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Chemical water quality studies in the Central Patagonian Region of Chile following the eruption of Volcan Hudson

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Abstract

In February/March, 1993, a range of water-quality variables were measured in nine freshwater lakes at different locations in Region XI, Chile. Seven of the lakes, situated between the Rio Ibanez (46 °08′S) and Lago Lapparent (46 °14′S), are characterised by low concentrations of minerals and nutrients, similar to the oligotrophic lakes of the Araucanian district of Chile (39 °S to 42 °S).

Sulphate concentrations were disproportionately high at each of these sites and it is proposed that this results from the deposition of volcanic ash following the eruption of Volcan Hudson in August, 1991. The concentration of sulphate found in a ninth lake well to the north of the ash deposition zone was 35 fold lower than those typically measured within the main study area.

Lago Lapparent is a large 'blue' lake receiving glacial sediments, that forms the southern boundary of the area studied. Concentrations of minerals and nutrients found at this site were generally even lower than those found in the other seven lakes within the area. Organochlorine pesticides were not detected at any of the sites after solid phase extraction of 250 ml water samples.

Introduction

Extensive limnological studies have established that the lakes of the Araucanian district of southern Chile (39 °S to 42 °S) are typically classified as oligotrophic, monomictic and temperate (Loeffler, 1960; Campos et al., 1983, 1984, 1987, 1988, 1990, 1992a, 1992b). These lakes receive high rainfall (2000 mm yr^{-1}), have high transparency and low phosphate concentrations. Nitrate concentrations are also low but show more variability than phosphate. The principal cations and anions are calcium, sodium and bicarbonate. The high concentrations of silica are derived from the volcanic soils of the area.

Similar studies have also been pertormed on Lake del Toro (51 °12′S) and Lake Sarmiento (51 °02′S) which are located in the Torres del Paine National Park (Campos et al., 1994a, 1994b). Lake del Toro is classified as a temperate, oligotrophic polymictic lake receiving glacial sediments. Lake Sarmiento is a subsaline lake with a mean salinity of 1.9 g l^{-1}.

Approximately midway between the Araucanian lakes and the lakes of Torres del Paine is an area of Region XI that contains numerous lakes and is bordered to the south by the large lake, Lago Lapparent (46 °14′S). Situated at a height of 500–600 m a.s.l. this area is composed of volcanic acidic rocks with some black shales and carbonates (Mpodozis & Ramos, 1990) and lies immediately south of the Rio Ibanez (Figure 1). Region XI has remained inaccessible until the construction of a modest gravel road, the Carretera Austral, in the 1980's and is still only sparsely settled, with limited agricultural activity consisting mainly of the grazing of sheep and cattle on mountain pastures south of the Cerro Castillo National Park. No reports have been found in the literature

