



Monitoring of Water Surface Area in Alaska's Arctic National Parks

Update with 2019 data

Natural Resource Data Series NPS/ARC/NRDS—2020/1263



ON THE COVER

The bed of a lake that drained in 2019 in northern Bering Land Bridge National Preserve. This lake was ice- and snow-covered on a May 15th Landsat image and then drained prior to the next cloud-free Landsat Image on June 15. In the background is a lake that drained in 2018, with yellow color due to flowers of the annual plant *Senecio congestus*. Photo date 10 July 2019, camera location latitude 66.572765°, longitude -164.123988°

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Data Series is intended for the timely release of basic data sets and data summaries. Care has been taken to assure accuracy of raw data values, but a thorough analysis and interpretation of the data has not been completed. Consequently, the initial analyses of data in this report are provisional and subject to change.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

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Contents

	Page
Figures.....	iv
Tables.....	vi
Appendices.....	vi
Abstract.....	vii
Acknowledgments.....	vii
Introduction.....	1
Study Area	2
Methods.....	6
Identification of surface water.....	6
Trend analysis.....	7
Results.....	8
Discussion and Conclusions	17
Literature Cited	18

Figures

	Page
Figure 1. Study area location.	2
Figure 2. Mean annual air temperature for Kotzebue, Alaska, 1980–2019 (National Weather Service data from NOAA Regional Climate Centers, 2019) and the Mt. Noak NPS climate monitoring station (33 km north-northwest of Kotzebue)	3
Figure 3. Mean annual precipitation at Bettles and Kotzebue, 1980-2019	4
Figure 4a. Lake area change in the western part of the study area (BELA)	11
Figure 4b. (Upper) Lake area change in the central part of the study area (CAKR, KOVA, and NOAT).....	12
Figure 5. Water trend with time for three example subsections	13
Figure 6. Count of new lake drainage events by year, 2001-2019, by NPS unit, based on DSWE water mapping (upper) and SWIR < 600 water mapping (lower)	14
Figure 7. Loss of water area by year of the lakes that were identified as “drained” in BELA during 2001-2019, based on DSWE and SWIR < 600 water mapping methods.....	15
Figure 8. Lake loss in northeastern BELA. Areas that lost water between 2017 and 2018 are shaded in green, and areas that lost water from 2018 to 2019 are shaded in yellow	16
Figures A1-A2. Oblique aerial photographs of lakes in northern BELA with mud exposed due to lowered water levels.....	21
Figures A3-A8. Oblique aerial photographs of lakes in northern BELA with mud exposed due to lowered water levels.....	22
Figures A9-A14. Oblique aerial photographs of lakes in northern BELA with mud exposed due to lowered water levels.....	23
Figure A15. Camera locations for the photographs in Figs. A1 through A14.	24
Figure B1. Aerial view of drained lake 128.....	26
Figure B2. Cardinal direction photos from the GPS point in drained lake 128.	27
Figure B3. Aerial view of drained lake 314.....	28
Figure B4. Cardinal direction photos from GPS point in drained lake 314.	29
Figure B5. Aerial view of drained lake 154.....	30
Figure B6. Vegetation of drained lake 154, in area of dense <i>Senecio congestus</i> flowers.....	31
Figure B7. Cardinal direction photos from GPS point in drained lake 154.	32

Figures (continued)

	Page
Figure C1. Lake analysis subsections in Bering Land Bridge National Preserve.....	34
Figure C2. Lake analysis subsections in Cape Krusenstern National Monument	34
Figure C3. Lake analysis subsections in Kobuk Valley National Park	35
Figure C4. Lake analysis subsections in the Noatak National Preserve	35
Figure C5. Lake analysis subsections in Gates of the Arctic National Park and Preserve	36

Tables

	Page
Table 1. Dynamic Surface Water Extent (DSWE) pixel values.....	6
Table 2. Lake area change 2000-2019 by ecological subsection ^A	9
Table A1. Camera date, time, location, and orientation for Figs. A1 through A14	24
Table B1. Location data for reconnaissance plots on 3 lakes that drained in 2018 ^A	25
Table C1. Subsection codes and names by NPS unit.....	33

Appendices

	Page
Appendix A: Oblique aerial photographs of newly drained lakes from 2019	21
Appendix B: Observations of revegetation on lakes drained in 2018.....	25
Appendix C: Location Maps of Lake Analysis Subsections.....	33

Abstract

The area of lakes and ponds in the five National Park Service (NPS) units in northern Alaska from the 1980s to 2019 was summarized using data from Landsat satellite images. During the period for which annual Landsat data are available (2000-2019), most of the study area showed either declining water area or weak trends. The areas with rapidly declining water area had lakes of thermokarst origin in ice-rich permafrost, where sudden lake drainage events were common. The year 2019 had the most lake drainage events of any year in the period 2000-2019, with the great majority of lake drainages occurring in the lowlands of northern Bering Land Bridge National Preserve (BELA). Water surface area trends were computed here using both the new USGS dynamic water surface extent product and the existing ARCN water mapping protocol (a simpler method based on the same Landsat data). The two methods produced generally similar results. This report includes oblique aerial photographs of some newly drained lakes in BELA from 2019, and also photos and data that illustrate the growth of new vegetation on the beds of lakes that drained in 2018.

Acknowledgments

Thanks to Amy Larsen, Matt Macander, and Peter Neitlich for helpful discussions, Peter Neitlich and Celia Miller for help with fieldwork, and Celia Miller for review comments.

Introduction

Lakes and ponds in lowland permafrost regions are both abundant and uniquely dynamic. Water bodies are of great interest to the National Park Service (NPS) as habitat for aquatic wildlife and as indicators of changes in the hydrologic balance. Thus the NPS Arctic and Inventory and Monitoring Network (ARCN) has included monitoring of surface water area as a part of the Terrestrial Landscape Patterns and Dynamics Vital Sign (Lawler et al. 2009; Swanson 2017a). Our monitoring of water surface area is based on analysis of Landsat images, which are available from 1984 to the present, with consistent annual coverage beginning in the year 2000. I recently summarized the trends in water surface area across ARCN through 2017, with preliminary analysis of 2018 data (Swanson 2019). This analysis showed that an unprecedented number and area of lakes were lost in Bering Land Bridge National Preserve (BELA) in 2018, as a result of rapid drainage through breaches in the lakes' banks associated with permafrost thaw. Our informal observations in BELA 2019 suggested that lakes continued to be lost at an alarming rate. Thus I re-assessed water surface area across ARCN, including all available Landsat data through 2019 for the months with unfrozen water (June-September). In the present report I have reproduced most of the graphics from my 2019 report, revised to include data through the summer of 2019. I also included photographs, taken opportunistically during other fieldwork in the summer of 2019, of some newly drained lakes in BELA (Appendix A) and also the vegetation colonizing the beds of lakes that drained in 2018 (Appendix B).

