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Freshwater Phytoplankton from Argentina

Reservoirs of the Peri-Pampean region

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With 2 figures and 3 tables

Abstract: In this chapter we analyze the reservoirs of the Peri-Pampean region comprised in the arid western corridor, taking into account their biogeographic areas and the characteristics of their basins. Since many of these reservoirs are impacted by agriculture, tourism and effluents from industries and urban areas, they are typically meso-eutrophic and with low levels of dissolved oxygen in the hypolimnion during summer. The Río Tercero Reservoir receives an additional impact from the change in operation prescribed for the functioning of a nuclear power plant. This water body, located in the "El Espinal" region, is oligo-mesotrophic, and its plankton has varied in composition and biomass during the pre- and post-operational periods of the plant. In all the reservoirs here studied, blooms have been registered, most frequently and recurrently produced by Cyanobacteria *(e.g., species of Dolichospermum* and *Microcystis*), and have been associated with the presence of toxins in the reservoirs of San Luis and in the San Roque Reservoir of Córdoba. *Ceratium hirundinella* (Pyrrophyta), a species widely colonizing the Peri-Pampean region, was also associated with blooms. In many reservoirs of the area no studies have been performed at all, while in others the investigations have been scarce and motivated by specific objectives with the results usually being published in either private or classified reports.

Keywords: Phytoplankton, reservoirs, Argentina.

Introduction

Argentina has approximately 130 reservoirs, most of them are located in the arid and semi-arid regions (Gabellone & Casco 2006) and in basins that slope principally from west to east or from north to south. The presence of reservoirs is most significant in the catchments of the rivers Juramento, Salí-Dulce, Atuel, Colorado, Tercero, Negro, Chubut, Paraná and Uruguay. The characteristics of the reservoirs vary according to their location within the basins, the existence of other reservoirs upstream, the hydrologic features, and the biogeographical zone where they are located. The majority of the reservoirs are found in the biogeographical regions of "El Monte" (40%), "El Espinal" (19%), and "Las Yungas" (17%).

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The reservoirs were constructed for different purposes (Gabellone & Casco 2006). Those intended for irrigation are normally small and numerous, such as those encountered in the Mendoza Province and in the Argentine northwest; others as the Cabra Corral-El Tunal Complex in Salta or the Florentino Ameghino Dam in Chubut, have great volume. The reservoirs constructed for providing hydroelectric power are generally large and situated in rivers of high discharge, among the most distinctive being the serial reservoirs on the Limay River, the Mari-Menuco and Barreales on the Negro River, the Yacyretá on the Paraná River, the Salto Grande on the Uruguay River, and the Urugua-í on the Urugua-í River. In the region surrounding the pampas, the reservoirs of multiple uses predominate.

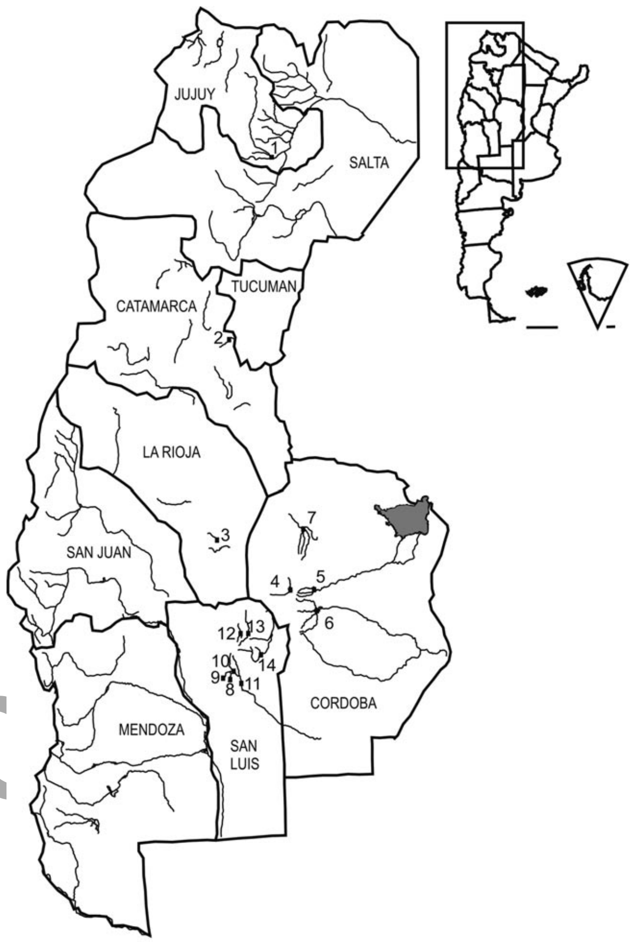

Fig. 1. Reservoirs of Peri-Pampean region: 1: Las Maderas Reservoir, 2: Sumampa Reservoir, 3: El Anzulón Reservoir, 4: La Viña Reservoir, 5: Los Molinos Reservoir, 6: Río Tercero Reservoir, 7: San Roque Reservoir, 8: Cruz de Piedra Reservoir, 9: Potrero de los Funes Reservoir, 10: La Florida Reservoir, 11: Paso de las Carretas Reservoir, 12: Luján Reservoir, 13: La Huertita Reservoir, 14: San Felipe Reservoir. Bar scale: 400 km.

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Within this context, the phycological studies on reservoirs in Argentina have been carried out for different purposes and as a consequence certain sites have been more thoroughly investigated than others. In general, the reservoirs for generation of energy have included previous feasibility studies and subsequent periodic monitoring performed by the hydroelectric companies and by basin authorities or binational entities. The reservoirs used to supply drinking water are monitored exhaustively by the provincial water and sanitation authorities, while those providing irrigation are controlled either by national or by provincial authorities. Therefore, a large part of the monitoring results are available only in technical reports or private materials that are difficult to access.

