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ORIGINAL PAPER

Major Ion Geochemistry of Nam Co Lake and its Sources, Tibetan Plateau

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Abstract The major cations and anions from lake water samples and its sources, including glacier snow, precipitation, stream, and swamp water in the Nam Co basin, central Tibetan Plateau, were studied. The concentrations of the major ions varied significantly in the five environmental matrices. Generally, the mean concentrations of most ions are in the order of lake water > swamp water > stream water > precipitation > snow. Rock weathering is the dominant process controlling the chemical compositions of the stream and swamp waters, with carbonate weathering being the primary source of the dissolved ions. The Nam Co lake water is characterized by high Na^+ concentration and extremely low Ca^{2+} concentration relative to other ions, resulting from evapoconcentration and chemical precipitation within the lake. Comparison with the water chemistry of other lakes over the Tibetan Plateau indicated that Nam Co is located in a transition area between non-saline lakes and highly saline lakes. The relatively low concentration of total dissolved solids is possibly due to the abundant inflow of glacial meltwater and relatively high annual precipitation.

Keywords Nam Co · Tibetan Plateau · Alpine lakes · Major ion geochemistry · Water · Weathering

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1 Introduction

The Tibetan Plateau is the largest and highest plateau in the world, home to the tallest mountain range, the Himalaya, and the highest mountain, Mount Everest (Qomolangma). The plateau covers an area of about 2.5×10^6 km^2, with an average elevation of over 4,000 m. Formed by tectonic plate collisions in the Cenozoic period, the uplift of the plateau began at least 50 Myear ago and reached its present altitude 35–15 Myear ago (Rowley and Currie 2006). The uplift of the plateau has greatly modified global climate (Kutzbach et al. 1989) and influenced monsoon intensity (Molnar et al. 1993). Climatically, the plateau lies at a critical junction of three climatic systems: the Indian monsoon, the East Asian Monsoon, and the cold polar airflow from the Siberian high pressure system. The human population density is sparse, and industrial activities remain minimal across most of the plateau, making it one of most remote and "pristine" regions in the world. However, concerns have been raised in recent years over the habitat loss due to excessive pasturing and unsustainable development, chemical contamination due to long-range transport of contaminants, and wide-scale systemic changes due to global climate change, all of which are threatening the unique and fragile alpine ecosystems and Tibetan culture.

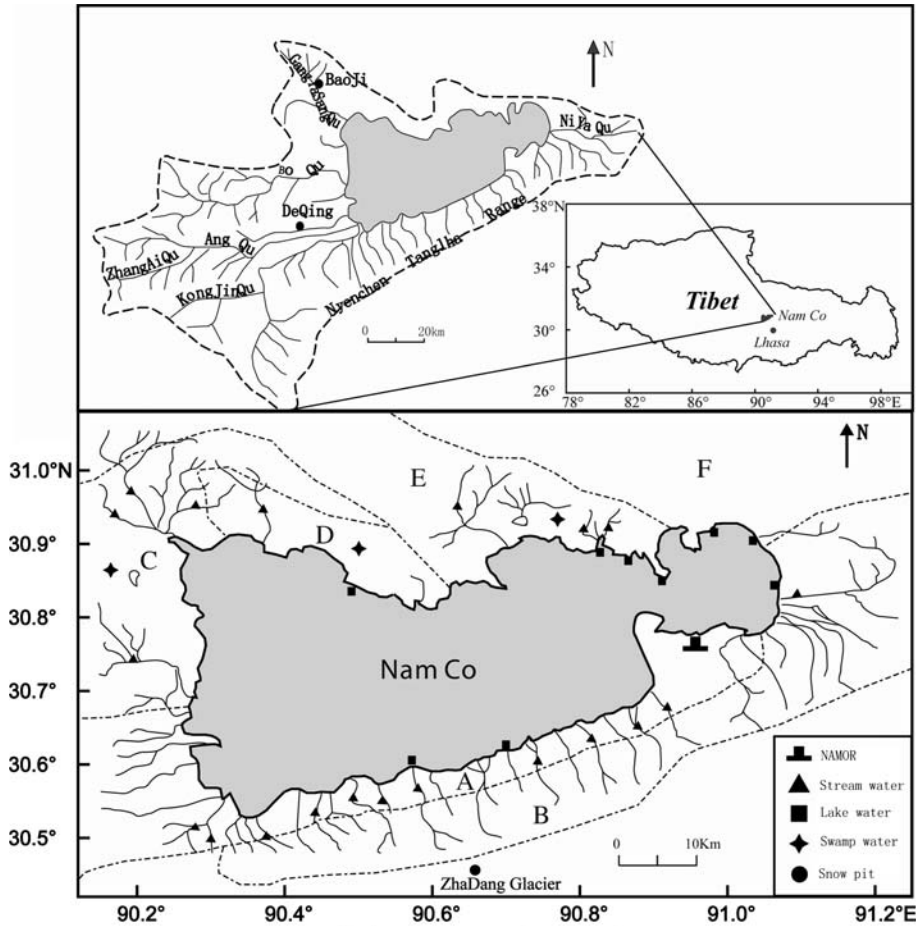
As the rooftop of the world, the Tibetan Plateau is the source of many major rivers in Asia, including the Changjiang (Yangtze River), Huanghe (Yellow River), the Yarlung Zangbu-Brahmaputra, and the Lancangjiang-Mekong. In addition to those large exorheic river systems that cut through the plateau, there are also a vast number of endorheic rivers and streams, most of which are seasonal and supplied by glacial meltwater and summer precipitation. These endorheic rivers and streams form more than 1,500 alpine lakes in the basins of the plateau. Whereas much scientific attention has been given to those exorheic rivers (e.g., Chen et al. 2002, 2005), few studies are available on the water quality and quantity and their evolution of the alpine lakes of the plateau.

