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Impact of stress and disturbance factors on the phytoplankton communities in Northeastern Brazil reservoir

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ABSTRACT

The ecology of phytoplankton reservoir communities plays a pivotal role in their management and in the development of inland fisheries in the water scarce semi-arid regions of Rio Grande do Norte State, Brazil. The hydrological conditions characterizing these reservoirs include infrequent rainfall and high evaporative loses. The phytoplankton assemblages in tropical climate are structured primarily on dry and wet cycles, not the annual temperature and light regime. The purpose of the current study was to investigate the ecological aspects of phytoplankton communities from three reservoirs during the period of July 2003–June 2004, which include atypical summer rainfall and reservoir overflow. The environmental data broadly divided into two categories, stress factors and disturbance factors. The stress factors deals with the impact of high particulate organic matter and low dissolved oxygen concentrations and disturbance factors, linked to water level fluctuation through flushing and reservoir drawdown, and these events are associated with the phytoplankton assemblages. Results indicated that the three distinct hydroperiods determined the structure of phytoplankton and chlorophyll levels and limited the presence and relative abundance of cyanobacterial species. Phytoplankton succession accompanied changes in clear and turbid water phase represented by the alternate dominance between diatoms and chlorophytes. Inundation and complete filling of reservoir stimulated "s" and "r" strategists species (<20 um) of unicellular and some colonial members of chlorophytes and cryptomonads in highly turbid water environment, and "c" strategist species in rest of the wet period following disturbance gradients. Statistical analysis elicited a significant relationship between particulate organic matter and relative abundance of smaller chlorophytes, which was deemed as stress factor. The flushing and reservoir drawdown indicate disturbance gradient and as a consequence high diversity. Furthermore, a substantial reduction in chlorophyll levels was registered in turbid water phase is related to the reduction of light penetration and re-suspension of sediments. Considering these results, it can be suggested that the well-managed reservoir drawdown can possibly maintain an environment free of eutrophication and cyanobacterial dominance.

Introduction

Northeast semi-arid reservoirs of Brazil are primarily utilized in order to fulfill the rural population need for irrigation, inland fisheries and for potable water purposes. As a result, these reservoirs can help to circumvent both the water scarcity and the increased demand caused by the Drought Polygon, characterized by recurrent severe droughts, (Bouvy et al. 2003, 2000; Chellappa and Costa 2003). In contrast to the South and Southeastern regions of Brazil, the State of Rio Grande do Norte State, localized in the Northeast of Brazil, is characterized by an extended summer followed by a brief monsoon. The main hydrodynamic characteristics include relatively low to moderate wind speed, strong evaporative losses, which are usually greater than annual rainfall, and long resident times. These characteristics can support the development of phytoplankton community that is structured on a schematic dry/wet cycle (Chellappa et al. 2004). Regarding the major ions encountered in the northeastern reservoirs, there is a persistent tendency to accumulate high concentrations of Na^{+} in comparison to Ca^{++} and Mg^{++} and Cl^{-} instead of SO_4 and CO_3 (Queiroz 1997).

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There is a considerable body of evidence indicating the increasing levels of eutrophication and frequent appearance cyanobacterial blooms in shallow waters on a worldwide scale (Falconer 2005). In Brazil, the dominance of cyanobacterial species, particularly *Cylindrospermopsis raciborski* and *Microcystis aeruginosa*, have been recorded in eutrophicated freshwater as well as coastal marine systems, together with the detection of toxins, including Microcystin LR and Cylindrospermopsin (Magalhães et al. 2003; Ferrão Filho et al. 2002; Molica et al. 2002). A similar cyanobacterial blooms was described in the Rio Grande do Norte State, in the form of sporadic events and related to fish kills (Chellappa et al. 2000; Costa et al. 2006); however, the perpetual dominance of toxic cyanobacterial species are considerably rare. In general, reservoirs in Rio Grande do Norte sustain different dominant phytoplankton species with high species diversity during an annual cycle. A plethora of factors underlie the phytoplankton distribution patterns. These include seasonal succession (Lund 1965), R–C–S strategy (Reynolds, 1998), which can be controlled either by top-down pressure or bottom-up nutrients (Gulati and van Donk 2002), trophic state (Barone and Naselli-Flores 1994), multidimensional environmental gradients (Fabbro and Duivenvoorden 2000) and various ecological associations for tropical and temperate waters (Huszar et al. 2000). Nonetheless, selective impact factors affecting tropical reservoir phytoplankton other than eutrophication are rather sparse. On the other hand, a set of environmental factors pertaining to stress and disturbance have been constructed for submerged weeds with positive repercussions on distribution patterns and optimized survival strategies to water management for temperate water bodies (Sabatini and Murphy 1996). Tavernini (2008) used hydroperiod in which precipitation regime underlined as a major factor for the inter-annual zooplankton distribution in nine temporary mountain pools of northern Italy.

The focus of this current study was on three reservoirs of semi-arid Rio Grande do Norte state of Brazil, which were constructed on intermittent streams and rivers and receive highly unpredictable and spatially heterogeneous annual rainfall. Additionally, these reservoirs are presently subjected to acute water scarcity due to prolonged period of drought in the region of El Niño years (Bouvy et al. 2000; Chellappa and Chellappa 2004). Phytoplankton investigations were carried out as a part of a continued monitoring reservoir limnology project of Northeast Brazil as a means to address three specific aims: (1) to determine how stress factors, such as particulate organic matter and low dissolved oxygen levels and disturbance factors, including water level fluctuation, increased turbidity and low light availability can impinge on phytoplankton community; (2) to emphasize how cyanobacterial population can be kept at lower levels under the influence of an unusual rainfall pattern; (3) to understand the environmental dynamics of the three hydroperiods of semi-arid region reservoirs.

