Phytoplankton community: indicator of water quality in the Armando Ribeiro Gonçalves Reservoir and Pataxó Channel, Rio Grande do Norte, Brazil

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Received March 19, 2007 – Accepted September 3, 2007 – Distributed May 31, 2009

(With 3 figures)

Abstract

The current study analysed spatial-temporal modifications of the phytoplankton community and water quality, during dry and wet seasons. The phytoplankton community was studied in three areas: Armando Ribeiro Gonçalves Reservoir (ARG), which is an important public use reservoir in RN, Pataxó Channel (PC-before water treatment), Itajá, RN, and after the water treatment (WTP). Water samples from the reservoir were collected during both dry (January, February and November, 2006) and wet seasons (March to June, 2006). Quali-quantitative analyses of phytoplankton were carried out. Results indicated a qualitative similarity of the phytoplankton community in the three areas. However, significant differences were registered in these areas in relation to species relative abundance, with dominance of potentially toxic cyanobacteria, such as *Planktothrix agardhii* Gomont (dry season) and *Microcystis aeruginosa* Kutz (wet season). Ecological indexes obtained higher values before water treatment. Nevertheless, densities of cyanobacteria (organisms/mL) gradually reduced in the waters of the reservoir and of the Pataxó Channel before and after water treatment. After the treatment, density values of cyanobacteria were adequate for human consumption, according to the values established by the Health Ministry.

Keywords: Pataxó Channel/RN, Phytoplankton, biological indicator, water quality.

Comunidade fitoplanctônica: indicadora da qualidade da água no Canal do Pataxó/RN

Resumo

O presente estudo teve como objetivo avaliar as mudanças espaço-temporais da comunidade fitoplanctônica e a qualidade da água, durante os períodos de estiagem e de chuvas. A comunidade fitoplanctônica foi estudada em três estações distintas: na Barragem Armando Ribeiro Gonçalves (ARG - um importante reservatório de abastecimento público no RN), no Canal do Pataxó (PC - antes do tratamento da água), Itajá, RN; e depois da Estação de Tratamento da Água (WTP). Na barragem foram realizadas amostras da água em ambos os períodos de estiagem (janeiro, fevereiro e novembro 2006) e de chuvas (março a junho 2006). A metodologia compreendeu análises quali-quantitivas do fitoplâncton. Os resultados indicaram uma semelhança qualitativa da comunidade fitoplanctônica nos três pontos de estudo. Contudo, ocorreram diferenças significativas entre a abundância relativa das espécies, com a dominância de cianobactérias potencialmente tóxicas, como *Planktothrix agardhii* Gomont (período de estiagem) e *Microcystis aeruginosa* Kutz (período de chuvas), nas três áreas estudadas. Os índices ecológicos obtiveram maiores valores antes da Estação de Tratamento da Água. Todavia, as densidades de cianobactérias (organismos/mL) diminuíram gradativamente nas águas da barragem, canal antes e após o tratamento, tornando-se, após o tratamento da água, apropriada ao consumo humano, segundo os valores preconizados pelo Ministério da Saúde.

Palavras-chave: Canal do Pataxó/RN, fitoplâncton, indicador biológico, qualidade da água.

1. Introduction

In the micro region of the semiarid Northeast of Brazil, the rational exploitation of water resources, considering their multiple uses, mainly that of supplying the population, will be a great challenge in this century. Various water resource management programs have been implemented in the state of Rio Grande do Norte to guarantee the quality of the water supply to the population of this region. The construction of the Armando Ribeiro Gonçalves (ARG) Reservoir and the Pataxó Channel (PC) before and after the water treatment plant (WTP) has benefitted several rural communities. In spite of the judicious use of reservoir water for sustainable development through a system of water pipelines, there has been a varying impact on water quality, ecology and social consequences that affect human health (SERHID, 2006).

Thus, knowledge of the physical, chemical and biological characteristics of impacted ecosystems is extremely important (Xavier, 2005). Physical and chemical analyses provide information on water conditions at the moment the measurements are taken, making them critical when the object under study is a lotic system, in which the water is continually renewed at each point; however, periodic measurements over a considerable time frame significantly increase the information value of physical and chemical methods (Lobo et al., 2002). Biological analyses can detect possible alterations in water quality, as well as the tendencies over time that are reflected in habitat changes or the nature of aquatic organisms.

A well-documented auto-ecology and the study of biotic communities, their distribution, species abundance in determinate sampling areas, are important factors to take into account for indicating water quality. Among biotic communities, algae are recommended for water quality assessment, since they have diverse spatial and temporal distribution (Schoeman and Haworth, 1986; Coste et al., 1991; Prygiel, 1991; Round, 1971). Phytoplankton consists of a large variety of algae with different forms and life history strategies to maximize productivity. Among these are planktonic genera such as *Microcytis, Anabaena, Nodularia, Planktothrix, Aphanizomenon, Cylindrospermopsis, Trichodesmium,* which possess gas vacuoles that help to float; or benthonic genera (*Lyngbya, Phormidium, Oscillatoria, Schizothrix*) that tend to occupy the sediment (Codd, 2005), and neutrally buoyant algae that have a similar density to water such as *Oocystis* and *Chlorella* and members of dinoflagellates and euglenophyceae to migrate freely in the water column (Reynolds, 1984).