In June 2005, the Nam Co Station for Multisphere Observation and Research (NAMOR) was established by the Chinese Academy of Sciences in the southeast shore of Nam Co (Lake Namtso) to thoroughly study the geology, hydrology, chemistry, biology, and ecology of the largest lake in Tibet. As a pioneer research supported by NAMOR logistic assistance, Li et al. (2007a) studied the major ionic chemistry of precipitation in this region and indicated that the geochemistry of atmospheric deposition is mainly influenced by the regional continental environment. However, studies on Nam Co water quality and related geochemical processes, though critical for understanding this unique alpine lake system, are yet absent. Here, we report the first study of the major ion geochemistry of Nam Co and its source waters. This article is aimed at (a) providing a baseline dataset of major ion concentrations in a Tibetan lake basin and (b) investigating the geochemical processes that control the major ion chemistry.

2 Study Area and Methods

2.1 The Nam Co Basin

Nam Co (30°30′–56′ N, 90°16′–91°03′ E; 4,718 m a.s.l.) is the largest lake in Tibet, the second largest saline lake on the Tibetan Plateau, and one of the highest large lakes in the world (Fig. 1). The lake has a surface area of 1,920 km^2 with a maximum depth of 122 m (Li et al. 2008). Located in the heart of the Tibetan Plateau, Nam Co drains a closed basin



A: Quaternary clay; B: Carboniferous carbonic rock;
C: Permian carbonic rock; D: Cretaceous Clastic rock and Carbonic rock;
E: Jurassic clastic rock and carbonic rock; F: Magma Rock.

Fig. 1 The Nam Co Basin showing the sampling sites

of about 1.06 × 10^4 km^2 isolated by the Gandise Range in the south, the Nyainqen Tanglha Range in the southeast, and the Northern Tibetan Plateau hills in the north.

The Nam Co Basin is located in a semi-arid to semi-humid area. The mean annual temperature is around −2 to 0°C (CAS 1982). The lake is ice-covered for 5 months, with a maximum ice thickness of 46 cm as observed by the Nam Co Station in 2007. The mean annual precipitation ranges from 300 to 410 mm (CAS 1982; Shao et al. 2004), and the mean annual evaporation is around 790 mm for the lake and 320 mm for its terrestrial basin (Zhu et al. 2004). Most of the precipitation occurs between June and October. As a closed-basin lake, the only loss of the water is through evaporation.

The major tributaries to the lake include the Angqu, Zhangaiqu, Gangyasangqu, Kongjinqu, and Niyaqu (Fig. 1). Most streams around the lake originate from high mountain glaciers. Streams in the south coast of Nam Co are short with steep falls, while streams in the west coast are relatively longer and flow through vast flat areas. The major supplies of these streams are glacial meltwater and precipitation. Wetlands are distributed mainly along the stream estuaries in the east and west coasts of the lake (Yuan et al. 2002).

The dominant soil type in the basin is alpine meadow soil. Most of the soils have a neutral to slightly alkaline pH (7–8) (Li et al. 2008). The basin is covered by alpine sedge mats consisting mainly of *Kobresia pygmaea* (Yuan et al. 2002). Geologically, the Nam Co basin is located on the Lhasa Terrain which was accreted during the Late Jurassic–Early Cretaceous, pervasively intruded by the Cretaceous–Tertiary Gangdese plutonic belt and overlain by volcanic rocks of equivalent age (Kapp et al. 2005). The southern and southeastern basins expose Cretaceous–Tertiary granitoids and orthogenises, Paleozoic to Cretaceous metasedimentary lithologies consisting of slate, phyllite, metaconglomerate, metalimestone, Cetaceous red sandstone, mudstone, and conglomerate, and Quaternary glacial, alluvial fan, fluvial, and lacustrine deposits (Kapp et al. 2005). The northern and western basins are underlain mainly by limestone, sandstone, quartz, and breccia. Some isolated broken hills stand close to the northeastern lakeshore; these hills are mainly composed of limestone, and some of the steeps are wave-eroded and developed into limestone caves. The bedrock geological setting of the Nam Co basin is shown in Fig. 1.

There are no industrial activities or urban development within the Nam Co basin, except for some small Tibetan villages. The basin is, however, a popular pasturing area. Degradation and desertification have been reported in the Pelgon County north of the lake due to natural causes and excess pasturing (Yuan et al. 2002).

2.2 Sampling and Sample Analysis

Stream, swamp, and Nam Co Lake surface water samples were collected in August and September, 2005, throughout the Nam Co Basin (Fig. 1) for the analysis of major cations and anions.