Materials and methods

Study area

Three reservoirs selected for this study are situated in semi-arid regions of Rio Grande do Norte State, which are characterized by low rainfall and high evaporative loss. These reservoirs are as follows: (1) João Alves reservoir (latitude 06°41′56″S and longitude of 36°37′76″) in the Municipality of Parelhas; it is raised across Serido River and receives water through an inflow from east of adjoining Paraiba State; (2) Marechal Dutra Reservoir (latitude 06°26′11″S and longitude of 36°38′28″W) in the Municipality of Acari; it was constructed across Acauã River of Piranha-Açu hydrographic basin; (3) Santa Cruz Reservoir (latitude 06°25′23″S and longitude of 36°07′27″W) in the Municipality of Santa Cruz; it was barraged across Trairi River of Trairi hydrographic basin. The drainage area is mainly composed of sparse xerophytic vegetation dominated essentially by *Acacia* and *Mimosa* species. The outflow is maintained regularly in accordance with the storage capacity and irrigation demands of the region. The main characteristics of these regions include humid semi-arid climate with high evaporation rates and irregular rainfall pattern. These reservoirs underwent full volume initially in January 2004 followed by great inundation from heavy unusual rainfall, thus triggering three different hydroperiods. The morphometric details are given in Table 1.

Table 1
Morphometry of selected reservoirs in Rio Grande do Norte State, Brazil.

Total accumulation capacity	João Alves Reservoir (Sertão)	Marechal Dutra Reservoir (Sertão)	Santa Cruz Reservoir (Agreste)
Surface area (m^2)	1.32 × 105	7.8 × 105	1.5 × 105
Total volume (m^3)	85.012.750	40.000.000	5.158.750
Outflow (m/s)	230	325	88
Maximum depth (m)	35	25	16.2
Mean depth (m)	18	8.6	6.9
Minimum depth (m)	4.6	3.8	2.5
Length (km)	18	12.5	7.85
Diameter (km)	2.085	1.85	0.95
Altitude (m)	80	205	25
Theoretical renewal time (years)	3.2	1.6	0,5
% Renewal time altered 2003–2004	72.5	65.8	80.00

Water sampling and analytical methods

Samples were collected at 2-week intervals from September 2003 to August 2004, from a fixed station close to the deepest region of the reservoir and collections were generally carried out between 9.00 and 10.00 AM. Samples were also collected from different depth profiles such as 0, 1, 5 and 8 m during dry period, 0, 1, 5 and bottom waters of each reservoir during January and February months and the rest wet period and integrated to analyze water chemistry characteristics and biological components. Water temperature, pH, dissolved oxygen and conductivity were measured with handle-held meter (WTW 340 I –MERCK). Light transparency was routinely assessed, using a 30 cm Secchi disc. The coefficient of light attenuation of euphotic zone was calculated from the values and multiplied by the recommended value of 2.7 for tropical waters (Margalef 1983).

Water samples for inorganic nutrients, reactive silicate, nitrate–nitrogen, ammonia–nitrogen and orthophosphate were collected utilizing a 2 dm^3 Van Dorn bottle at the surface and filtered through GF/C fiberglass filters. All the analyses were performed following the method of Golterman et al. (1978). Particulate organic matter, TP and TN were measured using Wetzel and Likens (2004) methods. Values are expressed as weighted averages in the water column and are presented as mean values of three hydroperiods during the annual cycle of 2003–2004. The hydrological cycle of these reservoirs point towards three defined periods: (1) Dry period with clear low water phase (September–December 2003); (2) Unusual rainy period (January and February of 2004) with turbid and high water phase; (3) Wet period (March–August 2004) with different levels of transparency due to water level fluctuations and sedimentation.

Phytoplankton sampling, chlorophyll extraction and statistical analysis

Samples were fixed in Lugol's iodine solution and counts of phytoplankton cell density were made from Sedgewick-Rafter Counting Cell and a minimum of 50 fields and 100 units (cells, trichomes or colonies). Sometimes more than 400 units were counted depending on the density. Results presented are the mean value of the counts. The biovolume procedure (based on simple geometric solids) was utilized by assuming a unit specific gravity (Rott 1981). For taxonomic species identification, the Brazilian manual of freshwater algal flora was used (Bicudo and Menezes 2005), and the classification methods were in accordance with van den Hoek et al. (1995) and Wehr and Sheath (2003). Most of the time a minimum of 200 units was counted at 400 × magnification, with large taxa counted at 200 ×. Ecological indices were measured from species diversity, evenness, Margalef's species richness index and dominant species index, similarity index (Pielou 1975) and dominance index. The aforementioned indices were elaborated from the programme Species diversity and Richness by Seaby and Henderson (2006). Water samples for chlorophyll analysis were stored at 4 °C in dark for 2 h and filtered on Whatman GF/C filters. Concentrations were detected after overnight extraction in 90% acetone and corrected for the values of phaeophytin degradation pigment (Marker et al. 1980). Carlson (1977) TSI index was utilized in order to calculate the trophic state of each reservoir.

Statistical analyses were performed through SPSS Statistica 10.0 software package. Data analysis was based on the log-transformed data and subjected to one-way analysis of variance (ANOVA) to test significance between the dependent (relative abundance of phytoplankton species) and independent (environmental parameters) variables. Linear regression analysis was used to test significance between chlorophyll levels and total nitrogen and phosphorus.

Results

Environmental parameters

Fig. 1 illustrate normal (1959–2002) and atypical pattern of rainfall distribution for the period of 2003–2004 around the reservoirs. The reservoirs exhibited three distinct environmental characteristics during the study period of 2003–2004 and the pattern of hydrographic variability was driven by unusual summer rain and reservoir drawdown. It is easily recognizable from the data obtained through secchi disc measurement, extension of euphotic zone and coefficient of light attenuation of the turbid water and clear water phase of the three phases of water quality (Fig. 2). The first phase was a dry one with no precipitation and pronounced evaporative losses (low and clear water phase). The second phase was characterized by a greater input of floodwater of rivers and its tributaries, during January and February of 2004, followed by an unusual high rainfall (high and turbid water phase). The third phase represented an extension of the wet season with mixing characteristics (falling water level and improved transparency). The depth profiles of the 2003–2004 cycle varied markedly from as low as 2.8 m in the dry period (September–December 2003) to 35 m during filling season (January–February 2004) and finally to 18.5 m in the remaining wet period (March–August 2004). As a result, a different disturbance regime was found for the annual cycle of 2003–2004 (Table 1).

