

Silica dynamics in a pampean lake (Lake Chascomús, Argentina)

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Received 10 April 2003; received in revised form 10 September 2003; accepted 11 September 2003

Abstract

Silica dynamics in a pampean lake, Lake Chascomús (Chaco-Pampa plain, Argentina) is described. Pampean lakes are shallow alkaline ecosystems, with circulation pattern corresponding to polymictic lakes, due to the nearly continuous vertical mixing that promotes a high concentration of suspended particulate matter and low transparency. A silica budget was calculated in Lake Chascomús in 1999–2000 using a one-box model that constitutes the first one for a shallow pampean lake. In general terms, the dissolved silica in Lake Chascomús contributed by streams and groundwater, the latter responsible for 70% of the incoming dissolved silica, was able to support the diatom production development. However, in the algal bloom period (spring and summer), the winter input contributed by the streams and groundwater was insufficient, and therefore, an extra source of dissolved silica was necessary. Dissolution of silicate mineral phases, or silica desorption from metallic oxides might provide the dissolved silica needed for the seasonal increase in diatom abundance.

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Keywords: Lake Chascomús; Biogenic silica; Silica dynamics; Silica budget; One-box model

1. Introduction

Silicon is a major component of the earth's crust (Jackson, 1964). The crystalline silica minerals, the most common being feldspars and quartz, are in general very stable. Weathering of Si from these minerals takes place mainly over multi millennial to million year time scales ($k=6 \times 10^{-14}$ mol cm² s⁻¹; Lerman, 1988). On the other hand, biogenic produced silica (amorphous opal), mainly found in the shells of several different aquatic organisms, is soluble at time-scales ranging from days to years ($k=2 \times 10^{-9}$ mol

cm² s⁻¹; Hurd, 1983; Dixit and Van Cappellen, 2002).

In the pH and temperature range (0–30 °C, pH 6–9; Golterman, 1975) and at the concentrations normally found in natural water ecosystems, all dissolved Si occurs as silicic acid. In spite of the fact that quartz is a major constituent in rocks, quartz does not control the silica concentration in solution because of its slow dissolution kinetics.

It is a well-known fact that the seasonal cycle of dissolved silica in lakes is intimately bound to the biological activity (Gibson et al., 2000; Kristiansen et al., 2001). Diatoms often constitute the most important members in the phytoplanktonic community and in many lakes they are the permanent predominant group (Hutchinson, 1975). In most lakes located in

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temperate climates, the dissolved silica concentration in freshwater varies markedly as a consequence of its seasonally use by planktonic and benthonic diatoms. On the other hand, in the deep lakes, a vertical distribution of dissolved silica is observed, consistent with the surficial use of it by diatoms and enrichment in the deep areas caused by diatom dissolution (Wetzel, 1983; Rickert et al., 2002).

In some freshwaters, the importance of in-and outflow of Si in dissolved or easily regenerable biogenic form (Conley, 1997) may be of greater importance, but in general, the Si cycle is dominated by biological uptake and regeneration within the lake (Willén, 1991). All these factors are, of course, dependent on the physical and chemical, as well as, on the food web characteristics of the water ecosystem in question. Diatoms are more likely to dominate under conditions of low temperature, low light, high turbulence and high nutrient concentrations (Reynolds, 1984; Sommer et al., 1986; Willén, 1991). Aggregation and sedimentation of the diatom cells in the final phase of the bloom are also common, since diatom aggregates achieve higher settling velocities than single cells. Although some of the biogenic Si is regenerated very rapidly in the epilimnion (Sommer, 1984), most of the labile Si in the ecosystem is frequently transported from the epilimnion to the hypolimnion and the sediment surface in a mass event (Tallberg, 2000). Since the regeneration of dissolved Si primary occurs in the hypolimnion during the period of summer stratification, the supply of dissolved Si to the photic layer can be limited, which may drastically influence the composition of the phytoplankton assemblage and especially the summer diatom species succession (Sommer et al., 1986; Van Donk and Kilham, 1990; Egge and Asknes, 1992).

The dissolution of diatom frustules is a very complicated process, that is dependent on pH, temperature, total dissolved solids of the environment, the species of diatom involved and the bacterial activity at the frustules surface (Bidle and Azam, 1999). In shallow freshwater lakes, the permanent burial of diatoms is usually not important (Sommer, 1988), and most Si contained in the settling diatom cells is released at the sediment surface on a time-scale of days to months (Hurd, 1983; Conley, 1997; Rippey, 1983). Since the Si concentrations in sediment inter-

stitial waters are several times higher than those in the water column (Hallmark et al., 1982), diffusion of silicate from the sediments surface to the hypolimnion is also an important pathway. While some properties of the sediment (e.g. pH) directly influence the dissolution of silica (Hallmark et al., 1982; Tan, 1994), the Fe and Al oxides and hydroxides content indirectly increase Si dynamics and these minerals have the ability to re-adsorb the released silicate (Edwards and Liss, 1973; Hallmark et al., 1982; Aston, 1983; Gelen et al., 2002). Such sorption and desorption mechanisms constitute a buffering mechanism.

Several authors have calculated dissolved silica mass budgets in lakes (Dickson, 1975; Parker et al., 1977; Nriagu, 1978; Johnson and Eisenreich, 1979; D'Elia, 1983; Schelske, 1985; Schelske et al., 1986a,b; Hecky et al., 1986; Conley et al., 1988; Bailey-Watts et al., 1989; Cornwell and Banahan, 1992; Conley et al., 1993; Michard et al., 1994; Stoermer et al., 1996; Callender and Granina, 1997; Hofmann et al., 2002). Most of these studies have focussed in the Laurentian Great Lakes or other Northern Hemisphere lakes, usually large and deep. Dissolved silica mass budgets in lakes located in the Southern Hemisphere are not common.

