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THE FRESHWATER LAKES OF THE LARSEMANN HILLS, EAST ANTARCTICA: CHEMICAL CHARACTERISTICS OF THE WATER COLUMN

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Contents

Abstract

Temperature, pH, conductivity, salinity, dissolved oxygen (DO), and turbidity, were measured in several lakes of the Larsemann Hills, East Antarctica, during early February 1996 and late February to early March 1997. Vertical profiles for seven lakes were obtained during early February 1996, and some chemical parameters (Al, Cl_2, SO_4^{2-}, SiO_2, and major cations) were measured during the autumn turn-over early in 1997. During the summer, these lakes have low salinity and conductivity (< 1‰ and ≤ 0.4 mS/cm, respectively), and the values remain constant for increasing depths. Temperatures range from approximately 6°C to 0°C, pH values are near neutral (approximately 7±1), turbidity values are extremely low (≤ 1 NTU), and all the lakes are close to DO saturation (± 10%). Higher conductivity (up to 5.5 mS/cm) and pH (up to 8.3) were measured in small lakes situated in the vicinity of presently occupied or abandoned research stations. Seawater input (sea-spray) is the main factor controlling the water composition.

Temperature, pH, and DO values in the water column of each lake are controlled by weather conditions, biological activity (also a function of weather conditions), and by the dimensions of the lakes. Stratification of the water column in terms of T, pH, and DO values was observed at day-time in some of the lakes. The constant conductivity and salinity values throughout the water column in each lake, however, suggest that water stratification is short-lived, and that the water column gets homogenized regularly during a 24-hour period. Consequently, water samples collected during the summer months at a depth of 0.3 m can be considered as representative (in terms of their major and trace element composition) of the entire water column.

Key words East Antarctica, Larsemann Hills, lake chemistry, water stratification

Abbreviations

NTU	nephelometric turbidity unit
DO	dissolved oxygen
mS/cm	milliSiemens/cm
T	temperature in °C

1. Introduction

The Larsemann Hills comprise an ice-free coastal 'oasis' covering approximately 50 km^2 (Pickard 1986) located on the southern shore of Prydz Bay, East Antarctica (Figure 1). This area of rocky peninsulas and islands is characterised by the presence of more than 150 freshwater lakes, the water chemistry of which is largely influenced by natural processes such as snow melt-water influx, sea-spray contamination, erosion of the country rock, biological activity, and evaporation (Burgess *et al.* 1988; Gillieson *et al.* 1990; Burgess and Kaup 1997). The presence of both occupied and abandoned bases within the Larsemann Hills, as well as a small year-round human population, may also have resulted in some anthropogenic input into the lake systems (Burgess *et al.* 1988; Burgess *et al.* 1992; Burgess and Kaup 1997; Ellis-Evans 1996, 1997).

An on-going study into the Larsemann Hills lake systems, is aimed at determining and quantifying the impact of natural versus human influences on a relatively pristine Antarctic environment (ASAC Projects 945, 1095, and 1157, Gasparon) The study concentrates on the chemical and physical characteristics of the lakes with particular emphasis on their trace metal chemistry. During the 1995/96 summer a preliminary investigation was carried out into the general chemical characteristics and possible stratification of the lakes. Samples of water, rock, bottom sediment and organic material of the lakes and their catchments were taken. The data presented here are the results of the preliminary investigation which was designed to provide the initial set of parameters necessary to characterise the chemistry of the lake systems. The preliminary investigation was also designed to ascertain whether or not water samples collected at a constant depth within the various lakes, could be considered representative of the water columns as a whole.

2. Location and setting

The Larsemann Hills (latitude 69°30'S, longitude 76°20'E) are located along the Ingrid Christensen coast of Princess Elizabeth Land, East Antarctica, approximately halfway between the Amery Ice Shelf and the Sørsdal Glacier, the latter forming the southern boundary of another ice-free coastal 'oasis', the Vestfold Hills (Figure. 1). The Larsemann Hills comprise a series of north-south oriented rocky peninsulas extending from beneath the Antarctic ice-sheet to the ocean. The main peninsulas (Mirror Peninsula, Broknes and Stornes) separated by extensive fjords and offshore islands, are bounded to the southeast by the Dålk Glacier, to the south by the ice-sheet and elsewhere by the waters of Prydz Bay.

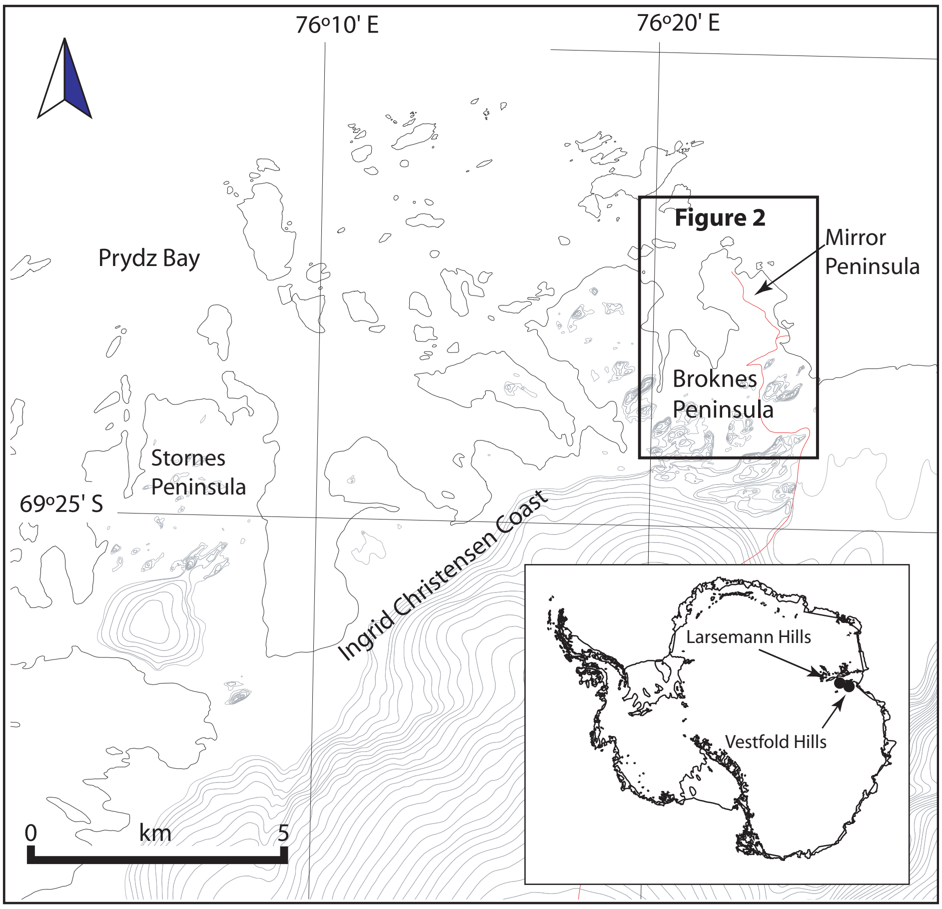

Figure 1: *Map of part of the Ingrid Christensen coastline showing the major peninsulas and offshore islands which make up the Larsemann Hills (modified after Carson* et al. *1995b); the area enlarged in Figure 2 is indicated. Inset map of Antarctica shows the approximate location of the Larsemann Hills relative to the Vestfold Hills.*

