Environ Monit Assess (2016) 188:489
DOI 10.1007/s10661-016-5497-7

Physical-chemical determinant properties of biological communities in continental semi-arid waters

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Received: 29 January 2016 / Accepted: 19 July 2016

Abstract Throughout human history, water has undergone changes in quality. This problem is more serious in dry areas, where there is a natural water deficit due to climatic factors. The aims of this study, therefore, were (i) to verify correlations between physical attributes, chemical attributes and biological metrics and (ii) from the biological attributes, to verify the similarity between different points of a body of water in a tropical semi-arid region. Samples were collected every 2 months, from July 2009 to July 2011, at seven points. Four physical attributes, five chemical attributes and four biological metrics were investigated. To identify the correlations between the physicochemical properties and the biological metrics, hierarchical cluster analysis (HCA) and canonical correlation analysis (CCA) were applied. Nine classes of phytoplankton were identified, with the predominance of species of cyanobacteria, and ten families of macroinvertebrates. The use of HCA resulted in the formation of three similar groups, showing that it was possible to reduce the number of sampling points when monitoring water quality with a consequent reduction in cost. Group I was formed from the waters at the high end of the reservoir (points P1, P2 and P3), group II by the waters from the middle third (points P4 and P5), and group III by the waters from the lower part of the reservoir (points P6 and P7). Richness of the phytoplanktons Cyanophyceae, Chorophyceae and Bacillariophyceae was the attribute which determined dissimilarity in water quality. Using CCA, it was possible to identify the spatial variability of the physicochemical attributes (TSS, TKN, nitrate and total phosphorus) that most influence the metrics of the macroinvertebrates and phytoplankton present in the water. Low macroinvertebrate diversity, with a predominance of indicator families for deterioration in water quality, and the composition of phytoplankton showing a predominance of cyanobacteria, suggests greater attention to the management of water resources.

Keywords Water quality · Hierarchical cluster analysis · Canonical correlation analysis

Introduction

Water is essential for the survival of all living things on the planet (Tundisi et al. 2015), but human action, through various economic activities and uncontrolled growth, has been the cause of increasing problems for water resources, affecting the water both quantitatively and qualitatively (Hering et al. 2015). Such changes in aquatic ecosystems may become irreversible, particularly in heavily populated and emerging countries such as Brazil. Furthermore, problems arising from drought make access to water even more restricted to populations which inhabit the dry areas of the world (Mosley 2015), such as the semi-arid northeastern region of

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Brazil. These environments are characterised by irregular rainfall and high rates of evaporation (Alvial et al. 2013).

Within this context, the State of Ceará has developed a strong policy for the construction and monitoring of reservoirs (Campos 2015) as a strategy to minimise the problems arising from drought and enable supply for human consumption and other uses (Andrade et al. 2007). However, the water stored in these semi-arid ecosystems are subject to a deterioration in quality due to the high rate of evaporation (Reca et al. 2015), nutrient concentration and material in suspension, that varies as a result of anthropogenic factors (Molisani et al. 2013; De Paula Filho et al. 2015) and biogeochemical processes (Molisani et al. 2013; Lacerda et al. 2014; De Paula Filho et al. 2015), with the consequent eutrophication of the body of water (Molozzi et al. 2011; Azevêdo et al. 2015; De Castro Medeiros et al. 2015).

Also of importance is the occurrence of toxic blooms of cyanobacteria and the constant risk of cyanotoxins in the water supply from reservoirs in the northeast of the country, demonstrating a need to implement measures for the control of such blooms, with a view to improving water quality. To this effect, Piccin-Santos and Bittencourt-Oliveira (2012) carried out studies into reservoirs in the southeast and northeast of Brazil and identified 14 taxa of cyanobacteria, of which 11 were identified as potential producers of toxins. According to those authors, the occurrence of these taxa in the reservoirs under study emphasises the need for continuous monitoring of the quality of the water for human consumption.

An excess of nutrients, especially phosphates, in semi-arid reservoirs, is the result of such economic activities as agriculture, livestock (Santos et al. 2014; Lira et al. 2014; Kumar et al. 2015) and fish farming (Bezarra et al. 2014), and of domestic and industrial sewage (Wang et al. 2015; Du et al. 2014; Perrin et al. 2014). It is at this juncture that Lopes et al. (2014) propose the implementation of programs for the continuous monitoring and protection of the water resources of reservoirs inserted in the semi-arid northeastern region, as a way of guaranteeing the quality of the water for its respective uses.

However, monitoring based on physicochemical properties is not sufficient to meet the multiple use of the water, being particularly deficient in assessing the ecology of an ecosystem (Melo et al. 2015). It is therefore extremely important to include biological attributes in traditional monitoring systems. These include the use of bioindicator species (Azevêdo et al. 2015), mainly employing macroinvertebrates and phytoplankton (Van Ael et al. 2015).

The inclusion of bioindicators gives a more complete assessment of the effects caused by the various sources of pollution. It is important to note that little is known of the biodiversity of the biological communities which exist in the aquatic ecosystems of the tropical semi-arid region. There is a similar or even greater scarcity of information regarding the correlations that may exist between the biological, physicochemical attributes of aquatic ecosystems and their spatial and temporal distribution in the region (Dolédec et al. 2015).

In this context, Box et al. (2008) highlight the importance of studies into a survey of the biological diversity of ecosystems inserted in arid and semi-arid regions with a view to comparisons with future research, so as to understand the changes in aquatic ecosystems and the interference of human activity. From the above, the hypothesis of this work is that the waters of the Orós reservoir are dissimilar as regards biological attributes; the aims being (i) to verify correlations between the physicochemical attributes and the richness of macroinvertebrates and phytoplankton and (ii) to verify the similarity between different points of a body of water in a tropical semi-arid region from the biological attributes.

Material and methods

Description of the study area

The research was carried out in the waters of the Orós reservoir (6° 8′ 31″ S–6° 20′ 26″ S and 38° 54′ 56″ W–39° 13′ 28″ W), located on the upper middle third of the Jaguaribe River, in the semi-arid tropical region of Brazil (Fig. 1). The storage capacity of the reservoir is 1.9 billion cubic meters (m^3), with a contributing watershed of 25,000 km^2. The reservoir contributes to the water supply for a population of about five million people, who are downstream of the reservoir and in the metropolitan region of Fortaleza, in the State of Ceará (DNOCS 2015), as well as contributing to irrigation projects, industrial activities, tourism and fish farming.