A total of 48 precipitation samples were collected on NAMOR during August 2005–July 2006. A 152-cm deep snow pit was sampled at 5 cm intervals on May 21, 2006 at the col of the Zhadang glacier (5,800 m a.s.l.), 50 km southwest of the station (Fig. 1). The major ion chemistry of the precipitation and snow pit samples have been reported and discussed by Li et al. (2007a), and here, we incorporated the data of mean ionic concentrations into this article to impel the discussion. Stream, swamp, and lake surface water samples were collected in pre-cleaned polyethylene bottles at sites shown in Fig. 1. The bottles were rinsed three times with sample water. Great caution was taken to minimize potential contamination during the sampling process.

All the samples were kept frozen and immediately transported to the laboratory of the Institute of Tibetan Plateau Research, CAS. Upon arrival in the lab, all the samples were melted at the room temperature and analyzed for major ions. Analysis of major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+, and NH_4^+) was carried out by ion chromatography (IC) using a Dionex ISC 2000 ion chromatograph, an IonPac CS12A column, 20 mM methanesulfonic acid (MSA) eluent, and CSRS suppresser. Major anions (Cl^-, NO_3^-, and SO_4^{2-}) were analyzed by Dionex ISC 2500 ion chromatograph, using an IonPac AS11-HC column, 25 mM KOH eluent, and ASRS suppresser. The detection limits were 1 $\mu g\ l^{-1}$ for all ions and analytical precision was within 5%. Analysis of field blanks showed that contamination during the sampling procedure, transportation, and treatment were not significant.

The alkalinity was calculated by the difference between the sum of all the cations and that of the anions (in equivalents). Since the pH of stream and swamp water are generally lower than 8.8, CO_3^{2-} can be neglected. However, the pH of lake water (around 9.4) is highly alkaline (Li et al. 2008), hereby the contribution of CO_3^{2-} in the alkalinity cannot be neglected. The concentrations of HCO_3^- and CO_3^{2-} in lake water are calculated from the total carbonate concentration based on the following equation:

$$HCO_3^- = CO_3^{2-} + H^+; \quad \log K_{a2} = -10.33$$

Assuming the pH of all lake samples is 9.4, the HCO_3^- and CO_3^{2-} should account for ~89.5% and ~10.5% of total carbonate (Qian and Ma 2005). The concentration of the total dissolved solids (TDS) was calculated by summing up all the ions including the estimated concentration of HCO_3^- and CO_3^{2-}.

3 Results and Discussion

The dissolved ions were present in a wide range of concentrations in the five environmental matrices (Table 1). In general, the mean concentrations of most ions are in the order of lake water > swamp water > stream water > precipitation > snow.

3.1 Chemistry of the Atmospheric Precipitation

The TDS of precipitation and glacier snow in the Nam Co Basin is very low, compared with that of stream, swamp, and lake waters. The cations are dominated by Ca^{2+}, and anions by HCO_3^-. As suggested by Li et al. (2007a), major ion concentrations in precipitation were higher than those in snow pit samples, due to the relatively higher local aerosol inputs (Cong et al. 2007). The precipitation chemistry in the Nam Co basin is mainly influenced by the regional environment, dominated by crustal dust aerosols. Wind blown lake salt aerosols also affect precipitation chemistry, especially in summer. Sea salt contribution is the least due to the long distance of transport.

3.2 Stream and Swamp Water

Stream and swamp waters in the Nam Co basin showed similar major ion compositions (Table 1). On an equivalence basis, Ca^{2+} and Mg^{2+} were the dominant cations, accounting for ~86% of total cations in stream water and ~87% in swamp water; Ca^{2+} alone accounted for 63% and 67% of total cations in stream and swamp water, respectively. Anions were dominated by HCO_3^- and SO_4^{2-} which constituted ~98% of total anions in stream water and ~97% in swamp water; HCO_3^- alone accounted for 82% and 91% of total anions in stream and swamp water, respectively. When pooling stream and swamp waters together, HCO_3^- correlated significantly with Ca^{2+} and Mg^{2+} ($r = 0.95$ and 0.84, respectively), and a close correlation was also found between Ca^{2+} and Mg^{2+} ($r = 0.81$).

The weathering of rock-forming minerals, with a minor contribution from atmospheric and anthropogenic sources, is the major source of dissolved ions in most aquatic systems (Stallard and Edmond 1983). Gibbs (1970) suggested that a simple plot of TDS versus the weight ratio of $Na^+/(Na^+ + Ca^{2+})$ could provide information on the relative importance of three major natural mechanisms controlling surface water chemistry: (1) atmospheric precipitation; (2) rock weathering, and (3) evaporation and fractional crystallization. The composition of the swamps and most streams in the Nam Co drainage basin falls in the rock-weathering domain, suggesting that their chemical compositions are mainly

Table 1 Major ion concentrations (μeq l^{-1}) of water samples in the Nam Co Basin