Table 2 addresses all environmental variables for both clear and turbid water phases in the three hydroperiods. Temperature varied from 26.0 to 29 °C in the first period (dry season) and exhibited either a thermally weak stratification or a diurnal warming and nocturnal cooling. The second period, which comprised January and February of 2004, had temperature recordings from 28.0 to 29 °C, together with a heavy water flow to reservoir from the feeder river input. During the third period (wet season) there was an oscillation from 28.0 to 30.2 °C. Mixing events were frequent during both wet periods of samplings due to wind action, sediment suspensions and turbulence. The temperature difference between surface and bottom water did not exceed from 1.5 to 2.0 °C. The pH remained near neutral to mildly alkaline (Santa Cruz Reservoir) and typically alkaline (Marechal Dutra and João Alves reservoirs) with the minimum of 8.3 and the maximum of 9.3. The mean conductance ranged from 709 to 1072 μS (at 25.0 °C), during the study period. The values showed a significant variation during the year, progressively increasing from 320 to 1050 μS in the dry period and from 355 to 1072 μS in the wet period. The mean values of dissolved oxygen fluctuated from 5.7 mg L^{-1} in dry period to 4.8 mg L^{-1} in wet period, reaching the minimum of 2.7 mg L^{-1} in January 2004, which coincided with a high bacterial decomposition rate. The percentage of dissolved oxygen saturation remained at 80–120% throughout the entire water column. Moreover, depletion in oxygen and saturation to 65% in bottom waters were registered during the weak stratification of dry period. A complete anoxic hypolimnion was not observed in either of the three hydroperiods.

In January 2004, noteworthy changes were observed, including full reservoir with a perturbed environment amid two important attributes: rapid nutrient increase and decreased transparency.

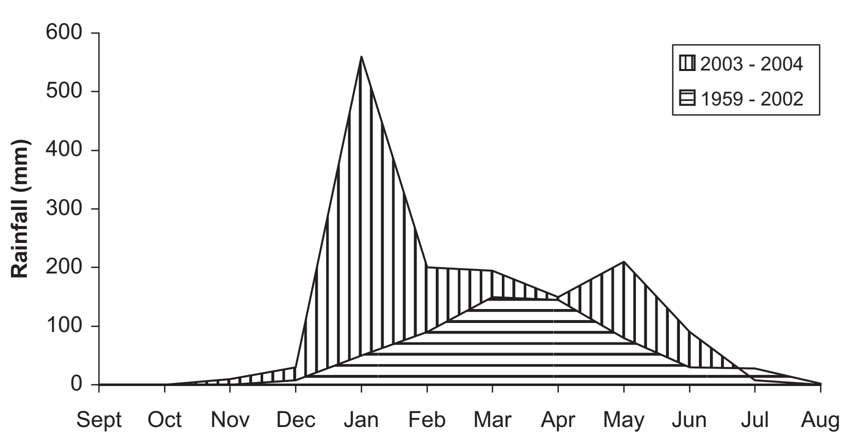

Fig. 1. General rainfall pattern and 2003–2004 rainfall of reservoirs, Rio Grande do Norte State, Brazil.

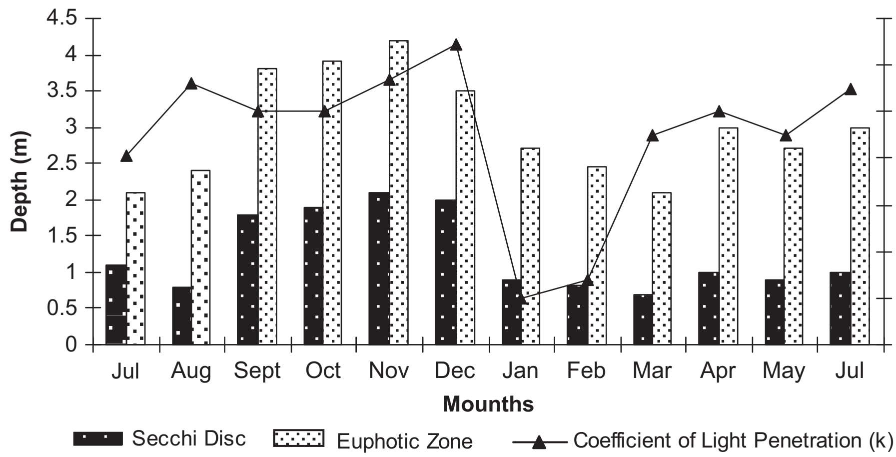

Fig. 2. Mean data of euphotic zone, secchi disc, and coefficient of light penetration (K).

Table 2
Summary of environmental variables data (mean values and range) and chlorophyll *a* found during the three hydroperiods of reservoirs João Alves (*), Marechal Dutra (**) and Santa Cruz/RN (***) Brazil.