In this work, the silica budget of a shallow pampean lake (Lake Chascomús, Chaco-Pampa plain, Argentina) is estimated. This is the first study on silica dynamics in this environment. The Chaco-Pampa plain is one of the most extended plain regions of the world where a multiannual succession of humid and dry climates, as well as its geomorphology, result in the development of wetland systems and very shallow lakes (Iriondo, 1999). Previous work has showed that groundwater is an important water source in pampean lakes (Miretzky et al., 2000, 2001a). Dissolution of amorphous silica whose sources are volcanic glass shards and biogenic silica derived from plant or animal remains also present in the Pampean loess most likely controls the high dissolved silica concentrations in groundwater (mean value 63 ppm) (Miretzky et al., 1998, 2001b).

2. Study area description

Chascomús shallow lake is part of the “Sistema de las Encadenadas de Chascomús” (35°30' S to

35°34' S and 58°17' W to 58°44' W) in the Salado River drainage basin, Chaco-Pampa plain, Argentina (Fig. 1). Lake Chascomús (mean depth 1.5 m, surface area 30.1 km², volume 47 km³; Dangavs, 1976), is a shallow alkaline system with high concentrations of suspended particulate matter and low transparency (average Secchi disk readings 0.19 m; Romero and Conzonno, 1997). The principal tributaries are Vitel and Valdéz streams, while San Felipe, Tamborini and Monte Brown streams are minor ones. Girado stream is the only outflow stream (Fig. 1).

The regional geological characters are those of low topographic slope great plain areas (Auge and Hernandez, 1983): surface geologic monotony; little tectonic deformation; predominance of fine sediments and continuity and areal extension of the geological units, where Cretaceous, Tertiary (Lower and Upper),

Plio-Pleistocene and Pleistocene (Middle and Upper) sediments are superimposed over the Precambrian crystalline basement. The principal characteristics of the regional stratigraphic sequence (Salado River sedimentary basin) are shown in Table 1 (Zambrano, 1974). The Pampean sediments or Pampean loess (Middle and Upper Pleistocene) are of special importance in the chemical composition of the groundwater and have been previously described (Miretzky et al., 2001b).

The region has a wet climate and a mean temperature between 13 and 16 °C. Mean annual precipitation (1961–1990) was between 850 and 950 mm. Although precipitation is high in the summer, the precipitation–evaporation balance is usually negative in this season. The region is characterized by very gentle slopes (0.3 m km⁻¹; Sala, 1975).

