

# Role of lithology, weathering and precipitation on water chemistry of lakes from Larsemann Hills and Schirmacher Oasis of East Antarctica

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**Abstract** Schirmacher Oasis and Larsemann Hills areas represent two different periglacial environments of East Antarctica. Schirmacher Oasis is characterized by a vast stretch of ice-shelf in the north and East Antarctic Ice Sheet (EAIS) to its south. Whereas, in Larsemann Hills area the northern and north-western boundary is coastal area and EAIS in the southern part, exhibiting polar lowland between the marine and continental glacial ecosystems. Physico-chemical parameters of water samples from different lakes of both of these two distinct locations are quite contrasting and have indicated influence of lithology, weathering, evaporation and precipitation. The lake water chemistry in Larsemann Hills area is mainly governed by the lithology of the area while Schirmacher lakes exhibit influence of precipitation and rock composition. All major ions of lake waters indicate balanced ionic concentrations. The atmospheric precipitation has significantly modified the ionic distributions in the lakes and channels. Carbonation is the main proton supplying geochemical reactions involved in the rock weathering and this is an important mechanism which controls the hydrochemistry. The lake water hydrochemistry differs widely not only between two distant periglacial zones but also within a short distance of a single periglacial entity, indicating influence of territorial climate over hydrochemistry.

**Keywords** lake water, ionic concentration, Schirmacher Oasis, Larsemann Hills, East Antarctica

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## 1 Introduction

Coastal lakes and ponds of Antarctic periglacial environment offer a great opportunity to document and characterize the unpolluted baseline data of its various

components. The lake water samples were used to characterise the ionic characteristics and effect of local environment. The extensive ice-sheet of Antarctica retreated during the Late Pleistocene and this recession continued till Holocene epoch (Ingólfsson, 2004). As a result of this temporal evolution, lakes and ponds were formed on maritime islands, peninsulas and along the margins of the

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continent. These lakes offer a unique opportunity to study the recent chemical character of lacustrine eco-system in a de-glaciated terrain as well as the influence of the proximal ice-sheet and marine eco-system on the hydrochemistry. During winter, the lakes become anoxic and acquire oxygen only after the frozen top melts. Mixing of fresh ice-melt water, sediment influx and aeration takes place in summer season. A continuous cycle of freezing and melting of the lakes in winter and summer brings significant changes in physico-chemical, biological and sedimentological properties of the water and lake-bottom sediments respectively. The de-glaciated areas gain importance to study water-rock interaction due to the high rate of chemical weathering with minimal anthropogenic impact (Brown, 2002). The meltwater has a significant role in the glacial processes as it involves in shaping the landform through various erosional, depositional and associated with fluvio-glacial processes influenced by climate change (Eyles, 2006).

Significant earlier studies to reconstruct the paleoenvironment of Larsemann Hills have revealed a heterogeneous and complex history (Gillieson, 1991; Burgess et al., 1994; Burgess et al., 1997; Verleyen et al., 2004; Hodgson et al., 2005). Over 150 fresh water lakes occur in the Larsemann Hills (Gillieson, 1991) ranging from small ephemeral ponds to large water bodies. It has been suggested that many Antarctic lakes follow an evolutionary sequence as de-glaciation occurs (Priddle and Heywood, 1980; Burgess et al., 1994). Some of the lakes have preserved the evolutionary sequence of the de-glaciation (Priddle and Heywood, 1980; Burgess et al., 1994). Work on glacial sediments of Vestfold Hills and East Antarctic coastal oases have been done to describe the paraglacial sedimentary processes (Fitzsimons, 1996, 1997). Studies using biological and physical markers drawn from lake sediments of this region as paleoenvironmental indicators have also been done (Ellis et al., 1998). The ionic characters of lake waters of South Grovnes (Bharati promontory) and sedimentary processes in Larsemann Hills area have been dealt (Shrivastava et al., 2011; Asthana et al., 2013). In Antarctica, Webster et al. (1994) has emphasized on the role of geochemical processes which affects the melt water chemistry and is responsible for the formation of saline ponds in Victoria valley and Bull Pass region in Antarctica. Shrivastava et al. (2011) showed the hydrochemistry of lakes in Bharati Promontory, Larsemann Hills, East Antarctica emphasizing the dominant role of lithology in the ionic concentration. Asthana et al. (2014) observed the combination of lithology, atmospheric precipitation and evaporation in the hydrochemistry of Fisher and Broknes Island, Larsemann Hills, Antarctica. Solute in the meltwater through the subglacial channel at the rock-ice and meltwater interface has been described by Trudgill (1986). These studies indicate the high rate of chemical weathering in glaciated regions resulting from long residence times of meltwater in contact with the bed

rock.

In this context, this particular study has been carried out to give an insight into the chemical characteristics of the interconnected and isolated lakes in the Larsemann Hills area and in Schirmacher Oasis of East Antarctica. These lakes get supply of abundant melt water from polar ice sheet and pass through different geological outcrops and finally drain in the lakes on the ice shelf or in the ocean. We have also explained the interaction between lithology of the catchment, material influx into the lake systems, precipitation and evaporation of the two different periglacial environments of East Antarctica. Their comparative characteristics along with the processes involved in the lake water chemistry from the two very distinct areas of East Antarctic periglacial ecosystem have also been discussed.

## 2 Study area

Larsemann Hills (69°23'S–69°33'S and 75°34'E–76°53'E) is an ice-free polar oasis on the Ingrid Christensen Coast, Princess Elizabeth Land (Figure 1) that includes Grovnes Island, Fisher Island and Broknes Peninsula, Stornes Peninsula, along with several islands, promontories and nunataks. This area represents a polar lowland periglacial climate with relatively less precipitation, restricted period of snow melting, low rates of ice melt, persistent strong katabatic winds that blow from the south-east on most summer days. The deglaciated terrain constitutes a transitional zone between marine and glacial ecosystems manifesting gently rolling hills, glacially polished and striated bed rock hummocks (roches moutonnees), scoured surfaces and broad valleys interspersed with lakes of varying dimensions.

The Schirmacher Oasis (Figure 2), dotted by many fresh water lakes is an ice free area in East Antarctica (70°44'33"S–70°46'30"S and 11°22'40"E–11°54'00"E) is bordered by East Antarctic Ice Sheet (EAIS) to its south and ice shelf to its north. The retreat and advances of the polar ice sheet lead to the appearance and disappearance of rocky exposures respectively and opening up of many lakes in due course of time (Ravindra et al., 2002; Asthana et al., 2013; Shrivastava et al., 2012). Some of these lakes melt during austral summer period, whereas almost all of these remain ice covered during austral winter period. Most of the lakes in the Schirmacher Oasis are landlocked freshwater category that was formed by natural processes of ice erosion and meltwater carried by surface channels from snow beds and ice slopes (Richter and Bormann, 1995; Verlecar et al., 1996; Ravindra et al., 2002; Priscu and Foreman, 2009). Unlike perennially ice-covered lakes in the Antarctic continent, the freshwater lakes in the Schirmacher Oasis are modulated primarily by annual weather cycles resulting in the intermixing of lake waters through surface channels.

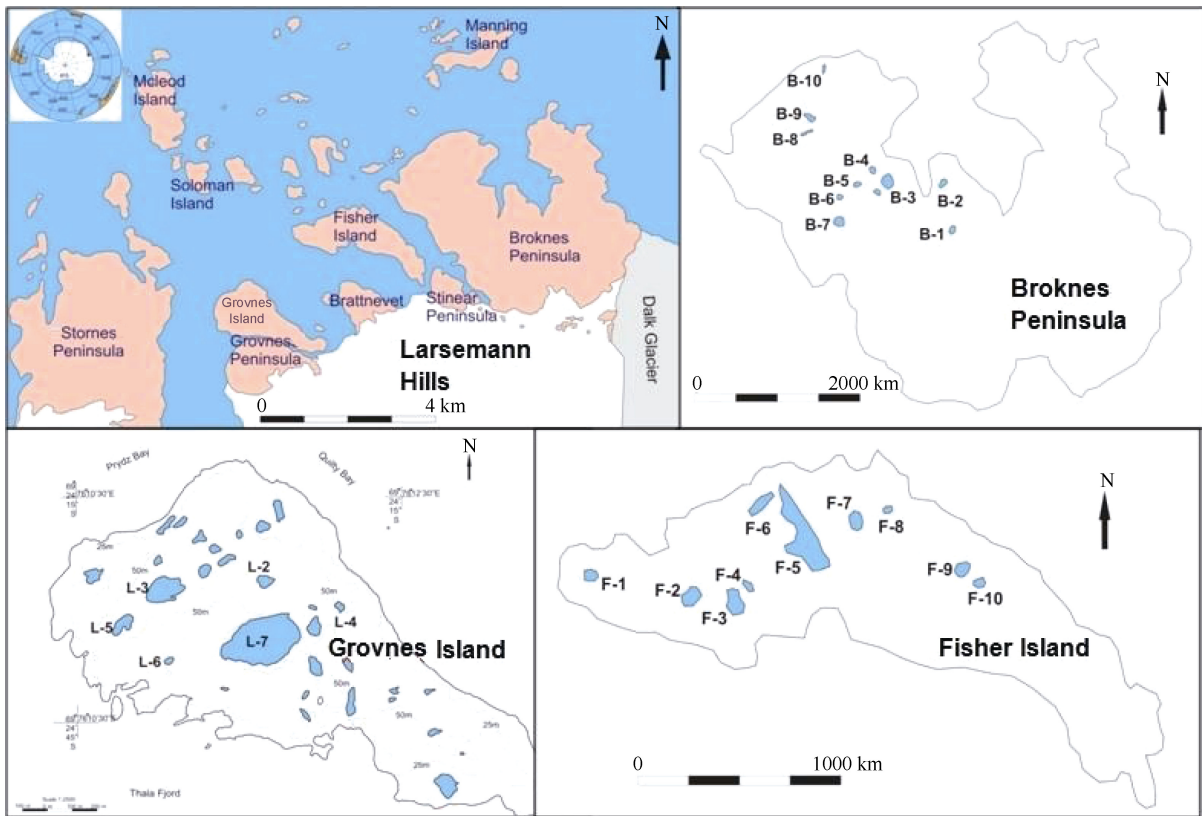


Figure 1 Location map of lakes in Larsemann Hills area of East Antarctica.

