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Chemical characteristics of pond waters within the debris area of Lirung Glacier in Nepal Himalaya

Maya P. BHATT*, Toshiyuki MASUZAWA[1)]†, Mineko YAMAMOTO[1)] and Nozomu TAKEUCHI[2)]

Department of Environmental Science and Engineering, Kathmandu University, Dhulikhel, Kavre, P. O. Box: 6250, Kathmandu, Nepal
[1)]Graduate School of Earth Environmental Sciences, Nagoya University, Nagoya 464-8601, Japan
[2)]Department of Earth Sciences, Graduate School of Science, Chiba University, Chiba 263-8522, Japan
*e-mail corresponding author: bhatt.maya@yahoo.com

ABSTRACT

Water samples were analyzed from ponds developed within the debris-covered area of Lirung Glacier (28º 12.9'N, 86º 39.9'E; 4000 m a.s.l.) in the Himalayas of Nepal during the pre-monsoon to post-monsoon period of 1996. Major chemical species were classified into three groups based on their relationships relative to the sum of cations: conservative (SiO_2, Ca^{2+}, K^+, and Alkalinity), semi-conservative (Na^+, Mg^{2+}, and SO_4^{2-}) and non-conservative (NH_4^+, NO_3^- and Cl^-). The dominant processes determining the chemical composition of glacier pond water were sulfide oxidation coupled with carbonate dissolution and chemical weathering of aluminosilicate as indicated by the conservative and semi-conservative species. Calcium and alkalinity appeared as the dominant cation and anion, respectively, among all samples within the basin. Compared to the discharge waters at the outlet of the glacier, most of these pond waters have lower major solutes as well as alkalinity. The availability of fresh reactive minerals at the base of the glacier, coupled with higher temperature in discharge waters than in the ponds, may be the prime factors resulting in higher concentrations of most solutes in the discharge waters than in the ponds. In the ponds, higher concentrations of major solutes as well as alkalinity were observed in the monsoon than the pre-monsoon and post-monsoon seasons, suggesting the role of hydrolysis condition in chemical weathering rates. Ponds within the debris area of Lirung glacier in central Nepal Himalaya are likely to increase in importance if global warming accelerates the rate of glacial melting.

Key words: debris-covered Lirung glacier ponds, glacial meltwaters, Nepal Himalaya

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1. INTRODUCTION

Meltwaters from mountain glaciers of the Himalayas are the dominant water resources for Nepal. It is, therefore, important to examine the geochemical processes that control the chemical composition of meltwaters in addition to examining the amount of meltwaters. There are two types of glacier in the Himalaya, debris-free and debris-covered glaciers (Sakai *et al*. 1997). This difference may affect not only discharge amounts but also the chemical composition and fluxes of dissolved species in meltwaters.

Rapid tectonic uplift, numerous glacial fluctuations and intense weathering driven by an active monsoon climate have resulted in high rates of denudation in central Nepal Himalaya (Barnard *et al*. 2006). Solute flux in meltwaters from glaciated catchments is higher than the global mean (Reynolds & Johnson 1972; Eyles *et al*. 1982; Collins 1983; Sharp *et al*. 1995) and is particularly high in the tectonically active Himalayan regimes (Sarin *et al*. 1992; Collins *et al*. 1996; Collins 1998; Galy & Frane-Lanord 1999; Hasnain & Thayyen 1999; Bhatt *et al*. 2000). There have been a few studies on the chemistry of lakes in the Himalayan region (Kamiyama 1984; Tartari *et al*. 1998; Chakrapani 2002; Das & Dhiman 2003) but little is known about the chemistry of ponds or lakes within the debris area of the glacier itself.

Controls on surface water chemistry can be divided into three categories based on factors affecting their chemistries: those affected primarily by atmospheric precipitation, rock dominance and evaporation-crystallization processes (Gibbs 1970). In some environments, physical erosion appears to have primary control on the chemistry of surface waters (Stallard & Edmond 1983; Drever 1988; Edmond & Huh 1997; Harris *et al*. 1998; Gaillardet *et al*. 1999; Dalai *et al*. 2002; Millot *et al*. 2002; Das & Dhiman 2003; Dupre *et al*. 2003; West *et al*. 2005).

Glaciers provide an extreme case of erosion-enhanced weathering (Anderson *et al*. 1997), although the full impact of glacial action on water chemistry is not well described.

Glaciers in the Himalaya are retreating at high rates in recent decades (Yamada *et al*. 1992; Fujita *et al*. 2006) and forming many unstable lakes within the debris area. The Lirung glacier has recently developed a variety of ponds within its debris area, presumably due to accelerated melting due to global climatic change (Sakai *et al*. 2000). The size of the lakes has increased with time, posing a threat to downstream communities because the large volume of water that can become part of a glacier lake outburst flood (GLOF). These floods result in loss of lives, natural resources and property including infrastructure worth millions of dollar. For example, Thso Rolpa Glacier Lake in Nepal increased its size about seven fold since 1950. A glacier lake Dig Thso in the Khumbu region near Mt. Everest collapsed during the monsoon season in 1985 and the flood caused loss of lives and destroyed physical infrastructure (Vuichard & Zimmerman 1986).

