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Patterns in solute chemistry of six inlet streams to Lake Hövsgöl, Mongolia

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A number of characteristics of the Lake Hövsgöl watershed, such as the lake's location at the edge of the Central Asian continuous permafrost zone, provide a unique opportunity to evaluate possible anthropogenic impacts in this remote area in northern Mongolia. In this study, we compared stream solute concentrations in six sub-watersheds in the Lake Hövsgöl watershed. Water samples were collected during the summer months between 2003 and 2005. Concentrations of Cl^- ranged from 9.8 to 51.3 μmol/L; average nitrate concentrations were very low and ranged from undetectable to 1.1 μmol/L and average SO_4^{2-} concentration at sampling stations with minimal animal grazing ranged from 66 to 294 μmol/L. Average dissolved organic carbon (DOC) concentrations ranged from 642 to 1,180 μmol C/L. We did not find statistically significant differences in DOC concentrations among the six streams, although DOC concentrations tended to be higher in the two northernmost streams, possibly related to differences in the active layer above the permafrost. Dissolved organic nitrogen (DON) concentrations were correlated with DOC concentration, and followed the same spatial pattern as those for DOC. In streams in this remote watershed, total dissolved nitrogen was made up of mostly organic N, as has been found for other regions distant from anthropogenic N sources. Overall, these results suggest that future research on the dynamics of DOC and DON in this watershed will be especially insightful in helping to understand how changes in climate and land use patterns will affect transformations, retention, and export of dissolved organic matter within these sub-watersheds in the Lake Hövsgöl region.

Key words: dissolved organic matter, grazing, Lake Hövsgöl, permafrost, watershed

INTRODUCTION

Mongolia has one of lowest population densities in the world (2 individuals/km^2) (United Nations Population Division 2006). Lake Hövsgöl is one of the most important sources of freshwater in Mongolia, holding about 70 percent of its surface freshwater. Lake Hövsgöl is a large and deep tectonic lake (surface area = 2,760 km^2, z_{max} = 262 m) and is part of the Baikal Rift system (Goulden et al. 2006). The lake's watershed occupies an area of 4,920 km^2; the outflow from the lake, the Eg River, flows eastward into the Selenge River and into Lake Baikal. An important his-

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torical characteristic of Lake Hövsgöl and its watershed has been the general absence of anthropogenic impacts, resulting in pristine water quality. Recently, however, there has been increasing concern regarding the impacts of livestock grazing and climate change in the watershed. More than 90 streams enter Lake Hövsgöl, but only between 20 and 25 of these have substantial discharge (Myagmarjav and Davaa 1999). Further details on Lake Hövsgöl and its watershed are in Goulden et al. (2006).

The Lake Hövsgöl watershed is at the southern edge of the Central Asian continuous permafrost zone (Brown et al. 1995). The major biomes in the watershed are taiga forest and steppe grassland. Permafrost commonly occurs in the watershed but varies spatially. Trends in climate and changes in permafrost in the watershed are similar to results from other studies showing warming and thawing of permafrost in northern latitudes (Osterkamp and Romanovsky 1999, Osterkamp and Jorgenson 2006).

Compared to the western side of the basin, the streams on the east side of the lake are larger and have more continuous flow into the lake. As part of a comprehensive long-term biogeochemistry research program, we selected six stream valleys on the eastern shore of Lake Hövsgöl in which to monitor stream solute chemistry. This paper summarizes some patterns in spatial variation in stream chemistry and the influence of watershed characteristics that may affect patterns in solute chemistry of inlet streams to Lake Hövsgöl. Understanding patterns in other watershed attributes and whether they are related to differences in livestock grazing pressure is an important focus of ongoing research in the watershed. Thus increased understanding of the biogeochemistry of Lake Hövsgöl and continued monitoring are needed to better evaluate the effects of climate change and other anthropogenic disturbances.

MATERIALS AND METHODS

Study area

The Lake Hövsgöl watershed (Fig. 1) is located in a remote region of Mongolia and hence there were considerable challenges for conducting all aspects of this study including sample collection and analyses. However, the importance of this region, not only to Mongolia but also to East Asia as a whole, and its unique situation with respect to nomadic grazing and climate change, make it imperative to continue the ongoing efforts in research, training, establishing an ecological database, and beginning to understand hydrology and biogeochemistry of this watershed (Tsogtbaatar and Goulden 2000).