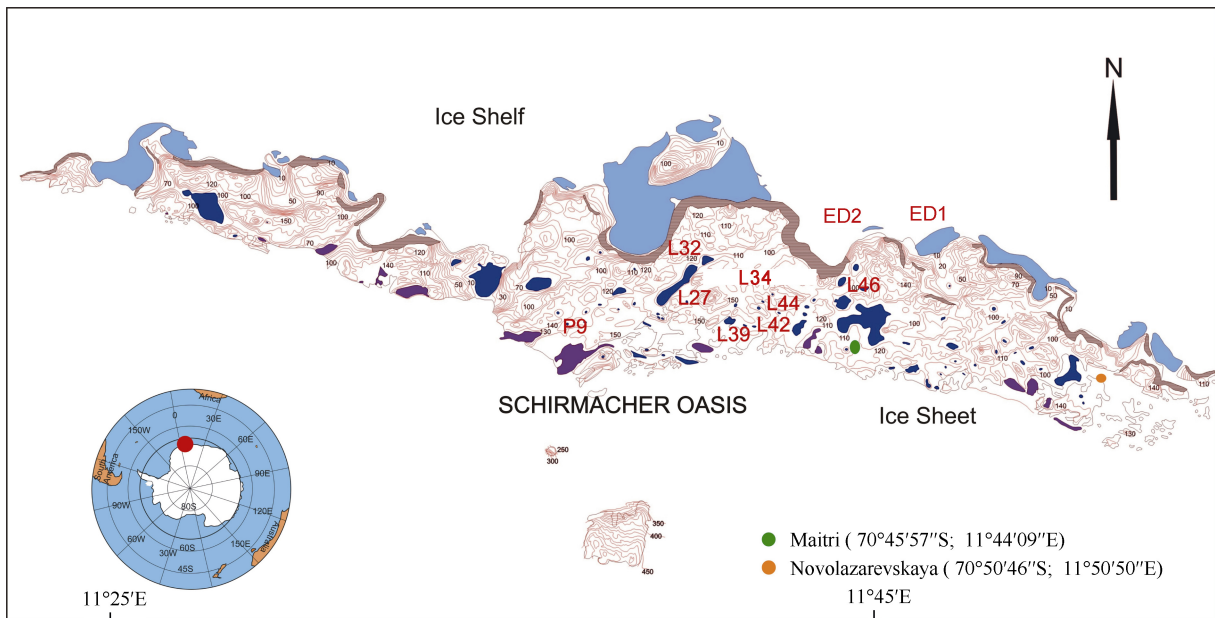


Figure 2 Location of lakes in Schirmacher Oasis, East Antarctica.

### 3 Materials and methods

From Larsemann Hills area, 25 lakes and from Schirmacher Oasis, 10 lakes have been taken for this study. The lakes of Schirmacher oasis fall in two different drainage lines. Neutralized plastic bottles were rinsed with the lake water

and duplicate samples for each were collected from lakes during austral summer. The locations of all the samples are given in Table 1. It was assumed that the chemical equilibrium is attained and the lake water is homogeneous during the period (Gasparon et al., 1997). The parameters like conductivity, pH and temperature of the water were

recorded on site. One set of samples was acidified using 10% (by volume) HNO<sub>3</sub> solution to preserve the sample and another set of sample was kept without acidifying it. Sodium, Potassium, Calcium and Magnesium were analysed by Atomic Absorption Spectrometer (Analyst-100 Perkin Elmer) in absorption mode using strontium salts as buffer. Chloride was analysed by titrimetric method with potassium chromate indicator and standard AgNO<sub>3</sub>. Lower detection limit of 0.1 ppm for silica was achieved using 50 mm cell in Aquamate Thermospectronic Spectrophotometer. Method for Fluoride determination using Zr-Erichrome Cyanin-R was improvised for accurate

determination of Fluoride up to 0.01 ppm. Carbonate and bicarbonate determination was done titrimetrically using 0.01 N HCl, phenolphthalein and methyl orange indicators, respectively. Sulphate was determined by Turbidimeter using APHA-method upto the lower limit of detection of 1 ppm. Boron was analysed by using Boron-test kit supplied by E. Merck and Nitrate by developing colour using phenol-disulphonic acid with 50-mm cell. All the chemical analyses were done at chemical laboratories, Geological Survey of India (GSI), Faridabad. After the analysis, the values have been plotted on different diagrams and correlation analysis has been performed.

**Table 1** Location of lake water samples from Larseman Hills and Schirmacher areas of East Antarctica

	Sample No.	Latitude	Longitude	Elevation/m
Fisher Island	F-1	69°23'34.95"S	76°13'20.81"E	3
	F-2	69°23'38.38"S	76°14'07.94"E	3
	F-3	69°23'39.03"S	76°14'27.91"E	4
	F-4	69°23'36.87"S	76°14'34.18"E	4
	F-5	69°23'27.38"S	76°14'58.02"E	4
	F-6	69°23'22.84"S	76°14'38.18"E	2
	F-7	69°23'25.65"S	76°15'23"E	5
	F-8	69°23'23.86"S	76°15'37.11"E	3
	F-9	69°23'34.09"S	76°16'11.05"E	6
	F-10	69°23'35.85"S	76°16'18.46"E	6
Broknes Peninsula	B-2	69°23'10.62"S	76°20'47.95"E	9
	B-3	69°23'09.20"S	76°19'44.35"E	23
	B-4	69°23'11.12"S	76°19'13.06"E	38
	B-5	69°23'14.72"S	76°19'10.26"E	40
	B-6	69°23'15.77"S	76°18'50.12"E	43
	B-7	69°23'27.52"S	76°18'46.06"E	42
	B-8	69°22'50.50"S	76°18'16.78"E	35
	B-9	69°22'44.76"S	76°18'19.33"E	31
	B-10	69°22'25.41"S	76°18'33.82"E	7
	Grovnnes Island	L-2	69°24'26.27"S	76°11'39.9"E
L-3		69°24'27.60"S	76°11'03.62"E	8
L-4		69°24'32.85"S	76°11'58.74"E	9
L-5		69°24'32.68"S	76°11'47.04"E	7
L-6		69°24'37.49"S	76°11'04.42"E	11
L-7		69°24'34.41"S	76°11'40.23"E	10
Schirmacher Oasis		L-39	70°45'53.15"S	11°41'43.25"E
	L-42	70°45'44.17"S	11°42'43.69"E	161
	L-44	70°45'38.89"S	11°42'49.58"E	144
	L-46	70°45'27.22"S	11°43'47.90"E	94
	ED-1	70°45'04.98"S	11° 44'19.12"E	56
	P-9	70°45'58.37"S	11°36'40.12"E	211
	L-27	70°45'29.50"S	11°39'08.53"E	151
	L-32	70°45'12.10"S	11°40'16.09"E	111
	L-34	70°45'12.29"S	11°41'27.39"E	97
	ED-2	70°45'06.38"S	11°42'40.74"E	57

## 4 Observations

Lakes in South Grovnes, Fisher Island and Broknes Peninsula vary in depth from very shallow to over 30 m with size ranging from small ponds to 0.13 km<sup>2</sup>

area. Most of the lakes in Fisher Island and Broknes Peninsula are land-locked whereas few proglacial lakes in Broknes Peninsula are connected to the polar ice in south. The physico-chemical parameters are given in Table 2.