	Dry period (Sept–Dec 2003)	Jan–Feb 2004 (unusual rainy months)	Wet period (Mar–Aug 2004)
pH	8.9 (8.3–9.3)* 9.0 (8.8–9.2)** 7.2 (7.0–7.4)***	8.8 (8.7–8.9)* 8.2 (8.0–8.4)** 6.9***	8.5 (8.3–8.7) * (8.0–8.6)** 7.5 (7.2–7.8)***
Temperature (°C)	27.5 (26–29)* 29.2 (29.5)** 28.0 (27.8–28.2)***	28.0 (28–29.0)* 29.5 (29–29.8)** 28.2***	29.9 (28–30.2)* 30.2 (30.8–30.6)** 28.6 (28.2–29.0)***
Depth (m)	8.0 (8–10.0)* 5.6 (5.2–5.8)** 3.9 (3.6–4.8)***	35.0 (35.0)* 25.0 (25.0)** 16.0 (15.8–16.4)***	18 (16–20)* 21.2 (20.0–23.5)** 12.5 (12.0–14.5)***
Secchi disk (m)	1.5 (1.0–2.0)* 1.2 (0.8–1.4)** 0.25 (0.22–0.28)***	0.8–1.2 (1.0)* 0.6** 0.18***	1.5 (1.4–2.0)* (1.0–1.2)** 0.20 (0.20–0.3)***
Conductivity ($\mu S\,cm^{-1}$)	810 (320–1050)* 735 (705–788)** 1890(1850–1924)***	1025 (1005–1030)* 995 (940–1050)** 1950 (1900–2050)***	709 (355–1072)* 804 (798–810)** 1950 (1900–2050)***
Dissolved oxygen ($mg\,L^{-1}$)	5.7 (4.2-6.8)* 7.6 (6.4–8.8)** 3.8 (3.6–4.2)***	8.7 (8.5-8.9)* 4.0 (3.8–4.2)** 2.5***	4.9 (3.7-6.2)* 4.8 (4.5–5.6)** 3.15 (3.0–3.3)***
Oxygen saturation (%)	90 (80–100)* 95 (80–100)** 83 (80–88)***	125* 105 (100–110)** 102***	85 (80–95)* 110 (90–120)** 108 (105–110)***
NO_3–N (μM)	90 (80–100)* 17 (20–34)** 1.5 (1.0–2.2)***	148 (146–150)* 42 (40–44)** 1.8***	130 (122–148)* 54 (58–62)** 2.5 (2.0–3.0)***
NH_4–N (μM)	82 (104–120)* 39 (34–48)** 42 (38–44)***	135 (130–140)* 118 (110–126)** 73***	60 (52–88)* 92 (88–94)** 78 (75–85)***
PO_4–P (μM)	12 (8–15)* 68 (60–74)** 0.5 (0.0–1.0)***	22 (18–30)* 115 (100–130)** 1.2***	18 (12–26)* 113 (105–122)** 1.0 (0.8–1.2)***
Reactive silica (S) μM	1450 (1280–1800)* 980 (1088–995)** 1052 (985–1120)***	1850 (1800–1900)* 1120(1058–1185)** 1052***	1650 (1400–1800)* 1055 (980–1115)** 1085 (985–1120)***
Chlorophyll *a* ($\mu g\,L^{-1}$)	14.6 (3.8–22.8)* 34.8 (32.5–39.7)** 5.2 (5.0–5.8)***	4.5 (4.0–5.0)* 8.3 (7.5–9.7)** 3.0***	8.25 (3.2–12.8)* 15.6 (12.5–17.8)** 9.3 (8.0–9.8)***

Values of nitrate–nitrogen remained from a low value of 1.5 (Santa Cruz) to a high value of 90 μM (Marechal Dutra) in the dry period and from 1.8 to 148 μM in the second hydroperiod (January and February 2004), with a similar trend in the third hydroperiod (March–August 2004). In January 2004, a heavy precipitation elicited an unusual input of water, leading to peak ammonia concentrations of up to 135 μM in Marechal Dutra Reservoir. Orthophosphate concentrations were low during clear water phase of the dry period with a substantial increase in João Alves Reservoir during both second and third hydroperiods of turbid

Table 3
List of phytoplankton species and their relative abundance of dry/wet period of João Alves Reservoir of Parelhas/RN Brazil.

Bacillariophyceae	**Hydroperiod 1 (dry period)**		**Hydroperiod 2 (Jan–Feb)**		**Hydroperiod 3 (wet period)**	
	Cel mL^{-1}	R.A (%)	Cel mL^{-1}	R.A (%)	Cel mL^{-1}	R.A (%)
Amphypleura sp.	1.080	0.20			–	–
Aulacoseira granulata (Ehrenberg) Simonsen	156,480	35.0	49	12.2	100,800	24.00
Aulacoseira distans (Ehrenberg) Simonsen	122,000	23.10			89,000	18.00
Cyclotella meneghiniana Kützing	111,900	15.00			47,200	12.60
Cyclotella stelligera (Cleve & Grunow) Van Heurek	6.000	1.44			11,780	6.40
Frustulia rhomboides (Ehrenberg) De Toni	480	0.10			–	–
Sellaphora bacillum Ehrenberg	–	–			1220	0.50
Navicula crytocephala Kütz.	–				800	0.70
Navícula viridula (Kütz.) Ehrenberg	–				420	0.90
Nitzschia linearis (C.Agardh) W.Sm.	180	0.04			–	–
Surirella capronii Bréb.	5100	1.12			–	–
Subtotal	**49.7×10^5**	**76.00**	**49**	**12.20**	**34.1×10^5**	**62.90**
Chlorophyceae and Zygnemaphyceae						
Chlamydomonas spp.			22	5.48		
Chloromonas spp.			38	9.48		
Chlorogonium gracile Matw			26	6.48		
Pteromonas spp			28	6.98		
Phacotus lenticularis (Ehr.) Stein			14	3.5		
Tetraspora spp			36	8.9		
Actinastrum gracillimum Smith	–	–			66	0.15
Ankistrodesmus falcatus (Corda) Ralfs	60.0	0.01			660	1.46
Ankistrodesmus fusiformis Corda	–	–			480	0.73
Botryococcus braunii Kützing	–				360	0.80
Botryococcus protuberans West & West	–	–			360	0.80
Chlorella vulgaris Beijerinck	–	–			120	0.26
Closterium parvulum Näg.	–	–			66	0.15
Closteriopsis acicularis (G.M.Sm) Bel. et. Sw		62	15.5			
Closteriopsis longissima Lemmermann	–	–			66	0.15
Coelastrum cambricum Archer	–	–			420	0.60
Coelastrum microporum Näg.	–	–			480	0.70
Crucigeniella apiculata (Lemmermann) Komárek	–	–			180	0.40
Crucigenia quadrata Morren	–	–			120	0.26
Dictyosphaerium ehrenbergianum Näg.	24,000	10.05			180	0.40
Nephrocytium agardhianum Näg.	18,000	7.04			240	0.50
Golenkinia radiata (Chodat) Wille	–	–			66	0.15
Oocystis borgei Snow		–			33,000	12.10
Oocystis lacustris Chodat	–	–			16,000	7.33
Pandorina morum Bory	–	–			240	0.50
Pediastrum duplex Meyen	–	–			180	0.40
Radiococcus nimatus (De Wildeman) Schmidle	–	–			360	0.80
Scenedesmus acutus Meyen	–	–			180	0.40
Scenedesmus dimorphus (Turp.) Kütz	–	–			66	0.15
Scenedesmus quadricauda (Tupin) Brébisson	–	–			66	0.15
Sphaerocystis schroeteri Chodat	–	–			120	0.26
Staurodesmus triangulares paralelus (Smith) Tham	1980	140			–	–
Tetrastrum elegans Playfair			28	6.98		
Tetrastrum punctatum (Schimidle) Ahlstrom & Tiffony	–	–			120	0.26
Subtotal	**4.4×10^4**	**18.5**	**246**		**3.8×10^5**	**26,99**
Cyanophyceae						
Chroococcus turgidus (Kütz.) Näg	360	1.64			720	2.30
Oscillatoria articulata Gardner	60	0.12			166	0.30
Oscillatoria lacustris (Kléb.) Geitler	60	0.12			144	0.20
Oscillatoria limnetica Lemm.	60	0.12			180	0.36
Pseudanabaena catenata Laut.	–	–			300	0.70
Planktothrix agardhii (Gomont) Anag.and Komar.			46	11.5	220	0.50
Subtotal	**4.8×10^2**	**2.00**	**46**	**11.5**	**1.5×10^3**	**4.20**
Dinophyceae						
Gymnodinium sp.	560	1.40			765	2.85
Peridinium pusillum (Penard) Lemmermann	350	1.00			650	2.00
Peridinium volzii Lemmermann	130	0.20			125	0.15
Subtotal	1.4×10^4	2.6			1.5×10^4	5.0

