



Alaska Shallow Lake Monitoring Program

Limnology of Denali National Park and Preserve

Natural Resource Data Series NPS/CAKN/NRDS—2012/410



ON THE COVER

View of Alaska Range from a Shallow Lake in Denali National Park and Preserve
Photograph by Amy Larsen

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Introduction

The Central Alaska Network Vital Signs Monitoring Program is based on a conceptual model that emphasizes the fundamental importance of water in the structure and function of park ecosystems. The network focuses water monitoring on two types of water resources, shallow lakes and streams. In 2006, the Central Alaska Network (CAKN) began implementing the Shallow Lake Monitoring Project. The goal of the project is to monitor the physical, chemical and biological properties of standing water. Shallow lakes and ponds were selected as the medium for monitoring standing water for three primary reasons: 1) they are abundant, 2) they provide diverse ecological functions, and 3) they are sensitive to climate warming. In 2009, the Arctic Network (ARCN) adopted the Shallow Lake Monitoring Protocol (SLMP) and we began monitoring shallow lakes in ARCN parks as well.

Rationale for Sampling Shallow Lakes

Abundance

Tens of thousands of lakes are distributed throughout the National Parks and Preserves in the subarctic and arctic zones of Alaska. Lake density ranges greatly across the two networks from low density areas in the mountains of Wrangell-St. Elias National Park and Preserve to high densities in Bering Land Bridge National Preserve. This wide distribution across a variety of landscapes allows ample opportunity to access and sample lakes throughout the network parks, and provides an excellent platform for field experiments.

Ecological Diversity

Shallow lakes serve a diverse array of ecological functions. The interactions of physical, biological and chemical components of a shallow lake, such as soils, water, plants and animals, enable the ecosystem to perform vital services including flood abatement, water quality improvement, biodiversity enhancement, carbon management, and aquifer recharge (Mitsch and Gosselink, 1986). In addition, lakes behave as microcosms, or small theatres where the ecological interactions of organisms and their environment can be more easily tracked. Because they have distinct boundaries, they are easier to sample than other wetland ecosystems.

Climate Change Implications

Data collected over the past 50 years shows that shallow lakes are sensitive to climate warming and that these important ecosystems are at risk of disappearing. Research conducted in Alaska (Riordan *et al.*, 2006; Klein *et al.*, 2005; Yoshikawa *et al.*, 2002) and Russia (Smith *et al.*, 2005) indicates that lakes in the Subarctic are decreasing in size and number.

Shallow lakes are sensitive to climate warming because permafrost, common in Alaska, prevents infiltration and impedes drainage of the upper unfrozen soil layers (Ford and Bedford, 1987). Extensive permafrost degradation has been documented in western Canada (Beilman *et al.*, 2001), Russia (Pavlov, 1994), China (Ding, 1998), Mongolia (Sharkuu, 1988) and interior Alaska (Osterkamp *et al.*, 2000).

Several studies in Alaska have linked lake drying with permafrost degradation (Yoshikawa and Hinzman, 2003), (Jorgenson *et al.*, 2001). When permafrost degrades and the thawed ground

sinks below the current water level, new wetlands are often formed. On the other hand, if permafrost degradation enhances drainage, as often happens in upland areas, wetlands can be converted into a drier ecosystem. Under either condition, permafrost degradation changes the hydrologic cycle altering wetland ecosystems. While relatively few studies have focused on the physical and chemical properties of the shallow lakes undergoing these changes, the few that have been conducted demonstrate that these systems are changing both physically and chemically (Schindler *et al.*, 1996).

Shallow Lake Monitoring Objectives

With these important distribution, ecosystem and climate change issues in mind, the monitoring project for the networks has developed four measurable objectives:

1. Detect decadal-scale trends in the area, distribution, and number of shallow lakes and ponds in Central Alaska and Arctic Network Parks.
2. Detect decadal-scale trends in the water quality of shallow lakes and ponds in Central Alaska and Arctic Network Parks.
3. Detect decadal-scale trends in the structure and composition of vegetation in shallow lakes and ponds in Central Alaska and Arctic Network Parks.
4. Detect decadal-scale trends in macroinvertebrate taxa richness in shallow lakes and ponds in Central Alaska and Arctic Network Parks.

In addition to addressing these basic objectives we seek to better understand the spatial and temporal variation among lakes in this complex environment.

Methods

Synoptic Sampling

Study Area

Synoptic samples were collected from 122 lakes in Denali National Park and Preserve (DENA) seasonally from 2006 to 2008 (Figure 1). We sampled lakes DENA-001 to DENA-030 in 2006. In 2007 these lakes were all re-sampled with the exception of DENA-027 and DENA-028, which could not be reached due to poor weather conditions. These two sampling events provide us with some information regarding the seasonal variation in water chemistry within the park. In 2008, we sampled lakes DENA-031 to DENA-122, and water samples were collected from DENA-027 and DENA-028.

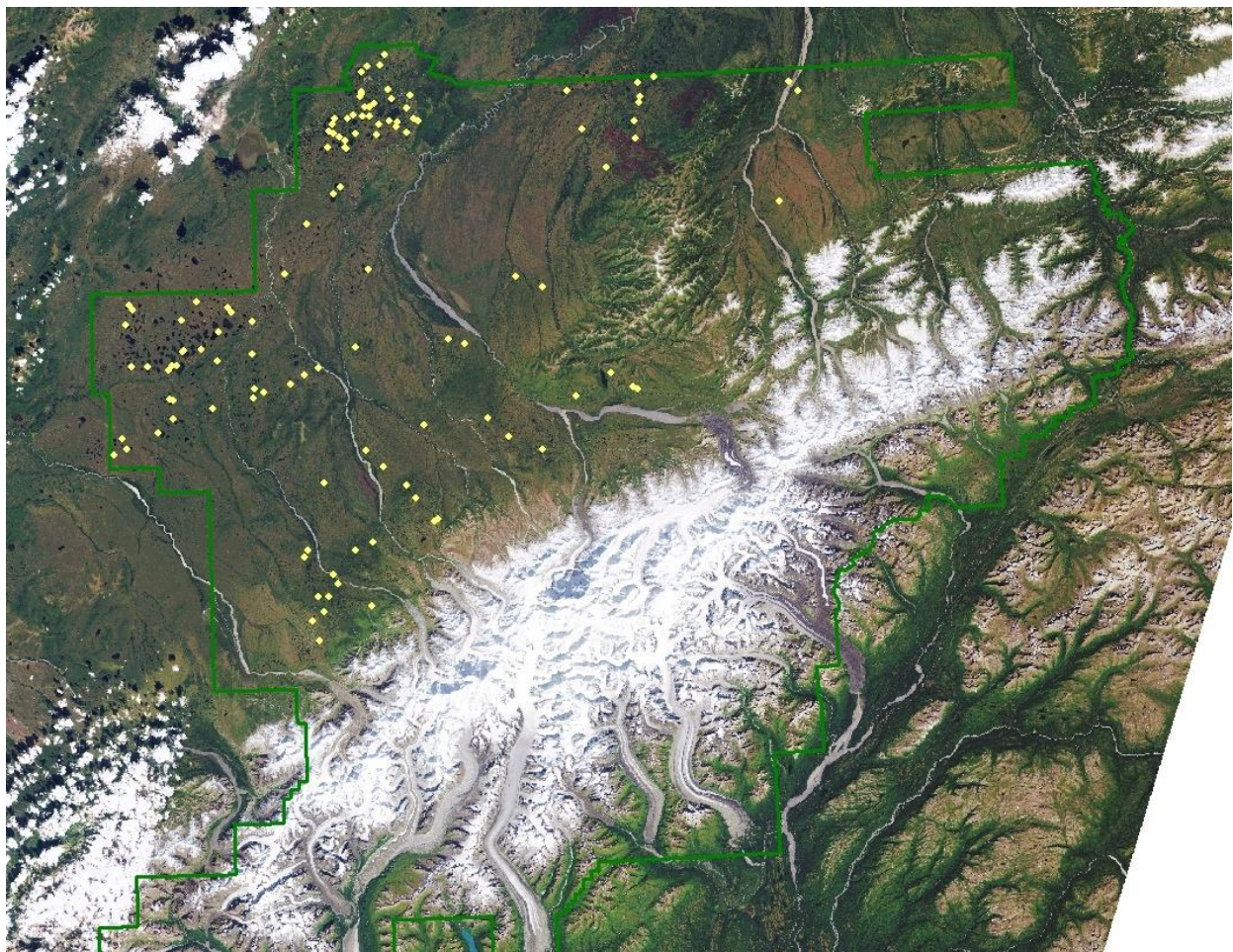


Figure 1. Location of the 122 shallow lakes sampled during the 2006-2008 field seasons in Denali National Park and Preserve

Lakes were selected using an un-equal probability sample, with lakes close to roads and navigable waters having a higher probability of being selected. This was achieved by drawing an un-equal probability General Randomized Tessellation Stratified (GRTS) sample. This design ensured that lakes selected for sampling were spread out uniformly across the park.

Sampling Schedule

Lakes were sampled during an eight-week window between mid-June and mid-August over the course of three summers. Lakes sampled in 2006 and 2007 were sampled for the full suite of environmental monitoring variables in accordance with the Shallow Lake Monitoring (SLM) protocols. During the 2008 field season, lakes were sampled using an abbreviated sampling technique that involved only a single water sample and one vegetation transect at each lake. No invertebrate samples were collected in 2008, and nested frequency surveys were not performed.

Water Sampling

In 2006 and 2007, water samples were collected in triplicate at each lake. In 2008, single samples were collected from each lake. Grab samples were collected 50 cm below the surface and processed according to SLM protocols. Unfiltered aliquots of water were frozen for specific conductivity, total nitrogen (TN), total phosphorus (TP) and alkalinity analysis. Aliquots were filtered through a membrane filter, with 250 mL stored frozen and analyzed for nitrate (NO₃), ammonia (NH₃), orthophosphate (PO₄), sulfate (SO₄), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), and chloride (Cl), and 125 mL stored refrigerated for analysis of dissolved organic carbon (DOC) and silica (Si). Chlorophyll-a (Chl_a) samples were collected by filtering 600-800 ml of lake water through a Gelman A/E glass fiber filter, then storing the filter frozen and in the dark until extraction.