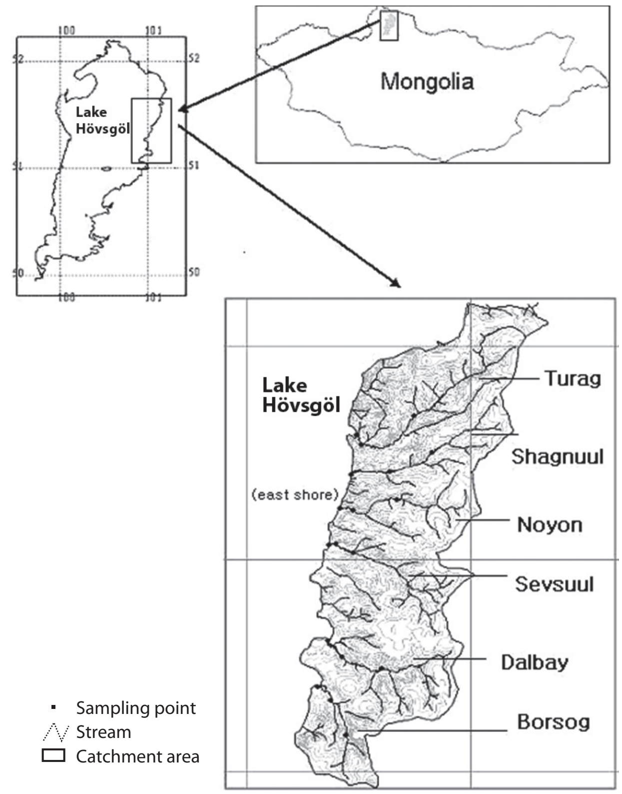

Fig. 1. Map showing location of the Lake Hövsgöl watershed and streams in this study.

There is considerable variation in size and grazing intensity among the six sub-watersheds we studied (Table 1). The stream valleys ranged from the heavily grazed northern valleys, Turag and Shagnuul; central Noyon and Sevsuul with moderate grazing; and southernmost Dalbay and Borsog with little or no grazing pressure. Forest cover in this area is composed almost exclusively of larch (*Larix sibirica*), with very few other tree species present. Shrubs are abundant in the downstream area of each valley and the river channels are not always well defined while the upper areas of the sub-watersheds have steeper slopes and well defined stream channels. Mosses and cool season sedges such as *Kobresia sibirica* and *K. Bellardii*, which are characteristic of Mongolia's alpine tundra (Hilbig 1995), contributed most of the plant biomass in the riparian zone of the ungrazed Borsog and Dalbay valleys. *Carex duriuscula*, *Leymus chinensis*, *Potentilla anserine*, and *Plantago depressa*, indicators of overgrazing, are dominant species in plant communities in Sevsuul, Shagnuul and Turag valleys (Ariuntsetseg personal communication). Percent cover values for total lichens,

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moss, and plants varied among the sites, and ranged between 70 and 95 percent, but decreased with increased grazing intensity. The estimated bare ground cover generally showed the opposite pattern, and ranged from 60 to 6 percent.

Common bedrock types in the Lake Hövsgöl region include Pliocene basalts and Devonian granosyenite (Batkhishig 2006). The soils in the study watersheds have a range of pH values, from 5.1 to 7.0, a wide range of cation exchange capacities (9.3-70.8 meq/100 g), and a wide range of percent base saturation (38.3-82.9) (Table 2).

Climate

The Lake Hövsgöl watershed receives more than 70 percent of its annual precipitation from May to October, with winters being dry and very cold (typical mid-winter temperature < -20°C). The total annual precipitation during 2003 to 2005 ranged from 241 to 412 mm (average 308 mm), with most of the precipitation occurring during July and August. There is evidence that climate change may be occurring more intensively in northern Mongolia than in other regions of Mongolia (Namkhaijantsan 2006). For example, the number of precipitation days (at least 2 mm of precipitation) has increased, but the average annual precipitation has not increased significantly. There has been a significant decrease in the number of frost days, indicating significant winter warming, and a significant increase in extremely hot days (Nandintsetseg et al. 2007). The overall increase in ambient temperatures and the longer growing season is potentially increasing evapotranspiration rates in the Hövsgöl watershed.

Livestock inventory

Livestock numbers in the sub-watershed during the study period are shown in Table 3, and were used as the basis for assigning grazing intensity categories. Livestock in the grazed portions of the watershed included sheep, goats, yaks, cows, and horses. The number of livestock in the sub-watersheds decreased from north to south and provided a gradient of grazing intensity (highest in Turag and Shagnuul, moderate in Noyon and Sevsuul, and lowest in Dalbay and Borsog) that we examined the relationships to other variables including vegetation cover, permafrost, or indices of human activity in the sub-watersheds (Ariuntsetseg unpublished). The livestock survey also showed a general increasing trend in the

Table 1. Descriptive characteristics of sub-watersheds in the Lake Hövsgöl watershed: latitude, longitude, catchment area (km^2), forested area in watershed (km^2), elevation of upper reach sampling station (m), stream length (km), and grazing intensity

Site	Latitude (N)	Longitude (E)	Area (km^2)	Forested area (km^2)	Elevation of upper reach station (m)	Stream length (km)	Grazing intensity
Turag	51°17´	100°51´	218.9	80.2	1,696	38.4	High
Shagnuul	51°16´	100°56´	111.1	44.4	1,856	25.1	High
Noyon	51°13´	100°52´	130.4	66.7	1,756	21.4	Moderate
Sevsuul	51°09´	100°47´	142.9	95.8	1,674	22.1	Moderate
Dalbay	51°00´	100°49´	186.1	136.1	1,727	28.3	Low
Borsog	50°55´	100°45´	91.4	65.8	1,725	14.6	Low

Table 2. Selected mineral soil characteristics for each sub-watershed (Data from Batkhishig 2006)

Site	pH (H_2O)	CEC (meq/100 g)	Base saturation (%)
Turag	5.8-7.0	9.3-15.1	82.6-82.9
Shagnuul	5.6-6.5	23.2-70.8	69.5-75.8
Noyon	6.6-6.7	9.7-14.7	76.6-82.4
Sevsuul	6.0-6.3	12.1	71.1
Dalbay	5.1-6.1	11.7-38.7	38.3-64.0
Borsog	5.1-6.1	13.7-33.9	38.1-65.6

CEC, cation exchange capacity.