**Table 2** Physico-chemical parameters of lake waters from Larsemann Hills and Schirmacher area of East Antarctica

Sample No.	pH	EC/ (mmho·cm <sup>-1</sup> )	TDS/ (mg·L <sup>-1</sup> )	Na <sup>+</sup> / (mg·L <sup>-1</sup> )	K <sup>+</sup> / (mg·L <sup>-1</sup> )	Ca <sup>2+</sup> / (mg·L <sup>-1</sup> )	Mg <sup>2+</sup> / (mg·L <sup>-1</sup> )	Cl <sup>-</sup> / (mg·L <sup>-1</sup> )	NO <sub>3</sub> <sup>-</sup> / (mg·L <sup>-1</sup> )	SO <sub>4</sub> <sup>2-</sup> / (mg·L <sup>-1</sup> )	HCO <sub>3</sub> <sup>-</sup> / (mg·L <sup>-1</sup> )	SiO <sub>2</sub> / (mg·L <sup>-1</sup> )	
Fisher Island	F-1	7.21	194.1	113	31.2	1.8	5.6	2.4	57.8	0.15	9.5	15.3	< 0.1
	F-2	6.75	26	15	5.2	0.5	1.6	0.3	7	0.09	3.7	6.1	< 0.1
	F-3	7.49	127.4	74	15.6	1.1	4.8	6.8	35.2	0.12	8.9	21.4	< 0.1
	F-4	8.2	1179	684	195	9.6	28	18	334.1	0.16	12.2	131	1.86
	F-5	7.38	121.5	70	21.7	1.1	4	4.4	35.2	0.12	11.3	21.4	< 0.1
	F-6	8	275.5	160	43.3	2	8	7.8	75.4	0.17	12.6	21.4	< 0.1
	F-7	7.16	84	49	16	0.8	3.2	3.9	25.1	0.1	8.8	12.2	< 0.1
	F-8	7.69	607.6	352	93	5	8	14.6	178.4	0.14	37	21.4	0.22
	F-9	7.81	465.6	270	81.5	1.4	6.4	5.8	128.1	0.08	26.4	24.4	1.64
	F-10	8.2	1032	599	170	8	22	17.5	316	0.15	15.2	67.1	1.36
Broknes Peninsula	B-2	6.94	1040	603	177	6	14.4	22.4	309.1	0.15	45.3	48.8	2.02
	B-3	5.74	499.4	290	88	3.1	7.2	9.2	141	0.18	36.7	18.3	0.25
	B-4	6.3	437.9	254	79.7	3.8	2.4	8.3	123.1	0.18	28.6	18.3	0.37
	B-5	5.95	272.2	158	45.1	2	4	7.3	77.9	0.18	19.4	15.3	0.11
	B-6	6.23	249.1	144	35	1.8	2.4	7.8	72.9	0.24	14.8	12.2	< 0.1
	B-7	6.44	348.4	202	50	2.4	4	8.8	100.5	0.1	20	15.3	< 0.1
	B-8	5.91	274.5	159	43.5	1.8	4	4.9	77.9	0.13	15.7	15.3	< 0.1
	B-9	6.56	381.2	221	56.3	2.6	4	9.7	108	0.14	26.7	12.2	< 0.1
	B-10	7.15	655.5	380	109.2	5	8	10.7	183.4	0.15	45.6	15.3	0.1
	Grovnes Island	L-2	6.35	174	103	22.9	0.9	3.2	2.7	42	0.61	5	8.5
L-3		6.56	202	119	28.8	1.6	2.7	3	51	0.92	7	10.4	4.7
L-4		6.36	212	125	27.9	1.2	3.7	3.4	52	1.26	8	8.5	4.6
L-5		7.21	2500	1475	328	15.1	63.2	54	659	3.12	113	84.8	9.4
L-6		7.26	307	181	37.3	1.7	12.5	4.9	58	1.17	15	32.9	4.2
L-7		6.84	61	26	10	0.5	0.9	1	14	2.51	1	6.7	3.4
Schirmacher Oasis		L-39	7.1	15.74	9	0.49	0.3	1.6	1.46	5.4	0.4	0	6.1
	L-42	7	13.3	8	0.1	0.05	1.6	1.46	2.7	0.4	0.5	6.1	0.05
	L-44	6.8	20.13	12	0.4	0.25	1.6	1.94	2.7	0.4	0.5	12.2	0.05
	L-46	6.8	94.84	55	4.13	2.1	7.2	4.37	16	0.4	2.4	30.5	1.5
	ED-1	6.9	81.64	47	4.13	0.7	2.4	5.83	21.4	0.4	2.2	12.2	0.1
	P-9	7.4	8.61	5	0.29	0.15	0.8	0.49	1.3	0.01	0	3.1	0.5
	L-27	7.1	20.33	12	0.53	0.45	0.8	1.46	2.7	0.04	2	6.1	1.5
	L-32	7.1	15.46	9	0.69	0.3	0.8	0.97	2.7	0.04	0	6.1	0.5
	L-34	7.4	39.99	23	1.5	0.3	1.6	2.92	10.7	0.6	1.2	6.1	0.1
	ED-2	7.1	81.54	47	0.3	0.05	8.8	4.37	16	0.04	7	15.3	20

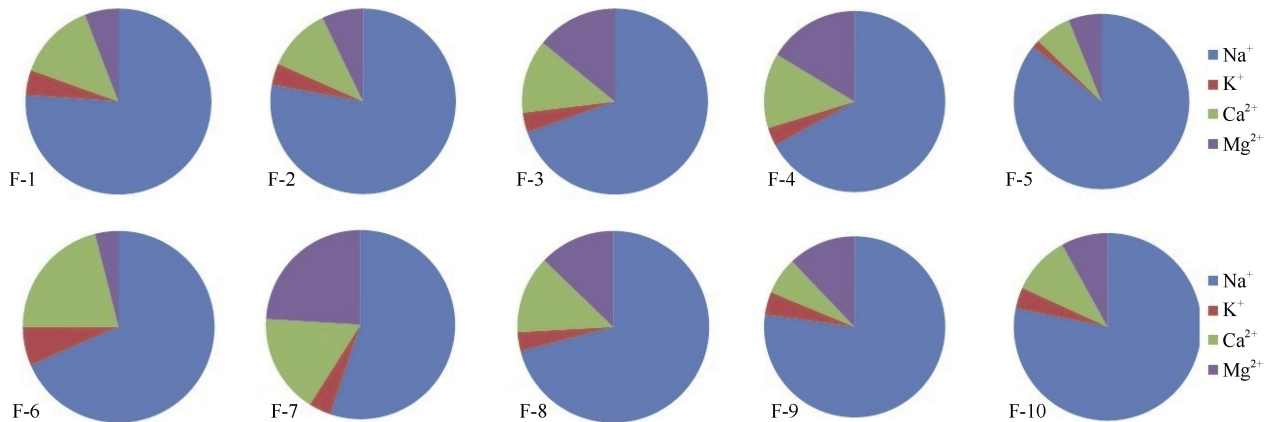
### 4.1 Fisher Island

The pH values of the lake waters from Fisher Island range between 6.75 and 8.2 (Table 2) indicating slightly acidic to

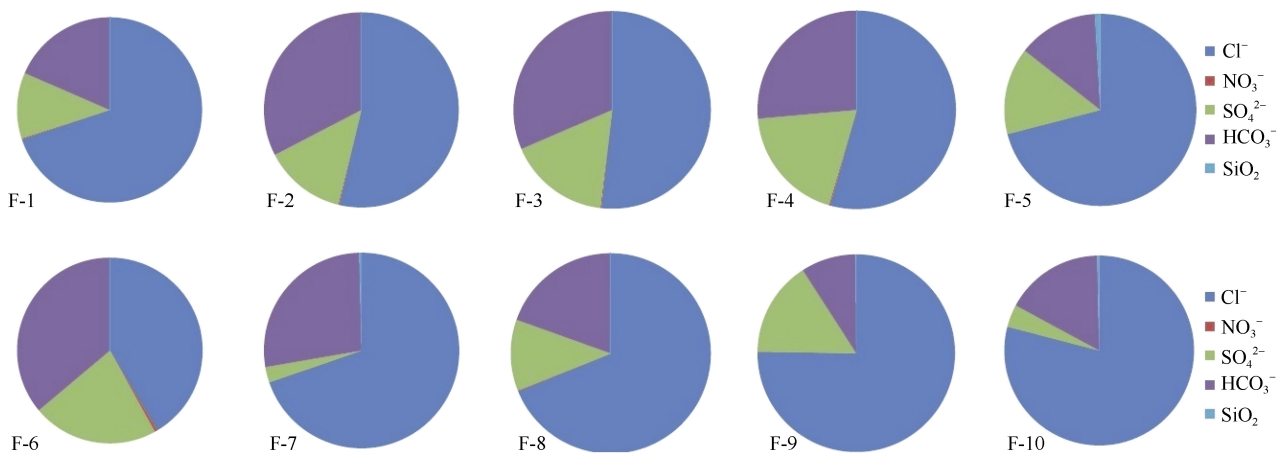
weak alkaline nature. Wide variation in electrical conductance (EC, 26 mmho·cm<sup>-1</sup> to 1179 mmho·cm<sup>-1</sup>) of water samples is recorded. Total Dissolved Solids (TDS) range from 15 to 684 ppm (Table 2) whereas the cationic

concentrations range from  $\text{Na}^+$  (5.2 to 195 ppm),  $\text{K}^+$  (0.5 to 9.6 ppm),  $\text{Ca}^{2+}$  (1.6 to 28 ppm) and  $\text{Mg}^{2+}$  (0.3 to 18 ppm) (Figure 3). Likewise, the anionic concentrations  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$  and  $\text{SiO}_2$  ranged from 7 to 334.1 ppm, 0.08 to 0.17 ppm, 3.7 to 37 ppm, 6.1 to 131 ppm and <0.1 to 1.86 ppm, respectively (Figure 4). The north east facing

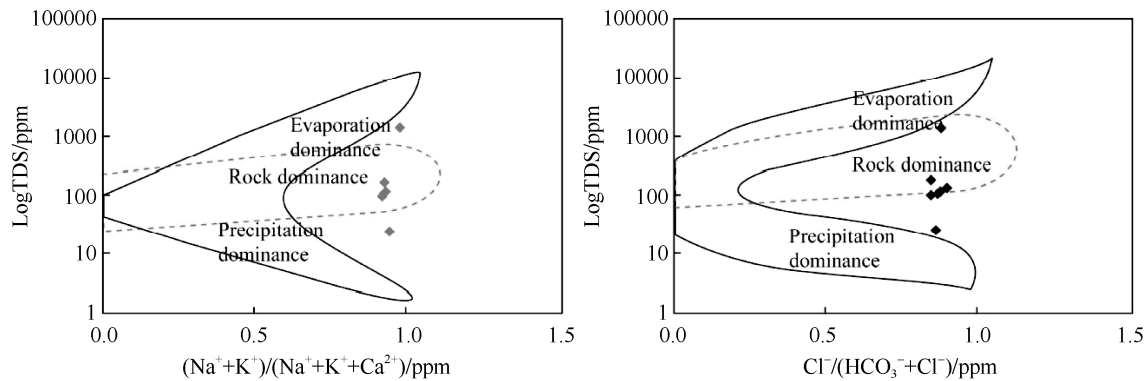
ponds show higher concentration of  $\text{Cl}^-$  compared to other lakes. Various physicochemical parameters, ionic concentrations and plots of the major ions within the Gibb's boomerang (Gibbs, 1970) envelope for lake waters from Fisher Island are shown in Figure 5. The overall ionic characteristics are shown by Piper Plot in Figure 6.