Samples	Date	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	NO_3^-	SO_4^{2-}	Alkalinity	TDS (mg l^{-1})
Precipitation	8/05–7/06	15.4	18.1	14.5	7.4	65.6	19.2	10.4	15.5	76.0	9.2
Snow pit	5/26/06	4.7	9.3	1.4	3.1	34.7	4.6	4.0	5.2	39.5	4.1
Streams											
R2	9/09/05	41.2	0.8	9.1	526	911	3.2	12.3	500	973	110
R3	9/09/05	373	6.3	34.4	780	1,680	18.7	13.9	905	1,940	216
R4	9/09/05	92.1	0.9	13.2	45.7	236	4.0	11.8	53.3	319	30.8
R5	9/09/05	41.6	10.9	9.8	34.4	205	4.7	8.8	90.1	198	23.2
R6	9/09/05	73.8	1.1	17.3	65.1	432	3.4	11.8	128	446	46.0
R7	9/09/05	71.1	3.0	21.3	43.1	322	3.6	4.7	137	315	35.7
R8	9/09/05	39.2	1.2	10.6	50.0	198	2.5	8.0	24.9	264	23.7
R10	9/09/05	188	14.2	24.7	148	312	37.6	6.6	101	542	53.2
R11	9/09/05	51.7	1.7	11.8	51.2	574	2.9	13.4	205	469	53.2
R13	9/09/05	155	2.8	14.0	139	649	13.1	10.3	88	848	75.8
R14	9/09/05	368	4.5	30.7	510	1,000	37.6	6.8	182	1,690	149
R16	9/09/05	370	3.6	22.9	669	1,140	44.1	15.3	208	1,940	171
R17	9/10/05	172	6.2	10.8	528	1,100	24.8	10.9	317	1,460	139
R18	9/10/05	406	9.3	23.8	553	1,650	26.8	17.3	116	2,480	209
R19	9/10/05	114	3.5	6.9	609	1,320	9.3	17.9	476	1,550	156
R20	9/10/05	393	12.6	34.0	373	1,210	29.8	2.2	101	1,890	160
R22	9/10/05	244	9.1	21.7	398	1,520	15.0	0.6	112	2,070	174
R23	9/10/05	165	18.8	18.4	223	772	29.9	7.6	161	1,000	93.1
R24	9/10/05	70.8	10.8	8.0	480	964	5.3	7.9	152	1,370	119
R27	9/10/05	63.5	9.2	10.3	359	1,510	3.3	10.8	414	1,530	150

Table 1 continued

Samples	Date	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	NO_3^-	SO_4^{2-}	Alkalinity	TDS (mg l^{-1})
Swamps											
Z1	9/10/05	109	16.7	7.8	149	1,260	15.3	7.0	44.5	1,480	123
Z2	9/10/05	414	14.4	18.1	561	1,500	43.6	46.5	234	2,180	195
Z5	9/10/05	106	16.5	6.2	372	957	15.7	5.6	87.7	1,350	114
Nam Co											
L1	9/09/05	6,990	16.6	473	3,510	273	1,180	24.0	2,800	7,260	784
L2	9/09/05	6,760	15.4	443	3,430	342	963	3.5	2,420	7,600	769
L4	9/10/05	6,840	17.0	442	3,870	301	958	4.0	2,400	8,110	801
L5	9/10/05	7,530	21.6	533	3,520	340	1,380	2.3	3,300	7,260	830
L6	9/10/05	8,170	20.7	579	3,770	271	1,540	3.2	3,680	7,590	890
L7	9/10/05	7,100	15.7	486	3,540	321	1,210	5.7	3,120	7,130	796
L8	9/10/05	8,140	17.9	524	4,370	327	1,150	2.1	2,900	9,330	935
L9	9/10/05	10,100	21.4	672	5,340	363	1,470	3.0	3,660	11,400	1,150
L10	9/10/05	6,700	19.9	497	3,230	215	1,340	2.6	3,110	6,210	738

Notes: Data for precipitation and snow pit are cited from Li et al. (2007a). The alkalinity was calculated from a charge balance between all the other cations and anions

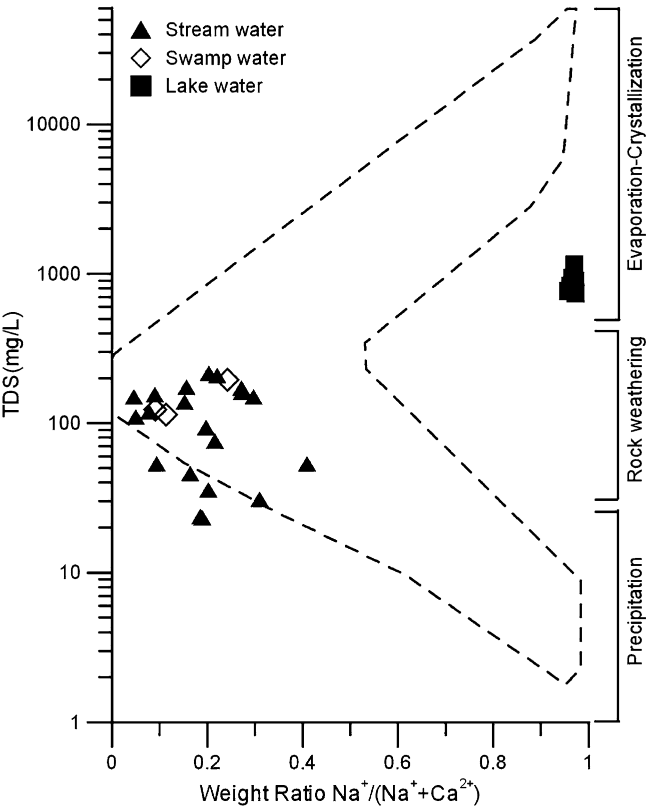


Fig. 2 Plot of TDS versus weight ratio of $Na^+/(Na^+ + Ca^{2+})$ of water samples in the Nam Co basin (after Gibbs 1970)

controlled by rock weathering (Fig. 2). A few stream water samples fall outside the boomerang region that encompasses most surface waters in the world. These stream waters are characterized by relatively low TDS content due to their glacial meltwater source.

