Condition of lakes in the Arctic Coastal Plain of Alaska: water quality, physical habitat, and biological communities

A report prepared for the Alaska Department of Environmental Conservation

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Introduction

The Arctic Coastal Plain ecoregion is bounded on the west and north by the Arctic Ocean and extends south to the foothills of the Brooks Range. The coastal plain is underlain by continuous permafrost and has low topographic relief that inhibits drainage and results in a landscape dominated by thaw lakes and wetlands. Thaw lakes are formed by thermokarst, which is differential thawing of permafrost (Frohn et al. 2005). Thaw lakes are shallow (<4 m deep, Arp et al. 2012), elliptical and have similar orientation perpendicular to the predominant wind direction (east and east-northeast, Urban and Clow 2013). Deeper lakes are less common on the coastal plain, but may form in thaw lakes as soils thaw and subside and within floodplains or dunes (Arp et al. 2012, Hinkel et al. 2012b). Thaw lake basins may drain due to stream meandering, lake coalescence, coastal erosion, or other mechanisms and drained basins are slightly more numerous than thaw lakes on the Arctic Coastal Plain (Frohn et al. 2005, Hinkel et al. 2007). Connected thaw lakes are important summer rearing habitats for fish and deep lakes provide overwintering habitat. There have been few studies of lake invertebrate or diatom communities, but evidence suggests diverse communities in lentic habitats (Lougheed et al. 2011, Balasubramaniam et al. 2017). Permafrost degradation from climate change is increasing thaw lake depths and area (Hinkel et al. 2007).

Human activities on the Arctic Coastal Plain, such as military installations and oil and gas exploration and development, can impact lake habitats by alterations to hydrology and pollution from point and nonpoint sources. Existing military activities include the Distant Early Warning (DEW) radar stations along the Arctic Coast, constructed in the 1950s, which were converted to the Northern Warning System (NWS) sites of today. The Arctic Coastal Plain has some of the largest oil and gas reserves in the world. Production in Prudhoe Bay, the largest oil field in North America, began in 1969. Other potential oil developments include the National Petroleum Reserve-Alaska (NPR-A) in the western coastal plain and the 1002 area of the Arctic National Wildlife Refuge on the eastern coastal plain. Annual lease sales have been held for parts of NPR-A since 1999 and the 1002 area has been recently opened by congress to oil and gas leasing.

The objective of this project was to assess the condition of freshwater resources in the Arctic Coastal Plain ecoregion of the National Petroleum Reserve of Alaska (NPR-A). Probabilistic sampling of freshwater resources provides an opportunity to assess the status of and changes in quality to these valuable habitats. These habitats and resources are intrinsically dynamic and have the potential to be affected by direct and indirect anthropogenic activities. Changes in habitats are expected to continue and potentially accelerate due to increasing temperatures attributed to climate change and oil and gas development. Information garnered from these surveys will establish a clear benchmark of the reference condition for NPR-A habitats as there are currently minimal human disturbances (Stoddard et al. 2006).

The project was conducted as part of the National Aquatic Resource Surveys (NARS), which is a program designed to monitor the condition of fresh and coastal waters across the country. In Alaska, NARS is implemented through a collaboration between the U.S. Environmental Protection Agency, the Alaska Department of Environmental Conservation, and the University of Alaska Anchorage. This report summarizes physical habitat measurements; water chemistry; and diatom, macroinvertebrate, phytoplankton, and zooplankton communities collected from lakes sampled in 2013.

Methods

Study Area

The Arctic Coastal Plain ecoregion of NPR-A extends over 10.8 million acres from the Arctic Ocean on its western and northern boundaries to the foothills of the Brooks Range along its southern edge. Average monthly air temperatures on the coastal plain are below freezing for approximately eight months of the year (October through May) with the coldest temperatures in January (-25.2˚C at Utquiaġvik and -29.6˚C at Umiat) and the warmest temperatures in July (4.9˚C at Utquiaġvik and 12.8˚C at Umiat, Western Regional Climate Center, https://wrcc.dri.edu/summary/Climsmak.html). Temperatures are moderated along the coast throughout the year. Annual precipitation is low, totaling 115 mm at Utquiaġvik and 122 mm at Umiat, with a little over half falling as rain during the summer months.

Study Design

A generalized random tessellation survey design (GRTS, Stevens and Olsen 2004) was used to select sample locations for wetlands sampled in 2011 and lake sites were selected based on their proximity to the sampled wetlands. Sample weights were used to estimate the sampled population extent and generate the statistical summaries for water quality parameters using the spsurvey package and the R statistical computing software (Kincaid and Olsen 2016, R Core Team 2017). Weights were adjusted after implementation of the study design to account for sites not sampled due to weather, landowner denial, or not meeting the target population criteria. The study design results include the total number of sites sampled, information on sites that were not sampled, the ability of the sample frame to represent the target population, and the extent of the sampled population.

The lakes target population was natural freshwater lakes greater than one hectare in surface area and one meter in depth that are bordered by palustrine emergent wetlands. Lakes greater than one hectare in area were selected from the waterbody dataset in the USGS National Hydrography Dataset (NHD) to create the sample frame. The waterbody dataset does not have depth information so lake depth was measured in the field to determine if lakes met the target criterion.

Thirty-five base lakes were selected that were closest to the wetlands sampled in 2011 (Lomax and Merrigan 2017). The five next closest lakes to the wetland sampling site were designated as alternate lakes. The nearest lake to each wetland was visited first for sampling. If that lake was too shallow, then one or more of the remaining five lakes was evaluated for sampling until a lake with suitable depth was found. In some cases, another lake was selected in the field because none of the six lakes could be sampled.

Evaluated lakes were weighted for statistical analysis using the formula

$$wgt_i = \frac{A}{n} * a_i,$$

where A= total area of palustrine emergent wetland (PEM) in the region (coastal or inland), n = number of lakes planned to be sampled in the region (17 for coastal and 18 for interior), and a_i = total area of PEM wetland nearest to lake i. The total area of PEM wetland by region nearest to each lake was calculated by intersecting Thiessen polygons (constructed in GIS for all lakes in the region) with PEM wetland polygons. The weights were adjusted to sum to the total number of lakes in the region by

$$wgt\_final_i = wgt_i * \frac{N}{\sum wgt_i},$$

where N = the total number of lakes by region, so that the sum of the final weights equals the number of lakes in the region. When a base lake was evaluated and replaced by an alternate lake, the weight for base lake was used as the weight for the alternate lake. The same weight applies to both lakes because the probability of selecting the alternate lake was determined by the selection of the base lake.

