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Arctic Lake Physical Processes and Regimes with Implications for Winter Water Availability and Management in the National Petroleum Reserve Alaska

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Abstract Lakes are dominant landforms in the National Petroleum Reserve Alaska (NPRA) as well as important social and ecological resources. Of recent importance is the management of these freshwater ecosystems because lakes deeper than maximum ice thickness provide an important and often sole source of liquid water for aquatic biota, villages, and industry during winter. To better understand seasonal and annual hydrodynamics in the context of lake morphometry, we analyzed lakes in two adjacent areas where winter water use is expected to increase in the near future because of industrial expansion. Landsat Thematic Mapper and Enhanced Thematic Mapper Plus imagery acquired between 1985 and 2007 were analyzed and compared with climate data to understand interannual variability. Measured changes in lake area extent varied by 0.6% and were significantly correlated to total precipitation in the preceding 12 months ($p < 0.05$). Using this relation, the modeled lake area extent from 1985 to 2007 showed no long-term trends. In addition, high-resolution aerial photography, bathymetric surveys, water-level monitoring, and lake-ice thickness measurements and growth models were used to better understand seasonal hydrodynamics, surface area-to-volume relations, winter water availability, and more permanent changes related to geomorphic change. Together, these results describe how lakes vary seasonally and annually in two critical areas of the NPRA and provide simple models to help better predict variation in lake-water supply. Our findings suggest that both overestimation and underestimation of actual available winter water volume may occur regularly, and this understanding may help better inform management strategies as future resource use expands in the NPRA.

Keywords Alaska · Arctic lakes · Climate change · Lake hydrology · Lake ice · Water resources · Winter water use

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Introduction

Arctic ponds and lakes play an important role in the human water and food supply, hydrologic and biogeochemical cycling, and wildlife habitat provision (Boyd 1959; Bollinger and Derksen 1996; Rovansek and others 1996; Bowling and others 2003; Cott and others 2008a; Cott and others 2008b), yet they are vulnerable to both climate change and local anthropogenic pressures (Vorosmarty and others 2000; Smith and others 2005; Hinkel and others 2007; Smol and Douglas 2007). Arctic lakes are dominant landforms often occupying >20% of the land surface (Sellmann and others 1975; Hinkel and others 2005). Lakes, ponds, and wetlands provide crucial feeding and nesting sites for a great diversity and abundance of bird species that migrate annually over long distances (Alerstam and others 2001). Those lakes having depths exceeding the maximum thickness of the winter ice cover can provide habitat for fish and other aquatic organisms, which are vital to many terrestrial food webs and human subsistence fisheries (Berkes and Jolly 2001). These same lakes may also provide the major source of liquid water for villages and industry during long arctic winters when most other freshwater reservoirs are frozen. Thus, variability and shifts in the hydrologic budget of these lakes directly impact the social and ecologic vitality of the arctic (Boyd 1959; Alessa and others 2008).

The results from a number of recent studies suggest that high-latitude lakes and ponds have been undergoing rapid change associated with climate change. Using remote sensing, several studies examined whether the abundance and/or surface area of high-latitude lakes have changed in response to increasing air and soil temperatures in recent decades (Klein and others 2005; Smith and others 2005; Riordan and others 2006; Yoshikawa and Hinzman 2003) and/or variability in precipitation (Plug and others 2008). For example, Smith and others (2005) examined coarse resolution satellite imagery to detect surface-area changes in lakes ($\geq$40 ha) from 1973 to 1997/98 across a broad expanse of Siberia (approximately 500,000 km^2). During this time, they found that lakes had decreased by 11%, although these changes were not uniform across the study area. Lake abundance and surface area decreased in the zones of discontinuous, sporadic, and isolated permafrost, and it increased in the zone of continuous permafrost. Lake change in Alaska also appears to follow this general pattern, although interpretation differs as to the relative roles of increasing aridity and permafrost dynamics (Riordan and others 2006; Yoshikawa and Hinzman 2003). In contrast, changes in tundra lakes in the western Canadian Arctic have been shown to vary with precipitation with no apparent decadal-scale trend (Plug and others 2008).

Lakes provide the major available and energy-independent source of liquid water during the winter (Boyd 1959; Alessa and others 2008; Sibley and others 2008). Recently, winter water demand has increased throughout much of United States and Canadian arctic coastal plain because of expanding industrial activities (Sibley and others 2008), such as in the National Petroleum Reserve Alaska (NPRA) (Cott and others 2008b). Current activities in the NPRA associated with oil and gas leasing and exploration consist of two primary components: winter seismic survey activity and winter exploratory drilling (United States Department of the Interior–Bureau of Land Management [USDOI-BLM] 2005; Cott and others 2008b). Seismic survey activity typically entails the construction of ice airstrips and withdrawal of water from lakes for camp (i.e., domestic) use. Winter seismic survey exploration is less concentrated than exploratory drilling and tends to use less water because ice roads and ice pads are not constructed (NRC 2003). If seismic surveys indicate quantities of recoverable oil and gas and development leases are acquired, and if exploratory drilling commences, ice roads and ice pads, in addition to ice airstrips, are constructed. All of these activities require extraction of liquid water from the frozen lakes.

A typical exploratory well requires 14 to 45 days of continuous operation (National Research Council [NRC] 2003). It is estimated that 0.57 ha-m of water is used while drilling a single exploratory well, another 0.14 ha-m of water is required for camp use, and another 0.23 to 0.34 ha-m of water is required per kilometer to build an ice road that is 15 cm thick and 9 to 11 m wide (United States Army Corps of Engineers [USACE] 1998; NRC 2003). If a site is found to contain quantities of recoverable oil, and a fixed pumping station is constructed, then water demand and use increase dramatically owing to enhanced oil recovery operations. At sites operated in the Prudhoe Bay region, water use has averaged approximately 400 ha-m/y since 2001, and 70% of this has been used for enhanced oil recovery operations since 2004 (C. Fay, 2008, personal communication). It is therefore essential to understand how much fresh water is available in the NPRA and how this quantity varies regionally, seasonally, and over the long term, particularly during winter. Such understanding would aid in developing sustainable lake water–use policy that protects arctic lake ecosystems and the important services they provide.

Two key aspects required for evaluating winter water supply from lakes are the water balance at freeze-up and ice thickness throughout the winter. Currently, most lake water–use limits are based on static measurements of bathymetry, which may be recorded at varying times during the summer and result in annual use permits based on fixed volume estimates. However, the typical natural pattern is for lake levels and water storage to be maximized immediately after snowmelt in May through June and to decrease into autumn because of summer evaporative loss (Woo 1980; Rovansek and others 1996; Mendez and others 1998; Bowling and others 2003; Woo and Guan 2006). Thus, water balance at freeze-up is likely lower than regulatory estimates. Similarly, the under-ice water volumes available for extraction are based on a conservative ice thickness of 2.1 m (USDOI-BLM 2005). However, lake ice grows progressively through the arctic winter and may vary considerably from year to year and from lake to lake depending on temperature, snow cover regimes, and lake characteristics. Thus, better understanding the seasonal and interannual variation in lake-water budgets and ice thickness would help greatly inform management of winter water use from lakes, which is becoming increasingly critical in the NPRA. In this article, we begin to examine these issues by quantifying variability and presenting simple models of lake surface-water area, water storage, and ice-growth development in a region where lakes are a critical resource for wildlife, local residents, and expanding industry.