Lake depth was measured along the two major axes of the lake at a minimum of 20 locations. Depths were measured using a Speedtech 5 and geotagged with spatial data using a Trimble GPS unit.

Vegetation Sampling

Vegetation sampling began in 2007, at which time we measured frequency of plant species in Nested Frequency Plots every 4 meters along each of three permanent transects near the lake monument, and attempted to use line-intercept techniques to estimate percent cover by plant community. This line-intercept method proved very challenging to employ because of the difficulty in identifying the transition zones between plant communities.

In 2008, we modified the vegetation sampling technique to include percent cover using a species-based line-intercept method. This greatly improved the sampling technique and has been adopted permanently in the SLMP. With this method, percent cover is estimated by noting the beginning and end point of each species along a transect that bisects the littoral zone. Percent cover is determined by calculating the total distance for which a species is present along each transect, then dividing that sum by the overall length of the transect.

Macroinvertebrate Sampling

Three macroinvertebrate samples were collected from each of the lakes in 2006 and 2007. Invertebrate samples were collected along the vegetation sampling transect using the

standardized sweep technique (Oswood *et al.*, 2001) in accordance with the SLM protocols. Specimens were sorted and identified by ABR Inc.; when possible, all specimens were identified to genera and enumerated.

Results and Discussion

Synoptic Sampling

Physical description

Lakes throughout Alaska, including within Denali, are not evenly distributed (Arp and Jones, 2009). Some regions have high lake density due to the geomorphological processes that have occurred in that area. In Denali, lakes occur on only a very small percentage of the total landscape; only 1.15% of the landscape is occupied by lakes. Like much of Alaska, the distribution of lakes in Denali is related to the complex geologic history of this region. Lakes with a common origin tend to be grouped into lake districts where large numbers of lakes are concentrated. Within each district, lake basins may resemble each other in certain general characteristics (Hutchinson, 1957), yet differ markedly in size, depth and geochemistry. The physical, chemical and biological processes occurring in the lake are largely dependent on watershed characteristics, especially the soil composition, bedrock, and topography.

Abundance and Distribution

The geomorphic and morphometric analyses presented here are based on data available in the USGS National Hydrography Dataset (NHD). This dataset includes all lakes ≥ 0.01 ha in surface area. There are 12,202 lakes distributed throughout the park. The vast majority of lakes (91.5%) are located on the north side of the Alaska Range and are concentrated in four subsections: the Eolian Lowlands (EL), Glaciated uplands (GU), Glaciated Lowlands (GL), and Minchumina Basin Lowlands (MBL) (Table 1). Subsection was determined for each lake sampled in the study (Table 2).

Table 1. Number of lakes found in each subsection within Denali National Park and Preserve.

Subsection	Lake Number
MBL	1861
EL	4870
NAM	134
LFPTF	182
LFPT	364
GL	1740
BM	22
AFPTF	32
AM	370
GU	2700
SM	72
TAMP	31
TBL	50
TBMP	66
BLM	64
BORK	22
AORK	30

Table 2. Subsection designation for each lake sampled in Denali National Park and Preserve in 2006-2008.

Subsection	Lakes Sampled	Lithology
Eolian Lowlands	DENA-015, DENA-016, DENA-017, DENA-018, DENA-019, DENA-020, DENA-021, DENA-023, DENA-027, DENA-028, DENA-032, DENA-033, DENA-034, DENA-035, DENA-040, DENA-041, DENA-042, DENA-043, DENA-044, DENA-048, DENA-049, DENA-050, DENA-051, DENA-054, DENA-055, DENA-056, DENA-057, DENA-058, DENA-059, DENA-060, DENA-061, DENA-062, DENA-063, DENA-064, DENA-065, DENA-066, DENA-067, DENA-068, DENA-069, DENA-070, DENA-075, DENA-076, DENA-079, DENA-080, DENA-086, DENA-087, DENA-088, DENA-089, DENA-090, DENA-091, DENA-092, DENA-093, DENA-099, DENA-105, DENA-108, DENA-114, DENA-115, DENA-116, DENA-117, DENA-122	Unconsolidated eolian
Glaciated Lowlands	DENA-081, DENA-095, DENA-096, DENA-098, DENA-100, DENA-103, DENA-106, DENA-107, DENA-109, DENA-110, DENA-111, DENA-112	Unconsolidated drift
Glaciated Uplands	DENA-082, DENA-083, DENA-084, DENA-085, DENA-094, DENA-097, DENA-101, DENA-102, DENA-104, DENA-113	Unconsolidated drift
Lowland Floodplains and Terraces	DENA-120, DENA-121	Unconsolidated alluvium
Minchumina Basin Lowlands	DENA-001, DENA-002, DENA-003, DENA-004, DENA-005, DENA-007, DENA-008, DENA-009, DENA-010, DENA-011, DENA-012, DENA-013, DEAN-014, DENA-022, DENA-024, DENA-025, DEAN-026, DEAN-029, DENA-030, DENA-031, DENA-036, DENA-037, DENA-038, DENA-039, DENA-045, DENA-046, DENA-047, DENA-052, DENA-053, DENA-071, DENA-072, DENA-073, DENA-074, DENA-077, DENA-078	Unconsolidated alluvium
Teklanika Alpine Mountains and Plateaus	DENA-118	Unconsolidated-Nenana gravels
Teklanika Boreal Mountains and Plateaus	DENA-119	Unconsolidated-eolian

The highest lake density (d_L) is found in the toe slopes of the Alaska Range in the GU and GL and in the two lowland areas, EL and the MBL, (

In addition to lake abundance, shoreline density, a measure of how much shoreline a lake contains, can also be an important lake measure. Shoreline Density (SD) is the sum of all lake perimeters divided by the total lake area in a region. SD is often related to lake origin, and tends to be higher in the mountainous regions of the park where many of the lakes lie in valleys and amongst glacial moraines and irregularly-shaped basins (Figure 3). Low-lying lakes in the park, such as those concentrated in the MBL and EL, tend to have lower SD values.

). The remaining subsections had very few lakes, and density was well below the park average ($d_L = 0.5$ lakes/km²).

Limnetic ratio (LR), a measure of how much of the land surface is covered by lakes, is commonly used to estimate lake abundance on the landscape. Much like density, LR varies across the park; it is highest in the two lowland areas, MBL and EL (

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). The LR is inversely related to lake density in Denali. The glaciated regions (GU and GL) have numerous small lakes, while the lowlands have a smaller number of lakes but higher surface area per lake. The lakes with the largest surface area are found in the two subsections with the lowest elevation (EL and MBL).

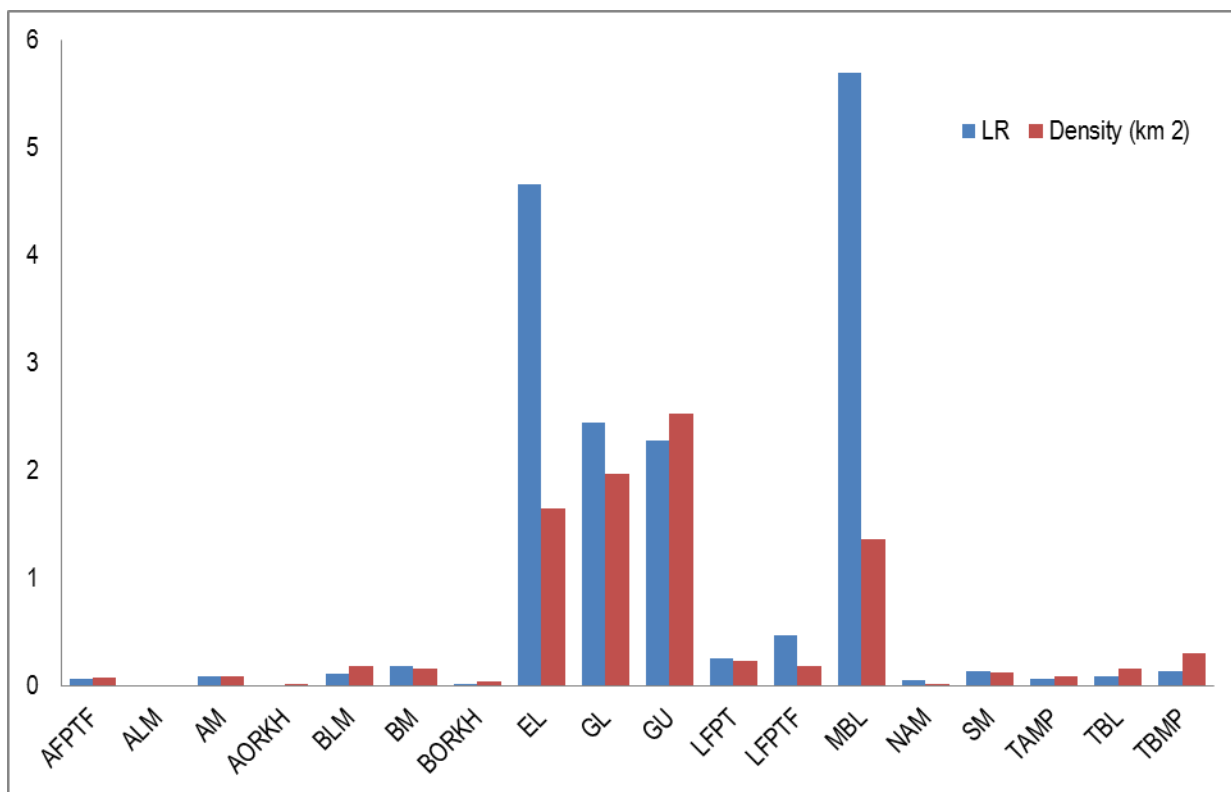


Figure 2. Lake density and limnetic ratio of lakes found in each subsection of Denali National Park and Preserve.