Table 3. Number of livestock during 2003 to 2005 for each sub-watershed (sheep units)

Site	2003	2004	2005
Turag	2,103	3,330	2,463
Shagnuul	2,777	3,002	3,319
Noyon	856	439	963
Sevsuul	644	438	588
Dalbay	515	530	853
Borsog	0	51	102

Table 4. Number of families herding livestock during 2003 to 2005 for each sub-watershed

Site	2003	2004	2005
Turag	17	22	18
Shagnuul	9	12	11
Noyon	4	2	2
Sevsuul	3	3	2
Dalbay	1	1	2
Borsog	0	2	2

number of livestock from 2003 to 2005, although not in every sub-watershed. Estimates of the number of families living in each sub-watershed based on on-site interviews are shown in Table 4. For example, during 2004, the number of families in each sub-watershed ranged from 17 to 22 for Turag (high grazing intensity) and from 0 to 2 for Borsog (low grazing intensity).

Sampling sites

Sub-watersheds were chosen to study the gradient of grazing intensity based upon livestock density (0-3,330 sheep units) (Table 3) and number of families (0-22) (Table 4) living within each sub-watershed. The number of livestock in each sub-watershed was obtained from results of surveys conducted of local families. For each sub-watershed stream, water samples from three locations, designated as upper, middle, and lower reach stations, were sampled for chemical analysis. Stream solute concentrations were compared among the sub-watersheds. Because grazing intensity at the upper elevation stations was minimal in all sub-watersheds, these sampling stations represented reference areas with respect to grazing impacts within each sub-watershed.

Comparisons were also made using combined results from middle and lower reach stations in each sub-watershed to evaluate the effects of watershed characteristics such as grazing intensity (low, moderate, high) on solute chemistry. Non-parametric Kruskal-Wallis multiple comparisons and linear regressions were performed on untransformed data using SAS ver. 8.2 (SAS 2002) and Statistica ver. 7 (StatSoft 2000).

Chemical analyses

Grab samples of streamwater were collected in precleaned bottles during the summer period from 2003 to 2005 at the three stations in each stream valley. The upper stations in the upper part of each valley were selected above areas where livestock grazing might impact the streams. The middle and lower stations (near the lake) were selected in the grazing areas of each valley (Fig. 1). Water samples were filtered using 0.45 μm membrane filters and shipped to the analytical laboratories by international courier. Stream pH was measured in the field with a TOA 20P pH meter (DKK-TOA, Tokyo, Japan). Water samples were collected once in 2003 and twice in 2004, and analyzed by the Research Center for Environmental Changes, Taiwan. Major anion concentrations (Cl^-, SO_4^{2-}, NO_3^-) were determined using a Dionex ICS-90 ion chromatograph (Dionex Corp., Sunnyvale, CA, USA) equipped with an AS9-HC column (Dionex Corp.). Major cation concentrations (NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}) were measured using a Dionex ICS-1500 (Dionex Corp.) ion chromatograph equipped with a heated CS12A column (Dionex Corp.). Dissolved organic carbon (DOC) concentration was measured using an O.I. Analytical 1010 TOC analyzer (O.I. Analytical, College Station, TX, USA). Laboratory QA/QC protocols were used such as blanks and duplicate sample analysis. A certified reference river water sample (NRC SLRS-4) was used as an independent reference sample with each batch of water samples. Total dissolved phosphorus (TDP) concentration was measured only during 2004 using persulfate digestion and the procedure of Menzel and Corwin (1965).

In 2005 water samples were collected three times – once each during early June, July, and August and were analyzed at the SUNY-ESF Biogeochemical Laboratory in Syracuse, NY. Prior to analyses, samples were refrigerated. Anion concentrations were measured using ion chromatography (DX-120; Dionex Corp.). Cation concentrations were determined using inductively coupled plasma-optical emission spectrophotometer (ICPOES, Perkin Elmer 3500DV; Perkin Elmer, Waltham, MA, USA). DOC was analyzed with a TOC analyzer (Dohrman Phoenix 8000; Teledyne-Tekmar, Mason, OH, USA). Total dissolved nitrogen (TDN) was measured using persulfate oxidation (Ameel et al. 1993) with an Auto Analyzer 3 using methods described by Mitchell et al. (2001). Dissolved organic nitrogen (DON) was calculated by subtracting the concentrations of NH_4-N and NO_3-N from that of TDN. The Biogeochemical Laboratory at SUNY–ESF follows extensive QA/QC procedures. Every analytical sample batch included calibration QC samples, detection limit QC samples, an analytical blank, and replicate analysis. The laboratory participates in the United States Geological Survey (USGS) audit program (Branch of Quality Systems, Standard Reference Sample Project) to ensure data quality.

