or thermocline in the Salto Santiago reservoir

In the winter, the TRC corresponding to the months of July presented a mean minimum value 11.80 x 10^{-7}J in the IAT and a maximum value of 20.90 x 10^{-7}J at POS, whereas in the summer, characterized by the months of January, this variation occurred between 207.7 x 10^{-7}J and 311.41 x 10^{-7}J at the CAV and DAM points, respectively (figure 3). According to the results, the mean maximum and minimum values in winter showed that the reservoir presented moments of circulation as showed in fig 2. At the CAV and IAT points, the accumulated sums of TRC were 81.165 and 68.48 x 10^{-7}J, respectively, while at DAM and POS, the values of 125.27 and 113.7 10^{-7}J were recorded, respectively. The related values are low, characterizing the weak stratification due to the small temperature variations, indicating a mixture of the layers, which correspond to the circulation. In the summer, the TRC values were quite high, with the sum of 681.76, 623.1, 907.5 and 934.24 10^{-7}J at the CAV, IAT, POS and DAM sites, respectively. These values are characteristic of strong stratification, their specification being the formation of compartments with probability different chemical, physical and biological composition. The TRC is the quantification of energy stored between two different temperature layers or thermocline. Its extended effect may affect the distribution of organisms and the development of physiological adaptations by organisms for their survival.

The higher the value of TRC or the stronger the thermocline, act as a protective structure for the reservoir against the processes caused by wind, atmospheric instability, Langmuir circulation (Străskraba and Tundisi, 2000), and other parameters capable of creating destabilization, such as pressure. The low or near-null values show that the reservoir is subject to external action, causing a mixture of compartments and a state of vulnerability, instability, stirring, and mixture (Nyamien andTundisi, 2017).

Chemical components

The thermal structure affects the distribution of the chemical and biological components of the reservoir. These consequences are observed in the long run when this structure remains.

In this study, pH had a minimum of 5.5 and a maximum of 7.5, with a mean value of 6.90 ± 0.21 and 6.95 ± 0.52 in the winter and summer periods, respectively. The variation of standard deviation is greatest in summer due to the stratification. This variation was like those observed by Santos et al. (2011) in the Monjolinho reservoir, in São Paulo, Brazil. According to Salami (1996), the acidity of the water is due to the decomposition of the organic matter coming from the surrounding vegetation, which releases the carbonic gas, however close to the neutrality, which is the optimal situation.

The **dissolved oxygen** (DO) showed a minimum variation of 3.44 mg. L^{-1} in January 2008 at IAT and a maximum variation of 9.66 mg. L^{-1} in January 2010 at DAM in the summer, with a mean value of 5.67 ± 1.47 mg. L^{-1}. In winter, the minimum value of 2.58 mg. L^{-1} was recorded in July 2009, and the maximum value of 11.62 mg. L^{-1} at CAV in July 2011, with a mean of 6.97 ± 1.74 mg. L^{-1}. Similar value was found by Santos et al. (2001) in Monjolhno, SP. According to Santos et al. (2011), they show an inversely proportional relation of dissolved oxygen to temperature. According to this author, high concentrations of oxygen may be related to turbulent flow, high rates of photosynthesis, and low demand for DO by the heterotrophic aquatic community, in addition to the absence of an effluent. The values recorded did not indicate periods of anoxia at the points sampled.

Total phosphate (Ptotal) is integral to the effluent, comprising by products of the metabolisms of organisms, agricultural fertilizer, and synthetic detergent. It is limited to small amounts, as it is insoluble. It is responsible for algal growth, being characterized by eutrophication (Weiner, 2008). Its main function is to sequester the metal ion Fe, AL, Ca and maintain alkaline conditions. In this study, the total phosphorus concentration in the summer had a minimum value of 0.027 mg. L^{-1} in 2010 at POS and a maximum value of 5.42 mg. L^{-1} at POS in 2009, with an average of 0.34 ± 1, 19 mg. L^{-1}. In the winter, in turn, the minimum value was 0.027 mg. L^{-1} in 2010 at CAV, with a maximum of 1.17 mg. L^{-1} in 2009 at CAV and a mean value of 0.102 ± 0.04 mg. L^{-1}. Despite this variation, the values found are not very different from those recorded by Santos et al. (2001) in the Monjolinho reservoir (Figure 5F). The different value found between winter and summer is the stratification effect.