A total of 43 lakes were evaluated for sampling and 24 lakes were sampled, eight in the coastal region and 16 in the inland region (Figure 1). The remaining 19 lakes did not meet the depth criterion. Approximately 54% of lakes in the NHD were not representative of the target population, 95% CI [33, 74]. This over-coverage of the sample frame likely represents both shallow lakes and lakes that are not bordered by palustrine emergent wetlands. The sampled population represents the remaining 46% of lakes in the sample frame, 95% CI [26, 67].

Ten additional sites were strategically selected and sampled based on input from locals in the surrounding communities. Many of these “targeted” sites had historical or active disturbances nearby, but some were selected because they are part of the Circum-Arctic Lakes Observation Network (CALON, Table 1).

Table 1. Targeted lake sites.

Site number	Description
41	Formerly used defense site, very close to Arctic coast. Three ADEC contaminated sites within 500 meters of this lake. Cleanup complete at two sites. Third site is an old landfill that requires cleanup. Surface water samples collected in 2005 had elevated metals and hydrocarbons (ADEC Site Report: Kogru River / FUDS Western Landfill Cells 1, 2, and 3).
44	At Cape Simpson, very close to Arctic coast. Open ADEC contaminated site for legacy oil wells. Water samples high in chromium in 1990 (ADEC Site Report: BLM East Simpson # 2). Site currently managed as part of Legacy Well Program with BLM. Three other open contaminated sites from historic oil drilling approximately five km to the south.
45	At Point Lonely, very close to the Arctic coast. Part of the DEW line radar stations operated by the U.S. Air Force from 1953 to 1989. ADEC has 12 contaminated sites nearby, 11 of which are closed and one is active for PCB contaminated soil (ADEC Site Report: Lonely AFS Dewline – Module Train SS012).
47	Just outside of Utquiaġvik and close to a road. ADEC has several contaminated sites in Utquiaġvik, approximately five km away.
48	Adjacent to Inigok, no contaminated sites in this area.
51	CALON lake 6 km southeast of Inigok (INI-003).
52	CALON lake in Ikpikpuk River delta, very close to Arctic coast (IKP-001).
53	CALON lake in Ikpikpuk River delta, very close to Arctic coast (IKP-003).
54	CALON lake with a boat launch and road access to Utquiaġvik (BRW-100).
59	CALON lake in Pik dunes 23 km north of Inigok (INI-006).

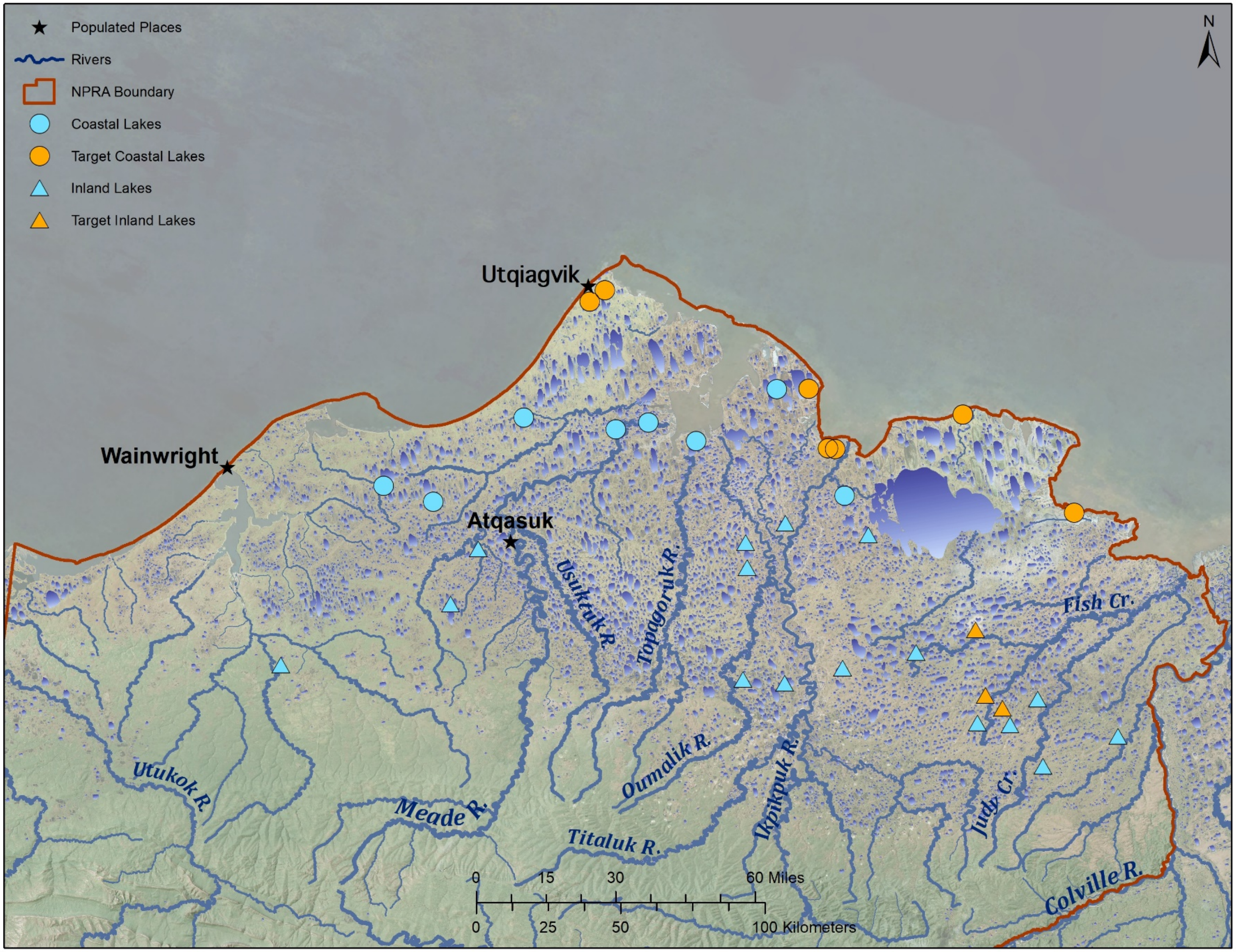

Figure 1. Map of targeted and random lake sites in Arctic Coastal Plain of NPR-A.

Field Sampling

Field work began on July 16th and ended August 7th, 2013. The target period was selected to reflect summer conditions after spring snowmelt. Water quality was characterized using in-situ field measurements in addition to laboratory samples of major ions, nutrients, suspended solids, and chlorophyll *a*. Physical habitat measurements included maximum depth, littoral zone depth, area, substrate, heights and angles of lakeshores, aquatic macrophyte cover, human influence and riparian vegetation. Physical habitat measurements were collected at 10 transects around the lake shore and summarized as metrics for individual sites.