RESULTS

Upper sampling station stream chemistry

Among the stations with little to no grazing (upper stations), we found some differences in solute concentrations in the six streams. Average concentrations of Cl^- tended to be higher in Turag and Sevsuul and ranged from 9.8 to 51.3 μmol/L (Table 5). The average SO_4^{2-} concentration at these stations ranged from 66 to 294 μmol/L; Turag had the highest average SO_4^{2-} concentration and Borsog and Noyon showed the next highest average SO_4^{2-} concentrations of 150.5 and 139.9, respectively (Table 5). Average NO_3^- concentrations were low and ranged from undetectable to 2.6 μmol/L (Table 5). Ammonium (NH_4^+) concentrations were also low and ranged from below 1.0 μmol/L (near detection limit) to 9 μmol/L. The distribution of NH_4^+ concentrations was highly skewed with 23 values out of 30 samples having NH_4^+ concentrations below the detection limit.

Base cation concentrations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) were also variable among the upper stations; the average concentrations are summarized in Table 5. None of the differences among the upper stations in base cation concentration were statistically significant using Kruskal-Wallis multiple comparison tests ($P > 0.05$).

The northernmost and central streams (Turag and Shagnuul, Noyon and Sevsuul, respectively) showed generally higher DOC concentrations, although this difference was not consistent (Table 5). Average DOC concentrations ranged from 642 μmol/L at Borsog to 1,180 μmol/L at Shagnuul. Similar to the pattern for DOC, DON concentrations tended to be higher in the northern and central streams (Table 5). Overall, DON concentrations ranged from 16 to 46 μmol/L (Table 5).

Stream chemistry at the middle and lower stations

We also found differences in stream chemistry among the streams at the middle and lower sampling stations (grouped by grazing intensity) (Table 6). Using Kruskal-Wallis multiple comparison tests, we found significant differences in nutrient concentrations for only a few solutes. For example, concentrations of Cl^- were higher in streams with the highest grazing pressure (Turag and Shagnuul) (Table 6). Average concentrations of Ca^{2+}, Mg^{2+}, and SO_4^{2-} were also highest in streams with the highest grazing intensity (Table 6). Average stream pH did not vary among the sites, and ranged from 7.7 to 8.0. Although we found some higher solute concentrations

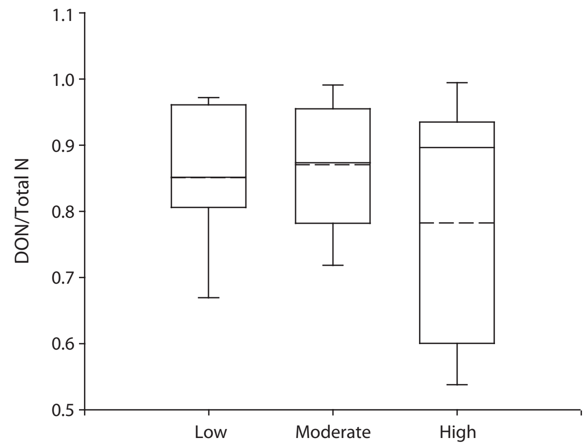

Fig. 2. Box plot of the fraction of total dissolved nitrogen as dissolved organic nitrogen (DON/Total N) for the middle and lower sampling stations by grazing pressure. For each box, whiskers and box outline represent the 5th, 25th, 75th, and 95th percentiles. The median is shown as a solid line, and the mean is shown as a dashed line.

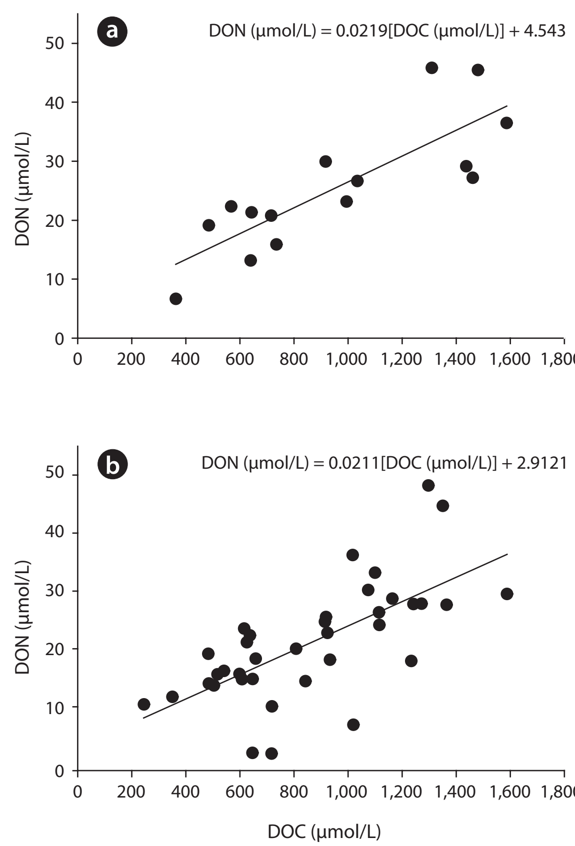

Fig. 3. (a) Relationship between concentration of dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) in streamwater at the upper sampling stations. Equation for the best-fit regression line shown ($r^2 = 0.457$). (b) Relationship between concentration of DOC and DON in streamwater at the middle and lower sampling stations. Equation for the best-fit regression line shown ($r^2 = 0.670$).