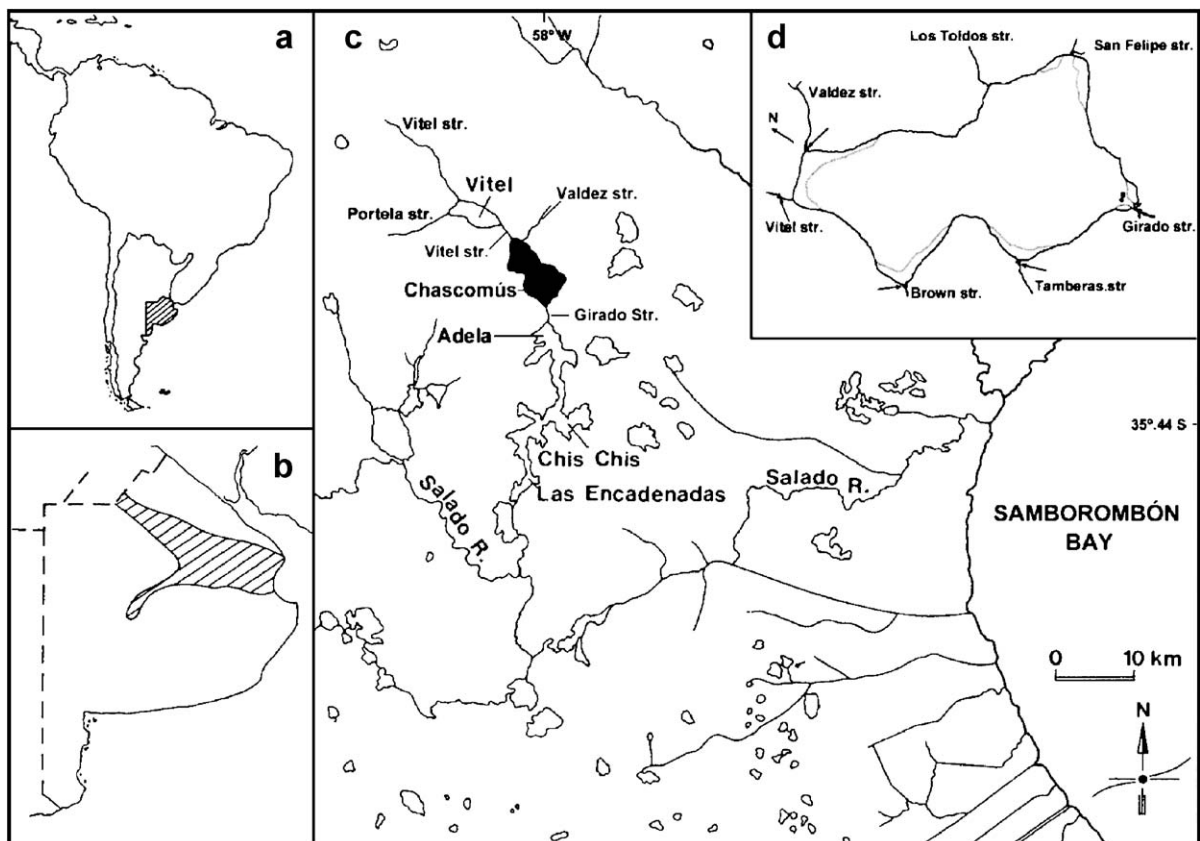


Fig. 1. (a) South America, Argentina, Buenos Aires Province; (b) Salado River drainage basin; (c) Sistema de las “Encadenadas de Chascomús”; (d) Lake Chascomús tributaries and emisary.

Table 1
Salado River sedimentary basin: stratigraphical sequence

Thickness (m)	Formation	Age	Lithology
0–10	Post-Pampeano	Holocene	silty clays
10–120	Pampeano	Pleistocene	brown and dark reddish clayey and sandy silts, rich in calcium carbonate in the shape of concretions and layered beds (loess sediments) of volcanic origin
30–80	Arenas Puelches	Plio-Pleistocene	dark yellowish to whitish, medium to fine grained friable quartzose sands
100–900	Paraná	Upper Miocene	marine sediments characterized by greenish clays in the upper 50 m and by dark greyish and whitish clayey sandstones in the middle and lower parts
90–400	Olivos	Lower Miocene	dark reddish continental claystones and sandstones with abundant gypsum
<1000	Las Chilcas	Lower Tertiary	greyish and greenish silts
<3000	Río Salado and General Belgrano	Cretacic	sands with subordinated clays and silts
	Basament	Paleozoic	quartzites

Pampean lakes are shallow alkaline ecosystems, with a circulation pattern corresponding to polymictic lakes. Nearly continuous vertical mixing occurs that promotes a high concentration of suspended particulate matter and low transparency. The water column is almost always thermally homogeneous, saturated with dissolved oxygen and with a high content of dissolved organic matter, mainly humic substances (Conzonno and Fernandez Cirelli, 1987, 1988). The benthos has aquatic macrophytes at different development stages. They show a typical profile of “pfanne” or “wanne” (similar to a washbowl) with a shoreline development of less than 4, indicating simple geometrical slope, and a maximum depth of 4 m. The shoreline development is the relation between the coastal length and circumference related to the lake area. If the lake is circular, the shoreline development is 1.

Upper sediments are sandy silt, silt and clayey silt, with a calcium carbonate content between 1% and 20% and organic matter lower than 15%. The nutrient and organic matter concentrations, phytoplankton biomass, presence of aquatic macrophytes, the frequency and intensity of algae blooms and the observed fish community all point to the fact that the lake is eutrophic (Ringuelet, 1962; Quirós and Drago, 1999).

Because of their depth, the biogeochemical dynamics of pampean shallow lakes are intricately tied to climate conditions, and the annual precipitation and evaporation volumes are of the same order of magni-

tude as the lake volume. During flood periods, precipitation reaching the land surface is stored in depressions forming shallow lakes and marshes. The water exceeding the storage capacity of the depressions moves very slowly on the surface as sheet flow. Infiltration is very high due to regional lack of slope and soil characteristics, and the water table is near the land surface at most places. As a consequence, groundwater and surficial water are strongly interrelated.

3. Material and methods

Lake Chascomús water column samples and surficial sediments (upper 5 cm) were collected monthly from April 1999 to June 2000 at three sampling stations located along a transect along the lake's longer axis. Also, the water column height was monthly measured. The stations were documented by satellite (GPS Garmon). Monthly water samples (15) of Vitel, Valdez and Girado tributaries were collected and stream surficial rate and section area were measured in order to calculate the discharge, as no data were available in the literature.

The water samples were filtered using 0.45 µm acetate cellulose membrane (Micro Separations, MSI), and were stored in polyethylene bottles. Silica was determined spectrophotometrically at 815 nm (1 cm path length Jasco 7850 spectrophotometer) after re-

duction of silicomolybdate in acidic solution to “heteropoly blue” by ascorbic acid (APHA, 1993). Biogenic silica in water column was determined after alkaline digestion at controlled temperature (Paasche, 1973; Conley, 1998) by the same method. Determinations were performed in duplicate with a relative error of < 1.0% for all analyses.

Total diatom abundance and percentage composition of Chascomús and tributaries water and sediment samples were determined (relative error 5–8%). The diatomological techniques have been previously described (Miretzky et al., 2002). Diatom silica content of sediment was calculated by measurement of the biovolume after Conley et al. (1989).

Precipitation and air temperature data during the sample period (April 1999–June 2000) were obtained from the Instituto Tecnológico de Chascomús (INTECH). Air temperature statistical data (1941–1990) were obtained from the Servicio Meteorológico Nacional. Evaporation values were calculated with the BALUBA 1.0 program (1991).

The errors in the time determination used in the calculation of the surface rate were 0.5%, the error in the width bridge measure 0.3% and the error in the determination of the river section was 3%, therefore,

the total error in the discharge measure was smaller than 5%.

4. Results and discussion

Lake Chascomús hydrologic level and precipitation–evaporation balance during the sampling period (May 1999 to April 2000) is shown in Fig. 2. Lake mean annual volume was 48.2 h m^3 (47 h m^3 ; Dangavs et al., 1996). The annual precipitation–evaporation balance was positive (7.04 h m^3) although was negative from October 1999 to March 2000.