Biological communities sampled included diatoms, macroinvertebrates, phytoplankton, and zooplankton. Phytoplankton and zooplankton samples were collected in the center of the lake and also in the littoral zone. Diatoms were sampled from the top two centimeters and also from a lower depth of a sediment core collected at the lake center. The lower sample was intended to capture historical diatom communities, but only eight of the lower samples yielded enough diatomaceous material to allow for counts so they were not used in this analysis.

Macroinvertebrates were sampled at the 10 habitat transects and composited. Diatoms and macroinvertebrates were processed and identified at UAA. Phytoplankton and zooplankton samples were processed and identified by Jason Bahr with Aquatic Research and Restoration Institute.

Detailed field operations and lab methods manuals are provided on the U.S. EPA National Aquatic Resource Survey website (https://www.epa.gov/national-aquatic-resource-surveys/manuals-used-national-aquatic-resource-surveys).

Results and Discussion

Physical Habitat

Continuous habitat measurements were summarized using boxplots for four different groups: targeted lakes, coastal lakes, inland lakes, and all lakes (Figure 2). There were 10 targeted lakes, eight coastal lakes, and 16 inland lakes, which summed to a total of 34 lakes.

Lake depths ranged from 0.5 to 8.9 meters and only two lakes were deeper than four meters. The single deepest lake was a targeted lake in the Pik Dunes, approximately 20 km south of Teshekpuk Lake. Littoral zone depths were measured approximately 10 meters offshore at 10 equally spaced stations around each lake and averaged less than one meter at most lakes, except for some coastal lakes with mean littoral zone depths up to two meters. The majority of lakes were small, 70% were less than 0.5 km^2 in area.

Human influence observations within the riparian zone were most common in the targeted lakes, although low levels of human influence were also observed at four coastal and three inland lakes. Two of the targeted lakes had no evidence of human activity. Banks within one meter of the shoreline were mostly flat (< 5 degrees), although the targeted lakes had higher variation in shoreline angles than the random lakes, possibly due to disturbances. Macrophyte cover in the littoral zone of the lakes was generally low, averaging less than 5%, although four lakes had cover greater than 20%. Organic substrates were most common in the coastal lakes, while sand substrates had higher prevalence in the inland lakes. Bare ground cover was mostly observed in the targeted lakes, most likely due to disturbance along the lake shore. The inland lakes tended to have higher woody ground cover and understory vegetation than the coastal lakes, most likely due to warmer temperatures (Tape et al. 2006). All lakes had high cover of herbaceous ground cover (median cover > 50%) and the random lakes had notable standing water in the riparian zone (median cover > 10%).

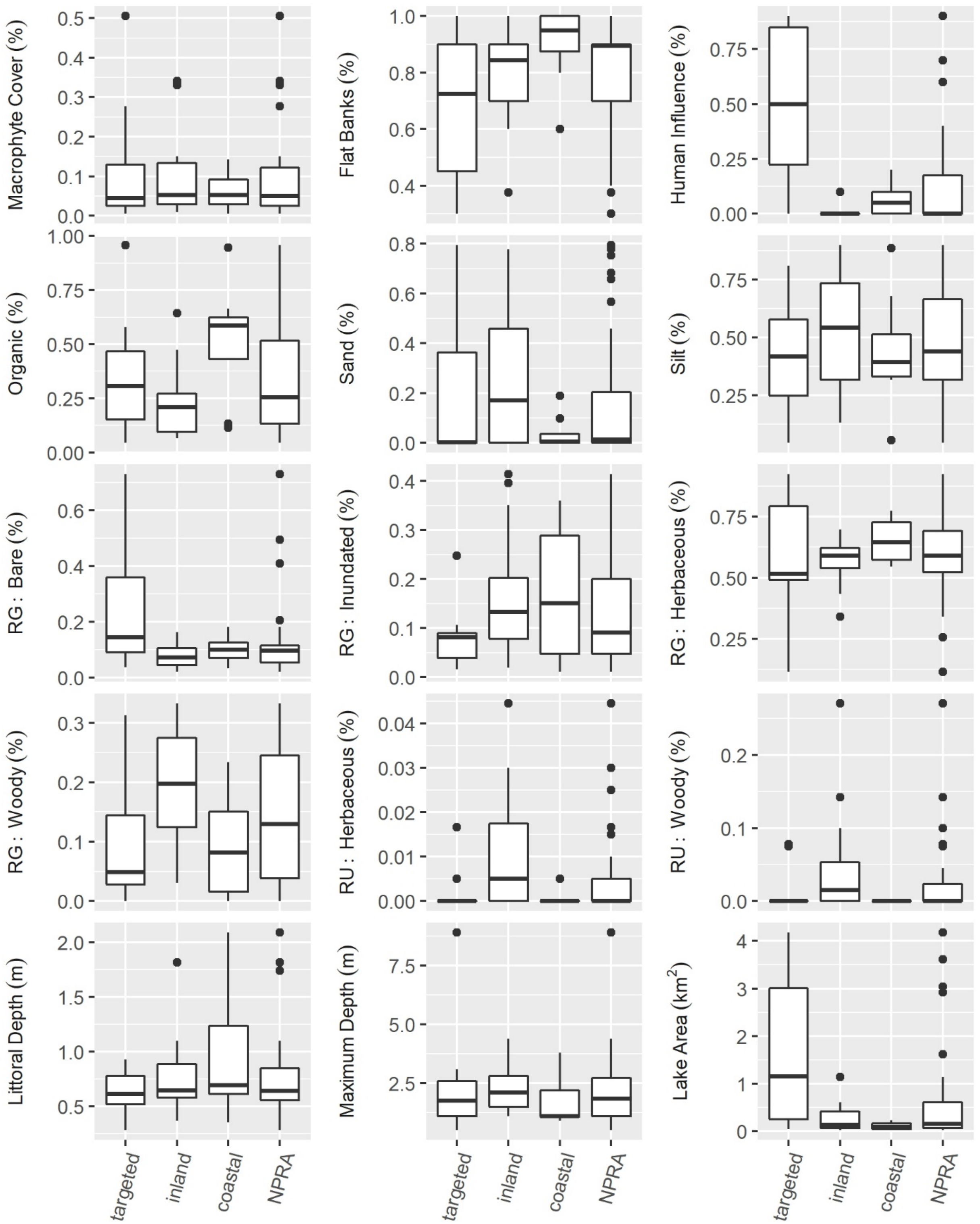

Figure 2. Boxplots for lake physical habitat variables for targeted, inland, coastal, and all sites combined (NPR-A). Boxes include the 25th – 75th percentiles of the data, whiskers extend to 1.5 times the interquartile range, and individual points are outliers. RG = riparian groundcover, RU = riparian understory.