The climate of the Upper Jaguaribe Watershed is of type BSw'h', hot semi-arid, with rains in the summer/autumn, an average monthly temperature always above 18 °C and average annual sunshine of 2800 h (CEARA

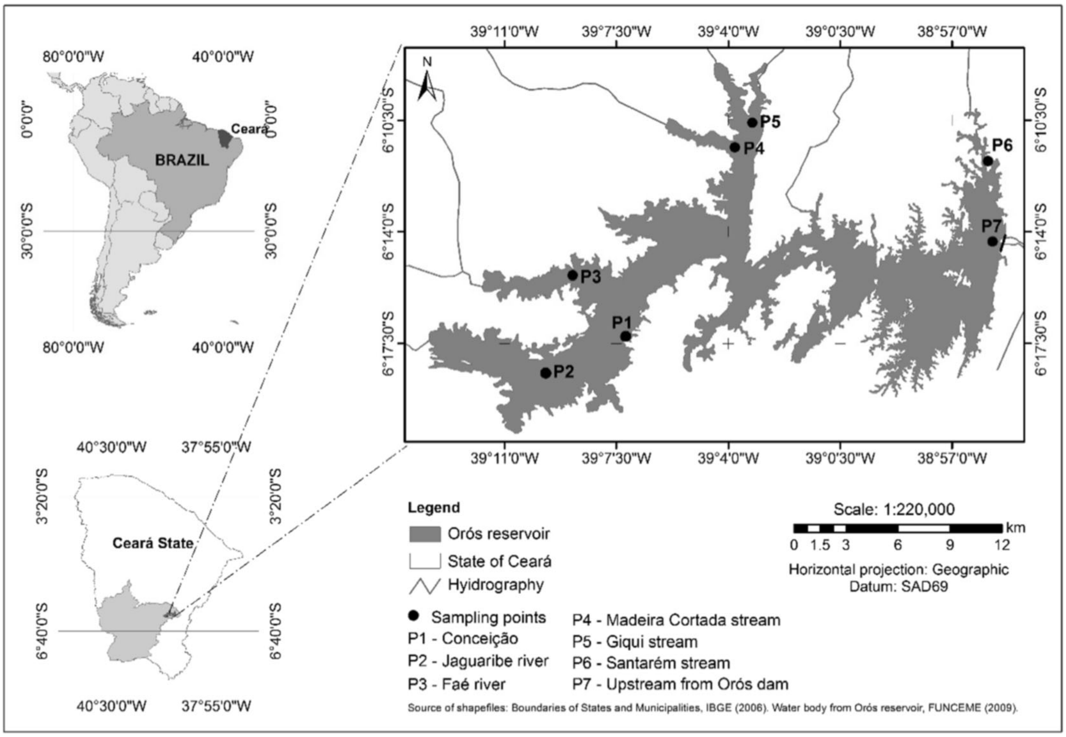

Fig. 1 Map of the Orós reservoir with collection points

1992). The rainfall regime is characterised by high spatial and temporal variability, with the irregularity of the regime being the main limitation on the rainfall in the region, and not the annual rainfall depth (Bressiani et al. 2015). The rainfall regime comprises two distinct seasons, a rainy season, concentrated from January to May and a dry season (from June to December). Average rainfall is 750 mm year^{-1}, while the average depth evaporated from the surface is 2945 mm annually (FUNCEME 2015).

The geology of the area is marked by the preponderance of rocks of the Precambrian crystalline basement (81 %), with a predominance of homogeneous and heterogeneous migmatites, gneiss and quartzite (Santana 2009). The watershed is made up of a wide variety of soils, with a predominance of Dystrophic Red-Yellow Argisols, Litholic Neosols, Chromic Luvisols, Fluvic Neosols and Vertisols (Brazilian System of Soil Classification) (Dantas et al. 2011). Many of these soils appear degraded through erosive processes intensified throughout the historical evolution of land use and occupation (Sales et al. 2014). The predominant ground cover is caatinga, which appears heavily degraded and partly devoid of its original condition, both from a physiognomic and floristic point of view (Toledo et al. 2014). Riparian forests, also fairly degraded, are found on the floodplains. At some places in the watershed, evidence of a process of desertification can now be clearly identified (Costa 2013).

Collection and sampling of attributes

Collection of the ten physical and chemical, and four biological attributes (Table 1) were carried out every 2 months from July 2009 to July 2011, at seven sampling points, six corresponding to the confluence of major tributaries (P1, Conceição; P2, Jaguaribe; P3, Faé; P4, Madeira Cortada; P5, Jiqui; P6, Santarém) and one (P7) located near the spillway of the reservoir (Fig. 1).

At each sampling point, triple samples of the macrophytes *Eichhornia crassipes* were taken, using a D-net with a mesh of 500 μm, and stored in hydrated ethyl alcohol (80 %). In the laboratory, the roots of the macrophytes were washed to remove any macroinvertebrates. These were separated, kept in ethyl alcohol (70 %) and appropriately labelled. The sorted macroinvertebrates were identified at the genus level with the help of identification keys from Brusca and Brusca (2007) and Mugnai et al. (2010). The community

Table 1 Attributes analysed, methodologies and references

Attribute	Methodology	Reference
Temperature (°C)	Mercury-filament thermometer 0–60 °C	APHA (2005)
Electrical conductivity (dS m^{-1})	Conductivity	
Secchi transparency (m)	Visualisation by Secchi disc	
pH	Potentiometric	
Total suspended solids (SST) (mg L^{-1})	Vacuum filtration with a glass fibre membrane of 0.45 μm porosity; drying at 103–105 °C	
Dissolved oxygen (mg L^{-1})	Azide modified Winkler method–iodometry	APHA (2005)
Total phosphorous (TP) (mg L^{-1})	Spectrophotometric—ascorbic acid	
Soluble orthophosphate (OPS) (mg L^{-1})		
Total ammonia nitrogen (TKN) (mg L^{-1})	Spectrophotometric—macro-Kjeldahl distillation followed by direct nesslerisation	
Nitrate (mg L^{-1})	Spectrophotometric—sodium salicylate	Rodier (1975)
Ric Mac[a]	Collection in a D-net (500 μm) with subsequent identification by key. The number of identified families associated with macrophytes of *E. crassipes* were considered	Brusca and Brusca (2007), Mugnai et al. (2010)
Ric Cya[b]	Bright-field microscopy with slides prepared from sediment obtained by centrifugation at 1500 rpm for 5–10 min for estimation of cyanobacteria density and identification of phytoplankton using dichotomous identification keys	Bourrely (1972), Komárek (1983), Streble and Krauter (1987), Komárek and Anagnostidis (1999), Bicudo and Menezes (2006), Cybis et al. (2006), Sant'anna et al. (2006)
Ric Chl[c]		
Ric Bac[d]		