Orthophosphate, or inorganic phosphorus

This soluble compound is the most preferable form of algae and more stable in aqueous solution. Such forms play a regulatory role in the metabolism of aquatic microorganisms and are rapidly processed in the euphoric zone. The variation of its concentration is caused by mineralization by bacteria. In this study, the minimum values obtained in summer and winter were 0.017 mg. L^{-1} at DAM and 0.027 mg. L^{-1} at CAV in 2010. Maximum values reached 0.15 mg. L^{-1} at CAV in 2009 in the winter and 0.12 mg. L^{-1} at IAT in 2008 in the summer, with mean values of 0.094 ± 0.04 mg. L^{-1} in the winter and 0.067 ± 0.03 mg. L^{-1} in the summer. The results showed that, in the winter, there is a strong influence of the basin due to surface runoff. In the summer, it presented slightly higher values, which were, however, similar in the reservoirs of Salto Grande and Canoa I, according to Nogueira (2005).

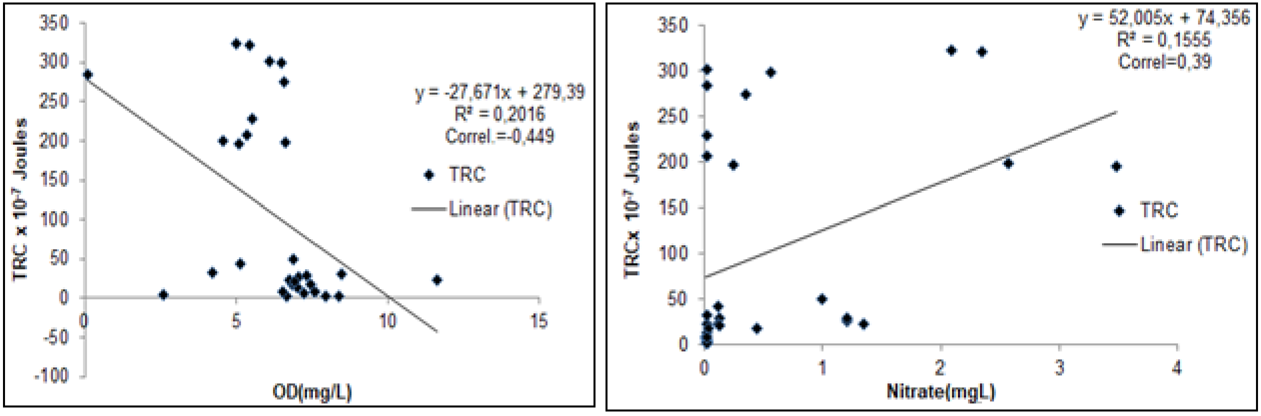
The chemical oxygen demand (COD) is used as an indicator of organic pollution. The results in the period show that, in the summer, the minimum value of 5.84 mg. L^{-1} and maximum value of 66.86 mg. L^{-1} were observed at POS and CAV, respectively, with a mean value of 22.22 ± 21.71 mg. L^{-1}. In the winter, a minimum value of 1.77 mg. L^{-1} and a maximum value of 32.19 mg. L^{-1} were recorded at IAT and POS, respectively, with a mean value of 10.35 ± 6.89 mg. L^{-1}. The high value in summer is the consequence of the separation of hypolimnium from metalimnium. The suspended matter in the period had a minimum value of 0.63 mg. L^{-1} in 2008 at POS and a maximum value of 13.16 mg. L^{-1} at BAR in 2009, with a mean value of 4.34 ± 4.19 mg. L^{-1} in the winter. In the summer, the minimum and maximum values were 0.8 mg. L^{-1} at POS in 2009 and 271.3 mg. L^{-1} at BAR in 2009. The maximum value observed at DAM may be related to events such as the rainfall observed, the high productivity of phytoplanktonic organisms, or dissolved or suspended material. In spite of this alteration in general, both in the winter and in the summer, the material in suspension presented low values. The minimum and maximum values obtained in summer are comparable to those obtained by Freitas et al. (2011) in the Cruzeta reservoir, Rio Grande do Norte.

Chlorophyll is one of the main agents responsible for photosynthesis. Its horizontal distribution depends on other factors such as wind patterns, proximity of nutrient sources, etc. (Pereira et al., 2004). In the study period, chlorophyll in the summer ranged from 0.09 mg. L^{-1} in IAT (2007), POS (2011) and a maximum of 3.18 mg. L^{-1} in IAT (2010). 0.78 ± 0.73 mg. L^{-1}. In winter, this parameter presented a minimum of zero in CAV (2008) and maximum of 2.0 mg. L^{-1} in CAV (2007) with an average of 0.60 ± 0.5 mg. L^{-1}. These values were much higher than the Cruzeta values in Rio Grande do Norte (Freitas et al., 2011)