Water Quality

Water quality samples collected at all 34 lakes included nutrients, major ions, and in-situ parameters. Adjusted weights were used to plot continuous distribution functions (CDFs) for all water chemistry parameters, except those parameters with high percentages of non-detect samples (Appendix A). Raw values were summarized using boxplots for four groups: targeted lakes, coastal lakes, inland lakes, and all lakes in NPR-A (Figure 3).

Lake water quality was characterized using calcium, chloride, magnesium, sodium, ammonia, nitrate + nitrite, Kjeldahl nitrogen, phosphorus, total suspended solids, dissolved oxygen, pH, specific conductance, temperature, and chlorophyll *a*. The majority of sites had concentrations below method detection limits (MDL) for ammonia (97% ND), nitrate + nitrite (97% ND), Kjeldahl nitrogen (85% ND), and potassium (47% ND). Total phosphorus and total suspended solids had eight and one non-detect, respectively, which were replaced with one-half the detection limit for CDFs and boxplots. We compared our results to several publications documenting lake water chemistry in the Arctic Coastal Plain of Alaska (Alexander et al. 1989, Kling et al. 1992, Gregory-Eaves et al. 2000, Koch et al. 2014, Hinkel et al. 2017), in addition to lake studies from northern Canada (Pienitz et al. 1997, Dean et al. 2016).

Nitrogen concentrations were low in most of the sampled lakes. Only six lakes had results above detection limits for one or more of the nitrogen parameters. Five of the six reported nitrogen results were for Kjeldahl nitrogen and results ranged from 1.1 – 3.0 mg/L (the MDL was 1.0 mg/L). Total phosphorus concentrations ranged from below the MDL (0.01 mg/L) to 0.798 mg/L. The maximum phosphorus value in the dataset was 14 times higher than the next highest value. The median total phosphorus concentration across all lakes was 0.017 mg/L. Chlorophyll *a* concentrations ranged from 0 to 21 µg/L and the median value was 0.75 µg/L.[1] The detection limits for the inorganic nitrogen and Kjeldahl nitrogen parameters were too high to make comparisons with other published data, but recent studies indicate increasing nutrient concentrations in arctic freshwaters due to permafrost thaw (Wrona et al. 2006, Frey and McClelland 2009, Lougheed et al. 2011). The total phosphorus and chlorophyll *a* maximums are higher than values reported for the Barrow ponds, where increased temperatures and nutrients over the last 40 years have led to changes in macroinvertebrate community composition (Lougheed et al. 2011).

The nutrient results indicate that most of the lakes are either oligotrophic or mesotrophic. The upper limits for oligotrophic and mesotrophic conditions are 10 and 30 µg/L for total phosphorus and 3.5 and 9 µg/L for chlorophyll *a*, respectively (Nürnberg 1996). Ideally, trophic condition is assessed using average summer values as nutrient concentrations

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[1] Note from laboratory: The complex calculations used to differentiate the various chlorophyll species magnify error at low concentrations and sometimes produce negative values, which are reported as 0.0.

vary over time. Nutrients in arctic thaw ponds have been shown to decrease as the summer progresses (Koch et al. 2014) and, because our samples are from July and August, our estimates of trophic condition may be biased low. Total phosphorus results indicated that 76% of the lakes were mesotrophic, while chlorophyll *a* indicated only 15% of the lakes were mesotrophic.

Targeted lake 44 at Cape Simpson was an outlier for both parameters, with a total phosphorus concentration of 0.80 mg/L and chlorophyll *a* of 21 µg/L, indicating eutrophic conditions. This lake also had the second highest value for Kjeldahl nitrogen, 2.6 mg/L. Possible causes leading to nutrient enrichment in Arctic lakes include seabirds (Brimble et al. 2009), thermokarsting (Bowden et al. 2008), or changes in lake water balance, where evaporation surpasses inflows, and nutrients become concentrated (Lewis et al. 2015).

Lake 44 was also an outlier for total suspended solids, which is the concentration of particles trapped by a filter. Lake 44 had TSS of 390 mg/L, an order of magnitude higher than the other lakes (the next highest value was 11 mg/L), which indicates that thermokarst features along the lakeshore may have caused the elevated TSS and nutrients (Bowden et al. 2008).

Due to a high detection limit for Kjeldahl nitrogen, we could not calculate N:P ratios to explore nutrient limitation in these lakes. Several studies have reported nitrogen as the common limiting nutrient in Arctic freshwaters, although sometimes both nitrogen and phosphorus are co-limiting (Pienitz et al. 1997, Koch et al. 2014). Total phosphorus was weakly correlated to chlorophyll *a* concentrations (r = 0.38 with one outlier removed), providing further evidence that either nitrogen or both nutrients are limiting to lake productivity in July.

The majority of lakes in NPR-A (91%) had dissolved organic carbon (DOC) concentrations below 20 mg/L. Two lakes had concentrations below 50 mg/L and one of the inland lakes (34) had a concentration of 330 mg/L. DOC concentrations above 100 mg/L are not exceptional and have been reported in Arctic lakes and other lakes types across Alaska (Gregory-Eaves et al. 2000). High DOC in lake water likely results from the high organic contents in saturated soils across NPR-A (MacLean et al. 1999). This lake also appeared to be connected to an alluvial tributary of the Chipp River.

Major ion chemistry indicated that sodium, magnesium, and chloride were strongly correlated and associated with coastal lakes. Two targeted lakes in the Ikpikpuk River delta (52 and 53) had high concentrations of all major ions and specific conductance indicating sea spray or coastal inundation were altering their water chemistry. Calcium concentrations were higher in inland lakes and was positively associated with pH indicating calcium carbonate leaching from underlying geology on the coastal plain and Brooks Range (Hinkel et al. 2017).

Lakes in NPR-A are shallow, clear, and have limited to no shade due to a lack of large woody vegetation (e.g., trees). In-situ parameters measured along depth profiles were stable, with two exceptions. pH measurements decreased rapidly in a few of the deeper lakes to suspiciously low readings (<2), which were flagged. One of the deep targeted lakes had a thermocline in which temperatures dropped rapidly to a depth of six meters where they stabilized 5°C colder than surface temperatures. Due to stability in the remainder of the in-situ parameters collected and problematic pH readings at depth, we used surface measurements for comparisons across the lake groups. Additionally, specific conductance lab and field values were strongly correlated (*r* = 0.99), so field measurements were used for analysis. Lake temperatures ranged from 8.3°C to 18.5°C. On average, coastal lakes were approximately 4°C colder than inland lakes due to colder air temperatures along the coast (Hinkel et al. 2012a). Dissolved oxygen concentrations were high at all lakes (> 9.5 mg/L). pH ranged from 5.1 to 8.3 and most of the lakes tended towards moderate acidity as 70% of the lakes had pH below seven. Specific conductance values ranged from 44 to 4170 µS/cm and targeted lakes had significantly higher values than the randomly selected lakes.