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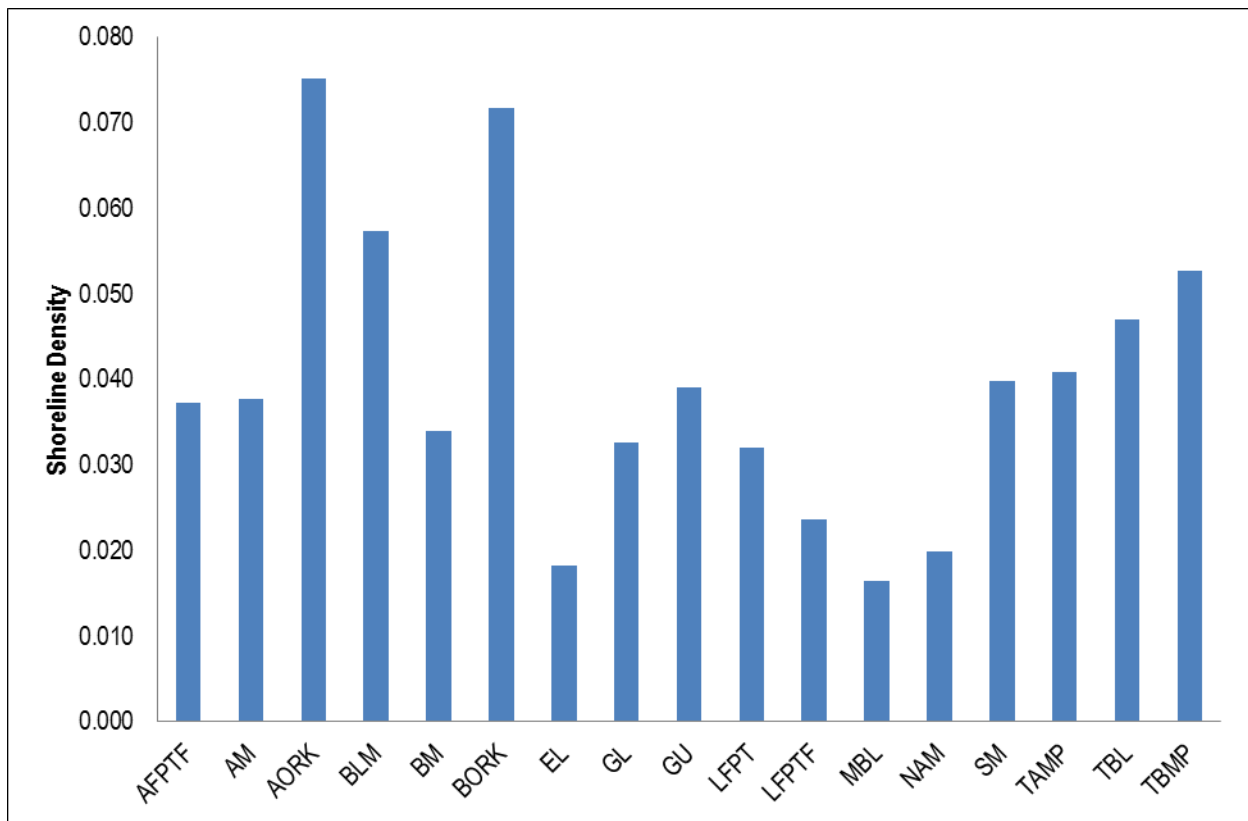


Figure 3. Shoreline density estimated for each subsection of Denali National Park and Preserve.

Lake Types

Lakes were formed by four major processes in Denali: fluvial, glacial, eolian, and thermokarst. The majority of lakes in the MBL are formed in depressions where permafrost has thawed and water has in-filled the depression (thermokarst). These lakes tend to be very circular with few indentations (Plate 1, background). Lakes formed by fluvial processes tend to be long and narrow with a smooth shoreline and are distributed along floodplains (Plate 1, foreground).



Plate 1. In the foreground you see typical fluvial lakes, and in the background there are large numbers of old thermokarst lakes that have been modified by infilling.

Lakes found between the Kantishna and Muddy Rivers also tend to have uniform lake margins with few undulations. These lie in ancient dune fields deposited after the Pleistocene glaciation. The dune field is composed mostly of parabolic and longitudinal dunes 3-45 m in height and 15 m to 5 km in length (Collins, 1985). Many lakes have formed in the interdunal depressions and have a characteristically square shape (Plate 2).

Contemporaneous with the eolian sands are thick silt deposits on the northeast flanks of Bearpaw Mountain and of Castle Rocks. Lakes in these regions tend to have highly convoluted shorelines surrounded by low hills (Plate 3). The most convoluted lakes lie in the mountainous areas of the park where glacial debris was deposited after retreat of the glaciers. Large blocks of ice melted, leaving steep-sided depressions. Many of these depressions filled with water, forming irregularly shaped lakes (Plate 4).



Plate 2. Parabolic dune lakes commonly found west of the Foraker River.



Plate 3. Deep lakes characteristic of the northeastern corner of the park. The lakes are formed in depressions created by thick eolian deposits of silt.



Plate 4. Convoluted lakes found in the mountainous regions of the park. Lakes have large boulders in the substrate and little organic matter in the lake sediment.

Watershed features such as size, shape, and slope are related to water quality and can also help explain spatial and temporal variation among lakes. Unfortunately, acquiring data on these features is difficult in Alaska because we do not have high-resolution digital elevation models that can be used to draw accurate watershed boundaries. This is especially problematic in low-lying areas such as the EL and the MBL where the vast majority of lakes reside.

In an attempt to understand lake variation we calculated the hypsometric index (Equation 1), which is the elevation distribution of a land area. The HI was calculated by subsection, and this index can help us understand the topographic context in which lakes lie. The HI ranged from 0.11-0.67 among subsections (Figure 4). The index shows that the MBL has very little topographic relief compared to any of the other subsections in the park. The EL subsection had a slightly higher HI because much of the subsection is located in low-lying hills at the toe slopes of the Alaska Range. The majority of lakes are located within more hilly and mountainous terrain. The other lake-rich areas (GL and GU) have higher HI values than the EL and MBL.

Equation 1. Hypsometric Index (HI)

$$HI = \frac{\text{Mean Elevation} - \text{Minimum Elevation}}{\text{Maximum Elevation} - \text{Minimum Elevation}}$$

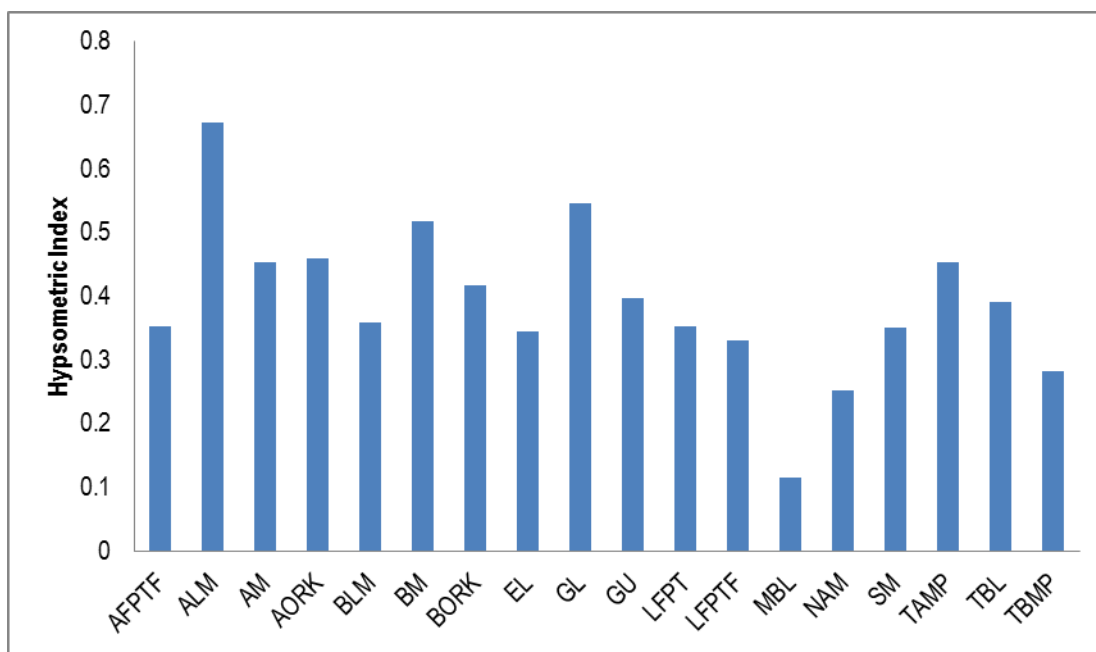


Figure 4. Hypsometric index for each subsection of Denali National Park and Preserve.

Lake Substrate

Lake bottoms in DENA display great variability. Lake bottoms in the glaciated uplands and lowlands tend to be dominated by large rocks covered with a thin layer of sediment characteristic of a recently glaciated environment. Lakes in the low-lying areas tend to have sediments dominated by sand, silt or organic muck.

Lake Area and Depth

Lakes sampled in DENA ranged in size and depth (Table 3). Lake area ranged from 1 to 375 ha, mean depth ranged from 0.5 to 7.2 m, and maximum lake depth ranged from 0.5 to 19.1 m. Maximum depth ($r^2 = 0.266$, $p < 0.001$) and mean depth ($r^2 = 0.199$, $p < 0.001$) were positively related to lake elevation. Lake area was also significantly related to elevation ($r^2 = 0.216$, $p < 0.01$) (Figure 5), but elevation explained only a small portion of the variation in lake size because low-lying areas have a wide range of lake sizes.

Lake order, the position of a lake in the flow system, also explains a significant amount of variation in lake size. Lakes lower in the flow system tend to be larger (Figure 6). Wetlands in Alaska are largely recharged by snow melt, so lake area and depth vary annually depending on the winter snow pack, and seasonally depending on summer precipitation.