The dominant control of rock weathering in the major ion chemistry of the streams and swamps in the Nam Co basin provides a means of probing into the weathering reactions in the basin, as weathering of different parent rocks (e.g., carbonate, silicate) yields different combinations of dissolved cations and anions in solution (Garrels and Mackenzie 1971; Stumm 1992). The high concentration of HCO_3^- and its positive correlation with Ca^{2+} and Mg^{2+} as discussed above indicate carbonate weathering as a major source of HCO_3^-, Ca^{2+}, and Mg^{2+}. Stoichiometrically, the carbonate weathering reactions demand that carbonate-derived Ca^{2+} and Mg^{2+} should be equal to the carbonate-derived HCO_3^-. A plot of $(Ca^{2+} + Mg^{2+})$ versus HCO_3^- (Fig. 3a) shows that in most stream and swamp samples, $(Ca^{2+} + Mg^{2+})$ is close to HCO_3^- with an average equivalent ratio of 1.08. The average equivalent ratios of Ca^{2+}/HCO_3^- (0.8) and $(Ca^{2+} + Mg^{2+})/(HCO_3^- + SO_4^{2-})$ (0.9) are also close to 1, indicating these ions likely resulted from corresponding carbonates (e.g., calcite and dolomite) and sulfates (e.g., gypsum). Na^+ and K^+ are most likely derived from sulfate minerals and silicates. The $(Ca^{2+} + Mg^{2+})$ versus total cations (Fig. 3b) show that most of the points are close to the equiline, i.e., 1:1 with an average

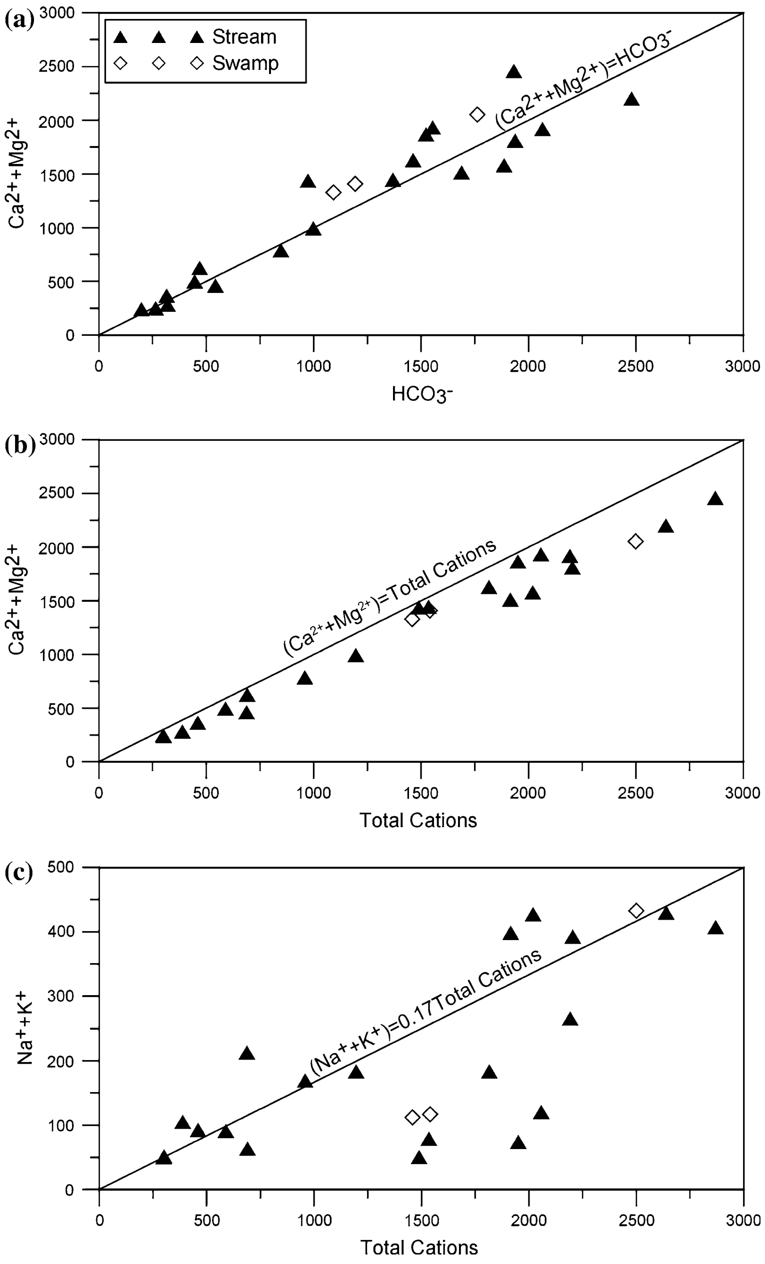


Fig. 3 Scatter diagram between (**a**) ($Ca^{2+} + Mg^{2+}$) versus HCO_3^-; (**b**) ($Ca^{2+} + Mg^{2+}$) versus total cations; and (**c**) ($Na^+ + Ca^{2+}$) versus total cations (Unit: μeq l^{-1})