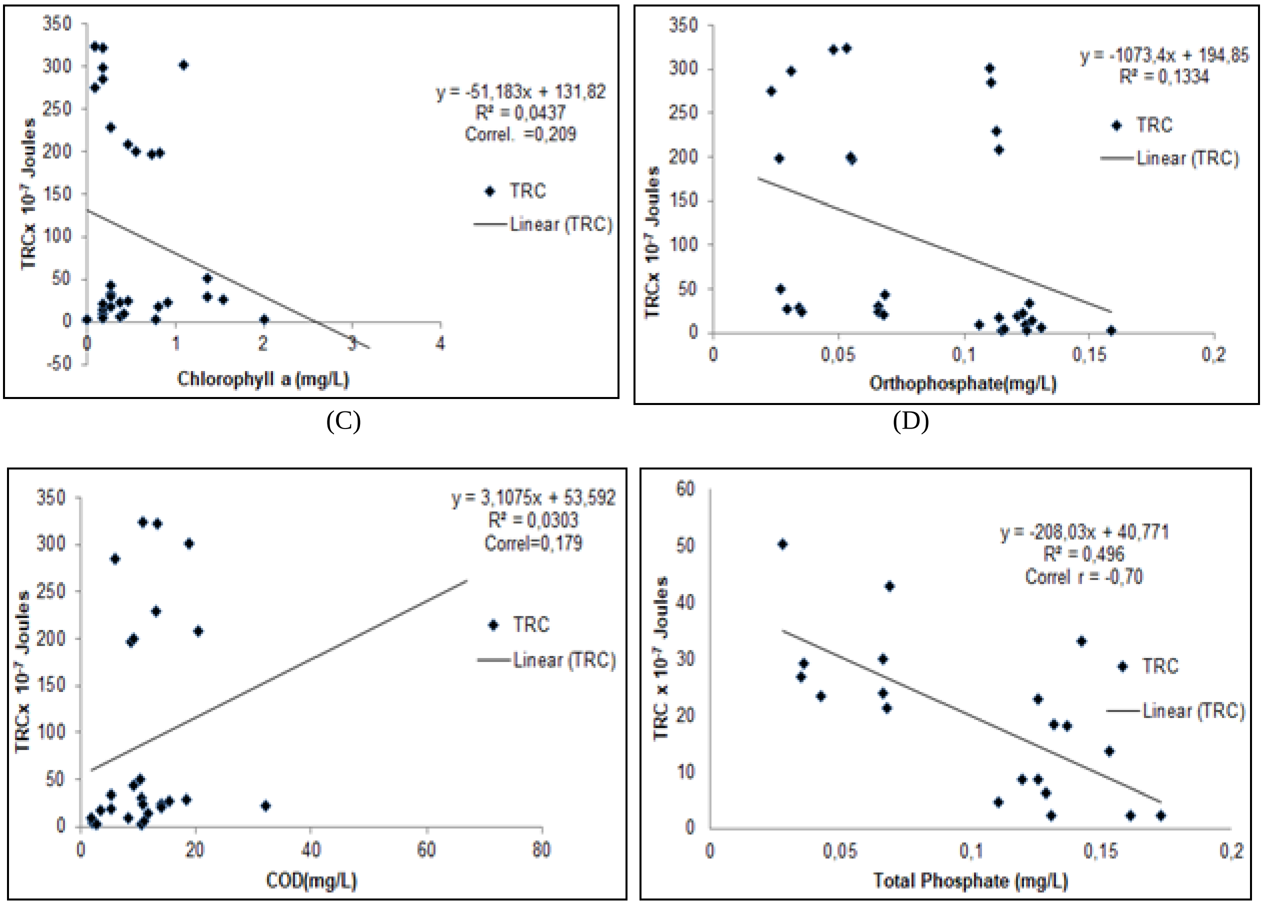
Among the major nitrogen compounds absorbed by aquatic plants in the summer, nitrate values were 0.02 mg. L^{-1} in 2008 and 2009 at all points, with 3.48 mg. L^{-1} at CAV (2011), with a mean value of 0.73 ± 1, 0 mg.L^{-1}. Despite being low, this mean value was higher than that found by Santos et al (2011) in Monjolinho.

Study of TRC correlations with chemical and biological compounds

The figure 4 showed the variations of the TRC with the function of the component concentrations over the period. The observation of the figures shows that parameters Nitrate (Figure 4b) and COD (figure 4e) had a positive relation with the TRC. Not with standing, the correlation calculation showed values of 0.39, 0.179, all of which being < 0.5 respectively, i.e., not significant. The analysis of the coefficients of determination in these cases also showed that the TRC influenced the concentration of these parameters. The figures 4a, 4c, 4d and 4f show that parameters orthophosphate, chlorophyll, dissolved oxygen and total phosphate had a negative correlation with the TRC. Nevertheless, among these correlations, total phosphate, orthophosphate and dissolved oxygen had a negative and significant correlation coefficient of r = -0.70, r = -0.70 and r = -0.44, respectively. The evaluation of the coefficients of determination showed that, despite these correlations, the TRC influences the concentration of orthophosphate and total phosphate by 49% and that dissolved oxygen by 20%.