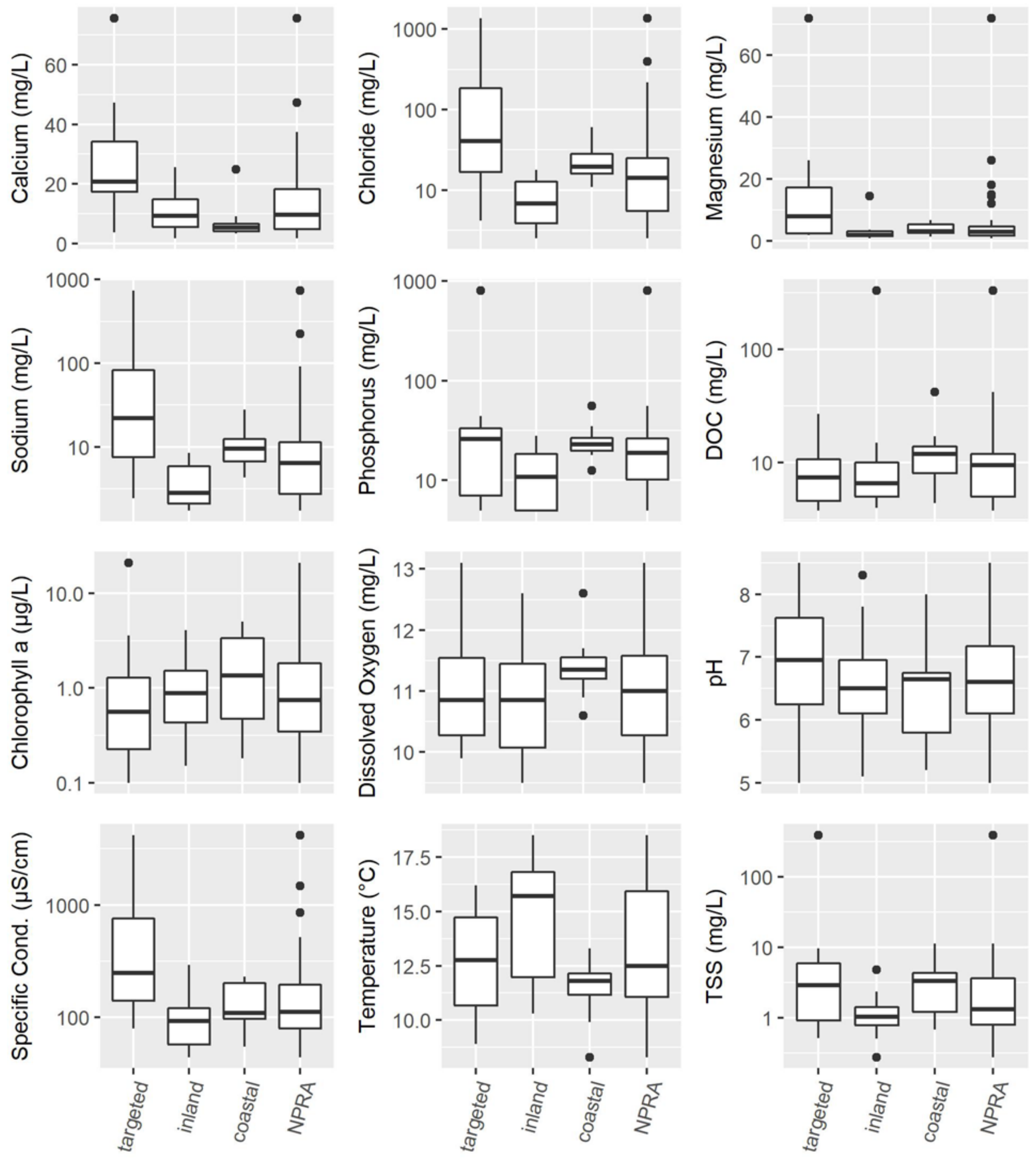

Figure 3. Boxplots for lake water quality parameters for targeted, inland, coastal, and all sites combined (NPR-A). Boxes include the 25th – 75th percentiles of the data, whiskers extend to 1.5 times the interquartile range, and individual points are outliers. Y axes were log-transformed for several variables to lessen influence of outliers and show differences between groups.

Biological Communities

For each of the biological community datasets, we used several measures to investigate patterns in diversity. We calculated gamma, alpha, and beta diversity to investigate differences across communities and studies at different scales (Table 2). Gamma diversity is the total number of taxa identified. Alpha diversity is the mean number of taxa for all sites. Beta diversity was calculated as the gamma diversity divided by the alpha diversity and reflects the number of distinct communities in a dataset; a beta diversity of one indicates that every site shares the same taxa. Shannon and Simpson diversity indices include information on taxa abundances and were calculated for each site and averaged for each study. Shannon's index was calculated as

$$H' = \sum_{i=1}^{S} p_i * \ln(p_i),$$

where p_i is the proportion of taxa i and S is the total number of taxa. Shannon's index is the log of the number of taxa of equal abundance. Simpson's index was calculated as

$$Diversity = 1 - \sum_{i=1}^{S} p_i^2,$$

where p_i is the proportion of taxa i and S is the total number of taxa. Simpson's index represents the likelihood that two randomly chosen individuals will be different taxa. For both indices, higher values indicate higher diversity.

At some sites sampled for macroinvertebrates, not all final taxonomic identifications were made to the lowest possible rank (e.g. genus for Ephemeroptera) because some organisms were either early instars, pupae, or lacking diagnostic characteristics. Taxonomic identifications left at a higher rank than other organisms at the same site (e.g. Baetidae and *Baetis* sp.) were removed for biodiversity calculations to avoid double-counting.

Tables of all taxa from each of the biological communities are provided in Appendix B. For each taxa, average abundances, maximum abundances, and frequencies are provided. All statistical analyses were run in the R statistical computing software using the tidyverse and vegan packages (Oksanen et al. 2017, R Core Team 2017, Wickham 2017).

Table 2. Biodiversity indices for lake biological communities.