When reservoirs and lakes become more eutrophicated, the diversity of phytoplankton composition gradually decreases, which leads ultimately to cyanobacteria dominance and toxin production (Chellappa, 1990; Andersen, 1997; Azevedo et al., 1994). In recent years, community ecology has been viewed from the ecological complexity theme, which includes spatial and temporal complexities of biological species. Both are considered important pillars in the understanding of distribution over space and time (Loehle, 2004). Long-term dominance of cyanobacteria species is related to the increased productivity of shallow lakes, whereas colonial species generally dominate in deeper lakes and interfere in the pattern of phytoplankton distribution (Schreus, 1992).

One of the distinguishing characteristics of reservoirs in the northeast of Brazil is that the irregular rainfall and the rate of reservoir drawdown determine the distribution of plankton communities. It has also been recognized early on that eutrophication of reservoirs stimulates cyanobacterial blooms and decline in diversity, thus posing a double disadvantage in many of these water-starved regions (Bouvy et al., 2003; Chellappa et al., 1998). Many of the underlying mechanisms and key variables had been made for the timing of initiation and termination of bloom formation and the extent of damage caused by the toxicity of cyanobacterial species in Brazil.

The aim of the present study was to characterize the phytoplankton community of the Armando Ribeiro Gonçalves Reservoir and the Pataxó Channel before and after water treatment, to understand the distribution pattern of community structure, cyanobacterial dominance and the diagnosis of water quality through regular biomonitoring, establishing the degree of diversity/dominance ratio of the phytoplankton community.

2. Material and Methods

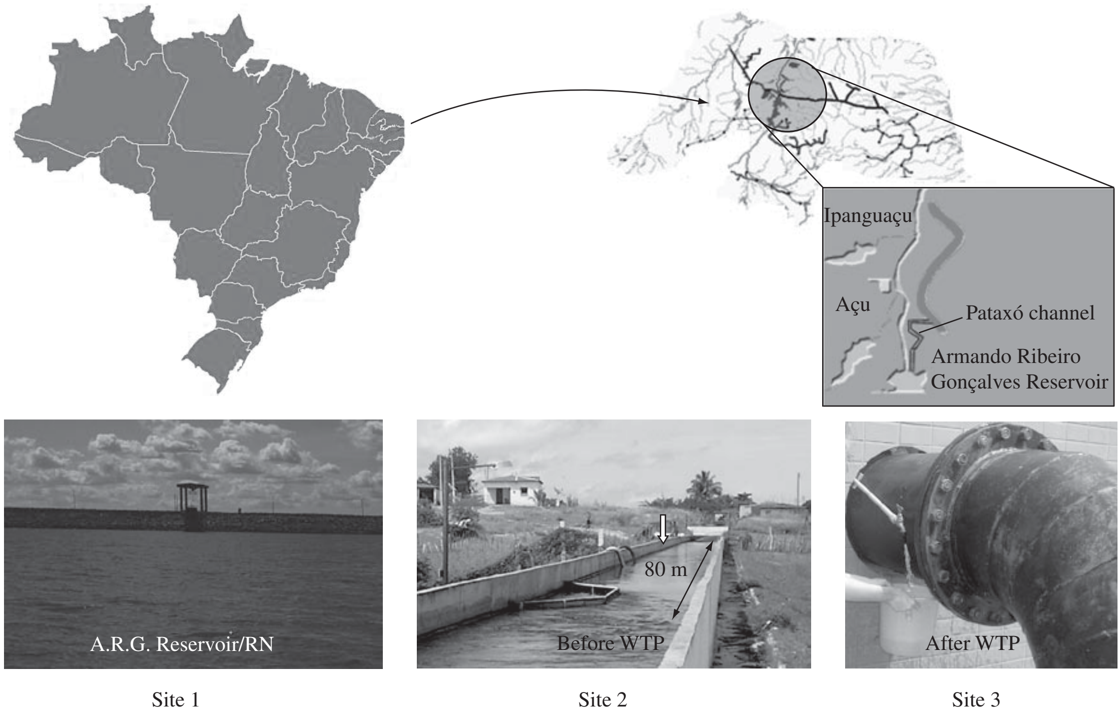
The study was conducted in Armando Ribeiro Gonçalves (ARG), Pataxo Channel (PC), and at a site after the water treatment plant (WTP). These sampling sites are situated in the semiarid zone of the state of Rio Grande do Norte, Brazil between the coordinates 5° 40' 12.10" S and 36° 52' 43.18" W. The Pataxó Channel (PC) was built to alleviate the water deficit problem in a number of cities in the countryside of Rio Grande do Norte. The system consists of an important class of tropical bodies of water with their own interaction between physical, chemical and biological processes. This interaction creates a strong seasonality according to variations in light, nutrients and mixing in the environment, which differs significantly from other tropical water systems. The channel is a long body of water about 2 m deep and its volume depends on the discharge of water from the reservoir in Assu (ARG). The channel was constructed with reinforced concrete with a mean width of 2.70 m, height of 2 m and unidirectional current flow varying between 0.5 and 0.7 m/s. This is an example of a closed-river system with marked variations in water level in the rainy season, which rapidly levels off, and a minimal supply of water and nutrients during the dry period, when local processes dominate. The channel water is well mixed, a longitudinally uniform water column, rich in dissolved nutrients with a clear and murky phase. This system is not deep enough to undergo seasonal stratification and is subject to regular cyanobacteria blooms because of low water flow, high surface temperature, alkalinity, pH and a moderate input of nutrients. The third site is located at the water treatment plant (WTP) near BR-304 highway approximately 80 m from the Pataxo Channel. The water is treated with chemical additives under the supervision of the Water and Sewage Company of Rio Grande do Norte – CAERN (Figure 1). This limnological characteristic, along with moderate water flow, creates a favorable habitat for the growth of phytoplankton and periphytic algae and floating aquatic macrophytes.