The basement geology of the Larsemann Hills consists of a composite mafic-felsic orthogneiss over which lies a metasedimentary sequence of upper amphibolite to granulite facies paragneisses. This is intruded by various pegmatite and peraluminous granite bodies (Carson *et al.* 1995a). The lakes, located in rocky depressions formed largely as a result of glacial erosion, range from less than 1 m to 38 m deep (Gillieson *et al.* 1990). The climate of the Larsemann Hills during the summer months (late December to early March) is dominated by late-evening to early-morning (10-11pm to 9-10am) katabatic winds originating from the ENE or NE. These persistent katabatic winds are thought to result in the lakes being well-mixed, particularly at the height of summer when most of the lakes are unfrozen for periods of up to two months (Burgess *et al.* 1988; Gillieson *et al.* 1990; Burgess *et al.* 1992; Burgess and Kaup 1997). With the exception of the most saline lakes (No Worries Lake, Sarah Tarn and Lake Reid) the lakes are ultra-oligotrophic, and characterised by short food chains and relatively low microbial diversity. Vertical, horizontal, and temporal variations in community structures are known to occur, and climatic factors (such as daily and seasonal variations in temperature and ice-cover) have a profound impact on the biota (Ellis-Evans 1996).

In the ten years prior to 1998 the Larsemann Hills were host to as many as three international stations and one base, the sites of which are no more than three kilometres apart. Zhong Shan station (People's Republic of China), which is occupied throughout the year, and the currently unoccupied Progress II station (Russia) are located on Mirror Peninsula, whereas the largely dismantled Russian station Progress I and a small Australian summer base, Law base, are located on the easternmost area of Broknes (Figure 2).

3. Methods

This study, which concentrated on the lakes of Mirror Peninsula and Broknes involved the *in situ* use of a Grant/YSI 3800 Water Quality Logging System to measure variations in water temperature, pH, conductivity, salinity, dissolved oxygen (DO) and turbidity with depth. The pH and DO probes were calibrated in the field immediately prior to use, according to the manufacturer's instructions. The other YSI 3800 system probes were factory calibrated. Details of sampling procedures can be found in Gasparon and Burgess (2000). Cl_2, SiO_2, SO_4^{2-}, and Al^{3+} concentrations were measured in the field immediately after sampling using a portable Hach DR/2000 spectrophotometer. One of the fibreglass field huts at Law Base was used for this field analysis. Samples were analysed in the field to minimise the risk of contamination and to avoid the risk of sample deterioration during storage. However, the ambient temperature during analysis was considerably lower (approximately +2°C to +5°C) than the recommended temperature (+10°C to +30°C), and laboratory facilities were limited, so that it was often impossible to perform simple operations such as sample dilution. Despite the low ambient temperature, accuracy checks done using Hach standards gave results that were within 10% of the recommended values, and the results reported here are within the analytical limits of the instrument. The concentration of six cations (Ca, Mg, Na, and K, and Fe and Mn) was measured in the University of Queensland laboratories by conventional AAS techniques on acidified samples (see Gasparon and Burgess [2000]). Instrument specifications and analytical techniques are listed in the Appendix.

The individual lakes logged during February 1996 were chosen to measure the relative effects on the water chemistry of proximity to the coast, the ice sheet, the Chinese and Russian stations and the Australian base (Figure 2).