Vitel and Girado stream discharge were measured monthly. Groundwater discharge was calculated by means of a one-box model that takes into account the monthly silica mass balance. In this model, it is proposed that Chascomús water column and a thin layer of 0.3 cm upper lacustrine sediment (average lake sedimentation rate 3.3 cm year^{-1} ; Dangavs et al., 1996) constitute a compartment or one box (Fig. 3). This compartment behaves as an ideally stirred continuous tank with convection being the principal mass transport process. Due to the shallow depth of the lake and the wind mixing process, Lake Chasco-

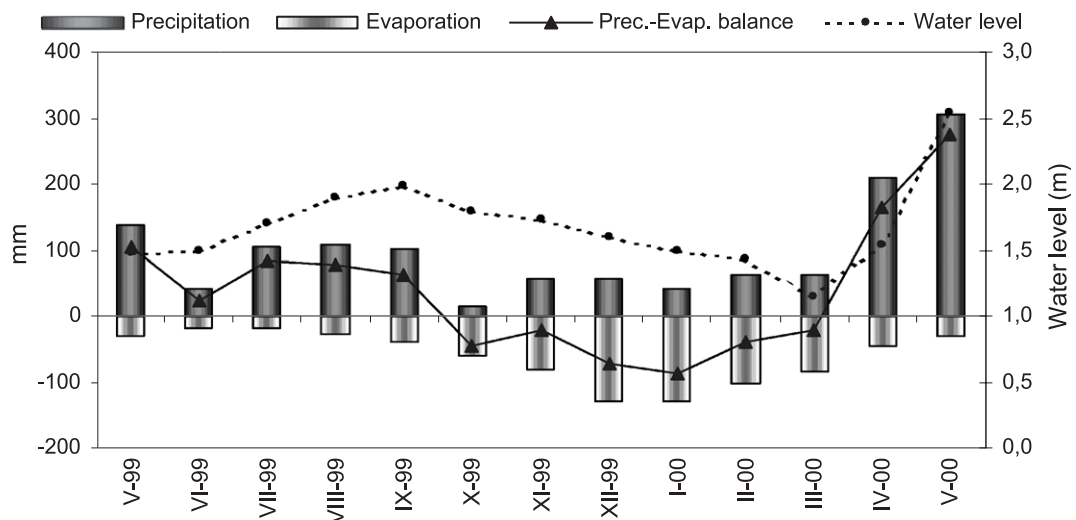


Fig. 2. Lake Chascomús hydric level and precipitation–evaporation balance during 1999–2000.

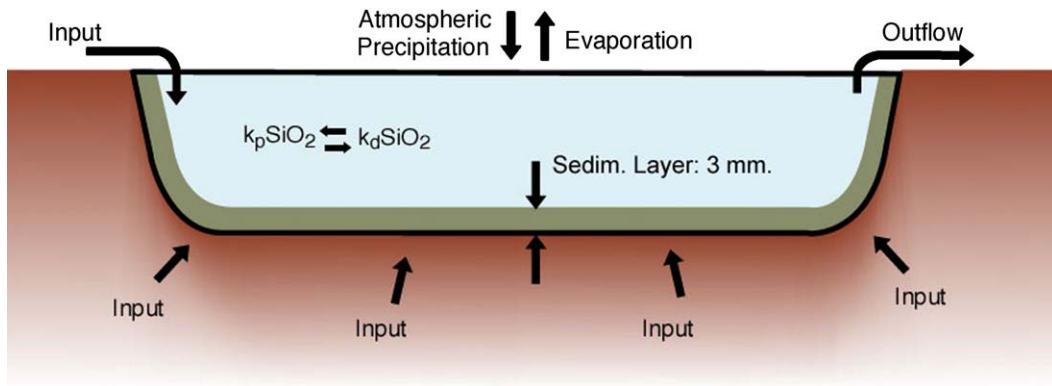


Fig. 3. One-box model diagram.

mús is a chemically homogeneous system where, consequently, diffusion process can be neglected.

The monthly silica mass balance in the one box model is

$$M_f = M_i + M_{V_a} + M_{V_i} + M_{gwater} - M_{G_i} \quad (1)$$

where M_f : total silica mass in the month under consideration; M_i : total silica mass in the previous month; M_{V_a} , M_{V_i} and M_{gwater} : total silica mass input of the tributaries (Valdéz and Vitel streams) and groundwater; and M_{G_i} : total silica mass of the outflow stream (Girado stream).

Also, total silica mass in the one-box in the actual month will be

$$M_f = (M_{SS} + M_{BS})_{water\ column, f} + (M_{SS} + M_{BS})_{sediment\ layer, f} \quad (2)$$

$$M_i = (M_{SS} + M_{BS})_{water\ column, i} + (M_{SS} + M_{BS})_{sediment\ layer, i} \quad (3)$$

where M_{SS} is the mass of dissolved silica and M_{BS} is the biogenic silica mass; f: actual month; i: previous month.

Stream volume input was calculated by the monthly measured discharge rate. Runoff and Valdez stream and other minor tributaries (Tamborini, Mount Brown, San Felipe) volume inputs (V_{V_a}) were calculated as follows (error smaller than 5%).

$$V_{water\ column, f} = V_{water\ column, i} + V_{V_a} + V_{V_i} + V_{groundw} - V_{G_i} + V_{pp} - V_{Ev} \quad (4)$$

where, V = volume; pp = precipitation; Ev = evaporation; and the other subscripts as before.