Table 3 (*continued*)

Bacillariophyceae	Hydroperiod 1 (dry period)		Hydroperiod 2 (Jan–Feb)		Hydroperiod 3 (wet period)	
	Cel mL^{-1}	R.A (%)	Cel mL^{-1}	R.A (%)	Cel mL^{-1}	R.A (%)
Cryptophyceae						
Cryptomonas stigmatica Wislouch	220	0.9	12	3.0	166	0.7
Rhodomonas minuta Skuja	60	0.1	8	2.0	120	0.3
Subtotal	**2.8×10^2**	**1.0**	**20**	**5.0**	**1.8×10^2**	**1.0**
Euglenophyceae						
Euglena acus Ehrenberg			40	9.9		
Subtotal			**40**	**9.9**		

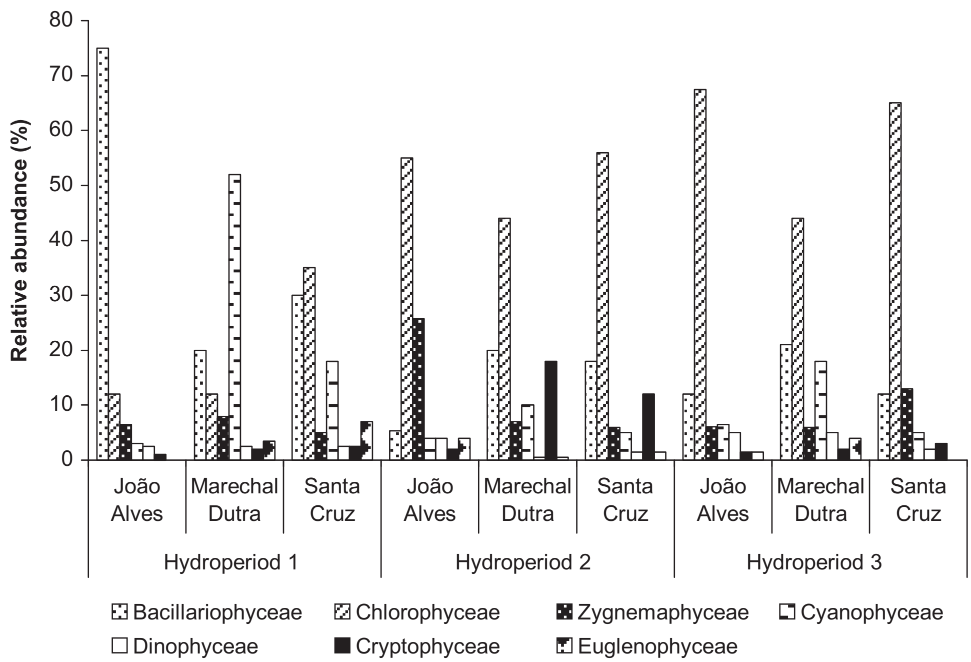

Fig. 3. Phytoplankton composition of reservoirs in three hydroperiods.

water phase. Soluble reactive silicate concentrations remained high, with a minimum of 980 μM in the dry period to a mean 1850 μM in the second hydroperiod, and remained at 1650 μM throughout the wet period. Transparency values were deemed as low to moderate (Table 2). The dynamics of euphotic region encompassed shifts from transparent water in dry period to low with the turbid water flow in the second hydroperiod to further recover the transparency with falling water levels and increasing dissolved inorganic nutrients, in order to promote more phytoplankton biomass. Chlorophyll concentrations ranged from 3.8 to 22 μg L^{-1} during the dry period, and the levels collapsed in January to a minimum of 4.0 μg L^{-1} due to turbid water condition and low light penetration. This was followed by an improved clear water phase with gradual sedimentation of particulate organic matter. As a consequence, the biomass increased to 8.2 (Marechal Dutra), 9.3 (Santa Cruz) and 15.6 μg L^{-1} (João Alves) during the wet period of 2004. The clear water phase of dry months and the larger coefficient of light penetration stimulated more chlorophyll levels compared to the turbid water condition of wet months.