Study Area

The study area is located in the NPRA, entirely within the zone of continuous permafrost (Fig. 1). The study area was broken down into two distinct subareas: the eastern NPRA (E-NPRA) and the northern Teshekpuk Lake Special Area (N-TLSA) based on differing environmental conditions and current and projected water uses as well as availability of overlapping Landsat satellite imagery. The E-NPRA study area consists of lakes recently identified as "nonthaw" lakes formed in the depressions of undulating, sandy alluvial, marine, and eolian deposits with low to moderate ground ice contents. The N-TLSA lakes are interpreted as true thaw lakes developed in silty marine deposits that are extremely ice rich (Jorgenson and Shur 2007) (Table 1).

The NPRA spans an area of 9.5 million ha on the North Slope of Alaska, bounded by the Brooks Range to the south and the Beaufort and Chukchi Seas to the north and west, respectively, and is covered with snow and ice for 9 months of the year. The area provides molting habitat for an abundance of waterfowl (Bollinger and Derksen 1996), critical caribou calving grounds (Persen and others 2007), and is considered to be rich in petroleum reserves (Houseknecht and Bird 2006). The NPRA was initially established as the Naval Petroleum Reserve Number 4 in the 1920s and set aside as an oil reserve, although the NPRA did not undergo serious exploration until after the mid-1940s. The area was explored extensively by the United States Navy and the

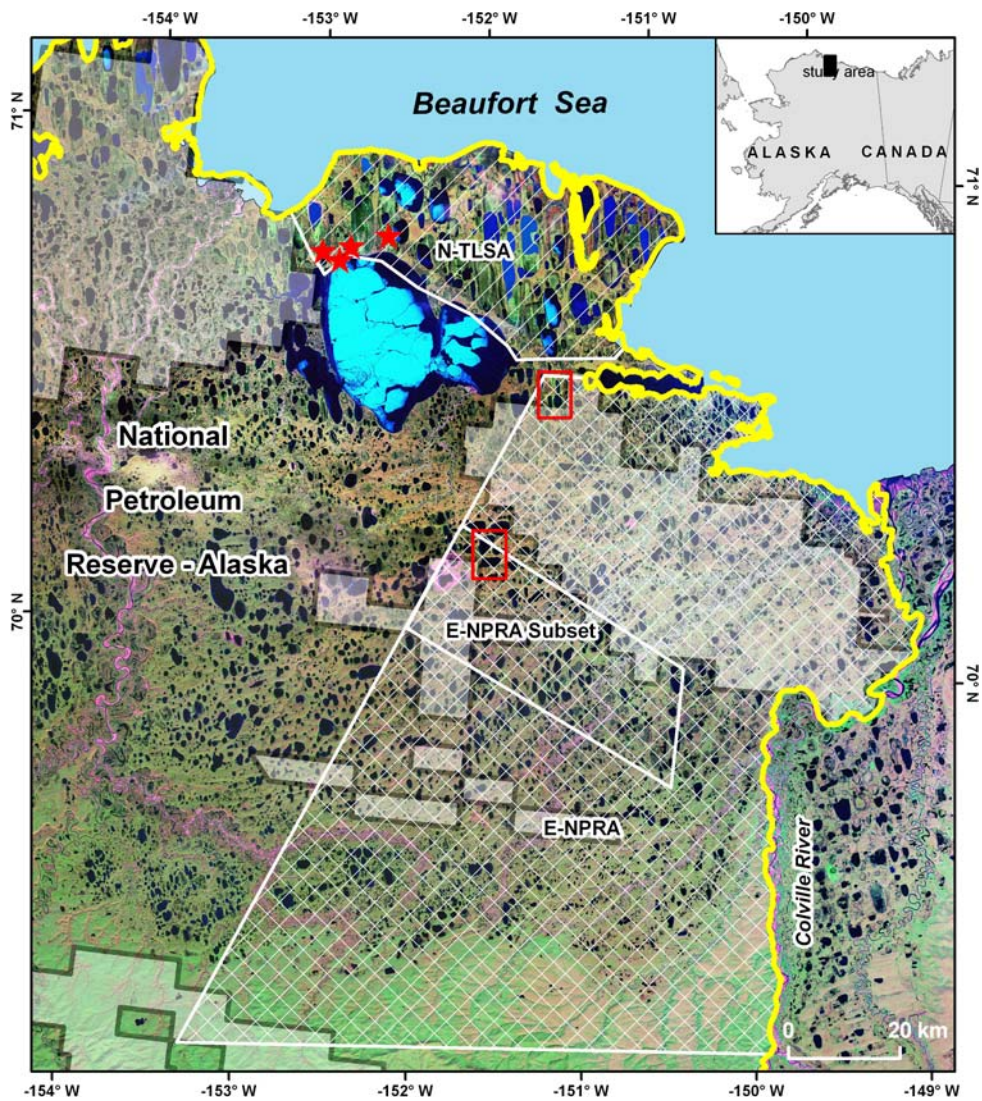

Fig. 1 Landsat mosaic of portion of northern Alaska with remote-sensing study area highlighted by hatched regions. The yellow boundary outlines the NPRA; the red boxes represent subsets in Fig. 3; and the red stars represent lakes with detailed bathymetric and survey data collection. The gray shaded regions are active federal leases within the NPRA

Table 1 Characteristics of study areas in the Arctic Coastal Plain, AK

Study area	Area (km^2)	Lake density (per km^2)	LAE (% surface area)	Dominant lake type[a]
E-NPR-A	962,221	1.82	10.4	Depressional lakes
E-NPRA interior subset	102,981	1.48	11.6	Depressional lakes
TLSA	158,589	0.51	21.9	Oriented, thermokarst lakes

[a] Data from Jorgensen and Shur (2007)

United States Geological Survey from 1944 to 1953, drilling nearly 36 test wells and 45 core tests. Between 1974 and 1982, exploration recommenced with the drilling of an additional 28 exploratory wells (NPRA Legacy Data Archive 2008). During this time Naval Petroleum Reserve Number Four was transferred to the United States Department of the Interior and renamed the National Petroleum Reserve Alaska. Since 1998, winter seismic survey activity has increased (Jones and others 2008), and 25 exploratory wells have been drilled in the NPRA.

Materials and Methods

To more fully understand arctic lake hydrodynamics, we combined remotely sensed imagery (satellite and aerial) to measure lake surface area, performed analysis and modeling of interannual lake variation in relation to climate, conducted bathymetric surveys coupled with water-level monitoring, and compared modeled lake-ice growth with field measurements. This local- and regional-scale analysis of lake variation is intended to provide a general understanding of arctic lake hydrodynamics in a context relevant to managing lake ecosystems and water supply. We also intend this analysis to provide basic concepts and models to serve as a starting point for better predicting lake-water supply and to help identify where uncertainty exists in managing sustainable lake-water use.

