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Basic Limnological Survey of Twenty-One Northern and Central Mongolian Lakes

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Abstract

This survey report presents basin morphology, water quality, and sedimentological data from twenty-one Mongolian lakes, and is meant to be used as a resource for future geological and biological investigations. The lakes are organized in three separate groups based on geographic location, and the survey results from each lake are described in detail. A short discussion of local and regional factors influencing solute concentrations and pH levels of the lakes' waters is presented. The lakes present at latitudes lower than N 50°00' (i.e. central and north/central lakes) are distributed across an area of approximately 150,000 km^2 and vary considerably with respect to their water quality characteristics. Regional precipitation patterns as a function of geographic location and/or catchment specific processes are indentified as the driving mechanisms for variations in solute concentrations and pH levels in these lakes. The surveyed lakes present at latitudes higher than N50°00' (i.e. northern lakes) are distributed across a smaller area (approximately 180 km^2) and have relatively little variation in water quality characteristics. These lakes straddle the local taiga/alpine tundra transition zone, and elevation (i.e. valley placement) is identified as the driving mechanism for inter-lake variations in solute concentrations and pH levels.

Key words: limnology, lake, water quality, survey, sediment cores

Introduction

The diverse ecology/geology of Mongolian lakes has long been recognized (Berkey & Morris, 1927) and a history of limnological monitoring within Mongolia exists (Kondratiev, 1929; Dulmaa, 1979; Kozhov *et al.*, 1965; Kuznetsov, 1968; Tserensodnom, 1971; Sevastyanov & Dorofeyk, 2005), yet a great number of Mongolian lakes remain unstudied. Of the 3,500 lakes distributed throughout Mongolia's rugged and sparsely populated landscape, most have remained isolated from human activities. Such isolation has preserved a great number of natural, undisturbed lake systems, offering biologists and geologists the unique opportunity to study such systems in their pristine state.

Here, we report observations on the physical and chemical properties of twenty-one northern and central Mongolian lake systems, the majority of which were previously unstudied (Table 1; Fig. 1). The simple objective of this study is to provide a basic understanding of the nature of each lake system. Furthermore, this paper aims to document the baseline conditions of each ecosystem in order to better assess any future alterations.

Materials and Methods

Physiolimnological data were collected during June, July, and August of 2005 (Table 2). Lake names were assigned as labeled on existing topographical maps, or, when unlisted, informal local names were designated. Elevations and locations were recorded using a Garmin GPS 76 hand-held unit. Transparency measurements via Secchi disk were taken during the late morning to early afternoon hours, and were measured off the shaded side of the boat. Water temperature, dissolved oxygen (DO), specific conductivity

Table 1. General surveyed lake data and sediment core information.

Lake Name	Location N	Location E	Elevation (m.a.s.l.)	Surface area (km^2)	Sediment core ID	Water depth at coring site (m)	Length of core (m)
Central Mongolia							
Shireet Nuur	46° 31.490	101° 50.051	2429	--	SHR-A-25-VI-05	6.0	0.88
Höh Nuur	47° 29.069	098° 33.473	2300	12.97	HOH-A-27-VI-05	8.0	0.71
Tsagaan Nuur	47° 38.961	097° 15.623	2257	3.55	TSA-A-03-VII-05	21.2	1.07
					TSA-B-03-VII-05	10.9	0.36
North-central Mongolia							
Terhkiin Tsagaan Nuur	48° 08.529	099° 39.646	2158	59.99	TTN-A-29-VI-05	14.0	0.88
Khar Nuur	48° 20.541	096° 11.903	1978	90.86	HAR-A-04-VII-05	12.8	0.70
Baga Nuur	48° 24.972	095° 57.350	1982	7.98	BAG-A-05-VII-05	15.0	0.79
					BAG-B-05-VII-05	8.2	0.79
Tsegeen Nuur	48° 43.712	095° 51.750	1877	1.45	TGN-A-06-VII-05	8.7	0.68
Kholboo Nuur	49° 02.659	097° 09.615	1952	25.2	HOL-A-01-VII-05	7.5	1.20
Zuun Nuur	49° 03.858	099° 27.999	2012	18.65	ZUN-A-16-VIII-05	12.7	1.11
Bust Nuur	49° 07.829	097° 26.499	1983	--	BST-A-30-VI-05	12.1	1.35
Oigon Nuur	49° 09.184	096° 38.024	1667	73.46	----	----	----
Sangiin Dalai Nuur	49° 11.034	099° 01.990	1705	181.9	----	----	----
Gandan Nuur	49° 11.933	098° 46.013	1897	23	----	----	----
Tsavdan Nuur	49° 14.553	095° 39.201	1705	12.17	TVD-A-06-VII-05	1.0	0.50
Tunamal Nuur	49° 25.130	098° 31.848	1885	9.78	TUN-A-14-VIII-05	9.7	1.10
Northern Mongolia							
Sanjin Nuur	51° 13.910	099° 01.397	2090	0.08	SAN-A-6-VIII-05	17.4	1.05
					SN-A-03		
					SN-B-03		
					SN-C-03		
Mustei Nuur	51° 14.354	099° 00.354	2353	0.34	MUS-A-7-VIII-05	19.4	1.25
Ganbold Nuur	51° 20.076	098° 52.532	2102	0.12	GAN-A-10-VIII-05	21.9	0.93
					GAN-B-10-VIII-05	18.5	1.04
Tsogtoo Nuur	51° 20.738	098° 53.842	2063	0.38	TSO-A-9-VIII-05	4.0	1.30
Batbold Nuur	51° 20.856	098° 52.496	2150	0.14	BAT-A-8-VIII-05	12.0	1.21
Mandakh Nuur	51° 22.323	098° 57.494	1978	1.35	MAN-A-8-VIII-05	6.0	1.68

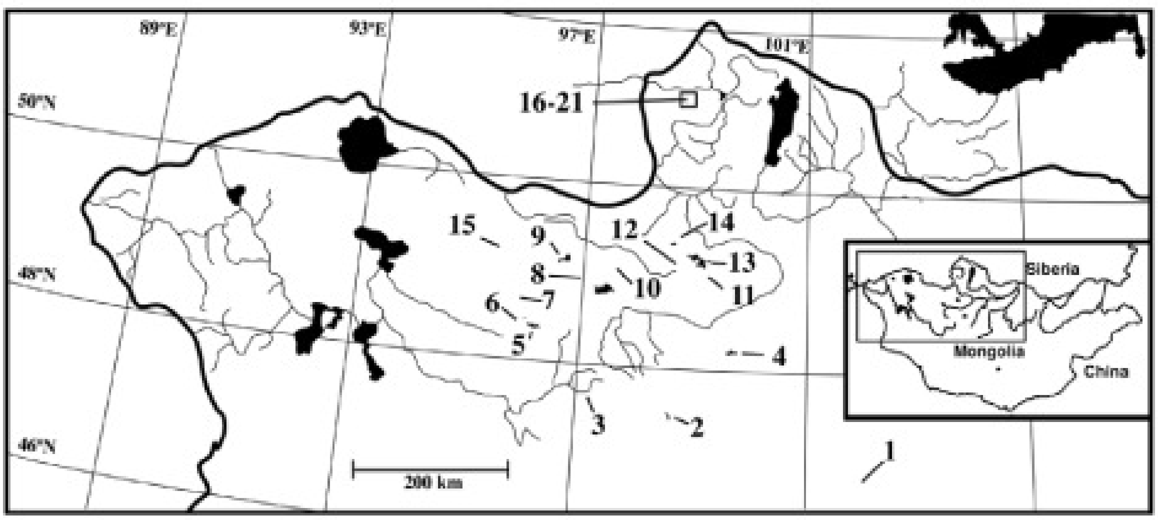

Figure 1. Mongolian Lake Survey Site Map. 1 = Shireet Nuur, 2= Höh Nuur, 3= Tsagaan Nuur, 4 = Terkhiin Tsagaan Nuur, 5 = Khar Nuur, 6= Baga Nuur, 7 = Tsegeen Nuur, 8 = Kholboo Nuur, 9 = Oigon Nuur, 10 = Bust Nuur, 11 = Zuun Nuur, 12 = Gandan Nuur, 13 = Sangiin Dalai Nuur, 14 = Tunamal Nuur, 15=Tsavdan Nuur, 16-21 = Sanjin Nuur, Mustei Nuur, Ganbold Nuur, Batbold Nuur, Tsogtoo Nuur, Mandakh Nuur.

Table 2. Physical and physiolimnological characteristics of surveyed lakes.