Combining the previous equations (Eqs. (1)–(4)) results in

$$V_{groundw} = [M_f - M_i - M_{V_i} + M_{G_i} + C_{V_a}(V_{water\ column, i} - V_{water\ column, f} + V_{V_i} - V_{G_i} + V_{pp} - V_{Ev})] / (C_{groundw} - C_{V_a})$$

where C = total silica concentration.

This equation enables us to calculate the monthly volume input of groundwater in Lake Chascomús by determining the total silica mass in the box, groundwater and tributaries, tributaries discharge and the precipitation and evaporation volume. All these data have been previously measured or calculated.

It should be mentioned that the floodgates that communicate Chascomús and Vitel Lakes (located in the stream Vitel) and Chascomús and Adela (located in the Girado stream) (Fig. 1) were closed during the months December 1999 and January, February and March 2000 in order to prevent the water level from lowering too much in the dry seasons (to allow fishing craft to use the lake). During the summer, when the floodgates are closed, the Valdéz stream and the minor streams are practically dry, and the runoff is minimal. At this time, Lake Chascomús behaves as a closed system, with groundwater the only possible input.

The average monthly volume inputs of the tributaries and groundwater is shown in Fig. 4. The contribution of the streams was larger in autumn and winter 1999, in coincidence with the highest precipitation. Groundwater input is displaced some months in regard

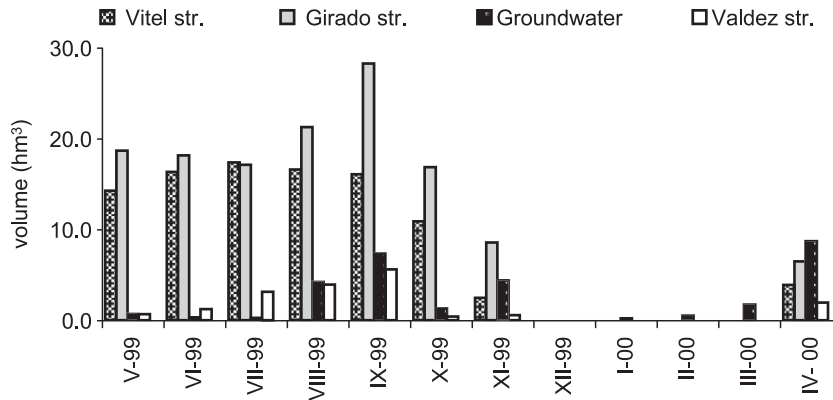


Fig. 4. Lake Chascomús monthly inputs and outflow average volume (h m³).

to surficial water, being important only in the spring (August–November) 1999. During the year of the study, the total volume input by the stream Vitel was 96.7 h m³, that of the Valdéz and minor streams 17.4 h m³, groundwater 29.6 h m³ and the outflow by Girado stream was 145.0 h m³. Underground input was ca. 26% of surface water input or ca. 20% of total input approximately. The average residence time of the lake water was ca. 4 months.

Fig. 5 shows the monthly concentration values of dissolved silica (SS) and biogenic silica (BS) in Chas-

comús shallow lake during the sampling period. Dissolved silica values remain relatively constant (average concentration value 2.27 ppm) until September (spring) and they gradually diminish to a value of 0.1 ppm (lower limit of dissolved silica requirement by diatoms) during the summer. In April 2000 the silica value increased to 1.61 ppm. The biogenic silica concentration increased from October 1999 to March 2000: average concentration value 12.7 ppm, (the December value is anomalous and was not considered in the mean value) and concentration values diminished

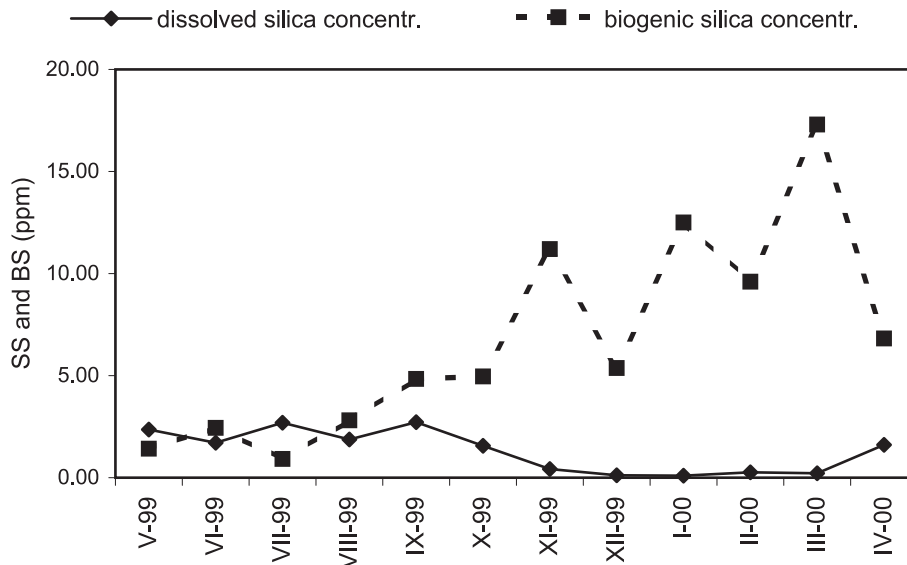


Fig. 5. Lake Chascomús monthly dissolved and biogenic silica concentration in water column (ppm).

again in April 2000 to a value of 6.82 ppm. Consequently we can affirm that the decrease of dissolved silica in Lake Chascomús in spring and summer coincides with the diatom growth (increase of biogenic silica). It is probable that in December 1999 when diatom abundance was low, but chlorophyll *a* concentration was high (0.142 ppm), cyanobacteria dominated the phytoplankton. This is favoured by the high temperatures that promote loss of dissolved inorganic carbon, in particular carbon dioxide, and increases in pH (Izaguirre and Vinocur, 1994; Miretzky et al., 2002).