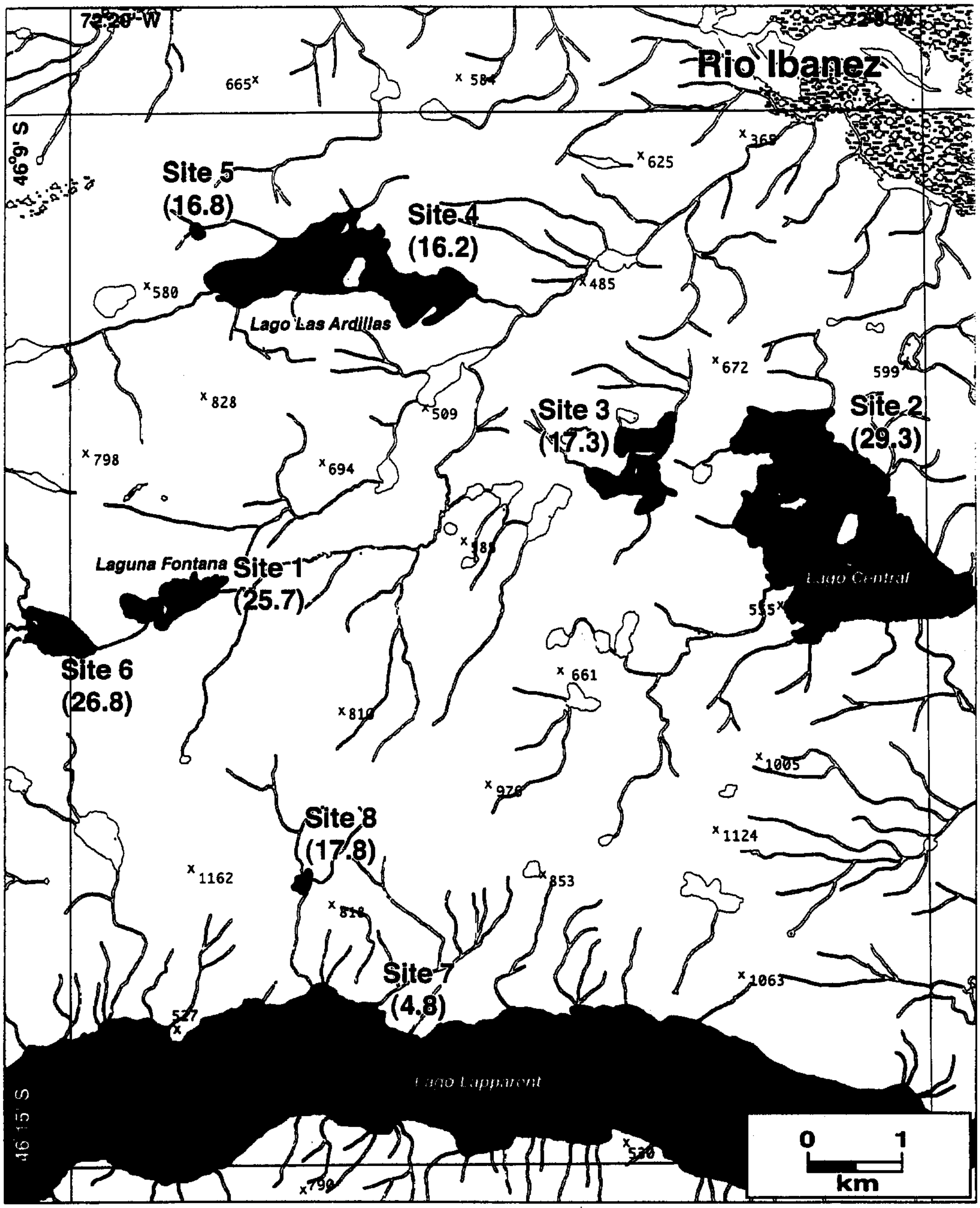

Figure 1. Map of the region between the Rio Ibanez and Lago Lapparent showing the location of the lakes studied. Mean sulphate concentrations are shown in brackets.

concerning these lakes, most of which appear to be similar in their physical and chemical characteristics to the Araucanian lakes. In contrast, Lago Lapparent bears more similarity to Lake del Toro.

In August 1991, Volcan Hudson, situated north-west of the Cerro Castillo National Park, erupted violently after being dormant for twenty years. The prevailing westerly winds carried the resulting cloud across Chile and Argentina to the Falkland Islands and deposited large quantities of volcanic ash across the area of this study, resulting in considerable damage to property and loss of livestock. At one site close to Lago Central, ash depths of 40-50 cm were reported locally and this appeared to be typical of the whole area.

A principal aim of the 1993 study was therefore to measure a range of water-quality variables at eight of these lakes (Table 1) and by comparison with previous studies on similar Chilean Lakes (Campos et al., 1983, 1984, 1987, 1988, 1990, 1992a, 1992b, 1994a, 1994b), to assess whether there were any adverse effects resulting from the eruption of Volcan Hudson or the limited settlement of this area. There is apparently no information available in the literature concerning levels of pesticides and other organic pollutants in Patagonian lakes and so samples from each of the lakes studied were also analysed for organochlorine pesticides. With the exception of Lago Lapparent, the lakes sampled had exceptionally low turbidity allowing visibility to considerable depths. Lake shores that were not rocky generally supported a dense growth of reeds and in the shallower regions of Laguna Fontana there was considerable growth of aquatic vegetation characterised by *Potomageton* and *Equisetum* spp. Filamentous green algae was only very occasionally observed in shallow water on the shoreline.

Lago Lapparent is an inaccessible lake, blue in colour and much larger than any of the other lakes sampled (Table 1). There was no evidence of aquatic vegetation in this lake and local information suggested that no fish are present.