Lake name	Date measured	Max depth measured (m)	Surface temp (°C)	Bottom temp (°C)	Average SpC (mS cm^{-1})	Average D.O. (mg L^{-1})	Average pH	Depth of metalimnion (m)	Secchi depth (m)
Central Mongolia									
1. Shireet Nuur	25-June-05	6	14	9.07	0.069	7.96	8.86	--	3.5
2. Höh Nuur	27-June-05	8	10.2	9.38	0.059	8.58	8.69	--	8
3. Tsagaan Nuur	03-July-05	27	14.5	4.21	0.231	7.48	8.42	6	5.2
Northern/Central Mongolia									
4. Terkhiin Tsagaan Nuur	29-June-05	13	13.6	9.56	0.149	7.78	8.54	8	2.4
5. Khar Nuur	04-July-05	12	13.9	9.68	0.54	8.21	9.12	--	4
6. Baga Nuur	05-July-05	14.5	16.6	8.74	0.345	6.38	8.71	6.5	1.3
7. Tsegeen Nuur	06-July-05	8.5	17.7	1.71	12.8	5.18	8.93	5	0.5
8. Kholboo Nuur	01-July-05	7.5	15.5	15	2.67	7.57	9.33	--	1.3
9. Zuun Nuur	16-Aug-05	10	14	13.4	4.67	5.54	9.02	--	1
10. Bust Nuur	30-June-05	12	14.6	5.5	3.19	7.77	9.28	7	2.2
11. Oigon Nuur		--	--	--	--	--	--	--	--
12. Sangiin Dalai Nuur	15-Aug-05	6.5	15.4	14.99	5.06	6.35	9.19	--	--
13. Gandan Nuur	06-July-05	4.5	14.3	14.28	0.397	6.09	8.72	--	--
14. Tsavdan Nuur	15-Aug-05	0.5	--	--	--	--	--	--	--
16. Tunamal Nuur	14-Aug-05	8	16.02	15.79	5.65	6.17	9.09	--	1
Northern Mongolia									
16. Sanjin Nuur	06-Aug-05	16	11.9	4.63	0.01	6.95	7.32	6	4.75
17. Mustei Nuur	07-Aug-05	25	13.9	5.09	0.006	7.53	7.07	7	11.2
18. Ganbold Nuur	10-Aug-05	20	12.7	3.67	0.027	6.39	7.01	2	5.6
19. Tsogtoo Nuur	09-Aug-05	1	16.6	--	0.017	6.3	7.62	--	3.8
20. Batbold Nuur	09-Aug-05	12	15.8	5.3	0.017	7.15	7.47	3.5	6
21. Mandakh Nuur	08-Aug-05	6	18.2	10.4	0.019	6.58	7.49	4	5.8

(SpC), and pH measurements were taken using a Hydrolab Quanta G water quality monitoring system at a 0.5 m interval until a depth of 10.0 m, after which a 1.0 m interval was deemed appropriate. Exceptions to this method occurred when clear metalimnetic characteristics were visible above or below 10.0 m and, thereby, the measurement routine was altered to best resolve stratification. Water depth measurements were routinely recorded using a Garmin GPS 176 sonar unit. Lake water total dissolved solids (TDS) concentrations were calculated from average water SpC and temperature values (Fofonoff, 1985).

Short sediment cores were collected with a percussion corer designed to retrieve an undisturbed sediment water interface. The uppermost, unconsolidated sediments of each core were extruded in the field by upward extrusion into a sampling tray fitted to the top of the core barrel. Deeper core sections were stored in polycarbonate tubes, and either transported intact to the University of Pittsburgh or to the National University of Mongolia for sampling, and ultimately stored in cold room facilities at 4°C.

All sediment cores were split, photographed, and Munsell color, texture, and sedimentary structures noted. Diatom samples were counted on sediment samples from one northern Mongolian lake (Sanjin Nuur) using untreated smear slides due to the high abundance of unaltered diatoms present in the sediment (Table 3). A minimum of 300 diatom valves were identified and cataloged using a compound microscope with oil immersion optics at 1000′ magnification. Taxonomy of diatoms was based on Krammer & Lange-Bertalot (1986; 1991) and Flower *et al.* (1998).

Radiocarbon ages were determined on

Table 3. Diatom species present in Sanjin Nuur core SN-B-03 sediments

Diatom species	Average occurrence from all analysed samples (percent, n = 85)	Diatom species	Average occurrence from all analysed samples (percent, n = 85)
Aulocoseira ambigua	0.2	*Fragilaria tenera*	2.7
Aulocoseira subarctica	0.2	*Fragilaria pinnata*	<0.1
Aulocoseira alpigena	0.8	*Fragilaria capucina*	0.3
Aulocoseira lirata	2.0	*Frustulia sp.*	<0.1
Amphora sp.	<0.1	*Gomphonema.sp*	0.1
Amphora libyca	<0.1	*Karayvia sp.*	<0.1
Asterionelle formasa	0.5	*Neidium sp.*	<0.1
Achnanthes sp.	<0.1	*Navicula sp.*	0.1
Achnanthes latestrota	<0.1	*Navicula sp. (small)*	<0.1
Achnanthes sp. (egg)	0.1	*Navicula cf. atomus*	<0.1
Achnanthes stolida	0.1	*Nitzschia sp.*	<0.1
Achnanthidium minutissimum	1.1	*Nitzschia cf. recta*	<0.1
Cyclotella sp.	72.0	*Nitzschia palea*	<0.1
Cymbella sp.	<0.1	*Nitzschia debilis-sippen*	<0.1
Craticula sp.	<0.1	*Pseudostaurosira brevistriata*	0.5
Diatoma sp.	<0.1	*Pinnularia sp.*	<0.1
Encyonema sp.	0.1	*Pinnularia lundii*	<0.1
Encyonema minuta	0.1	*Pinnularia braunii*	<0.1
Eunotia sp.	0.1	*Pinnularia divergentissima*	<0.1
Eunotia praerupta	<0.1	*Pinnularia interrupta*	<0.1
Eunotia muscicola var tridentula	<0.1	*Pliocaenicus costatus var sibiricus*	18.8
Eunotia subarcuotoides	<0.1	*Stauroneis foenicentron*	<0.1
Eunotia sp.	<0.1	*Stauroneis sp.*	<0.1
Eunotia bilunaria	<0.1	*Stauroneis ancept*	<0.1
Eunotia muscicola var muscicola	<0.1	*Surirella sp.*	<0.1
Euntotia monodon var bidens	<0.1	*Tabellaria flocculosa*	0.1
Epithema sp.	<0.1	*Tabellaria fenestrata*	<0.1
		Tetracycles sp.	<0.1

Table 4. Radiocarbon age dates

Lab number	Core	Depth (m)	Sample type	$\delta^{13}C$	Radiocarbon age (yr. B.P.)	Error (+/- yr)	Median probability calibrated age (cal yr B.P.)	1-Sigma calibrated age range (cal yr B.P.)	2-Sigma calibrated age range (cal yr B.P.)
UCI-25172	SAN-A-6-VIII-05	1.03	Aquatic macro	-15.4	2360	20	2354	2343-2359	2338-2456
UCI- 25167	MUS-A-7-VIII-05	1.07	Aquatic macro	---	8380	90	9376	9293-9488	9136-9532
UCI-25165	GAN-B-10-VIII-05	1.00	Aquatic macro	-19.7	1450	20	1337	1312-1350	1304-1376
UCI-25167	TSO-A-9-VIII-05	1.29	Aquatic macro	---	8710	40	9655	9560-9699	9547-9816
UCI-25164	BAT-A-8-VIII-05	1.19	Aquatic macro	---	7255	35	8085	8014-8157	8000-8167
UCI-25166	MAN-A-8-VIII-05	1.56	Aquatic macro	---	865	15	764	742-780	733-792

sediment samples from six lakes by accelerator mass spectrometry (AMS) at the University of California - Irvine Keck Carbon Cycle AMS Facility (UCI; Table 4). All samples consisted of aquatic plant macrofossils and were pretreated with standard acid-base-acid techniques (Abbott & Stafford 1996). Calibrated ages were determined with the CALIB REV4.4.2 Radiocarbon Calibration Program (Stuiver & Reimer 1993; Stuiver *et al.*, 2005) and presented in cal yr B.P. (1950 = 0 cal yr B.P.).

Results

All surveyed lakes were located between 46-52°N and 95-102°E (Fig. 1). For ease of discussion we group lakes by their latitudinal location. Central Mongolian lakes are considered those present between N46°00' and N48°00' (n = 3). North-central Mongolian lakes are those present between N48°00' and N50°00' (n = 12). Northern Mongolian lakes are those present at latitudes higher than N50°00' (n = 6).