[a] Richness of the macroinvertebrate family associated with the roots of *E. crassipes* macrophytes

[b] Species richness for Cyanophyceae

[c] Species richness for Chorophyceae

[d] Species richness for Bacillariophyceae

structure was then determined by analysing the richness of the macroinvertebrate family at each collection point, considering all the collections made: Ric Mac—richness of the macroinvertebrate family associated with the roots of the macrophyte *E. crassipes*.

In the field, samples of phytoplankton were collected by dragging a plankton net of 30 to 50 cm in diameter and a porosity of 20 μm. The equivalent of 500 mL of water was collected at each point and placed into previously washed and decontaminated amber containers. The samples were preserved in acetic Lugol solution and then forwarded to the laboratory for analysis. All the collection procedures were carried out following the recommendations of APHA (2005) and Bicudo and Menezes (2006).

Community structure was then similarly determined by analysing the richness of the phytoplankton species at each collection point, considering all the collections made: (i) Ric Cya—species richness for Cyanophyceae; (ii) Ric Chl—species richness for Chorophyceae; and (iii) Ric Bac—species richness for Bacillariophyceae. For choosing the attributes, the following studies, developed by Andrade et al. (2007), Andrade et al. (2008), Palácio et al. (2009), Silva (2013), Lopes et al. (2014), Rocha et al. (2015) and Ferreira et al. (2015), were considered when identifying the main attributes of water quality from reservoirs inserted in the Brazilian semi-arid region.

Analysis of the data

With the aim of confirming or rejecting the hypothesis of dissimilarity in the water quality of the reservoir in relation to biological attributes (Table 3), hierarchical cluster analysis (HCA) by the agglomerative method was carried out using the SPSS 16.0 software. This was followed by canonical correlation analysis (CCA) for correlations between the physicochemical attributes and the biological communities of macroinvertebrates and phytoplankton present in each similar group defined by the HCA. The attributes being investigated were considered when performing the CCA (Table 1). The analyses were carried out using the R-Project statistical program, v. 3.1.0 (R Development Core Team 2014). The principle of this multivariate technique is to develop a linear combination for each set of variables (X and Y) so that the association is maximised. With this method, there is no distinction between the independent and dependent variable; there are only two sets of variables, where the maximum correlation between the two is sought (Manly 2004).

Results and discussion

Composition of the biological communities

Tables 2 and 3 show the composition of the phytoplankton, and data for the richness of the macroinvertebrate families associated with macrophytes of the species *E. crassipes*, and species richness for the phytoplankton, respectively. Nine classes of phytoplankton were identified (*Cyanophyceae*, *Chlorophyceae*, *Bacilariophyceae*, *Chlamydophyceae*, *Crysophyceae*, *Dinophyceae*, *Euglenophyceae*, *Xantophyceae* and *Zygnemaphyceae*) in the waters of the reservoir.

Among the classes of greater abundance were the *Cyanophyceae* or cyanobacteria, *Chlorophyceae* and *Bacillariophyceae*, with the cyanobacteria being the most abundant of all the classes. For the class of cyanobacteria, from a total of 109 species, the prominent species are *Planktotrix agardii*, *Cylindrospermopsis raciboskii* and *Microcysitis aureaginosa*, which, according to Ammar et al. (2014) and Beamud et al. (2016), are potentially toxic to humans.

The problem here is that the waters of this reservoir make up part of the supply for around five million inhabitants from municipalities in the Jaguaribe Valley and the metropolitan area of Greater Fortaleza. Due to the current conditions of water quality, the cost of treating the water and making it suitable for human consumption according to the standards of the World Health Organisation (WHO 2008) is high. WHO recommends a maximum value for cyanobacteria (microcystin-LR) of 1 μg L^{-1}. For Cao et al. (2011), these species are strong competitors for both nutrients and light and indicate a deterioration in water quality.

In this context, studies by Costa et al. (2006), Costa et al. (2009) and Fonseca et al. (2015) in reservoirs in the State of Rio Grande do Norte demonstrate the importance of monitoring the quality of water for human consumption and the standards for potability, in the face of concentrations over the maximum limits suggested by WHO (1 μg/L). For macroinvertebrates, ten families were found (*Atyidae*, *Cybaeidae*, *Libellulidae*, *Perilestidae*, *Dyticidae*, *Hydrophilidae*, *Elmidae*, *Chironomidae*, *Ampularidae*, *Thiaridae* and *Planorbidae*), with molluscs from the families of *Ampularidae*, *Thiaridae* and *Planorbidae* being the most abundant, as per a study published for semi-arid ecosystems by Carvalho et al. (2013) and Rocha et al. (2015). The families found are indicators of both a deterioration in water quality and of the unfavourable environmental conditions for families sensitive to changes in the aquatic ecosystem. Ngodhe et al. (2014) found that the biological communities of macroinvertebrates responded with precision to the conditions of water quality, noting that they can be considered as biomarkers for bodies of water.

These studies show that in semi-arid reservoirs, the macroinvertebrate fauna comprises few species and that they suffer from the influence of such environmental factors as low rainfall, drought and variations in water level (Mehler et al. 2014), as well as from human activities, which affect both the quantity and quality of the water in these artificial ecosystems (Schmidlin et al. 2011; Braga et al. 2015; Azevêdo et al. 2015). The predominance of molluscs in semi-arid reservoirs was also noted by Rocha-Miranda and Martins-Silva (2006) and Callisto et al. (2014). According to these authors, the occurrence of these molluscs in reservoirs is a concern to public health, especially of riparian communities, since these organisms are intermediate hosts of trematodes which can infect man. Rocha et al. (2015) showed that the richness of macroinvertebrate families can be an important attribute in monitoring water quality in bodies of water in tropical semi-arid regions.