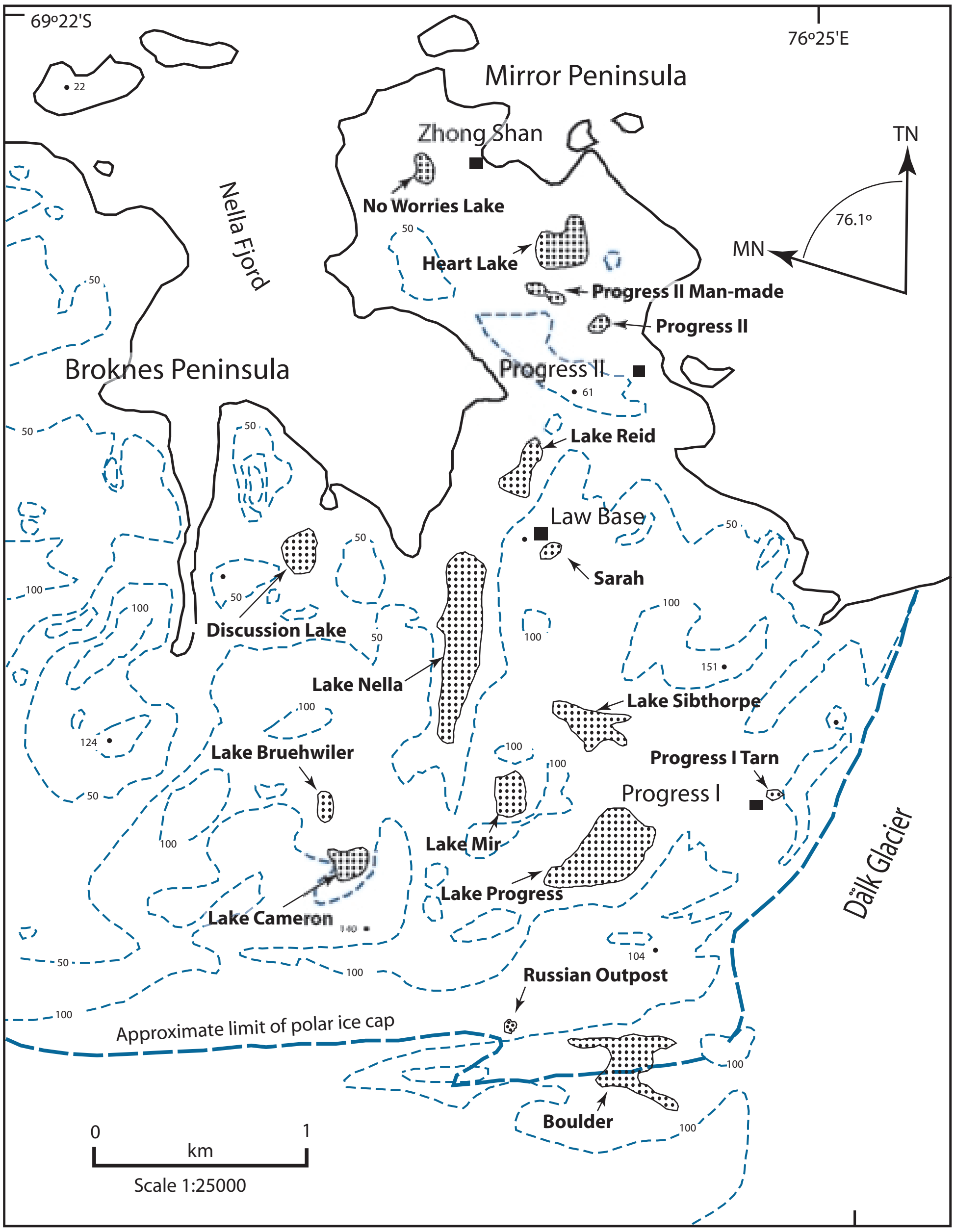

Figure 2: *Map of the Mirror Peninsula and eastern part of Broknes showing the location of the lakes (stippled) for which data were collected during February 1996 and February/March 1997. Limited topographic detail (contours and elevations in metres) is also included (modified from Australian Surveying & Land Information Group 1996). Note that true and magnetic north are correct for the position of Law base in August 1990; magnetic north moves westerly by approximately 0.8° per year.*

Water logging of the lakes on Mirror Peninsula and Broknes was performed during the first week of February 1996, with two profiles of Lake Scandrett performed on consecutive days. Logging was performed at increasing depths throughout the water column with increments of between 0.20 m and 0.50 m. Logging was performed in the approximate centre of each lake to maintain consistency between the methods used in this and subsequent sampling studies. As a result, the bottom depths for which data are available do not necessarily correspond to maximum lake depths. Water quality analysis was also undertaken during an intensive phase of water sampling for trace metal analysis in mid- to late February and early March 1997. These measurements, however, were only taken at the depth of sampling (0.30 m).

The Russian Outpost Tarn, a small body of melt water at the contact between the ice sheet and a rocky outcrop, is not a permanent lake. The water from this location represents the composition of pristine ice sheet melt water (that is, it has little or no interaction with basement rock, sediments, microbial organisms or sea spray and is free from any anthropogenic input). This tarn was completely frozen during February/March 1997 and therefore water samples could not be collected then.

4. Water logging results (February 1996)

The results of the water quality logging performed on seven of the Larsemann Hills lakes during February 1996 are presented in Table I. The results of a similar range of measurements undertaken during February 1997 are presented in Table II. Mean temperatures and wind-speeds for the days over which logging was undertaken are presented in Table III. The 1996 weather data reported here were obtained at Davis station in the Vestfold Hills, approximately 110 kilometres to the east of the sampling location, as no data were available from the nearby Zhong Shan station. Davis station and Zhong Shan station experienced similar weather conditions over the 1996 sampling period. The climatic data for February 1997 are as measured at Zhong Shan station.

General characteristics of the Larsemann Hills lakes

The lakes investigated in this study have summer temperatures ranging from approximately 0°C to 6°C, pH near neutral (approximately 7±1), low salinity and conductivity (<1‰ and ≤0.4 mS/cm, respectively, with the exception of Sarah Tarn), extremely low turbidity (≤1 NTU), and are close to oxygen saturation (±10%). These values are typical of well-mixed, oligotrophic melt water Antarctic lakes, and are similar to those measured elsewhere in Antarctica (e.g. Caprioli *et al.* 1994). Relatively small lakes in the vicinity of

Table I: Water quality logging data recorded in early February 1996 throughout the depth profiles of seven lakes within the Larsemann Hills.

Lake	Date	Time	Depth (m)	Temperature (°C)	pH	Conductivity (mS/cm)	Salinity (‰)	DO (%)	DO (mg/L)	Turbidity (NTU)
Sarah Tarn	1/2/96	1731	0.10	5.9	8.13	5.43	2.9	108.9	13.06	2
Broknes Peninsula		1732	0.30	5.9	8.15	5.45	2.9	111.0	13.31	2
(2.5 m, 5000 m^2)		1734	0.50	5.9	8.18	5.45	2.9	111.0	13.31	2
		1736	1.00	5.8	8.21	5.46	2.9	110.8	13.31	2
		1741	1.50	5.9	8.26	5.46	2.9	112.3	13.46	2
		1742	1.80	5.9	8.26	5.45	2.9	112.7	13.51	2
		1745	1.95	5.9	8.28	5.46	2.9	113.9	13.65	2
No Worries Lake	4/2/96	1314	0.05	6.4	7.50	1.18	0.6	107.1	12.86	2
Mirror Peninsula		1319	0.30	6.4	7.51	1.18	0.6	101.0	12.13	2
(3.8 m, 9000 m^2)		1324	0.50	6.4	7.52	1.18	0.6	105.4	12.66	2
		1332	1.00	6.4	7.53	1.18	0.6	106.3	12.76	2
		1334	1.50	6.3	7.53	1.18	0.6	106.2	12.78	2
		1338	2.00	6.2	7.53	1.18	0.6	107.1	12.93	2
		1341	2.50	6.2	7.52	1.18	0.6	108.4	13.09	2
		1346	3.00	6.0	7.50	1.18	0.6	107.4	13.03	2
		1349	3.50	6.0	7.52	1.18	0.6	107.3	13.02	2
		1354	3.80	6.0	7.49	1.23	0.6	109.1	13.23	61

Note: numbers in parentheses represent the maximum depths of the lakes (as presented in Gillieson *et al.* (1990)), and the approximate dimensions of the lake, respectively. Dates are presented as day/month/year; times are local time (Zhong Shan time), given according to the 24 hour clock.
DO = dissolved oxygen (in % local saturation and mg/L). NTU = nephelometric turbidity units.