The geochemistry of glacier meltwaters, pond waters and ice cores from Nepal Himalaya has been documented by various authors, but the chemistry of pond waters within the debris areas of the glaciers has not been well understood (Kamiyama 1984; Watanabe *et al.* 1984; Jenkins *et al.* 1995; Reynolds *et al.* 1995; Gardner & Walsh 1996; Harris *et al.* 1998; Tartari *et al.* 1998; Bhatt *et al.* 2000; Quade *et al.* 2003; Tipper *et al.* 2006).

The primary objective of this paper is to report the chemical composition of pond waters collected from the debris-covered areas of Lirung Glacier, Nepal Himalaya, as a part of Crysphere Research Expedition in Himalaya (CREH) Expedition from May to October 1996 (Fujita *et al.* 1997; Nakawo *et al.* 1997; Sakai *et al.* 1997) and to discuss their chemical composition relative to that of glacial meltwater outlet during the same period to elucidate important geochemical processes occurring within the debris area (Bhatt *et al.* 2000). Data from Bhatt *et al.* (2000) were used in this paper just to compare with chemistry of pond waters.

2. STUDY AREA

2.1. Site Description

Lirung Glacier (28º 12.9'N, 86º 39.9'E) in the Langtang Valley is one of the typical mountain glaciers with a debris-covered area in the Himalayas. The total area of Lirung Glacier basin is 13.8 km^2, of which 33% is a steep bedrock wall, 16% is debris-covered glacier

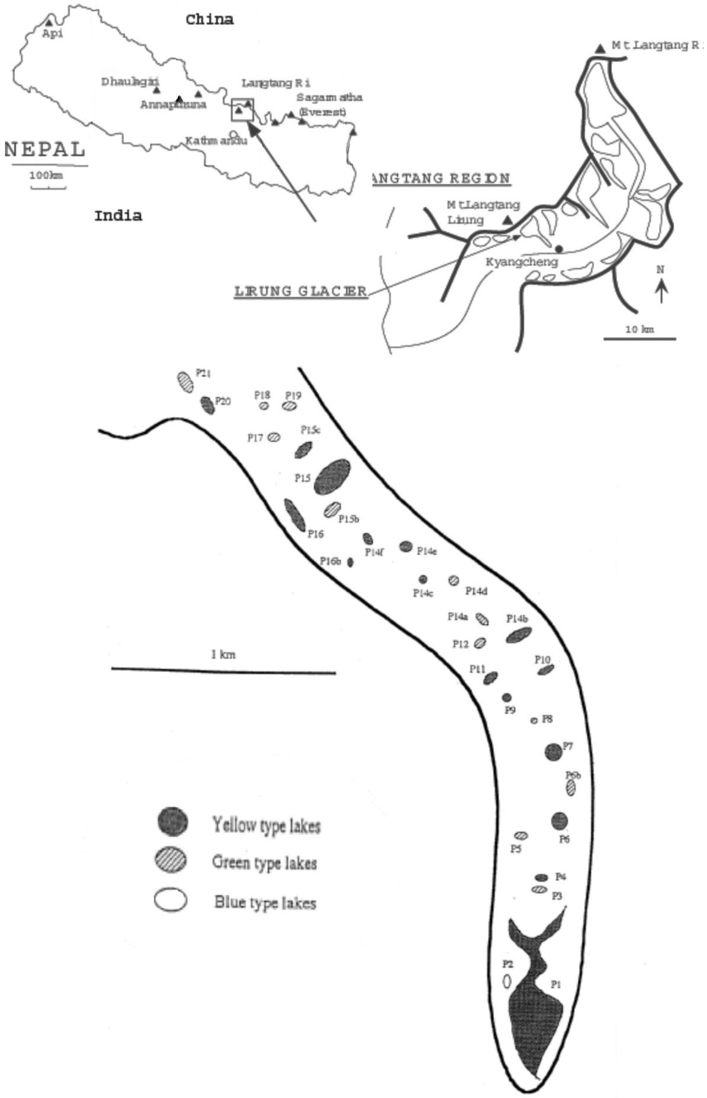

Fig. 1. Locations and numbers of ponds within the debris area of Lirung Glacier in Nepal Himalaya (Sakai *et al.* 2000). Lirung outlet is located just below discharge point of P1.

and the rest (51%) is debris-free ice (Fukushima *et al.* 1987). The debris-covered area of Lirung Glacier and the locations of 28 ponds identified in 1996 are shown in Figure 1. Ponds were numbered starting from the glacial outlet, 4000 m a.s.l. to the inlet to the debris-covered area, about 4400 m a.s.l. (Sakai *et al.* 2000; Fig. 1). Pond 1 was the biggest and directly flowed out to the outlet of the glacier. Pond 2 was the only isolated pond in the debris area that contained water of high clarity. Other pond waters were usually turbid with or without ice cliffs (Sakai *et al.* 2000) and were yellow or sometimes green in color. Different ponds are classified based on their visible color although the discussion is based on physico-chemical parameters. Takeuchi and Kohshima (2000) classified three classes of ponds within the debris area of Khumbu glacier in east Nepal based on species composition of living organisms.