Reservoirs in the northwest of Argentina have been studied systematically in Tucumán and Santiago del Estero (see Tracanna et al., this volume) and in Salta (Salusso 2005). In the other provinces of the region (Jujuy, Catamarca, La Rioja, and San Juan), the reservoirs are in general small in size and number and involved almost exclusively in irrigation. Among the few studies undertaken, investigations were carried out on the phytoplankton of the Sumampa Dam in Catamarca (Silverio et al. 2004), the proliferation of *Ceratium hirundinella* in the Las Maderas Dam in Jujuy (Bazán et al. 2007), and the plankton of the El Anzulón Reservoir in La Rioja (Ringuelet 1942) (Fig.1).

In the Province of Mendoza there are ten reservoirs, all located within the phytogeographic Province of “El Monte” and emplaced on large rivers: e Atuel, Diamante and Mendoza; those dams are used mainly for hydroelectric power and there is no available documentation. The province of San Luis has 10 reservoirs located in the phytogeographic “El Monte” province and classified as multiuse. The majority of these water bodies have been studied since 1995 (González del Cid 2000, González et al. 1999). In the province of Córdoba there are more than 18 reservoirs within the multiuse category, and most all of them located in the phytogeographic Province of “El Espinal”. A large number of studies have been undertaken in these systems though results are difficult to access since many of those data have been documented in proceedings from national meetings or in reports of public utility companies (Fig. 1).

Reservoirs of the Province of Catamarca

In the Province of Catamarca, the Sumampa Reservoir (Fig. 1, Table 1) was investigated by Silverio et al. (2004) during September 2000 because of a drop in the fish yield under conditions of a red coloration in the water. The authors found a high total algal density (2.1 10^8 ind. ml^{-1}), a dominance of *Ceratium hirundinella*, a low diversity (1.8), and only 14 phytoplankton species: *Strombomonas* sp., *Anisonema perosgeobium* (Euglenophyceae), *Ceratium hirundinella* (Dynophyceae), *Uroglena botrys* (Chrysophyceae), *Chlorobotrys fluitans* (Xanthophyceae), *Melosira varians*, *Aulacoseira granulata*, *Fragilaria* sp., *Eunotia* sp., *Cymatopleura solea* (Bacillariophyceae), *Pyramimonas* sp. (Prasinophyceae), *Eutetramorus planctonicus*, *Chlamydomonas* sp., *Rhizoclonium* sp. (Chlorophyceae).

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Table 1. Characteristics of the reservoirs analyzed. Volume: up to the level of the spillway.

	Area (Ha)	Volume (Hm^3)	Coordinates	Altitude (m a.s.l.)	Years of construction
Sumampa	220	17.5	27º55´S 65º30´W	515	1969
Cruz de Piedra	141	7.2	33º00´S 66º12´W	917.5	1938–1941
Potrero de los Funes	103	9.1	33º13´S 66º14´W	917.5	1927
La Florida	652	105.0	33º06´S 66º01´W	1,030	1945–1953
Paso de las Carretas	756	73.4	33º19´S 65º53´W	746	1972–1982
Esteban Agüero	107	19.4	42º55´S 66º17´W	60	1994–1997
Luján	30	3.6	32º18´S 65º55´W	689.8	1958
La Huertita	430	50.5	32º25´S 65º43´W	972	1975–1981
San Felipe	1,543	813.0	32º48´S 65º28´W	841	1938–1941
La Viña	1,050	242.0	31º47´S 65º01´W	846	1939–1944
Los Molinos	2,500	399.0	31º50´S 64º25´W	769	1948–1953
San Roque	1,600	190.0	31º22´S 64º27´W	600	1888; replaced 1944
Río Tercero	4,600	700.0	32º11´S 64º23´W	657.5	1936

Reservoirs of the Province of San Luis

An attempt to resolve the water deficit led to the construction of dams in the Province of San Luis, where the climate is semiarid to arid, with precipitation occurring between the months of September and April. Between the years 1927 and 1997 multipurpose reservoirs were created (Table 1), and in some cases, the intensive recreational activities undermined the quality of the drinking water.

González del Cid (2000) performed seasonal phytoplankton samplings in reservoirs of the central zone beginning in winter 1995 (Cruz de Piedra, Potrero de los Funes, La Florida, and Paso de las Carretas) and summer 1998 (Esteban Agüero), and in reservoirs of the northern zone these started in January 1997 (Luján, La Huertita, and San Felipe) (Fig. 1). Table 2 shows the principal species found on the basis of their maximum relative abundance. The reservoir Cruz de Piedra has been classified as eutrophic with a tendency toward hypertrophy. It has been characterized by high phosphate concentrations (a mean of 58 $\mu g\ L^{-1}$), a mean value of chemical oxygen demand of 5.8 $\mu g\ L^{-1}$, and a Secchi depth of 0.5 m when Cyanobacteria predominated. During summer a high index of total fecal coliforms and total heterotrophic bacteria were recorded. The most abundant Cyanobacteria registered were *Microcystis aeruginosa* sp., *Dolichospermum circinalis* and *D. spiroide*s; several other species of *Dolichospermum* or *Anabaena* were also abundant during autumn and the spring. Previous documentation exists of blooms of *D. spiroides* occurring at the end of the summer and the beginning of the fall from as early as 1988. Species of the Peridiniales were numerous throughout the entire year, with *Peridinium gatunense* reaching a state of dominance during the summer. Bacillariophyceae were not abundant: only the species of *Aulacoseira* succeeded. Among Chlorophyta, the Chlorococcales predominated during autumn and spring, except for *Botryococcus braunii*, that dominated in winter. The Desmidiaceae participated to only a lesser extent during summer, and were not registered at all during spring. *Eudorina elegans*, on the contrary, dominated during spring.