Table I: Continued

Lake	Date	Time	Depth (m)	Temperature (°C)	pH	Conductivity (mS/cm)	Salinity (‰)	DO (%)	DO (mg/L)	Turbidity (NTU)
Lake Nella*	1/2/96	2044	0.05	3.5	6.57	0.128	0.1	98.8	12.83	1
Broknes Peninsula		2045	0.30	3.5	6.56	0.128	0.1	99.1	12.87	1
(8.2 m, 157000 m^2)		2046	0.50	3.5	6.54	0.128	0.1	99.1	12.87	1
shallow log		2048	1.00	3.5	6.50	0.128	0.1	99.5	12.92	1
		2052	1.50	3.5	6.25	0.128	0.1	100.3	13.03	1
		2058	2.00	3.5	6.45	0.128	0.1	101.7	13.20	1
		2101	2.30	3.6	6.49	0.128	0.1	98.4	12.74	1
Lake Nella*	2/2/96	1140	0.05	3.4	6.59	0.128	0.1	104.3	13.57	1
Broknes Peninsula		1141	0.30	3.4	6.57	0.128	0.1	104.0	13.54	1
(8.2 m, 157000 m^2)		1143	0.50	3.4	6.56	0.128	0.1	104.5	13.59	1
deep log		1144	1.00	3.4	6.59	0.128	0.1	103.1	13.42	1
		1145	1.50	3.4	6.59	0.128	0.1	102.8	13.38	1
		1155	2.05	3.4	6.29	0.128	0.1	102.7	13.36	1
		1202	2.50	3.4	6.40	0.128	0.1	102.6	13.35	1
		1205	3.00	3.4	6.46	0.128	0.1	100.3	13.05	1
		1208	3.50	3.4	6.50	0.128	0.1	101.9	13.26	1
		1210	4.00	3.4	6.52	0.128	0.1	102.2	13.30	1
		1212	4.50	3.4	6.54	0.128	0.1	101.6	13.22	1
		1213	5.05	3.4	6.55	0.128	0.1	99.8	12.99	1
		1215	5.50	3.4	6.56	0.128	0.1	100.4	13.07	1
		1216	6.00	3.5	6.57	0.128	0.1	100.8	13.09	1
		1217	6.55	3.5	6.57	0.128	0.1	101.0	13.11	1
		1219	7.00	3.8	6.57	0.126	0.1	102.0	13.13	1

* Ellis-Evans (personal communication) quotes a maximum depth of approximately 18 m.

Table I: Continued

Lake	Date	Time	Depth (m)	Temperature (°C)	pH	Conductivity (mS/cm)	Salinity (‰)	DO (%)	DO (mg/L)	Turbidity (NTU)
Lake Cameron	2/2/96	1458	0.05	5.4	7.21	0.296	0.1	112.3	13.87	1
Broknes Peninsula		1459	0.30	5.4	7.21	0.296	0.1	110.6	13.66	1
(7.6 m, 16000 m^2)		1501	0.50	5.5	7.21	0.298	0.1	109.4	13.49	1
		1503	1.00	5.4	7.20	0.294	0.1	112.9	13.95	1
		1506	1.50	5.4	7.18	0.290	0.1	111.1	13.72	1
		1508	2.05	5.2	7.17	0.298	0.1	111.4	13.84	1
		1511	2.50	5.0	7.16	0.294	0.1	109.5	13.67	1
		1513	3.00	4.9	7.15	0.298	0.1	108.9	13.62	1
		1519	3.50	4.9	7.04	0.298	0.1	111.1	13.90	1
		1522	4.00	4.8	7.01	0.296	0.1	110.8	13.91	1
		1525	4.50	4.8	7.04	0.302	0.1	108.3	13.59	1
		1527	5.00	4.7	7.02	0.292	0.1	108.0	13.58	1
		1528	5.50	4.7	7.02	0.296	0.1	106.6	13.41	1
		1530	6.00	4.6	7.01	0.294	0.1	105.6	13.32	1
		1532	6.50	4.6	7.00	0.298	0.1	107.2	13.53	1
		1533	7.05	4.7	7.01	0.300	0.1	106.5	13.39	1
		1536	7.20	4.8	7.03	0.302	0.1	108.3	13.59	23

Table I: Continued

Lake	Date	Time	Depth (m)	Temperature (°C)	pH	Conductivity (mS/cm)	Salinity (‰)	DO (%)	DO (mg/L)	Turbidity (NTU)
Lake Progress	3/2/96	1121	0.05	3.5	7.20	0.304	0.1	118.6	15.40	1
Broknes Peninsula		1126	0.30	3.5	7.16	0.304	0.1	109.9	14.27	1
(34 m, 103000 m^2)		1129	0.50	3.4	7.14	0.306	0.1	110.2	14.34	1
		1131	1.00	3.5	7.11	0.304	0.1	110.2	14.31	1
		1133	1.50	3.4	7.10	0.306	0.1	111.4	14.49	1
		1134	2.05	3.4	7.10	0.306	0.1	109.5	14.25	1
		1137	2.50	3.5	7.08	0.304	0.1	110.2	14.31	1
		1138	3.00	3.4	7.08	0.306	0.1	111.4	14.49	1
		1140	3.50	3.5	7.06	0.304	0.1	107.5	13.96	1
		1143	4.00	3.4	7.05	0.306	0.1	110.2	14.34	1
		1148	6.00	3.4	6.96	0.306	0.1	109.6	14.26	1
		1151	8.00	3.4	6.93	0.306	0.1	104.3	13.57	1
		1153	10.00	3.4	6.92	0.306	0.1	102.0	13.27	1
		1156	12.00	3.4	6.92	0.306	0.1	99.1	12.89	1
		1200	14.00	3.4	6.93	0.306	0.1	96.4	12.54	1
		1202	16.00	3.4	6.91	0.306	0.1	94.0	12.23	1
		1206	18.00	3.4	6.93	0.306	0.1	92.1	11.98	1
		1210	20.00	3.4	6.93	0.306	0.1	89.9	11.70	1
		1214	22.00	3.5	6.94	0.304	0.1	87.7	11.38	1
		1219	24.00	3.8	7.06	0.304	0.1	92.6	11.93	7

Table I: Continued

Lake	Date	Time	Depth (m)	Temperature (°C)	pH	Conductivity (mS/cm)	Salinity (‰)	DO (%)	DO (mg/L)	Turbidity (NTU)
Russian	3/2/96	1605	0.00	0.1	6.26	0.068	0.0	97.1	13.85	5
Outpost Tarn		1604	0.05	0.2	6.28	0.068	0.0	97.9	13.93	1
edge of polar ice cap		1603	0.30	0.2	6.32	0.068	0.0	99.2	14.11	1
(2 m, 500 m^2)		1558	0.50	0.3	6.45	0.068	0.0	99.8	14.15	1
80% ice cover in 1996		1601	1.00	0.4	6.37	0.066	0.0	102.5	14.49	1
		1556	1.30	0.7	6.53	0.070	0.0	103.3	14.48	1
Heart Lake	4/2/96	1113	0.05	5.8	7.07	1.40	0.7	102.8	12.52	1
Mirror Peninsula		1121	0.30	5.8	7.13	1.41	0.7	105.9	12.90	1
(4.5 m, 27000 m^2)		1119	0.50	5.9	7.13	1.41	0.7	106.3	12.90	1
shallow log		1116	0.85	6.2	7.11	1.40	0.7	110.0	13.26	2
Heart Lake	4/2/96	1146	0.05	5.9	7.19	1.40	0.7	108.3	13.16	1
Mirror Peninsula		1145	0.30	5.9	7.20	1.40	0.7	108.2	13.15	1
(4.5 m, 27000 m^2)		1138	0.50	5.8	7.19	1.40	0.7	108.1	13.16	1
deep log		1137	1.00	5.8	7.19	1.39	0.7	107.6	13.11	1
		1135	1.50	5.8	7.19	1.39	0.7	108.1	13.16	1
		1132	2.00	5.8	7.14	1.41	0.7	107.3	13.07	1
		1129	2.55	5.8	7.15	1.41	0.7	106.7	13.00	3
		1142	3.00	5.9	7.14	1.40	0.7	109.8	13.35	1

presently occupied or abandoned stations (Sarah Tarn, No Worries Lake and Heart Lake) have higher pH values (up to 8.3) and higher conductivity values (up to 5.5 mS/cm in Sarah Tarn). The chemical characteristics of the lakes and the chemical differences between lakes are discussed in Gasparon *et al.* (1997) and Gasparon and Burgess (2000)