Rainfall data, air temperature and wind velocity were obtained from EMPARN (Agricultural Research Enterprise of Rio Grande do Norte).

Limnological analyses were based on in situ sampling using Van Dorn bottles (3 L) for the vertical water column collections at three depth strata: surface, middle (20 m) and bottom (30 m). The following parameters were analyzed in all the samples: pH, temperature, electrical conductivity and dissolved oxygen (WTW Multi 340i multiparameter kit), nitrate, (Golterman et al., 1978), orthophosphate (APHA, 1985) ammonium, total nitrogen and phosphorus (Golterman et al., 1978) and turbidity unit was analyzed with the LaMotte 2020 turbidimeter. The higher concentrations of total nitrogen and phosphorus are principle factors governing eutrophication in the Armando Ribeiro Gonçalves (ARG). The origin of enrichment emanates from catchments agro-fertilizers runoff, raw effluents from cage culture practiced on the shallow margins of the reservoir and the unchecked practice of detergent use by the local population in areas at a distance from the same reservoir.

Phytoplankton samples were collected with a 20 µm mesh net filtering 21 L of raw water and preserved in Lugol iodine, as recommended by Huszar and Giani (2004). The samples were analyzed in the laboratory with a TM800 Taimim microscope, using 40x magnifications. Taxonomic identification of the main genera and species was based on the works of Smith (1950), Desikachary (1959), Bicudo and Menezes (2005), Prescott (1970), Barber and Haworth (1981), Parra et al. (1983) and Wehr and Sheath (2003). Quantitative determination of the phytoplankton community was obtained though sedimentation and counting 1 mL of sedimented samples through a Sedgwick-Rafter counting chamber. During the counting, the following were considered individuals: isolated cells, whole colonies and filaments containing more than 10 cells. Relative species abundance and numerical density were obtained during the study period.

The following ecological index values were obtained through quantitative analysis: species richness, calculated according to Margalef (1958); Shannon-Wiener's (1949) diversity index; and equitability according to



Site 1

Site 2

Site 3

Figure 1. Location of the study area and collection sites. Site 1 = Armando Ribeiro Gonçalves Reservoir; Site 2 = Before the treatment plant (WTP); and Site 3 = After the treatment plant.

Pielou (1975). Pearson's correlation ($p < 0.05$) was used to find out the levels of significance relations among groups of phytoplankton with environmental variables using the Statistics 6.0 program.

3. Results

The total annual rainfall recorded (Jan/06 to Nov/06) is typical of semiarid regions in northeastern Brazil, with a maximum value in April of 190.4 mm and minimum in the dry period (January, February and July to November). Mean air temperature varied from 30.16 °C in January/06 to 26.95 °C in April/06. On collection days, average maximum temperature was 29.2 °C in January and average minimum temperature was 26.9 °C in the first half of April/06. Wind velocity varied little over the year, with means between 2.8 and 0.76 m/s. Wind speed influenced limnological characteristics through water column mixing. In the Armando Ribeiro Gonçalves reservoir, transparency was 0.40 m in the rainy period and 0.2 m in the dry season. In the Pataxó Channel, transparency varied from 0.51 m in January (dry period) with a depth of 0.70 m, to 0.95 in April (rainy period) with a depth of 1.3 m.

The mean of the physical-chemical variables during the dry and rainy periods analysed at the Armando Ribeiro Gonçalves Reservoir, in the Pataxó Channel and after the treatment plant, with maximum and minimum values during the study period, are presented in Table 1.

Table 2 presents the means of inorganic nutrients during the dry and rainy periods, with minimum and maximum values during the study period at the Armando Ribeiro Gonçalves Reservoir, Pataxó Channel and after the WTP. The Armando Ribeiro Gonçalves Reservoir had the lowest nutrient concentrations during the highest rainfall period and highest concentrations during the dry period. In the Pataxó Channel and after the water treatment plant (WTP), the nutrient values were moderate, with the lowest values after water treatment.

An absolute value for total nitrogen and phosphorus, when transformed into an N:P relation, showed a low N:P ratio as proposed by Schereus (1992). This is compatible with the abundance of cyanobacteria with a low N:P relation in the Pataxó Channel (before the WTP) and lower abundance after the WTP during most of the study period.

Table 3 shows a list of the phytoplankton species found in the Armando Ribeiro Gonçalves Reservoir, in the Pataxó Channel (before the WTP) and after the WTP during the study period. The phytoplankton community of the Armando Ribeiro Gonçalves Reservoir, the Pataxó Channel and after the treatment plant, was represented by the following taxonomic groups: *Cyanophyceae, Chlorophyceae, Euglonophyceae and Bacillariophyceae*, neverthless the group *Cyanophyceae* figured as the most representative group in the three sampling stations (Figure 2) during January and June and in November of 2006.