The monthly contributions and the outflow of dissolved and biogenic silica mass (*t*) were calculated for the tributaries and outflow stream. Fig. 6a,b shows the dissolved and biogenic silica concentration of the tributaries. It should be noted that groundwater only contributes with dissolved silica. The concentration value of Vitel dissolved silica remained relatively

constant during the entire year with a mean value of 9.09 ppm. On the other hand, Valdez values were larger in winter than in spring (mean concentration value 13.7 and 8.27 ppm, respectively). The dissolved silica concentration of the groundwater was assumed constant during the entire year and its average value was of 63.5 ppm (Miretzky et al., 2001b). The biogenic silica concentration was lower in Vitel and Valdez streams than the dissolved silica concentration. This is the opposite for Girado stream (outflow stream) due to the fact that it has similar silica concentrations to Lake Chascomús.

Fig. 7 shows the dissolved silica concentration values in pore water and the biogenic silica concentration in the upper 0.3 cm of lacustrine sediments. The latter increased notably in the spring 1999 and then diminished in summer 2000. The same tendency, although less marked, is observed in pore water

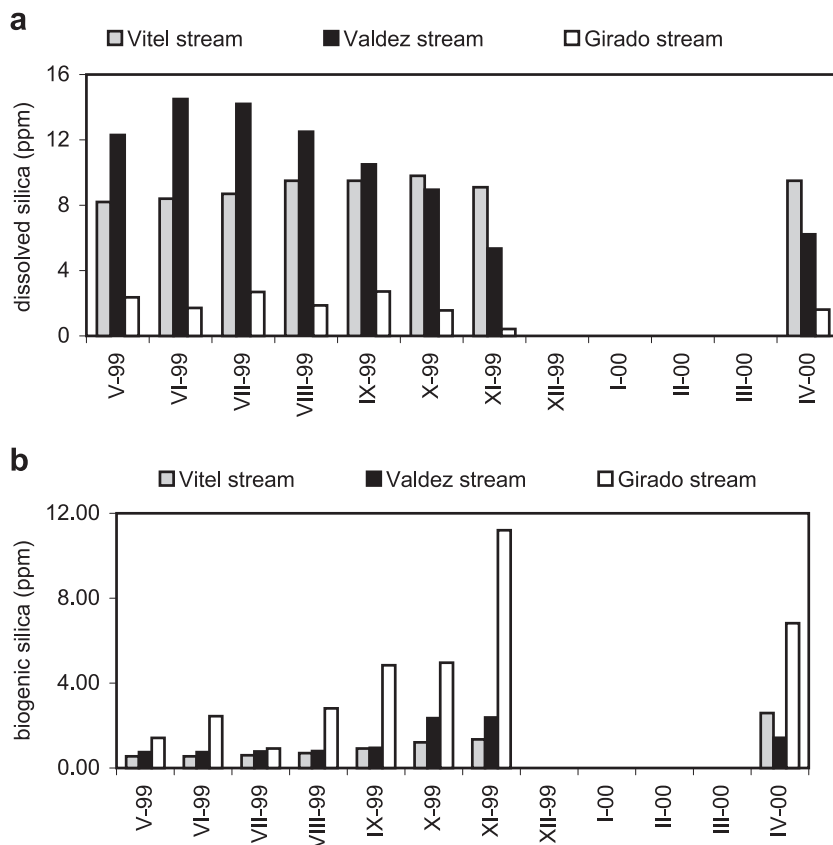


Fig. 6. Lake Chascomús tributaries (a) monthly dissolved silica concentration (ppm); (b) monthly biogenic silica concentration (ppm).

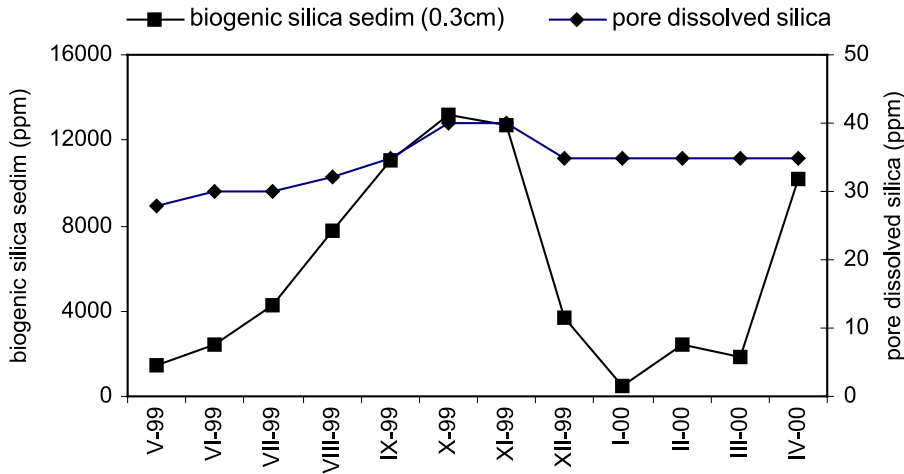


Fig. 7. Lake Chascomús monthly biogenic silica in sediments and pore dissolved silica concentration (ppm).

dissolved silica. Amorphous silica is more soluble than crystalline silica ($K_{ps} = 10^{-4}$ for quartz at 25 °C and $K_{ps} = 10^{-2.74} - 10^{-2.69}$ at 25 °C for amorphous silica; Alexander et al., 1954; Greenberg and Price, 1954; Siever, 1962). Thus, the maximum concentration of dissolved silica in natural waters in contact with the solid phase is fixed at 109.2–122.5 ppm at 25 °C. Therefore, the pore water is undersaturated with respect to amorphous silica, and it is probable that diatoms continue dissolving until pore water silica concentration reaches the equilibrium value.