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Table 2. The principal species recorded in the reservoirs of the San Luis Province and their maximum relative abundance recorded in each reservoir. The table summarizes the data presented by González del Cid (2000). Reservoirs: CP, Cruz de Piedra; PF, Potrero de los Funes; LF, La Florida; PC, Paso de las Carretas; EA, Esteban Agüero; L, Luján; LH, La Huertita; SF, San Felipe. Relative abundances: (D) dominant, (VA) very abundant, (A) abundant, (F) frequent, (S) scarce, (R) rarely found.

TAXA / RESERVOIR	CP	PF	LF	PC	EA	L	LH	SF
CYANOPHYTA								
Anabaena aff. *circinalis*	VA	R				S	A	A
A. spiroides	S	S	F			VA	VA	F
A. aphanizomenoides	A					F	A	VA
Gomphosphaeria lacustris		R				D	D	F
Microcystis aeruginosa	F	F				R	S	VA
Rhaphidiopsis mediterranea						D		D
EUGLENOPHYTA								
Euglena sp.	A	F					R	R
Strombomonas aff. *verrucosa*	A							
PYRROPHYTA								
Ceratium hirundinella				D	D	F	R	R
Peridiniopsis sp.	A	S	F	R		R		
Peridinium gatunense	D	D	D	A		A	D	D
P. willei	S	F	A	S	F	A	F	F
CHRYSOPHYTA								
Mallomonas sp.	R		A			F	R	
Pseudotetraedron limneticum						F		VA
Bacillariophyceae								
Aulacoseira distans	A	A	F	F		A	R	R
A. granulata	A	VA	VA	A	S	D	D	VA
A. granulata var. *angustissima*	S			F			A	A
Cymatopleura solea	S	VA	S	F		F	R	S
Fragilaria crotonensis				R		A	R	D
Nitzschia sigma	S	A	R	S				S
Rhopalodia gibba	R	S	A	S	R	S	F	R
Synedra ulna	F	A	A	S	R	F	A	F
CHLOROPHYTA								
Botryococcus braunii	D	D	S	R		S	S	F
Closterium aciculare	S	D	D	A	R	F	VA	A
Coelastrum microporum	A	F	A			S	F	F
C. reticulatum	R	VA	D	D		S	F	R
Dictyosphaerium ehrenbergianum	S	VA				R		
Elakatothrix gelatinosa	R	R	R	S		R	VA	
Eudorina elegans	D	S	S			S		
Eutetramorus fotii	VA	D	D	F	D	F	A	VA
E. planctonicus	A	F	A	S		F	S	S
E. tetrasporus		F	F			F	A	A

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Table 2. cont.

TAXA / RESERVOIR	CP	PF	LF	PC	EA	L	LH	SF
Kirchneriella irregularis	S					VA	R	
Oocystis lacustris	S	F	F	S	R	S	R	A
O. marssoni			VA	F				
O. parva	S	VA	F		R	S	F	F
Pediastrum duplex	F	F	F			S	S	VA
P. simplex		F		S		A	F	VA
Staurastrum paradoxum	S	A	VA	R	S		S	S
S. planctonicum	R	F	VA	A	A	S	A	S
Staurastrum sp.	A	VA	VA	S		R	F	S
S. tetracerum	S		S	F		F	F	A
S. cuspidatus	S	D	VA	F	R	S	S	S

The reservoir Potrero de los Funes is characterized as mesotrophic with a tendency towards eutrophy, having a maximum phosphate concentration of 39 µg L^{-1} and a mean value of 28 µg L^{-1} along with a Secchi depth of 1.16 m. González del Cid (2000) identified 14 species of Cyanobacteria exhibiting maxima in summer, though never becoming abundant. Of the four species of Euglenophyta, *Euglena* sp. was frequent during winter. Among the Pyrrophyta, the genus *Peridinium* was present throughout the year, with *P. gatunense* being very abundant during summer and dominant in fall. Of the 33 Bacillariophyceae recorded *Aulacoseira granulata* and *Aulacoseira*. sp. were abundant during the entire year, and *Cymatopleura solea* during the spring. The highest species richness for the Chlorococcales was registered during the autumn, at a time when *Coelastrum reticulatum* became very abundant. Within this group, *Eutetramorus fotii* was abundant throughout the year, *Dictyosphaerium ehrenbergianum* during winter, and *Oocystis parva* during spring. Finally, the Desmidiaceae (*Closterium aciculare, Staurodesmus cuspidatus*, and *Staurastrum* sp.) dominated during winter.

The reservoir La Florida has been classified as oligotrophic, with a mean phosphate concentration of 17 µg L^{-1} and Secchi depth at 3.2 m. The genus *Peridinium*, represented by three species, was abundant during the entire year. Of these three, *P. gatunense* became particularly abundant and even dominated during summer and autumn. The Bacillariophyceae, with 2[illegible] species, showed the highest richness during autumn; *Aulacoseira granulata* and *Aulacoseira*. sp. were abundant throughout the year, while *Epithemia sorex, Ulnaria ulna*, and *Rhopalodia gibba* predominated during summer. Twenty species of Chlorococcales were reported as distributed over the different seasons of the year with the exception of *Eutetramorus fottii* that was always abundant and dominated during winter. *Oocystis* was represented by *O. lacustris* and *O. marsonnii* in autumn and spring and by *O. parva* and *O. solitaria* in winter and summer. Seven species of Desmidiaceae were very abundant during almost the entire year, except for summer.