The temporal pattern showed a difference in the number of species, with 45 taxons recorded in the dry period and 57 in the rainy period. Spatial distribution indicated the surface samples of all four classes, with the dominance of Cy*anophyceae* species such as *Planktothrix agardhii* Smith (53.21%), *Oscillatoria* sp. (21%) in the dry period and *Microcystis aeruginosa* Kutz (42.2%) in the wet period. The Chlorophyceae were represented by species from the genera *Closteriopsis, Closterium, Coelastrum, Dictyosphaerium, Eudorina, Oedogonium, Oocystis, Palmella, Pandorina, Staurastrum, Tetradesmus* and *Tetraspora.* Among the chlorophyceae, the species of desmidiales, *Closterium* sp. and *Staurastrum* sp. predominated with a relative abundance of 10 and 8%, respectively, when compared to the other members of chlorophyceae with a relative abundance of less than 1%. However, the diatom species were found on the surface, mid-column and the bottom waters of the Assu reservoir, with *Aulocoseira granulata* Ehr of varying levels of abundance from sur-

Table 1. Average spatio-temporal distribution of physical-chemical variables at the Armando Ribeiro Gonçalves Reservoir, Pataxó Channel and after the water treatment plant (WTP) during the study period.

Armando Ribeiro Gonçalves Reservoir										
	Temperature (ºC)		**pH**		**Dissolved oxygen ($mg.L^{-1}$)**		**Conductivity ($\mu S.cm^{-1}$)**		**Turbid (NTU)**	
	Dry	**Rainy**	**Dry**	**Rainy**	**Dry**	**Rainy**	**Dry**	**Rainy**	**Dry**	**Rainy**
Surface	29.6	28.6	8.54	7.44	6.11	5.22	382	222	15	12
Mid-Column	28.2	28	8.28	7.69	4.25	3.81	359	212	10.2	9.8
Bottom	26.2	25	8.12	7.1	1.24	2.14	361	203	5.1	5
Pataxó channel (Before WTP)										
Average	29.73	29.62	8.74	8.34	5.685	5.636	242	234.12	6.45	4.59
min-max	(28.5-31.2)		(7.67-9.67)		(4.08-6.84)		(203.0-277.0)		(1.6-8.4)	
After WTP										
Average	29.53	29.02	7.42	7.68	3.708	4.7	233.6	239.12	1.55	2.97
min-max	(25.0-32.5)		(7.21-8.26)		(3.05-6.19)		(206.0-282.0)		(0.061-5.0)	

Table 2. Average spatio-temporal distribution of inorganic nutrient concentrations at the Armando Ribeiro Gonçalves Reservoir, Pataxó Channel and after the water treatment plant (WTP) during the study period.

	Nitrate (mmol/L^{1})		**Amoniumn (mmol/L^{1})**		**Orthophosfate (mmol/L^{1})**		**NT (mmol/L^{1})**		**PT (mmol/L^{1})**		**N:P Ratio**
	Dry	**Rainy**	**Dry**	**Rainy**	**Dry**	**Rainy**	**Dry**	**Rainy**	**Dry**	**Rainy**	
Armando Ribeiro Gonçalves Reservoir											
Surface	0.24	0.05	0.79	0.46	0.58	0.25	6.3	5	2.16	1.098	6:1
Mid-column	0.15	0.04	0.57	0.34	0.32	0.24	5.1	4.5	2.12	1.085	5:1
Bottom	0.09	0.06	0.59	0.17	0.29	0.21	6	4	2.1	1.08	6:1
Pataxó channel (Before WTP)											
Average	0.099	0.304	0.16	0.365	0.075	0.075	2.775	1.815	0.103	0.037	3:1
min-max	(0.068-0.498)		(0.058-0.823)		(0.03-0.1)		(0.84-3.62)		(0.018-0.19)		4.5:1
After WTP											
Average	0.052	0.231	0.06	0.277	0.039	0.033	1.258	0.662	0.015	0.009	8.5:1
min-max	(0.005-0.387)		(0.035-0.639)		(0.003-0.065)		(0.12-1.98)				6:1

Table 3. List of phytoplankton species found along the Armando Ribeiro Gonçalves reservoir, Pataxó Channel and after the water treatment plant (WTP) during the study period.

	Dry			**Rainy**		
	A.R.G Reservoir	**Before WTP**	**After WTP**	**A.R.G Reservoir**	**Before WTP**	**After WTP**
CYANOPHYCEAE						
Anabaena sp.	x	x	x	x	x	x
Aphanizomenon flos-aquae Komarek	x	x	x	x	x	x
Aphanocapsa sp.	x	-	-	x	x	x
Chrococcus minutus Copeland	x	x	x	x	x	x
Coelomorum tropicalis Senna	x	x	x	x	x	x
Coelosphaerium kuetzingianum Smith	x	x	x	x	x	x
Cylindrospermopsis raciborskii (Woloz.) Seenayya and Subbaraju	x	x	x	x	x	x
Cylindrospermum sp.	x	x	x	x	x	x
Gloeothece sp.	-	-	-	x	x	x
Gomphosphaeria lacustris Chodat	x	x	x	x	x	x
Limnothrix sp.	-	-	-	x	x	-
Lyngbya sp.	x	x	-	x	x	x
Merismopedia sp.	x	x	x	x	x	x
Microcystis protocystis Crow	-	-	-	x	-	-
Microcystis aeruginosa Kutz.	x	x	-	x	x	x
Nostoc sp.	x	x	x	x	x	x
Oscillatoria articulata Gardin	x	x	x	x	x	x
Oscillatoria granulata Gardin	x	x	x	x	x	x
Oscillatoria lacustre Geitler	x	x	x	x	x	x
Oscillatoria limosa Smith	x	x	x	x	x	x
Oscillatoria sancta Kling	x	x	x	x	x	x
Oscillatoria sp.	x	x	x	x	x	x
Oscillatoria splendida Grev	x	x	x	x	x	x
Phormidium autumnale Komarek	x	x	-	x	x	x
Phormidium richardsii Drouet	x	x	-	x	x	x

Table 3. Continued...