Table 5. Three-year average streamwater chemistry (μmol/L) at the upper sampling stations during 2003 to 2005 (mean ± standard error)

	Cl	SO_4	Ca	Mg	Na	K	NO_3	NH_4	pH	DOC	N	Total N	Total P
Turag ($N = 6$)	51 ± 12.6^{a}	281 ± 60.8^{a}	395 ± 81.1^{a}	290 ± 54.1	166 ± 27.7^{a}	20.6 ± 5.0^{a}	3 ± 1.4^{a}	1 ± 0.6^{a}	7.8 ± 0.11^{a}	834 ± 183.8^{a}	23 ± 1.7^{a}	26 ± 1.8^{a}	0.2 ± 0.03^{a}
Shagnuul ($N = 4$)	22 ± 8.3^{b}	120 ± 37.5^{b}	415 ± 56.9^{a}	261 ± 38.5^{b}	171 ± 21.6^{a}	15.0 ± 3.2^{a}	0.5 ± 0.0^{a}	3 ± 1.6^{a}	7.9 ± 0.24^{a}	$1{,}179 \pm 158.5^{a}$	46 ± 0.2^{a}	49 ± 1.3^{a}	0.1 ± 0.05^{a}
Noyon ($N = 5$)	10 ± 2.0^{c}	140 ± 41.4^{b}	340 ± 68.2^{a}	343 ± 64.6^{a}	302 ± 63.8^{a}	16 ± 3.7^{a}	1 ± 0.9^{a}	2 ± 0.7^{a}	7.8 ± 0.18^{a}	895 ± 188.9^{a}	29 ± 5.1^{a}	31 ± 4.5^{a}	0.2 ± 0.01^{a}
Sevsuul ($N = 5$)	13 ± 2.8^{b}	66 ± 11.1^{c}	457 ± 74.8^{a}	364 ± 59.7^{a}	250 ± 23.7^{a}	19 ± 4.1^{a}	0.5 ± 0.4^{a}	0.5 ± 0.1^{a}	7.9 ± 0.08^{a}	$1{,}011 \pm 232.5^{a}$	22 ± 4.6^{a}	22 ± 4.7^{a}	0.6 ± 0.42^{a}
Dalbay ($N = 3$)	16 ± 3.4^{b}	105 ± 19.0^{b}	305 ± 88.5^{a}	233 ± 40.5^{b}	222 ± 43.5^{a}	16 ± 2.8^{a}	0.5 ± 0.6^{a}	1 ± 0.6^{a}	8.0 ± 0.18^{a}	936 ± 187.6^{a}	15.9 ($N = 1$)	16.5 ($N = 1$)	0.2 ± 0.06^{a}
Borsog ($N = 5$)	12 ± 3.1^{c}	151 ± 32.5^{b}	278 ± 46.2^{a}	215 ± 39.4^{b}	245 ± 51.6^{a}	18 ± 4.0^{a}	1 ± 0.6^{a}	2 ± 0.6^{a}	7.4 ± 0.12^{a}	642 ± 93.5	18.0 ± 5.9^{a}	21 ± 5.0^{a}	0.2 ± 0.04^{a}

The number of analyses for each stream is shown; sites are listed from north to south.
DOC, dissolved organic carbon.

Table 6. Three-year average stream chemistry (μmol/L) at the lower and middle stations grouped by grazing intensity during 2003 to 2005 (mean ± standard error)

	Cl	SO_4	Ca	Mg	Na	K	NO_3	NH_4	pH	DOC	DON	Total N	Total P
Low ($N = 23$)	20 ± 2.8^{b}	119 ± 10.8^{a}	377 ± 26.8^{b}	275 ± 16.2	272 ± 16.7^{a}	21 ± 2.3^{a}	0.5 ± 0.2^{b}	1.5 ± 0.5^{a}	7.7 ± 0.06^{a}	847 ± 62.4^{a}	19 ± 2.2^{a}	21 ± 2.3^{a}	0.3 ± 0.03^{a}
Moderate ($N = 26$)	14 ± 2.5^{c}	95 ± 13.7^{b}	371 ± 21.9^{b}	337 ± 18.8^{b}	258 ± 13.9^{a}	18 ± 1.9^{a}	0.7 ± 0.3^{b}	2 ± 0.5^{a}	8.0 ± 0.09^{a}	868 ± 49.4^{a}	25.7 ± 3.5^{a}	28.6 ± 3.3	0.2 ± 0.03^{a}
High ($N = 21$)	41 ± 5.3^{a}	264 ± 27.2^{a}	532 ± 39.4^{a}	389 ± 33.9^{a}	240 ± 21.6^{a}	23 ± 1.6^{a}	2 ± 0.7^{a}	2 ± 0.8^{a}	7.8 ± 0.06^{a}	946 ± 88.3^{a}	18.8 ± 2.6^{a}	24 ± 2.8^{a}	0.3 ± 0.13^{a}

The number of analyses for each stream is shown; sites are listed from north to south. Averages followed by the same lower case letter are not significantly different ($P > 0.05$).
DOC, dissolved organic carbon; DON, dissolved organic nitrogen.

in the streams with the highest grazing intensity (Turag and Shagnuul), there were no large differences in average solute concentration between the low and moderate grazing sites. This was especially apparent in our results for DON and TDN (Table 6), where concentrations varied little among the streams grouped by grazing intensity. We did not find a statistically significantly difference in DOC concentration among sites with high, moderate, or low grazing intensity, but the average DOC concentration was highest at the high grazing intensity sites (Table 6). The average stream DOC concentrations were 847 ± 62, 868 ± 49, and 946 ± 88 (standard error) μmol/L in the low, moderate, and high grazing intensity sites, respectively. The fraction of total dissolved N as DON ranged from 0.53 to 0.99, and showed no apparent pattern with grazing intensity or active layer thickness (Fig. 2).