Lake Change Detection Using Landsat Imagery

Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) satellite imagery were used for analysis of lake surface-area variation from 1985 to 2007. Landsat TM and ETM+ are multispectral sensing platforms consisting of six bands in the visible and infrared portion of the electromagnetic spectrum with a 30-m spatial resolution. Two Landsat TM scenes were acquired from August 2, 1985 and August 22, 2007, and the overlapping portions were defined as the E-NPRA study area. Additional Landsat imagery from August 28, 1995 (TM) and August 1, 2000 (ETM+) covered limited portions of the study area and were incorporated to better analyze change during multiple years. In addition, imagery available over the N-TLSA for July 22, 1985, July 29, 2002, July 22, 2005, and August 22, 2007, allowed for changes in detection for lakes of different origin and environmental conditions.

An image object-oriented segmentation algorithm was used to classify the Landsat imagery into water and nonwater binary images using the middle infrared band (band 5). Briefly, the segmentation parameter within eCognition® was set at a scale parameter of 10, grouping pixels into like objects. These like objects were further grouped by running a spectral-differencing segmentation using the same-scale parameter. After the second segmentation the imagery was classified into water and nonwater binary images based on threshold values of the image objects. Frohn and others (2005) described a similar approach to the classification of lakes within this region and reported classification accuracies of 97%. The classified images were converted from raster image files to vector files to assess changes in lake area and lake abundance. A minimum lake size of 10 ha was chosen as the cut-off for the lake change analysis.

All 10-ha lakes were then classified into deep and shallow/turbid water objects using band 3 (red) and the image object-oriented segmentation algorithm. In this instance the lake classification from the use of band 5 was used to isolate lake perimeters in band 3, which were subsequently segmented a single time using a scale parameter of 10 and then classified into deep/clear versus shallow/turbid water objects. Analysis of band 3 in this manner is somewhat limited in that it assumes that (1) light attenuation is an exponential function of depth, (2) water quality does not vary within an image, and (3) color of the substrate is constant (Jupp 1988). Furthermore, Sass and others (2007) found that band 3 is affected to a large degree by turbidity and chlorophyll A concentrations, which may be independent of depth. However, within the NPRA, lakes exhibit relatively low productivity, and lakes that are turbid are often shallow; thus, the method provides a crude means of assessing depth of penetration zones, and whether change is being manifest in shallow or deep water environments. Owing to the 30-m spatial resolution of the Landsat imagery, the delineation of lake perimeters is limited; however, because all imagery used was of the same spatial and spectral resolution, it is believed that this allows for relevant comparisons.

To better understand sources of interannual variation in lake surface-area extent (LAE) and lake density in these two study areas, we compared climate data from Barrow, AK (located 100 to 200 km northwest), with these LAEs using simple linear and nonlinear regression, with particular emphasis on varying durations of precipitation and temperature for the period before image acquisition. Resulting regression equations from this analysis were used to model estimates of summer LAE for each study area from 1985 to 2007 to provide a long-term assessment of interannual variability and to identify trends in LAE for the region.

Lake Bathymetry Analysis

During 2007, bathymetric profiles were surveyed from a number of lakes to describe how lake surface area relates to basin morphometry and volume. Bathymetric surveys were conducted with a combination of global positioning system (GPS)–linked depth soundings from an inflatable raft (Alpacka®) and detailed total station (NIKON Model 362®) surveys of the exposed shoreline and littoral shelves. Vertical aerial photography was acquired with a Kodak 14 N® digital camera mounted in the belly port of a Cessna 206 airplane to compliment these surveys and compare them with historic photographs. Lake water levels were continuously monitored at several lakes with unvented pressure transducers (Onset HOBO U20®) corrected to atmospheric barometric pressure monitored within 5 km of each site from late July 2007 through summer 2008.

We calculated water volumes for four distinct lake types in late July (time of surveys), just before ice formation in late September (from water-level records), and again in early May when all lakes were frozen to near maximum ice thickness. These measurements were used to describe how basin morphometry interacts with surface area and volume, ultimately determining water availability from varying lake types. This analysis is used to provide a quantitative description of how changes in lake-water volumes control surface area and depth for varying lake types as well as geomorphic and climatic conditions.

Ice Thickness Modeling

To better understand regional and interannual variation in lake-ice growth and maximum ice thickness, we modeled annual ice growth using a modified Stefan equation:

$$Z = \alpha\sqrt{\mathrm{AFDD}} \tag{1}$$

where Z is ice thickness in cm, α is ice-growth coefficient set at 2.7 for snow-free lakes and 2.4 for snow-covered lakes, and AFDD is accumulated freezing degree days in °C (USACE 2002). Ice-growth curves were modeled using mean daily air temperature data at Barrow from 1985 to 2007, and regional comparisons were made during the 2003–2004 winter with meteorologic station data from Drew Point (N-TLSA) and Fish Creek (E-NPRA). Ice-thickness measurements gathered at Imikpuk Lake near Barrow (Alaska Lake Ice and Snow Observatory Network [ALISON] 2008) were compared with modeled ice-growth curves to assess model accuracy.

Results

Interannual Variation in Lake Surface Area

Changes in both lake surface area and abundance were detected among the Landsat scenes. In the two image mosaics that constituted complete coverage of the E-NPRA study area, LAE decreased by 0.8% from 100,800 ha in 1985 to 99,950 ha in 2007. Aerial and field reconnaissance conducted on August 23, 2007, showed that some larger lakes had exposed shelves and likely accounted for much of the reduction in surface area. Furthermore, classification of the imagery into deep versus shallow/turbid water pixels shows that 92% of the reduction occurred in pixels identified as shallow or turbid water, whereas 8% of the reduction occurred in pixels classified as deep-water pixels (Fig. 2). Although this is a crude assessment of lake depth, the change accounted for by shallow-water pixels is likely a result of variability in climate conditions, whereas loss of deep-water pixels may represent actual geomorphic change through thermokarst processes; development of this type of analysis is critical to understanding more fully the operative causes of lake area change. Lake numbers also decreased by 4.3% from 1,865 in 1985 to 1,785 in 2007. However, these change statistics are somewhat misleading because they represent lakes that disappeared completely as well as lakes that merged or broke apart. Therefore, total surface area is the more representative attribute of the landscape-scale change in lakes taking place.

Analysis of just two dates of imagery provides little understanding about the range in interannual variability or the ability to detect long-term trends and causal mechanisms of lake change. Thus, additional Landsat imagery from 1995 and 2000, was acquired for a small portion (approximately 11% of area; approximately 10% of lakes) of the E-NPRA with overlapping domains to allow for more in-depth analysis of variability associated with these lakes (Fig. 1 and Table 1). Analysis of the time series of Landsat imagery within this subarea reveals that LAE decreased by 0.6% between 1985 and 2007 and is therefore fairly representative of the E-NPRA. However, the time series shows increases in lake surface area from 1985 to 2000 before decreasing by 4.0% between 2000 and 2007.