Community	Study (sample size)	Gamma	Alpha	Beta	Shannon	Simpson
Diatoms	All Lakes (31)	474	53	8.9	3.0	0.89
	Random Lakes (22)	359	51	7.0	2.9	0.87
Macroinvertebrates	All Lakes (34)	131	28	4.7	2.3	0.82
	Random Lakes (24)	113	29	3.9	2.4	0.83
Phytoplankton	All Lakes (34)	49	14	3.5	1.3	0.62
	Random Lakes (24)	48	16	3.0	1.4	0.65
Zooplankton	All Lakes (34)	55	11	5.0	1.4	0.61
	Random Lakes (24)	49	12	4.1	1.4	0.62

Diatoms

Three of the lakes did not have enough diatoms in the lake sediment to count (4, 7, and 51). Diatoms were the most diverse of the four communities (Table 3), which may be partly due to taxonomic resolution; diatoms are identified to species, while the other biological communities were identified more commonly to genus or higher taxonomic groups. Average site richness at each lake was 53. The five most common diatom taxa were found in approximately two thirds of the lakes (frequencies from 21 to 24) and included *Encyonema silesiacum*, *Staurosira construens* var. *venter*, *Achnanthidium minutissimum*, *Amphora copulata*, and *Staurosirella pinnata* (Table 3). There were 13 taxa that occurred in at least half of the lakes. Three of the most abundant taxa overlapped the most common taxa. *S. pinnata*, *A. minutissimum*, and *S. construens* var. *venter* all had average relative abundances greater than 5%. Other abundant taxa included *Pseudostaurosira brevistriata* and *Nitzschia perminuta*, whose average relative abundances were greater than 2%. Approximately half of the diatom taxa were rare, occurring in only one of the sampled lakes (221 taxa). Some of these “rare” taxa may be morphologically distinct forms of more abundant taxa.

Common diatom taxa found in this study have been previously reported from Arctic Alaska (Patrick and Freese 1961, Foged 1981, Gregory-Eaves et al. 1999, Antoniades et al. 2008). The impressive diversity of diatoms in Arctic Alaska lakes has also been previously documented. Neils Foged (1971) identified 400 different diatom taxa from a single sediment sample from a lake in our study area. Diatoms have been successfully used as bioindicators in North America and Europe, and in a rapidly changing environment could lend insights into how biological communities are being affected by these changes.

Table 3. Diatom taxa that occurred in 50% or more of all lakes.

Taxa Name	Frequency (%)	Mean Relative Abundance (%)
Encyonema silesiacum (Bleisch) Mann	77	1.55
Staurosira construens var. *venter* (Ehrenberg) Hamilton	77	5.59
Achnanthidium minutissimum (Kützing) Czarnecki	74	7.06
Amphora copulata (Kützing) Schoeman et Archibald	74	0.65
Staurosirella pinnata (Ehrenberg) Williams & Round	68	14.98
Nitzschia perminuta (Grunow) Peragallo	65	2.19
Sellaphora laevissima (Kützing) Mann	61	1.24
Sellophora rectangularis (Gregory) Lange-Bertalot & Metzeltin	61	1.30
Pseudostaurosira brevistriata (Grunow) Williams & Round	61	2.37
Amphora ovalis (Kützing) Kützing	55	0.70
Navicula cryptocephala Kützing	55	1.06
Navicula vulpina Kützing	55	1.94
Sellaphora bacillum (Ehrenberg) Mann	55	0.41

Macroinvertebrates

Macroinvertebrates were the second most diverse community in the lakes. Average site richness across all lakes was 28 and there were 23 taxa that occurred in at least half of the lakes. There were six taxa that occurred in 80% or more of the lakes (frequencies of 28 to 32, Table 4): roundworms (*Nematoda*), segmented worms (*Oligochaeta*), seed shrimp (*Ostracoda*), and three genera of non-biting midges (Chironomidae: *Corynoneura* sp., *Procladius* (Holotanypus) sp., and *Paratanytarsus* sp.). The taxa with the highest densities included roundworms, three different genera of non-biting midges (*Paratanytarsus* sp., *Procladius* (Holotanypus) sp., and *Zalutschia* sp.), one caddisfly (*Grensia praeterita*) and a polychaete worm (*Manayunkia speciosa*). Aquatic insect diversity was dominated by the true flies (Diptera), and specifically the non-biting midges (Chironomidae), which comprised over half of the total diversity across all lakes (69 distinct taxa). Other important aquatic insect orders were represented in smaller numbers: one stonefly taxa, two mayfly taxa, seven caddisfly taxa, and nine beetle taxa were found across all lakes. The stonefly (*Nemoura* sp.) and two caddisflies (*Grensia preaterita* and *Micrasema scissum*) were relatively common (frequencies of 22 to 27). One of the worm taxa (*M. speciosa*), which was found at 13 lakes, is a host for two parasites that have negatively affected survival and productivity of juvenile salmon in the Klamath River, California (Willson et al. 2010).

Table 4. Macroinvertebrate taxa that occurred in 50% or more of all lakes. The taxa Limnephilidae, Chironomidae, and Orthocladiinae were mostly early instars and could not be resolved to a lower taxonomic level.

Order	Family	Taxa Name	Mean Density (no./m^2)	Frequency (%)
-	-	Nematoda	57	94
Diptera	Chironomidae	*Corynoneura* sp.	19	91
-	-	Oligochaeta	26	88
Diptera	Chironomidae	*Procladius* (Holotanypus) sp.	32	85
Diptera	Chironomidae	*Paratanytarsus* sp.	47	82
-	-	Ostracoda	25	82
Diptera	Chironomidae	*Stictochironomus* sp.	10	79
Trichoptera	Limnephilidae	Limnephilidae	28	79
Diptera	Chironomidae	*Tanytarsus* sp.	24	76
Trombidiformes	Lebertiidae	*Lebertia* sp.	3	74
Diptera	Chironomidae	*Cladotanytarsus* sp.	24	71
Plecoptera	Nemouridae	*Nemoura* sp.	19	71
Trichoptera	Limnephilidae	*Grensia praeterita*	30	71
Diptera	Chironomidae	*Parakiefferiella* sp.	13	65
Trichoptera	Brachycentridae	*Micrasema scissum*	11	65
Basommatophora	Physidae	*Physa* sp.	5	59
Diptera	Chironomidae	Chironomidae	2	59
Diptera	Chironomidae	*Chironomus* sp.	9	56
Diptera	Chironomidae	*Orthocladius* (Pogonocladius) sp.	20	56
Diptera	Chironomidae	*Zalutschia* sp.	28	56
Diptera	Chironomidae	Orthocladiinae	3	53

Phytoplankton

Phytoplankton taxa densities were averaged across the samples collected from the lake center and the littoral zone. Densities were calculated as organisms per milliliter of sample. The most common phytoplankton were three cyanobacteria (Cyanophyceae) that were found in almost every lake (frequency ≥ 97%, Table 5): *Synechococcus* sp., *Aphanocapsa* sp., and *Aphanothece* sp. The same three taxa also had the highest average densities across all lakes, ranging from 3,914 to 36,744 individuals/ml. The maximum phytoplankton density recorded was 113,426 individuals/mL for *Synechococcus* sp. Other common phytoplankton taxa include a green algae (*Chlamydomonas* sp.), two golden algae (*Dinobryon* sp. and *Erkenia subaequiciliata*), and *Cryptomonas ovata* (frequencies from 20 to 26). Cyanobacteria include many nitrogen-fixing species and a lake study from the Arctic foothills of Alaska indicate that nitrogen more strongly regulates phytoplankton production than phosphorus (Levine and Whalen 2001).