The correlation matrix between stream nutrient concentrations at the upper stations is shown in Table 7. At the least grazing-impacted sites (i.e. upper stations only), some of the more interesting relationships between nutrients included our finding that DOC concentrations were strongly correlated with DON and TDN concentrations (Fig. 3). We also found that DOC concentrations were negatively correlated to SO_4^{2-} concentrations (P = 0.019), TDP concentrations were negatively correlated to pH (P = 0.030), and that TDP concentrations were positively correlated to DOC concentrations (P = 0.004). We found strong positive correlations between SO_4^{2-} and Cl^- concentrations (P < 0.001) and also between SO_4^{2-} and NO_3^- concentrations (P < 0.001). Concentrations of base cations Mg^{2+}, Na^+, and K^+ were generally positively related to each other (Table 7).

DISCUSSION

Differences among streams

Many watershed attributes have been related to variation in stream chemistry such as geology (Dillon and Kirchner 1975, Newton et al. 1987, Holloway et al. 1998), influence of riparian zones (Lowrance et al. 1984), soil characteristics (Kaňa and Kopáček 2006), vegetation cover (Cronan et al. 1987, Lovett et al. 2004), topography and elevation (Lawrence et al. 2000, Sueker et al. 2001), and other variables. A wide variety of disturbances, including forest cutting (Bormann et al. 1968), agricultural activity (Lowrance et al. 1984), and livestock grazing (Schepers and Francis 1982, Belsky et al. 1999) are also known to affect stream chemistry. The small number of samples

Table 7. Correlation coefficients (*r*) between solute concentrations at the upper stations (only statistically significant relationships are shown; *P*-values in parenthesis)

	pH	Cl	NO_3	SO_4	Ca	Mg	Na	K	NH_4	DOC	DON	Total N	Total P
pH													-0.9136 (0.030)
Cl			0.4482 (0.013)	0.8251 (< 0.0001)		0.3847 (0.048)		0.5321 (0.004)					
NO_3				0.6924 (< 0.0001)		0.4589 (0.016)	0.4069 (0.035)	0.3963 (0.041)					
SO_4						0.4784 (0.012)		0.6030 (0.001)		-0.4405 (0.019)			
Ca						0.6770 (0.001)	0.4430 (0.021)	0.4718 (0.013)					
Mg							0.7708 (< 0.0001)	0.7102 (< 0.0001)					0.7176 (0.009)
Na								0.5716 (0.002)		-0.4914 (0.009)	-0.5704 (0.026)	-0.5244 (0.045)	
K										-0.5527 (0.003)	-0.5706 (0.026)	-0.5522 (0.033)	
NH_4													*N* < 3
DOC											0.8184 (0.0002)	0.7818 (0.001)	0.7641 (0.004)
DON												0.9918 (< 0.0001)	*N* < 3
Total N													*N* < 3

DOC, dissolved organic carbon; DON, dissolved organic nitrogen.

limited our ability to fully evaluate all the factors affecting the stream chemistry of these six sub-watersheds, but our results allow us to speculate that the most important factors affecting spatial patterns in stream chemistry in the Lake Hövsgöl watershed likely include, in addition to livestock grazing, geologic characteristics, soil type, and thickness of the active layer above permafrost.

Carey (2003) compared soil water DOC concentrations between a north-facing area with permafrost and a south-facing area with only seasonal frost in the Granger Basin (Yukon) and found higher DOC concentrations in the area with permafrost. The suggestion of a decreasing trend in stream DOC concentration from the northern to the southern sub-watersheds in the Lake Hövsgöl watershed is consistent with the patterns found in Alaskan forests underlain by permafrost (MacLean et al. 1999, Petrone et al. 2006). This pattern results from differences in hydrological flowpaths between areas with more extensive permafrost cover and areas with less extensive permafrost. In areas with less permafrost, water can infiltrate deeper into the soil profile; DOC adsorption occurring in the soil reduces the amount of DOC that can be moved to streams. Although we did not have access to data on active layer depths at each study site, short-term monitoring of permafrost in the six valleys showed that active layer thickness varies from 1.4 m in Dalbay valley in the south to 4.8 m in Turag valley in the north (Sharkhuu et al. 2007).

Average stream DOC concentrations did not vary in a consistent pattern from the northern sites (such as in Turag and Shagnuul) to the southern sites (except Borsog, where we found the lowest DOC conentrations) in the Lake Hövsgöl sub-watersheds. If grazing activity leads to lower vegetation cover and increased bare soil in riparian areas, there is the possibility of higher losses of dissolved organic matter from soil to the streams. Thus, we cannot ignore the possibility of livestock grazing influencing stream DOC or other solute concentrations in the Lake Hövsgöl sub-watersheds where livestock are present. Certainly, further studies of the Hövsgöl ecosystem, including impacts of animal grazing and permafrost thickness on streamwater chemistry, are needed.