Hierarchical cluster analysis

To identify dissimilarity in the quality of the water from the reservoir, the HCA technique was employed, based on the richness metrics of the macroinvertebrate aquatic organisms and on the phytoplankton (Table 3). The dendrogram demonstrates that the optimal cutoff point for the rescaled distance cluster combine is between

Table 2 Biodiversity of phytoplankton and macroinvertebrates of the Orós reservoir

Bacillariophyceae
Amphora sp.
Aulacoseira granulata
Aulacoseira sp.
Cyclotella sp.
Cymbella sp.
Melosira granulata
Melosira sp.
Navicula sp.
Nitzschia sp.
Rhopalodia gibba
Chlamydophyceae
Chlamydomonas sp.
Eudorina sp.
Volvox sp.
Volvox globator
Chlorophyceae
Actinastrum gracillimum
Actinastrum sp.
Ankistrodesmus sp.
Ankyra ancora
Ankyra sp.
Chlorella sp.
Closteriopsis sp.
Closterium sp.
C. reticulatum
Coelastrum sp.
Crucigenia sp.
Coelastrum microporum
Crucigenia fenestrata
Crucigenia tetrapedia
Crucigeniella apiculata
Crucigeniella crucifera
Crucigeniella sp.
Dicloster sp.
Dictyospphaerium sp.
Eudorina spp.
Golenkinia sp.
Golenkiniopsis sp.
Kirchineriella lunaris
Kirchineriella obesa
Kirchneriella sp.
Micractinium sp.
M. contortum
M. irregulare
M. griffithii
Oocystis sp.
Paradoxia multiseta
Pediastrum duplex
Pediastrum simplex
Pediastrum tetras
Quadrigula spp.
Scenedesmus sp.
Scenedesmus acuminatus
Scenedesmus bernadii
Scenedesmus bicaudatus
Scenedesmus disciformis
Scenedesmus smithii
Selenastrum sp.
Tetraedron caudatum
Tetraedron muticum
Tetraedron minimum
Tetrastrum sp.
T. heteracanthum
T. staurogeniaeforme
Treubaria sp.
Crysophyceae
Chrysococcus sp.
Cyanophyceae
Aphanizomenon sp.[a]
Aphanocapsa sp.
Anabaena circinalis[a]
Anabaena sp.[a]
Choroococcus sp.[a]
Coelomorum sp.
Coelosphaerium sp.
Cylindrospermopsis racisborkii[a]
Cylindrospermopsis sp.[a]
Geitlerinema sp.
Gloeothece sp.
Merismopedia sp.
Microcystis aeruginosa[a]
Microcystis sp.[a]
Nostoc sp.
Phormidium sp.
Planktolyngbia sp.
Planktothrix agardhii[a]
Pseudanabaena sp.[a]
Raphidiopsis sp.[a]
Snowella sp.
Spirulina sp.
Spirulina sp.
Synechococcus sp.
Synechocystis sp.
Dinophyceae
Peridinium sp.
Euglecophyceae
Euglena sp.
Euglena acus
Phacus sp.
Strombomonas sp.
Trachelomonas sp.
Xanthophyceae
Isthmochloron sp.
Isthmochloron lobulatum
Tetraplektron sp.
Zignemaphyceae
Closterium sp.
Cosmarium sp.
Euastrum denticulatum
Euastrum sp.
Staurastrum gracile
Staurastrum sp.
Xanthidium sp.
Macroinvertebrates
Ampularidae
Atydae
Chironomidae
Dyticidae
Elmidae
Hydrophilidae
Libellulidae
Perilestidae
Planorbidae
Thiaridae

Source: Silva (2013) with modifications

[a] Species of cyanobacteria with toxic potential

Table 3 Macroinvertebrate and phytoplankton family richness in the Orós reservoir

Biological attribute	Collection point						
	P1	P2	P3	P4	P5	P6	P7
Ric Mac[a]	24	29	26	36	30	33	34
Ric Cya[b]	53	52	53	47	45	52	49
Ric Chl[c]	21	17	25	24	18	16	18
Ric Bac[d]	16	15	21	17	11	18	18

[a] Richness of the macroinvertebrate family associated with the roots of *E. crassipes* macrophytes

[b] Species richness for Cyanophyceae

[c] Species richness for Chorophyceae

[d] Species richness for Bacillariophyceae

8.68 and 13.12, determined by interpolation, since from this point, there is greater distance in the measure of similarity for forming subsequent groups (Fig. 2).

It can be seen in Figs. 2 and 3 that similarity analysis of the biological attributes resulted in the formation of three groups. Group I, formed from the points in the upper part of the watershed of the Alto Jaguaribe (P1, P2 and P3); group II, from the points in the middle third (P4 and P5); and group III, from the points in the lower part (P6 and P7).

The formation of distinct homogeneous regions demonstrates the dissimilarity in water quality. Similarity in water quality, employing the abundance metrics of macroinvertebrates, was also used by Elias et al. (2014) in studies of rivers in Tanzania. The differences between the three groups can be explained from an earlier study by Rocha et al. (2015) based on physicochemical attributes and the metrics of the macroinvertebrates. On the basis of this study, species richness for the Cyanophyceae, Chorophyceae and Bacillariophyceae was the determinant attribute in the formation of group I, where values showed statistically significant differences (at a level of 1 %, one-way ANOVA test) to the other groups (Table 4). This is a group formed by waters with higher values for the richness of these phytoplankton. The determining presence of these organisms suggests the release of domestic sewage (Batista et al. 2014; De Paula Filho et al. 2015), the development of farming activities (Lopes et al. 2014; De Paula Filho et al. 2015) and fish farming (Silva 2013; De Paula Filho et al. 2015), either being discharged directly into the water or by means of surface runoff.