Table 3. Morphometric characteristics of lakes sampled in Denali National Park and Preserve

Lake	Lake area (ha)	D _L	Secchi depth	Mean depth	Maximum Depth
DENA-001	9.92	1.39	1.7	0.83	1.7
DENA-002	4.51	1.42	2.8	1.43	2.7
DENA-003	1.38	1.40	0.8	0.41	0.7
DENA-004	23.85	2.02	1	0.57	0.9
DENA-005	0.66	1.87	5.4	1.98	5.3
DENA-006	0.98	1.24	0.9	0.56	0.8
DENA-007	0.10	1.22	2.1	1.22	2.0
DENA-008	7.33	1.78	2.9	0.82	2.5
DENA-009	0.85	1.24	1.7	0.85	1.6
DENA-010	5.67	1.32	2.6	1.15	2.5
DENA-011	77.79	1.28	1.5	0.97	1.4
DENA-012	15.54	1.18	1.7	1.13	1.6
DENA-013	9.34	1.16	1.3	0.72	1.0
DENA-014	7.94	1.44	1.2	0.72	1.1
DENA-015	49.89	1.26	1.5	0.76	1.1
DENA-016	23.06	1.07	1.3	1.03	1.3
DENA-017	17.63	1.14	1.6	0.85	1.6
DENA-018	74.57	1.09	1.8	0.75	1.1
DENA-019	6.16	1.10	2.7	0.91	2.2
DENA-020	15.68	1.70	1.7	0.57	0.9
DENA-021	4.39	1.27	4.6	1.40	4.5
DENA-022	14.77	1.08	1.3	0.91	1.2
DENA-023	19.09	1.29	1.6	0.75	1.3
DENA-024	8.35	1.22	1.5	0.81	1.3
DENA-025	1.06	1.12	1.4	0.76	1.3
DENA-026	10.47	1.31	2.8	0.83	2.0
DENA-027	22.31	2.69	8.4	5.67	8.4
DENA-028	33.04	1.05	0.7	0.63	0.7
DENA-029	3.75	1.15	3.3	1.14	3.1
DENA-030	13.80	1.13	1.2	0.74	1.1
DENA-031	82.90	1.06	1.5	1.21	1.5
DENA-032	1.94	1.11	1	0.85	1

DENA-033	5.42	1.24	4.4	2.46	4.4
DENA-034	16.03	1.05	7.5	5.52	7.5
DENA-035	35.06	1.12	1.3	1.04	1.3
DENA-036	1.55	1.52	1.3	1.03	1.3
DENA-037	74.30	1.49	1.2	0.82	1.2
DENA-038	7.56	1.04	1	0.83	1
DENA-039	8.31	1.19	1	0.90	1
DENA-040	14.34	1.16	3.4	2.43	3.4
DENA-041	27.30	1.08	5.3	2.82	5.3
DENA-042	20.15	1.25	2.7	1.76	2.7
DENA-043	5.15	1.05	0.8	0.73	0.8
DENA-044	128.38	1.16	1.7	1.18	1.7
DENA-045	42.36	1.72	1.9	1.52	1.9
DENA-046	375.67	3.37	1	0.61	1
DENA-047	2.74	1.32	1.9	1.05	1.9
DENA-048	321.92	1.69	1.9	1.69	1.9
DENA-049	3.44	1.24	2.3	1.81	2.3
DENA-050	80.84	1.14	1.4	1.07	1.4
DENA-051	131.85	1.40	1.9	1.33	1.9
DENA-052	31.91	1.32	1.2	0.86	1.2
DENA-053	13.19	1.43	2.2	1.85	2.2
DENA-054	5.44	2.06	8.2	4.31	8.2
DENA-055	1.91	1.56	4.8	2.99	4.8
DENA-056	61.75	1.06	0	2.78	7.7
DENA-057	10.85	1.72	7.7	3.94	5.3
DENA-058	2.93	1.41	5.3	2.75	5.2
DENA-059	17.57	1.21	5.2	1.49	1.7
DENA-060	18.82	1.93	1.7	5.43	9.4
DENA-061	17.95	2.21	9.4	0.79	1
DENA-062	9.75	1.38	1	1.10	1.5
DENA-063	21.35	1.72	1.5	1.69	2.8
DENA-064	13.37	1.17	2.8	1.09	1.3
DENA-065	44.62	1.51	1.3	1.00	1.7
DENA-066	9.59	1.47	1.7	0.63	0.7
DENA-067	29.91	1.08	0.7	0.91	2.6
DENA-068	1.05	1.87	2.6	4.40	7
DENA-069	1.49	1.26	7	5.17	9.5
DENA-070	0.82	1.22	9.5	0.69	0.9
DENA-071	61.66	1.11	0.9	1.10	1.4
DENA-072	8.04	1.35	1.4	1.01	1.5
DENA-073	2.22	1.06	1.5	1.33	1.8
DENA-074	1.74	1.13	1.8	1.56	2.8
DENA-075	225.48	1.57	2.8	0.97	1.6
DENA-076	284.88	1.19	1.6	1.25	1.6
DENA-077	132.96	1.14	1.6	1.13	1.3
DENA-078	117.71	1.96	1.3	2.19	4
DENA-079	0.84	1.14	4	2.51	4.2
DENA-080	1.25	1.32	4.2	3.70	7.5
DENA-081	2.60	1.70	7.5	1.47	6
DENA-082	0.60	1.53	6	4.06	7.5
DENA-083	1.22	1.20	7.5	5.46	11.2

DENA-084	1.11	1.25	11.2	3.00	5.9
DENA-085	1.31	1.22	5.9	1.29	1.6
DENA-086	84.28	1.23	1.6	0.94	1.1
DENA-087	48.21	1.20	1.1	1.31	1.6
DENA-088	9.51	1.44	1.6	1.64	3.1
DENA-089	1.00	1.63	3.1	2.26	3.8
DENA-090	2.25	1.16	3.8	3.66	7.7
DENA-091	2.03	1.16	7.7	2.22	3.8
DENA-092	0.53	1.39	3.8	2.09	3.3
DENA-093	2.74	1.66	3.3	2.45	4.9
DENA-094	1.95	1.27	4.9	1.57	3.8
DENA-095	1.54	1.47	3.8	2.92	6.1
DENA-096	1.55	1.80	6.1	7.14	13.4
DENA-097	6.88	1.40	13.4	2.51	4.7
DENA-098	0.28	1.06	4.7	0.89	1.6
DENA-099	2.70	1.22	1.6	6.91	11.4
DENA-100	0.59	1.25	11.4	3.56	8.8
DENA-101	1.54	1.47	8.8	6.15	19.1
DENA-102	3.06	1.43	19.1	3.07	6.5
DENA-103	1.08	1.63	6.5	2.99	5.1
DENA-104	1.14	1.38	5.1	0.19	0.5
DENA-105	0.72	1.09	0.5	3.30	5
DENA-106	1.53	1.39	5	3.48	4.8
DENA-107	1.09	1.91	4.8	0.43	0.8
DENA-108	3.94	1.55	0.8	1.84	7
DENA-109	2.24	2.02	7	0.94	1.1
DENA-110	1.61	1.29	1.1	3.65	9
DENA-111	4.45	1.95	9	0.83	1.7
DENA-112	1.08	1.67	1.7	1.18	3
DENA-113	0.55	1.79	3	3.89	6.4
DENA-114	2.51	1.20	6.4	7.18	16.9
DENA-115	27.68	3.08	16.9	1.61	2.4
DENA-116	46.58	1.63	2.4	3.73	7.3
DENA-117	2.03	1.15	7.3	5.57	8.7
DENA-118	1.60	1.26	8.7	1.88	3.6
DENA-119	2.41	1.28	3.6	1.34	1.7
DENA-120	3.25	1.21	1.7	0.99	1.3
DENA-121	2.10	1.29	1.3	3.92	5.9
DENA-122	1.01	1.63	5.9	0.85	1

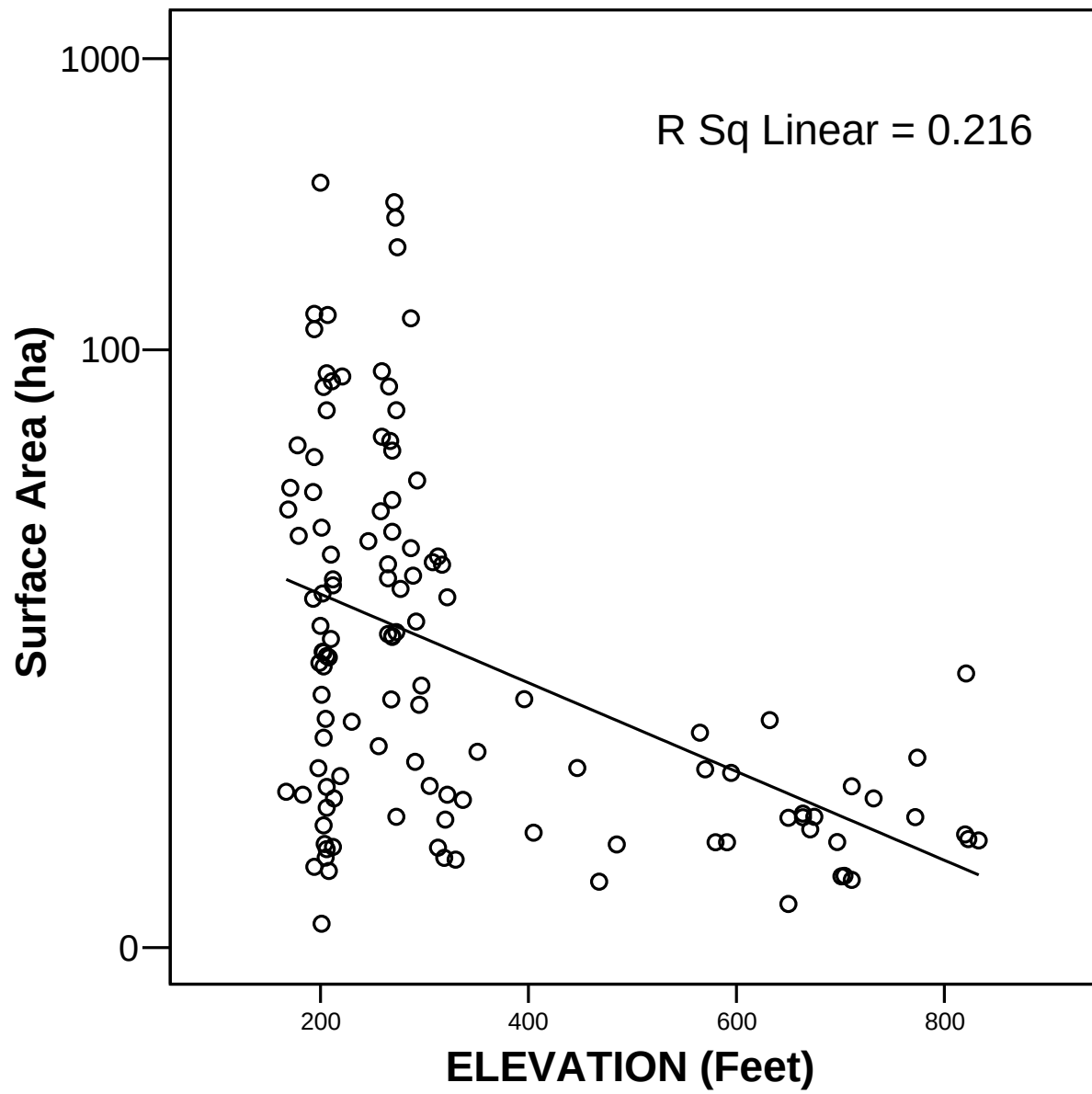


Figure 5. Linear relationship between lake surface area and elevation.