The impacts of animal grazing on stream temperature, sediment yield, and water quality have been well documented (e.g. Li et al. 1994). If livestock grazing were directly affecting solute concentrations in the streams, we would most likely expect increases in concentrations of TDP, NH_4^+, NO_3^- and Cl^- (Schepers and Francis 1982). In the present study, we did not focus on riparian zone processes or possible differences in sediment deposition among streams with differing grazing intensities. Vegetation surveys, however, showed large differences in vegetation cover and bare ground exposure among the sub-watersheds. The role of bare ground exposure in affecting stream solute concentrations could be a focus of future research in the watershed. The suggestion that future work in the Lake Hövsgöl watershed should include the quantification of sediment deposition processes in the streams also warrants further investigation.

Our study has provided the first estimates of DON concentration in streams in the Lake Hövsgöl watershed. The TDN pool in these streams was made up of mostly organic nitrogen, while inorganic N accounts for a small fraction of total N. On average, the proportion of total N as organic N did not seem to vary among the sub-watersheds, and ranged from 58% to 99% of the total dissolved N (Fig. 2). This measure of the importance of organic N is similar to results from other regions (McHale et al. 2000), especially in regions with little anthropogenic input of N (Perakis and Hedin 2000). Fig. 3 compares the relationship between DOC and DON for the sampling stations with minimal or no livestock (upper stations), and the relationship between DOC and DON in the streams with livestock. Between the data sets, there was no difference in the slope of this relationship ($P > 0.05$), indicating that the source of dissolved organic matter may not differ between the potentially least impacted upper stations and the middle and lower sampling stations.

Moreover, research on the dynamics of DOC and DON transport in this watershed would be especially useful in helping to identify patterns related to climate change and possible effects of human activities in this region. One implication of our study is that as air temperature increases and permafrost active layer depths increase in this watershed, recently-thawed soils may act as a source of both dissolved inorganic and organic N to streams (Petrone et al. 2007). Understanding the relationship between soil C/N ratios and surface water chemistry will be required in future studies of the Lake Hövsgöl watershed. Other studies have shown that soil characteristics, including soil C/N ratio, are a key variable in understanding differences in retention and export of nutrients, especially C and N (Currie et al. 1996, Aitkenhead-Peterson et al. 2005).

CONCLUSION

Lake Hövsgöl is among the most pristine freshwater ecosystems in temperate regions. Our stream chemistry monitoring results show that more research is needed to better understand the patterns in dissolved solute concentrations in the study area. We can speculate that differences in solute concentrations among these streams can possibly be affected by livestock grazing, and also affected by the thickness of the permafrost active layer and general soil characteristics in the sub-watersheds. Our finding that stream DOC concentrations did not consistently vary from the northern (Turag and Shagnuul) to the southern sites (Dalbay and Borsog) demonstrates the importance of initiating further studies on soil and stream water chemistry and hydrological processes at Lake Hövsgöl in this remote region in central Asia. Specifically, our results show that more research on characterization and dynamics of DOC and DON in soils, soil solution, stream water, and their hydrological linkages in this watershed will be especially useful in helping to identify important indicators and understand patterns in dissolved organic matter transformations, retention, and export related to climate change in this region.

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LITERATURE CITED

Aitkenhead-Peterson JA, Alexander JE, Clair TA. 2005. Dissolved organic carbon and dissolved organic nitrogen export from forested watersheds in Nova Scotia: identifying controlling factors. Global Biogeochem Cycles 19: GB4016.

Ameel JJ, Axler RP, Owen CJ. 1993. Persulfate digestion for determination of total nitrogen and phosphorus in low-nutrient waters. Am Environ Lab 1: 1-11.

Batkhishig O. 2006. Soils of the Lake Hövsgöl area and its watershed. In: The Geology, Biodiversity and Ecology of Lake Hövsgöl (Mongolia) (Goulden CE, Sitnikova T, Gelhaus J, Boldgiv B, eds). Backhuys Publishers, Leiden, pp 93-114.

Belsky AJ, Matzke A, Uselman S. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. J Soil Water Conserv 54: 419-431.

Bormann FH, Likens GE, Fisher DW, Pierce RS. 1968. Nutrient loss accelerated by clear-cutting of a forest ecosystem. Science 159: 882-884.

Brown J, Farrians OJ Jr, Heginbottom JA, Melnikov ES. 1995. Circum-Arctic Map of Permafrost and Ground Ice Conditions. USGS Circum-Pacific Map Series, Map CP-45. National Snow and Ice Data Center/World Data Center for Glaciology, Boulder, CO.

Carey SK. 2003. Dissolved organic carbon fluxes in a discontinuous permafrost subarctic alpine catchment. Permafrost Periglacial Process 14: 161-171.

Cronan CS, Conlan JC, Skibinski S. 1987. Forest vegetation in relation to surface water chemistry in the north branch of the Moose River, Adirondack Park, N.Y. Biogeochemistry 3: 121-128.

Currie WS, Aber JD, McDowell WH, Boone RD, Magill AH. 1996. Vertical transport of dissolved organic C and N under long-term amendments in pine and hardwood forests. Biogeochemistry 35: 471-505.

Dillon PJ, Kirchner WB. 1975. The effects of geology and land use on the export of phosphorus from watersheds. Water Res 9: 135-148.

Goulden CE, Sitnikova T, Gelhaus J, Boldgiv B. 2006. The Geology, Biodiversity and Ecology of Lake Hövsgöl. Backhuys Publishers, Leiden.