ratio of 0.85. The relatively high contribution of ($Ca^{2+} + Mg^{2+}$) to the total cations and the very low contribution of ($Na^+ + K^+$) to the total cations (Fig. 3c) suggest that carbonate weathering is the major source of the ions, while the contribution from silicate weathering is minor (Pandey et al. 1999; Sarin et al. 1989). To study the relative importance of two major proton-producing reactions—carbonation and sulfide oxidation, the equivalent ratio of ($HCO_3^-/HCO_3^- + SO_4^{2-}$), called the C-ratio (Brown et al. 1996), is calculated. Generally, a C-ratio of 1.0 would signify carbonic acid weathering involving pure dissolution and acid hydrolysis, consuming protons come from atmospheric CO_2. Conversely, a ratio of 0.5 would suggest coupled reactions involving the weathering of carbonates by protons derived from sulfide oxidation. For the stream and swamp waters in the Nam Co basin, the C-ratio is always higher than 0.6, signifying that carbonic acid weathering is the major proton producer.

The dominant role of carbonate weathering in controlling chemical composition of inflow waters is further supported by the wide distribution of carbonate rocks in the Nam Co basin (Fig. 1).

3.3 Lake Water

The major ion composition of the Nam Co lake water is characterized by HCO_3^- and SO_4^{2-} as the dominant anions, and Na^+ and Mg^{2+} as the dominant cations; Ca^{2+} was extremely low compared with other cations. On an equivalence basis, Na^+ accounted for ~62% of total cations and HCO_3^- accounted for ~65% of total anions. Furthermore, low standard deviations of major ion concentrations indicate the lake surface water was mixed well. The result is in general agreement with the previous survey conducted by Zhao et al. (2003), which reported that all the soil samples around the lakeshore were carbonate-rich sandstone and conglomeration.

Dissolved salts in the lake water can be derived from a variety of physical, chemical, and biological processes in the drainage basin. Three sources have been named by Berner and Berner (1996) as the possible causes of dissolved salts into the lake waters, which include (1) sea salts carried by the atmospheric transport and deposited in lakes, (2) weathering of silicate, carbonate, evaporite, and sulfide minerals in the drainage basin, and (3) anthropogenic input. As discussed earlier, the contribution of sea salts to ion composition of precipitation is of least importance due to the long distance transport. This, together with the very low annual precipitation rate (300–410 mm), suggests that the sea salts play a negligible role in the ion composition of the Nam Co lake water. Anthropogenic impact is also minimal, due to the sparse population and almost non-existent industrial activities in the area. Additionally, airborne substances and underground water can also contribute to the ionic load in the lake. Although no data is available, we suspect their contributions are minor. The geochemical evolution in evaporative lakes without river outlets is primarily controlled by inflow composition, selective removal processes of dissolved species, and concentration processes in the lake basin (Yan et al. 2002). Inflow streams around Nam Co are the major supply of the lake water and thus contribute most of the ionic load of the lake water. Compared with the stream and swamp waters in the basin, the Nam Co lake water is characterized by the enrichment of Na^+ and depleted in Ca^{2+}. The enrichment of Na^+ in lake water has been observed in many evaporative lakes in Tibetan Plateau (e.g., Wang and Dou 1998; Yang et al. 2003). The mean annual evaporation in Nam Co basin is approximately 790 mm (Zhu et al. 2004), which is twice the mean annual precipitation. In addition, the water balance of Nam Co in the last 15 years was negative as estimated by the records of lake sediment (Mügler et al. 2008). Salinity in Nam Co lake water has been increasing in the last 200 years and has experienced an intensive increase since the middle of 1960s, as inferred from the increasing trend of the lake water conductivity, which is reconstructed based on its relationship with the diatom in the lake sediments. This is mainly due to the significant evaporation resulting in the negative water balance (Wang et al. 2006). Therefore, we conclude that the enrichment of Na^+ is mainly due to the evapoconcentration. The depletion of Ca^{2+} is another notable characteristic of lake water, most likely due to the selective removal processes operating in the lake (e.g., Banks et al. 2004). Since Nam Co lake water has reached a high pH and salinity, the mineral precipitation (such as bio-induced Ca-carbonate) would be the most important selective removal process (Yan et al. 2002). This is supported by the study carried out by Li et al. (2008), in which carbonates are the major components of the lacustrine sediments from Nam Co. Additionally, the lake sediment is enriched of monohydrocalcite, which is linked to an alkaline environment and the presence of bacteria, algae, diatoms, and ostracodas (Li et al. 2008). The calculation of saturation indices (1–1.2) of calcite also signify that lake waters are significantly supersaturated with respect to calcium carbonate, indicating that the HCO_3^- concentrations are high enough to facilitate carbonate mineral precipitation. Thus, the depletion of Ca^{2+} in the lake water is likely due to its removal by carbonate precipitation and biological activities.