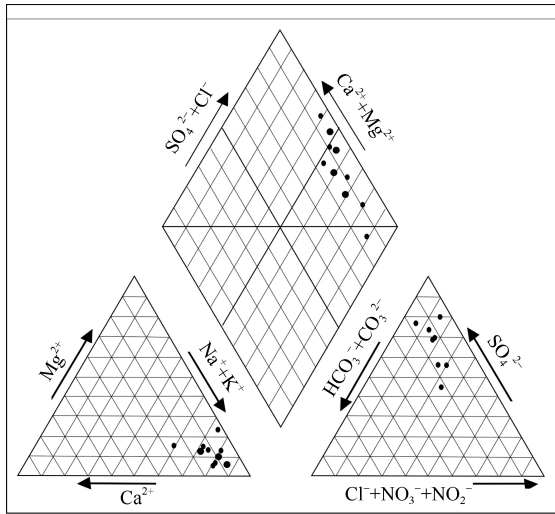
**Figure 3** Cationic distributions in lake waters of Fisher Island, Larsemann Hills area.



**Figure 4** Anionic distributions in lake waters of Fisher Island, Larsemann Hills area.



**Figure 5** Gibb's Plot showing the major ion concentration and related environmental set up in Fisher Island, Larsemann Hills area.



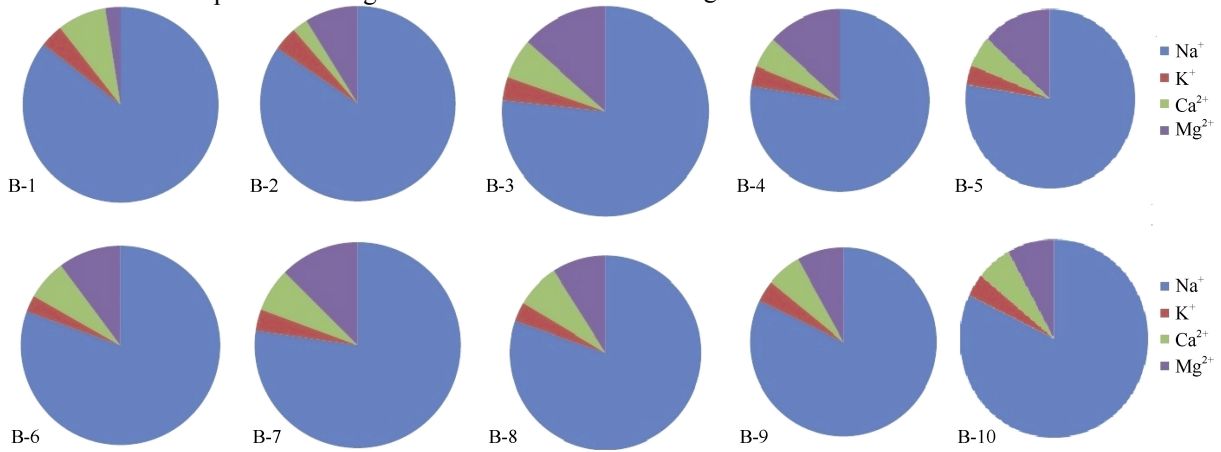
**Figure 6** The Piper's diagram showing influence of strong acids and weak acids in the lake water chemistry of Fisher Island, Larsemann Hills area, East Antarctica.

**4.2 Broknes Peninsula**

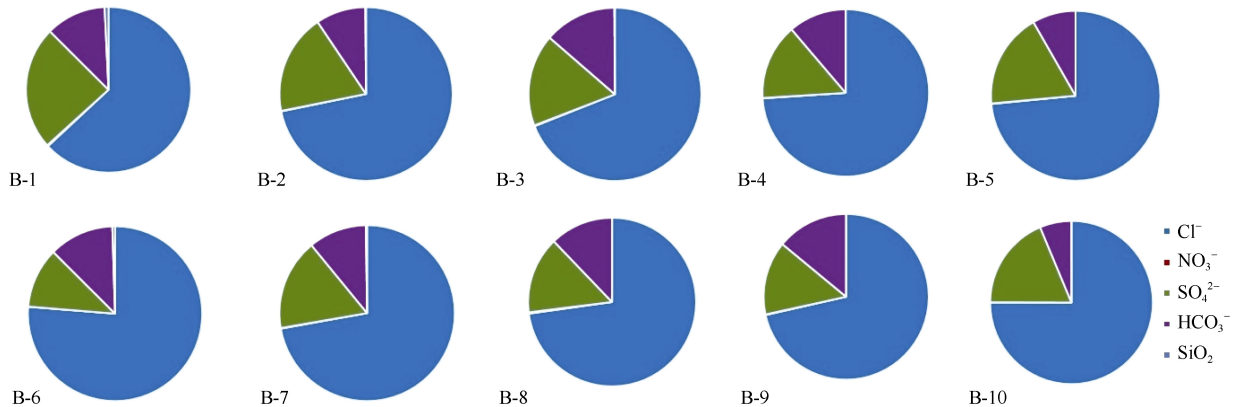
The water quality parameters of the lakes from Broknes Peninsula including pH, EC, TDS and ionic concentrations are given in Table 2. The pH values range from 5.74 to 7.15

indicating acidic to near neutral nature with only one lake showing feebly alkaline pH conditions. The conductivity (EC) and TDS values are also variable. High EC ( $249.1 \text{ mmho}\cdot\text{cm}^{-1}$  to  $1040 \text{ mmho}\cdot\text{cm}^{-1}$ ) and TDS (144 ppm to 603 ppm) values are in contrast to the considerably lower values of fresh water lakes of Schirmacher range. Accordingly, the ionic concentrations of major cations  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ranges from 35 to 177 ppm, 1.8 to 6 ppm, 2.4 to 14.4 ppm and 4.9 to 22.4 ppm respectively (Figure 7). The anionic concentrations  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$  and  $\text{SiO}_2$  ranged from 72.9 to 309.1 ppm, 0.1 to 0.24 ppm, 14.8 to 45.6 ppm, 12.2 to 48.8 ppm and  $<0.1$  to 2.02 ppm, respectively (Figure 8). Here also the north-east facing ponds/lakes have higher concentration of  $\text{Cl}^-$  as compared to other lakes. This indicates influence of salt spray from the ocean under the influence of dominant wind pattern of the region. The plots of major ions within the Gibb's boomerang envelope are shown in Figure 9. The overall ionic characteristics of lake waters from Broknes Peninsula are shown by Piper Plot in Figure 10.

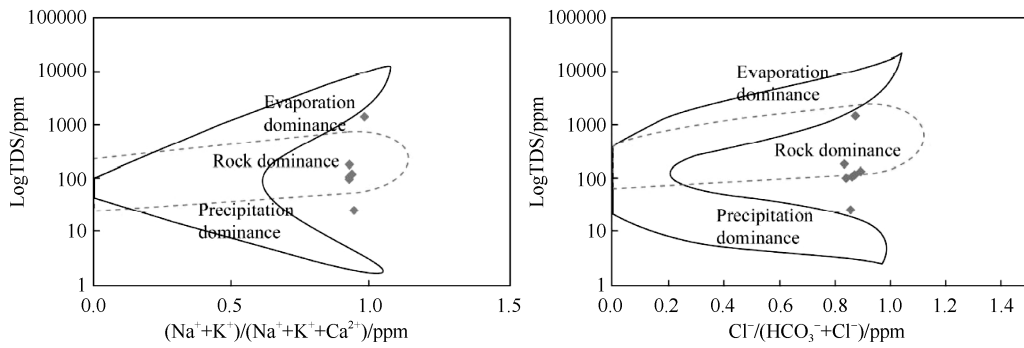
It is observed that in general, the lakes of Fisher Island have lower conductivity and TDS than those in Broknes Peninsula. This difference might reflect the greater amount of fresh water input in the former or the time elapsed since the deglaciation in latter.



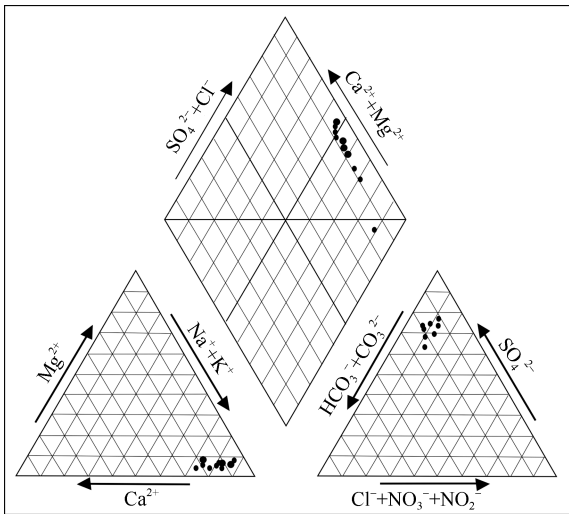
**Figure 7** Cationic distributions in lake waters of Broknes Peninsula, Larsemann Hills area.



**Figure 8** Anionic distributions in lake waters of Broknes Peninsula, Larsemann Hills area.



**Figure 9** Gibb’s Plot showing the major ion concentration and related environmental set up in Broknes Peninsula, Larsemann Hills area.



**Figure 10** The Piper’s diagram showing influence of strong acids and weak acids in the lake water chemistry of Broknes Peninsula, Larsemann Hills area, East Antarctica.