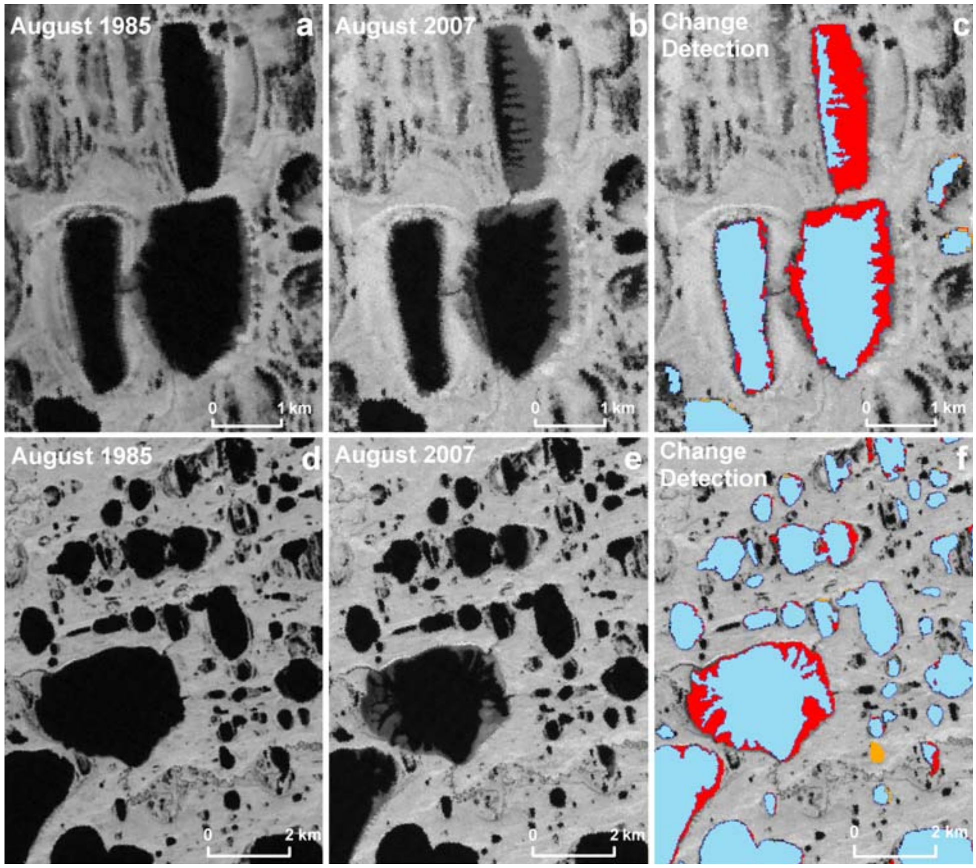

Fig. 2 Comparison of two regions (**a** through **c** and **d** through **f)** within the study area showing lake shrinkage between 1985 and 2007. The change detection images (**c** and **f**) show lake surface area in 2007 (blue) as well as depth of penetration zones responsible for shrinkage between 1985 and 2007. Red pixels are shallow/turbid waters, and orange pixels are deep/clear waters

We also acquired four late-summer, overlapping Landsat images for the N-TLSA study area (Fig. 1 and Table 1) for 1985, 2002, 2005, and 2007. This area is different than the E-NPRA in that lakes are principally of thermokarst origin and tend to be larger, yet often more uniformly shallow (Jorgenson and Shur 2007). Comparing the images that span the full record of remotely sensed imagery (1985 to 2007) shows a 0.4% reduction in LAE and a decrease in the number of lakes detected from 179 to 168. However, like in the E-NPRA subset, analysis of multiple years in the N-TLSA showed that the lowest LAE occurred in 2007, whereas the highest occurred in 2005.

These comparisons highlight the dynamic nature of these lakes and demonstrate interannual variability rather than directional lake shrinkage or expansion, but they provide little information on controlling processes. Thus, we compared relevant Barrow climate data to LAE in the N-TLSA and E-NPRA subset. The annual precipitation at Barrow from 1985 to 2007 averaged 11.1 cm (calculated by water year from October to September) and ranged from 5.5 cm in 1991 to 18.2 cm in 2004 (Fig. 3a). During this same period, summer (June, July, and August) air temperatures averaged 3.8°C and ranged from 2.2°C in 1988 to 6.1°C in 1989 (Fig. 3a). Long-term trends were not evident for this 22-year period. Snow depth in May averaged 14.3 cm and ranged from 2.5 cm in 1990 to 27.4 cm in 2006. We found that precipitation totals 12 months before LAE measurements explained considerable variation in LAE in both the N-TLSA ($r^2 = 0.97$, $p = 0.02$) and E-NPRA subsets ($r^2 = 0.90$, $p = 0.05$), suggesting a 0.11% and 0.06% increase, respectively, in LAE per 1 cm annual precipitation (Fig. 4). Because precipitation explained relatively high levels of variation in late summer LAE (90% to 97%) despite the few years we had for comparison ($n = 4$), other climate variables such as temperature (a proxy for evapotranspiration) and snow depth were not found to correlate to LAE. Using the Barrow precipitation record, we estimated that LAE in the N-TLSA subset ranged from 21.4% to 23.6% and in the E-NPRA subset ranged from 11.4% to 12.6% (Fig. 3b). Importantly, this analysis suggests considerable interannual variation in LAE but no decadal-scale trends for this period of record, 1985 to 2007, for which we have available Landsat TM and ETM+ imagery.

Interlake Variability in Bathymetry and Hydrogeomorphology

Although lake surface area can be readily quantified over large extents, water availability is also a function of lake

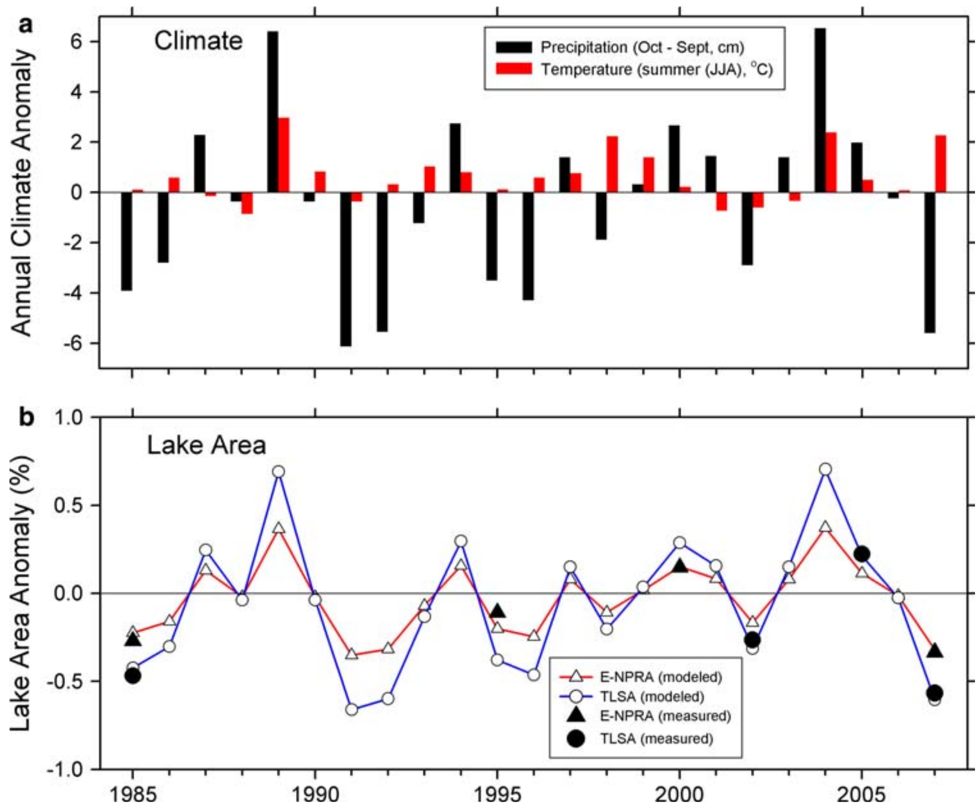

Fig. 3 Approximate average interannual variation of precipitation and air temperatures as measured at Barrow (**a**) and measured and modeled LAE during late summer at the study sites (**b**)