Study Area

The study area is in the five National Park units that make up ARCN: Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Gates of the Arctic National Park and Preserve (GAAR), Kobuk Valley National Park (KOVA), and Noatak National Preserve (NOAT) (Figure 1). ARCN is a region of mostly arctic tundra with some boreal forest present in the low-elevation, southern parts of the non-coastal parks (Jorgenson et al. 2009). Long-term mean annual air temperatures (MAAT) in 1981-2010 were -4 to -6°C in the coastal parks (BELA, CAKR) and at low elevations in the far western NOAT, southern KOVA, and southern GAAR. Elsewhere in ARCN MAATs were -6 to -10°C (Daly et al. 2008, PRISM Climate Group 2020).

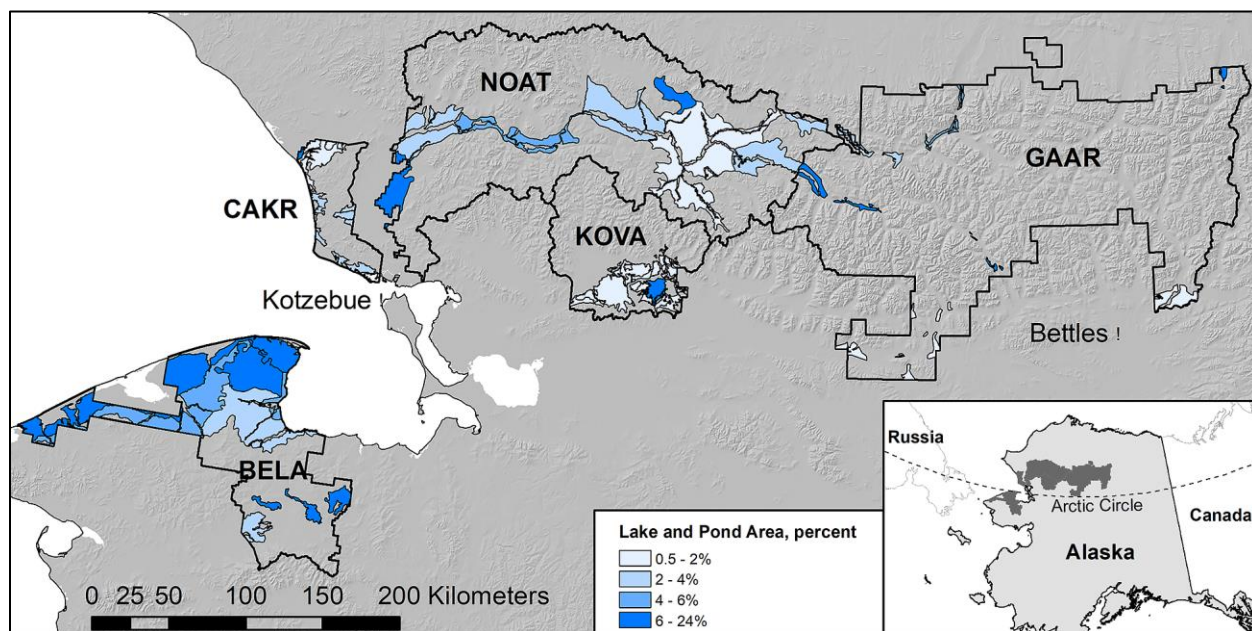


Figure 1. Study area location. The ecological subsections analyzed for water surface area are displayed, with their lake and pond surface area in percent. The excluded areas are subsections that had less than 0.5% lake and pond surface area. National Park Service unit abbreviations are: Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Gates of the Arctic National Park and Preserve (GAAR), Kobuk Valley National Park (KOVA), and the Noatak National Preserve (NOAT).

Long-term temperature records (since 1929) at Kotzebue reveal record high temperatures during the past five years (Figure 2). The long-standing highest mean annual temperature record of -4.6°C set in 1950 was broken just prior to the study time interval (-3.6°C in 1978). This record was broken again in 2003 (-3.0°C); the new record was essentially tied in 2004, then broken again in 2014 (-2.0°C), 2016 (-1.6°C) and 2018 (-0.9°C). The Kotzebue National Weather Service data were missing for part of the summer of 2019 so I was unable to compute a mean annual air temperature for 2019, but our shorter time series of temperatures from the Mt. Noak NPS climate monitoring station, 33 km north-northwest of Kotzebue in CAKR, closely parallels Kotzebue and shows a mean annual air temperature in 2019 that was near the record high from 2018 (Figure 2). Annual precipitation

fluctuated without a strong long-term trend during the study time interval at both Kotzebue and Bettles (Figure 3).