Turbidity, salinity and conductivity are constant with depth throughout the water column, whereas temperature, pH and DO generally vary with depth. Except where the bottom sediments were disturbed by the arm of the water logging unit, all the lake waters have consistently low turbidity values (1 to 2 NTU). Likewise, low salinity measurements of between 0‰ and 0.7‰ were obtained for all the lakes apart from Sarah Tarn, which had the highest salinity reading of 2.9‰. The lakes with the lowest salinity values (0.1‰) are Lake Nella, Lake Progress, Lake Cameron and the Russian Outpost Tarn. No Worries Lake and Heart Lake have slightly higher salinity readings (0.6‰ to 0.7‰). Although conductivity was low (0.07 mS/cm to 5.5 mS/cm) and remained fairly constant with depth within all the lakes, a similar trend of increasing conductivity is evident. This trend runs from Lake Nella, Lake Progress, Lake Cameron and the Russian Outpost Tarn through No Worries Lake and Heart Lake to Sarah Tarn.

Water temperature varied slightly with depth in some of the lakes, although variations did not exceed 0.8°C. Only Sarah Tarn maintained constant temperature (5.8°C to 5.9°C) with depth throughout the water column. By comparison, Lake Nella, Heart Lake (shallow log; the deep log did not reach the bottom of the lake) and Lake Progress maintained a constant temperature throughout the water column to within one or two metres of the bottom, where the water temperature then increased to above that of the surface temperature. Lake Cameron and No Worries Lake had slightly warmer surface temperatures. These remained stable for the first one to two metres and then decreased gradually with depth. The Russian Outpost Tarn, located on the edge of the ice sheet, had the lowest water temperatures (0.1°C to 0.7°C) and differed from the other Larsemann Hills lakes in that it displayed a gradual increase in water temperature with depth.

In terms of pH, all the lake waters examined can be considered slightly acidic to slightly alkaline in character (pH 6.3 to pH 8.3). Sarah Tarn is the most alkaline (pH 8.13 to pH 8.28) and although the range of values is small it appears to show a gradual increase in pH with depth. The Russian Outpost Tarn also demonstrates this gradual increase with water depth over a narrow range of slightly acidic pH values (6.26 to 6.53) whereas pH values remain fairly stable in No Worries Lake (pH 7.49 to pH 7.53). The other lakes all exhibit a general decrease in pH with depth.

Another parameter which varied between the lakes was DO, although the values obtained indicated that all seven Larsemann Hills lakes studied were close to oxygen saturation. The Russian Outpost Tarn displays a gradual increase in DO with depth and No Worries Lake, Heart Lake and Sarah Tarn have fairly constant DO concentrations. However, the other lakes display an overall decrease with depth with a slight increase at the bottom of the water column, similar to that observed for temperature.

5. Water chemistry results (February/March 1997)

Results of water analysis for February/March 1997 are reported in Table II. Compared with previously published analyses (Gillieson *et al.* 1990), the 1997 samples have consistently lower Ca, Mg, Na, and K (see Table IV) with the exception of Lake Mir (higher values in 1997) and Lake Cameron (similar values in 1990 and 1997). The chemical signature of the 1997 samples, however, is similar to that of the 1990 samples, with Na dominating the cation chemistry in all the lakes, and minor amounts of Mg>Ca>K. Thus, cation ratios are similar in the two sets of samples, and suggest dominance of seawater in the lake water chemistry.

Concentrations of Al and Cl_2 were extremely low in all the samples and only Lake Cameron and Lake Bruehwiler showed appreciable Cl_2 concentrations. Concentrations of SiO_2 were also low, with the exception of Progress I Tarn, and similar to those of other Antarctic lakes (see e.g. Gragnani and Torcini 1991; Caprioli *et al.* 1994). SO_4^{2-} concentrations are directly correlated with conductivity and salinity.

6. Discussion

Summer stratification of the water column

Despite some minor variations of certain parameters as a function of depth, the results of this study indicate that the water columns of the Larsemann Hills lakes were unstratified in terms of salinity, conductivity and turbidity during early February 1996. This suggests that when the lakes are unfrozen at the height of summer their waters are well-mixed by the prevailing katabatic winds, as suggested by Gillieson *et al.* (1990). However, the minor but systematic variations with depth in temperature, pH and DO suggest that more complex processes may be occurring within some of the lakes.

Climatic conditions, such as air temperature, extent of cloud cover and wind-speed clearly account for differences in water temperatures between 1996 and 1997. In general, water temperatures are a function of climatic conditions, the lake's dimensions and the depth of the water column. Another factor that must be taken into account when considering variations in water temperature (as well as in other chemical parameters) is the possibility of influx into the lakes of surface melt water and shallow-level ground water. Thin layers of loose sediments (typically tens of centimetres in depth, but locally exceeding one metre) can be found along the shores of most of the Larsemann Hills lakes. Surface melt water and shallow-level ground water have been observed to flow into the lakes during the summer months. During a warm, sunny day these waters will be generally warmer than the lake waters (because of the combined effect of solar radiation and heating by the relatively warm regolith). Once they have entered the lake, they may remain within the surface layers due to their relatively low density, until the katabatic winds start blowing again at night time.

Small and shallow lakes, such as Sarah Tarn, Heart Lake and No Worries Lake, can be expected to heat up very quickly during a relatively warm (air temperature above freezing) and sunny day, and even relatively light winds during the day may prevent the formation of temperature (as well as pH and DO) gradients by constantly mixing the water column irrespective of the influx of surface and ground waters. The constant water temperature of Sarah Tarn and Heart Lake could thus be due to a combination of:

- their relatively shallow depth (maximum depths are = 2.5 m and 4.5 m, respectively; Gillieson *et al.* 1990);
- their small size; and
- their exposed location

These factos may result in greater mixing by the prevailing winds than the other lakes.

The fact that Sarah Tarn and Heart Lake are the most saline of the Larsemann Hills lakes (Gillieson *et al.* 1990) also suggests they may be subject to the greatest influx of sea spray (Gasparon and Burgess 2000). No Worries Lake also has relatively high salinity but this is partly due to anthropogenic input (Ellis-Evans 1996; Gasparon and Burgess 2000). The existence of a temperature gradient in No Worries Lake may be due to the fact that this small lake is more sheltered from the wind than the other two, and therefore the wind speed on the day when the measurements were taken was too weak to accomplish complete temperature homogenisation of the water column.