Table 2 compares major ion concentrations between Nam Co and other lakes over the Tibetan Plateau. Lake Duoqing Co, Pumoyong Co, Chen Co, Kongmo Co, and Yanzho are located in the southern Tibetan Plateau, Lake 1/2, Buji Co, Hang Co, Cuoe, Cuomorong, and Seling Co are close to Nam Co, while Lake Qinghai, Qingshuihu, Kusaihu, and Tuosuhai lie in the northern part of the Tibetan Plateau. TDS in the Nam Co water is low–intermediate among all the lakes. Generally, lakes with higher TDS have Na^+ and Cl^- as the dominant ions, while Ca^{2+} and SO_4^{2-} are the major ions in lakes with lower TDS. Ion composition patterns vary with TDS, while TDS tends to increase with the latitude. Southern lakes contain mostly fresh water with lower TDS, while northern lakes tend to be alkaline with higher TDS. It has been recognized (CAS 1982) that on large scale, there is a climatic pattern transition from warm-wet to cold-dry from the south to the north over the Tibetan Plateau, mainly resulting from the precipitation gradient induced by the decreasing influence of the Indian summer monsoon. Thus, lakes exhibit transitions in the order of fresh water lakes–saline lakes–highly saline lakes (CAS 1984). Nam Co is geographically located in the transition area between non-saline lakes and highly saline lakes, and accordingly displays intermediate TDS. Nevertheless, local climatic conditions and environment within basins play a significant role on geochemistry of lake water. TDS in Nam Co is relatively low compared with the nearby lakes. This is possibly due to the abundant inflow supplies from glacial meltwater (CAS 1984) and relatively high annual precipitation.

3.4 Ions Evolution in the Nam Co Lake Basin

Ternary diagrams of cations and anions (Fig. 4) were plotted to evaluate the evolution of solutes from the glacier snow to streams and to lake water in the Nam Co basin.

As shown in Fig. 4, Ca^{2+} is abundant in the glacier snow, due to the dry deposition of dust aerosols on the glacier surface, especially during winter and spring (Li et al. 2007a). Meanwhile, calcium is the major element in the aerosols collected in the glacier area in the Nam Co basin even during summer season as suggested by Li et al. (2007b). The relative abundance of TDS experienced a sharp increase during its evolution from the glacier snow to the stream water (Table 1), due to the release of solutes from the stream beds. This is understandable because the relative ionic abundance increases rapidly during its evolution from glacier snow to proglacial water (e.g., Fortner et al. 2005). Besides, streams were

Table 2 Major ion concentrations in lake water from the Tibetan plateau

Lake name	Latitude (°N)	Longitude (°E)	Altitude (m a.s.l.)	Area (km^2)	TDS (mg l^{-1})	K$^+$ (μeq l^{-1})	Na$^+$ (μeq l^{-1})	Ca^{2+} (μeq l^{-1})	Mg^{2+} (μeq l^{-1})	Cl$^-$ (μeq l^{-1})	SO$_4$$^{2-}$ (μeq l^{-1})	HCO$_3$$^-$ (μeq l^{-1})
Nam Co[a]	30.72	91.66	4,718	1,920	855	517	7,600	306	3,840	1,240	3,040	6,480
Duoqing Co	28.15	89.35	4,485	60	930	230	6,742	1,098	5,842	1,410	6,267	4,228
Pumoyong Co[b]	28.63	90.38	5,030	1,233	207	–	–	–	–	–	–	–
Chen Co	28.94	90.52	4,438	39	1,250	389	7,368	5,364	4,295	305	15,530	2,503
Kongmo Co	29.02	90.41	4,446	40	310	230	957	2,246	741	85	1,770	2,262
Yanzho	29.12	90.44	4,462	638	1,030	230	4,741	150	11,027	1,833	3,248	6,998
Lake 1	30.678	90.856	4,718	0.5	240	46	270	4,880	1,498	37	96	1,813
Lake 2	30.679	90.854	4,712	0.5	170	43	470	1,287	2,214	14	42	1,621
Buji Co	30.83	90.20	4,790	1.1	2,330	2,573	22,906	389	3,752	8,121	6,681	13,068
Hang Co	31.32	91.79	4,370	2.7	700	506	8,017	768	1,720	386	427	3,778
Cuoe	31.47	91.51	4,515	61	14,120	230	185,996	10,429	19,091	57,992	101,460	25,059
Cuomorong	31.62	92.07	4,410	3.6	1,050	143	8,221	339	8,558	96	1,697	6,297
Seling Co[c]	31.76	88.95	4,530	1,640	18,540	–	–	–	–	–	–	–
Qingshuihu	35.41	93.64	4,450	2.9	5,120	1,123	67,004	135	6,776	10,168	62,019	1,583
Kusaihu	35.69	92.94	4,475	254	13,650	3,422	193,660	150	5,686	31,354	160,870	1,354
Lake Qinghai[d]	36.89	100.19	3,169	4,260	14,380	4,051	172,739	650	66,500	148,101	49,583	19,672
Tuosuhai	37.17	96.97	2,797	166	35,430	281	413,706	3,693	180,868	403,407	164,172	17,110