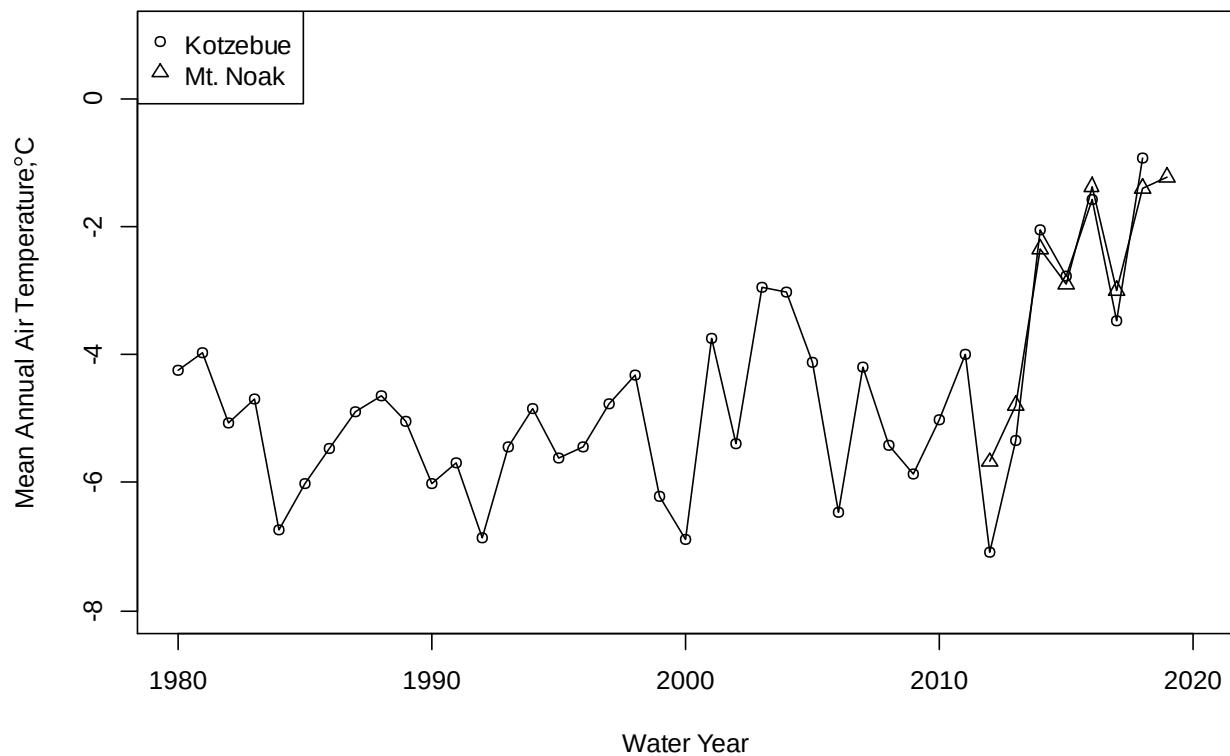


Figure 2. Mean annual air temperature for Kotzebue, Alaska, 1980–2019 (National Weather Service data from NOAA Regional Climate Centers, 2019) and the Mt. Noak NPS climate monitoring station (33 km north-northwest of Kotzebue). Means were computed for water years (October–September). Kotzebue data are not available for 2019, so the Mt. Noak data are presented as a substitute.

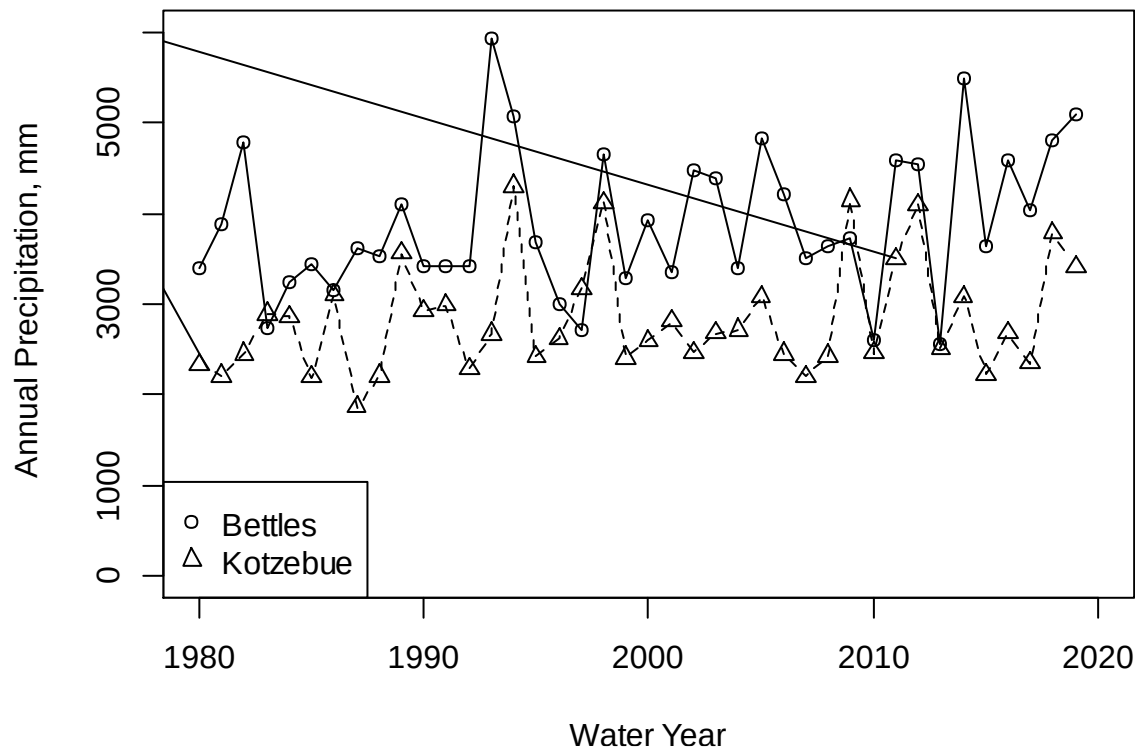


Figure 3. Mean annual precipitation at Bettles and Kotzebue, 1980-2019. Annual totals were summed for the water year, October-September. Mann-Kendall trend tests for 2000-2019 (the period with reliable annual Landsat coverage used for surface water trend analysis in this report) for precipitation were positive but clearly non-significant at Kotzebue. $p=0.63$ and positive but probably non-significant Bettles $p=0.15$).

Most of ARCN lies within the continuous permafrost zone (permafrost is present across 90% or more of the landscape; Jorgenson et al. 2008). Permafrost is discontinuous (present on 50% to 90% of the landscape) in the southern half of KOVA and the two southern lowland extensions of GAAR (Figure 1).

Lakes of multiple origins and hydrologic conditions are present in ARCN, and ecological subsections provide a useful way to stratify the landscape into regions with relatively consistent hydrological and physiographic conditions (Larsen et al. 2017). Ecological subsections are areas of land with a relatively uniform climate and a consistent pattern of landforms, soils, and vegetation (Cleland et al. 1997). Subsection maps are available for all of ARCN (Jorgenson 2001; Jorgenson, Swanson, and Macander 2001; Swanson 2001a, 2001b; Boggs and Michaelson 2001). In addition, subsections provide a way to avoid various non-target areas, including 1) salt water bodies (lagoons), 2) large floodplains (e.g. the Noatak River), where most of the water is in rivers and subject to large year-to-year variations associated with the timing of the images; and 3) mountainous areas, where there are very few lakes but extensive terrain shadows that are difficult to differentiate from water on Landsat images. Thus I analyzed the lake area trends for all lowland subsections in ARCN with at least 0.5% cover by surface water bodies, excluding those where surface water was dominantly rivers or salt water. Note that this analysis does not include the large lakes in the foothills of southern GAAR

(Narvak, Nutuvukti, Selby, and Walker); these are steep-sided, outlet-controlled lakes that fluctuate little in area while being subject to terrain shadow issues that confound water area mapping. Maps of the subsections analyzed for water surface area in this report, by NPS unit, are given in Appendix C.