Methods

All of the lakes, with the exception of that at site 9, were sampled at a number of locations, usually about 100 m apart, in order to encompass the range of habitat types present at each lake. At some of the sites the constraints imposed by the size of the lakes, their accessibility and the time available, limited the survey to a section of one shoreline. At most locations at least one sample was taken from as far offshore as possible. Electrical conductivity and pH were measured on-site using battery powered electrodes. Dissolved oxygen was measured onsite using a Hanna H1 8543 dissolved oxygen meter and by the Winkler titration method using the Merck test kit. Alkalinity was measured on-site using a Hach titrator (Camlab Ltd., Nuffield Road, Cambridge CB4 1TH).

Water samples were collected in acid-washed, rinsed polyethylene bottles and filtered on site through 0.45 μm millipore filters using a hand vacuum pump, for analysis in the field laboratory. 50 ml aliquots of each sample were transfered to individual acid-washed containers, acidified to pH1 with concentrated Aristar grade nitric acid and sealed for transport to the U.K. for further analysis. Determinations of nitrate, phosphate and sulphate were performed in the field laboratory using Hach quantitative test kits and a Hach DR/700 portable colorimeter (Camlab Ltd). Determination of cations was performed on acidified samples returned to the U.K. using a JY-70 plus inductively-coupled plasma atomic-emission spectrometer (ICP-AES).

Solid-phase extraction of organic compounds was performed on 250 ml filtered samples from each lake by passage through Waters Sep-pak C18 cartridges at a rate of approximately 20 ml per min using a 50 ml sterile syringe. The cartridges were activated prior to passage of the samples with 5 ml of Aristar grade methanol and excess water was expelled from the cartridges after passage of the samples. Each cartridge was sealed in a foil envelope for transport to the U.K., stored at -4 °C immediately upon return and analysed by gas liquid chromatography (GLC).

Results

Of the eight lakes sampled within the area of this study, seven exhibit a very similar profile of physical characteristics, nutrient levels and trace elements and vary in surface area between 0.05 km^2 and 3.45 km^2. The remaining lake, Lago Lapparent shows some differences and is much larger, with a surface area of 23.47 km^2 (Table 1).

Dissolved oxygen concentrations were high at all sample sites with values ranging from 88.14% saturation to 111.21% saturation when measured by the Winkler titration method (Table 2). At most of the sites dissolved oxygen concentration was also measured by means of a portable dissolved oxygen meter. The agreement between the results obtained by the two methods is good (Table 2). On only two occasions was the discrepancy in mean values greater than 2.1% saturation, with the electrode generally giving a slightly higher result than the Winkler titration.

Bicarbonate alkalinity values were generally low (Table 2). The lowest mean value of 9.15 mg l^{-1} was recorded at Lago Lapparent. Other values were in the

Table 1. Morphometric parameters of lake sample sites.

Parameter	Laguna Fontana (Site 1)	Lago Central (Site 2)	Lake NW of Lago Central (Site 3)	Lago Las Ardillas (Site 4)	Lake W of Lago Las Ardillas (Site 5)	Lake SW of Laguna Fontana (Site 6)	Lago Lapparent (Site 7)	Lake N of Lago Lapparent (Site 8)	Lake N of Cerro Castille
Altitude (m)	600	450	450	450	500	600	450	700	250
Maximum Length (km)	1.14	4.4	1.1	2.8	0.15	0.84	17.75	0.25	0.25
Maximum Width (km)	0.3	1.7	0.94	0.9	0.1	0.4	2.0	0.15	0.20
Shoreline (km)	3	13	4.5	7	1	2	45	0.5	0.6
Surface Area (km^2)	0.42	3.45	0.5	1.37	0.05	0.35	23.47	0.06	0.05
Estimated Maximum Depth (m)	25–30	50–100	25–50	100–150	10	25–30	250+	10	5

range 17.26 to 46.72 mg l^{-1}, with the highest values being recorded at sites 2 and 3.

Determinations of phosphate levels indicate that they were generally low with most samples in the range 0.01 to 0.20 mg l^{-1} (Table 2). Values in excess of 0.50 mg l^{-1} were recorded in only four samples from different lakes. Nitrate levels were generally in the range 2 to 4 mg l^{-1} but considerable variation was found between samples from individual lakes, with the highest values usually being measured close to settlements (Table 2).