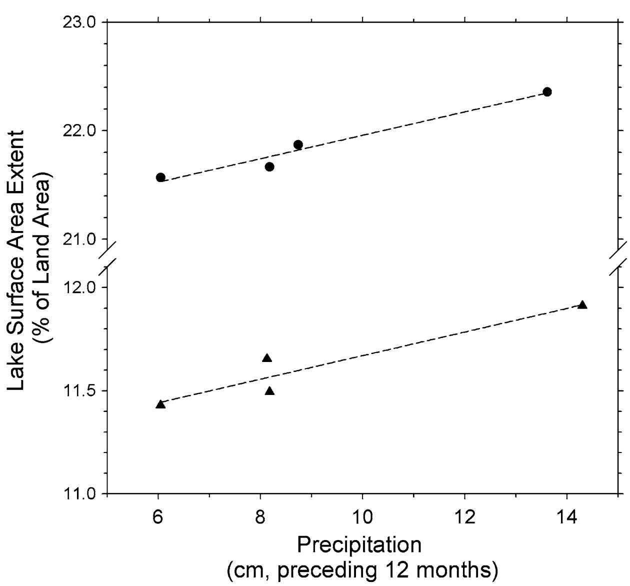

Fig. 4 Changes in lake surface area for N-TLSA (for 1985, 2002, 2005, and 2007) and E-NPRA (for 1985, 1995, 2000, and 2007) in relation to Barrow precipitation totals for the preceding 12 months

depth and morphometry, and these can vary considerably among lakes within a region, among regions with differing surficial geology and lake-forming processes, and with seasonally and interannually fluctuating water levels. To begin addressing how variations in LAE may relate to water availability and aquatic habitats, we mapped the bathymetry and shoreline topography of four lakes with varying origins and geomorphic conditions in the N-TLSA. These were coupled to lake level monitoring in 2007 and long-term areal photographic comparisons to address seasonal and long-term water availability. Although these lakes are not necessarily representative of all lakes in the study area, they provide an example of the variability associated with lake morphometry and bathymetry and demonstrate how lowering lake levels correspond to surface area and volume changes.

The lakes surveyed in the N-TLSA span a size range that varies by an order of magnitude. The smallest study lake is Qaviarat Lagoon, which formed along the margins of Teshekpuk Lake and had a 6.5-ha surface area in late July. By contrast, Lake 31 is a recently and partially drained basin, with a 67.7-ha surface area in late July (Table 2). The respective volumes and depths of these lakes in late July were 4.6 ha-m and 0.71 m for Qaviarat Lagoon and 92.0 ha-m and 1.36 m for Lake 31. Between late July and late September when ice formed on lake surfaces, lake levels progressively decreased in three of these lakes (Lake 11 was not monitored) by 5 to 10 cm, resulting in a change in surface area ranging from <1% in Lake 31 to approximately 50% in Derksen Basin, with proportionally greater volumetric changes of 4% and 65%, respectively (Table 2 and Fig. 5). The morphometry of Qaviarat Lagoon created a differing response with a 9% decrease in surface area and

Table 2 Bathymetric characteristics of four lakes in the TLSA of varying type and successional stage[a]

Lake	Early May 2007 (under ice)			Late July 2007 (survey period)			Late September 2007 (measured stage before ice formation)			Full-basin capacity (current)			Dimensional adjustment (%)	
	d	SA	V	d	SA	V	d	SA	V	d	SA	V	d	SA
Dersksen Basin	Frozen solid			0.12	58.6	7.0	0.08	31.4	2.4	0.23	102.9	23.4	34	66
Lake 31	0.09	4.6	0.4	1.36	67.7	92.0	1.31	67.2	87.9	1.38	68.0	94.0	69	31
Qaviarat Lagoon	Frozen solid			0.71	6.5	4.6	0.73	5.9	4.3	0.82	14.2	11.6	44	56
Lake 11	0.62	10.6	6.7	1.79	18.4	33.0	–	–	–	1.75	19.7	34.5	65	35

[a] d = mean depth (m); SA = surface area (ha); V = volume (ha-m)

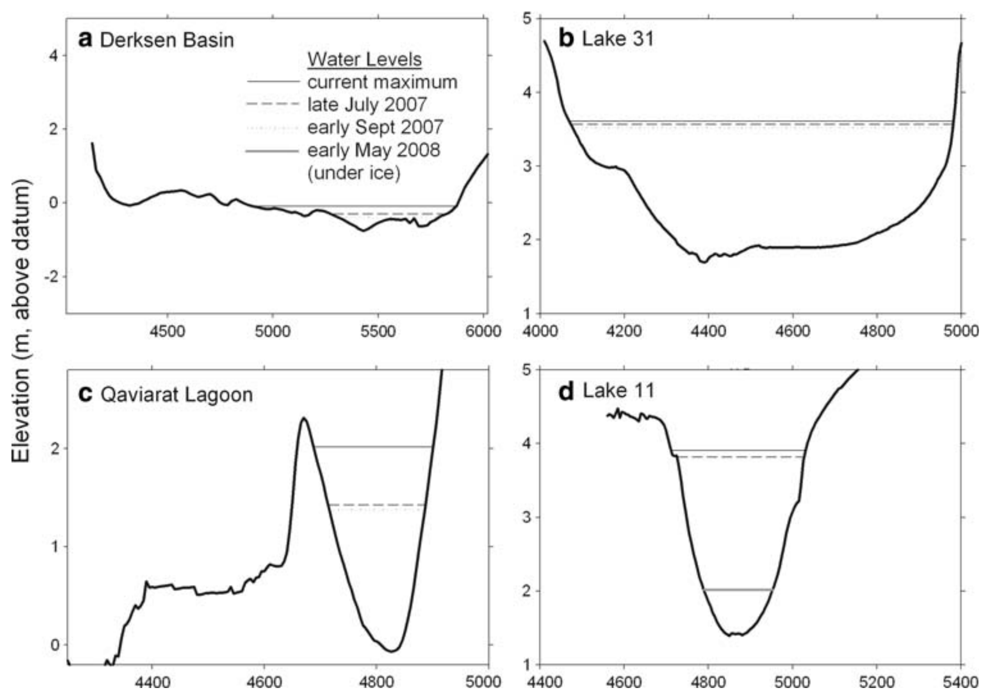

Fig. 5 Cross-sections of four lakes in the N-TLSA showing morphology relative to water levels (**a** Derksen Basin, **b** Lake 31, **c** Qaviarat Lagoon, **d** Lake 11)

a 7% decrease in volume, and the 2007 summer water levels were well below maximum capacity compared with Lakes 11 and 31. This differing response of Qaviarat Lagoon is also seen in the higher mean depth with smaller volume in September than July because of the drying shallow shoreline zones (Table 2).