The geomorphological settings of the lakes in ARCN can be joined into three broad classes, based on the subsection reports cited above and Hopkins (1963): 1) thaw-lake plains; 2) ice-rich loess over other unconsolidated deposits (glacial drift, volcanic ash and pumice, colluvial deposits); and 3) glacial drift and eolian sands with moderate to low ice content. The thaw-lake plains have ice-rich permafrost, and numerous shallow lakes overlap the outlines of older, drained lakes. Inter-lake surfaces are quite flat and only a few meters above the current lake levels. The ice-rich loess and loess over other deposits have lakes in depressions of thermokarst origin or mixed thermokarst and other (glacial, eolian) origin, separated by gently sloping uplands. Local relief ranges from a few meters to as much as 35 m on very ice-rich “yedoma” deposits (Shur et al. 2009). While drained lake basins are present in these areas, they do not blanket the surface as in thaw-lake plains. Ground ice contents in the thaw-lake plains and ice-rich loess correspond to the “High” ice content class (>40% ice by volume in the upper 5 m) mapped by Jorgenson et al. (2008). The glacial drift and eolian sands are late Pleistocene deposits where lake basins appear to be primary depressions that have been only slightly modified by thermokarst. The glacial drift and eolian sands fall in the “low” (<10% ice by volume in the upper 5 m) and moderate (10 to 40% ice by volume in the upper 5 m) ice content classes of Jorgenson et al. (2008).

Methods

Identification of surface water

Surface water area was mapped using Landsat data as described in Swanson (2017a, 2017b, 2019) with one important modification: I used the USGS Landsat Dynamic Surface Water Extent (“DSWE”; USGS 2019, Jones 2019) water rasters in addition to producing surface water extent rasters locally from Landsat data. Previously I mapped water by applying a simple threshold criterion to the shortwave infrared (SWIR) band of all the available Landsat data: pixels with $SWIR < 600$ were classified as “water”. The Landsat data were accessed via the U.S. Geological Survey’s (USGS) “Landsat Analysis-Ready Data” collection (ARD; Sauer and Dwyer 2018), which contains atmospherically corrected surface reflectance data organized into a regular grid of 150 km x 150 km tiles. Starting in 2019 the USGS began producing the DSWE surface water product, by applying multiple water-recognition criteria to the same Landsat ARD scenes. DSWE has been extensively peer-reviewed, it is available nationwide, and the file download size (and therefore download time) is about one fourth of ARD. For the present report I ran the analysis through 2019 using both the DSWE water rasters downloaded from USGS, and water rasters produced locally by applying the “ $SWIR < 600$ ” criterion to the Landsat ARD.

The DSWE product classifies each pixel into various water or wetland classes (Table 1). I recoded the DSWE pixels labeled “water, moderate confidence” and “water, high confidence” to +1, all other land and wetland classes to -1, and pixels where clouds, cloud shadows, or snow obscured the ground to “No Data”. The resulting rasters thus identify true open water, as opposed to wetlands or pixels with mixtures of water and land. Simply summing a stack of these recoded rasters for a selected time interval yields positive values for pixels that were water on a majority of scenes with data for the time interval.

Table 1. Dynamic Surface Water Extent (DSWE) pixel values.

DSWE Pixel Value	DSWE Interpretation	Recoded here as
0	Not water	-1
1	Water – high confidence	+1
2	Water – moderate confidence	+1
3	Potential wetland	-1
4	Water or wetland – low confidence	-1
9	Cloud, cloud shadow, and snow	No Data
255	Fill	No Data

In my previous analyses I found that stacks of Landsat images for single years had significant areas of no data, especially from 2003 to 2012, when Landsat 7 had a scan line correction failure and

Landsat 8 was not yet operational. This same issue affected the DWSE data, and thus I adopted the same solution as before: I stacked all the data for 3 consecutive years and classified as “water” any pixel for which the majority of available values were “water”. Each 3-year composite value was assigned to the middle year of the three. One of the tiles (tile 001004, far western BELA) had 15 DSWE scenes from 2000-2002 with obviously erroneous values, such as extensive land areas mapped out in the ocean. I eliminated these scenes from the analysis and still obtained satisfactory composite values for these years. A few small patches of “no data” appeared on the resulting 2000 composite, which I filled by values from 1999 and 2001 where those two matched.

Trend analysis

Consistent annual data Landsat became available starting in 1999, and thus my three-year running computations are from 2000 (1999-2001) through 2018 (2017-2019). Data from the final year of this study (2019) were sufficient to compute a water raster for 2019 as a single year. I examined trends in the total area of water by subsection on the 2000-2019 time series using linear regression and Mann-Kendall trend tests with Theil-Sen slope (Marchetto 2015; R Core Team 2017). Sporadic data from 1984-1989 were aggregated to produce a “1980s” water raster (plotted at year 1986 in the graph) and similarly all data from the 1990s were aggregated to produce a “1990s” water raster (plotted at 1995 in the graph).

Results

The results presented here are from the USGS DSWE water mapping unless otherwise noted. Many ecological subsections showed significantly declining water area from 2000 to 2019 (Table 2, Figure 4). The subsection with by far the most rapid decline was the Bering Straits Lower Coastal Plain (BSLCP), with a 2000-2019 rate of loss over 120 ha of water per year (Table 2) and a decline from over 8 to 8.5% total water cover in 2000-2005 to less than 7% in 2019 (Figure 5). This is the northernmost subsection along the north coast of BELA (cross-hatched in Figure 4). The three subsections with the fastest rates of water area loss were all in BELA (Table 2). Half of the subsections with statistically significant declines in water area actually had quite small rates of loss: less than 5 ha of water per year (Table 2). See Appendix C for subsection locations.

Water surface areas in many subsections had weak or non-significant trends (the areas colored pink and light blue in Table 2 and Figure 4). An example is the Middle Noatak Uplands (MNU in Figure 5), where the p -value for the slope was 0.40 and the range of variation quite narrow, from about 4.1 to 4.3% water cover.

The sole subsection with a significant (Mann-Kendall test $p = 0.02$) positive trend in water area, the Kotlik Coastal Plain in CAKR (KOP in Figure 5) also exhibited a rather narrow range of variation (about 1.90 to 2.15% cover), a very low overall rate of change (less than 1 ha yr^{-1}), and values that were actually higher in 2003-2004 than any time since. Inspection of the new water areas there showed that they were mostly on the margins of lakes, suggesting minor thermokarst expansion.