	Dry			Rainy		
	A.R.G Reservoir	**Before WTP**	**After WTP**	**A.R.G Reservoir**	**Before WTP**	**After WTP**
Planktothrix agardhii Gomont	x	x	x	x	x	x
Pseudanabaena limnetica Komarek	x	x	x	x	x	x
Raphidiopsis curvata Geitler	x	x	x	x	x	x
Rivularia sp.	-	-	-	x	x	x
Sphaerocavum brasiliense Azevedo et Sant' Anna	-	-	-	x	-	-
Synechocystis sp.	x	x	-	x	x	x
CHLOROPHYCEAE						
Botryococcus braunii Kutzing	-	-	-	x	-	-
Chlamydocapsa bacillus (Teiling) Fott	-	-	-	x	-	-
Closteriopsis longíssima Prescott	x	x	x	x	x	x
Closterium sp.	x	x	x	x	x	x
Coelastrum sp.	x	x	x	x	x	x
Crucigenia sp.	-	-	-	x	x	x
Dictyosphaerium sp.	x	x	x	x	x	x
Eudorina sp.	x	x	x	x	x	x
Oocystis sp.	x	x	x	x	x	x

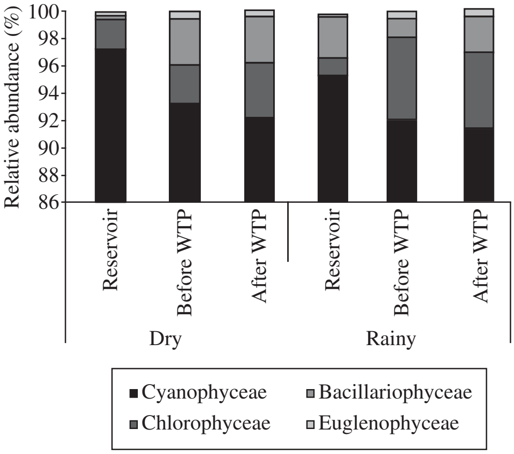


Figure 2. Temporal and spatial relative abundance of the groups phytoplancton in the Armando Ribeiro Gonçalves Reservoir, Pataxó Channel (Before the treatment plan) and after the treatment plant during the study period.

face to bottom and seasonally. In the mid column of the Assu reservoir, the most abundant species continued to be *Planktothrix agardhii* Smith (31.2%) and *Oscillatoria* sp. (21%) in the dry period and *Microcystis aeruginosa* Kutz (35.23%) in the rainy season. The other dominant species was *Navicula* sp., found regularly in both dry and rainy periods and at all depths, with a greater abundance at the bottom of 34.25% in the dry season and 29.54% in the rainy season. Only three euglenophyceae species were found (*Euglena* sp., *Phacus* sp. and *Trachelomonas volvocina* Ehr), generally in the mid water column during both the dry and rainy periods.

Cyanophyceae were persistently dominant in the Pataxó Channel before, and reduced dominance after, the water treatment plant (WTP). It includes species from the genera *Anabaena, Aphanizomenon, Chrococcus, Coelomorum, Coelosphaerium, Cylindrospermopsis, Cylindrospermum, Gomphosphaeria, Lyngbya, Merismopedia, Microcystis, Nostoc, Oscillatoria, Phormidium, Planktothrix, Pseudoanabaena, Rhaphidiopsis* and *Synecocystis.* The largest number of taxons was found in the dry period both in the Pataxó Channel (51) and after the WTP (47). Species from the Cyanophyceae group had higher relative abundance during the study period, with greater dominance of the species *Planktothrix agardhii* Gomont, of 52.53 and 87.47% before and after the WTP, with numerical density varying between 7,644 and 17,776 filaments/mL, also being abundant in the cyanophyceae class during the dry period. In the rainy season, the species *Microcystis aeruginosa* Kutz had a relative abundance between 31.36 and 65.32% before the WTP and between 35.21 and 71.21% after the WTP with the density of 20,400 to 34,500 individuals/mL.

The species of euglenophyceae, represented by *Euglena* sp., *Phacus* sp. and *Trachelomonas volvocina* Ehrenberg and the diatoms, represented by the genera *Amphora, Aulacoseira, Cylindrotheca, Cymbella,* *Navicula, Nitzchia* and *Synedra* are found in smaller proportions.