In the reservoir Paso de las Carretas, considered oligotrophic although lacking physicochemical data, Cyanobacteria were scarce. *Ceratium hirundinella* predominated throughout the year and reached dominance during autumn, in coincidence with the greatest species

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richness of Bacillariophyceae. On the contrary, Chlorococcales prevailed during summer, with *Coelastrum reticulatum* becoming dominant. In the reservoir Esteban Agüero, also classified as oligotrophic but with no physicochemical data, *Ceratium hirundinella* and *Eutetramorus fottii* predominated during the entire year, with the former attaining dominance during summer and autumn and the latter during spring and summer.

Among the reservoirs of the northern zone, the Luján is notable for its lower species richness recorded during summer and autumn. Among the 14 species of Cyanobacteria identified, *Gomphosphaeria lacustris* and *Raphidiopsis mediterranea* dominated during winter. Species of Pyrrophyta were frequent throughout the year, with *Peridinium gatunense* dominating in autumn. Of the 30 species of Bacillariophyceae recorded, *Aulacoseira granulata* was abundant during the entire year and became dominant during winter. In all these reservoirs, *Gomphosphaeria lacustris* dominated during winter, *Dolichospermum spiroides* was very abundant during summer, and *D. circinalis* became prevalent in spring. In La Huertita, the greatest number of Cyanobacteria species was found (23). The Pyrrophyta were also frequent: *Peridinium gatunense* was abundant during almost the entire year and codominated with *Ceratium hirundinella* in autumn. Of the total of 30 species of Bacillariophyceae, the abundance of *Aulacoseira granulata* was notable throughout the whole year as was it dominated during autumn and winter. Among the Chlorophyta, *Elakatothrix gelatinosa* became very abundant during summer and *Closterium aciculare* during the entire year. In the reservoir San Felipe, 21 species of Cyanobacteria were identified; *Microcystis aeruginosa* and *Raphidiopsis mediterranea* dominated during summer and autumn, respectively. Five euglenoid species were also registered during summer and *Peridinium gatunense* was the most abundant in winter and spring. The greatest participation of Heterococcales was recorded in this reservoir, *Pseudotetraedron enorme* and *P. limneticum* especially contributed during the fall. The flora of Bacillariophyceae exhibited a marked variability over time: 14 species present during summer were not found during the winter, whereas 15 species were recorded exclusively during winter. *Fragillaria crotonensis* dominated during summer, while *Aulacoseira granulata* was abundant during the entire year. Among the Chlorophyta, the most notable abundance corresponded to *Eutetramorus fottii*, *Pediastrum simplex* and *P. duplex*; with 11 *Scenedesmus* species occurring during the summer and autumn.

The greater number of species of Cyanobacteria was recorded at San Felipe and La Huertita reservoirs. The reservoir Cruz de Piedra exhibited the greatest proportion of Cyanobacteria, with 83% of those organisms being potentially toxic.

Reservoirs of the Province of Córdoba

The Province of Córdoba has over 20 reservoirs whose estimated area is about 15,000 ha (Manzini et al. 2009). Although the majority are located in semiarid regions and are of multipurpose use, these have different water qualities as well as morphometric and hydrologic characteristics; several were classified as meso-eutrophic.

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The reservoir La Viña

The reservoir Ingienero Medina Allende (La Viña), located in the western portion of the Sierras Grandes, was constructed in an endorheic region (Fig. 1; Table 1). This reservoir has a dam of 107 m high, and contains abrupt downward slopes over a rocky surface. The principal touristic use of the river is for sport fishing, specifically for the pejerrey *Odontesthes bonariensis* (Manzini et al. 2009). From monthly studies at five sampling stations during successive years, Rodríguez et al. (2005a) identified differences in trophic states that occurred within the water body throughout the annual cycle. During spring and summer the reservoir was classified as eutrophic with Cyanobacteria blooms (*Microcystis aeruginosa*, *Anabaena variabilis*, *A. flos-aquae*, and *Dolichospermum spiroides*) in correspondence with high concentrations of chlorophyll *a* (mean, 13 µg L^{-1}), nitrogen and phosphorus. During autumn and winter the reservoir became mesotrophic with blooms of *Ceratium hirundinella* (Rodríguez et al. 2005a, Bazán et al. 2007), low water transparency and occasional massive fish mortality. During colder months the lowest values of chlorophyll-*a* were recorded (mean, 8 µg L^{-1}). The authors attributed those changes to differences in the climatic conditions, the drop in the water level as a result of increased water consumption for irrigation during dry periods, along with the increased duration of the photoperiod and the high numbers of tourists during the summers.

The reservoir Los Molinos

The region surrounding the Los Molinos is semiarid. Even though the reservoir is used as a source of potable water, it receives an input of phosphorus from the cattle raising and farming activities within the area and from the impact of tourism (Fig. 1; Table 1). As of the year 2001 five sampling sites have been monitored at five different water depths. Eutrophic conditions were detected along with oxygen deficits in the hypolimnion, excessive concentrations of nutrients at the lake bottom, scant water transparency and blooms of Cyanobacteria and Pyrrophyta. The reservoir was catalogued as meso-eutrophic. Blooms of *Ceratium hirundinella* were observed during summer and beginning of autumn (Cossavella 2003, Bazán 2006). These blooms reached a maximum chlorophyll-*a* concentration of 163 µg L^{-1} in December 1999 (Bazán et al. 2005), while during November 2004 attained a density peak of 90 10^3 cells L^{-1} (Instituto Superior de Recursos Hídricos); blooms occurred during successive summers with mean phosphorus concentrations of about 125 µg L^{-1}. The blooms of 1999, 2005 and 2006 (maximum surface density of 1.9 10^6 cells L^{-1}) were associated with fish mortality. On various occasions the phenomenon of algal autolysis was observed, when the loss of intracellular contents into the water column evokes a drop in its optical density (Bazán et al. 2007). Likewise, during 2005 and 2006, these authors documented blooms of *Microcystis* sp. with a concomitant production of microcystins in 100% of the samplings. The blooms of this species, however, reached maximum chlorophyll-*a* concentrations of only 8.2 µg L^{-1}, lower than those attained by the blooms of *C. hirundinella*.