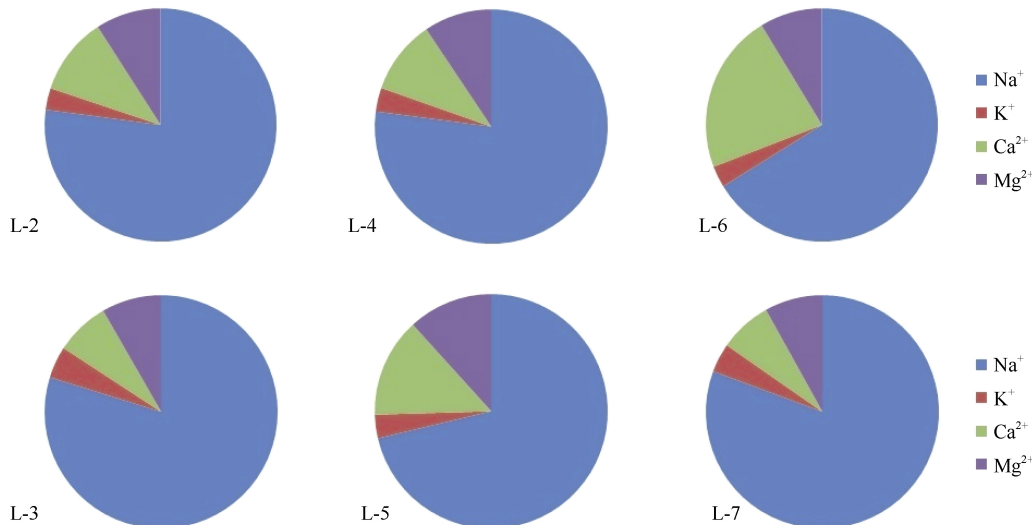
**4.3 Grovnes Island**

The lakes are slightly acidic to feebly basic with pH value ranging from 6.35 to 7.26 (Table 2). The lakes of this island

are located over garnet bearing quartz-plagioclase-microcline-biotite gneisses bed rock. The distributions of cations (Figure 11) and anions (Figure 12), EC and TDS value in all the sampled lakes are fairly uniform, except one isolated lake, situated in a depression. The Gibb’s diagram for major cations and anions from lake waters of Grovnes Island is shown in Figure 13. In Piper’s diagram (Piper, 1944; Karanth, 1987) the position of lake water sample in Segment-7 of anions base triangle (Figure 14).

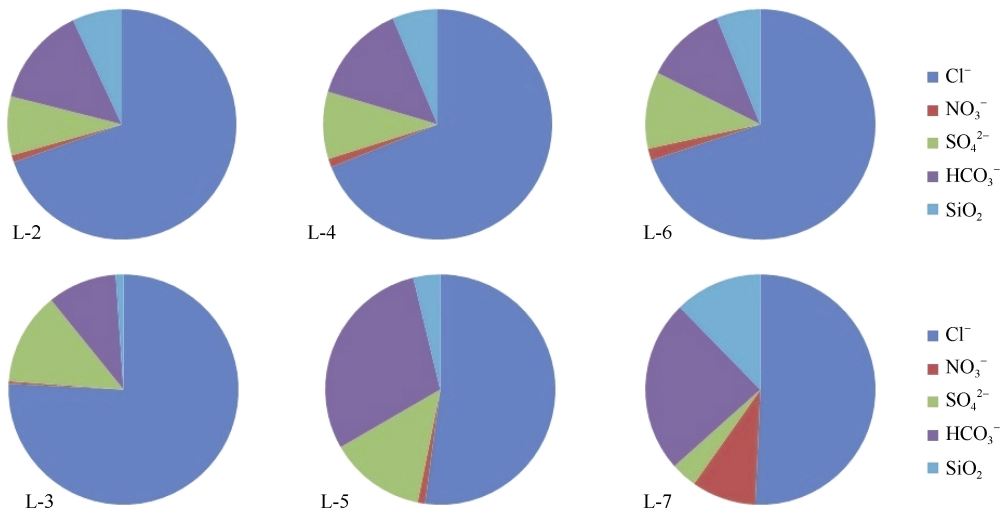
**4.4 Schirmacher Oasis**

Most of the lakes are slightly acidic in nature except few, which are mild basic in nature. The average pH values vary between 6.8 and 7.4 (Table 2). The bedrock of these lakes is composed of abundant garnet bearing quartz-plagioclase-microcline-biotite gneisses. There was a general increase in the EC, TDS and pH values of the interconnected lake water from the polar ice sheet to the edge of the ice shelf for both the channels. There is an increase of EC and TDS values from 8.61 to 94.84 mmho·cm<sup>-1</sup> and 5 to 55 mg·L<sup>-1</sup>, with the distance from the polar ice sheet to ice shelf. These values are comparable to those reported in other available studies (Ali et al, 2010; Verleyen et al, 2012) from the region.

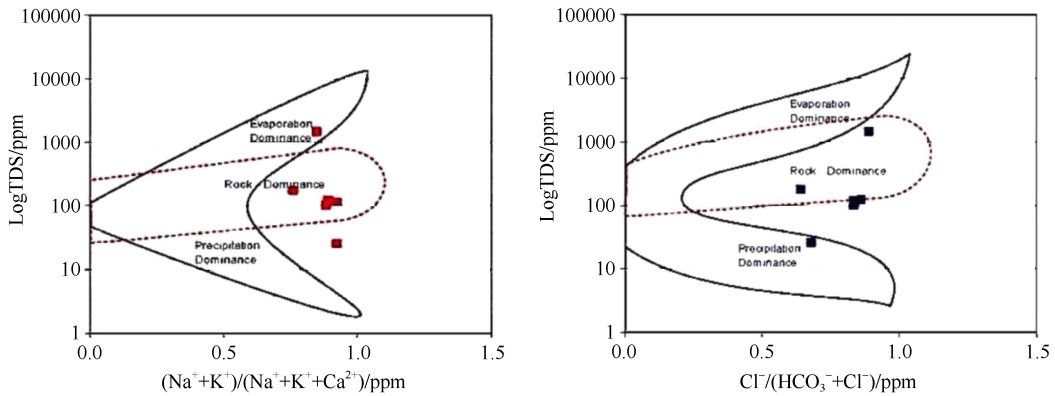


**Figure 11** Cationic distributions in lake waters of Grovnes Island, Larsemann Hills area.

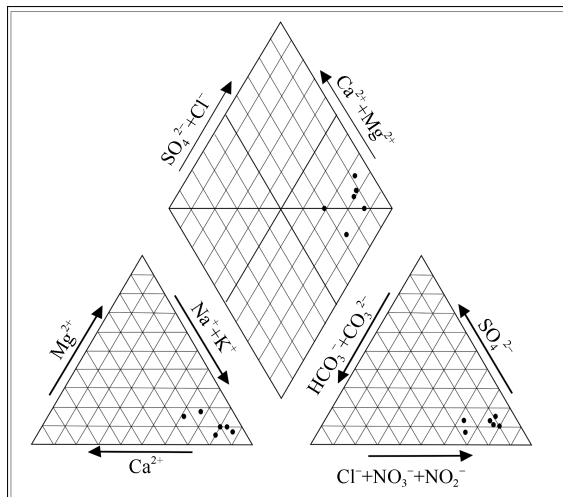




**Figure 12** Anionic distributions in lake waters of Grovnes Island, Larsemann Hills area.



**Figure 13** Gibb's Plot to showing the major ion concentration and related environmental set up in Grovnes Island, Larsemann Hills area.



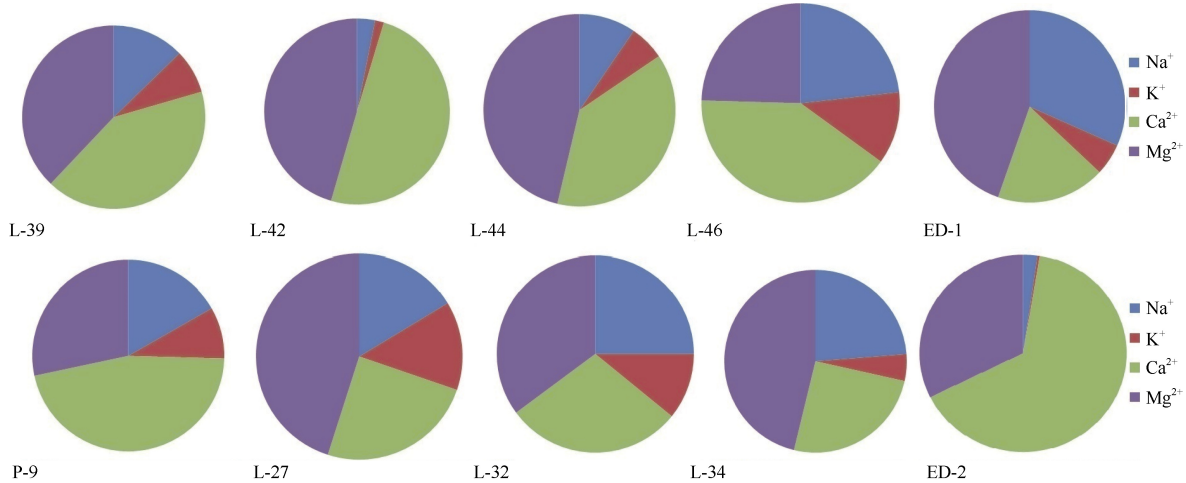
**Figure 14** The Piper's diagram showing influence of strong acids and weak acids in the lake water chemistry of Grovnes Island, Larsemann Hills area.