Central Mongolian Lakes

All central and north-central Mongolian surveyed lakes are of deflation basin origin. They primarily reside in granodiorite bedrock and have large surface area/depth ratios. They are all located in steppe, forest steppe, or dessert-steppe ecosystems. When visible inputs or outputs were seen, the lakes were given an open basin status, although the large surface area of some lakes prohibited proper investigation of basin hydrology. The assignment of an open basin status to the central and north-central lakes is therefore largely arbitrary, and the assumption that lakes are not open systems should be taken with caution.

Shireet Nuur (Table 1) is located within the Naiman Nuur protected area. The northeastern basin was explored for this study and yielded a maximum depth measurement of 6.0 m. The water temperature profile spanned 14.0°C at the surface water interface to bottom water values of 9.1°C and lacked a clear thermocline (Table 2). DO values spanned 9.84 – 8.83 mg L^{-1} and similarly exhibit a generally homogeneous profile. Water conditions were basic (pH 8.32 - 9.65), fresh (SpC 0.068 mS cm^{-1}, TDS 44.1 mg L^{-1}), and moderately clear (Z_{secchi} = 3.5 m). Sediment core SHR-A-25-VI-05 (Table 1) consists of homogenous clay with no visible stratigraphic horizons.

Höh Nuur (Table 1) is an open system consisting of a western and southern basin, of which only the southern basin was investigated due to inclement weather. The southern basin is entirely surrounded by raised grasslands, while the western basin is surrounded by steep-sided hills. The lake has a surface area of approximately 13.0 km^2. Depths of up to 12.0 m were observed, but local residents claim the western basin is deeper with submerged trees present. Local residents also claim shell materials are often found along the shoreline, although no shell materials were observed during the time of sampling. The temperature profile exhibited an isothermal profile with values ranging from 10.2 – 9.4°C (Table 2). DO had its highest concentration (9.84 mg L^{-1}) at the air-water interface. Water conditions were slightly basic (pH 8.14 - 8.90), fresh (SpC 0.059 mS cm^{-1}, TDS 37.7 mg L^{-1}) and extremely clear (Z_{secchi} = 8.0 m). Sediment core HOH-A-27-VI-05 (Table 1) sediments consist of dark brown homogenous clay with no visible stratigraphic ho-

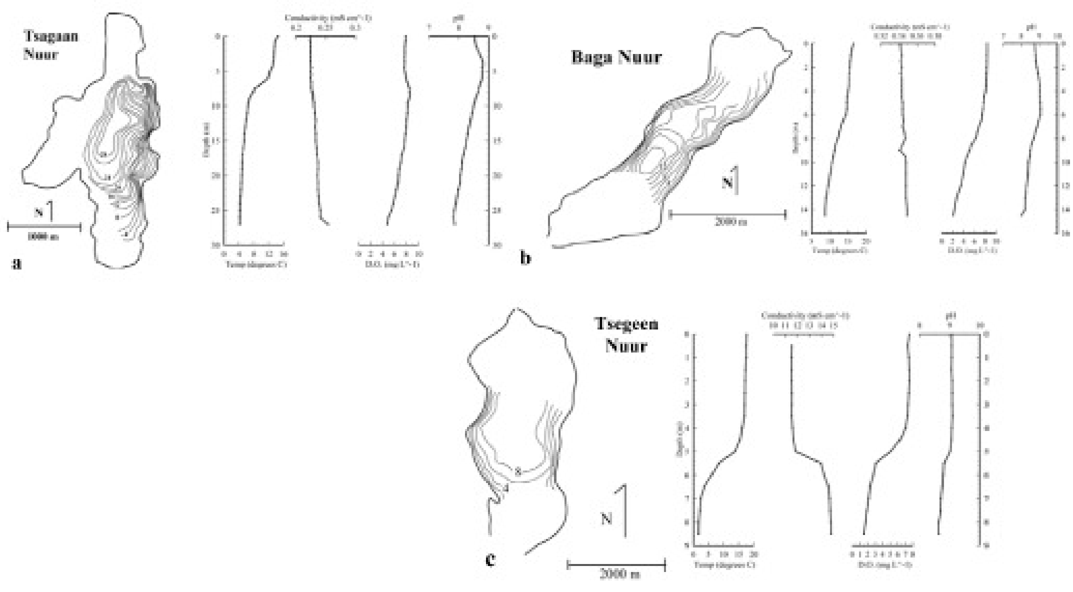

Figure 2. (a) Tsagaan Nuur bathymetric map and water column physical profile, (b) Baga Nuur bathymetric map and water column physical profile, (c) Tsegeen Nuur bathymetric map and water column physical profile.

rizons.

Tsagaan Nuur (Table 1) is an open system located within the Otgon Tenger Strictly Protected Area. A large central basin and a smaller western basin are present, with only the central basin being studied (Fig. 2a). The lake has a surface area of approximately 3.5 km^2, and a maximum observed depth of 28.0 m. Water temperatures ranged from 14.5 – 4.2°C with a clear thermocline present at a depth of 6.0 m (Fig. 2a, Table 2). DO values ranged from 8.60 – 4.77 mg L^{-1} and exhibited a slight metalimnetic oxygen maximum, likely attributed to phytoplankton growth. The water was slightly basic (pH 8.54 – 7.87), fresh (SpC 0.22 mS cm^{-1}, TDS 158 mg L^{-1}), and moderately clear (Z_{secchi} = 5.2 m). Sediment core TSA-A-3-VI-05 (Table 1) consists of organic rich clay with thick beds (>10 cm) to diffuse sub-millimeter laminations. Sediment core TSA-B-3-VI-05 (Table 1) consists of massive gravel material with no visible stratigraphic features.

North-Central Mongolian Lakes

Terkhiin Tsagaan Nuur (Table 1) is a relatively large open system with two east-west basins and a surface area of approximately 60 km2. A maximum depth of 14.0 m was found in the central area of the western basin. Water temperatures ranged from 13.6 – 9.6°C with a thermocline present from 7.0 – 9.0 m (Table 2). DO values ranged from 8.46 – 5.77 mg L^{-1} and exhibited a clinograde profile. The water was basic (pH 8.33 – 8.01), fresh (SpC 0.0149 mS cm^{-1}, TDS 96 mg L^{-1}), and relatively clear (Z_{secchi} = 2.4 m). Sediment core TTN-A-29-VI-05 (Table 1) consists of bioturbated organic clay with no visible stratigraphic horizons.

Khar Nuur (Table 1) is present in a desert/steppe ecosystem surrounded by grasslands to the south and sand dune fields to the north (Fig. 3). Abundant shell material was present along the shoreline. A maximum depth of 12.8 m was observed in the central region of the lake. Water temperatures ranged from 13.9 – 9.7°C with a slight thermocline occurring from 4.0 - 6.0 m (Table 2). Dissolved oxygen values ranged from 8.96 – 7.81 mg L^{-1} with the highest values occurring in the bottom waters. The water was basic (pH 8.9 – 9.6), slightly brackish (SpC 0.545 mS cm^{-1}, TDS 355 mg L^{-1}), and clear (Z_{secchi} = 4.0 m). Sediment core HAR-A-04-VII-05 (Table 1) consists of organic rich clay with trace shell fragments and visible stratigraphic horizons. Thin beds (<10 cm) to laminations (<1 cm) are present in the sediment core, including thin (<10 cm) sand deposits (Fig. 4b).

Baga Nuur (Table 1) is located just northwest of Khar Nuur with a sand dune field separating the lakes (Fig. 3). A maximum depth of 15.0 m was observed in the central region of the lake. Water temperatures ranged from 16.6 – 8.7°C with a slight thermocline occurring from 6.0 – 8.0 m (Table 2; Fig. 2b). DO values ranged from 8.38 mg L^{-1} at the surface-water interface to 2.15 mg L^{-1} at bottom depths. The water was basic (pH 9.07 – 8.00) with the highest observed pH values occurring in the depths directly overlying the thermocline. The water was fresh (SpC 0.345 mS cm^{-1}, TDS 218 mg L^{-1}) and relatively turbid (Z_{secchi} = 1.3 m). Abundant macrophyte communities surrounded the shoreline to a water depth of 4.0 m. Sediment cores BAG-A-05-VII-05 and BAG-B-05-VII-05 (Table 1) consist of organic rich clay with shell fragments and sand horizons (Fig. 4a).