Deeper and larger lakes, such as Cameron Lake, show a temperature, pH and DO gradient in the water column after a relatively warm and sunny day with mild wind. It is likely, however, that these parameters are homogenised overnight due to the strong katabatic winds, the temperature drop, and the marked decrease in solar radiation. Also, surface and ground water fluxes into Cameron Lake seem to be larger than in any other lake in the

Table II: February-March 1997 analytical data

Sampling Site	Sarah Tarn	Lake Reid	Lake Nella	Progress II Tarn	Progress II Man-Made Tarn	Heart Lake	No Worries Lake	Lake Progress
Lake dimensions (m^2)	5000	26000	157000	1000	1500	27000	9000	103000
Maximum water depth (m)	2.5	3.8	8.2	1.5 (approx.)	2 (approx.)	4.5	3.8	34
Ice-cover (lake area %)	50	60	10	80	80	80	90	90
Water-logger data								
Date	18/2/97	19/2/97	19/2/97	20/2/97	20/2/97	22/2/97	22/2/97	25/2/97
Time of sampling	1511	1330	1432	1438	1514	1410	1603	1636
Depth (m)	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Temperature (°C)	0.5	0.5	1.7	0.6	0.3	0.8	1.2	0.3
pH	8.20	8.65	8.60	7.67	7.52	6.53	7.07	7.58
DO (mg/L)	13.04	12.86	11.89	12.76	12.58	12.52	12.66	11.80
DO (% saturation)	95.98	93.80	88.50	93.00	90.90	91.70	93.40	84.50
Conductivity (mS/cm)	5.52	3.76	0.140	2.47	2.79	1.64	1.39	0.272
Salinity (‰)	2.9	1.9	0.1	1.2	1.4	0.8	0.7	0.1
Turbidity (NTU)	3	0	0	0	0	7	2	9
Chemical analyses (mg/L)								
Cl_2	0.01	0.02	0.01	0.02	0.05	0.03	0.02	0.06
SiO_2	0.124	0.146	0.861	0.786	0.761	0.444	0.815	2.70
SO_4^{2-}	ar	49	1	ar	ar	ar	ar	11
Al^{3+}	nd	0.001	nd	nd	nd	nd	nd	0.001
Ca^{2+}	12.6	5.0	0.3	3.7	4.3	2.5	6.2	0.5
Mg^{2+}	36.4	14.5	0.44	10.1	11.3	6.95	13.1	0.96
Na^+	247	135	4.48	83.5	88.1	62.0	125	9.43
K^+	7.60	4.64	0.13	2.97	3.23	2.21	4.51	0.31

Table II: Continued

Sampling Site	Lake Cameron	Lake Bruehwiler	Lake Discussion	Progress I Tarn	Boulder Lake	Lake Sibthorpe	Lake Mir	Davis Tarn Vestfold Hills
Lake dimensions (m^2)	16000	6000	17000	1000	158000 (approx.)	48000	17000	7000 (approx.)
Maximum water depth (m)	7.6	1	4	1	unknown	3.5	3	3 (approx.)
Ice-cover (lake area %)	100	100	100	100	100	100	100	100
Water-logger data								
Date	27/2/97	27/2/97; 1/3/97	28/2/97	2/3/97	2/3/97	2/3/97	4/3/97	9/3/97
Time of sampling	1400	1500; 1522	1246	1630	1750	1940	1440	1134
Depth (m)	0.30	0.30	0.30	0.30	0.30	0.20	0.30	0.15
Temperature (°C)	0.4	0.2	0.4	0.2	0.0	0.1	0.3	-0.2
pH	7.60	7.37	7.71	8.17	7.87	6.27	7.19	8.01
DO (mg/L)	12.42	11.30	11.76	14.08	12.89	12.46	12.85	12.18
DO (% saturation)	89.90	80.70	84.5	100.40	91.60	89.00	92.00	93.40
Conductivity (mS/cm)	0.346	0.424	0.358	0.360	0.034	0.112	0.328	20.64
Salinity (‰)	0.2	0.2	0.2	0.2	0.0	0.1	0.2	11.9
Turbidity (NTU)	2	3	0	0	0	100 (bottom sediments disturbed)	0	10
Chemical analyses (mg/L)								
Cl_2	0.15	0.12	0.02	0.03	0.00	0.03	0.00	0.04
SiO_2	1.324	3.60	1.248	8.30	0.123	0.826	0.729	ar
SO_4^{2-}	3	18	18	22	2	1	5	ar
Al^{3+}	0.001	nd	nd	0.004	nd	nd	0.009	nd
Ca^{2+}	1.6	0.3	0.6	1.8	nd	0.1	2.1	66.9
Mg^{2+}	2.74	1.01	2.00	1.33	0.16	0.36	3.67	173
Na^+	20.1	9.01	9.01	9.53	2.04	3.65	32.7	1172
K^+	0.68	0.26	0.32	0.27	0.05	0.10	1.36	35.3

DO = dissolved oxygen; NTU = nephelometric turbidity units; nd = not detected (below detection limits); ar = above analytical range; Approx. = approximate data (due to lack of precise measurements or to natural fluctuations). Lake Bruehwiler was sampled on 27/2/97 but water-logger data were recorded on 1/3/97. Fe and Mn were lower than 0.1 mg/l in all samples

Table III: Climatic data recorded for the days over which water quality data logging of the Larsemann Hills lakes was performed.

Date	Minimum temperature (°C)	Maximum temperature (°C)	Mean temperature (°C)	Mean windspeed (km/hr)	Maximum sustained windspeed (km/hr)
1996					
February 1	4.1	na	5.3	24.8	37.0
February 2	na	7.7	2.1	27.6	50.0
February 3	na	na	2.2	17.4	33.5
February 4	na	3.6	1.3	13.0	27.8
1997					
February 18	-4.4	-4.0	-4.2	30.9	35.2
February 19	-6.3	-5.6	-6.1	27.8	35.2
February 22	-7.4	-2.1	-4.8	31.5	64.8
February 25	-4.8	-2.7	-3.4	33.9	38.9
February 27	-6.8	-5.3	-6.1	22.2	29.4
March 2	-13.7	-6.5	-8.8	28.7	50.0
March 4	-4.2	-2.7	-3.3	37.0	50.0
March 9	-8.1	-4.7	-5.7	16.1	24.1

Note: Data for February 1996, 2/3/997, and 9/3/1997 are as recorded at Davis station in the Vestfold Hills. Data for February 1997 and 4/3/1997 are as recoded at Zhong Shan station in the Larsemann Hills; na = not available.