In Schirmacher lakes the cations and anions are shown in Figures 14 and 15.  $Mg^{2+}$  is the dominant cation in lakes

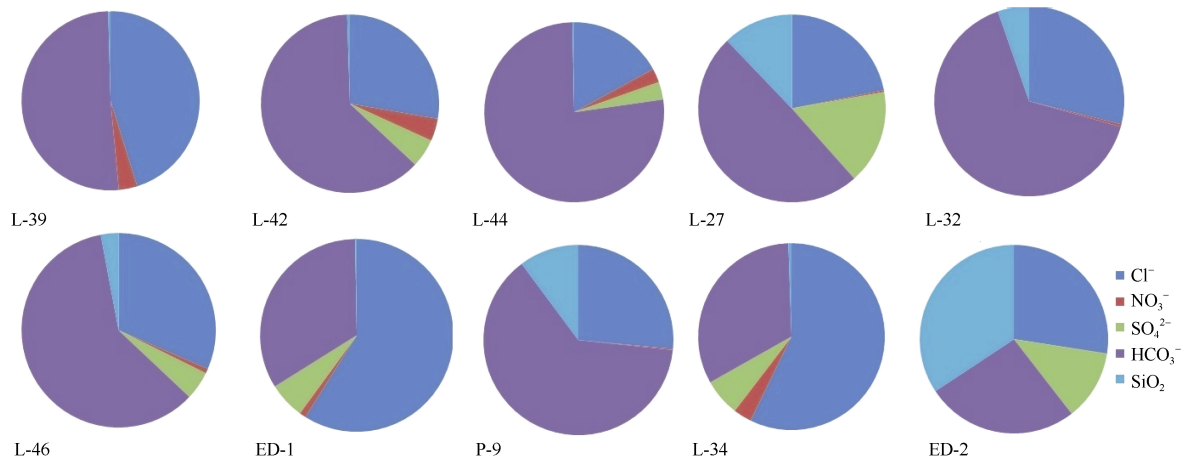
L-39, L-42, L-44, L-46, ED-1 and ED-2 (channel A) while  $Ca^{2+}$  is the dominant cation in lakes P-9, L-27, L-32 and L-34, (channel B) accounting 35.76% and 46.37% of the total cations respectively (Figure 15). For channel A, the average  $Mg^{2+}$  concentration was  $1.46\text{--}5.83\text{ mg}\cdot\text{L}^{-1}$  followed by  $Ca^{2+}$  ( $1.6\text{--}7.2\text{ mg}\cdot\text{L}^{-1}$ ) and  $Na^+$  ( $0.1\text{--}4.13\text{ mg}\cdot\text{L}^{-1}$ ), respectively. In cationic abundance  $Mg^{2+}$  was followed by  $Ca^{2+}$ ,  $Na^+$  and  $K^+$  accounting 34.2%, 21.9% and 8% respectively. For channel B, the  $Ca^{2+}$  concentration was  $0.8\text{--}1.6\text{ mg}\cdot\text{L}^{-1}$  followed by  $Mg^{2+}$  ( $0.49\text{--}2.92\text{ mg}\cdot\text{L}^{-1}$ ) and  $Na^+$  ( $0.29\text{--}1.5\text{ mg}\cdot\text{L}^{-1}$ ), respectively. In cationic abundance  $Ca^{2+}$  was followed by  $Mg^{2+}$ ,  $Na^+$  and  $K^+$  accounting 37%, 12% and 4.5% of the total cations respectively. For both channels,  $HCO_3^-$  is the dominant anion accounting 54.73% and 45.2% of the total anions respectively. For channel A, the average  $HCO_3^-$  concentration was  $6.1\text{--}30.5\text{ mg}\cdot\text{L}^{-1}$  followed by  $Cl^-$  ( $2.7\text{--}21.4\text{ mg}\cdot\text{L}^{-1}$ ) and  $SO_4^{2-}$  ( $0.0\text{--}2.4\text{ mg}\cdot\text{L}^{-1}$ ), respectively. In anionic abundance  $HCO_3^-$  was followed by  $Cl^-$ ,  $SO_4^{2-}$  and  $NO_3^-$  accounting 39.3%, 4.5% and 1.4% respectively. For channel B, the  $HCO_3^-$  concentration was  $3.1\text{--}6.1\text{ mg}\cdot\text{L}^{-1}$  followed by  $Cl^-$  ( $1.3\text{--}10.7\text{ mg}\cdot\text{L}^{-1}$ ),  $SO_4^{2-}$  ( $0.0\text{--}2.0\text{ mg}\cdot\text{L}^{-1}$ ) and  $NO_3^-$  accounting 41.2%, 12.6% and 1% of the total

anions respectively (Figure 16). The low value of  $\text{Cl}^-$  is because of its large distance (~80 km) from the coastline. The Gibb's diagram (Figure 17) has been plotted to understand the effect of lithology, evaporation and precipitation. The Piper plot (Figure 18) showed that majority of samples for channel-A fell in the category of  $\text{Mg}^{2+}\text{-HCO}_3^-$  and  $\text{Ca}^{2+}\text{-HCO}_3^-$  type water. But a considerable number of

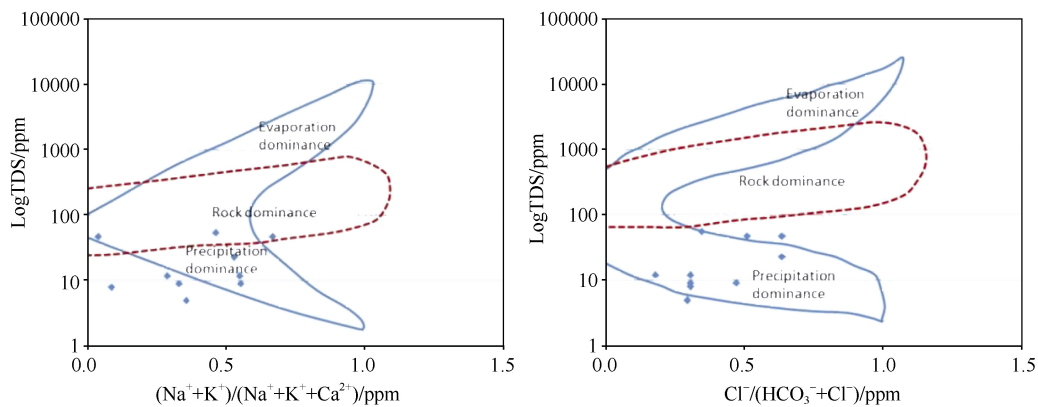
samples also fell in  $\text{Mg}^{2+}\text{-Cl}^-$  and  $\text{Ca}^{2+}\text{-Cl}^-$  types of water. For Channel-B also similar entities are there except a slight dominance of  $\text{Ca}^{2+}$  and  $\text{HCO}_3^-$  influence. From this diagram it is clear that for both the channels, alkaline earth metals ( $\text{Ca}^{2+}+\text{Mg}^{2+}$ ) are considerably higher than the alkalis ( $\text{Na}^++\text{K}^+$ ). However, there is no dominance of any acids except a slight higher concentration of weak acids in the diagram.



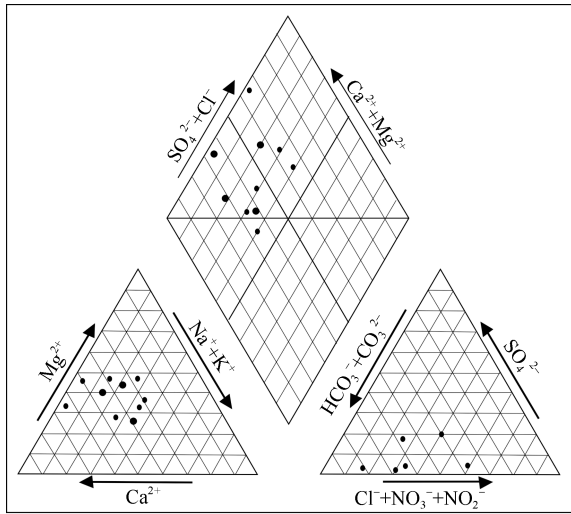
**Figure 15** Cationic distributions in lake waters of Schirmacher Oasis, East Antarctica.



**Figure 16** Anionic distributions in lake waters of Schirmacher Oasis, East Antarctica.



**Figure 17** Gibb's Plot showing the major ion concentration and related environmental set up in Schirmacher Oasis.



**Figure 18** The Piper's diagram showing influence of strong acids and weak acids in the lake water chemistry of Schirmacher area.

## 5 Discussion

### 5.1 Broknes and Fisher islands

Five water samples (F-4, 6, 8, 9, 10) from Fisher Island depict more alkaline nature than the rest. These samples also show higher EC, TDS values contributed mainly by  $\text{Na}^+$  (43.3–195 ppm) and  $\text{Cl}^-$  (75.4–334.1 ppm) contents. However, water sample F-8 with high  $\text{Na}^+$  (93 ppm) and  $\text{Cl}^-$  (178.4 ppm) does not correspond to a higher alkalinity as shown by the rest four samples. This pattern may be attributed to increased alkalinity of water samples by addition of the sea salt either directly to the lake or through the precipitating snow. Secondly, the location of the lake also plays an important role in deciding the water chemistry. Smaller land-locked lakes receiving less snow melt and poor drainage show higher TDS and alkalinity.

The contribution of the sea salt is also corroborated by intra-elemental correlation. It is seen that all major cations ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) that are present in the sea salt show good correlation with each other with values of Na:K–(0.99), Na:Ca–(0.95), Na:Mg–(0.91). Good correlation of  $\text{Cl}^-$  with  $\text{Na}^+$  (0.99),  $\text{K}^+$  (0.97),  $\text{Ca}^{2+}$  (0.95) and  $\text{Mg}^{2+}$  (0.94) supports the contention above whereas the affiliation of the  $\text{HCO}_3^-$  with  $\text{Ca}^{2+}$  (0.96) appears to be a more plausible explanation.

Water chemistry of samples from Broknes Peninsula shows a complete contrast from those of Fischer Island in having a predominantly acidic character. It also differs in having a less variable TDS concentration (144–380 ppm with one peak at 603 ppm). Though the intra-elemental correlation can be established here between Na:K (0.96) and Na:Ca (0.92), it is not as good in Na:Mg (0.87). The correlation of  $\text{Cl}^-$  with major cations is established in these samples having value over 0.9. However, the relation of  $\text{HCO}_3^-$  with  $\text{Ca}^{2+}$  (0.87) is not very explicitly brought in Broknes lake waters as compared to those of Fischer Island. Although the analytical data brings out the contribution of

the sea salt in Broknes Peninsula resulting in addition of chlorides, bicarbonates and sulphates and it also highlights the fact that the chemistry of the water is controlled by the location of the water body.