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The reservoir San Roque

The reservoir San Roque is located in the Valley of Punilla (Fig. 1), it was constructed for multiple uses, the most essential being the supply of potable water for the city of Córdoba. The climate is subtropical with moderate winters. The normal range in the fluctuation of the reservoir's water is of about 8 m (Table 1). The city of Villa Carlos Paz, situated on the shore of the reservoir, has the highest density of tourism in the Province of Córdoba, and as a result the reservoir is subject to a high level of pollution whose principal source is the discharge of untreated sewage effluents. This water body is therefore eutrophic and can even reach hypereutrophy if the human impact is not controlled.

The initial studies on the phytoplankton of the reservoir were reported by Guarrera (1948) and García de Emiliani (1977). Much later, investigations were carried out on the phytoplankton indicating that the dynamics and processes of eutrophication previously described were still being observed (Prosperi 1999, 2002, Ruibal et al. 2000, Bustamante et al. 2001). Surveys continue up to the present day (Rodríguez et al. 2005b, 2006), while separate studies have analyzed the production of toxins by the Cyanobacteria (Ruibal et al. 2001) and the blooms of *Ceratium hirundinella* (Alexander & Imberger 2009).

During 1946, Guarrera (1948) found that *Melosira*, *Cyclotella*, and *Microcystis* were abundant all year round and recorded a total of 54 genera – fluctuating around 19 per month, except in summer, when 45 genera were recorded. Chlorophyta were represented by the greatest number of genera throughout the year, whereas with respect to abundance, Chlorophyta and Cyanobacteria predominated during summer, Cyanobacteria in autumn, Bacillariophyceae in winter, and Chlorophyta in spring. In addition he made reference to two blooms: one in summer by *Microcystis* sp. and one in winter by *Cyclotella* sp.

Various studies mentioned the increasing degree of eutrophization in the reservoir, which gradually reduced the number of algal genera, principally green algae and diatoms (Prosperi 2002). Moreover, blooms were repeated (Prosperi 1983), to the extent that up to two blooms could occur within the span of a single month: Cyanobacteria during spring and summer (*Anabaena* sp. and *Microcystis sp*.) and of the Bacillariophyceae *(Melosira sp.)* and Pyrrophyta (*Peridinium* sp.) during autumn and winter. Between 1999 and 2000 the dominant components of the phytoplankton in the reservoir were species of *Microcystis, Anabaena, Aulacoseira, Melosira,* and *Closterium* along with *Ceratium hirundinella*. During the summers of 1998–1999 and 1999–2000 blooms of *C. hirundinella* occurred and displaced the above genera. According to Prosperi (2002), those blooms could have been related to a migration of algae from the south, as it was later indicated by Mac Donagh et al. (2005) for the reservoir Río Tercero. Between September of 1999 and May of 2000 high algal densities and elevated chlorophyll-*a* concentrations were observed at highest water levels between two structural walls of the reservoir, when the water column became stratified, the nitrogen/phosphorus ratio decreased, and *Anabaena* sp. dominated. *Microcystis* sp. also became pronounced at the station located near the water treatment plant intake, and this event attributed to the conditions in wind velocity, water temperature and concentration of dissolved oxygen. *C. hirundinella* constituted the greatest contributor to total algal biomass between November 1999 and April 2000; greater cell density occurred at the water surface evidencing a high correlation with chlorophyll-*a* concentration. *Anabaena* sp. proliferated once again during August and September 2000. During the summer 2000–2001 blooms of

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Cyanobacteria were once again recorded in the reservoir (Bustamante et al. 2001), whereas during the summer 2001–2002, a major bloom of *Ceratium hirundinella* occurred (Alexander & Imberger 2009).

The high density and frequency of cyanobacterial blooms require studies involving the analysis of toxin levels. The results indicated that such blooms produced toxicity during all four seasons of the year: the presence of variants of MC-LC and MC-RR were detected (Amé et al. 2003, 2010, Amé & Wunderlin 2005). The concentration of toxins proved high, with levels of MC at 6 mg L^{-1} being measured at the reservoir's center (Ruibal Conti et al. 2005).