2.2. Geologic Setting

The Langtang Lirung area lies in a complex transition zone between the high Himalayan metasediments (south) and Tethyan sedimentary series (north). The lithology consists entirely of high grade metamorphic rocks with traces of igneous rocks including migmatities, gneisses, schists, phyllites and granites (Inger & Harris 1992). Bedrock consists of biotite, quartz, and plagioclase with minor muscovite, alkali feldspar, ilmenite and sillimanite. Biotite, quartz and plagioclase are the dominant silicates in the bedrock with lesser amounts of muscovite, alkali feldspar, ilmenite and sillimanite. Sulfide bearing minerals also present within the basin.

3. MATERIALS AND METHODS

3.1. Sample Collection

Pond waters were sampled during the pre-monsoon, monsoon and post-monsoon periods. Discharge waters were sampled nearly weekly at the outlet of the glacier from 16 May to 26 October 1996 for chemical analysis (Bhatt *et al.* 2000). Each water sample was filtered with a pre-weighted 25 mm or 47 mm GELMAN Supor polyethersulfone filter with a pore size of 0.2 μm by using a hand vacuum pump or a syringe and stored in a 50 ml polyethylene (PE) bottle for major species analyses, and in a similar bottle acidified with HCl to 0.06M, for PO_4-P. At the time of sampling air and water temperature, electrical conductivity and the pH of ponds and discharge waters were measured.

3.2. Analytical Methods

Electrical conductivity (EC) and pH were measured at the time of sampling using a Horiba B-173 and Horiba B-212, respectively. Suspended sediment (SS) was calculated from the net dried residue on the filter after drying in a vacuum oven at 60ºC for 48 hours. Major cations (Na^+, K^+, Mg^{2+}, Ca^{2+}, and NH_4^+) and anions (Cl^-, NO_2^-, NO_3^- and SO_4^{2-}) were determined by cation (DIONEX DX-100) and anion (DIONEX QIC) chromatography, respectively. Alkalinity was determined by acid titration and dissolved silica (SiO_2) and PO_4-P spectrophotometrically (Hitachi 124) by the standard molybdenum blue methods. The details of sampling and analytical methods are described by Bhatt *et al.* (2000). Detection limits for SS, alkalinity, Cl^-, NO_3^-, SO_4^{2-}, PO_4-P, Na^+, K^+, Mg^{2+}, Ca^{2+}, NH_4^+ and SiO_2 were 1 mg l^{-1}, 1 μeq l^{-1}, 0.2 μM, 0.3 μM, 0.3 μM, 0.03 μM, 0.1 μM, 0.2 μM, 0.1 μM, 0.1 μM, 0.2 μM and 0.2 μM respectively.

Analytical errors were <2% for Cl^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Mg^{2+}, Ca^{2+}, and SiO_2, <4% for NH_4^+ and <5% for PO_4-P. Sea-salt contribution can be estimated using the molar ratios of various elements found in marine aerosols (Keene *et al.* 1986; McDowell *et al.* 1990; Millot *et al.* 2002; Bhatt & McDowell 2007). Chloride concentration was used as a reference species to correct the contribution of sea-salt in Lirung glacier meltwaters in central Himalaya for SO_4^{2-}, Na^+, K^+, Mg^{2+}, and Ca^{2+} and present the sea-salt corrected concentrations with an asterisk.

4. RESULTS AND DISCUSSION

The average physical parameters and concentration of major chemical species in discharge water at the Lirung outlet and in pond water samples within the debris area of Lirung Glacier are summarized in Table 1. The water samples were slightly alkaline among all types of ponds. Suspended sediment was nearly three times higher in the monsoon season than in the pre-monsoon and post-monsoon seasons. Among all sample types including the discharge water, the clear blue isolated pond (P2) showed the highest concentration of sum of cations within the basin (Fig. 2). This pond was formed at the bottom of the moraine, and was surrounded by large boulders that separated it from the main discharge of the Lirung. The pond receives fresh reactive minerals from the wall of the moraine and temperature was higher than most ponds as it contacts neither the ice cliff nor water flowing through the ice. The high availability of fresh reactive minerals and high temperature appeared to be the prime causes for the higher concentrations of cations in this pond than others.

Major solutes as well as alkalinity appeared highest in the blue type of pond, followed by yellow and green ponds. Yellow ponds were surrounded by rocks and some ice cliffs, and received mineral grains from the surrounding areas, whereas the green ponds were surrounded mostly by ice cliffs and did not receive much mineral input from the surrounding areas. The differences in chemistry between these two types of ponds were probably due to the availability of fresh reactive minerals and variation in temperature. The variation in major solutes as well as alkalinity among all types of samples within the debris area of the glacier was prima-

Tab 1. Comparison of average physical parameters and chemical concentrations of major chemical species of discharge waters at the Lirung outlet with the pond water samples during pre-monsoon, monsoon and post-monsoon seasons in 1996 within the debris area of Lirung Glacier.