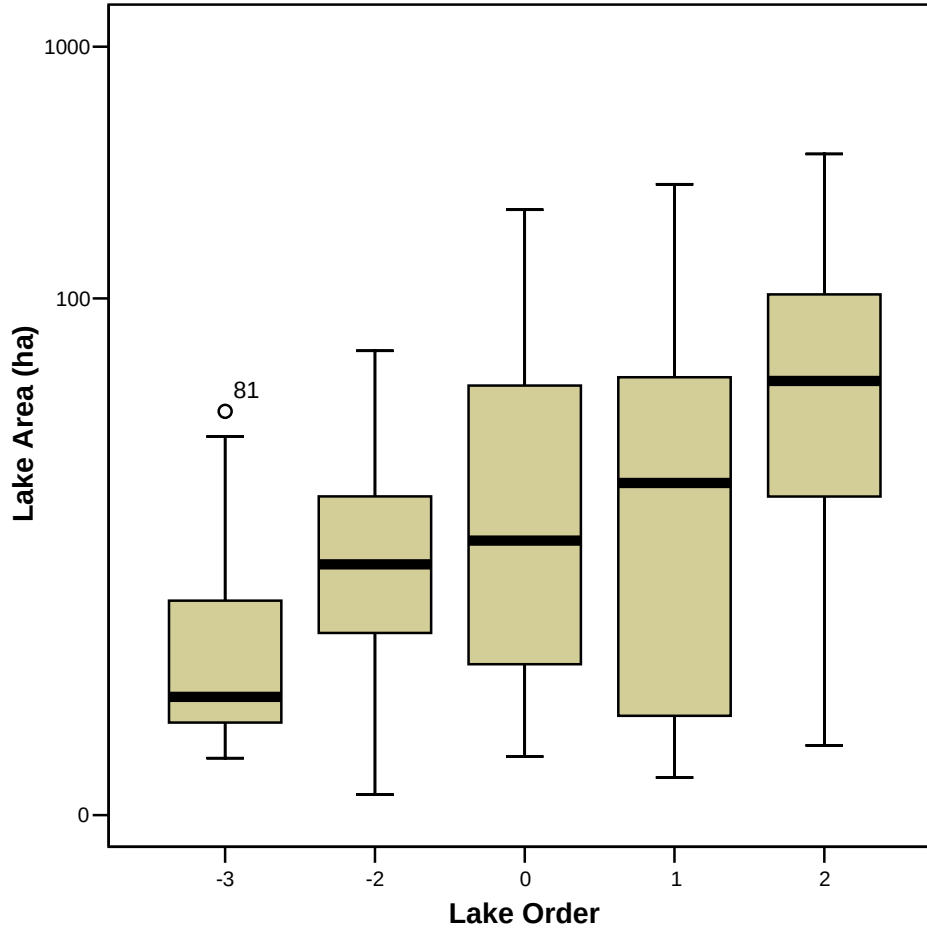


Figure 6. Box plot of lake surface area by lake order. Lake order indicates the relative position of lakes from high to low in the landscape. Lakes with negative numbers represent lakes isolated from other lakes and lakes with positive numbers indicate a higher degree of lake connectedness.

Shoreline Development Index

Shoreline length and lake surface area estimates were acquired by digitizing shorelines from recent satellite imagery to calculate the Shoreline Development Index (D_L) for each lake sampled (Equation 2). Shoreline development is an important measure because it represents the potential for development of littoral communities (Hutchinson, 1957), which frequently represent the most productive region of the lake ecosystem.

Equation 2. Shoreline Development Index (D_L)

$$D_L = \frac{S}{2\sqrt{A\pi}} \quad \text{where } S \text{ is the shoreline length in meters and } A \text{ is the area of lake in square meters}$$

A lake with a D_L of 1 is a perfect circle. Only a few lake types typically approach this lower limit, but these include crater lakes, kettle lakes and thaw lakes (Hutchinson, 1957). Because

there are numerous kettle lakes and many young thermokarst lakes in Alaska, it is not uncommon to see low D_L values in the park. Long linear lakes or highly convoluted lakes have higher D_L values.

Values for D_L in DENA ranged from 1.04 to 3.37. Although D_L did not differ significantly among subsections, there were considerable differences in the shoreline density among areas in the park. Shoreline density tended to be highest in the Glaciated Uplands (GU), and lowest in the large wetland complexes of the Minchumina Basin Lowlands (MBL) and the Eolian Lowlands (EL).

Temperature and Light Penetration

Epilimnetic temperature ranged from 8.3 to 21.9 °C, and was significantly negatively related to elevation ($r = -.676, < .001$) (Figure 7) and positively correlated with latitude ($r = 0.490, < .001$).

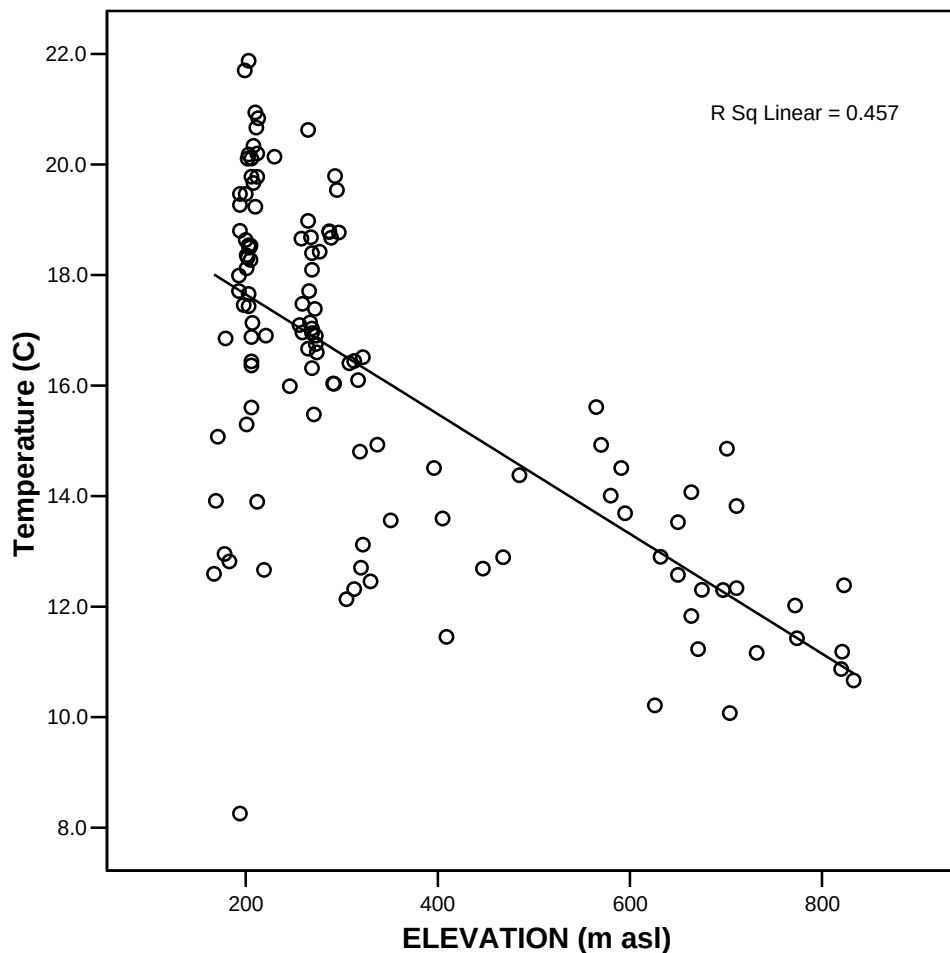


Figure 7. Linear relationship between elevation and epilimnetic temperature.

Secchi depth, an estimate of light penetration, varied from 0.3 to 5.25 m. Light transmission is a function of the amount of dissolved and particulate material in the water column, and indicates what portion of the water column is available for photosynthetic activity (Wetzel, 1983). Most of the lakes in Denali are brown-water lakes with Secchi depths less than 1.5 m (Figure 8). The Secchi disk was visible on the bottom of 34 of the 106 lakes in which the Secchi depth was measured, indicating that the entire lake is available for primary production at the time of sampling in nearly 1/3 of the lakes sampled.

Secchi was negatively correlated with several factors including temperature, TN, TP and DOC. All of these factors are related to primary production and likely influence the production of autochthonous inputs to the lake. Secchi was positively correlated with elevation, alkalinity, Ca and SO_4^- . High-elevation lakes in Denali tend to be surrounded by alpine vegetation and low shrub communities with thin peat, so there is little organic material being contributed to the lake.