[a] This study; [b] Ju et al. (in press); [c] Wang and Dou (1998); [d] LIZIG (1979); others: Yang et al. (2003)

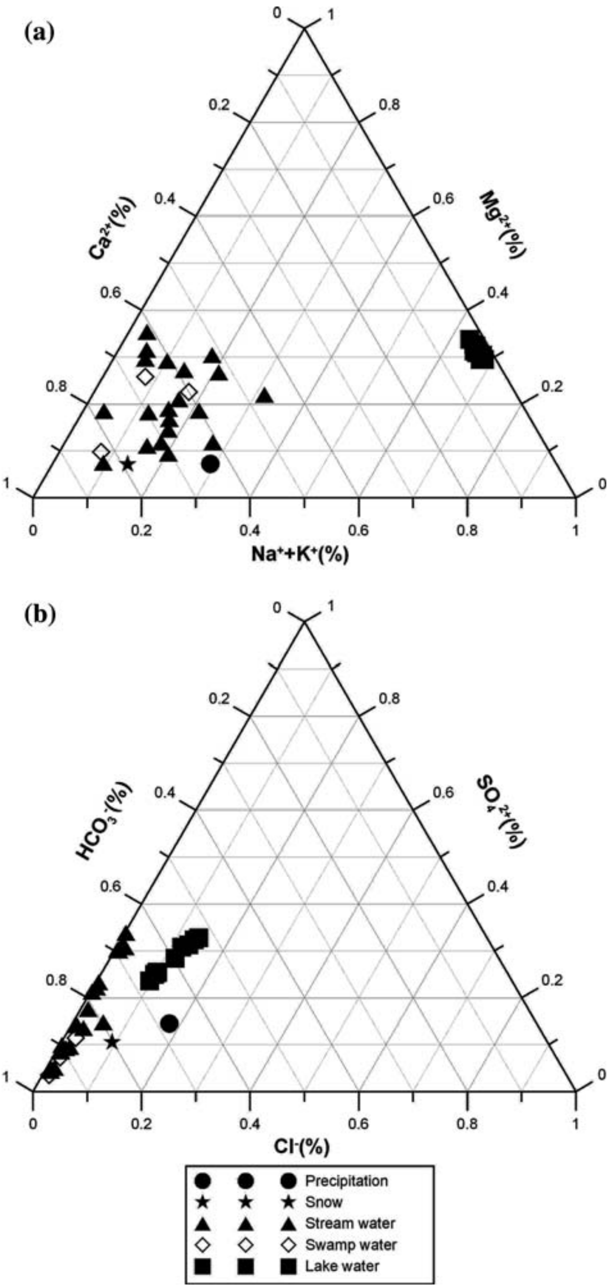


Fig. 4 Ternary plot of percentage equivalents of cations (**a**) and anions (**b**) in samples from the Nam Co Basin

mostly sampled in the lower reaches and downstream variations of ionic load generally display an increase trend (e.g., Singh and Hasnain 2002). The runoff is rich in Ca^{2+} and Mg^{2+} before it empties into the lake where their concentrations decrease due to the

Table 3 Summary of the major ion geochemistry in the Nam Co basin

Sample types	Dominant ions	Major sources	Geochemical processes
Atmospheric precipitation	Na^+, HCO_3^-	Local dusts and aerosols, lake salts	Influence of local environment
Stream and swamp water	Ca^{2+}, HCO_3^-	Glacial meltwater, release of ions from stream bed, and precipitation	Rock weathering, especially carbonate weathering
Lake water	Na^+, HCO_3^-	Inflow and precipitation	Evapoconcentration and chemical precipitation

chemical precipitation in the lake. On the contrary, Na^+ and K^+ are relatively low in the stream water but are the dominant cations in the lake water due to the evapoconcentration and the Ca^{2+} removal. The ternary diagram of anions, however, shows relatively little difference in various waters due to the predominance of HCO_3^- in all the waters. The relative abundance of HCO_3^- increases when the meltwater flows through the bedrocks, resulting from the rock weathering as discussed earlier. The relative abundance of SO_4^{2-} and Cl^- increases during the evolution of stream to lake water, signifying the salinity trend of lake water.

4 Conclusions

This study represents the first effort in establishing a database for the major ion concentrations of the Nam Co lake and its sources. The mean concentration of almost all the major ions in the various environmental matrices is of the order lake water > swamp water > stream water > precipitation > glacier snow. The major ion geochemistry of various water matrices are summarized in Table 3. The geochemistry of the atmospheric precipitation in the Nam Co area is predominantly influenced by the regional crustal aerosols. Chemical compositions of stream and swamp waters are controlled by rock weathering particularly by the weathering of carbonates which is abundant in the basin. The lake water is characterized by enrichment of Na^+ and depletion in Ca^{2+}, due to the evapoconcentration effect and Ca^{2+} removal by chemical precipitation and biological activities.

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