Tsegeen Nuur (Table 1; Fig. 3) has a maximum observed depth of 8.5 m in the central region of the lake (Table 2). Water temperatures ranged 17.66°C to 1.71°C with a clear thermocline present at 5.0 - 6.5 m (Fig. 2c). Tsegeen Nuur water was mesosaline (SpC 12.8 mS cm^{-1}, TDS 10,691 mg L^{-1}) and basic (average pH 8.9). DO values showed a strong clinograde profile with values ranging from 7.52-1.71 mg L^{-1}. Water clarity was low (Z_{secchi} = 0.5 m). Sediment core TGN-A-06-VII-05 (Table 1) consists of grey clay with thin-to-medium beds of highly organic black clay. Diffuse laminations are present in the organic horizons (Fig. 4d).

Kholboo Nuur (Table 1) consists of two large basins connected by a small intermittent strait (Fig. 5). Only the northeastern basin was explored for this study. Maximum observed depth of 8.5 m occurred along the southwestern shore (Table 2). Water temperatures were relatively consistent (15.5 – 15.0°C), and DO displayed a homogeneous profile (8.00 – 7.16 mg L^{-1}). The water was basic (9.38 – 9.24 pH), oligosaline (SpC 2.67 mS cm^{-1}, TDS 1726 mg L^{-1}), and relatively turbid (Z_{secchi} = 1.3 m). Sediment core HOL-A-01-VII-05 (Table 1) consists of clay with interspaced diffuse sub-

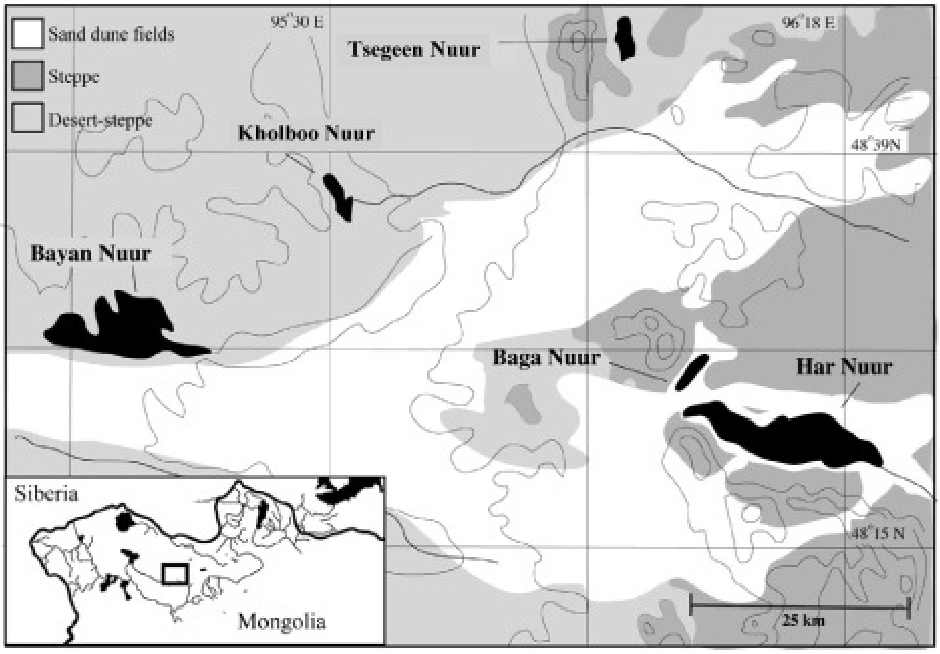

Figure 3. Map showing spatial distribution of Kholboo Nuur, Khar Nuur, Baga Nuur, Bayan Nuur, and Tsegeen Nuur as well as surrounding lakes and ecological zones.

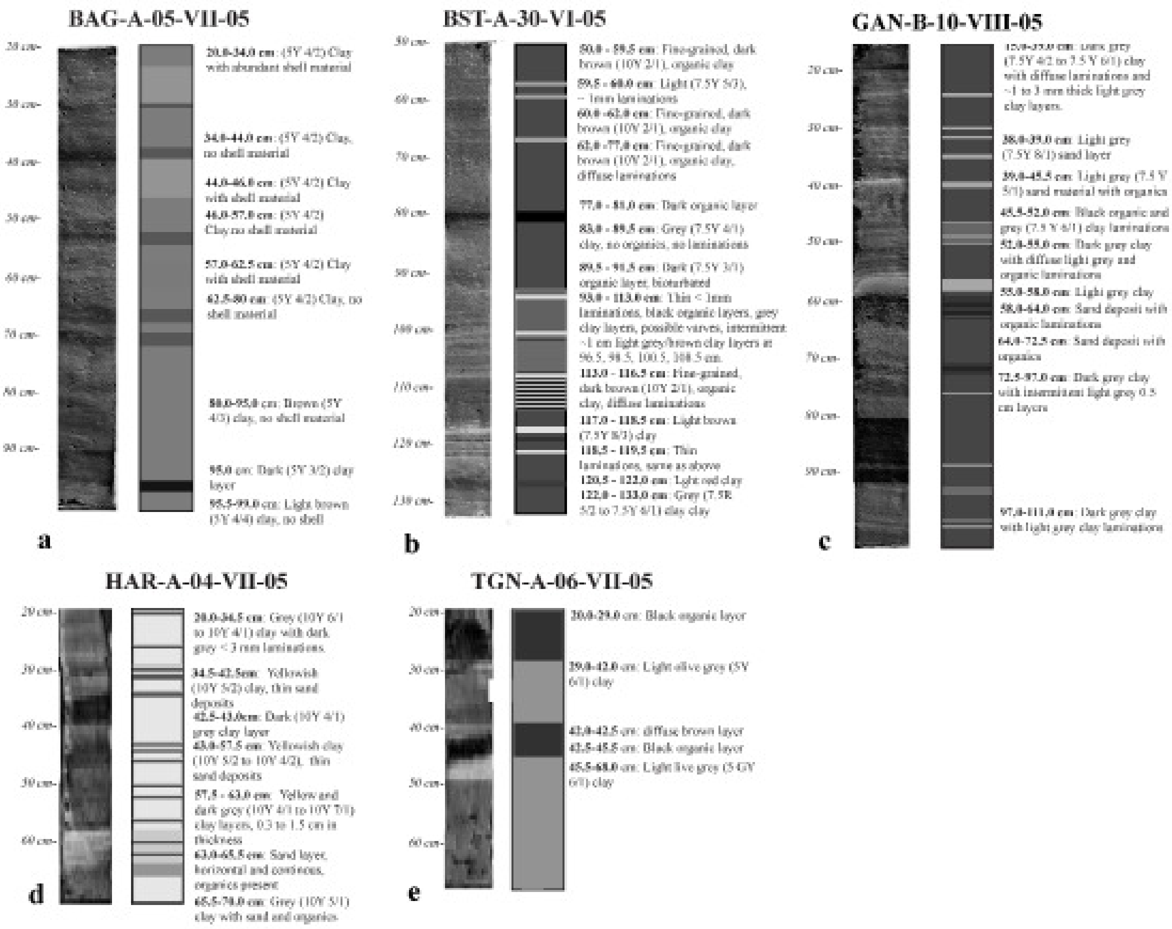

Figure 4. Stratigraphic descriptions of core samples (a) BAG-A-05-VII-05, (b) HAR-A-04-VII-05, (c) BST-A-30-VI-05, (d) TGN-A-06-VII-05, (e) GAN-B-10-VIII-05.

millimeter dark and light brown laminations and limited bioturbation.

Oigon Nuur (Table 1) is a large (surface area approximately 73.5 km^2), shallow (Z_{max} = 3.5 m) (Table 2), mesosaline lake located northwest of Kholboo Nuur (Fig. 5). Due to extremely inclement weather, neither water quality data nor sediment cores were acquired.

Bust Nuur (Table 1) is a relatively large lake northwest of Kholboo Nuur (Fig. 5). The lake is circular with a small island located in the center. Only the lake area northwest of the island was surveyed for this investigation. A maximum depth of 12.0 m was found (Table 2). Water temperatures ranged from 14.6°C to 5.5°C with a clear thermocline at 7.0 - 9.0 m depth. The DO values ranged from 9.1 – 3.8 mg L^{-1} and the DO profile was consistent with the temperature profile. The water was basic (pH 9.2) and oligosaline (SpC 3.19 mS cm^{-1}, TDS 2388 mg L^{-1}). Sediment core BST-A-30-VI-03 (Table 1) consists of organic-rich clay with visible stratigraphic horizons. Multiple sections of diffuse sub-millimeter laminations exist within the core with massive intervals of organics and clay (Fig. 4c).