To provide a quantitative description of lake morphometry relative to volume, we calculated proportional responses in mean depth and surface area with dynamic lake volumes or water budgets (Table 2). For Lakes 11 and 31, >60% of lake volume change is accounted for by varying depth as qualitatively described by their bowl-shaped cross-sections (Fig. 5b and d). For Derksen Basin, 66% of lake change is explained by varying surface-area as described by its flat undulating bed (Fig. 5a). Qaviarat Lagoon had more even responses to changing water balance with 56% occurring by depth and 44% by surface-area (Table 2 and Fig. 5c).

Derksen Basin, formerly known as North Lake (Weller and Derksen 1979), was a former lake that drained when its shoreline was breached by Teshekpuk Lake through lateral erosion sometime between 1955 and 1976 (Fig. 6). It is now essentially a wetland with a mean depth of 0.12 m and low late July water volume. Based on the current and historic elevations of the basin's outlet, we estimated that its maximum water volume is currently 23.4 ha-m and before initial drainage was approximately 700 ha-m, a nearly 2-m reduction in mean depth, which is expressed as a 230% decrease in surface area and a 3,100% reduction in water volume. Lake 31 was more recently tapped and partly drained by the expanding, lower elevation Lake 29 to the east (Fig. 7). Summer 2007 lake levels were essentially at the current maximum capacity of 94 ha-m, and we estimated that its predrainage capacity was 164 ha-m, a 74% reduction in hydrologic storage and a reduction in mean depth from

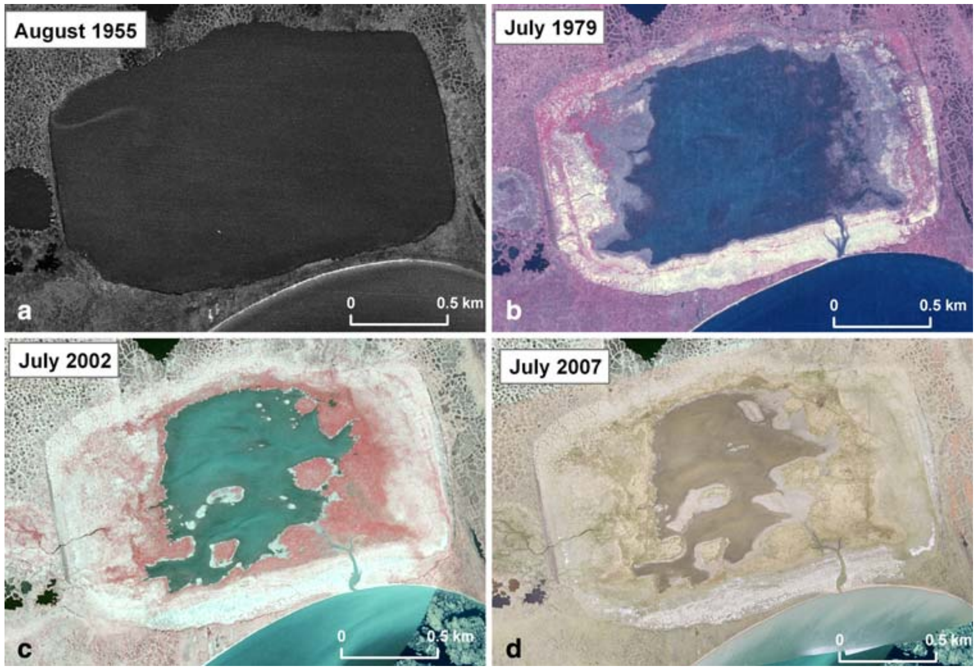

Fig. 6 Aerial photography time series of Derksen Basin (formerly North Lake) between 1955 and 2007

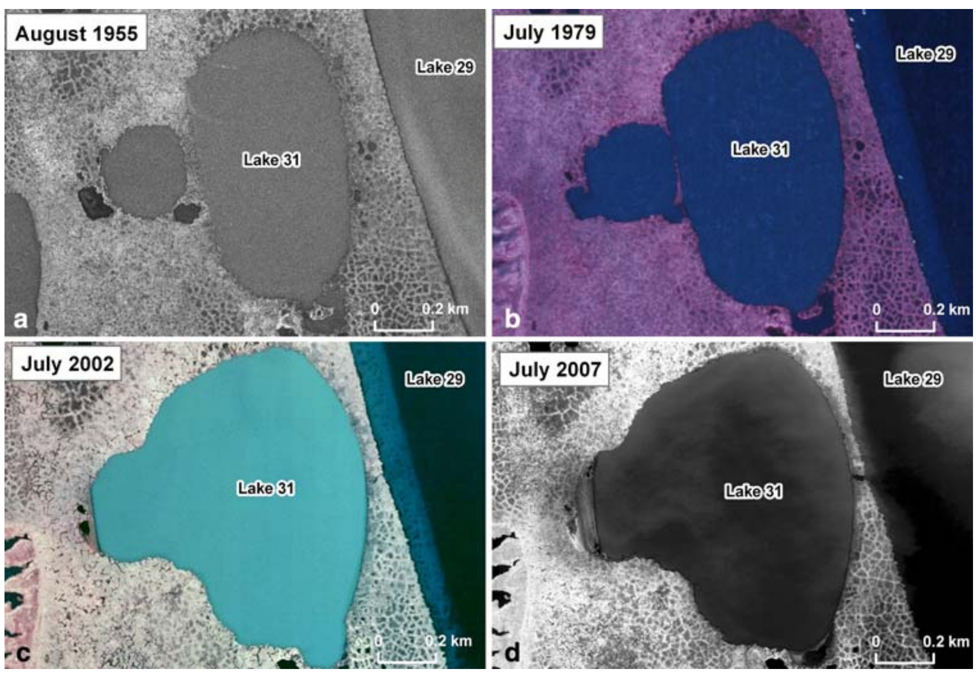

Fig. 7 Aerial photography time series of Lake 31 between 1955 and 2007

2.2 to 1.4 m, with an associated surface area change of only 4% (Table 2 and Fig. 5b). These changes in mean lake depth are particularly relevant to winter water availability because maximum ice thickness is commonly assumed to exceed 2 m. Of these four lakes surveyed in the N-TLSA, only Lake 11 currently contained quantities of liquid water through the entire winter (Table 2 and Fig. 5d), which is fairly representative of the percent of lakes in the N-TLSA that contain quantities of liquid water in the winter (Mellor 1985).