### 5.2 Grovnes Island

The distribution of cations and anions, EC and TDS value in all the sampled lakes are fairly uniform except for Lake-5 where the ionic concentration, EC and TDS, are very high. High ionic and TDS concentration in Lake-5 disassociates itself from other lakes suggesting either marine influence or older age of water or both (Houslow, 1995). Lake-5 is situated in an isolated depression on the north-western edge of the area which is poorly drained with mainly silt and little clay sized sediments. This may be the reason behind higher ionic and TDS concentration of Lake-5. This allows us to state that marine influence which is by and large uniform for all the lakes in the area is less significant for Lake-5. Further, excessive  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  ions and high TDS value of Lake-5, are indicative of older age of water, as compared to the other lakes (Gibbs, 1970; Hem, 1985). On the contrary, lakes 6 and 7 have very low ionic concentration as well as TDS value, indicating younger age of water that has uniform inflow/outflow pattern due to large snow trap bowl (especially in case of Lake-7) and sufficient overflow regime. The characteristic deviations in Lake-5 and Lake-7 are mainly due to confined nature of basin for the former and huge snow trap bowl for the latter, thus allowing a intermixing of water and greater input by way of accumulation, respectively (Shrivastava et al., 2011).

The lake water chemistry of the area is greatly influenced by chemistry of the host rock rather than precipitation and evaporation as reflected in the Gibb's diagram [ $\text{TDS vs } (\text{Na}^++\text{K}^+)/(\text{Na}^++\text{K}^++\text{Ca}^{2+})$ ] and [ $\text{TDS vs } \text{Cl}^-/\text{shift of the plot of Lake-5 towards the evaporation dominance field indicates a probable perched nature of the lake without proper drainage and loss through evaporation, howsoever little.}$

By far  $\text{HCO}_3^-$  is greater than  $\text{SiO}_2$ , in all the lakes except L-5, indicating a silicate weathering which has helped in the liberation of  $\text{Ca}^{2+}$  ion from plagioclase feldspar and from other ferromagnesian minerals and also supporting possible weathering and liberation of ions from granites (Raymahashay, 1986, 1996).

The factor [ $2 \times (\text{Na}^++\text{K}^+-\text{Cl}^-)$ ] is more than  $\text{SiO}_2$ , in case of lakes 6 and 7, reflects about the weathering of granitoids or granite gneiss as the source (Houslow, 1995). The normal (decreasing) order of mobility of elements during weathering, in case of granite, is in the order of  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{Si}^{4+}$  and  $\text{Al}^{3+}$ . This order may vary because of primary mineralogy, abundance and rate of release of these elements into the water (Feth et al., 1964; Raymahashay, 1996).

For Lakes 2, 3, 4 and 5, the factor [ $2 \times (\text{Na}^++\text{K}^+-\text{Cl}^-)$ ]

is less than  $\text{SiO}_2$  which advocates about the weathering and influence of ferromagnesian rich source rock.  $\text{Na}^+$  and  $\text{K}^+$  might have been liberated from plagioclase and  $(\text{HCO}_3^- + \text{Cl}^-)$ . Low values of TDS in relation to cationic and anionic ratios for Lake-7 assigns greater importance to precipitation dominance rather than lithological control which is not true for other lakes (Gibbs, 1970). Lake-7 is the largest and the deepest, has a huge snow trap bowl and, therefore, influenced by precipitation. As evaporation is negligible in the polar region, none of the lakes falls into the domain of evaporation dominance except for Lake-5 which is a marginal case. The dominance of  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  of alkali elements over the bicarbonate of alkaline elements is well exhibited by Grovnes lake waters. The Piper's diagram shows influence of strong acids over weak acid which might have helped in decomposition of silicate minerals in the rocks. The position of these data in Segment-2 of cation base triangle shows alkalis have exceeded alkaline earth elements, which is characteristic of acidic rocks. The samples fall in Segment-7 of diamond grid in Piper's diagram which suggests non-carbonate alkali (primary salinity) exceeded 50%. The plots of the most water analysis of the lakes are restricted in Segment-7, indicating a strong possibility of marine influence in these lakes. Moreover, from the field observation and almost linear trends of plot, it is evident that mixing of two kinds of water took place in varying proportions.

We can anticipate that the rock weathering would have controlled the  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{SiO}_2$  and  $\text{HCO}_3^-$  content of water in Grovnes Island. In general terms the nature and amount of dissolved species in natural water would have been influenced by mineralogy. The gneissic bodies of the study area mainly consist of quartz, K-feldspar (orthoclase and microcline), plagioclase feldspar, biotite, amphibole, garnet, opaque minerals and heavy minerals. Alteration of biotite, plagioclase and K-feldspar is also common feature in gneissic rocks. These minerals and alterations may have influenced the ionic composition of lake water of Grovnes Island (Karanth, 1987). Numerous examples have appeared in the literatures which indeed support the idea that in an unpolluted environment, where anthropogenic activities are negligible, water quality can be correlated with minerals present in the bed rock (Drever, 1988; Raymahashay, 1996).

### 5.3 Schirmacher Oasis

In Schirmacher Oasis area lake waters near the ice sheet are more acidic than the rest parts except that of L-34. All the lakes in this study have very low ionic concentration and TDS value, indicating younger age of water, with uniform inflow and outflow pattern. There was a wide variation in the ionic concentration from the polar ice sheet to the edge of the oasis. The total anion concentrations far outnumber that of the cations. The ratio of TDS/EC varies between 0.42 and 0.6, confirming the reliability and quality of the analytical results and there is a good correlation between these two parameters. The low concentration of  $\text{K}^+$  and

$\text{NO}_3^-$  in the lakes connected by surface channels may be due to the observed rich biodiversity in terms of algae and lichen affect as reported by the decoupling of  $\text{K}^+$  and  $\text{NO}_3^-$  from other ions, i.e., their consistently low concentration in the ponds and streams near Lake Basen, western Dronning Maud Land, East Antarctica by Lehtinen and Luttinen (2005). The average dissolved silica concentration in the both the channels A and B was calculated to be within  $0.5\text{--}1.5 \text{ mg}\cdot\text{L}^{-1}$  except the ED-2 in channel B, where it reaches upto  $20 \text{ mg}\cdot\text{L}^{-1}$ .

Topography is one of the important factors influencing the hydrochemistry of lake waters (Wolock et al., 1990). The total ionic concentrations in these lakes are comparatively lower than rest of the world. In the Schirmacher region, the elevation of the lakes connected by channel A varies from 130 m above mean sea level near polar ice sheet to  $\sim 0$  m near the ice shelf. Most part of the channel has an elevation of 90–100 m. The slope of the channel A is moderate on transition from polar ice sheet to the main oasis where proglacial lake L-39 is located. In the downward direction, the slope becomes gentle and a steep slope is observed on transition to the ice shelf. For channel B also, situations are similar where the elevation varies from 135 m above mean sea level near polar ice sheet to 0 m near the ice shelf, most part of which has an elevation of 100–110 m. The slope of this channel is moderate near proglacial lake P-9 and becomes gentle in the downward direction, but attains a steep slope on its transition to the ice shelf. The cation and anion concentrations for all the samples are plotted which shows that there is a negative trend with respect to the elevation except that observed in case of lake L-46. The exceptional case of lake L-46 may be due to its catchment encompassing a large area with lake L-47 and L-51. The outflow of lake L-49 goes to lake L-47 and L-51 before getting partly intermixed with lake L-46. All these indicate that when the melt water starts from the polar ice sheet, it has less total ionic strength. When these channels connecting different lakes flow through the Schirmacher Oasis, the gentle slopes of the channels allow the upper part of the melt water to go out of the concerned lake system with less effect on the weathering from incorporated geological materials. However, the increase in the slope value accounted for steep increase or decrease in the elevation is responsible for generation of more intermixing of melt water with the weathered products of the geological units, which in turn produce more ionic concentration in the downward direction.

In the polar areas, the vast ice sheets move forward due to the pressure melting at its base (Eyles, 2006). During the summer periods, the fringes of the polar ice sheet to the south of the Schirmacher Oasis produce enormous quantity of glacial melt water. The chemical composition of glacier melt water demonstrates that chemical weathering takes place beneath the glacier (Reynolds and Johnson, 1972; Raiswell, 1984). The rate and mechanism responsible for dissolved ion release in the meltwater of glacier streams