Zuun Nuur (Table 1) is relatively large lake (surface are approximately 17.5 km^2) located southeast of Sangiin Dalai Nuur (Fig. 6). Only the western basin was investigated in this study. A maximum observed depth of 12.7 m occurred just east of the large southwestern peninsula (Table 2). Water temperatures were relatively consistent (14.0 - 13.4°C), and DO displayed a homogeneous profile (6.18 – 5.00 mg L^{-1}). The water was basic (pH 8.99 – 9.04), oligosaline (SpC 4.670 mS cm^{-1}, TDS 3254 mg L^{-1}), and turbid (Z_{secchi} = 1.0 m). Sediment core ZUN-A-16-VIII-05 (Table 1) consists of grey fine clay with visible stratigraphic horizons. Multiple sets

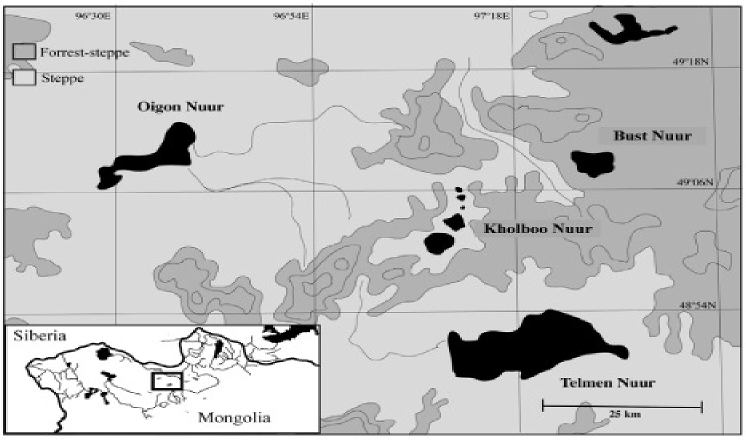

Figure 5. Map showing spatial distribution of Kholboo Nuur, Bust Nuur, and Oigon Nuur as well as surrounding lakes and ecological zones.

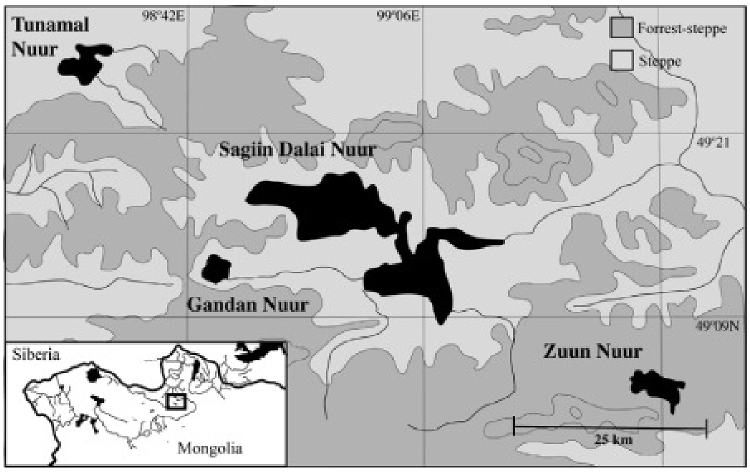

Figure 6. Map showing spatial distribution of Gandan Nuur, Sangiin Dalai Nuur, Zuun Nuur and Tunamal Nuur as well as surrounding ecological zones.

of sub-millimeter laminations, silt layers, sand layers, and organic horizons are present.

Gandan Nuur (Table 1) is located southwest of Sangiin Dalai Nuur (Fig. 6) and has maximum observed depth of 5.2 m located in the center region of the lake (Table 2). Abundant macrophytes were present throughout the lake. Water temperatures were consistent to a depth of 4.5 m (14.3°C) and DO displayed a homogeneous profile (6.18 – 6.11 mg L^{-1}). The water was slightly basic (pH 8.71) and fresh (SpC 0.398 mS cm^{-1}, TDS 243 mg L^{-1}). Secchi depth measurements were not taken and a sediment core was not retrieved due to inclement weather.

Sangiin Dalai Nuur (Table 1) is the largest lake (surface area approximately 181.9 km^2) in this study and is comprised of two large basins (Fig. 6). Only the southeastern basin was surveyed due to the extreme size of this lake. A maximum depth of 6.5 m was found 3.5 km offshore (N49°11.034, E099°01.990). All physical characteristics measured throughout the water column displayed a consistent profile. The water was warm throughout (15.5°C), basic (pH 9.2), oligosaline (SpC 5.06 mS cm^{-1}, TDS 3411 mg L^{-1}), and DO values were high (5.06 mg L^{-1}). No sediment cores were retrieved due to high wave action and inclement weather.

Tunamal Nuur (Table 1; Fig. 6) has a maximum depth of 9.7 m observed in the central region of the lake (Table 2). Water temperatures were consistent throughout the water column (16.3 – 15.8°C) and DO displayed a homogeneous profile (9.07 - 9.10 mg L^{-1}). The water was basic (9.07 pH), oligosaline (SpC 5.65 mS cm^{-1}, TDS 3724 mg L^{-1}), and turbid (Z_{secchi} = 1.0 m). Sediment core TUN-A-14-VIII-05 (Table 1) consists of highly organic dark grey clay. Two distinct clay horizons make up the majority of the core with sub-millimeter diffuse laminations present in the basal sediments.

Tsavdan Nuur (Table 1) is a hypersaline lake with a consistent depth of 1.0 m. A thick salt crust was present at the sediment water interface and active salt precipitation was occurring in the water column. Sediment core TVD-A-06-VII-05 (Table 1) was retrieved through a perforation in the salt crust and consists of course grained dark grey clay with dipping sand and gravel deposits.

Northern Mongolian Lakes

All northern lakes associated with this study are open systems located within the Baruun Taiga mountain complex west of the Darkhad Valley, Hövsgöl Aimag (Fig. 7). The lakes

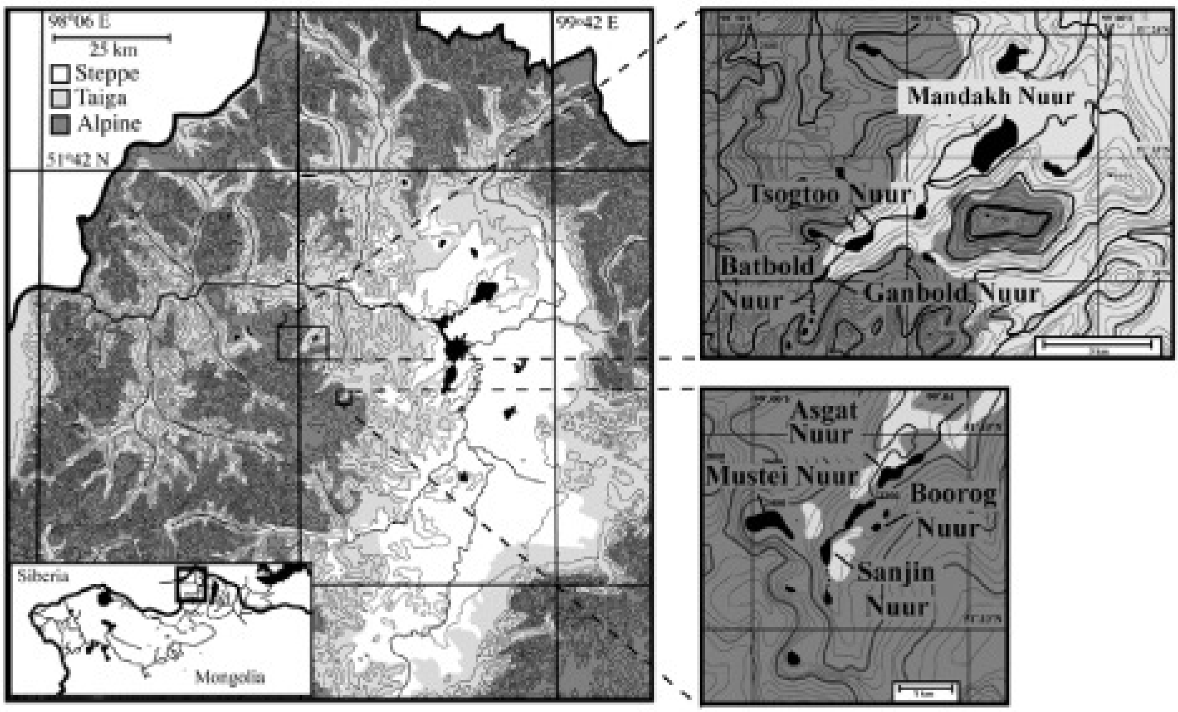

Figure 7. Locations of surveyed lakes in the Baruun Taiga Mountains of northern Mongolia. The lakes are present in two glacially-scoured valleys located approximately 15 km apart and are at the alpine tundra/taiga transition zone.

all straddle the local tree line and the taiga/alpine tundra transition zone. Evidence for late Pleistocene glaciation in the watershed is provided by the presence of cirque and moraine complexes and surveyed lakes likely originate from pro-glacial processes. The region is characterized by continuous permafrost.