The reservoir Río Tercero

The reservoir Río Tercero is emplaced in a temperate subtropical region; the principal economic activities affecting this water body are agriculture and cattle-raising, the generation of electric power, summer tourism and nautical sports. This reservoir was filled in 1936: from that time on it functioned as a hydroelectric center and since 1983 it also supply water for cooling a nuclear-energy plant. This implies that the water level of the lake had to be maintained above the minimal height above sea level of 650 m (Fig. 1; Table 1). Accordingly, two reservoirs were constructed upstream in order to ensure the availability of water independent of precipitation. The effluent from the reservoir is the Río Tercero River with two further reservoirs located downstream. When the nuclear-power center was started up, two functional periods were defined: the pre- and the post-operational, distinguished by the difference in the mean water depth and the permissible range of variation over the year, e. g., the preoperational range of 3–15 m became reduced to 6–7 m during the post-operational period. The rise in water temperature produced in cooling the nuclear reactor affects only a localized portion of the reservoir and thus does not create general conditions conducive to an increase in algal productivity (Mac Donagh 2007). Casco et al. (2002) analyzed the nutrient records since 1978 for the pre-operational period, and found that the concentrations of TP varied between 23 and 147 µg L^{-1}. During the post-operational period, the values became limiting on various occasions during the years 1998–2000, but later returned to levels similar to the earlier period. TN exhibited comparable values from the beginning of the monitoring through 2004 (average 239 µg L^{-1}, maximum 600 µg L^{-1}), but later increased (average 600 µg L^{-1}, with peaks up to 5,000 µg L^{-1}). The values of silica were always much greater than those cited as limiting for Bacillariophyceae (1.6–11 mg L^{-1}).

The phytoplankton were monitored from 1977 through 1981 (Boltovskoy et al. 1981, Mariazzi & Conzonno 1980, Mariazzi et al. 1981, 1983, 1984, 1989, Gómez 1988) and then, from the middle of the 1990's up to the present (Mariazzi et al. 1994, Mariñelarena et al. 2010, Mariazzi et al. 1992, Casco et al. 2002, Mac Donagh 2007, Mac Donagh et al. 2005, 2009). The various successive research teams, however, used different methodologies; the central zone of the reservoir was a common monitored location. On the basis of the available literature for all these years, Table 3 lists the principal species with respect to their abundance and the constancy of their registration over time. A total of 237 species were identified pertaining to the following orders: 104 Chlorophyta, 67 Chrysophyta (64 Bacillariophyceae and 3 Chrysophyceae), 41 Cyanobacteria, 7 Pyrrophyta, 8 Cryptophyta, and 10 Euglenophyta.

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Table 3. Principal species recorded in the Río Tercero Reservoir during the period 1977–2009.

CHLOROPHYTA		**CHRYSOPHYTA**
Actinastrum gracillinimum	*S. falcatus*	CHRYSOPHYCEAE
A. hantzschii	*S. intermedius*	*Chrysidalis peritaphrena*
Ankistrodesmus falcatus	*S. ovoalternus*	*Mallomonas* sp.
A. gracile	*S. quadricauda*	*Synura* sp.
Ankyra judayii	*Schroederia antillarum*	BACILLARIOPHYCEAE
Botryococcus braunii	*S. indica*	*Achnantes minutissima*
Chlamydomonas spp.	*S. setigera*	*Actinocyclus normanii*
Closterium acerosum	*Sphaerocystis schroeterii*	*Asterionella formosa*
C. aciculare	*Spondylosium planum*	*Aulacoseira alpigena*
C. acutum var. *variabile*	*Staurastrum cuspidatum*	*A. granulata*
C. dianae	*S. gracile*	*A. granulata* var. *angustissima* f.
C. kutzingii	*S. paradoxum*	*spiralis*
C. parvulum	*Staurodesmus cuspidatus* var.	*A. granulata* var. *angustissima*
C. setaceum	*curvispina*	*A. italica*
Coelastrum astroideum	*Tetraedron minimum*	*Cocconeis placentula*
C. microporum	*Tetrastum triangulare*	*Cyclotella meneghiniana*
C. pulchrum	*Tribonema vulgare*	*Cymbella affinis*
C. reticulatum		C. tumida
Cosmarium wembarense	**CYANOPHYTA**	*Epithemia adnata*
Crucigenia tetrapedia	*Anabaena laxa*	*E. sorex*
Crucigeniella apiculata	*A. spiroides*	*Fragilaria crotonensis*
Dictyosphaerium	*Aphanocapsa elachista*	*Gomphonema acuminatum*
Ehrenbergianum	*Chlorogloea microcystoides*	*G. parvulum*
Didymocystis bicelullaris	*Chroococcus dispersus*	*G. subclavatum*
D. fina	*C. minimus*	*G. truncatum*
Diplochloris lunata	C. minutus	Gyrosigma acuminatum
Elakatothrix gelatinosa	Coelosphaerium kuetzingianum	Hantzschia amphioxys
Fusola viridis	C. naegelianum	Melosira varians
Kirchneriella microscopica	Lyngbya limnetica	Navicula cryptocephala
K. obesa	Merismopedia tenuissima	N. cuspidata
K. rosellata	Microcystis aeruginosa	N. radiosa
Monoraphidium arcuatum	M. flos-aquae	*N. notha*
M. circinale	*M. holsatica*	*Nitzschia acicularis*
M. contortum	*Oscillatoria chalybea*	*N. hungarica*
M. dybowskii	*Pseudoanabaena catenata*	*N. recta*
M. grifithii	*P. mucicola*	*N. sigma*
M. minutum	*Spirulina* sp.	*Rhoicosphaenia curvata*
M. tortile	*Synechococcus* aff. *leopoliensis*	*Rhopalodia gibba*
Oocystis parva		*Stephanodiscus* sp.
Pandorina morum	**CRYPTOPHYTA**	*Surirella ovata*
Pediastrum boryanum var.	*Cryptomonas erosa*	*Synedra* sp.
clathratum	*C. ovata*	*S. ulna*
P. duplex	*C. pusilla*	
P. simplex	*Rhodomonas minuta*	**EUGLENOPHYTA**
Pseudoquadrigula sp.		*Euglena acus*
Quadricoccus ellipticus	**PYRROPHYTA**	*E. caudata*
Scenedesmus acutus	*Peridinium gatunense*	*E. intermedia*
S. dimorphus	*Ceratium hirundinella*	*E. proxima*
S. disciformis	*Glenodinium penardiforme*	*E. variabilis*
S. ecornis	*Gymnodinium* aff. *inversum*	*Phacus acuminatus*
		Trachelomonas sp.