vary with lithology (Collins, 1979). Weathering of bedrock is likely to occur when water flows at the ice–rock interface. In glacial environment, proton ( $H^+$ ) appears to be accountable for the weathering of rock-forming minerals. The carbon dioxide reacts with water and forms the weak carbonic acid, which dissociates into  $H^+$  and  $HCO_3^-$ . Sulphide oxidation is another mechanism, which is responsible for the production of hydrogen ions (Veizer and Mackenzie, 1971). These produced hydrogen ions then react with carbonate, silicate or aluminosilicate minerals, which result in release of cations, dissolved silica and clay minerals (Raiswell, 1984). The melt water produced out of the glacier is influenced by its nature of contact with the bedrock at its base, the mineralogy of the catchment area and the processes of weathering associated with it aided by the composition of the atmospheric precipitation (Singh and Hasnain, 1998). For both of the channels, the lake water chemistry is highly influenced by snow precipitation than host rock and evaporation as seen in the Gibb's diagram [(TDS) vs  $((Na^++K^+)/(Na^++K^++Ca^{2+}))$ ] for cations and [(TDS) vs  $(Cl^-/(HCO_3^-+Cl^-))$ ] for anions. The atmospheric precipitation has significantly obliterated the ionic distributions in the channels (Shrivastava et al., 2011). Low values of TDS obtained during summer period are possibly due to heavy meltwater discharge from polar ice sheet during this period. The relationship between  $(Ca^{2+}+Mg^{2+})$  vs. TZ+ shows that most of the points fall above/close to 1:1 equiline. The relatively high contribution of  $(Ca^{2+}+Mg^{2+})$  to the total cations (TZ+) and high  $(Ca^{2+}+Mg^{2+})/(Na^++K^+)$  ratio vary between 1.7 and 20.4 for channel A and 1.8 and 37.6 for channel B, indicate that carbonate weathering is a major source of dissolved ions in the interconnected lakes of the Schirmacher Oasis. The relationship between  $Na^++K^+$  and TZ+ shows that all points fall above 1:1 equiline with a low ratio indicating a relatively low contribution of dissolved ions from silicate weathering.  $Na^+$ ,  $K^+$  and dissolved silica in the channels are mainly derived from the weathering of silicate minerals, with clay minerals as byproducts from their catchment areas. The values of  $HCO_3^-$  greater than  $SiO_2$  in almost all the lakes indicates a silicate weathering which has helped in the discharge of  $Ca^{2+}$  ion from plagioclase feldspar and other ferromagnesian minerals such as pyroxene and biotite. This support the possible weathering and ion liberation from granites (Raymahasay, 1996). In the interconnected lake water,  $Na^+$  and  $K^+$  are mainly derived from the granulites and associated rocks of the Schirmacher Oasis. Micas, orthoclase ( $KAlSi_3O_8$ ) and albite are common parental minerals for  $Na^+$  and  $K^+$  release in the meltwater, which may react with water and carbonic acid and accumulate clay minerals in the sediments. Water draining carbonates show  $Ca^{2+}$  and  $Mg^{2+}$  dominated reservoirs and  $Ca^{2+}/Na^+$  ratios close to 50,  $Mg^{2+}/Na^+$  ratios close to 10 and  $HCO_3^-/Na^+$  ratios close to 120 (Meybeck, 1986; Négrelet et al., 1993). The chemical composition assigned for silicate end member is  $Ca^{2+}/Na^+=0.35+0.15$ ,  $Mg^{2+}/Na^+=0.24+0.12$ , and

$HCO_3^-/Na^+=2+1$  (Gaillardet et al., 1999). The observed equivalent ratios of  $Ca^{2+}/Na^+=0.58-16$  for channel A and 1–29.3 for channel B,  $Mg^{2+}/Na^+=1.06-19.6$  for channel A and 1.4–14.6 for channel B and  $HCO_3^-/Na^+=2.96-61$  for channel A and 4–51 for channel B in the interconnected lakes of the Schirmacher Oasis are higher than those of melt waters draining silicate lithology and much lower than those of waters draining carbonate lithology. These ratios indicate that chemical compositions of the lake water of the Schirmacher Oasis are influenced by carbonate weathering followed silicate weathering. The scatter plot of  $(Ca^{2+}+Mg^{2+})$  vs.  $(HCO_3^-+SO_4^{2-})$  falling above 1:1 equiline indicate the weathering of silicate rocks (Pandey et al., 1999). The most important mechanism responsible for rock mineral weathering is acid hydrolysis (Raiswell, 1984). The relative importance of two major proton producing reactions – carbonation and sulphide oxidation can be evaluated on the basis of the C-ratio. Brown et al. (1996) proposed estimation of C-ratio ( $HCO_3^-/HCO_3^-+SO_4^{2-}$ ). If C-ratio is 1.0, it indicates the significance of carbonation reaction involving acid hydrolysis and pure dissolution, consuming protons from atmospheric  $CO_2$ . Conversely if C-ratio is 0.5, it suggests coupled reaction involving carbonate weathering and protons derived from oxidation of sulphide. The average C-ratio for the lakes connected by channel A and B is 0.93+0.06 and 0.86+0.14, respectively, which suggests that the major proton producing reaction is through carbonation. The coupled reactions involving dissolution of  $CO_2$  and carbonate dissolution control the hydrochemistry of the Schirmacher Oasis. Contribution of atmospheric input to the chemical composition of river water has been studied by many researchers (Meybeck, 1983; Sarin et al., 1989; Pandey et al., 1999). The importance of atmospheric input for river water composition can also be determined by the ratio of ions to chloride.  $Na^+$  and  $Cl^-$  constitute the majority of sea-salt aerosols in the coastal Antarctic atmosphere.  $Na^+/Cl^-$  ratio gradually decreases towards inland Antarctica in central Dronning Maud Land (Mahalinganathan et al., 2012). The relationship of  $(Na^++K^+)$  vs.  $Cl^-$  shows that  $(Na^++K^+)$  content is much lower than  $Cl^-$  and average  $Na^++K^+/Cl^-$  ratio for the study area is significantly lower than expected from marine aerosols. The average equivalent ratios of  $Na^+/Cl^-=0.15+0.09$  for channel A and 0.17+0.09 for channel B; and  $K^+/Cl^-=0.07+0.05$  for channel A and 0.08+0.07 for channel B are significantly lower than those of sea water (i.e.,  $Na^+/Cl^-=1.0$  and  $K^+/Cl^-=0.2$  respectively). These ratios indicate relatively major contribution from atmospheric precipitation to the observed dissolved ion budgets of the Schirmacher Oasis lake water. But the high ratio of  $Mg^{2+}/Na^+=1.1-14.6$  indicates the supply of cations from ferromagnesian geological formations including pyroxene granulites and mafic rich rocks. Meltwater evolution and relationship between water composition and rock type indicate carbonate weathering is the dominant process in decomposition of minerals in the water (Piper, 1944).



good correlation of  $\text{HCO}_3^-$  with all the cations i.e.,  $\text{Ca}^{2+}$  ( $r^2=0.62$ ) and  $\text{K}^+$  ( $r^2=0.72$ ), indicating the dominant role of bicarbonates in the weathering process. Good correlation was also observed between  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  ( $r^2=0.72$ ), probably resulting from dissolution of sulphate minerals. There is a strong correlation between  $\text{Mg}^{2+}$  and  $\text{Cl}^-$  ( $r^2=0.96$ ) indicating the dissolution of  $\text{MgCl}_2$  derived from the snow precipitation, which brings moisture from the Southern Ocean. Larsemann Hills lake water represents better correlation among different ionic parameters than lake waters of Schirmacher Oasis. This difference clearly reflects their two different environment and geographic set up.

## 7 Spatial variation of the TDS

There is a spatial variation observed in the TDS of both the channels A and B in the Schirmacher Oasis (Table 2). TDS was low near the lakes adjacent to the polar ice sheet and increases as the distance increases from the polar ice sheet and highest in the epishelf depressions. The low amount of TDS in the Proglacial lakes might have resulted due to the fact that these lakes receive huge amount of glacial melt directly from the polar ice sheet which obliterate the actual characteristic of these lakes and has least influence of the weathering by geologic units on which it is situated. These variations in the concentration of different ions may be possible due to different weathering intensities at different discharge values as it passes through different geological units. The study conducted by Stumpf et al. (2012) in Wright and Taylor valleys, Antarctica has shown that solutes increase away from glaciers, confirming significant chemical weathering. They have shown that the differences in stream chemistry are not due to differing bedrock mineralogy; rather the Leaching experiments show that drifts may significantly affect stream chemistry and aeolian additions of locally sourced dust to the glacier may also affect stream chemistry.

## 8 Conclusions

Lakes of the islands, peninsulas and promontories in Larsemann Hills exist in topographically or structurally controlled glaciated valleys and owe their existence to accumulation of seasonal snow (precipitation as well as drift) along with seasonal water flow in the depressions formed due to glacial erosion. The salt spray under the influence of dominant wind pattern has controlled the chemistry of north-eastern lakes. By and large lakes of Larsemann Hills area have fairly uniform chemical characteristics. The lithology of the area is dominant controlling factor in the ionic content of lake waters. The characteristic deviations in Lake-5 and Lake-7 are mainly due to confined nature of basin for the former and huge snow trap bowl for the latter, thus allowing an intermixing

of water and greater input by way of accumulation, respectively. The marine influence, mixing of two kinds of water and evaporation took place in varying proportions. The lakes of Fisher Island have lower conductivity and TDS than those in Broknes Peninsula and this difference can be attributed to relatively greater amount of fresh water input in Fisher Island or the greater time elapsed since deglaciation in case of lakes from Broknes Peninsula, which are thought to have remained exposed during the Last Glacial Maximum (LGM).

The surface melt water channels of Schirmacher Oasis connecting different lakes from polar ice sheet to the ice shelf generally drain in the north direction with maximum distance of 3 km. The lake waters quality is mainly controlled by precipitation, lithology and surface drainage. The role of salt spray has not been observed in any of the lakes in Schirmacher Oasis. The lake waters are fairly similar in hydrochemical parameters. The lakes adjacent to the polar ice sheet are slightly acidic while in the downward direction it becomes slightly alkaline in nature, possibly due to the lithological weathering while passing through ferromagnesian rocks in the region and its catchment areas. The lakes are highly influenced by snow precipitation. However, as it interacts with the geological units in its downward direction, the intensity of weathering increases. Carbonate weathering is the dominant process and partly controlled by silicate weathering. The equivalent ratios of  $\text{Na}^+/\text{Cl}^-$  and  $\text{K}^+/\text{Cl}^-$  are significantly lower than those of marine aerosols indicating higher contribution from atmospheric precipitation to the dissolved ion budgets in the Schirmacher Oasis. The increase in the topographic slope accounted may be responsible for more intermixing of melt water with the weathered products of the geological units, which in turn produce more ionic concentration in the downward direction. Large participation of snow in the lake hydrochemistry which is directly reflected by the gushing of melt water during austral summer seasons in the Schirmacher Oasis has been observed.

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