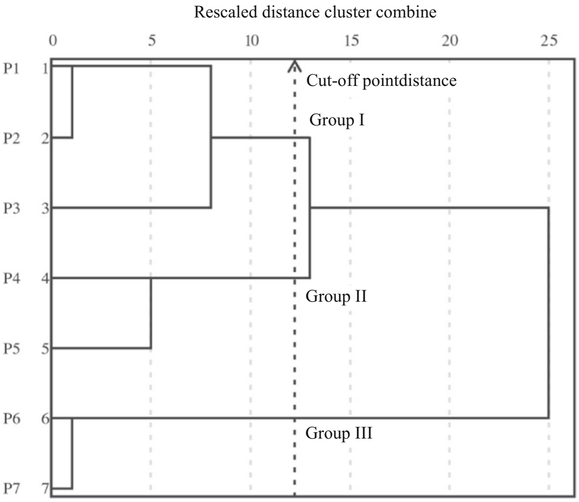

Fig. 2 Dendrogram showing clusters for the waters of the Orós reservoir

Recent studies (De Paula Filho et al. 2015) have shown that farming activities account for around 77.4 % of the nitrogen loading and 81.1 % of the phosphorus loading, with a strong contribution from livestock, 5944 t N year^{-1} and 2117 t P year^{-1}. Point sources for domestic effluent and fish farming occupy the second and third places, with emissions of 831 and 710 t N year^{-1} and 233 and 183 t P year^{-1}, respectively. Species richness for cyanobacteria was also the determinant attribute in the formation of groups II and III, whose values showed statistically significant differences (at a level of 1 %, one-way ANOVA test) to the other groups (Table 4).

The formation of distinct homogeneous groups for water quality shows that biomonitoring of the Orós reservoir may be accomplished by sampling only three of the seven points currently used, or by making use of composite samples for each group, resulting in a reduction in monitoring costs. Other studies developed from the similarity of physicochemical attributes confirm the present results. Andrade et al. (2008), Palácio et al. (2009) and Lopes et al. (2014) propose a reduction in the number of sampling points, with a consequent reduction in costs.

Canonical correlation analysis

According to Table 5 and Fig. 4, there is significant canonical correlation (r = 0.55, p < 0.05) (r = 0.92, p < 0.05) seen for group I (P1, P2 and P3) by Snedecor's F test, adjusted for Pillai's multivariate procedure. From the coefficients of the first canonical pair, a positive correlation can be seen between the attributes TKN ($r = -0.51$), TSS ($r = -0.54$) and nitrate ($r = -0.81$) of set I and the richness metrics of the Cyanophyceae (Cya) ($r = -0.54$) of

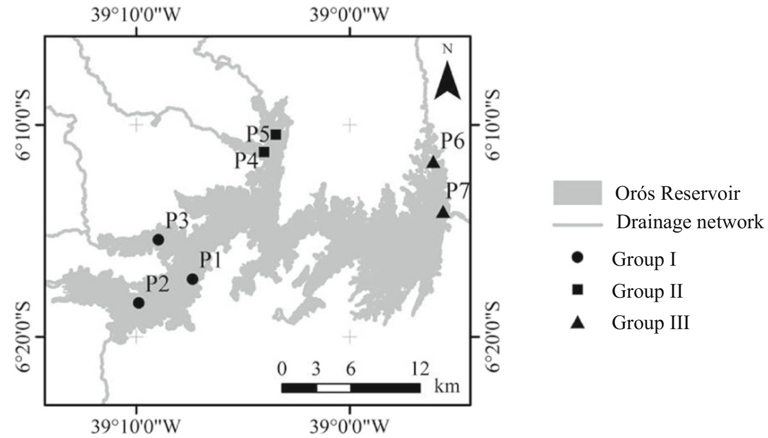

Fig. 3 Cluster analysis for the Orós reservoir

set II. From the coefficients of the second canonical pair, the CCA showed the richness metrics of the Chorophyceae (Chl) (r = 0.67), Bacillariophyceae (Bac) (r = 0.76) and macroinvertebrates (Mac) (r = 0.79) of set II as being positively correlated with the attribute T of set I (r = 0.53), and negatively correlated with EC (r = −0.72) and TP (r = −0.75).

It can be seen that the correlation between nitrate, TSS and TKN, and the richness metrics of Cyanophyceae, as well as the negative correlation of the attributes TP and EC for the organisms Mac, Chl and Bac, suggests the

Table 4 Statistics of the biological attributes of the Orós reservoir for the three groups defined by cluster analysis

Biological attribute	Statistic	Group		
		1	2	3
Ric Mac[a]	Mean	8.78 ± 2.64a	7.33 ± 2.59a	7.44 ± 1.60a
	Min	5	2	4
	Max	14	12	10
Ric Cya[b]	Mean	17.56 ± 3.83a	10.22 ± 3.31b	5.44 ± 0.94c
	Min	11	5	4
	Max	23	15	7
Ric Chl[c]	Mean	7.00 ± 3.78a	4.67 ± 2.22b	3.78 ± 1.98b
	Min	1	2	1
	Max	13	10	8
RicBac[d]	Mean	5.78 ± 2.59a	3.11 ± 1.48b	4.00 ± 1.33b
	Min	2	1	1
	Max	11	6	5

Means followed by different lowercase letters, differ on the line by one-way ANOVA test test at a level of 1%

[a] Richness of the macroinvertebrate family associated with the roots of *E. crassipes* macrophytes

[b] Species richness for Cyanophyceae

[c] Species richness for Chorophyceae

[d] Species richness for Bacillariophyceae

Table 5 Canonical correlations and canonical pairs between the attributes of set I (TKN, pH, CE, TSS, Ortho, Transp, TP, DO, nitrate and T) and set II (Mac, Cya, Chl and Bac) for points P1 P2 and P3 (group I)