Phytoplankton communities

Phytoplankton assemblages of three reservoirs comprised diverse taxa. The composition list together with their relative abundance is summarized in Table 3 and Fig. 3. The abundance of species sequence follows the order of Bacillariophyceae, Chlorophyceae, Cyanobacteria, Dinophyceae, and Cryptophyceae. In total, 63 algal taxa were found, out of which 39 were chlorophytes (62%), thus being the major contributor to the phytoplankton composition for the annual cycle of 2003–2004. Chlorococcales contributed significantly to the species list of chlorophytes during wet season and functioned as the dominant group. Bacillariophyceae was represented by 11 species, which account for the high relative abundance and important contributor to the total phytoplankton in the dry period of clear water phase. Among them, *Aulacoseira granulata*, *Aulacoseiradistans* and *Cyclotella meneghiniana* are the most abundant diatom species in all three reservoirs. Dinophyceae was represented principally by two species of *Peridinium* and one of *Gymnodinium* and represented a numerically reduced group. The number of species of cyanobacteria and their relative abundance were reduced in all three reservoirs throughout the study period with the marked absent of *Microcystis aeruginosa* and *Cylindropsermopsis raciborskii*. Figs. 4 and 5 show the changes in the diversity and abundance of phytoplankton species composition for all the three hydroperiods. The high water level of January and February samplings indicated muddy water environment tolerant species, including smaller sized algae of

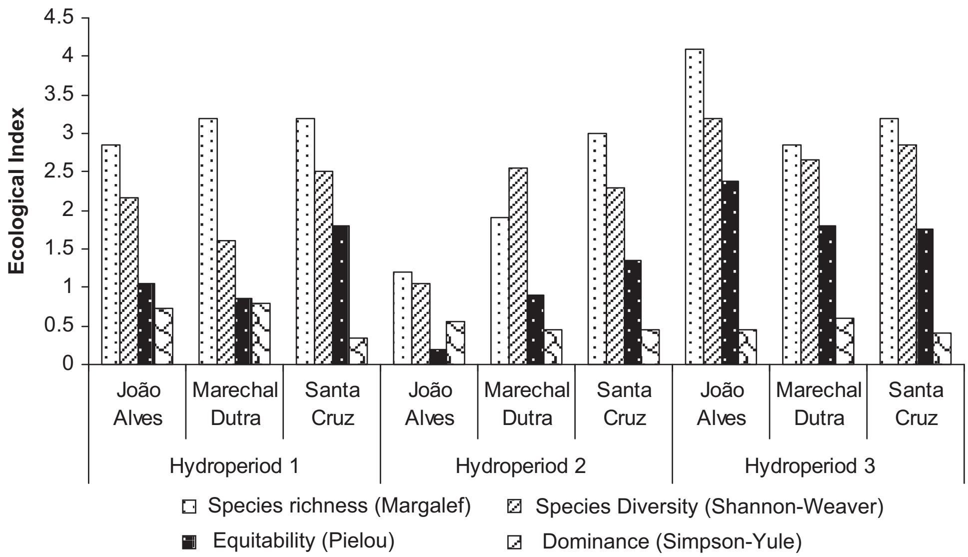

Fig. 4. Temporal variations of ecological indices of phytoplankton community in three hydroperiods of annual cycle 2003–2004.

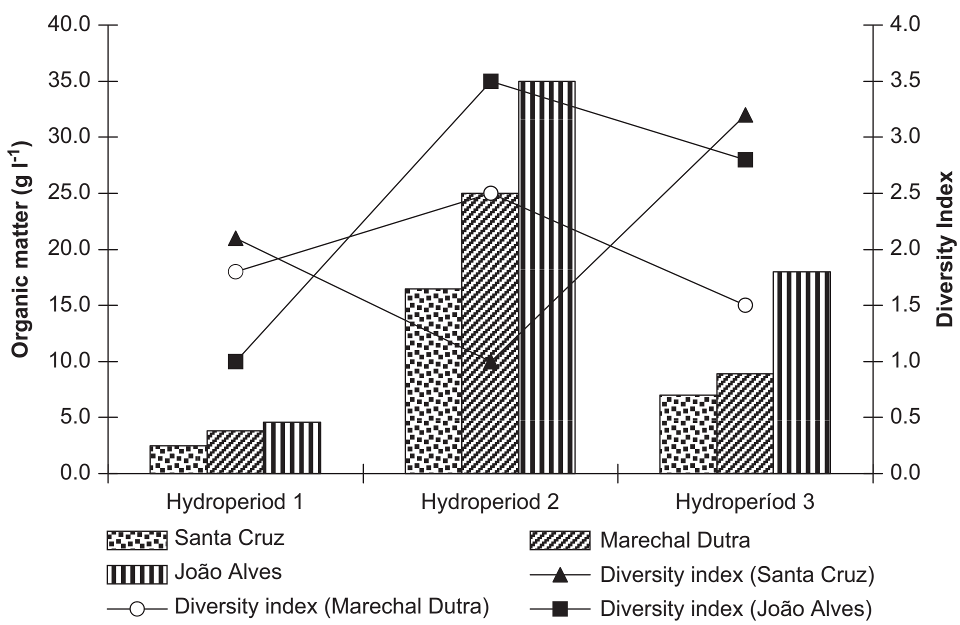

Fig. 5. Total suspended matter (g/L) and cumulative species diversity of phytoplankton corresponding to three hydroperiods of reservoirs.

Chlorophytes, Zygnematophyta, Cryptomonads and Euglenophytes, which were numerically reduced. The third hydroperiod determined sequential changes and sustained predominance of chlorophytes and zygnematophyceae. Shannon diversity index and Margalef species richness index exhibited higher values during the wet period and synchronized with the appearance of large numbers of Volvocales, Tetrasporales, chlorococcales and desmidiales species along with the species of *Cryptomonas* and *Rhodomonas* of cryptophyceae. The dominance index was reduced considerably due to the robust appearance of unicellular and colonial forms of chlorophytes and zygnematophytceae during wet season (second and third hydroperiods). Irrespective of notable dominance of *Aulacoseira* and *Cyclotella*, the moderate values obtained from the similarity index showed the co-existence nature of phytoplankton species. These species were mostly not competitive during third hydroperiod. The trophic index calculation for the three reservoirs presented different values, such as 44 to Marechal Dutra, 32 to João Alves of 18 to Santa Cruz, thus indicating an oligo-mesotrophic characteristic of the reservoir environment.