Table 2. Lake area change 2000-2019 by ecological subsection^A.

Subsection	NPS Unit	Permafrost	Subsection area, km ²	USGS DSWE			SWIR < 600		
				Lake area, %	Slope, ha yr ⁻¹	<i>p</i> -value	Lake area, %	Slope, ha yr ⁻¹	<i>p</i> -value
BSLCP ^B	BELA	thaw-lake plain	1630	6.7	-123.2	0.00	8.1	-89.9	0.00
BSUCP ^B	BELA	ice-rich	1327	5.0	-38.1	0.00	5.9	-19.6	0.00
DJ ^B	BELA	ice-rich	826	8.6	-11.1	0.00	9.8	-2.6	0.67
NIP ^B	KOVA	ice-rich	750	0.6	-8.9	0.00	1.3	-6.1	0.00
GBUCP ^B	BELA	ice-rich	1320	2.3	-7.9	0.01	3.0	1.7	0.58
IL ^B	BELA	ice-rich	339	22.5	-7.0	0.00	23.4	-5.1	0.00
AKP ^B	KOVA	ice-rich	381	0.8	-6.1	0.00	1.5	-4.5	0.00
NGL ^C	NOAT	ice-poor	655	3.8	-5.0	0.02	4.7	1.0	0.77
WUL ^C	CAKR	ice-rich	351	0.7	-2.9	0.00	0.9	-2.2	0.00
AHW ^C	KOVA	ice-poor	142	9.4	-2.4	0.00	12.1	1.8	0.26
GBLCP ^C	BELA	thaw-lake plain	116	4.5	-2.4	0.05	5.7	-1.3	0.06
UNB ^C	NOAT	ice-poor	2475	1.7	-1.5	0.63	2.0	9.8	0.03
KOY ^C	GAAR	ice-rich	230	1.8	-1.4	0.05	2.4	-0.4	0.56
LNMC	CAKR	ice-rich	97	3.3	-1.2	0.00	4.2	-0.5	0.03
KZL ^C	BELA	ice-rich	226	3.5	-1.1	0.06	4.7	1.7	0.01

^ANPS Unit: see Figure 1. Subsection: see Appendix C for full names and locations. Lake Area, %: water surface area of the subsection in 2019. Slope: rate of change in water surface area, ha yr⁻¹, by Theil-Sen non-parametric slope. *p*-value: F-test probability value for the Mann-Kendall trend test. USGS DSWE: water mapping by USGS DSWE product. SWIR < 600: water mapping by thresholding the Landsat SWIR band at 600.

^B Indicates subsections with significant ($p < 0.05$) negative slope steeper than -5 ha yr⁻¹, (also with red background color, and the color scheme matches Figure 4).

^C Indicates a non-significant negative trend, or loss of less than 5 ha yr⁻¹, (also with pink background color, and the color scheme matches Figure 4).

Table 2 (continued). Lake area change 2000-2019 by ecological subsection^A.

Subsection	NPS Unit	Permafrost	Subsection area, km ²	USGS DSWE			SWIR < 600		
				Lake area, %	Slope, ha yr ⁻¹	<i>p</i> -value	Lake area, %	Slope, ha yr ⁻¹	<i>p</i> -value
NOA ^C	GAAR	ice-poor	177	6.2	-1.0	0.02	7.0	1.3	0.09
IGU ^C	NOAT	ice-poor	984	2.6	-0.9	0.30	3.2	4.4	0.11
LNL ^C	NOAT	thaw-lake plain	404	8.6	-0.8	0.67	10.8	7.7	0.26
NGU ^C	NOAT	ice-poor	207	3.1	-0.8	0.17	3.9	1.4	0.05
KOB ^C	GAAR	ice-rich	240	0.8	-0.5	0.11	1.4	1.0	0.01
MNU ^C	NOAT	ice-poor	544	4.2	-0.4	0.40	4.6	1.5	0.09
NIG ^C	GAAR	ice-poor	78	3.6	-0.3	0.09	4.7	0.9	0.00
ACP ^C	CAKR	thaw-lake plain	112	2.0	-0.3	0.44	2.8	0.4	0.21
IMP ^C	CAKR	thaw-lake plain	18	8.0	-0.1	0.25	9.2	0.2	0.36
KGU ^D	NOAT	ice-poor	584	2.7	0.0	1.00	3.1	3.0	0.01
ITK ^D	GAAR	ice-poor	31	16.4	0.1	0.31	17.7	0.5	0.00
AGU ^D	NOAT	ice-poor	231	11.4	0.2	0.77	11.9	1.5	0.07
ALA ^D	GAAR	ice-poor	23	17.1	0.5	0.06	23.1	1.7	0.00
KIL ^D	GAAR	ice-poor	92	4.5	0.6	0.07	5.9	2.4	0.00
KOP ^D	CAKR	thaw-lake plain	118	2.1	0.7	0.02	2.5	1.1	0.00

^ANPS Unit: see Figure 1. Subsection: see Appendix C for full names and locations. Lake Area, %: water surface area of the subsection in 2019. Slope: rate of change in water surface area, ha yr⁻¹, by Theil-Sen non-parametric slope. *p*-value: F-test probability value for the Mann-Kendall trend test. USGS DSWE: water mapping by USGS DSWE product. SWIR < 600: water mapping by thresholding the Landsat SWIR band at 600.

^C Indicates a non-significant negative trend, or loss of less than 5 ha yr⁻¹, (also with pink background color, and the color scheme matches Figure 4).

^D Indicates a non-significant positive trend (*p* > 0.05) or positive trend of less than 1 ha yr⁻¹, (also with light blue background color, and the color scheme matches Figure 4).