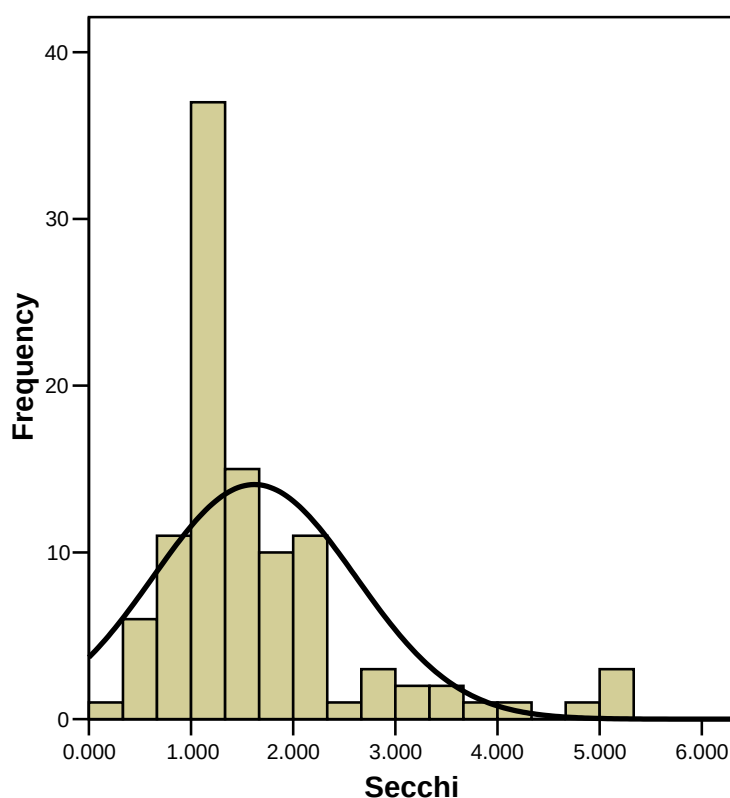


Figure 8. Frequency distribution of Secchi depth for all lakes in Denali.

Dissolved Organic Carbon (DOC)

Terrestrial sources of carbon play a key role in lake productivity, community structure and metabolic balances (Wetzel, 1983). DOC, a measure of organic carbon inputs to lakes, ranged from 2.01 to 35.01 mg/L in the sampled lakes, with a mean concentration of 14.98 and a median of 14.23 mg/L. DOC concentration is affected by a wide variety of factors including changes in

runoff (Schindler, 1997), temperature (Freeman *et al.*, 2001; Worrall *et al.*, 2006; Evans *et al.*, 2006; Weyhenmeyer and Karlsson, 2009), solar radiation (Hudson *et al.*, 2003), soil moisture (Worrall *et al.*, 2006), and atmospheric deposition (Freeman *et al.*, 2001; Evans *et al.*, 2006).

A large portion (42%) of the lakes in Denali have high DOC concentrations (>15mg/L). This is comparable to other forested ecosystems in Alaska (Gregory-Eaves *et al.*, 2000). These lakes are colored by humic acids that leach from the surrounding terrestrial vegetation. In undisturbed ecosystems, humic substances are linked to soil processes and are connected to vegetation development (Wetzel, 1983).

DOC levels are significantly different among regions of the park (Figure 9). The two lowland regions (MBL and EL) have the highest values as well as the most variability, while the alpine regions of the GU and GL have relatively low DOC with low variability. Lakes lower in the landscape are impacted by many more factors including groundwater inputs and connectivity, and tend to be more variable as a result (Kratz *et al.*, 2006).

Overall, DOC is negatively correlated with elevation (Figure 10). Alpine lakes in Denali are surrounded by alpine meadows and low shrubs that contribute less terrestrial vegetation than is seen in lakes lower in the landscape, where leaf litter from coniferous and deciduous trees is prevalent.

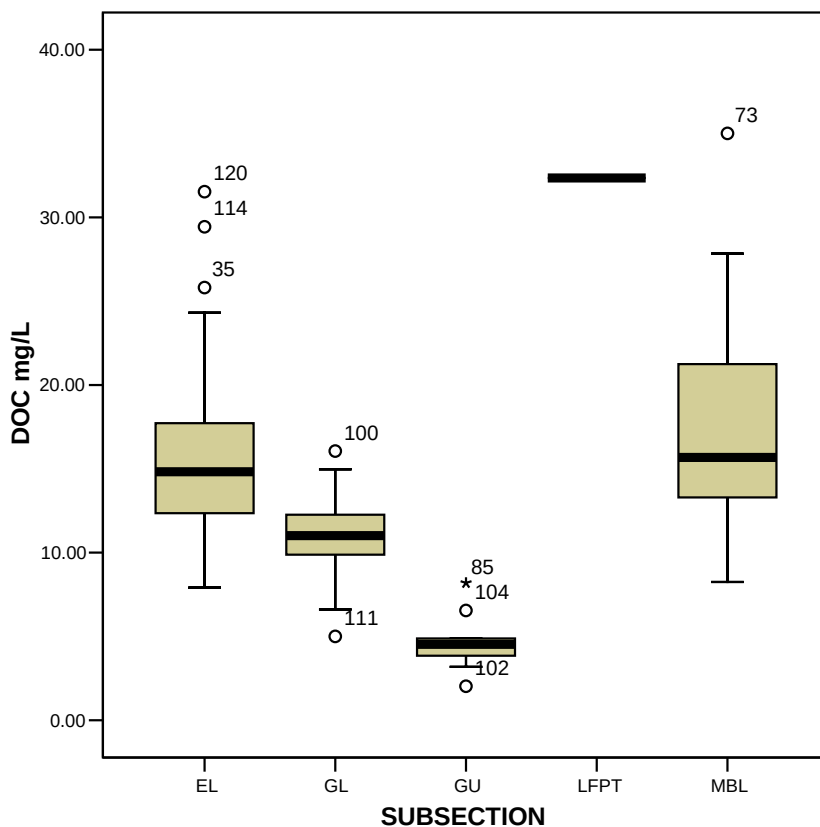


Figure 9. Boxplot of DOC found in lakes within each of the six subsections.

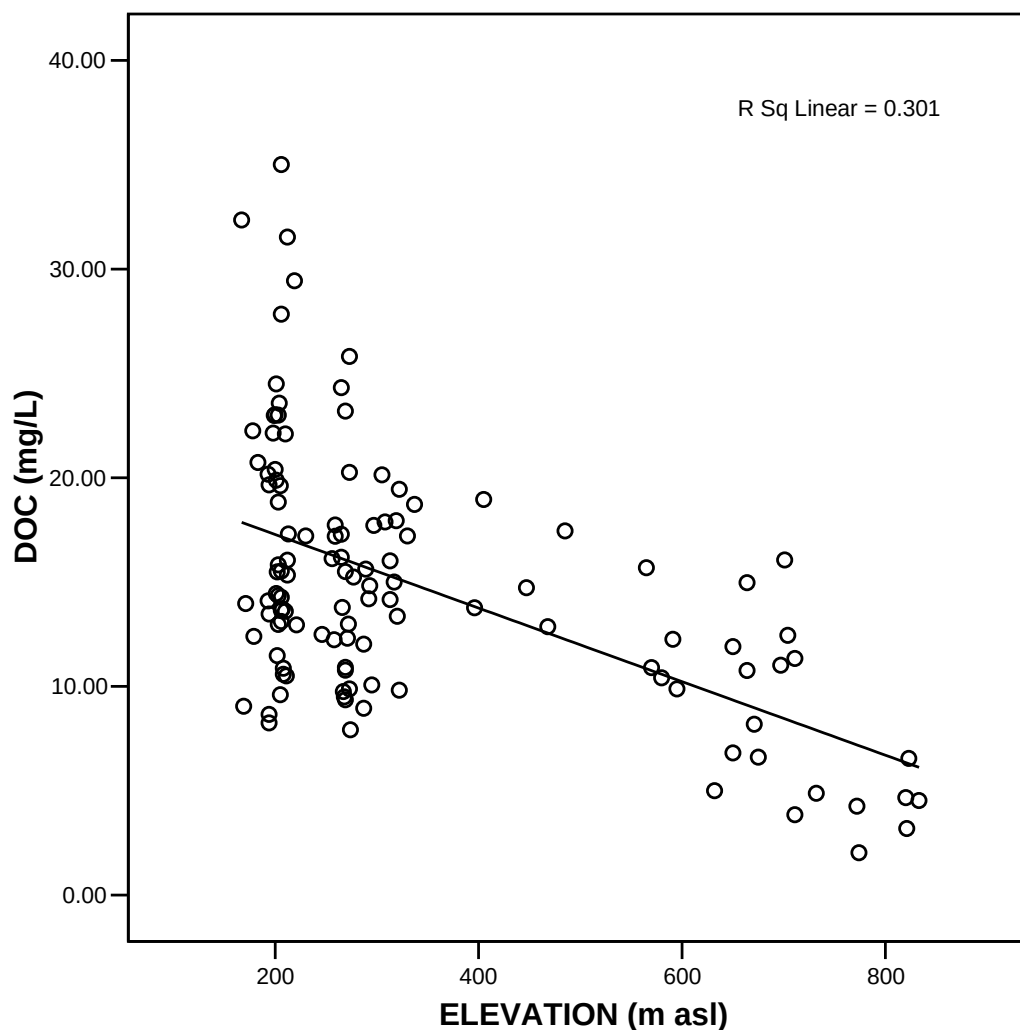


Figure 10. Linear relationship between elevation and DOC.

Water Chemistry

pH

Measurements of pH ranged from 5.4 to 9.0 with a median of 6.90 (Figure 11). Pearson correlation calculations for this area show that pH is positively correlated with specific conductivity, alkalinity, each of the base cations, SO_4^- , Cl^- , TN, and TP, and negatively correlated with DOC (

Table 4). pH is highly variable throughout the park, especially in the EL and the MBL (Figure 12). This variability results from the large numbers of interconnected lakes in low-lying areas.

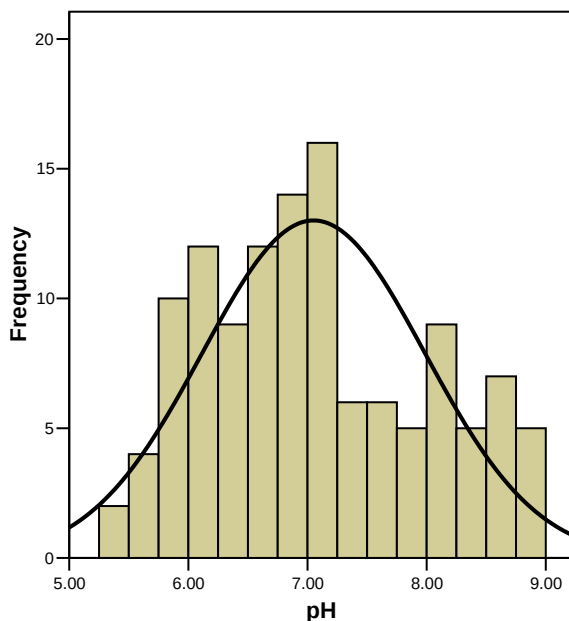


Figure 11. Frequency distribution of lake pH in Denali National Park and Preserve.