Set	Attribute	Canonical pair			
		1	2	3	4
		Canonical correlation[a]			
C1	TKN	−0.51	−0.23	−0.20	−0.16
	pH	0.23	0.05	−0.61	−0.05
	EC	0.11	−0.72	0.22	0.45
	TSS	−0.54	0.20	−0.22	0.17
	Ortho	0.26	0.08	0.52	−0.14
	Transp	0.26	−0.45	−0.25	−0.25
	TP	0.01	−0.75	−0.25	−0.25
	DO	−0.06	0.28	0.09	0.05
	nitrate	−0.81	0.00	0.42	−0.23
	T	−0.19	0.53	0.16	0.19
C2	Mac	−0.44	0.79	−0.14	−0.25
	Cya	−0.54	−0.35	0.42	0.45
	Chl	0.47	0.67	0.27	0.40
	Bac	0.35	0.76	0.09	−0.44
	R–canonical	0.92	0.55	0.42 ns	0.36 ns

ns not significant, *TKN* total ammonia nitrogen, *EC* electrical conductivity, *TSS* total suspended solids, *Ortho* soluble orthophosphate, *Transp* Secchi transparency, *TP* total phosphorous, *DO* dissolved oxygen, *T* temperature (°C), *Mac* richness of the macroinvertebrate family associated with the roots of *E. crassipes* macrophytes, *Cya* species Richness for Cyanophyceae, *Chl* species richness for Chorophyceae, *Bac* species richness for Bacillariophyceae

[a] Canonical correlations ≥0.5 were considered significant for the purpose of interpretation

Table 6 Canonical correlations and canonical pairs between the attributes of set I (TKN, pH, CE, TSS, Ortho, Transp, TP, DO, nitrate and T) and set II (Mac, Cya, Chl and Bac) for points P4 and P5 (group II)

Set	Attribute	Canonical pair			
		1	2	3	4
		Canonical correlation[a]			
C1	TKN	−0.14	0.61	−0.21	0.59
	pH	−0.52	0.34	−0.05	0.32
	EC	−0.53	0.44	0.10	−0.47
	TSS	−0.24	−0.22	−0.37	0.19
	Ortho	−0.28	0.09	0.04	−0.28
	Transp	0.52	−0.36	0.35	−0.32
	TP	−0.22	−0.23	0.04	0.57
	DO	−0.37	0.22	−0.27	−0.30
	Nitrate	−0.05	0.51	−0.27	−0.21
	T	−0.31	−0.44	0.33	−0.27
C2	Mac	0.64	−0.53	−0.19	−0.53
	Cya	0.44	0.81	0.24	0.00
	Chl	0.83	0.01	−0.16	−0.53
	Bac	0.53	−0.39	0.66	0.18
	R–canonical	0.94	0.56	0.33 ns	0.26 ns

ns not significant, *TKN* total ammonia nitrogen, *EC* electrical conductivity, *TSS* total suspended solids, *Ortho* soluble orthophosphate, *Transp* Secchi transparency, *TP* total phosphorous, *DO* dissolved oxygen, *T* temperature (°C), *Mac* richness of the macroinvertebrate family associated with the roots of *E. crassipes* macrophytes, *Cya* species richness for Cyanophyceae, *Chl* species richness for Chorophyceae, *Bac* species richness for Bacillariophyceae

[a] Canonical correlations ≥0.5 were considered significant for the purposes of interpretation

influence of surface runoff and the excessive intake of nutrients in the Orós reservoir, and demonstrates the high level of eutrophication of this aquatic ecosystem inserted in the semi-arid northeastern region. These results indicate the excessive discharge of sediment and nutrients that has helped contribute to the dominance of the cyanobacteria, as well as reducing the richness of the other phytoplankton (Chorophyceae and Bacillariophyceae) and macroinvertebrates. According to Moreira et al. (2014) and Palácio et al. (2015), this favouring of cyanobacteria in aquatic ecosystems is a concern to public health due to the toxins which are produced and suggests an environment in the process of eutrophication. Such observations have also been noted in previous studies by Silva (2013), Lopes et al. (2014), Ferreira et al. (2015) and Rocha et al. (2015), which found that points P1, P2 and P3, located in the upper part of the reservoir, have the highest values for sedimentation and nutrients, especially at point P2, the influx of the Jaguaribe River, with its high contribution of suspended materials.

It should also be noted that according to data released by IBGE (2015), over 88 % of the households in the municipalities inserted in the watershed of the Alto Jaguaribe have no sewerage system, with solid waste still being disposed of on open dumps. For fish farming, it is found that large amounts of organic waste are released directly in the form of excreta and uneaten feed (Azevedo et al. 2011), so contributing to the process of artificial eutrophication of the reservoirs (Bezerra et al. 2014). According to De Paula Filho et al. (2015), fish farming has a direct impact on the water quality of the reservoirs, where estimates point to a release of the order of 583 t N year^{-1} and 150 t P year^{-1}, having a direct impact on the quality of this body of still water.

Other studies developed in the semi-arid northeastern region by Araújo (2009), Chaves et al. (2013), Silva (2013), Cordeiro-Araújo et al. (2015) and De Paula Filho et al. (2015) also point to aquatic ecosystems with high concentrations of nutrients and sediment and the presence of species of cyanobacteria. Such studies suggest effective management programs with an emphasis on the reduction of nutrient input, so as to preserve water quality and safeguard public health.

The result of the CCA also showed that in group I (Table 5 and Fig. 4), among the analysed attributes, temperature showed positive correlations with the richness of macroinvertebrates, Chorophyceae and Bacillariophyceae. In this context, Ruiz and Lopez-Portillo (2007) in Mexico, Morelli and Verdi (2014) in Uruguay, Gichana et al. (2015) in Kenya and Aazami et al. (2015) in Iran, also found that the abiotic attribute of temperature is strongly correlated with variations in the macroinvertebrate communities. Here, in Brazil, Rodrigues et al. (2007) and Salvarrey et al. (2014) also found that temperature has a positive influence on macroinvertebrate communities. Similarly, temperature is also positively correlated with the phytoplankton communities of Chorophyceae and Bacillariophyceae, as shown by the studies carried out by Tian et al. (2014) and Sevindik and Celik (2014).