Besides the dominant species, the Cyanophyceae also included the species of *Anabaena* sp., *Aphanizomenon flos-aquae* Komarek, *Chrococcus minutus* Copelan, *Coelomorum tropicalis* Senna, *Coelosphaerium kuetzingianum* Smith, *Cylindrospermum* sp., *Gomphosfhaeria lacustris* Chod, *Lyngb*ya sp., *Merismopedia* sp., *Oscillatoria articulata* Gardin, *Oscillatoria granulata* Gardin, *Oscillatoria lacustre* Geitl, *Oscillatoria limosa* Smith, *Oscillatoria sancta* Kling, *Oscillatoria* sp., *Oscillatoria splendida Grev, Phormidium autumnale* Komarek, *Phormidium richardsii* Drouet and *Pseudanabaena limnetica* Komarek. A greater number of species were added in the rainy season, among them, *Aphanocapsa* sp., *Gloeothece* sp., *Rivularia* sp., and *Microcystis aeruginosa* Kutz being the most abundant in the majority of cases The species *Staurastrum* sp. was the most prevalent of the chlorophyceae, with a numerical density between 119 and 4,111 org/mL in the rainy period and from 194 to 1,003 org/mL in the dry period. The diatomaceae were represented mainly by the species *Aulacoseira granulata* Ehr (85-859 org/mL in the dry season and 35-566 org/mL in the rainy season), *Amphora* sp. (85-657 org/mL), *Cylindrotheca* sp. (88-208 org/mL) and *Navicula* sp. (28-424 org/mL), with the last three species present exclusively in the rainy period and absent in the dry period.

After the WTP, *Anabaena* sp., *Aphanizomenon flos-aquae* Komarek, *Chrococcus minutus* Copelan, *Coelomorum tropicalis* Senna, *Coelosphaerium kuetzingianum* Smith, *Cylindrospermum* sp., *Oscillatoria* sp., *Planktothrix agardii* Smith, and *Planktothrix rubescens* Gomont continued to be prevalent. These species represent over 90% of the cyanobacteria found in the community, with the relatively high percentage of *Planktothrix agardhii* Gomont, on average 78% in the dry season and 22% in the rainy season. However, the numerical abundance was restricted to 8,200 and 12,500 filaments/mL in the dry period and between 1,794 and 5,826 filaments/mL in the rainy period than those found before the WTP. In the rainy season, *Aphanocapsa* sp., *Gloeothece* sp., *Microcystis aeruginosa* and *Rivularia* sp. were additional species identified in the WTP.

The ecological indices for Margalef's species richness, Shannon's diversity, Bergen Parker's dominance and Pielou's similarity (co-existence) generally showed the highest values for phytoplankton before and after the water treatment plant. Figure 3 shows the values of phytoplankton biological indices during the study period. Species richness had values varying from 3.17 (2nd half of April, 2006) to 6.54 (2nd half of June, 2006) before the WTP and from 1.79 (1st half of March, 2006) to 4.32 (1st half of April, 2006) after the WTP. Lower values occurred during the dry season, with a mean of 4.08 before the WTP and 3.12 after the WTP in the rainy season (5.26 before the WTP and 3.59 after the WTP). The phytoplankton dominance indices had a minimum of 0.72 (2nd half of May, 2006) and maximum of 1.98 (1st half of Nov. 2006) before the WTP and values between 0.86 (2nd half of May, 2006) and 1.26 (1st half of Nov. 2006).

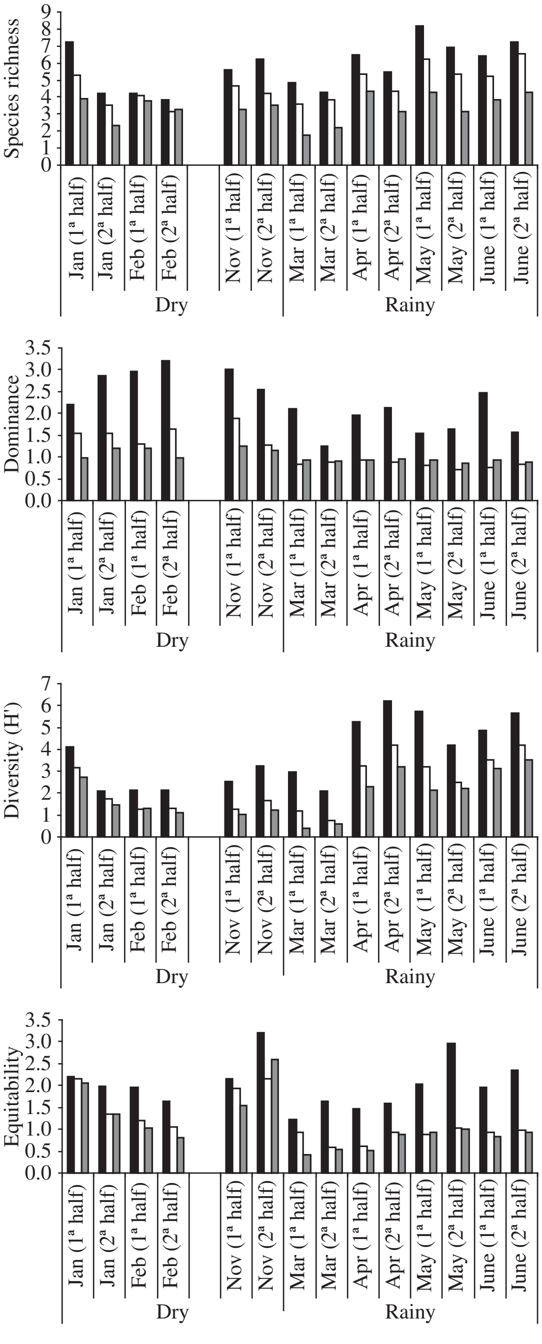


Figure 3. Ecological indices (Richness, Diversity, Dominance and Species equitability) of phytoplankton during the dry (Jan/06 and Nov/06) and rainy (Mar/06, Apr/06, May/06 and June/06) seasons.