The monthly diatom net mass produced, or the mass of new mineral phases containing newly formed Si, or the mass of adsorbed Si in mineral oxides (Rippey, 1980) can be calculated using reaction kinetics theory. The dissolved silica net mass entering the system in a one-month period is the difference between the inputs (Valdez, Vitel streams and groundwater) and the outflow (Girado stream). The net dissolved silica mass can follow at least two different pathways described by the following reactions



where BS: biogenic silica, SS: dissolved silica, P: mineral product, k_f : formation constant; k_d : dissolution constant.

The dissolved silica reaction rate in accordance with the previous reactions and considering that biogenic silica dissolution follows first-order kinetics

(Hurd and Birdwhistell, 1983; Wollast, 1974; Rimstidt and Barnes, 1980) results

$$(\Delta C_{SS}/\Delta t)_{\text{one box}} = -k_f C_{SS} + k_d - k_{fP} C_{SS} C_x^a C_y^b + k_{dP} + (\Delta C_{SS}/\Delta t)_{\text{enters}} \quad (5)$$

where x,y: represent mineral phases that may reaction with silica to form product P; a, b: stoichiometry coefficients.

The biogenic silica reaction rate results

$$(\Delta C_{BS}/\Delta t)_{\text{one box}} = k_f C_{SS} - k_d + (\Delta C_{BS}/\Delta t)_{\text{enters}} \quad (6)$$

Combining Eqs. (5) and (6), the mineral product reaction rate results

$$k_{fP} C_{SS} C_x^a C_y^b - k_{dP} = -(\Delta C_{SS}/\Delta t)_{\text{one box}} - (\Delta C_{BS}/\Delta t)_{\text{one box}} + (\Delta C_{BS}/\Delta t)_{\text{enters}} + (\Delta C_{SS}/\Delta t)_{\text{enters}} \quad (7)$$

The one-box model utilized in the above calculations makes the following assumptions:

- (a) All physical and chemical parameters determinations (e.g. flow rates, concentrations) were carried out once a month and it was considered that

the values obtained remained constant along that month.

- (b) The dissolution kinetics of aluminosilicates in seston or in lacustrine silts is very slow (Wollast, 1967; Paces, 1983; May et al., 1986; Velbel, 1985; Chow and Wollast, 1985; Sverdrup, 1990; White and Peterson, 1990; Brantley, 1992,) and was not taken in consideration in the month balances.
- (c) The lacustrine sediment porosity determined was 0.70 and was considered constant along the year of study.
- (d) The groundwater dissolved silica concentration was 63.5 ppm and was considered constant during the entire year. This concentration was the mean value of previous samplings in the area (Miretzky et al., 1998; 2001a,b). The lake section was considered constant and rectangular instead of pffanne form (30 km²; Dangavs et al., 1996) to calculate the monthly lake and sediment volume.
- (e) The atmospheric silica concentration was ignored.
- (f) Diffusion fluxes inside sediment pore water were not taken into account.

Fig. 8 shows the net seasonal biogenic silica mass (Eq. (6)) or new mineral phases (Eq. (7)) formed during the study period. In the autumn 1999, the dissolved silica input was enough for the diatom production and there were no new mineral phases

formed or dissolved, and neither net silica adsorption or desorption reactions on iron oxides surfaces were quantitatively important.

In the winter, the net dissolved silica input was large enough for diatom production and a small quantity of a new silica mineral phase was formed or silica adsorption took place. During the spring, the dissolution of mineral phases or Si desorption was necessary to sustain the diatom production. In the summer 2000 dissolution and/or desorption were also necessary, although in a lower measure. Finally, in autumn 2000 the net dissolved silica was again enough for diatom production, and for other mineral formation or other processes.

The annual balance resulted as follows: the net available dissolved silica was of 2679 t (1880 and 805 t for the groundwater and net river input, respectively), the diatom production was 2631 t and only 63 t (2.3%) were distributed between the formation of a mineral phase and the adsorption of Si on metallic oxides surfaces. The dissolved silica concentration in the water column was maximum in winter, due to the streams and groundwater inputs. However, the seasonality of the largest input does not coincide with the time of high diatom demand. The dissolution of mineral phases, or amorphous silica desorption processes on metallic oxides surfaces in spring and summer, were necessary to have dissolved silica for the seasonal algal bloom.