Table 4 addresses the significant results of one-way ANOVA. The dominant class, Bacillariophyceae, revealed a high significance between relative abundance and reactive silicate concentrations ($p<0.001$) and also to nitrate–nitrogen ($p<0.001$). The co-dominant group, Chlorophyceae, exhibited highly significant values to dissolved oxygen ($p<0.001$). Table 5 illustrates results of significant statistical test of regression analysis. Linear regression analyses elicited an inverse correlation between particulate organic matter content and relative abundance of phytoplankton species (<0.05 Table 4). Frequent re-suspension of sediments can enhance nutrients and decomposition rates. With increased concentrations of nutrients during the third hydroperiod, particularly total phosphorus and

Table 4
ANOVA showing significance between environmental and phytoplankton community of reservoirs, of Rio Grande do Norte State, Brazil.

Independent variables (relative abundance)	Dependent variables	*F*	*P*	Significant differences
Chlorophycae (RA)	Dissolved oxygen	73.62	0.0001	Surface water species
Bacillariophyceae	Reactive silicate	82.56	0.0001	Between diatoms to other phytoplankton
Bacillariophyceae (period)	Nitrate	–	–	January samples to other wet months
Dinophyceae	Transparency	0.88	0.055	Dry period species had differed to wet
Cyanobacteria	Temperature	0.75	0.0162	Between cyanobacteria to others
Chlorophyceae (RA)	Particulate organic matter	44.25	0.05	Second hydroperiod turbid water and smaller algae (<10 μ)
Chlorophyll *a*	Secchi-disk transparency	12.58	0.0059	Chlorophyll values in euphtotic region

Table 5
Regression equations relating to chlorophyll *a* (CHLA, $\mu g\,l^{-1}$) and total phosphorus (TP, $mg\,P\,l^{-1}$), to total nitrogen (TN, $mg\,N\,l^{-1}$) and phaeophytin levels (Phaeo, $\mu g\,l^{-1}$) in wet period (March–August 2004).

Log e chlorophyll *a* of RGN reservoirs	Intercept	Log e TP	Log e TN	Phaeophytin (Log e)	R^2	*n*
Santa Cruz	4.52 ± 0.40	0.65 ± 0.12***			0.65	23
Marechal Dutra	5.66 ± 0.18	0.92 ± 0.007***	0.48 ± 0.12**	0.62 ± 0.11**	0.74	23
João Alves	4.75 ± 0.12	0.84 ± 0.06***		0.75 ± 0.16**	0.88	23

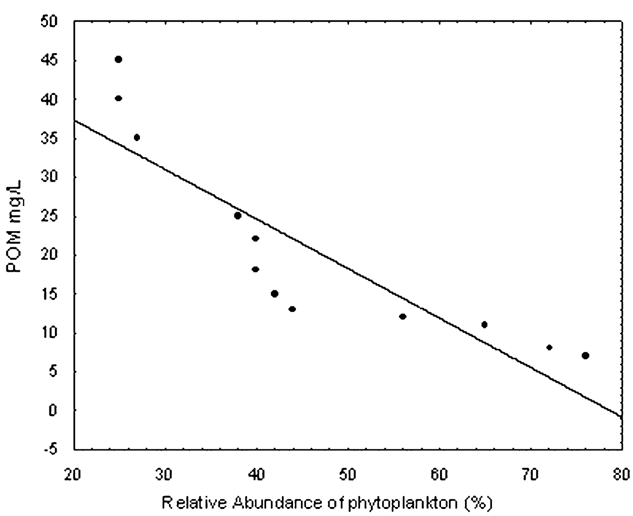

Fig. 6. Relation between particulate organic matter in the sediment suspension and relative abundance of phytoplankton in second hydroperiod. (Linear regression $R^2 = 0.77$; $P < 0.05$; $n = 12$).

total nitrogen, a significant increase in chlorophyll *a* levels occurred ($p < 0.001$). Total phosphorus (TP) and chlorophyll levels were related to all three reservoirs studied in the wet period ($R^2 = 0.65$ $p < 0.05$). Chlorophyll a and phaeophytin levels showed a significant relation ($R^2 = 0.74$, $R^2 = 0.88$ $p < 0.001$) both in Marechal Dutra and João Alves reservoirs, but not in Santa Cruz. Furthermore, Marechal Dutra Reservoir was the only system that presented a significant total N and chlorophyll *a* ($p < 0.01$) Fig. 6.

Discussion

Phytoplankton assemblages and biomass arise from the sum of all species responses to the variable environments of reservoirs, which, in turn are often contingent upon stable and unstable situation resulting from flushing and draw down characteristics. It is clear that the three reservoirs studied are greatly influenced by the variable hydrology as it progresses from drought to periods of rainfall and increased water flow, which stimulate stress and disturbance factors to determine phytoplankton composition, diversity and chlorophyll levels, in comparison to the usual dry and wet cycles (Bouvy et al. 2000, 2003; Chellappa and Costa 2003). These two factors are discernible during a shift from clear water (dry period) to turbid water phase (wet period). Stress factors influenced an increase in turbidity, particulate organic matter and reduced oxygen concentrations. As a consequence, it induced sequential changes of predominant phytoplankton species of *A. granulata, A. distans* and *C. meneghiniana* in environmentally constant clear water phase to dominant chlorophytes species of Volvocales, Tetrasporales, Chlorococcales, Desmidiales and Cryptomonads in the second hydroperiod. This hydroperiod underwent basin flushing, filling situation, limited algal flora of smaller species (<20 μm) of Chlorophyceae, and bloom of "r" strategists of the phytoplankton community with no particular preference of trophic status.