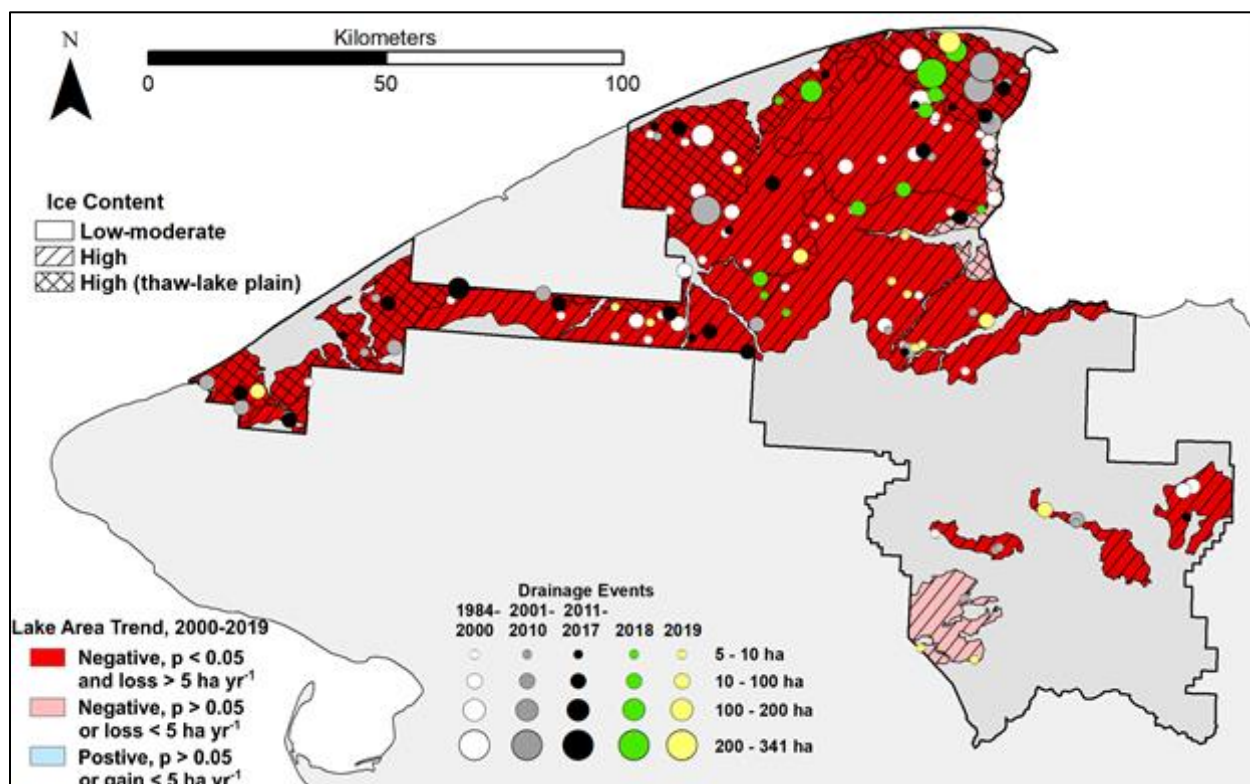


Figure 4a. Lake area change in the western part of the study area (BELA). Subsection colors give the overall trend in water area 2000-2017: red for decreasing and blue for increasing, with bright red indicating significance at $p < 0.05$ and rates of loss steeper than -5 ha yr^{-1} ; Circles mark the location of lakes that drained, with circle size proportional to the area lost and shading keyed to the years of drainage: white (1984-2000), gray (2001-2010), black (2011-2017), green (2018) and yellow (2019). Drained lakes were defined as those that had lost half or more surface area in 2019. The year that a lake first lost 25% or more of its area was identified as the year of drainage

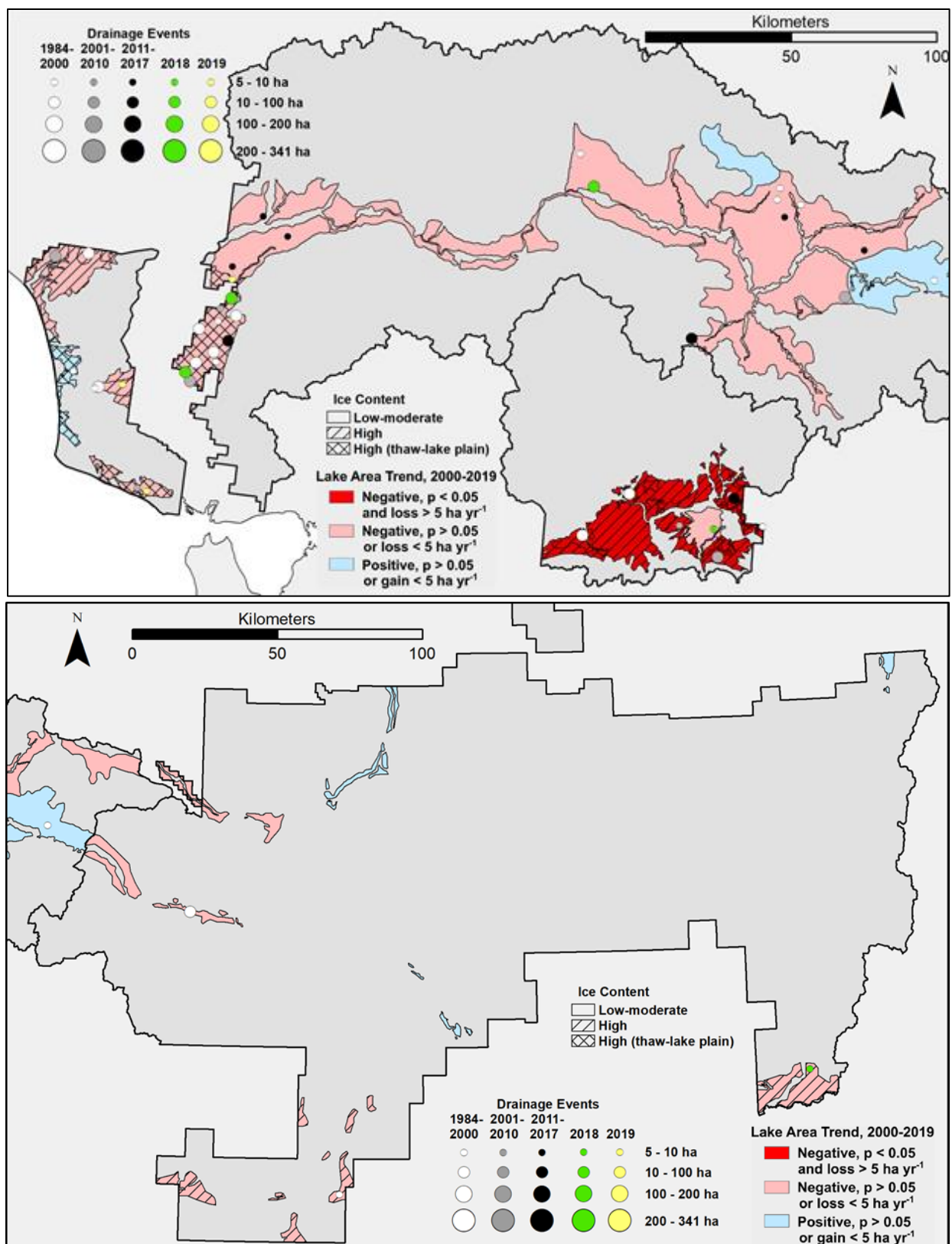


Figure 4b. (Upper) Lake area change in the central part of the study area (CAKR, KOVA, and NOAT). (Lower) Lake area change in the eastern part of the study area (GAAR and far western NOAT).