(A) (B)



(C) (D)

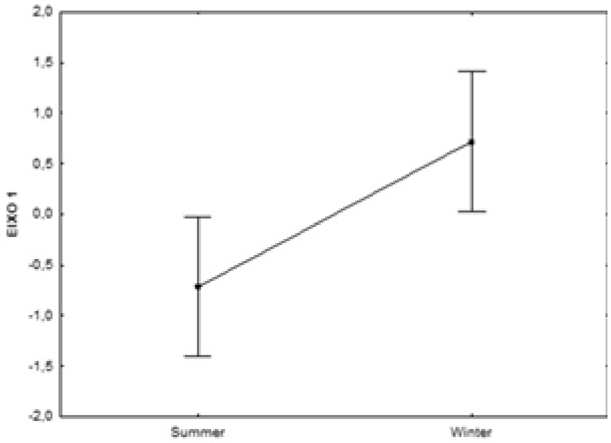
(E) (F)

Figure 4: Relation between TRC as a function of each chemical parameter during the study period, DO (a), Nitrate (b), Chlorophyll (c), Orthophosphate (d), COD (e) and total phosphate (f)

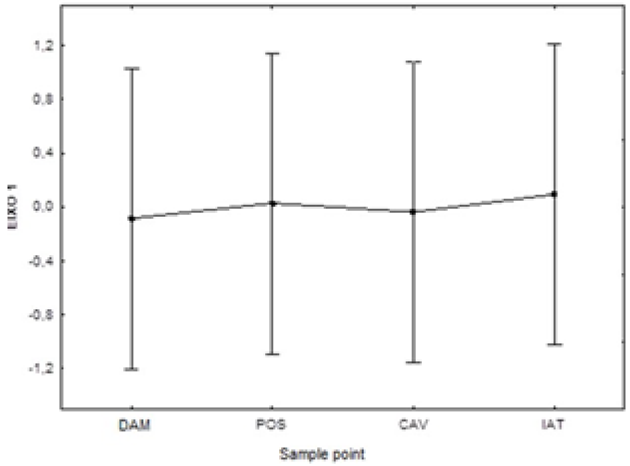
In ecological terms, high TRC values may cause oxygen deficit and a reduction in Ptotal, orthophosphate and chlorophyll in the deeper layers of the reservoir when stratification persists or becomes permanent. These reductions can lead to the death of aquatic organisms, while reducing the increase in primary production.

The analysis of variance at 5% significance performed to test the hypothesis of TRC equality in the period of January (summer), between sites IAT and CAV and between sites DAM and POS, presented p-values equal to 0.085 and 0.196 respectively, both higher than 0.05, indicating that the hypothesis of TRC equality was maintained. In the period of July (winter), the study between sites IAT vs CAV and DAM vs POS presented p-values of 0.328 and 0.406 respectively, both higher than 0.05 the hypothesis of equality of TRC between the sites in the summer being maintained. Regarding the evaluation of the hypothesis of equality between the entire summer and winter periods at the sites, a p-value equal to 1.0815×10^{-6} was found, i.e., less than 0.05, leading to the rejection of the hypothesis of equal TRC between summer and winter in the Salto Santiago reservoir.

Principal Component Analysis (PCA) revealed only one axis (EIXO1) that presented an auto value greater than at random (Broken-stick), and this axis showed an auto value of 2.73 and explained 34.18% of the data variability. Total dissolved phosphate and orthophosphate showed a positive contribution to the formation of the axis. Axis 1 clearly separated the summer and winter periods (Figure 5a). Total dissolved Phosphate and orthophosphate were the variables responsible for the separation of the winter season, in which the highest mean values for these variables were observed, 0.102mg/Land 0.094mg/L, respectively. Significant Differences in Axis 1 scores were observed between seasons (summer and Winter) (F1; 0.05=8.80; p<0.01). On the other hand, no pattern was observed for the sampling sites (Figure5b). (Statistic 7.0)



(a)



(b)

Figure 5: Temporal (a) and spatial (b) comparation of TRC in Salto Santiago reservoir indicating different between the period and equal between the sample point.

4. Conclusion

The Salto Santiago reservoir, based on the analysis of the thermal profiles, presented two distinct periods, a circulation with low TRC in the winter and a stratification with high TRC in the summer. This behavior confers a different thermal pattern in the summer and winter. Nevertheless, there is no spatial variation between the sites. The statistical analyses indicated that the stratification pattern is identical. The values of the chemical variables are not alarming, with a negative and significant correlation with Ptotal, orthophosphate, and dissolved oxygen, as well as a positive relation with COD, chlorophyll, and nitrate.

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