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During the pre-operational period, the dominant phytoplankton species were *Dolichospermum spiroides, Closterium aciculare, Sphaerocystis schroeterii, Actinocyclus normanii, Aulacoseira granulata*, and *Peridinium gatunense*, while the exclusive species (those not registered after 1983) were *Cosmarium turpinii* var. *eximium*, *Staurastrum cuspidatum, S. paradoxum, Staurodesmus cuspidatus* var. *curvispina, Gomphonema acuminatum, G. constrictum, Nitzschia hungarica, Synura* sp., and *Spirulina* sp. Noteworthy, Cryptomonadales species were not observed during this period but afterwards, not only they became continually present, but also reached a state of dominance during the post-operational period (Mac Donagh 2007). Gómez (1984a) described the distribution of *Closterium aciculare* over space and time and noted that, in general, it increased its abundance over the length of the reservoir's longitudinal axis. Several studies were conducted on the taxonomy and ecology of the Bacillariophyceae (Gómez 1984b, 1988, 1989, 1990a, b) and on the temporal and spatial distribution of the most abundant species, such as *Aulacoseira granulata, A. lirata* var. *alpigena*, *Actinocyclus normanii* fo. *subsalsa*, and *Cymbella affinis* (Gómez 1991a, b). The greater diatom abundance above the thermocline during stratification periods and the homogeneous distribution of that family during the isothermal-circulation periods were notable.

The studies on the post-operational period were carried out fragmentarily until 1999, when a systematic bimonthly monitoring begun at three sites in the main body of the reservoir and four in the thermal-diffusion zone conducted by the authors of this chapter and co-workers and extending up to the present time. During the period 1999–2000 we identified as the key structuring variables of the plankton the duration of the spilling period, a reduction in the phosphorus concentration of the water, and the possible input of plankton by advection from the upstream reservoirs. In addition, the occurrence of certain plankton species such as *Asplanchna girodii* (Rotifera) and *Ceratium hirundinella* and the changes in the relative contribution of certain groups of phyto- and zooplankton (e. g., an increase in the Cryptophyta and a decrease in the ciliates) could have modified the relationships within the planktonic community. We further analyzed the functional groups during this period by the criteria of Weithoff (2003) – e.g., motility, size, myxotrophy, nitrogen fixation, and silica requirement – in addition to morphological types and the presence or absence of mucilage, and discriminated 13 phytoplankton groups (Mac Donagh 2007).

Utilizing the body of information for the post-operational period, we plotted the abundance and biomass of the phytoplankton (Fig. 2A) and the species diversity (Fig. 2B) during the period 1999–2009, and found that the most characteristic phytoplankton species of the Río Tercero Reservoir pertain to Bacillariophyceae and Cryptophyta. *Cryptomonas pusilla* is present throughout the year and is generally one of the most abundant species. Because of its small size, however, this species fails to represent an appreciable contribution to the overall phytoplankton biomass. Among diatoms, *Actinocyclus normanii* was registered during almost the entire study period. The maximum phytoplankton abundance in the reservoir was recorded in the winter of 2000 (Fig. 2A) and was attributable almost entirely to an exceptional density of this species – in part as a result of the additional input from the upstream reservoirs, and evidenced by the low diversity in the riverine zone of the Río Tercero Reservoir (Fig. 2B). Among the more common accompanying species, we found other Bacillariophyceae (e.g., *Aulacoseira granulata* and *Cyclotella meneghiniana*) along with Chlorophyta (e.g., *Monoraphidium* spp.). *Ceratium hirundinella, Asterionella formosa*, *Fragilaria crotonensis, Microcystis aeruginosa, Dolichospermum spiroides* and *Closterium setaceum*

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became significant contributors in terms of biomass due to their large size. *C. hirundinella* was in particular responsible for the peaks in biomass during the summers following its invasion in 1999, while *M. aeruginosa* caused the maxima in different seasons of the year (e.g., June 2003, December 2003, and December 2004; Fig. 2A).

The long series of data records in this reservoir enables a reliable documentation of the incidence of biological invasions. In at least two circumstances these interlopers have been demonstrated to have responded to regional phenomena, *Ceratium hirundinella* and the mollusc *Limnoperna fortuneii*. The pattern of regional invasion by the former began in the South-Chilean lakes and subsequently became extended as far as the reservoirs of the north and central regions of Argentina (Mac Donagh et al. 2005). *C. hirundinella* was registered for the first time in the Río Tercero Reservoir in February 1999, but eventually became successfully established evincing elevated densities and a high biomass, and only in the most recent years exhibited lower values. *L. fortuneii* was observed for the first time in 1996 in this reservoir (Darrigran et al. 2009) and proliferated during the following years, to the extent that the greater depth of the photic zone recently observed may be attributed to the deleterious effect on the phytoplankton by filtration of this mollusc larvae. More recently an invasion by *Asterionella formosa* and *Fragilaria crotonensis* was registered during the winter of 2009, displacing other common Bacillariophyceae, despite Cryptophyta maintained their characteristic abundance.