The equitability indices before and after the WTP were significantly higher in the dry period as compared to the rainy period. The lowest values were observed in the 2nd half of March, 2006 (0.58) before the WTP and in the 1st half of March,2006 (0.41) after the WTP.

Table 4 shows a number of significant correlations between the environmental variables and the phytoplankton groups on the spatiotemporal scale. During the dry season significantly positive correlations were established between the Chlorophyceae, Bacillariophyceae and Euglenophyceae groups and nitrate before the WTP and between the Bacillariophyceae and nitrate after the WTP. There was a positive correlation between the Cyanophyceae group and temperature and between the Bacillariophyceae group and ammonium during the rainy period before the WTP and a negative correlation between the Bacillariophyceae and pH. During the rainy period, after the WTP, most of the correlations were negative between nitrate and the Chlorophyceae, Bacillariophyceae and Euglenophyceae groups, between the Cyanophyceae group and pH and between the Euglenophyceae group and orthophosphate. Positive correlations in this period occurred only between the Cyanophyceae and electrical conductivity. The total nitrogen and phosphorus levels correlated significantly with cyanobacterial dominance in both the dry and rainy season.

4. Discussion

Phytoplankton growth and development are mainly steered by available solar energy input, hydrodynamic forces like stratification and mixing and the resulting levels of nitrogen and phosphorus in semiarid Rio Grande do Norte State (Chellappa et al., 2006). The results of the present study were discussed within the parameters of reservoir and channel limnology, including seasonal variations in physical and chemical characteristics and phytoplankton diversity and the relative abundance. The ARG reservoir consisted of 27 cyanobacteria species (out of 45 phytoplankton species) during the dry period and 32 (out of 57 phytoplankton species) in the rainy season, similar to the numbers obtained between 2001 and 2003. There was a variation in this annual cycle only with respect to the greater succession of toxic cyanobacteria, *Microcystis aeruginosa* Kutz and *Cylindrospermopsis raciborskii* Woloz (Costa et al., 2006), whereas in this study, we observed a succession of *Planktothrix agardhii* Gomont *to Microcystis aeruginosa* Kutz. The relative abundance of *Planktothrix*, however, varied seasonally from 52% (water surface) during the dry season to less than 2% during the 32-40% bloom of *Microcystis aeruginosa* Kutz in the rainy season. The results of the current study are in accordance with the change in spatiotemporal dominance found in shallow waters in North Australia, where dominant species often change from *Anabaena circinalis* Bory to a small homogeneous population of cyanobacteria consisting of *Cylindrospermopsis, Planktolyngbya* and *Limnothrix* (Bormans et al., 2005). These authors discussed the relation between the index of monthly southern oscillation and the flow pattern of the Fitzroy River in North Australia, and identified a strong correlation between interannual climate variability and phytoplankton population dynamics. They also registered that the strong climate acts an important factor in cyanobacteria development owing to flow pattern seasonality and the variability resulting from the light-climate factor. However, under low-flow conditions, local climatic factors also affect the behavior of the mixture. In contrast, the present study found low water flow, high surface temperature and low N:P, resulting in high abundance of cyanobacteria, despite the fact that both the semiarid of North Australia and part of Northeast Brazil share certain climatic similarities.

The abundance of cyanobacteria among the diverse phytoplankton species is characteristic of the ARG reservoir, the Pataxó Channel (PC-before water treatment)

Table 4. Pearson's correlation between environmental variables and phytoplankton groups (N = 20; DF = 19; $p < 0.05$).

Variables	ARG Reservoir		Before WTP		After WTP	
	Dry	Rainy	Dry	Rainy	Dry	Rainy
Chlorophyceae and Nitrate	0.75	-	0.71	-	-	–0.77
Bacillariophyceae and Nitrate	0.84	-	0.74	-	0.75	–0.80
Euglenophyceae and Nitrate	-	-	0.87	-	-	–0.71
Cyanophyceae and Temperature	-	-	-	0.70	-	-
Bacillariophyceae and pH	-	–0.82	-	–0.87	0.97	-
Bacillariophyceae and Ammonium	-	-	-	0.80	-	-
Cyanophyceae and e pH	–0.85	-	-	-	0.71	–0.72
Euglenophyceae and Temperature	-	-	-	-	0.99	-
Cyanophyceae and Conductivity	-	0.79	-	-	-	0.74
Euglenophyceae and Orthophosfate	-	-	-	-	-	–0.86
Cyanophyceae and Total nitrogen	-	-	0.88	0.75	0.72	0.82
Cyanophyceae and Total phosphorus	0.92	0.85	-	-	-	-

and the water immediately after the waste treatment plant (WTP) site, with a similar distribution pattern. The ARG reservoir has a seasonal change in the abundance of cyanobacteria (from the dry to the rainy period) from *Planktothrix* to *Microcystis*, whereas the Pataxó Channel (before and after water treatment) maintained a constant abundance of *Planktothrix* despite seasonal change. The reservoir undergoes a change from filaments of *Planktothrix agardhii* Gomont to colonial *Microcystis aeruginosa* Kutz between the dry and rainy seasons, whereas the Pataxó Channel maintained a continual dominance of *Planktothrix agardhii* Gomont throughout the study period. There were also significant differences in the trophic state of the three sites studied.