Measured Parameters	Lirung Glacier Outlet (average)	Pond water samples within the debris area of Lirung Glacier		
		Pre-monsoon	Monsoon	Post-monsoon
Tw (ºC)	2.3	6.0	1.6	2.5
pH	8.0	7.7	8.3	7.9
EC (μS cm^{-1})	116	15	16	19
SS (mgl^{-1})	35	81	34	36
NH$_4$ (μeql^{-1})	0.90	8.36	0.20	0.26
Na (μeql^{-1})	30.6	10.4	3.1	6.4
*Na (μeql^{-1})	26.9	4.5	1.6	4.9
K (μeql^{-1})	21.2	14.2	14.3	12.8
*K (μeql^{-1})	21.1	14.1	14.2	12.8
Mg (μeql^{-1})	32.8	8	7.4	9.6
*Mg (μeql^{-1})	32.0	6.7	7.0	9.3
Ca (μeql^{-1})	248.6	121.4	129.6	114.8
*Ca (μeql^{-1})	248.4	121.2	129.5	114.8
Cl (μeql^{-1})	4.30	6.81	1.75	1.78
NO$_3$ (μeql^{-1})	16.1	13.4	6.9	5.6
PO$_4$ (μM)	0.02	0.03	0.00	0.01
SO$_4$ (μeql^{-1})	105.4	20.8	19.8	24.8
*SO$_4$ (μeql^{-1})	106	20	19.6	24.5
Alkalinity (μeql^{-1})	168.0	99.6	115.5	85.6
SiO$_2$ (μM)	39.1	18.8	22.3	18.5
Σanion (μeql^{-1})	295	140	145	118
Σcation (μeql^{-1})	333	154	154	144
SiO$_2$/Al$_2$O$_3$	3.73	3.94	3.66	3.83

Asterisks represent sea-salt corrected values. Tw = water temperature

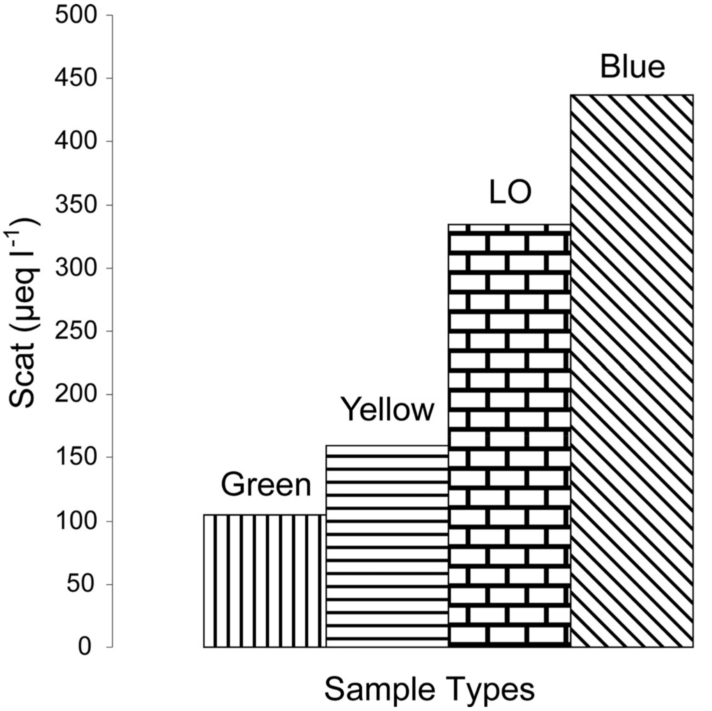

Fig. 2. Variation of average sum of base cations among the pond types (green, yellow, blue) within the debris area of the Lirung Glacier in Nepal Himalaya during pre-monsoon and post-monsoon period in 1996. Scat is the sum of cations. The average value of sum of base cations in discharge water at the Lirung outlet (LO) from May to October 1996 (Bhatt *et al.* 2000) is also shown.

rily due to the abundant availability of fresh reactive minerals, hydrolysis condition and temperature.

We found that three summary descriptions of our data proved useful in describing and interpreting our results. These were total concentration of dissolved species, which is represented by sum of cations in μeq l^{-1}, normalized chemical compositions of cations, anions and SiO_2, which are represented by equivalent compositions of cation and anions and the silicon to alkalinity ratio; and relationship of each chemical species to sum of cations. The sum of cations plotted against some released major chemical (conservative) species such as silicon, calcium, potassium and alkalinity indicating their synchronized appearance suggesting all these species released from the same source.