The high summer rain enabled to fill the three reservoirs, which was a rather rare occurrence since these reservoirs were constructed. The high water level with an extended turbid water environment suppressed the number of larger phytoplankton species (>20 μm), their abundance and diversity. The poor transparency in the turbid water phase of second hydroperiod is attributed to basin flushing and frequent re-suspension of sediment enhancement of particulate organic matter functioned as stress factor to reduce chlorophyll levels and relative abundance of phytoplankton species. These findings share similar observations made by Happey-Wood (1988) for the growth of diverse freshwater green algae, a growth strategy in response to critical environmental variables. The third hydroperiod presented a reduction in flushing, increased reservoir drawdown, improved water transparency and more dissolved inorganic nitrogen. The falling water level is due to forced irrigation demands and accentuated reservoir drawdown and the losses account for the changes in hydraulic balance, depth profile and water retention time. The transition from filling to receding water level (second to third hydroperiods) carries a potential development of environmental gradients, light and nutrient limitation. Such an improved environment sets stable situation with reduced turbidity and more light penetration, increased dissolved nutrients and enhanced growth of many green algae, diatoms, cryptomonads with few species of cyanobacteria. These species are able to successfully grow in the environment of the third hydroperiod. The wide spectrum of these phytoplankton species at intermediate disturbance level revealed an increase in species richness, diversity, equitability (co-existence of species), and finally attained stability. These characteristics bear a somewhat similar transition from high to low flow periods, as has been described for a riverine impoundment in semi-arid Australia (Fabbro and Duivenvoorden 2000).

The third hydroperiod presented increased reservoir drawdown and set up- sequential changes in the dominance of Chlorophytes, particularly *Oocystis borgei*, and *Oocystis lacustris*, while the rest of Chlorophytes and zygnematales shared many co-existing species. The frequency and intensity of fluctuating water levels varied greatly in accordance to irrigation demands and created an intermediary disturbance mediated changes from turbid to clear water phase. Fluctuating water levels act as a disturbance factor and created gradients of transparency and improved euphotic layer with high dissolved inorganic nutrients. The three shallow tropical reservoirs exhibited a reduction in theoretical retention time, varying nutrient levels during the well-mixed environment subjected to initial filling phase, and subsequent reservoir drawdown in the third hydroperiod that interfered with phytoplankton composition, diversity and chlorophyll levels.

It is well known that trophic state is one of the major environmental factors structuring phytoplankton assemblages and many green algae are also included in the trophic spectrum (Reynolds 1998; Salmaso 2000). However, in the current study it was demonstrated that hydrological characteristics rather than the trophic state were linked to phytoplankton structure. In fact, the reservoir filling and flushing events altered the trophic state (Eu-hypertrophic) as expressed by TP, and both Secchi disc measurement and chlorophyll levels were inferior to the expected value of 50–100 μg/l of TP, 25–75 μg/l of chlorophyll and 3.0 m of Secchi disc measurements.

A theoretical assumption that can account for this phytoplankton structure builds-up from the life history strategies for phytoplankton composition, which includes R-strategy (ruderal or opportunist) species, C-strategy (competing) species and S-strategy (stress tolerant) species, and addresses how species are associated with particular categories of water bodies (Reynolds 1988a). During the second hydroperiod of this study, there was a general increase of limited number of species belonging to Volvocales, Chlorococcales, Zygnematales, *Planktothrix agardhii* of cyanobacteria and Cryptomonads that could be considered equivalent to as S- and R-strategies due to the stress tolerance imposed by increased flushing, turbidity and particulate organic matter. The diversity increase associated with increased number of species of Chlorophytes, Zygnematophytes, and Bacillariophytes during wet period may be conceived to C-strategy and attributed to the impact of disturbance gradients (high, intermediate and low). The phytoplankton species essentially competes for improved light penetration and the availability of dissolved nutrients, which permit co-existence in shorter time scale, a tendency of heterogenous assemblages of homogenous environment similar to the proposal of Hutchinson (1961) plankton paradox. The favorable situation with more co-existing species is time bound and are likely to be shaded out and give way to the dominance of species of chlorophytes and Bacillariophytes and creating a self perpetuated superior competitors when the nutrients level dwindle.

A highlightened importance has been attributed to studies on species diversity due to the different types of environmental impacts. However, central questions still revolve around how species diversity is maintained, why it changes from environmentally constant situation to one that led to collapse and how can the recovery or species extinction happen in a perturbed situation. Environmental disturbance is one of the established events attributed to changes in species diversity. Disturbance regime per se and the magnitude are often related to changes in phytoplankton diversity (Reynolds 1988b, 1998; Padisák et al. 1993). In this study, the reservoir phytoplankton diversity of three hydroperiods varied considerably. The clear water phase of dry period presented an environmental constancy with moderate diversity, species richness, similarity and three species emerging as successfully dominant with little or no disturbance. The second hydroperiod showed precipitation abundance with a single forcing event from inundation, thus filling the reservoirs. Although this period is relatively short-lived, it could still account for high disturbance intensity and reduced phytoplankton diversity. In the subsequent wet period, diversity increased to higher levels due to a weak competitive reaction from co-existing species and their differential nutrient assimilation as a response to intermediate disturbance frequency. Flushing enhanced dilution and reservoir drawdown created environmental gradients that facilitated intermediary disturbance, reduced eutrophication and subdued appearance of cyanobacterial species.

This study high lightens the importance of stress and disturbance factors to trophic state to determine phytoplankton community structure, diversity changes and chlorophyll levels. Concomitantly, it reflects the importance of hydrologically induced impacts of stress, disturbance and resilience characteristics of dry and wet cycles of semi-arid northeast Brazil.

Phytoplankton abundance expressed as chlorophyll *a* concentrations exhibited a prominent decrease during the reservoirs filling phase (second hydroperiod), as a result of muddy water condition, decreased transparency and low Zeu/Zmix ratio of depth profile. In shallow reservoirs, sediment re-suspension often increased the TP and TN available for assimilation to phytoplankton species. The present study indicated a positive correlation between TP and chlorophyll *a* and to turbidity factor, which bears similarity to the model proposed by Dillon and Rigler's (1974). The values obtained through Carlson (1977) trophic index state to recognize the trophic level of the reservoir water indicated that all the reservoirs fall within an oligo-mesotrophic status.

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