All these phenomena are explained by two factors discussed in the results section, i.e. the differences in light availability at the ARG reservoir and at both surface-mixture and euphotic depths in the Pataxó Channel and the discrepant bio-availability at the nitrate and orthophosphate sites, nutrients that limit phytoplankton growth in general and cyanobacteria in particular. While these are the primary factors, another factor is the low water velocity in the Pataxó channel, despite synoptic-scale meteorology's being identical at both sites. Differences among the sites in specific mixtures in the temperature layers related to light in the water column create conditions that determine the composition of cyanobacteria populations. Statistical analyses pointed out that long-term dominance of cyanobacteria are usually correlated to multiple factors and not by a single factor (Schereus, 1992). The statistical results of the present study showed that besides temperature, conductivity, the total nitrogen and phosphorus, too, correlated significantly to the cyanobacterial dominance in all three sites.

Although turbidity decreases in the ARG reservoir in the rainy season, still low light intensity in the water column proved to be sufficient for phytoplankton growth. Only when the water column stratifies, do the particles sink slowly and are removed from the surface layer, thus initiating cyanobacteria growth. Cyanobacteria dominance in stratified systems has been reported by Oliver et al. (1999) in the Darling River in North Australia, where there was dominance of the species *Anabaena circinalis* Bory. If the depth of the mixture is greater than the penetration depth of light, phytoplankton biomass production remains low. Phytoplankton growth has been found to be negative when the depth of the mixture is more than four times greater than the euphotic depth (Talling, 1986). In stratified systems such as the ARG reservoir, floating cyanobacteria have a clear numerical advantage over other phytoplankton groups, with 32 of the 57 species. The longitudinal niche of the Pataxó Channel (before and after treatment) has a similar tendency, but is not influenced by stratification. The nutrient source was wind-borne, which induced the influx of nutrients to the water surface by the mixing of anoxic hypolimnetic water in the ARG reservoir, similar to that described by Bormans et al. (2004).

The ecological concept theory states that biodiversity, in relation to spatiotemporal heterogeneity, functional processes and species diversity, can provide a unifying theme for river ecology, given the productivity and the role of turbulent mixing (Ward and Tockner, 2001). The current study included the quantitative ecological aspects of species diversity, equitability, richness and dominance of the Pataxó Channel phytoplankton community (before and after treatment). The results indicated moderate values for species richness and diversity, even though the trophic state had changed from mesotrophic to oligotrophic and there had been an abundance of *Planktothrix* in the dry period and of *Microcystis* in the rainy period. The dominance index and the equitability relation for the diversity values were uncommon and influenced largely by the dominance of *Planktothrix* in the Pataxó Channel. However, the spatiotemporal heterogeneity of the phytoplankton community found at the ARG reservoir is quite different from that of the Pataxó Channel, which has low water flow with low to moderate water velocity. This increased species diversity, as has been observed with moderate disturbances found in many running water ecosystems (Reynolds, 1993). The seasonal variation was considered different between the study sites and was a further indication of temporal heterogeneity. A total of 45 taxons in the dry season and 56 in the rainy season were recorded in the Assu reservoir, while in the Pataxó Channel there were 51 and 47 taxons at the untreated and treated water sites, respectively, during the dry period.

Phytoplankton sucession follows R-C-S strategies both in natural and experimental conditions (Chellappa et al., 2006; Crossetti and Bicudo, 2005). Experiments performed in mesocosms revealed that the initial community mainly represented by R- and S-strategists (*Planktothrix, Cylindrospermopsis* and *Microcystis*) was gradually substituted by C-strategists *Cryptomonas* spp. chlorococcales in general (Crossetti and Bicudo, 2005). However, the present study clearly indicated that the cyanobacterium, *Planktothrix* overwhelmingly dominated during the dry period and was succeeded by the colonial cyanobacterium, *Microcystis aeruginosa* Kutz in the wet period and the members of chlorococcales simply co-existed along with these dominant species of cyanobacteria.

According to the Ministry of Health decree nº 518, of 25th March, 2004, the maximum density of cyanobacteria in the water supply must not exceed 20,000 cel.mL^{-1}, and raw water non-toxicity must be certified. In this study, cyanobacterial densities of *Planktothrix agardhii* Gomont in the dry season and of *Microcystis aeruginosa* Kutz in the rainy season in the Armando Ribeiro Gonçalves Reservoir and in the Pataxó Channel exceeded the density allowed by the Ministry of Health. After treatment, the water had densities well below these levels and was suitable for human consumption in terms of its density; however, further studies with biotrials are needed to verify the non-toxicity of this system.

This article emphasized how climatic conditions in the semiarid, specifically rainfall, results in high discharge flows, with changes in light, climate and influx of nutrients into the Armando Ribeiro Gonçalves Reservoir that sustain *Planktothrix agardhii* and *Microcystis* growth in the Pataxó Channel (before and after water treatment). It also highlighted the importance of depth differences in the Assu reservoir and Pataxó Channel and the variable trophic levels found in the physical and chemical conditions that favored dominance and led to the succession of cyanobacteria observed.

Acknowledgements — The first author would like to thank CNPq for the research grant (proc. nº 501375/2004-0). The second author would like to thank CAPES/MEC for the Master´s degree scholarship and the Universidade Federal do Rio Grande do Norte.

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