Although water-level fluctuations were not monitored in the E-NPRA study area, it is believed that even greater disparities exist between surface area to volume change given the wide, shallow shelves (Jorgenson and Shur 2007) and deep central basins, which range from 2 to 18 m (Winston and others 2008). The variation in morphometry in the lakes located in the N-TLSA subset compared with those in the E-NPRA subset show the need for a more dynamic and regional approach to managing lake-water resources in the NPRA.

Regional, Seasonal, and Interannual Variation in Lake-Ice Growth

The interaction of lake morphology and hydrology with lake-ice growth and its year-to-year variation are fundamental determinants of a number of limnologic processes of lakes in the NPRA and other high-latitude regions, including talik formation, ice-out timing, overwinter refugia for fish and other aquatic organisms, and winter water availability for villages and industry. Thus, we made comparisons of modeled lake-ice growth using air temperature data at several locations and estimated annual maximum ice thickness to better understand its variability in lakes in the NPRA.

Regional variation was addressed by comparing ice-growth curves in 2003 and 2004 using daily air temperature data from stations at Barrow (long-term record, northwestern NPRA), Drew Point (N-TLSA), and Fish Creek (E-NPRA). During the winter of 2003 to 2004, modeled ice growth initiated in mid-September (commencement of sustained subzero conditions), with maximum ice growth occurring in November and maximum thickness in May (Fig. 8). Using a snow-free α coefficient of 2.7 resulted in ice thickness at Barrow, N-TLSA, and E-NPRA on January 1 of 98, 101, and 102 cm, respectively, and on May 1 of 175, 181, and 184 cm, respectively. Model results using a more conservative α of 2.4 for snow-covered lakes at Barrow resulted in thinner ice throughout the season with measured ice thickness at one lake in Barrow plotting between the snow-free and snow-cover ice-growth curves (Fig. 8). These comparisons suggest little regional variation in ice growth and maximum thickness, although interlake variation in snow cover driven by local topography and lake size (Williams and others 2004), as well as other factors, may create considerable deviation from these modeled ice-growth curves.

To better understand interannual variation in lake-ice thickness, we estimated maximum ice thickness from 1985 to 2007 using Barrow air temperature data. Maximum ice thickness for this period averaged 180 cm and ranged from 169 cm in 2003 to 188 cm in 1992 with some evidence for decreasing and more variable ice thicknesses during this period (Fig. 9). We also collected ice-thickness measurements during 2007 and 2008 for lakes around Barrow and in the N-TLSA and found that our measurements were very close to modeled thickness, suggesting that lakes may no longer freeze to depths of 2 m given recent warming in the arctic.

Of the four lakes we surveyed in the N-TLSA, only Lake 11 supported perennial liquid water based on measurements in early May (Fig. 5d). Lake 31 also had liquid water during the winter of 2007, although the volume available in early May was not sufficient for any industrial water use, and by mid-April 2008 it was frozen to the bottom, presumably because of lower water budgets followed by the warm, dry 2007 summer. Before partial drainage (Fig. 7), however, this lake would have maintained nearly 40 ha-m of liquid water in the winter. Mellor (1985) classified lakes in the NPRA with side-looking airborne radar during one winter's maximum ice-growth period and found that for lakes >10 ha, only 23% of the lakes in the N-TLSA provided liquid winter water supplies, whereas 71% of the lakes in E-NPRA supply winter water. Given our findings, it is likely that these numbers have increased during the past 22 years and that contemporary regional analysis with radar imaging is needed.

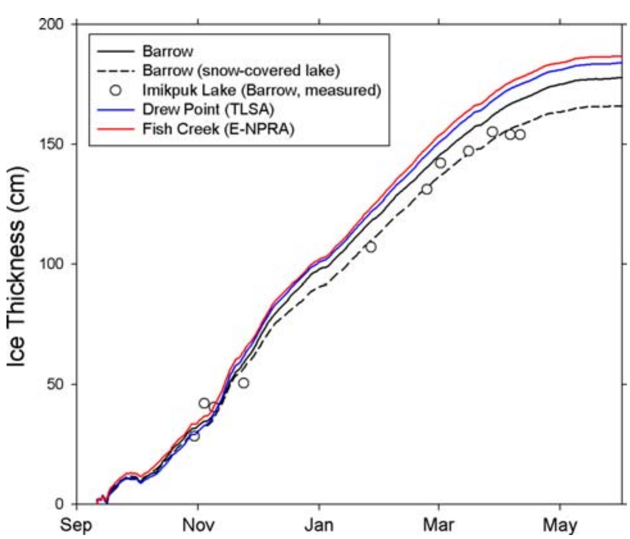

Fig. 8 Modeled ice thickness for lakes near Barrow and in the N-TLSA and E-NPRA in 2003/04

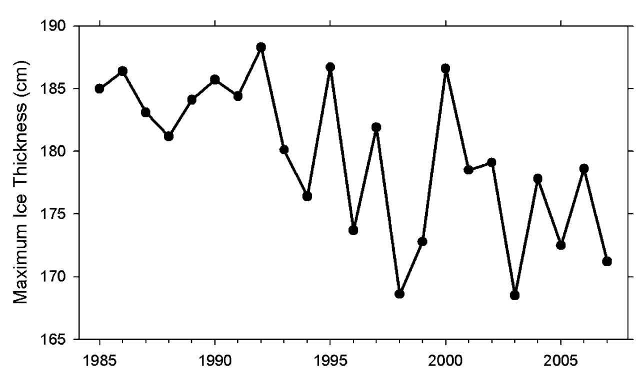

Fig. 9 Estimated maximum annual lake-ice thickness based on Barrow climate data between 1985 and 2007

Discussion

Variation and Uncertainty in Lake Hydrodynamics

Several high-profile studies of arctic landscapes have documented lake surface-area change using comparison of remotely sensed imagery from varying interannual time periods. For example, Smith and others (2005) showed a 12% increase in lakes atop continuous permafrost by comparing coarse resolution satellite imagery in 1973 to 1997/98 and attributing this to permafrost degradation in relation to climate warming. Our analysis of lake area change in the NPRA from 1985 to 2007 showed a 0.4% to 0.6% decrease in LAE. However, by comparing multiple years ($n = 4$) with overlapping images for the two portions of the NPRA, we found that LAE was highest in 2000 for the E-NPRA subset and highest in 2005 in the N-TLSA, despite 2007 having the lowest LAE of the four years analyzed for both areas.

Plug and others (2008) recently documented similar interannual fluctuations in lake surface area (±4%) in the western Canadian Arctic and suggested that annual fluctuations (as much as ±10%) are likely because of precipitation amounts during the 12 months before image acquisition. We made similar comparisons in our study and found that precipitation explained 90% to 97% of the interannual variation in lake area. Likely, comparison of more image dates would help us better understand other explanatory variables of lake hydrodynamics, such as snowpack water equivalent and summer evaporation rates, at the landscape scale.

These results, along with the work of Plug and others (2008), suggest that similar studies addressing lake change in both continuous (Smith and others 2005) and discontinuous (Riordan and others 2006) permafrost regions of the arctic warrant further analysis. Furthermore, Mars and Houseknecht (2007) analyzed the same 1985 and 2005 imagery that we analyzed for the N-TLSA and reported long-term directional increases in LAE. However, our incorporation of additional image dates showed otherwise and indicated that there have been brief periods of increasing LAE and decreasing LAE, with no apparent trend.