The values of sum of cations in discharge waters at the outlet ranged from 187 to 525 μeq l^{-1} with an average value of 334 μeq l^{-1} (Bhatt *et al.* 2000) as shown in Figure 2. Except for a clear isolated pond (Pond 2) the sum of cations values in yellow and green ponds were lower than the range of discharge waters. In most cases, sum of cations showed lower values in the post-monsoon period than those in the pre-monsoon period. Major solutes as well as alkalinity appeared higher in monsoon season among all types of ponds suggesting the role of hydrolysis condition to accelerate the rates of chemical weathering.

The major cationic and anionic compositions in μeq l^{-1} were $Ca^{2+} >> Mg^{2+} \geq Na^+ \geq K^+ >> NH_4^+$ and Alkalinity $> SO_4^{2-} >> NO_3^- > Cl^-$, respectively, similarly to those of the discharge waters (Bhatt *et al.* 2000). All cation and anion concentrations as well as their sums decreased with time while silica concentration increased. According to the equivalent compositions of cation and anions, the contribution of Ca^{2+}, SO_4^{2-} and NO_3^- decreased and that of alkalinity and Mg^{2+} increased in the post-monsoon season.

The silicon, calcium, potassium and alkalinity showed very strong correlations with sum of cations of the pond water within the debris area and average concentrations in the discharge waters (Bhatt *et al.* 2000) at the Lirung outlet (Fig. 3). Major solutes as well as alkalinity from the debris area of Lirung Glacier appeared higher than that of debris-free glaciers in the Himalayas

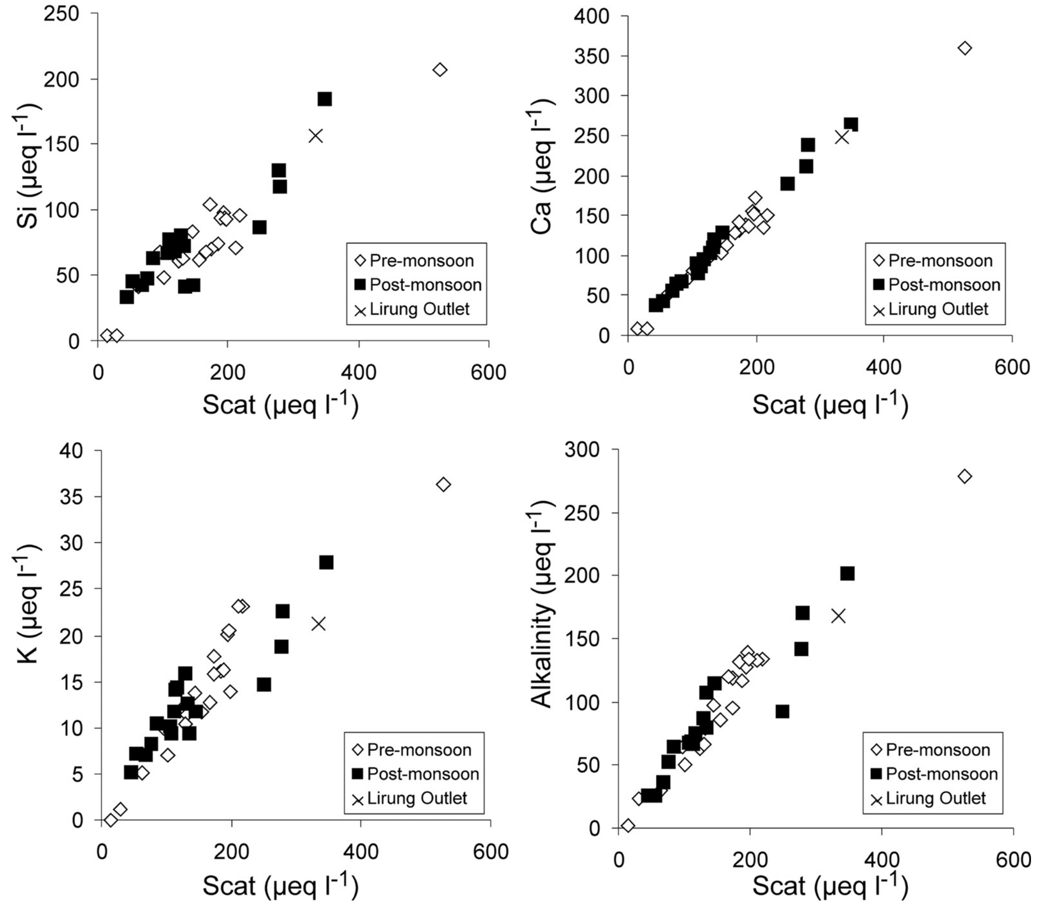

Fig. 3. Relationships of conservative chemical parameters and Σcations in pond water sampled in pre-monsoon period (open symbol) and in the monsoon or post-monsoon period (solid symbol) from debris area of Lirung Glacier in Nepal Himalaya. Average value of each chemical species and sum of cations of discharge water at the outlet sampled from May to October 1996 (Bhatt *et al.* 2000).

of Nepal. Debris covered areas of glaciers may play a significant role in increasing global solute yield (Anderson *et al.* 1997).