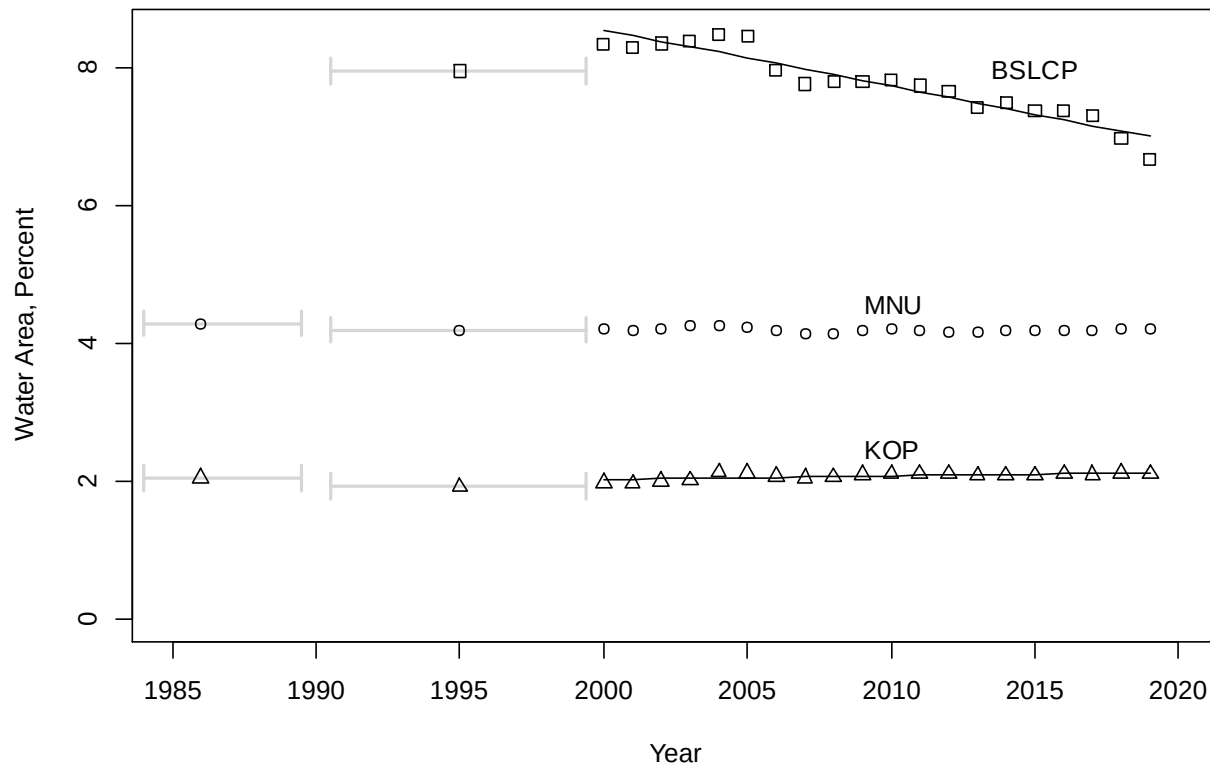


Figure 5. Water trend with time for three example subsections. The Bering Straits Lower Coastal Plain subsection (BSLCP, in BELA) is an area with significant downward trend from 2000 to 2019. The trend line is from a linear regression, $r^2 = 0.90$, F-test $p < 0.01$. The Middle Noatak Uplands subsection (MNU, in NOAT) is an area of non-significant trend in water area from 2000 to 2019. The Kotlik Coastal Plain (KOP, in CAKR) is an area with statistically significant positive trend from 2000 to 2019. The trend line is from a linear regression, $r^2 = 0.43$, F-test $p < 0.01$. The points plotted at years 1986 and 1995 with gray bars give pooled values for the 1984-89 and 1990-1999, respectively.

As was documented previously (Swanson 2019), areas with rapid loss of lake area coincide with areas that had multiple rapid lake drainage events (Figure 4). Rapid lake drainage events occurred almost exclusively in lakes of thermokarst origin, due to thermoerosion of new outlets (Jones et al. 2011, Swanson 2019). Subsections with ice-rich permafrost include thaw-lake plains (cross-hatched in Figure 4) and areas with ice-rich loess (hatched in Figure 4). The total count of new drained lakes in 2019 was the highest since annual Landsat records became available in 2000, and these lake drainages were predominantly in BELA (Figure 6). The total area of water lost in BELA due to lake drainages in 2019 was exceeded only by 2018 and 2006 (Figure 7). The largest single lake that drained in 2019 lost 173 ha of water and was in northern BELA (Figure 8). The Kotlik Coastal Plain (mentioned above because it had slightly increasing lake area) was unusual among thaw-lake plains in that it has had no lake drainage events since the year 2000. Photographs of lakes that drained in 2019 and vegetation recovery on lakes that drained in 2018 are in Appendix B and C.