The sulphate concentrations of all of the lakes within the study area were relatively high and variable, with the lowest values being recorded at Lago Lapparent (Table 2). The distribution of mean sulphate concentrations for each lake on a map shows that the highest values are found along an east-west line through the centre of the area, while values to the north and south are lower, presumably reflecting the relative amounts of volcanic ash deposited across this region (Figure 1). For comparative purposes a sample from a small lake well to the north of this region was analysed and this showed a much lower sulphate concentration of 0.7 mg l^{-1}.

Analysis of cations in acidified samples returned to the U.K. revealed that all of the lakes sampled had similar concentrations of sodium, potassium, magnesium, calcium and strontium with the exception ot Lago Lapparent where levels were substantially lower (Table 2). Low values for conductivity and alkalinity were also recorded at Lago Lapparent. The order of relative abundance of the four main cations in all of the lakes with the exception of site 3 was $Ca^{2+}>Na^{+}>Mg^{2+}>K^{+}$. At site 3 the order was $Ca^{2+}>Na^{+}>K^{+}>Mg^{2+}$.

Analysis of the samples for a range of other trace elements showed that none were present at concentrations in excess of 0.1 mg l^{-1} with the exception of zinc which was found at higher concentrations in six isolated samples (Table 2).

GC/FID and GC/ECD analysis of the sample cartridge eluates did not reveal evidence of organochlorine pesticides in any of the lakes in this survey.

Discussion

The results of this study indicate that all of the lakes sampled in the survey are very similar in character to the lakes of the Araucanian district and may be classified as oligotrophic, although the concentrations of nitrate found were considerahly higher than expected and probably result from the limited settlement of the areas close to the lakes. Phosphorus is generally considered to be the most significant limiting nutrient in the process of lake eutrophication (Schindler, 1974, 1977). Phytoplankton blooms may occur in lakes having concentrations as low as 0.3 mg l^{-1} nitrate nitrogen and 10 μg l^{-1} phosphorus (Sawyer, 1947) and phosphorus in particular plays a key role in the early stages of eutrophication (Vollenweider, 1968). The N:P atomic ratio most commonly encountered in inland waters is in the range 15–40 (Stumm & Baccini, 1978). In this study only one lake, Lago Central had a mean N:P ratio lower than 40, indicating that phosphorus lev-