Hilbig W. 1995. The Vegetation of Mongolia. SPB Academic Publishers, Amsterdam.

Holloway JM, Dahlgren RA, Hansen B, Casey WH. 1998. Contribution of bedrock nitrogen to high nitrate concentrations in stream water. Nature 395: 785-788.

Kaňa J, Kopáček J. 2006. Impact of soil sorption characteristics and bedrock composition on phosphorus concentrations in two Bohemian forest lakes. Water Air Soil Pollut 173: 243-259.

Lawrence GB, Lovett GM, Baevsky YH. 2000. Atmospheric deposition and watershed nitrogen export along an elevational gradient in the Catskill Mountains, New York. Biogeochemistry 50: 21-43.

Li HW, Lamberti GA, Pearsons TN, Tait CK, Li JL, Buckhouse

JC. 1994. Cumulative effects of riparian disturbances along high desert trout streams of the John Day Basin, Oregon. Trans Am Fish Soc 123: 627-640.

Lovett GM, Weathers KC, Arthur MA, Schultz JC. 2004. Nitrogen cycling in a northern hardwood forest: Do species matter? Biogeochemistry 67: 289-308.

Lowrance RR, Todd RL, Fail J Jr, Hendrickson O Jr, Leonard R, Asmussen L. 1984. Riparian forests as nutrient filters in agricultural watersheds. BioScience 34: 374-377.

MacLean R, Oswood MW, Irons JG III, McDowell WH. 1999. The effect of permafrost on stream biogeochemistry: a case study of two streams in the Alaskan (U.S.A.) taiga. Biogeochemistry 47: 239-267.

McHale MR, Mitchell MJ, McDonnell JJ, Cirmo CP. 2000. Nitrogen solutes in an Adirondack forested watershed: importance of dissolved organic nitrogen. Biogeochemistry 48: 165-184.

Menzel DW, Corwin N. 1965. The measurement of total phosphorus in seawater based on the liberation of organically bound fractions by persulfate oxidation. Limnol Oceanography 10: 280-282.

Mitchell MJ, McHale PJ, Inamdar S, Raynal DJ. 2001. Role of within-lake processes and hydrobiogeochemical changes over 16 years in a watershed in the Adirondack Mountains of New York State, U.S.A. Hydrol Process 15: 1951-1965.

Myagmarjav B, Davaa G. 1999. Surface Water of Mongolia. Interpress Publishing, Ulaanbaatar. (in Mongolian)

Namkhaijantsan G. 2006. Climate and climate change of the Hövsgöl region. In: The Geology, Biodiversity and Ecology of Lake Hövsgöl (Mongolia) (Goulden CE, Sitnikova T, Gelhaus J, Boldgiv B, eds). Backhuys Publishers, Leiden, pp 63-76.

Nandintsetseg B, Greene JS, Goulden CE. 2007. Trends in extreme daily precipitation and temperature near Lake Hövsgöl, Mongolia. Int J Climatol 27: 341-347.

Newton RM, Weintraub J, April R. 1987. The relationship between surface water chemistry and geology in the North Branch of the Moose River. Biogeochemistry 3: 21-35.

Osterkamp TE, Jorgenson JC. 2006. Warming of permafrost in the Arctic National Wildlife Refuge, Alaska. Permafrost Periglacial Process 17: 65-69.

Osterkamp TE, Romanovsky VE. 1999. Evidence for warming and thawing of discontinuous permafrost in Alaska. Permafrost Periglacial Process 10: 17-37.

Perakis SS, Hedin LO. 2000. Nitrogen loss from unpolluted South American forests mainly via dissolved organic compounds. Nature 415: 416-419.

Petrone KC, Jones JB, Hinzman LD, Boone RD. 2006. Seasonal export of carbon, nitrogen, and major solutes from Alaskan catchments with discontinuous permafrost. J Geophys Res 111: G02020.

Petrone KC, Hinzman LD, Shibata H, Jones JB, Boone RD. 2007. The influence of fire and permafrost on sub-arctic stream chemistry during storms. Hydrol Process 21: 423-434.

SAS. 2002. Statistical Analysis System for Windows. SAS Institute, Inc., Cary, NC.

Schepers JS, Francis DD. 1982. Chemical water quality of runoff from grazing land in Nebraska: I. Influence of grazing livestock. J Environ Qual 11: 351-354.

Sharkhuu A, Sharkhuu N, Etzelmuller B, Heggem ESF, Nelson FE, Shiklomanov NI, Goulden CE, Brown J. 2007. Permafrost monitoring in the Hövsgöl mountain region, Mongolia. J Geophys Res 112: F02S06.

StatSoft. 2000. Statistica. StatSoft Inc., Tulsa, OK.

Sueker JK, Clow DW, Ryan JN, Jarrett RD. 2001. Effect of basin physical characteristics on solute fluxes in nine alpine/subalpine basins, Colorado, USA. Hydrol Process 15: 2749-2769.

Tsogtbaatar J, Goulden CE. 2000. Mongolia long term ecological research. In: The International Long Term Ecological Research Network (Gosz JR, French C, Sprott P, White M, eds). Academy Printers, Albuquerque, NM, pp 28-29.

United Nations Population Division. 2006. World population prospects: the 2006 revision. http://www.un.org.esa/population/publications/wpp2006/wpp2006.htm. Accessed 5 February 2010.