Sanjin Nuur (Table 1) is a paternoster lake positioned at the headwall of the lower valley and drains northeastward (Fig. 7). Hydrologic inputs are limited to overflow from a small basin located to the south and snowmelt from the limited catchment (~1.0 km^2). A maximum depth of 17.4 m was observed in the southern regions of the lake with an average depth of 3.1 m (Table 2; Fig. 8a). The lake has a surface area of approximately 0.09 km^2. The lake was thermally stratified with water temperatures varying from an air-water interface value of 11.9°C to a water-sediment interface value of 4.6°C. A clear thermocline was visible at 6.0 - 8.0 m. The DO profile displayed a slight positive heterograde profile with a metalimnetic oxygen maxima occurring at 6.5 m (7.99 mg L^{-1}). The pH of the water was circumneutral (7.75 – 6.87 pH) with a maximum value occurring at the metalimnion. The lake water was extremely fresh (SpC 0.01 mS cm^{-1}, TDS 9.00 mg L^{-1}) and transparent (Z_{secchi} = 4.8 m). Four sediment cores (Table 1) ranging in length from 0.83 – 1.10 m consist of homogeneous diatomaceous clay with limited visible stratigraphic horizons. A basal age of approximately 2350 cal yr B.P. was determined on one Sanjin Nuur sediment core (SAN-A-6-VIII-05; Table 4).

The sediments of Sanjin Nuur core SN-B-03 contain 54 diatom species (Table 3) of 25 genera. The dominant species present in the sediments is an unidentified *Cyclotella* that is closely allied to *C. rossii* (Grunow) Håkansson. Other species that are abundant (>5% in any one sample) include *Pliocaenicus costatus* var *sibiricus*, *Fragilaria tenera*, *Achnanthidium minutissimum*, *Aulacoseira alpigena*, *Aulacoseira lirata*, *Aulacoseira ambigua*, and *Pseudostaurosira brevistriata*.

Mustei Nuur (Table 1) is located in a cirque formation above local tree-line (Fig 7). The only hydrologic input is surface runoff from its highly limited catchment. A maximum depth of 28.0 m was observed along the western shoreline (Table 2; Fig. 8b). The lake was thermally stratified with water temperatures varying from 14.0°C at the surface waters to a bottom water value of 5.1°. A clear thermocline was present at 6.0 - 8.0 m water depth. The lake is ultra-oligotrophic with an average specific conductivity value of 0.007 mS cm^{-1}. The water was circumneutral (pH 7.08), extremely fresh (SpC 0.007 mS cm^{-1}, TDS 7.00 mg L^{-1}) and exceptionally transparent (Z_{secchi}

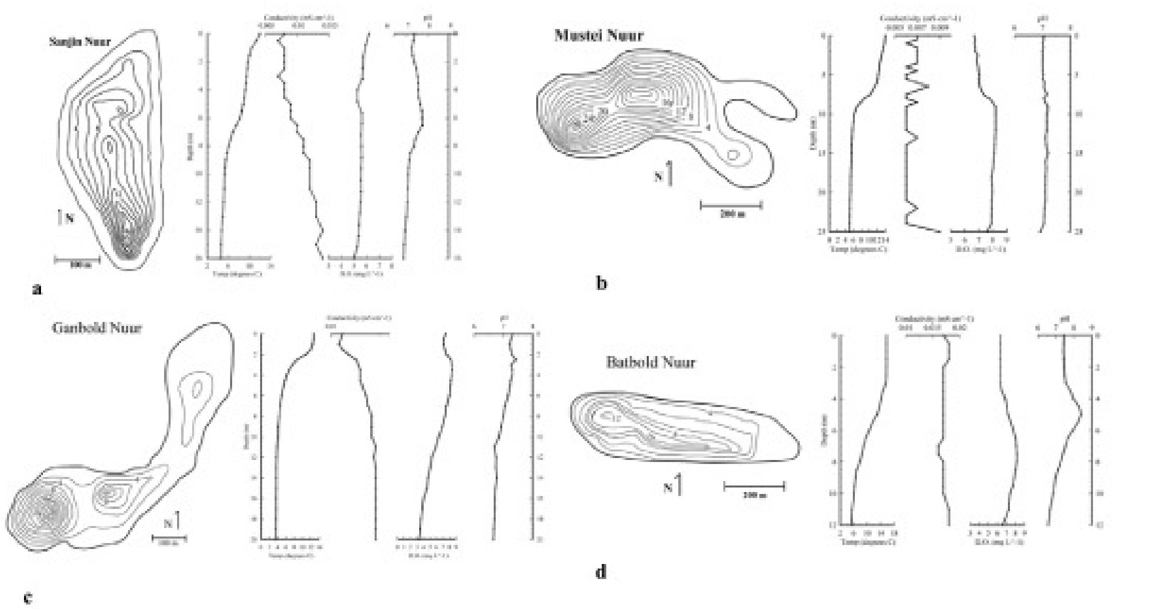

Figure 8. (a) Sanjin Nuur bathymetric map and water column physical profile, (b) Mustei Nuur bathymetric map and water column physical profile, (c) Ganbold Nuur bathymetric map and water column physical profile, (d) Batbold Nuur bathymetric map and water column physical profile.

= 11.2 m). Sediment core MUS-A-7-VIII-05 (Table 1) consists of diatomaceous clay with visible stratigraphic horizons and has a basal age of approximately 9370 cal yr B.P. (Table 4). Organics, silt and sand layers, bedding, and laminations are present throughout the sediment core.

Ganbold Nuur (Table 1) is located at the headwall of a valley with hydrologic inputs from several small basins located in the surrounding cirque complexes (Fig. 7). A maximum depth of 21.9 m was observed in along the southern shoreline (Table 2; Fig. 8c). The lake was thermally stratified with water temperatures varying from 12.7°C at the surface waters to 3.7°C at the bottom waters; the thermocline occurred at 1.5 - 3.0 m water depth. The dissolved oxygen values vary from a surface water value of 7.44 mg L^{-1} to a bottom water value of 3.32 mg L^{-1} and showed a positive heterograde profile with a metalimnetic oxygen maxima occurring at 3.5 m (8.38 mg L^{-1}). The water was circumneutral (pH 7.01), extremely fresh (SpC 0.027 mS cm^{-1}, TDS 20.00 mg L^{-1}), and highly transparent (Z_{secchi} = 5.6 m). Sediment cores GAN-A-10-VIII-05 and GAN-B-10-VIII-05 (Table 1) consist of diatomaceous clay with thick bedding and thin organic and silt laminations (Fig. 4e). A basal age of approximately 1330 cal yr B.P. was determined in core GAN-B-10-VIII-05 (Table 4).

Tsogtoo Nuur (Table 1) is located down-valley of Ganbold Nuur (Fig. 7). Its main hydrologic inputs are overflow from Ganbold Nuur and Batbold Nuur. A maximum depth of 4.0 m was observed in the central region of the lake (Table 2). Due to the shallow nature and the assumed homogeneity of the lake, only surface waters were measured for physical characteristics. Tsogtoo Nuur surface water had a temperature of 16.6°C, DO concentration of 6.3 mg L^{-1}, a pH of 7.62, and was fresh (SpC 0.017 mS cm^{-1}, TDS 15.0 mg L^{-1}). Light penetrated throughout the entire water column ($Z_{secchi} = Z_{max}$). Sediment core TSO-A-9-VIII-05 (Table 1) consists of homogenous clay with no visible stratigraphic horizons and has a basal age of approximately 9650 cal yr B.P. (Table 4).

Batbold Nuur (Table 1) is present above tree line in a cirque formation located directly west of Tsogtoo Nuur (Fig. 7). Its only hydrologic input is surface flow from its limited catchment. A maximum depth of 15.5 m was observed in the central regions of the lake (Fig. 8d). The lake is thermally stratified with water temperatures varying from surface water values of 15.8°C to bottom water values of 5.3°C, and has a thermocline occurring from 5.0 - 7.0 m (Table 2). The DO profile exhibits an orthograde profile with maximum values occurring at 7.5 m. The water had pH values ranging from 8.4 – 6.6 with a maximum value at 5.0 m, and was fresh (SpC 0.017 mS cm^{-1}, TDS 14.0 mg L^{-1}). Sediment core BAT-A-8-VIII-05 (Table 1) consists of clay with diffuse massive transitions and has a basal age of approximately 8080 cal yr B.P. (Table 4).