In the context of predicting lake aquatic habitat and water supply, especially overwinter liquid water volumes, understanding the relation between lake surface area, depth, and volume is essential. We emphasize here that lake-change detection conducted thus far only measures lake surface area from coarse resolution imagery, whereas change in water budgets and availability depends on lake basin morphometry, climate, and watershed processes. Work by Livingstone and others (1958) described the diverse array of lake-basin forms occurring in Arctic Alaska, representing major differences in water volume relative to surface area. Similar lake bathymetric surveys in zones of continuous permafrost on the Seward Peninsula describe a wide range of lake forms related to thermokarst and other processes (West and Plug 2008). Our work on a limited set of lakes in the NPRA also describe a wide range of lake geomorphic conditions both within regions (i.e., N-TLSA) and among adjacent regions. Interestingly, of the lakes we surveyed in the N-TLSA, those with only slight changes in surface area had greater changes in lake volume, suggesting that analysis of LAE dynamics may provide a poor estimate of interannual variation in lake-water storage. Similar surface area-to-volume relations were noted in the E-NPRA, where lakes have large littoral shelves (Jorgenson and Shur 2007) and narrow, deep central basins (Winston and others 2008) storing the majority of water. More comprehensive bathymetric mapping, as well as quantitatively relating lake hydrodynamic expression of volume to changes in surface area and depth, would help greatly in using remote-sensing analysis of LAE to predict and manage lake-water availability seasonally and annually.

The fieldwork results we present here are limited in the number of lakes surveyed and time periods of water-level monitoring, yet they suggest progressive decreases in lake-water balance through the summer, as has been described in intensive lake-water budget studies elsewhere in the arctic (Woo 1980; Rovansek and others 1996; Bowling and others 2003; Woo and Guan 2006). Based on the results of these studies, we suggest that understanding lake-water balance at the period preceding freeze-up is critical to the assessment of overwinter water availability. How water balance varies among lakes within a region and interannually with climate variability, coupled with existing depth structure relative to ice growth, is a fundamental aspect that likely dictates how lakes function in aquatic habitat provision.

In the N-TLSA, we specifically focused on three thermokarst lakes at differing stages of geomorphic succession; Lake 11 is full and likely expanding; Lake 31 is partly drained; and Derksen Basin is almost fully drained. Lake 11 is deep and has a low surface area-to-volume ratio, thus maintaining liquid water throughout the winter. Although both Lake 31 and Derksen Basin once had similar characteristics, they can no longer supply winter water because of partial drainage. Such episodic lake drainage and loss of these ecosystem services follow natural cycles that many thermokarst lakes experience during long periods of time (Hinkel and others 2003), yet examples of human-initiated lake drainage of thermokarst lakes in the NPRA also exist (Hinkel and others 2007). It is also interesting to note here that before lowering of Lake 31, its maximum depth (2.6 m) would have exceeded maximum winter lake-ice thickness. Now this lake freezes to its bed by the end of most winters. Therefore, before lake level lowering, Lake 31 could have provided over winter fish habitat and a source of liquid water for industrial use.

The important role of ice growth on both lake structure and water availability can not be overemphasized, yet the integration of ice dynamics into the science and management of lakes appears limited (Jefferies and others 1996; Sibley and others 2008). Maximum ice thickness of lakes in the NPRA is commonly assumed to be approximately 2.0 m (Jeffries and others 1996; USDOI-BLM 2005), yet modeled ice thickness for the years considered never exceeded 1.9 m, nor did measurements from Barrow (ALISON 2008), from the N-TLSA during 2007 (May 7) and 2008 (April 4 to 9), or from lakes located at the Alpine, Kuparuk, and Prudhoe Bay oilfields in 2008 (March) (Holland and others 2008). Thus, managing lake-water use based on 2.1 m, although a conservative strategy, likely deserves to be reconsidered. We found relatively little variation in ice thickness among regions based on station temperature data, although local and regional variation in snow cover, lake morphometry, distance to the coast, and topographic elevation are likely important factors in such comparisons (Williams and others 2004; Duguay and others 2002). In the N-TLSA, for example, we expect less interlake variation in ice thickness caused by snow cover for deeper lakes because of little topographic relief, whereas in many smaller lakes occurring in topographic depressions of inland portions of the E-NPRA might accumulate considerable snow that would affect ice growth. However, an important difference for lake ice and winter water availability is the bathymetry of lakes in the N-TLSA, where lakes have mean depths <2 m and generally lack deep pockets that could support fish and supply water. In addition, a number of lakes in the N-TLSA are affected by seawater intrusion, which affects lake-ice thickness to varying degrees.

Implications for Lake-Water Availability and Habitat Protection

Changes in water storage caused by variability in climate and geomorphic change will likely impact winter water availability for winter exploratory drilling and seismic survey activity as activities increase in the NPRA as well as impact overwinter fish habitat and wildlife habitat and forage for the next summer. Exploratory winter lake-water uses typically represent short-term water withdrawals, but such activities currently constitute the majority of the annual water demand (Baker 2002). Ongoing and expanding operations are expected to lead to long-term winter and summer water use when petroleum extraction begins.

Currently, for both short- and long-term lake-water use, potential winter water availability estimates are based on fixed volume estimates derived from static bathymetric surveys conducted during summer. For lakes with known fish populations, winter withdrawals are set at 15% to 30% of estimated below-ice volume (based on maximum ice thickness of 2.1 m); in lakes without known fish populations, even more water may be withdrawn during the winter (USDOI-BLM 2005). It is uncertain just how accurately these water-budget accounting methods represent actual overwinter water availability, how effective the current regulations and requirements are for protecting and sustaining aquatic life, and how dissolved oxygen levels decrease as water is extracted (Cott and others 2008; White and others 2008). It is also unclear as to what extent such short- and long-term water uses impact lake-water budgets (Lilly and Reichardt 2007) and detailed investigations regarding water withdrawal, water chemistry, and recharge are only recently being conducted (Chambers and others 2008).

Conclusion

The temporal comparisons conducted in this study provide an example of the relation between lake bathymetry and morphometry and underscores the need for seasonal lake monitoring and detailed lake-basin mapping coupled with remote-sensing analysis to understand lake-specific operative processes and hydrodynamics. The analysis also demonstrates the importance of recent geomorphic histories when assessing change as well as revealing implications for winter-water availability and ecosystem function. Lake-water storage is maximized after snow melt and decreases throughout the summer because summer evaporation typically exceeds precipitation in Arctic lakes. Analysis of Landsat TM and ETM+ imagery showed a great deal of interannual variation associated with lakes located in two different areas of the NPRA. The variation in late-summer LAE was significantly correlated to total precipitation during the 12 months leading up to image acquisition. These findings could provide simple models to be used to predict water storage and available winter-water supply if combined with high-resolution aerial photography, bathymetric surveys, water-level monitoring, and lake-ice thickness measurements and modeling. We believe that such dynamic models can better inform management strategies as resource use expands in the NPRA.

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