It can be seen in Table 6 and Fig. 5 that there was significant canonical correlation ($r = 0.56$, $p < 0.05$) and ($r = 0.94$, $p < 0.05$) for group II (P4 and P5) for the first and second canonical pairs, respectively, by Snedecor's *F* test adjusted for Pillai's multivariate procedure. From

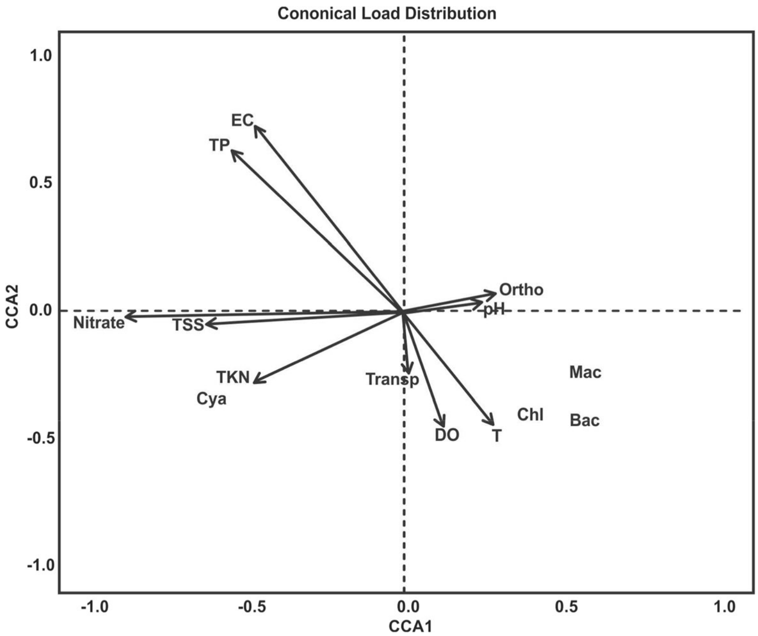

Fig. 4 Graphical representation of the canonical correlation analysis between the attributes of set I (TKN, pH, EC, TSS, Ortho, Transp, TP, DO, nitrate and T) and set II (Mac, Cya, Chl and Bac) for points P1, P2 and P3 (group I)

the coefficients of the first canonical pair, it can be seen that the richness metrics of the Bacillariophyceae (Bac) (r = 0.53), macroinvertebrates (Mac) (r = 0.64) and Chorophyceae (Chl) (r = 0.83) of set II are positively correlated with the physicochemical attribute (set I) Transp (r = 0.52) and negatively correlated with pH (r = −0.52) and EC (r = −0.53). Also, from the coefficients of the second canonical pair, the CCA showed that the richness metrics of the Cyanophyceae (Cya) (r = 0.81) in set II are positively correlated with the physicochemical attributes (set I) nitrate (r = 0.51) and TKN (r = 0.61).

As illustrated in Fig. 5, the richness of macroinvertebrates and of the phytoplankton Bacillariophyceae and Chorophyceae are grouped in the quadrant representing the attribute transparency. A reduction in transparency leads to a decrease in the richness of these aquatic organisms, which further

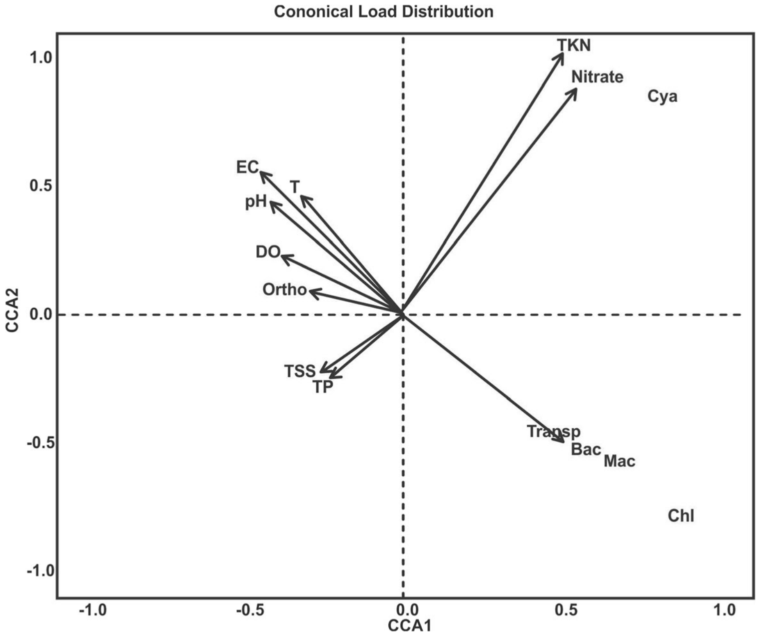

Fig. 5 Graphical representation of the canonical correlation analysis between the attributes of set I (TKN, pH, EC, TSS, Ortho, Transp, TP, DO, nitrate and T) and set II (Mac, Cya, Chl and Bac) for points P4 and P5 (group II)

Table 7 Canonical correlations and canonical pairs between the attributes of set I (TKN, pH, CE, TSS, Ortho, Transp, TP, DO, nitrate and T) and set II (Mac, Cya, Chl and Bac) for points P6 and P7 (group III)

Set	Attribute	Canonical pair			
		1	2	3	4
		Canonical correlation[a]			
C1	TKN	0.48	−0.20	0.35	0.12
	pH	0.65	−0.38	−0.06	0.46
	EC	0.24	0.14	−0.56	0.14
	SST	−0.36	0.18	0.15	−0.22
	Ortho	−0.25	−0.08	−0.08	−0.46
	Transp	0.05	0.17	−0.54	0.29
	TP	0.01	0.11	−0.04	−0.65
	DO	0.31	−0.05	−0.28	−0.11
	Nitrate	0.09	0.71	0.34	0.08
	T	0.26	−0.46	−0.11	0.26
C2	Mac	−0.67	0.22	−0.32	0.63
	Cya	0.35	0.51	−0.76	−0.19
	Chl	−0.64	−0.09	−0.74	0.16
	Bac	−0.71	0.16	−0.40	−0.56
	R–canonical	0.98	0.73	0.32 ns	0.23 ns

ns not significant, *TKN* total ammonia nitrogen, *EC* electrical conductivity, *TSS* total suspended solids, *Ortho* soluble orthophosphate, *Transp* Secchi transparency, *TP* total phosphorous, *DO* dissolved oxygen, *T* temperature (°C), *Mac* richness of the macroinvertebrate family associated with the roots of *E. crassipes* macrophytes, *Cya* species richness for Cyanophyceae, *Chl* species richness for Chorophyceae, *Bac* species richness for Bacillariophyceae

[a] Canonical correlations ≥0.5 were considered significant for the purposes of interpretation

leads to an imbalance in the food chain in the reservoir. In the broad sense, O' Neill et al. (2015) and Sharifinia et al. (2012) state that water of low transparency and high turbidity can reduce the abundance and richness metrics of invertebrates. Such conditions are generally unsuitable for most aquatic insects.