Table 2. Chemical Water Quality of Freshwater Lakes, Region XI, Chile

Parameter	Laguna Fontana (n=8)	Lago Central (n=4)	Lake NW of Lago Central (n=4)	Lago Las Ardillas (n=5)	Lake W of Lago Las Ardillas (n=5)	Lake SW of Laguna Fontana (n=3)	Lago Lapparent (n=5)	Lake N of Lago Lapparent (n=3)	Lake N of Cerro Castille
Temperature	15.1	17.2	17	19	15	19	14.6	17	
(°C)	(6–20)	(16–20)	(16–19)	(18–21)	(13–17)	(18–20)	(14–15)	(17)	
pH	7.3	7.7	7.5	7.0	7.4	7.3	7.6	7.3	
	(6.7–7.7)	(7.4–8.1)	(7.4–7.6)	(6.5–7.1)	(6.7–8.0)	(7.1–7.6)	(7.5–7.7)	(7.2–7.5)	
Conductivity	142	174	195	152	141	141	56	135	
($\mu S.cm^{-1}$)	(141–145)	(169–179)	(183–208)	(142–160)	(136–151)	(139–142)	(55–57)	(135–136)	
* Dissolved Oxygen	93.54	99.64	94.45	99.42	96.52	99.42	106.48	92.38	
(% saturation)	(80.65–99.16)	(95.86–109.80)	(92.93–101.66)	(91.02–105.93)	(95.26–97.57)	(88.14–111.21)	(101.50–111.02)	(87.19–99.65)	
	94.53	*101.72*	*96.53*	*99.42*	*101.50*	–	*101.50*	*92.38*	
	(81.45–101.36)	*(96.96–106.75)*	*(94.01–101.66)*	*(89.89–105.93)*	*(95.26–107.65)*	*(–)*	*(100.31–101.50)*	*(90.30–95.49)*	
Alkalinity	23.54	33.30	46.72	27.77	30.25	25.98	9.15	17.26	
($mg\ l^{-1}$)									
Nitrate	2.8	4.3	3.4	4.4	6.9	3.7	1.7	1.7	2.6
($mg\ l^{-1}$)	(0.2–5.3)	(2.6–7.9)	(2.6–4.4)	(3.1–6.2)	(4.4–9.7)	(3.1–4.4)	(0.4–3.5)	(0.4–4.4)	
Phosphate	0.12	0.30	0.05	0.63	0.19	0.12	0.20	0.1	0.02
($mg\ l^{-1}$)	(0.04–0.25)	(0.06–0.89)	(0.02–0.07)	(0.06–1.96)	(0.06–0.53)	(0.05–0.18)	(0.01–0.03)	(0.03–0.22)	
Sulphate	25.7	29.2	17.3	16.2	16.8	26.8	4.8	17.8	0.7
($mg\ l^{-1}$)	(24.5–26.7)	(10.0–66.7)	(16.4–18.6)	(14.5–19.6)	(13.2-21.9)	(23.9-32.9)	(1.3–11.8)	(16.6–18.6)	
Na^+	9.7	9.3	12.2	9.3	11.0	9.8	3.3	8.9	3.9
($mg\ l^{-1}$)	(9.4–10.4)	(8.9–10.1)	(11.9–12.6)	(9.0–9.6)	(9.2-12.4)	(9.2–10.8)	(3.1–3.6)	(8.7–9.0)	
K^+	1.6	3.6	6.5	2.7	2.9	2.5	0.3	2.2	1.4
($mg\ l^{-1}$)	(0.9–3.2)	(1.7–5.6)	(3.2–10.0)	(1.6–3.7)	(1.5–5.3)	(1.1–6.2)	(0.0–1.3)	(2.0–2.5)	
Ca^{2+}	17.4	23.4	21.8	17.0	13.1	16.1	7.5	15.3	8.2
($mg\ l^{-1}$)	(16.8–17.8)	(23.3–23.7)	(21.4–22.2)	(16.5-18.6)	(11.8–15.9)	(15.2–18.4)	(7.1–7.7)	(15.1–15.5)	
Mg^{2+}	3.6	4.5	5.3	4.2	4.5	3.4	0.9	3.6	1.5
($mg\ l^{-1}$)	(3.5–3.9)	(4.4–4.8)	(5.2–5.5)	(4.1–4.4)	(3.4-4.6)	(3.2–4.0)	(0.8–1.0)	(3.5–3.6)	
Sr^{2+}	0.07	0.13	0.13	0.08	0.09	0.07	0.03	0.08	0.05
($mg\ l^{-1}$)	(0.07–0.07)	(0.12–0.14)	(0.13–0.14)	(0.07–0.08)	(0.07–0.1)	(0.06–0.08)	(0.03–0.03)	(0.08–0.08)	
Si	7.8	4.4	0.7	4.8	2.9	8.2	2.4	4.6	0.2
($mg\ l^{-1}$)	(7.6–9.0)	(3.6–6.5)	(0.6–0.9)	(3.6–9.2)	(0.3–7.9)	(7.6–9.6)	(2.3–2.5)	(4.5–4.6)	
Zn^{2+}	0.1	0.01	0.01	0.12	0.1	0.01	0.01	0.23	0.01
($mg\ l^{-1}$)	(b.d.–0.4)	(b.d.–0.01)	(b.d.–0.01)	(0.01–0.35)	(b.d.–0.5)	(b.d.–0.01)	(b.d.–0.05)	(0.01–0.42)	

* Oxygen electrode determinations in italics

els are very low compared to nitrate nitrogen levels in most of the lakes and this could account for their low turbidity.

The variable levels of sulphate may result from the deposition of large quantities of volcanic ash during the 1991 eruption of Volcan Hudson. If this is the case, sulphate levels should decrease with time following the eruption. It was not possible to establish retention times for any of the lakes due to constraints of time and the inaccessibility of the terrain but in the case of two, Lago Central and the neighbouring lake at site 3, these are likely to be long since there are no outlets apparent. Conductivity, alkalinity and Ca^{2+} concentration were all higher at these two sites.

There was no evidence of the presence of lindane, DDT, DDD, DDE, aldrin or dieldrin in any of the lakes sampled at concentrations greater than 0.32 $\mu g\ l^{-1}$. In general, the use of solid-phase extraction techniques proved to be a success. It would have been impractical to collect and transport large volumes of water back to the UK for extraction by conventional techniques.

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