Table IV: Comparison between the 1997 data and those published in Gillieson *et al.* (1990)

		Na (ppm)	Mg (ppm)	Ca (ppm)	K (ppm)	Na/ (Ca+Mg+K)	Ca/ (Na+Mg+K)	T (°C)	pH	Conductivity (mS/cm)
Heart Lake	1997	62.0	6.95	2.50	2.21	5.3	0.04	0.8	6.53	1.640
	1990*	127.1	12.30	7.40	—	—	—	7.0	6.66	0.987
Lake Bruehwiler	1997	9.0	1.01	0.30	0.26	5.7	0.03	0.2	7.37	0.424
	1990*	20.8	3.50	1.30	0.80	3.7	0.05	8.0	6.74	0.145
Lake Reid	1997	135.0	14.50	5.00	4.64	5.6	0.03	0.5	8.65	3.760
	1990*	425.6	31.30	31.40	14.00	5.5	0.07	6.6	7.32	1.730
Lake Cameron	1997	20.1	2.74	1.60	0.68	4.0	0.07	0.4	7.60	0.346
	1990*	20.8	3.50	2.40	0.80	3.1	0.10	7.2	6.97	0.265
No Worries Lake	1997	125.0	13.10	6.20	4.51	5.2	0.04	1.2	7.07	1.390
	1990*	148.7	11.30	10.40	5.00	5.6	0.06	6.3	6.57	0.958
Sarah Tarn	1997	247.0	36.40	12.60	7.60	4.4	0.04	0.5	8.20	5.520
	1990*	538.8	50.40	46.80	16.40	4.7	0.08	6.0	7.32	3.340
Lake Mir	1997	32.7	3.67	2.10	1.36	4.6	0.06	0.3	7.19	0.328
	1990*	18.3	2.90	0.50	0.80	4.4	0.02	0.8	6.40	0.130
Lake Nella	1997	4.5	0.44	0.30	0.13	5.1	0.06	1.7	8.60	0.140
	1990*	19.7	2.20	0.90	0.80	5.1	0.04	3.7	6.86	0.139
Lake Progress	1997	9.4	0.96	0.50	0.31	5.3	0.05	0.3	7.58	0.272
	1990*	64.4	6.80	3.80	1.80	5.2	0.05	4.9	6.68	0.321
Seawater**		10560	1270	400	380	5.2	0.03			

* Analyses published in Gillieson *et al.* (1990) were carried out on samples collecte during the 1987 summer
** Seawater composition (for comparison) from Wedepohl (1971)

Larsemann Hills (Burgess, unpublished data) ; these fluxes of water with relatively high temperature may be partly responsible for the temperature gradient observed within the water column. Very large and relatively deep water bodies, such as Lake Nella and Lake Progress, appear to be less sensitive to short-term (24-hour day to night cycle) variations in weather conditions, and temperatures measured for these lakes are likely to remain relatively constant throughout a 24-hour period.

An increase in temperature at the lake bottom is a common feature of most of the lakes. Similar increases have been reported by Gillieson *et al.* (1990) as being attributed to the absorption of radiant energy by benthic mats of blue-green cyanobacteria and filamentous green algae. The location of the Russian Outpost Tarn, on the edge of the polar ice-cap, may also be responsible for its thermal characteristics. The gradual increase in water temperature with depth could be the result of constant snow melt water (and therefore relatively cold) run-off into the surface waters, the rate of which exceeds the rate of mixing.

The fact that the Larsemann Hills lakes are generally oxygen-saturated or oversaturated–presumably as a result of convective mixing of the water columns–is important since it could have major implications for the speciation and bioavailability of any trace metals present within the lake systems (Rose and Long 1988). As oxygen is more soluble at lower temperatures (e.g. Drever 1988), DO should increase with decreasing water temperature in well-mixed water bodies which are in equilibrium with the atmosphere. Only No Worries Lake shows this trend. Sarah Tarn and Heart Lake have relatively constant, saturated to slightly oversaturated DO levels which indicate strong interaction with the atmosphere (due to the strong winds), and thorough mixing of the water column. The Russian Outpost Tarn shows increasing DO concentrations for increasing depth, possibly reflecting low DO values of surface melt water. The three largest lakes (Lake Cameron, Lake Nella and Lake Progress) are oxygen-saturated or oversaturated at the surface, but the decreasing DO content with depth suggests that the day-time winds are not strong enough to mix the water column in these lakes at depths below 3 m to 6 m. One explanation for the increase in DO and temperature within the bottom layer of all the lakes could be oxygen production by photosynthesis within the benthic algal mats. The clarity of Antarctic lake waters, as demonstrated by their low turbidity values, could potentially allow enough solar radiation to reach the bottom of the lakes to enable such a process to occur. The increase in water temperature at the bottom of the lakes also suggests high radiative heating of the benthic mats.

Differences in conductivity, salinity, and pH between the lakes are caused by a number of factors, the most important being the extent of sea spray input into the lake. These factors are discussed elsewhere (Gasparon and Burgess 2000). All the Larsemann Hills lakes show constant salinity and conductivity values with depth, which suggests that no chemical stratification should be expected in terms of the concentration of the major cations (Na^+, Mg^{2+}, Ca^{2+} and K^+) and anions (Cl^- and HCO_3^-) and, presumably, trace elements. Interestingly, conductivity and salinity values remain constant even in those lakes where variations in the other parameters (temperature, DO values and pH) are observed as a function of water depth. Preliminary analyses (Gasparon *et al.* 1997; Gasparon and Burgess 2000) confirm that indeed trace element composition remains constant throughout the water column. We therefore conclude that, in terms of their major and trace element composition, all the lakes are well-mixed, and that constant conductivity and salinity in the water column indicates lack of chemical stratification as a function of depth. Minor variations in pH with depth observed in Lake Cameron and Lake Progress are positively correlated with DO values, and we suggest that biological activity is responsible for these trends. Our results also suggest that biological activity in the Larsemann Hills lakes does not seem to affect the distribution of inorganic components in the water column. Relatively sharp, but still minor, variations in pH values in Lake Nella at a depth between 1.5 m and 3.5 m are also likely to be due to biological activity, but their exact significance and importance are, at present, unknown.

Comparison between the 1996 and 1997 results

The 1997 water quality logging results were obtained at least two weeks later in the season than the 1996 results, at a time when air and water temperatures were considerably lower and average wind speeds were higher (see Tables II and III). In addition, whereas the lakes were completely free of ice during the 1996 sampling period (the only exception being the Russian Outpost Tarn–see Table II), they were experiencing between 10% and 100% ice-cover during the 1997 sampling period. However, the ice-cover was very thin (up to 5 cm) and extremely unstable (ice-cover formed overnight or no longer than 5-10 days prior to analysis), suggesting that the 1997 samples were obtained during the autumn turn-over, when the water column can be expected to be well-mixed.