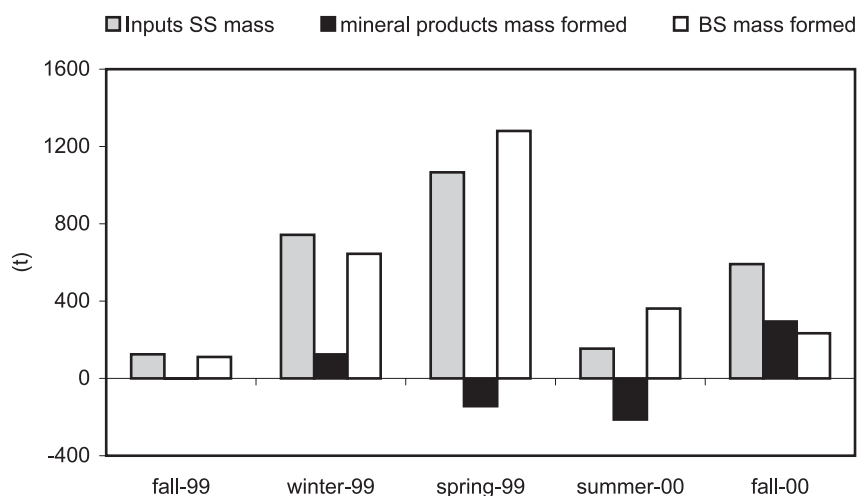


Fig. 8. Lake Chascomús seasonally dissolved silica inputs and biogenic silica production (t).

5. Lake Chascomús dynamics

There have been no other annual silica balances carried out in lakes in Argentina or in South America, therefore we must compare our results in Lake Chascomús with those from other regions such as the Great Lakes of the Northern Hemisphere, Loch-Leven (Scotland) and marine environment (Table 2). It is not surprising that in the Great Lakes, which have enormous surfaces and much greater depths than our system, the annual silica mass balances are very different. In the Lake Superior (Johnson and Eisenreich, 1979; Schelske, 1985) and in Lake Michigan (Conway et al., 1977; Schelske et al., 1984; Schelske, 1985) the external dissolved silica inputs to the system are smaller than the annual diatom requirement, and the internal recycling is the primary process during the entire year. In these lakes, only 5% of the biogenic silica produced is deposited in the sediments and most of the diatoms are dissolved in the water column. On the other hand, the Great Lakes resemble the oceans in the fact that the mass of dissolved silica in the water column is little affected by the annual dissolved silica input by rivers and streams, although a portion of it is used in the annual diatom cycle.

The studies carried out on silica balances in the Great Lakes use concepts of steady state, because the lake water mass is much bigger than the river and stream inputs (residence time 6.2–69 years). On the other hand, Lake Chascomús presents completely different dynamics, observed in the analysed period, when the contributions of the streams were 143 h m³ and the volume average of the lagoon was 48 h m³ (hydraulic residence time, 4 months).

Our results from Lake Chascomús are similar to those from a shallow lake of Scotland, Loch-Leven

(Bailey-Watts et al., 1989), where the dissolved silica inputs by streams are similar to the annual diatom production, but nevertheless internal recycling is necessary to support the seasonal increase in the diatom abundance. In this lake, there is no contribution of dissolved silica by groundwater. In the larger, but shallow lakes of central Canada, internal silica recycling and the diffusion of silica from the sediment pore waters, support the algal bloom (Hecky et al., 1986).

6. Conclusions

A silica budget was established in Chascomús shallow lake in 1999–2000 using a one-box model and first order kinetics for silica dissolution. The high silica concentration in shallow groundwater is responsible for 70% of the incoming dissolved silica in the shallow lake. Although groundwater contribution has been usually not considered in most of the silica mass balance calculations in other systems, in our case it cannot be neglected, being the principal source.

In general terms, the dissolved silica in Lake Chascomús contributed by streams and groundwater was able to support the diatom production through the year. However, in the algal bloom period, during spring and summer, the winter stock contributed by the streams and groundwater was insufficient, and therefore, an extra source of dissolved silica was necessary. The seasonality of the greatest dissolved silica contributions to the system did not coincide with the time of more diatom demand. This extra dissolved silica may be contributed by the dissolution of mineral silica phases, the silica desorption from metallic oxides surfaces, or perhaps, diffusion of Si from the sediment pore water.

Table 2

Comparative data of the silica dynamics in the Great Lakes, the oceans, Loch-Leven and Lake Chascomús after Johnson and Eisenreich (1979), Schelske (1985), Conway et al. (1977), Schelske et al. (1984), Bailey-Watts et al. (1989) and Conley (1997)

	SS water column, t	Inputs, t year ⁻¹	Residence time, year	Diatom production, t year ⁻¹
Michigan Lake	7.2×10^{12}	2×10^{11}	36	$5.2-6.4 \times 10^{12}$
Ontario Lake	0.75×10^{12}	1.2×10^{12}	6.2	5.9×10^{11}
Superior Lake	29×10^{11}	4.2×10^{11}	69	$2.4-6.8 \times 10^{12}$
Oceans	5.5×10^{18}	6×10^{14}	13000	$1.0-3.2 \times 10^{14}$
Loch Leven	333	953		985
Chascomús Lake	86	2951	0.3	2631

Although in the period sampled a silica mass balance was performed, the lake dynamics, are very susceptible to the climatic factors and our calculated mass balance only predicts the seasonality of the processes. The application of the one-box model allows qualitative understanding of lake behaviour, bearing in mind that the results obtained are only quantitatively valid for the studied period.

The dissolved silica budget established in this study constitutes the first one in a shallow pampean lake and contributes to the knowledge of these very abundant waterbodies in the extended Chaco-Pampa plain in Argentina.

Acknowledgements

We would like to thank the Universidad de Buenos Aires and the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) for the financial support for this project. [LW]

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