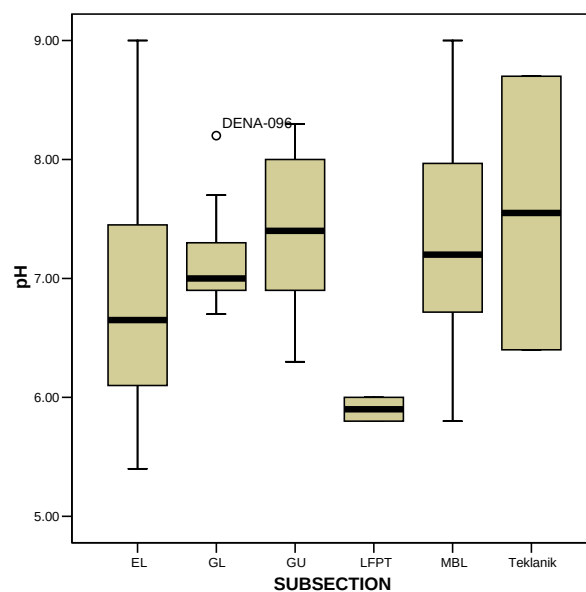


Figure 12. Boxplots showing pH within each major subsection of Denali National Park and Preserve

Table 4. Pearson values for the correlation of pH with other chemical constituents in Denali National Park and Preserve.

Ion	Pearson r	p
Na ⁺	0.380	<0.001
K ⁺	0.317	<0.001
Ca ²⁺	0.653	<0.001
Mg ²⁺	0.563	<0.001
Sp. Cond	0.670	<0.001
Alkalinity	0.672	<0.001
SiO ₂	0.300	<0.001
SO ₄	0.217	<0.05
Cl ⁻	0.265	<0.005
T N	0.240	<0.05
TP	0.293	<0.001
DOC	-0.257	<0.005

Table 5. Pearson values for the correlation of alkalinity (HCO₃⁻) with other chemical constituents in Denali National Park and Preserve.

Ion	Pearson r	p
Na ⁺	0.730	<0.001
K ⁺	0.526	<0.001
Ca ²⁺	0.921	<0.001
Mg ²⁺	0.890	<0.001
Sp. Cond	0.992	<0.001
Alkalinity	0.691	<0.001
SiO ₂	0.451	<0.001
SO ₄	0.292	<0.05
Cl ⁻	0.526	<0.05
T N	0.316	<0.05
TP	0.226	<0.05

Alkalinity

Alkalinity (HCO_3^-) ranged between 0.6 and 31.7 mg/L HCO_3^- , indicating a wide range in buffering capacity

Table 5). Alkalinity is generally imparted by carbonates, bicarbonates, and hydroxides, and in northern latitude regions also by humates. Alkalinity was strongly correlated with specific conductivity as well as all base cations and anions in lakes in DENA. These correlations are likely due to the dissociation of alkaline earth compounds (Wetzel, 1983).

Specific Conductivity

Nearly all of the lakes sampled within the park are dilute ($<100 \mu\text{S}/\text{cm}$). Specific conductivity ranged from 6.2 to 303.8 $\mu\text{S}/\text{cm}$ with a mean of 41.9 and a median of 23.7 (Figure 13). Only about 10% of the lakes sampled have specific conductivity values greater than 100 $\mu\text{S}/\text{cm}$. Each of these lakes had evidence of thermokarst activity, and the lakes with the highest conductivity (DENA-118, DENA-027, DENA-113, and DENA-070) had evidence of extensive thermokarst along the lake margin. DENA-027 and DENA-118 had large active thaw slumps, typically found in ice-rich permafrost, where sediment plumes were visible in the water column.

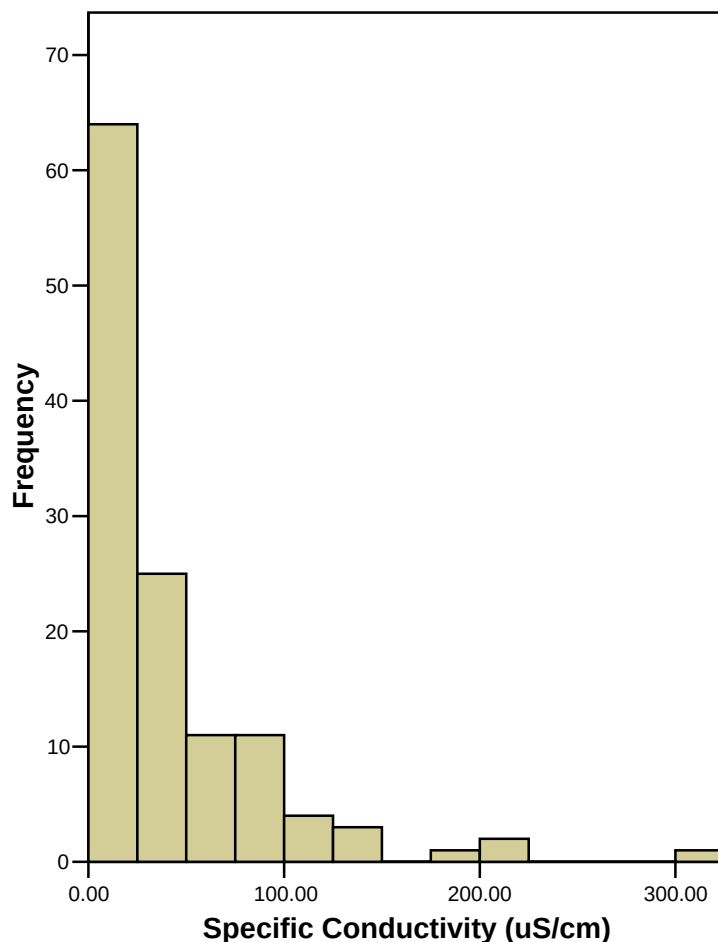


Figure 13. Frequency distribution of specific conductivity from each lake in Denali National Park and Preserve.

Ions

Cation and anion concentrations are low in most lakes. We observed large thaw slumps on a small number of lakes, and these lakes have high cation and anion concentrations as well as high specific conductivity, likely resulting from mineral sediments deposited in the lake basin. High ion concentrations and specific conductivity readings were also observed in large lakes with large catchments such as DENA-046, which is routinely flooded by the highly turbid waters of the Muddy River.

We used Aquachem to determine ion dominance in all lakes. Water type was calculated by first converting all measurements to meq/L, then transformed to meq%, and all parameters below 10% were removed from analysis (Aquachem, 2010). The remaining ions were treated as major ions and were included in the analysis. Ion dominance varied among lakes (Figure 14); Ca>Mg>Na are the three most dominant cations and HCO₃⁻ is the dominant anion.

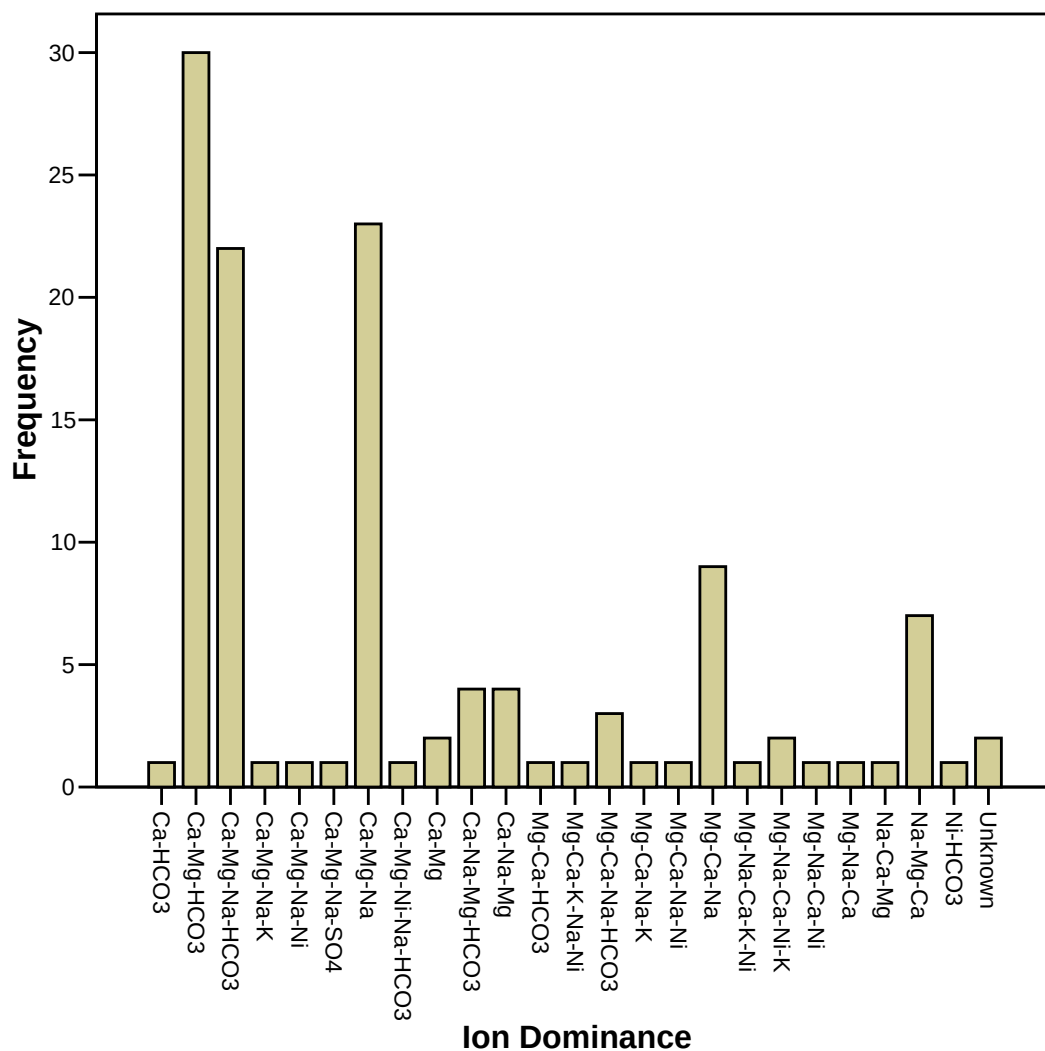


Figure 14. Frequency distribution of ion dominance of each lake in Denali National Park and Preserve.