Measured chemical species can be classified into three groups based on their relationships to sum of cations: conservative solutes as well as EC and alkalinity showing a very strong linear relationship (EC, SiO_2, Ca^{2+}, K^+ and Alkalinity); semi-conservative solutes showing a linear relationship with a lower slope at lower sum of cation values and a divergent (higher) slope at higher sum of cations (Na^+, Mg^{2+} and SO_4^{2-}), and a non-conservative type with no clear relationship or no relationship (NO_3^-, Cl^-, NH_4^+ and (PO_4^{3-}). The chemical species of conservative and semi-conservative types indicate that the dominant geochemical processes determining the chemical compositions of these pond waters are sulfide oxidation coupled with carbonate dissolution and chemical weathering of aluminosilicates as widely observed in mountain glaciers (Tranter & Raiswell 1991; Tranter *et al.* 1993; Hasnain & Thayyen 1999; Bhatt *et al.* 2000). Higher slopes at higher sum of cation of the secondary type species suggest that these species might have accumulated for a longer period in these ponds, especially for the clear isolated pond, Pond 2 (Fig. 2). The third type species, NH_4^+ was much higher and NO_3^- and Cl^- were higher in the pre-monsoon period than those in the monsoon or post-monsoon period. This suggests that NH_4^+ was dominantly and NO_3^- and Cl^- were significantly supplied from the atmosphere as precipitation or as dry fallout in the pre-monsoon period to these ponds. The absence of NH_4^+ and decrease in NO_3^- in these pond waters in the post-monsoon period might be due to their consumption by biological activities due to higher tem-

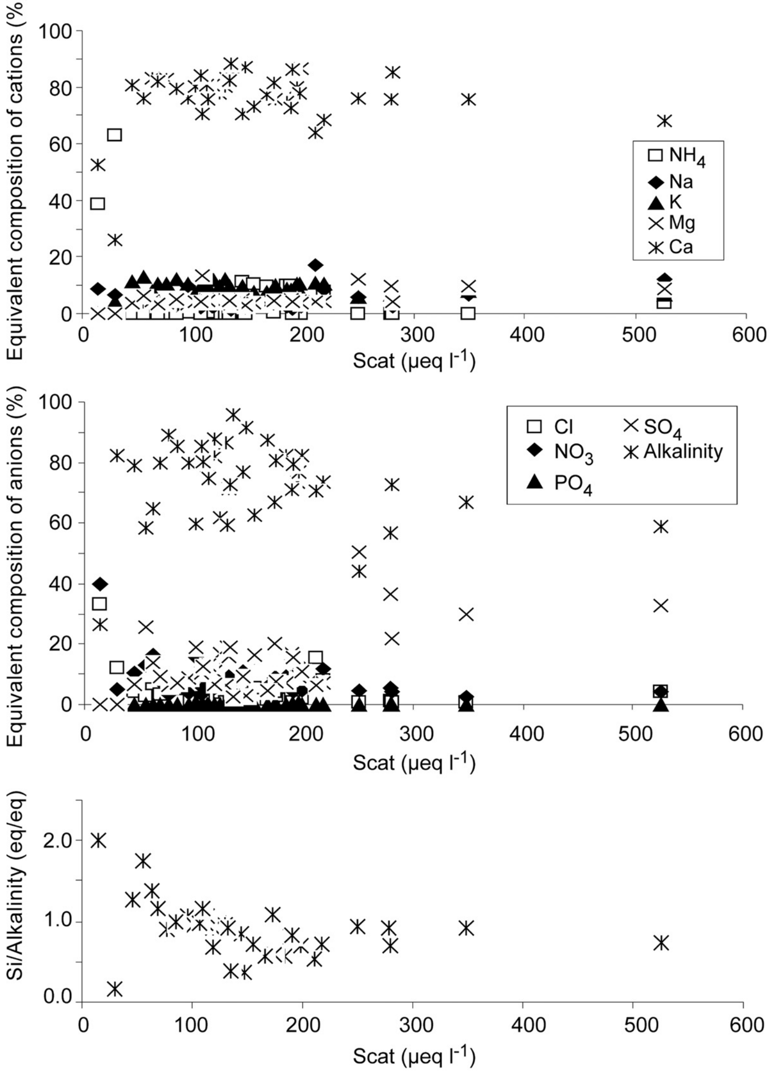

Fig. 4. Equivalent compositions of cations (%), those of anions (%) and silicon to alkalinity ratio (eq/eq) versus sum of cations in pond water within the debris area of Lirung Glacier in Nepal Himalaya for the pre-monsoon (left), monsoon (middle) and post-monsoon (right) periods in 1996.

peratures during the monsoon to post-monsoon period.