The data from 1999 onwards would indicate that the diversity of the phytoplankton in the reservoir has diminished gradually but progressively (Fig. 2B), although the interpretation of this variable is complex. After a period of various years in which species richness decreased, as of the year 2008 this parameter once again increased. As this finding coincided with an invasion by *A. formosa* and *F. crotonensis* and their subsequent domination among the plankton, no corresponding increment in values of diversity was observed. Within the context of the hydrologic functioning of the reservoir, an elevation in diversity has been noted around the spillway during conditions of intermittent spilling (e.g., in 1999) and a drop in diversity in the riverine zone of the reservoir owing to the massive input of upstream species – as it happened with *Actinocyclus normanii* in 2000 (Mac Donagh et al. 2009).

When the relative species composition of the reservoir between periods is analyzed, the increase in species richness during the post-operational appears as a striking event. The elevation in the number of species of Chlorophyta, Cyanobacteria, and Rotifera and the greater proportion of coccalean forms within the phytoplankton were probably related to the higher stability of the reservoir. Moreover, the influence that new species such as *Asplanchna girodii* and *Ceratium hirundinella* might have on the composition of the plankton community is noteworthy (Casco et al. 2002). Finally, the success in colonization of the reservoir by *C. hirundinella* was related to the favourable conditions for that species, the displacement of another species of Pyrrophyta (*Peridinium gatunense*), and an increase in the density of the predator *Asplanchna girodii* (Mac Donagh et al. 2005).

Final remarks

One still outstanding aspect of the region is the need to conduct studies on many of the reservoirs of which our knowledge is either lacking or incomplete. Indeed, even the two reservoirs

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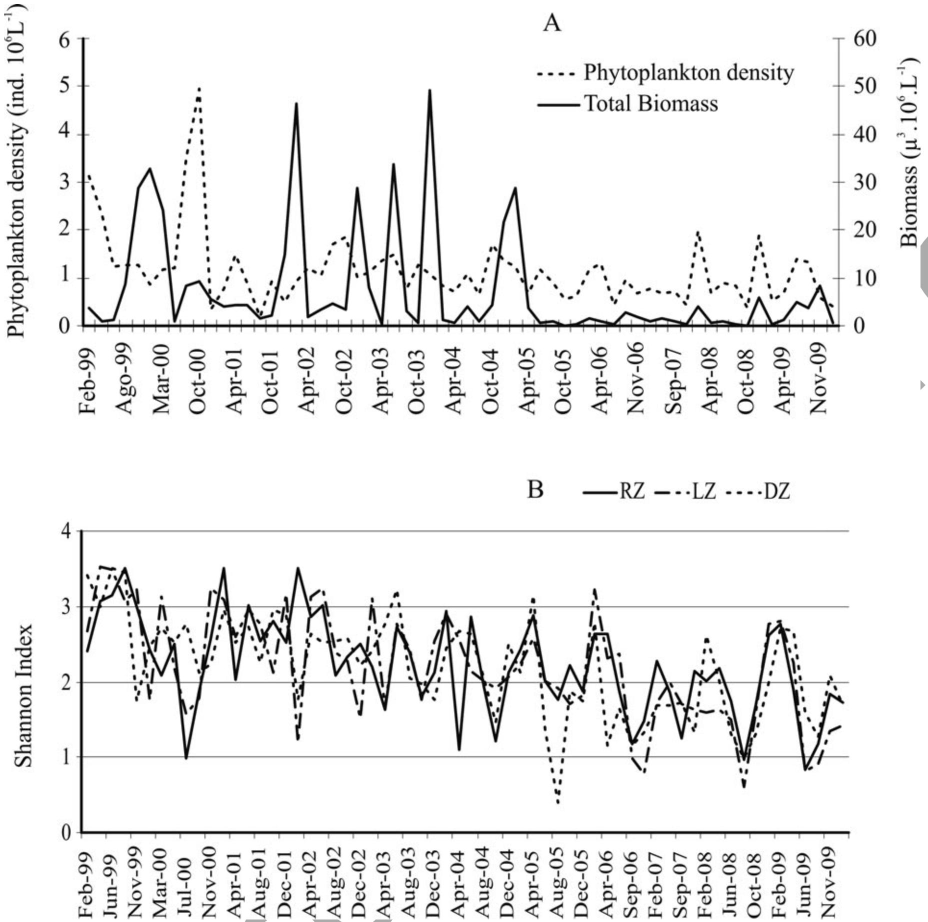

Fig. 2. Variation between the years 1999–2009 in the principal phytoplankton descriptors. The data are from bimonthly samplings. **A**: Phytoplankton abundance and biomass (average values from the photic zone in the central sampling site). **B**: Phytoplankton diversity in the photic zone at the sites indicated (RZ, riverine zone; CZ, lacustrine zone; DZ, dam zone).

with the most complete information should have their studies continued. First, the San Roque Reservoir needs further investigation because its functioning as a source of potable water turns it an environment of high health risk because of the recurrent algal blooms of lengthy duration and high density. The summer blooms of *Microcystis* sp. have been registered ever since 1946 and still continue to be. The problem of a questionable odor and unsavory taste of the drinking water caused by blooms of Cyanobacteria have been reported since 1971. Second, the Río Tercero Reservoir must be further studied because the functioning of the nuclear-power plant evoke changes such as the establishment of the minimum water level, the recirculation of water through the riverine zone of the reservoir and the creation of the downstream reservoir complex Cerro Pelado-Arroyo Corto. These changes were associated

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not only with decreases in the concentration of phosphorus and nitrogen, the indices of trophic state with respect to chlorophyll and the water transparency but also with qualitative and quantitative changes in the phytoplankton.

In conclusion, the proliferation of *Ceratium hirundinella* should be evaluated throughout the entire region since it was found in all the studied reservoirs from the year 1999 on. Moreover, the blooms of Cyanobacteria should be monitored because of the health risk caused by the production of toxins in bodies of water that are extensively used for human consumption and recreational activities.

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