Along the same lines, studies carried out in other aquatic ecosystems also point to the same trend. Wan et al. (2014) and Silva and Henry (2013) found that transparency is one of the main attributes influencing macro-invertebrate communities. Medeiros et al. (2013) and Veras et al. (2013) also point to the dominance of macroinvertebrates in semi-arid ecosystems, mainly molluscs, which are a result of the high sedimentation rates and low transparency. Tian et al. (2014) also pointed out the strong correlation between communities of phytoplankton and transparency in the Jiangdong reservoir in China. According to the abovementioned authors, the composition and succession of phytoplankton are influenced by the transparency of the water in reservoirs and rivers, being organisms that are very sensitive to the presence of sediment in the water, with bacillariophyta becoming dominant during the succession process. In Turkey, Sevindik and Celik (2014) argue that transparency is directly related to the dominance of certain species, especially of cyanobacteria, which are characteristic of anthropogenic environments.

Earlier studies carried out by Lopes et al. (2014) and Batista et al. (2014) also found that transparency shows higher average values and amplitudes at points P4 and P5, a result of the increase in chlorophyll concentrations in the water. High values for this attribute indicate an increase in phytoplankton biomass in these ecosystems, with this increase causing changes in the colour of the water.

The correlation of pH with these organisms was also expected, as this attribute is able to modify the metrics of aquatic organisms. It should also be noted that earlier studies by Silva (2013) and Lopes et al. (2014) showed that pH values were always alkaline. It is suggested that high pH values in semi-arid reservoirs can be attributed to the geology, the soils and the activities of the phytoplankton. Furthermore, in relation to group II, it can be seen that the attributes TKN and nitrate show significant correlation with the cyanobacteria and that nitrogenous elements therefore continue to have a positive influence on these organisms; this demonstrates that excess nutrient input also continues to take place at points P4 and P5.

It can be seen in Table 7 and Fig. 6 that there was significant canonical correlation ($r = 0.73$, $p < 0.05$) ($r = 0.98$, $p < 0.05$) for group III (P6 and P7) for the first and second canonical pairs, respectively, by Snedecor's F test, adjusted for Pillai's multivariate procedure. From the coefficients of the first canonical pair, it is seen that the richness metrics of the Chorophyceae (Chl) ($r = -0.64$), macroinvertebrates (Mac) ($r = -0.67$) and Bacillariophyceae (Bac) ($r = -0.71$) of set II are negatively correlated with the physical and chemical attribute pH of set I ($r = 0.65$). Also, from the coefficients of the second canonical pair, the CCA showed that the richness metrics of the Cyanophyceae (Cya)

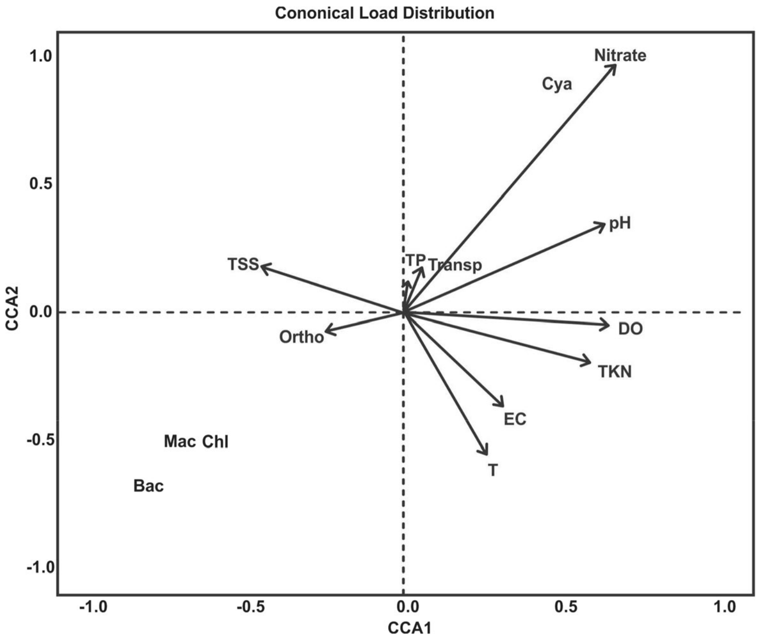

Fig. 6 Graphical representation of the canonical correlation analysis between the attributes of set I (TKN, pH, EC, TSS, Ortho, Transp, TP, DO, nitrate and T) and set II (Mac, Cya, Chl and Bac) for points P6 and P7 (group III)

(r = 0.51) in set II are positively correlated with the physicochemical attribute nitrate in set I (r = 0.71).

It should be noted that pH and nitrate are the main attributes that correlate with the biological communities. This demonstrates that despite the process of deposition that takes place throughout the reservoir, the waters leaving the spillway, at points P6 and P7, remain contaminated by cyanobacteria and large amounts of nutrients.

In short, by using canonical correlation analysis, it was possible to identify that the determinant attributes in the formation of group I were TSS, TKN, nitrate, total phosphorus, temperature and electrical conductivity, showing that the reservoir has received a lot of sediment and nutrients due to various human activities. For group II, the attributes were transparency, TKN, nitrate, EC and pH. Finally, for group III, the attributes which most correlated with the biological communities were nitrate and pH.

Conclusions

1. The Orós reservoir shows low macroinvertebrate diversity, with a predominance of families which are indicators of the deterioration in water quality, and a composition of phytoplankton showing a predominance of cyanobacteria.
2. With the multivariate analysis/HCA, it was possible to identify the formation of three distinct groups from the similarity of the biological communities, and the study identified the spatial variability of the chemical and physical attributes that most influence the metrics of the macroinvertebrates and phytoplankton in the Orós reservoir.
3. The excessive input of nutrients and sediment has contributed to the process of eutrophication of the surface waters of the Orós reservoir, affecting both the biological communities and the multiple uses of this resource.

Acknowledgments The authors wish to thank CNPq and CAPES for their financial support of this research.

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