The relationships of equivalent compositions of cations and anions and Si/Alkalinity ratio with the sum of cations of the discharge waters at the outlet were very consistent throughout the observed period from May to October 1996 (Bhatt *et al.* 2000) suggesting the same geochemical processes occurring within the basin, however concentration vary and their average values are slightly higher than pond water samples except the clear isolated pond, Pond 2 (Fig. 4). The data used in this paper from Bhatt *et al.* (2000) is for the comparison purpose that helps to understand the basic geochemical processes within the debris covered Lirung glacier in central Nepal Himalaya. This paper will help to better understand the chemistry of pond waters within the debris area of the glaciers and to elucidate major geochemical processes occurring within the debris area. All these pond water compositions were different from the discharge waters except for a clear isolated pond 2 with higher sum of cations. Pond 1 flowed out directly to the outlet and should give the same composition as that of discharge water. The higher weathering products such as sum of cations, silica and alkalinity mainly as bicarbonate appeared in Pond 1, 2, 16, and 21 is probably due to higher runoff with abundant availability of fresh reactive minerals (Tab. 2). Silicate weathering rate enhanced because of the increased runoff production in the basin as a result of the glacier melt (Anderson *et al.* 1997). Pond 2 was the only clear isolated pond within the debris area and gives higher sum of cation value than that of the discharge waters in the pre-monsoon period with higher contribution of NH_4^+ and Cl^-. The concentrations of dissolved species were lower in the post-monsoon period, probably due to dilution by precipitation during the monsoon period. Contribution of chemical load from sea-salt aerosol was less in post-monsoon period than the pre-monsoon period. Sodium and chloride were greatly affected while calcium and sulfate were least affected by marine aerosol. Hydrolysis condition increased during monsoon period and accelerates the weathering rates.

Chemical composition and sum of cations of some ponds were relatively similar to those of the discharge waters and hence these ponds water might have connected to the main discharge flow of the glacier.

Based on the mineralogical facts, the major aluminosilicate weathering, sulfide oxidation coupled with calcite dissolution appeared as prime regulating factors of chemical species within the debris area of Lirung glacier in central Nepal Himalaya. The tight relationships of calcium with the alkalinity among all types of samples within the basin further suggest the calcium carbonate dissolution as the dominant source of calcium and alkalinity within the Lirung Glacier drainage basin

Tab. 2. Physical parameters and chemical concentrations of major chemical species of some pond water samples during post-monsoon season in 1996 within the debris area of Lirung Glacier.

Measured Parameters	Pond 1	Pond 2	Pond 16	Pond 21
Tw (ºC)	2.6	6.7	0.6	1.0
pH	8.0	7.6	8.3	7.9
EC (μS cm^{-1})	37	44	34	36
SS (mgl^{-1})	85	6	59	14
NH_4 (μeql^{-1})	0.0	0.0	0.3	0.2
Na (μeql^{-1})	22.6	23.0	15.2	7.5
*Na (μeql^{-1})	20.0	20.9	13.5	5.9
K (μeql^{-1})	18.7	27.9	14.7	22.6
*K (μeql^{-1})	18.6	27.9	14.7	22.6
Mg (μeql^{-1})	26.4	33.8	30.0	11.4
*Mg (μeql^{-1})	25.8	33.3	29.6	11.0
Ca (μeql^{-1})	211.0	263.8	189.8	238.6
*Ca (μeql^{-1})	210.9	263.7	189.7	238.5
Cl (μeql^{-1})	3.0	2.4	2.0	1.9
NO_3 (μeql^{-1})	13.7	7.7	10.2	10.0
PO_4 (μM)	0.00	0.00	0.00	0.02
SO_4 (μeql^{-1})	90.4	90.2	105.4	51.4
*SO_4 (μeql^{-1})	90	90	105	51
Alkalinity (μeql^{-1})	141	201	92	170
SiO_2 (μM)	32.5	46.1	21.5	29.4
Σanion (μeql^{-1})	248	348	210	234
Σcation (μeql^{-1})	279	348	250	280
SiO_2/Al_2O_3	3.80	3.74	3.71	3.49

Asterisks represent sea-salt corrected values. Tw = water temperature

(Fig. 5). The significant relationship ($R^2 = 0.71$; $P<0.0001$) between calcium and sulfate among the different types of ponds within the debris area of Lirung glacier further support the widely observed sulfide oxidation coupled with carbonate dissolution as a major geochemical process in mountain glaciers (Fig. 6). The ionic content of water in these ponds released primarily as a result of chemical weathering of rocks in the watersheds and similar result of high altitude lakes in the Khumbu and Imja valley in Nepal Himalaya was reported earlier by Tartari *et al.* (1998).

Based on these results, most pond waters with lower sum of cations except for Pond 1, 2, 16 and 21 are considered to be isolated from the main discharge water flow of the glacier. Each of these ponds might be formed by local melting of ice cliffs appeared on the surface of the debris area probably as a result of global warming. The similarity of chemical compositions among these turbid ponds with lower sum of cations and the difference of their chemical compositions from the main discharge water composition may suggest the difference in chemical weathering mechanisms between the dominant weathering processes of the glacier probably at the flowing ice body-bed rock interface and the weathering processes associated with the formation of ponds on the surface of debris-covered area of the glacier.