Mandakh Nuur (Table 1) is the lowest and largest (surface area approximately 1.4 km^2) surveyed lake within the Baruun Taiga Mountains (Fig. 7). A maximum depth of 6.0 m was observed in the central region of the lake (Table 2). Water temperatures ranged from 18.4°C at surface waters to 10.4°C at bottom waters. Dissolved oxygen increased with depth from 6.16 – 7.11 mg L^{-1}. The water pH had an average value of 7.0 and was fresh (SpC 0.019 mS cm^{-1}, TDS 16 mg L^{-1}). Sediment core MAN-A-8-VIII-05 consists of organic-rich homogeneous clay with no visible stratigraphic horizons and has a basal age of approximately 760 cal yr B.P. (Table 4).

Discussion

In this study, the northern surveyed lakes are considered to be unique with respect to geological setting, physiolimnological and morphological characteristics, and origin, and are thereby discussed separately from the central and north-central lakes. The climate characteristics of the northern region are considered uniform across the northern lake systems as the area encompassing the northern surveyed lakes is relatively small (~180 km^2). Climatic variation is therefore not discussed as a mechanism for inter-lake physical and physiolimnological variations in the northern surveyed lakes. This assumption, coupled with the smaller surface area of the northern lake systems, allows for a more concise discussion of the mechanisms driving any inter-lake variability.

The overall large surface area of the central and north-central surveyed lakes resulted in a lack of specific data for some lakes (i.e.

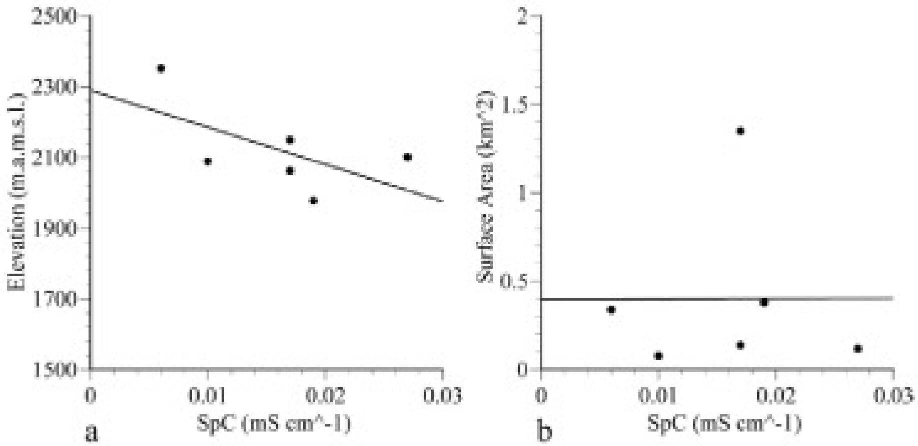

Figure 9. Specific conductivity values (mS cm^{-1}) plotted against a) elevation (m.a.s.l) and b) surface area (km^2) for the six surveyed northern Mongolian lake systems.

maximum depth, surface area). This lack of information, coupled with the significant spatial distribution of the lake systems, limits any discussion of inter-lake variability to general, large-scale influences (i.e. regional climate variations).

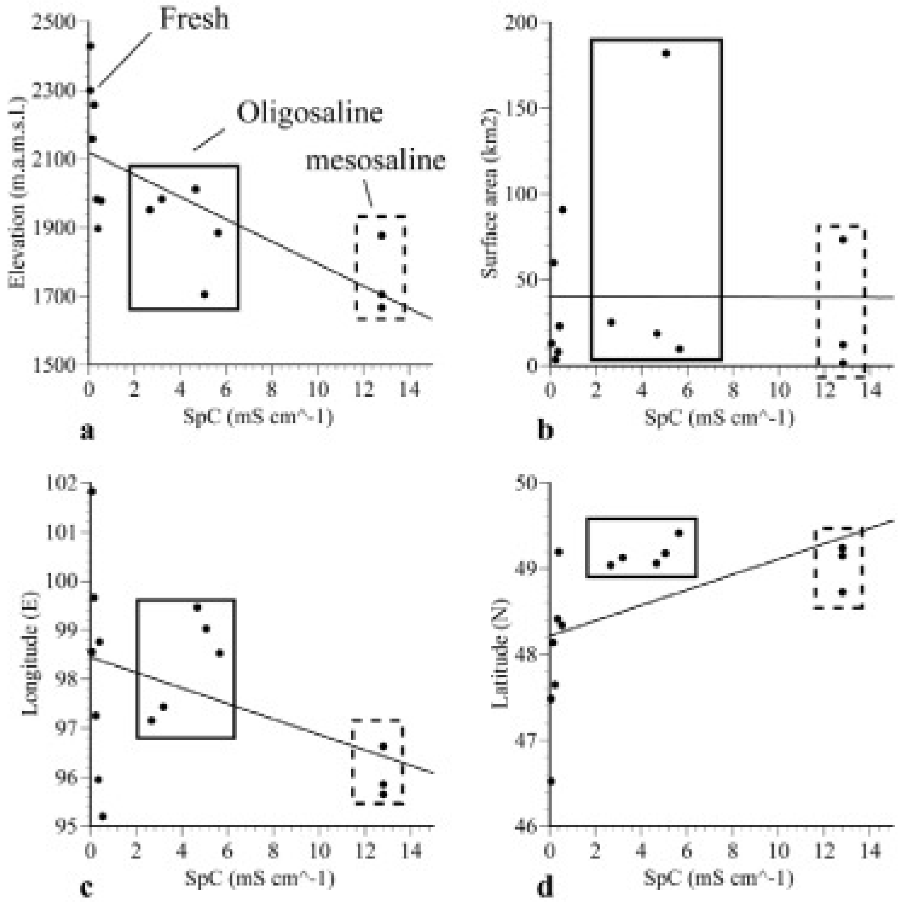

Figure 10. Specific conductivity values (mS cm^{-1}) plotted against (a) elevation (m.a.s.l.), (b) surface area (km^2), (c) longitude (°E), and (d) latitude (°N) for all the surveyed central and north-central Mongolian lake systems. The black rectangle encompasses the lakes designated as oligosaline and the dotted rectangle encompasses the lakes designated as mesosaline, determined from TDS concentrations. Specific lakes were omitted from the graphs dependent upon availability of data.

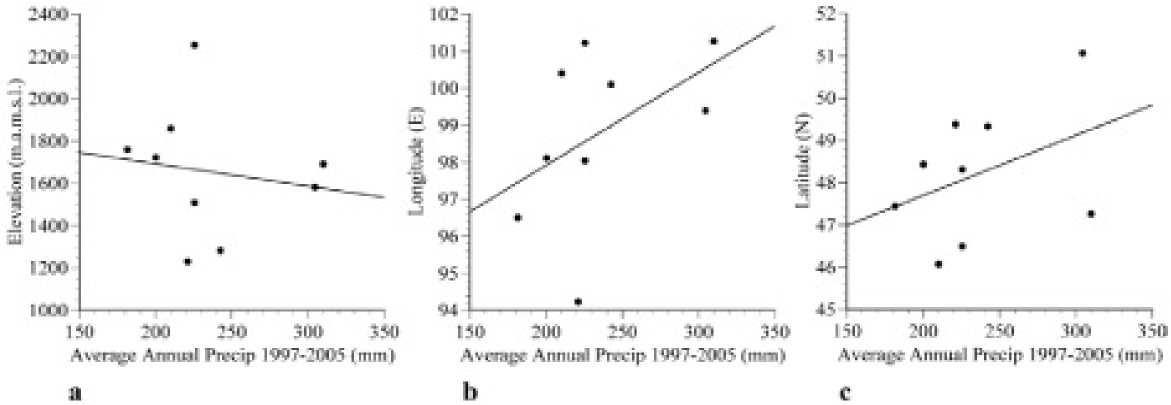

Figure 11. Average annual precipitation data from 1997-2005 from central/northern Mongolia WMO stations plotted against (a) station elevation, (b) station longitude, and (c) station latitude.

Factors Controlling Solute Concentrations in Mongolian Lake Water

The northern lakes varied little in their physical and physiolimnological characteristics, although a general negative correlation between elevation (i.e. valley placement) and SpC values exists (Fig. 9a). Such a correlation is expected, as a lower valley placement amplifies catchment size, increasing runoff and inflow sources and leading to a higher concentration of chemical solutes. Because the northern lakes are all open systems, elevation should be the dominant influence on solute concentration. This inference is supported by the lack of correlation between surface area and SpC concentrations (Fig. 9b).