Table 5. Phytoplankton taxa that occurred in 50% or more of all lakes.

Order	Family	Taxa Name	Mean Density (no./ml)	Freq. (%)
Chroococcales	Chroococcaceae	*Synechococcus* sp.	36744	100
Chroococcales	Chroococcaceae	*Aphanocapsa* sp.	3914	97
Chroococcales	Chroococcaceae	*Aphanothece* sp.	6821	97
Chroococcales	Chroococcaceae	Chroococcaceae	17508	97
Volvocales	Chlamydomonadaceae	*Chlamydomonas* sp.	843	76
Ochromonadales	Dinobryaceae	*Dinobryon* sp.	758	65
Ochromonadales	Ochromonadaceae	*Erkenia subaequiciliata*	2092	62
Cryptomonadales	Cryptomonadaceae	*Cryptomonas ovata*	240	59
Tetrasporales	Palmellopsidaceae	*Sphaerocystis* sp.	324	50
Zygnematales	Desmidiaceae	*Cosmarium* sp.	1119	50
Monomastigales	Monomastigaceae	*Monomastix* sp.	171	50

Zooplankton

Zooplankton taxa densities were averaged across the samples collected from the lake center and the littoral zone. Densities were calculated as organisms per cubic meter of water. The most common zooplankton taxa were two rotifers (*Keratella cochlearis* and *Conochilus unicornis*) and two copepods (*Diaptomus pribilofensis* and *Cyclops scutifer*), all of which occurred in at least 75% of the lakes (Table 6). Three of the most common taxa were also the most abundant: *K. cochlearis*, *C. unicornis*, *D. pribilofensis*, and *Kellicottia longispina* all had average densities greater than 10,000 organisms/m^3. Large-bodied zooplankton like *D. pribilofensis* and *C. scutifer* are considered important fish prey and have been observed in lakes and ponds from Toolik Lake to the Arctic coast (O’Brien et al. 1979, Kling et al. 1992). *C. scutifer* has also been found in stomachs of small lake trout (O’Brien et al. 1979).

Table 6. Zooplankton taxa that occurred in 50% or more of all lakes.

Order	Family	Taxa Name	Mean Density (no./m^3)	Freq. (%)
Ploima	Brachionidae	*Keratella cochlearis*	43894	94
Calanoida	Diaptomidae	*Diaptomus pribilofensis*	10128	91
Cyclopoida	Cyclopidae	*Cyclops scutifer*	5254	85
Flosculariaceae	Conochilidae	*Conochilus unicornis*	17418	76
Ploima	Brachionidae	*Kellicottia longispina*	10033	71
Ploima	Gastropodidae	*Gastropus stylifer*	4887	68

Summary

Lake habitats in NPR-A are generally small (< 1 km^2) and are characterized by shallow depths, flat banks, and low aquatic vegetation cover. A mixture of sand, silt, and organic substrates were observed along lakeshores, although organic substrates were more common in coastal lakes. Riparian vegetation was dominated by herbaceous plants, although inland lakes also had a significant woody plant component generally consisting of dwarf willow and similar shrubbery. Deep lakes are rare and only one deep lake was sampled, although it was not part of the probabilistic selection.

Lake water chemistry indicated a broad range of conditions across NPR-A: pH values ranged from moderately acidic to moderately alkaline, specific conductance values spanned three orders of magnitude, and water temperatures were mostly cold, although eight lakes had surface temperatures greater than 15°C. Nutrients were generally low except for one lake with very high nitrogen and phosphorus concentrations, which may stem from permafrost degradation. Coastal lakes had higher concentrations of major ions, most likely from coastal inundation or sea spray from storms.

Across the four biological communities sampled, over 700 different taxa were identified. Diatoms from lake cores were the most diverse community across all indices, indicating high richness and high evenness. Macroinvertebrates were the next most diverse community and non-biting midges made up the majority of the diversity, comprising over half of the total taxa. Cyanobacteria were the most common phytoplankton taxa and rotifers and copepods were the most common zooplankton taxa.

This study included 10 targeted sites, five of which had historic or active anthropogenic disturbances and five CALON lakes. Seven of the targeted sites were also proximal to the arctic coast, which could lead to saltwater intrusion into freshwater systems during storm surges. This confounded our ability to detect differences between the targeted lakes and the randomly selected lakes. The targeted lakes were larger and had higher levels of human influence, specific conductance, and concentrations of major ions.

Overall, this study provides a critical baseline of habitat, water chemistry, and biological communities from randomly selected lakes across NPR-A. Of the variables measured, there was no indication of current degradation at the human-influenced targeted lakes. For the five CALON lakes, this dataset provides a valuable reference for the summer index period from 2013.

Literature Cited

Alexander, V., S. C. Whalen, and K. . Klingensmith. 1989. Nitrogen cycling in Arctic lakes and ponds. Hydrobiologia 172:165–172.

Antoniades, D., P. B. Hamilton, M. S. V. Douglas, and J. P. Smol. 2008. Diatoms of North America: The freshwater floras of Prince Patrick, Ellef Ringnes, and northern Ellesmere Islands from the Canadian Arctic Archipelago. A.R.G. Gantner Verlag K.G., Konigstein, Germany.

Arp, A. C. D., M. S. Whitman, B. M. Jones, R. Kemnitz, G. Grosse, and F. E. Urban. 2012. Drainage network structure and hydrologic behavior of three lake-rich watersheds on the Arctic Coastal Plain, Alaska. Arctic Antarctic and Alpine Research 44:385–398.

Balasubramaniam, A., A. Medeiros, K. Turner, R. Hall, and B. Wolfe. 2017. Biotic responses to multiple aquatic and terrestrial gradients in shallow subarctic lakes (Old Crow Flats, Yukon, Canada). Arctic Science 3:277–300.

Bowden, W. B., M. N. Gooseff, A. Balser, A. Green, B. J. Peterson, and J. Bradford. 2008. Sediment and nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska: Potential impacts on headwater stream ecosystems. Journal of Geophysical Research: Biogeosciences 113.

Brimble, S. K., K. L. Foster, M. L. Mallory, R. W. Macdonald, J. P. Smol, and J. M. Biais. 2009. High arctic ponds receiving biotransported nutrients from a nearby seabird colony are also subject to potentially toxic loadings of arsenic, cadmium, and zinc. Environmental Toxicology and Chemistry 28:2426–2433.