The weathering type occurring within the debris covered Lirung Glacier was evaluated by considering the chemical composition of feldspar to calculate the ratios of silica to alumina based on the chemical composition of discharge and pond waters (Tardy 1971). If the silica to alumina ratio is greater than two, the weathering type is considered to be bisiallitization, in which base cations are completely removed and a portion of the silica remains in situ with two silica layers per alumina. According to Tardy (1971) bisiallitization corresponds to the neoformation of minerals with two silica layers per alumina layer. The average ratios of silica to alumina were 3.73, 3.94, 3.66 and 3.83 respectively for the discharge water at the outlet, pond samples in pre-monsoon, monsoon and post-monsoon respectively indicating that the bisiallitization type of weathering occurred within the debris covered Lirung Glacier (Tab. 1). Bisiallitization weathering, in which two moles of Si are produced for each mole of alumina, occurred within the debris covered Lirung Glacier in Central Nepal Himalaya.

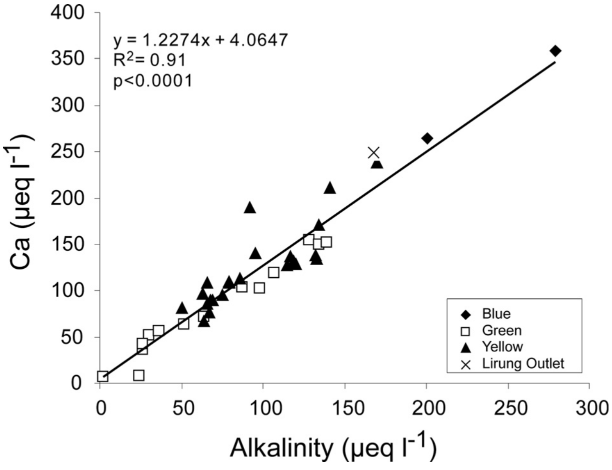

Fig. 5. Relationship between calcium and alkalinity in pond water samples within the debris area of Lirung Glacier from pre-monsoon to post-monsoon period in 1996. Average value of calcium and alkalinity of discharge water at the Lirung outlet sampled from May to October 1996 (Bhatt *et al.* 2000) is also shown.

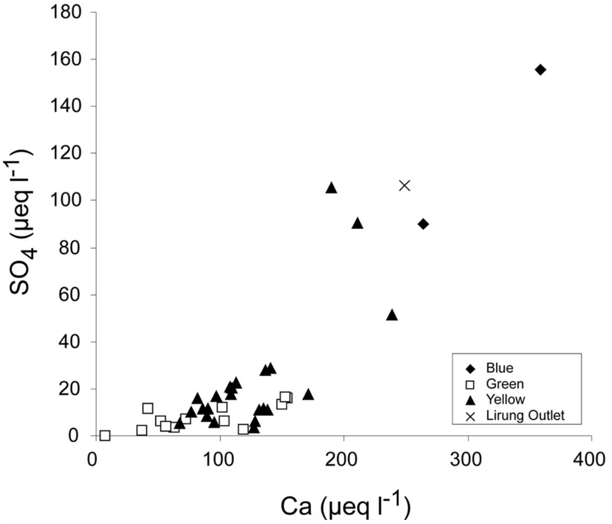

Fig. 6. Relationship between calcium and sulfate in pond water samples within the debris area of Lirung Glacier from pre-monsoon to post-monsoon period in 1996. Average value of calcium and sulfate of discharge water at the Lirung outlet sampled from May to October 1996 (Bhatt *et al.* 2000) is also shown.

5. CONCLUSIONS

Major chemical species were classified into three classes as conservative (SiO_2, Ca^{2+}, K^+, and Alkalinity), semi-conservative (Na^+, Mg^{2+}, and SO_4^{2-}) and non-conservative (NH_4^+, NO_3^- and Cl^-) based on their relationships relative to sum of cations. The chemical compositions of pond water were also dominated by sulfide oxidation coupled with carbonate dissolution and chemical weathering of aluminosilicate as indicated by the conservative and semi-conservative species. Sulphide oxidation coupled with carbonate dissolution within the subglacial drainage system has been widely observed in glacier meltwaters based on the evidence from the dominant chemical species like Ca^{2+}, alkalinity and SO_4^{2-}. Most of these pond waters having lower sum of cations than the discharge waters at the outlet were thought to be isolated from the main discharge water flow of the glacier. The spatial variability in chemical composition of pond waters within the debris area of the Lirung Glacier was probably due to the difference in chemical weathering mechanisms associated with other regulating factors within the basin. Variability of fresh reactive minerals and water temperature appeared as a prime factor for the spatial variability in chemistry among the pond types within the debris area of the glacier. Solutes as well as alkalinity appeared higher among all types of ponds during the monsoon season than pre-monsoon and post-monsoon season support that increased hydrolysis condition has strong role to accelerate chemical weathering rates. Global warming may have played an important role for the formation of these ponds within the debris area of the Lirung glacier in central Nepal Himalaya.

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