Central and north-central surveyed lakes varied considerably in their surface area (1.45 to 181.9 km^2), elevation (1667 to 2625 m.a.s.l.), latitude (N46°31 to N49°25), longitude (E095°39 to E101°50) and specific conductivity (0.059 to 12.8 mS cm^{-1}). Based on TDS concentrations, the lakes can be characterized as fresh, oligosaline, or mesosaline. Similar to the northern lakes, elevation has a negative correlation to solute concentration (Fig. 10a) and no correlation to surface area (Fig. 10b). Precipitation rates rather than catchment placement are likely responsible for solute concentration in the central and north-central lakes. However, annual average precipitation totals for surrounding WMO weather stations (Table 5) show an increasing trend in precipitation with decreased elevation (Fig. 11a), suggesting that precipitation as a function of elevation does not play a major role in solute concentration. A pattern of increased specific conductivity with decreasing longitude is observed (Fig. 10c) and is in agreement with local precipitation patterns (Fig. 11b). Yet, specific conductivity concentrations increase with latitude (Fig. 10d), opposite to the precipitation trends (Fig. 11c).

Factors Controlling pH of Mongolian Lake Water

All northern surveyed lakes had circum-neutral waters. Any variation in pH between

Table 5. WMO station information for central/northern Mongolia

WMO station ID	Station name	Latitude °N	Loongitude °E	Elevation (m.a.s.l.)	Total average annual precip. 1997-2005 (mm)
44203	Rinchinlhumbe	51.07	99.4	1583	304.5
44213	BaruunTuruun	49.39	94.24	1232	221.1
44225	Tosontsengel	48.44	98.12	1724	200.3
44231	Muren	49.34	100.1	1283	242.5
44237	Erdenemandal	48.32	101.23	1510	225.5
44272	Uliastai	47.45	96.51	1761	181.5
44275	Bayanbulag	46.5	98.05	2255	225.5
44282	Tsetserleg	47.27	101.28	1693	310
44287	Bayanhongor	46.08	100.41	1860	210.1

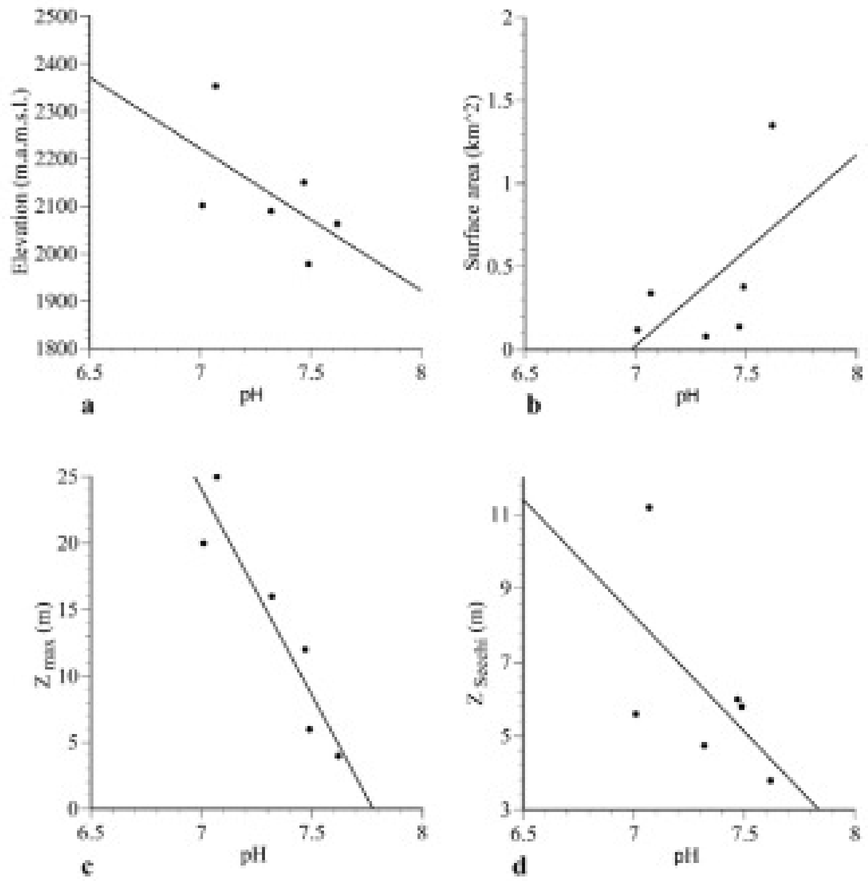

Figure 12. Average water pH verse (a) elevation (m.a.s.l), b) surface area (km^2), (c) maximum depth (m), and (d) Secchi disk depth (m) for the six surveyed northern Mongolian lake systems.

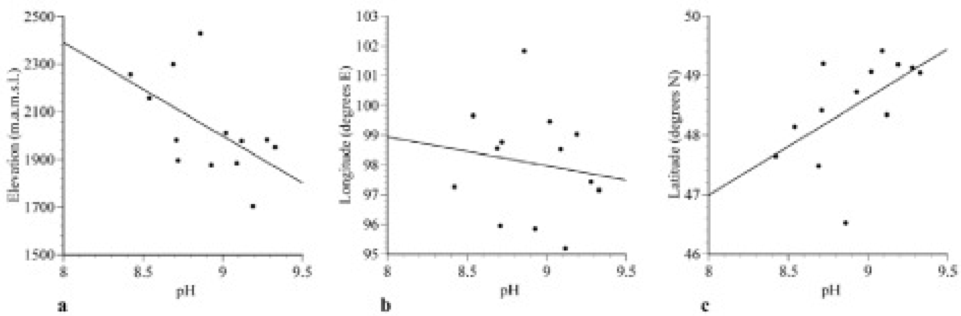

Figure 13. pH levels plotted against (a) elevation (m.a.s.l.), (b) longitude (ºE), and (c) latitude (ºN) for all the surveyed central and north-central Mongolian lake systems. Specific lakes were omitted from the graphs dependent upon availability of data.

such lake systems is likely to be a function of biological activity. A negative correlation between elevation and pH is found in these lake systems (Fig. 12a). These lakes straddle the local tree-line elevation. The catchments surrounding the upper lakes have thin and poorly developed soils with an exposed rocky substrate (metamorphosed granite) and sparse vegetation. The lower elevation lakes have soil development and vegetation within their broader catchment areas, likely resulting in an enhanced delivery of nutrients to the water column and, thereby, a high promotion of internal biological activity. The positive relation between pH and surface area (Fig. 12b) and the negative relation between pH and maximum depth (Fig. 12c) similarly suggest a biological component as the driving influence on water pH levels. The large shallow lakes provide a greater habitat for benthic species likely enhancing both biological diversity and production. The positive relation between pH and lake turbidity (Fig. 12d) support such inferences toward a biologically mediated mechanism.

The pH levels of the central and north-central lake systems are largely controlled by catchment specific processes, such as edaphic and/or hydrologic processes. If pH levels of such lake systems were determined by a climatic mechanism (i.e. precipitation), a positive relation between pH and elevation and longitude with a negative relation between pH and latitude would be expected, in accordance with the regional precipitation patterns (Fig. 11a-c). Actual findings (Fig. 13a-c) are in opposition to all of the above assumptions, supporting the inference of catchment specific pH determinants.

Conclusions

This survey provides basic but valuable information for twenty-one lake systems throughout central and northern Mongolia. The surveyed inflation depression lakes in central and north-central Mongolia exhibit a wide range of physical variation in their basin morphology, waters, and sediments, reflecting the complex geological, edaphic, and hydrologic conditions of the survey area. Using the data collected in this study, the lakes can be classified into three groups based upon chemical enrichment: fresh, oligosaline, and mesosaline. Evidence suggests catchment specific processes as determinates for inter-lake variability. The lakes located in the Baruun Taiga Mountains of northern Mongolia exhibit less physical variability, with any inter-lake variability likely attributed to valley placement (i.e. elevation).

Further investigation into the chemical make-up of each lake system is required before any accurate characterization can be completed. Major ion concentrations should be measured to examine the internal nutrient and chemical dynamics of each individual system. Furthermore, $\delta^{18}O$ and δD ratios of water samples should be measured to properly assign each lake system an open or closed basin status. The lake sediment cores also stand to provide a wealth of information about the lakes' ages, biological communities, chemistries, and the histories of regional climatology and ecology both within lakes and their surrounding watersheds. Therefore, with more intensive analysis of the materials collected as part of this survey, the basic nature of each lake system as presented by this investigation may be expanded to a complex and holistic study of the limnological and paleolimnological dynamics of each lake system, providing a more thorough understanding of the mechanisms determining inter-lake variability on a both spatial and temporal scales.

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