Dean, J. F., M. F. Billett, R. Baxter, K. J. Dinsmore, J. S. Lessels, L. E. Street, J. A. Subke, D. Tetzlaff, I. Washbourne, and P. A. Wookey. 2016. Biogeochemistry of “pristine” freshwater stream and lake systems in the western Canadian Arctic. Biogeochemistry 130:191–213.

Foged, N. 1971. Diatoms found in a bottom sediment sample from a small deep lake on the Northern Slope, Alaska. Nova Hedwigia. Cramer.

Foged, N. 1981. Diatoms in Alaska (Bibliotheca Phycologia, Band 53). Lubrecht & Cramer, Limited.

Frey, K. E., and J. W. McClelland. 2009. Impacts of permafrost degradation on arctic river biogeochemistry. Hydrological Processes 23:169–182.

Frohn, R. C., K. M. Hinkel, and W. R. Eisner. 2005. Satellite remote sensing classification of thaw lakes and drained thaw lake basins on the North Slope of Alaska. Remote

Sensing of Environment 97:116–126.

Gregory-Eaves, I., J. P. Smol, B. P. Finney, and M. E. Edwards. 1999. Diatom-based transfer functions for inferring past climatic and environmental changes in Alaska, U.S.A. Arctic Antarctic and Alpine Research 31:353–365.

Gregory-Eaves, I., J. P. Smol, B. P. Finney, D. R. S. Lean, and M. E. Edwards. 2000. Characteristics and variation in lakes along a north-south transect in Alaska. Archiv Fur Hydrobiologie 147:193–223.

Hinkel, K. M., C. D. Arp, A. Townsend-Small, and K. E. Frey. 2017. Can deep groundwater influx be detected from the geochemistry of thermokarst lakes in Arctic Alaska? Permafrost and Periglacial Processes 28:552–557.

Hinkel, K. M., B. M. Jones, W. R. Eisner, C. J. Cuomo, R. A. Beck, and R. Frohn. 2007. Methods to assess natural and anthropogenic thaw lake drainage on the western Arctic coastal plain of northern Alaska. Journal of Geophysical Research: Earth Surface 112:1–9.

Hinkel, K. M., J. D. Lenters, Y. Sheng, E. A. Lyons, R. A. Beck, W. R. Eisner, E. F. Maurer, J. Wang, and B. L. Potter. 2012a. Thermokarst lakes on the Arctic Coastal Plain of Alaska: spatial and temporal variability in summer water temperature. Permafrost and Periglacial Processes 23:207–217.

Hinkel, K. M., Y. Sheng, J. D. Lenters, E. A. Lyons, R. A. Beck, W. R. Eisner, and J. Wang. 2012b. Thermokarst lakes on the Arctic Coastal Plain of Alaska: geomorphic controls on bathymetry. Permafrost and Periglacial Processes 23:218–230.

Kincaid, T. M., and A. R. Olsen. 2016. spsurvey: Spatial Survey Design and Analysis.

Kling, G. W., W. J. O'Brien, M. C. Miller, and A. E. Hershey. 1992. The biogeochemistry and zoogeography of lakes and rivers in arctic Alaska. Hydrobiologia 240:1–14.

Koch, J. C., K. Gurney, and M. S. Wipfli. 2014. Morphology-dependent water budgets and nutrient fluxes in arctic thaw ponds. Permafrost and Periglacial Processes 25:79–93.

Levine, M. A., and S. C. Whalen. 2001. Nutrient limitation of phytoplankton production in Alaskan Arctic foothill lakes. Hydrobiologia 455:189–201.

Lewis, T. L., M. S. Lindberg, J. a. Schmutz, P. J. Heglund, J. Rover, J. C. Koch, and M. R. Bertram. 2015. Pronounced chemical response of Subarctic lakes to climate-driven losses in surface area. Global Change Biology 21:1140–1152.

Lomax, T., and D. Merrigan. 2017. Alaska Monitoring and Assessment Program (AKMAP) 2013 Arctic Coastal Plain NPR-A Lakes Survey Design. Anchorage, AK.

Lougheed, V. L., M. G. Butler, D. C. McEwen, and J. E. Hobbie. 2011. Changes in tundra pond limnology: Re-sampling Alaskan ponds after 40 years. Ambio 40:589–599.

MacLean, R., M. W. Oswood, J. G. Irons, and W. H. McDowell. 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.

Nürnberg, G. K. 1996. Trophic state of clear and colored, soft- and hardwater lakes with special consideration of nutrients, anoxia, phytoplankton and fish. Lake and Reservoir Management 12:432–447.

O'Brien, W. J., C. Buchanan, and J. F. Haney. 1979. Arctic zooplankton community structure: exceptions to some general rules. Arctic 32:237–247.

Oksanen, J., F. G. Blanchet, M. Friendly, R. Kindt, P. Legendre, D. McGlinn, P. R. Minchin, R. B. O'Hara, G. L. Simpson, P. Solymos, M. H. H. Stevens, E. Szoecs, and H. Wagner. 2017. vegan: Community Ecology Package.

Patrick, R., and L. R. Freese. 1961. Diatoms (Bacillariophyceae) from Northern Alaska. Proceedings of the National Academy of Sciences of Philadelphia 112:129–293.

Pienitz, R., J. P. Smol, and D. R. S. Lean. 1997. Physical and chemical limnology of 59 lakes located between the southern Yukon and the Tuktoyaktuk Peninsula, Northwest Territories (Canada). Canadian Journal of Fisheries and Aquatic Sciences 54:330–346.

R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Stevens, D. L., and A. R. Olsen. 2004. Spatially Balanced Sampling of Natural Resources. Journal of the American Statistical Association 99:262–278.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: The concept of reference condition. Ecological Applications 16:1267–1276.

Tape, K., M. Sturm, and C. Racine. 2006. The evidence for shrub expansion in Northern Alaska and the Pan-Arctic. Global Change Biology 12:686–702.

Urban, F. E., and G. D. Clow. 2013. Air Temperature, Wind Speed, and Wind Direction in the National Petroleum Reserve-Alaska and the Arctic National Wildlife Refuge, 1998-2011. Anchorage, AK.

Wickham, H. 2017. tidyverse: Easily Install and Load the "Tidyverse."

Willson, S. J., M. A. Wilzbach, D. M. Malakauskas, and K. W. Cummins. 2010. Lab rearing of a freshwater polychaete (*Manayunkia speciosa*, Sabellidae) host for salmon pathogens. Northwest Science:183–191.

Wrona, F. J., T. D. Prowse, J. D. Reist, J. E. Hobbie, M. Lucie, J. Lévesque, W. F. Vincent, F. J. Wrona, T. D. Prowse, J. D. Reist, J. E. Hobbie, and L. M. J. Levesque. 2006. Climate change effects on aquatic biota, ecosystem structure, and function. Ambio 35:359–369.