The limited amount of data obtained during 1997 clearly indicate that weather conditions have a dramatic effect on water parameters. Compared with the 1996 data, 1997 water temperatures are considerably lower as a result of lower air temperatures (see Table II). The partial to total ice-cover during 1997 prevented a strong interaction between the katabatic winds and the lake water, and this resulted in lower DO values being measured in 1997. Differences in pH, conductivity and salinity are more difficult to interpret as they may be due to a combination of factors, all related to the change in weather conditions. Among these factors are:

- the partial to total insulation of the lake system from the atmosphere (due to the ice-cover on the lake surface);

- the lack of surface- and ground-water input into the lake system (the regolith was totally frozen when the lakes were sampled in 1997, and no surface-water was observed);
- possibly, in the shallower lakes, the increased salinity of the remaining water after freezing of a substantial proportion of the water mass; and
- the changed level of activity of the lake biota.

It is not clear, however, whether the differences between the 1996 and 1997 data are due to incipient stratification of the water column during the autumn turn-over or to other causes. Large variations in temperature, pH, conductivity and chemical composition are known to occur in Antarctic lakes on a short-term (hourly) to long-term (seasonal) scale (e.g. Caprioli *et al.* 1994; Gragnani and Torcini 1991). The differences observed between the 1996 and 1997 data are well within the natural variability observed in other Antarctic lakes. As lake micro-organisms very sensitive to extremely small variations in chemical and physical parameters (e.g. Hawes 1983; Ellis-Evans 1996) we concede this variability may have profound effects on biological activity. . However, the aim of our study was to provide data on the 'typical' chemical composition of the Larsemann Hills lakes during the summer period in order to assess environmental impact on the lake waters. Thus, while a single analysis represents a 'snapshot' of the lake chemistry at a particular moment, a range of values is a more realistic representation of the 'typical' summer composition. Given that the differences observed between the 1996 and 1997 data are within the natural range observed in Antarctic freshwater lakes, we conclude that both 1996 and 1997 results represent the 'typical' summer composition of Larsemann Hills lakes.

Chemical composition of the lake waters

As already suggested by Gillieson *et al.* (1990), our results indicate that seawater input (sea spray) is the main factor controlling the water composition. It should be noted that the amount of sea spray input is not a function of the lake's linear distance from the shore but rather of the lake's exposure to winds carrying the sea spray. In particular, the availability of geomorphological 'corridors' along which the sea spray can be carried to the lake is of primary importance (see also Gore *et al.* 1996).

The reason for the difference between our results and those of Gillieson *et al.* (1990) (samples collected in the summer of 1987) is not clear. Once again, natural variability can account for large variations in water chemistry (Gragnani and Torcini 1991) but this does not explain why our values are systematically lower than those measured by Gillieson *et al.* (1990). The 1987 samples were obtained from the lake surface but sampling and analytical techniques differ substantially from those used in this study. Therefore, the observed differences between 1987 and 1997 data may well be due to differences in sampling techniques and sample treatment prior to analysis. Alternatively, the lower concentrations measured during 1997 compared with 1987 could reflect lower evaporation rates or higher melt water input into the lakes (both resulting in lower cation concentrations). These processes, however, do not account for the lower conductivities measured in 1987.

7. Conclusions

At the peak of summer the lakes of the Larsemann Hills, East Antarctica, generally have low salinity and conductivity (<1‰ and ≤0.4 mS/cm, respectively), temperatures ranging from approximately +6°C to 0°C, pH near neutral (approximately 7±1) extremely low turbidity (≤1 NTU), and are close to (DO saturation (±10%). Seawater input (sea spray) is the main factor controlling the water composition, and the chemical characteristics are typical of well-mixed, oligotrophic melt water Antarctic lakes. Some small (Sarah Tarn, No Worries Lake and Heart Lake) have higher pH values (up to 8.3) and higher conductivity values (up to 5.5 mS/cm in Sarah Tarn).

The major factors controlling the distribution of temperature, pH and DO values in the water column of each lake are weather conditions, biological activity (also dependent on weather conditions) and the lake's dimensions. During the day, absence of strong winds, relatively high air temperature and increased biological activity (due to solar radiation) may facilitate stratification of the water column, but only in terms of temperature, pH and DO values. Conductivity and salinity values are constant throughout the water column in each lake. We conclude that water stratification, if existing at all, is short-lived, and that the water column becomes homogenised again overnight by the action of the persistent, strong katabatic winds.

From an analytical point of view, constant conductivity and salinity throughout the water column indicate that the major and trace element composition of the water does not vary as a function of depth. This conclusion is supported by analytical results obtained on samples collected at different depths (Gasparon and Burgess 2000). Thus, water samples collected during the summer months at a depth of 0.3 m can be considered as representative (in terms of their major and trace element composition) of the entire water column. Our results also indirectly suggest that the water column was homogeneous overall when the samples were collected during the autumn turn-over. Complete night-time homogenisation of the water column, however, may be impossible when the surface of the lake is partially to totally frozen; samples collected at any depth in these circumstances cannot be automatically regarded as representative of the entire water column.

Appendix: Instrument specifications.

Grant/YSI 3800 Manufacutrer's specifications (for T=25 °C)

Parameter	Range	Resolution	Accuracy
Atmospheric pressure	50-110 kPa	0.1 kPa	±0.5%
Conductivity	0-100 mS/cm	2 mS/cm for 0-2 mS/cm 10 mS/cm for 2-20 mS/cm 50 mS/cm for 20-100 mS/cm	± 3% ± 4% ± 4%
Salinity	0-50‰	0.1‰	± 4.5%
Depth	0-30 m	0.05 m	± 0.45 m
Dissolved oxygen (mg/L)	0-20 mg/L	10 mg/L	± 0.03 mg/L
Dissolved oxygen (% local saturation)	0-200%	0.1%	0.2%
pH	0-14	0.01	± 0.04
Temperature	-5°C – +50°C	0.1°C	± 0.4 °C
Turbidity	0-1000 NTU	1 NTU	±5%

Hach DR/2000 Manufacutrer's specifications (for T=25 °C). All data in mg/L.
Other analytical details can be found the in the Hach DR/2000 Manufacturer's manual.
* Standard Methods for the Examination of Water and Wastewater

Parameter	Range	Precision	Analytical method*
Al^{3+}	0.001-0.220	± 0.004	8326
Cl_2 (total chlorine)	0.00-2.00	± 0.012	8167
SiO_2			
low range	0.000-1.600	± 0.0067	8186
high range	0.0-100.0	± 0.45	8185
SO_4^{2-}	0-70	± 0.9	8051

Atomic absorption specifications (for T=25°C). Blanks are reagent blanks.

Parameter	Blanks (mg/L)	Precision (%)
Ca^{2+}	0.00 – 0.17	0 – 11
Mg^{2+}	0.00	2 – 11
Na^{+}	0.01	0.2 – 1.4
K^{+}	0.01	0.1 – 2.4

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