Nutrients, Chla and Trophic Status

Concentrations of the major nutrients ranged from 0.140 to 2.310 mg/L TN and 0.004 to 0.217 mg/L TP. The correlation between TN and TP was highly significant ($r = 0.0764$, $p < 0.001$). Chla ranged from 0.29 to 23.04 mg/L with a mean concentration of 3.20 mg/L. Chla is highly correlated with both TN ($r = 0.353$, $p < 0.001$) and TP ($r = 0.574$, $p < 0.001$).

Pearson Correlation calculations show that TN is highly correlated with latitude ($r = 0.349$, $p < 0.001$), negatively correlated with elevation ($r = -0.374$, $p < 0.001$) and correlated with a variety of chemical characteristics (Table 6). TP had a similar relationships with latitude ($r = 0.179$, $p < 0.05$) and elevation ($r = -0.230$, $p < 0.01$) (Table 7).

Table 6. Pearson values for the correlation of TN with chemical characteristics in Denali National Park and Preserve.

Ion	Pearson r	p
pH	0.240	<0.050
Specific conductance	0.345	<0.001
TP	0.764	<0.001
PO ₄ ⁻	0.640	<0.001
NO ₃ ⁻	0.472	<0.001
NH ₃	0.584	<0.001
Si	0.348	<0.001
Na	0.413	<0.001
K	0.304	<0.001
Ca	0.191	<0.001
Mg	0.448	<0.001
Cl	0.253	<0.001
DOC	0.517	<0.001

Table 7. Pearson values for the correlation of TP with chemical characteristics in Denali National Park and Preserve.

Ion	Pearson r	p
pH	0.293	<0.050
Specific conductance	0.241	<0.010
TN	0.764	<0.001
PO ₄ ⁻	0.846	<0.001
NO ₃ ⁻	0.582	<0.001
NH ₃	0.710	<0.001
Si	0.561	<0.001
Ca	0.197	<0.050
Mg	0.259	<0.005

Total nitrogen, total phosphorus and Chlorophyll-*a* are commonly used to determine the trophic state of shallow lakes, but in Alaska TN can be dominated by organic forms of nitrogen that are not readily available for photosynthetic activity (Alexander and Gu, 1989). As such, TN will not be used as a metric of trophic state for the lakes in this study; only TP and Chl*a* measurements will be used for the determination of trophic state.

Total phosphorus concentrations indicate that 14 lakes are eutrophic (TP > 0.30 µg/L), 89 are mesotrophic (0.10 > TP < 0.30 µg/L) and only 19 are oligotrophic (TP < 0.10 µg/L) (Nurnberg, 1996). Chl*a* concentrations indicate that only 5 lakes are eutrophic (9 > Chl*a* < 25 µg/L), 23 are mesotrophic (3.5 > Chl*a* < 9 µg/L), and the remaining 94 are oligotrophic (Chl*a* < 3.5 µg/L) (Nurenburg 1996).

The ratio of nitrogen to phosphorus (N:P) has historically been used to identify the primary nutrient limiting phytoplankton productivity, with N:P values in excess of 20 indicating phosphorus limitation (Smith, 1984). In Denali, N:P ratios varied between 8 and 70. Nearly all lakes sampled, with the exception of DENA-086,-078, -105, -076, -045, -018, -046, -059, -008, and -048, are limited by phosphorus. Forward stepwise regression showed the Chl*a* was significantly related to TP ($r^2_{(1, 119)} = 0.329$, $P < 0.001$) and provided additional information suggesting phosphorus limitation.

Macroinvertebrates

Macroinvertebrate samples were collected from 30 lakes in early June in 2006 and again in mid-July in 2007. We identified 116 unique invertebrate taxa within the park (Table 8) represented by

6 phyla: Arthropoda, Annelida, Cnidaria, Mollusca, Nematoda and Platyhelminthes. The most diverse phylum was Arthropoda, which included 122 unique taxa. The vast majority - 116 taxa, - were in the class Insecta. Dipterans were by far the most diverse group of organisms, 44 genera of which are in the family Chironomidae. Chironomids are highly diverse in high-latitude regions of the world (Oswood, 1997). Taxa richness ranged from 16 to 62 taxa per sampling event, with a mean taxa richness of 43.

Table 8. Macroinvertebrate taxa found in Denali National Park and Preserve.

Phylum: Annelida
Class: Clitellata
Order: Rhynchobdellida
Family: Glossiphoniidae
Genus: <i>Glossophonia</i>
Genus: <i>Helobdella</i>
Class: Polychaeta
Order: Canalipalpata
Family: Sabellidae
Genus: <i>Manayunkia</i>
Phylum: Arthropoda
Class: Arachnida
Class: Branchiopoda
Order: Conchostraca
Order: Diplostraca
Class: Insecta
Order: Coleoptera
Family: Carabidae
Family: Chrysomelidae
Family: Curculionidae
Family: Dytiscidae
Genus: <i>Acilius</i>
Genus: <i>Agabus</i>
Genus: <i>Dytiscus</i>
Genus: <i>Graphoderus</i>
Genus: <i>Hydaticus</i>
Genus: <i>Hydroporus</i>
Genus: <i>Rhantus</i>
Family: Gyrinidae
Family: Haliplidae
Genus: <i>Haliphus</i>
Family: Hydrophilidae
Family: Scirtidae
Family: Staphylinidae
Order: Diptera
Family: Ceratopogonidae
Family: Chaoboridae
Genus: <i>Chaoborus</i>

Family: Chironomidae

Genus: *Ablabesmyia*
Genus: *Acamptocladius*
Genus: *Chironomus*
Genus: *Cladopelma*
Genus: *Cladotanytarsus*
Genus: *Corynoneura*
Genus: *Cricotopus*
Genus: *Cryptochironomus*
Genus: *Dicrotendipes*
Genus: *Endochironomus*
Genus: *Endotribelos*
Genus: *Glyptotendipes*
Genus: *Guttipelopia*
Genus: *Labrundinia*
Genus: *Larsia*
Genus: *Lauterborniella*
Genus: *Limnophyes*
Genus: *Metriocnemus*
Genus: *Microtendipes*
Genus: *Nanocladius*
Genus: *Nilothauma*
Genus: *Orthocladius/Cricotopus*
Genus: *Omisus*
Genus: *Orthocladius*
Genus: *Pagastiella*
Genus: *Parachironomus*
Genus: *Paracladopelma*
Genus: *Paraphaenocladius*
Genus: *Paratanytarsus*
Genus: *Phaenopsectra*
Genus: *Polypedilum*
Genus: *Potthastia*
Genus: *Procladius*
Genus: *Psectrocladius*
Genus: *Pseudochironomus*
Genus: *Rheotanytarsus*
Genus: *Stempellina*
Genus: *Stempellinella*
Genus: *Stenochironomus*
Genus: *Tanytarsus*
Genus: *Thienemannimyia*
Genus: *Tribelos*
Genus: *Xenochironomus*
Genus: *Zalutschia*

Family: Culicidae

Family: Dixidae

- Genus: *Dixella*
- Family: Dolichopodidae
- Family: Dytiscidae
- Genus: *Ilybius*
- Family: Empididae
- Family: Ephydriidae
- Family: Hydroptilidae
- Genus: *Oxyethira*
- Family: Muscidae
- Family: Psychodidae
- Genus: *Pericoma*
- Family: Sciomyzidae
- Family: Syrphidae
- Family: Tabanidae
- Family: Tipulidae
- Genus: *Dicranota*
- Genus: *Erioptera*
- Genus: *Helius*
- Genus: *Limonia*
- Genus: *Tipula*
- Order: Ephemeroptera
 - Family: Baetidae
 - Genus: *Procladius*
 - Family: Caenidae
 - Genus: *Caenis*
 - Family: Siphonuridae
 - Genus: *Parametopus*
- Order: Hemiptera
 - Family: Veliidae
 - Genus: *Microvelia*
- Order: Lepidoptera
- Order: Odonata
 - Family: Aeshnidae
 - Genus: *Aeshna*
 - Genus: *Anax*
 - Family: Coenagrionidae
 - Genus: *Coenagrion/Enallagma*
 - Family: Lestidae
 - Genus: *Lestes*
 - Family: Libellulidae
 - Genus: *Leucorrhinia*
 - Genus: *Libellula*
- Order: Trichoptera
 - Family: Brachycentridae
 - Genus: *Micrasema*
 - Family: Hydroptilidae
 - Genus: *Hydroptila*

Family: Leptoceridae
 Genus: *Ceraclea*
 Genus: *Mystacides*
 Genus: *Oecetis*
 Family: Limnephilidae
 Genus: *Limnephilus*
 Genus: *Nemotaulius*
 Family: Phryganeidae
 Genus: *Agrypnia*
 Genus: *Banksiola*
 Genus: *Phryganea*
 Family: Polycentropodidae
 Genus: *Neureclipsis*
 Class: Malacostraca
 Order: Amphipoda
 Family: Hyalellidae
 Genus: *Hyalella*
 Class: Maxillopoda
 Class: Ostracoda
 Phylum: Cnidaria
 Class: Hydrazoa
 Order: Anthoathecatae
 Family: Hydridae
 Genus: *Hydra*
 Phylum: Mollusca
 Class: Bivalvia
 Order: Veneroida
 Family: Pisidiidae
 Class: Gastropoda
 Order: Basommatophora
 Family: Lymnaeidae
 Genus: *Stagnicola*
 Family: Physidae
 Genus: *Physa*
 Family: Planorbidae
 Phylum: Nematoda
 Phylum: Platyhelminthes
 Class: Turbellaria

Conclusions

This sampling effort completes the first round of monitoring in DENA shallow lakes. Continuous monitoring efforts will continue annually in the park. Sampling efforts were highly successful. A second round of sampling will commence in summer 2013. At that time the original 30 lakes will be re-sampled and an additional set of 40 lakes will be sampled.

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