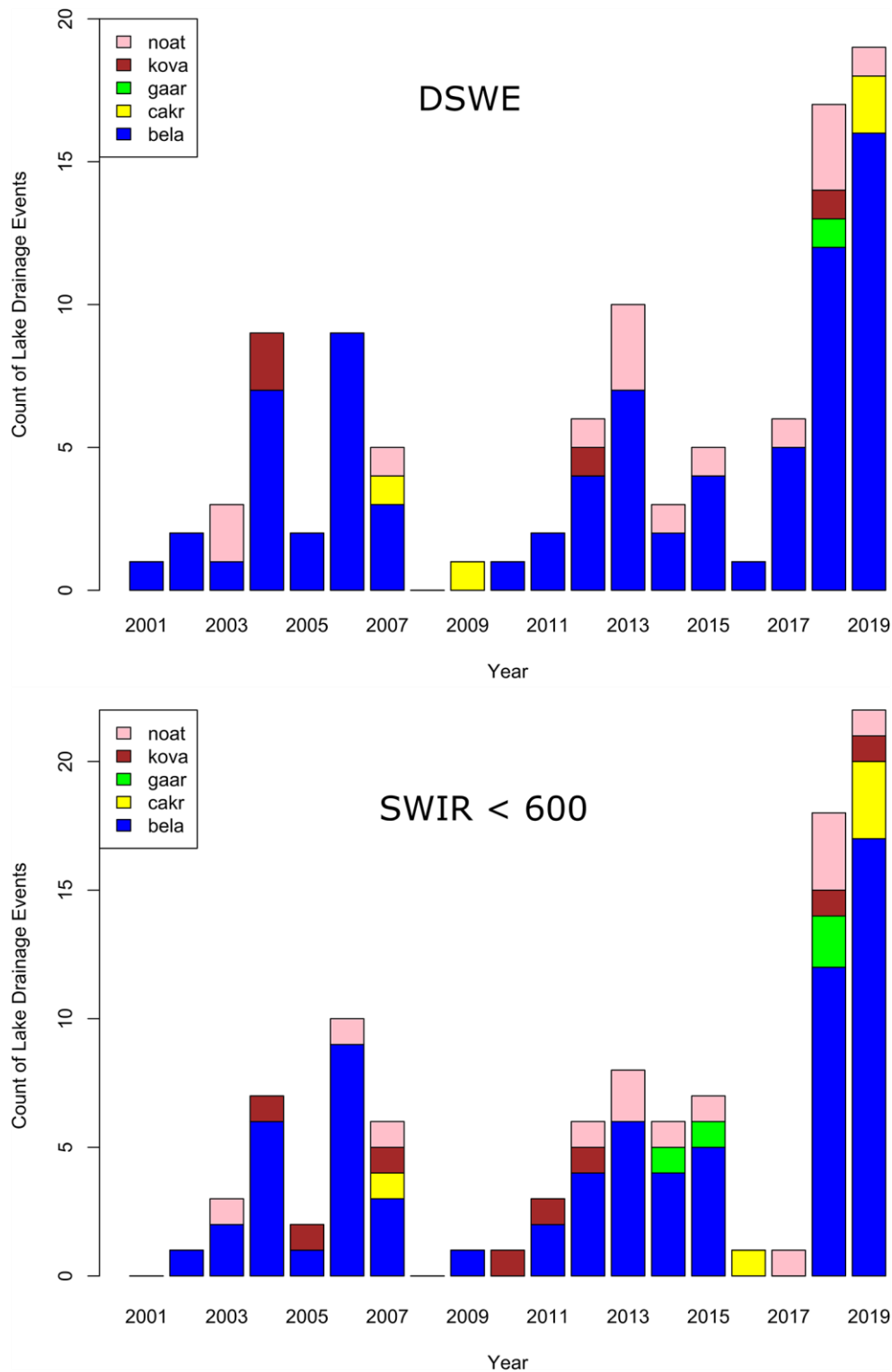


Figure 6. Count of new lake drainage events by year, 2001-2019, by NPS unit, based on DSWE water mapping (upper) and SWIR < 600 water mapping (lower). "Drained" lakes were defined as those that had a maximum area of 5 ha or more and lost more than 50% of their area during the study time period, with the year of drainage defined as the first year that they lost 25% or more of their area relative to the preceding year.

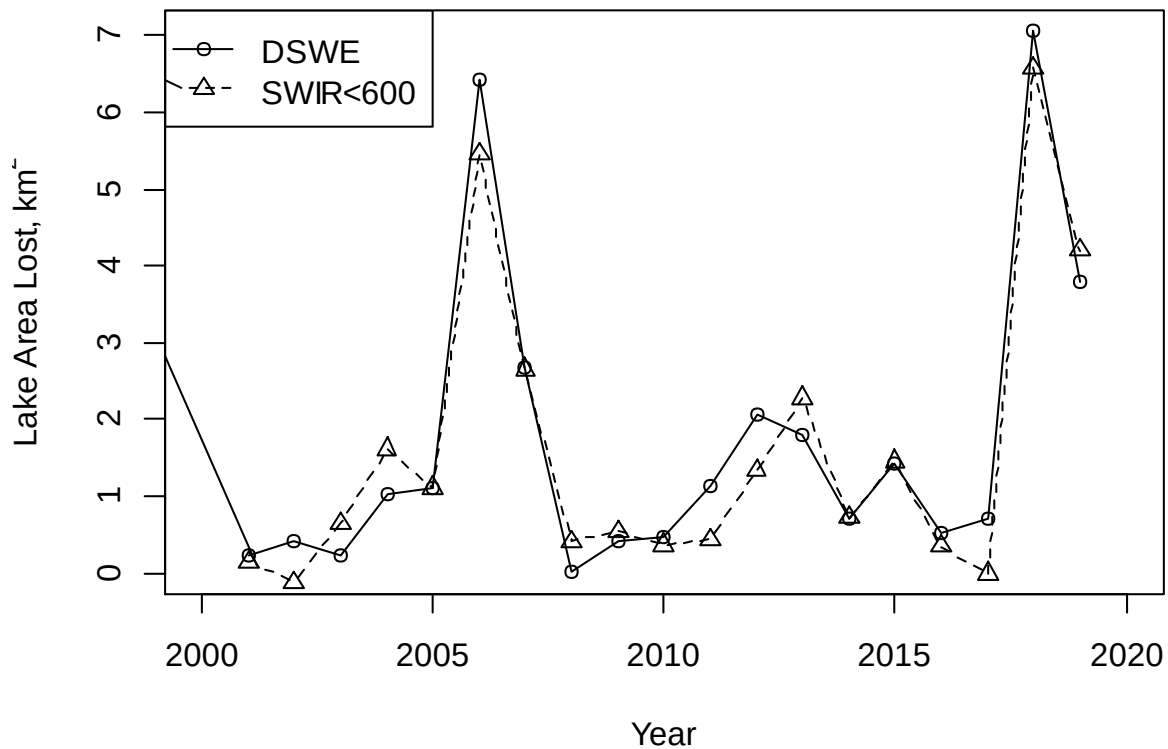


Figure 7. Loss of water area by year of the lakes that were identified as “drained” in BELA during 2001-2019, based on DSWE and SWIR < 600 water mapping methods. “Drained” lakes were defined as those that had a maximum area of 5 ha or more and lost more than 50% of their area during the study time period.

The portion of the BSLCP in far northeastern BELA and adjacent private land has experienced the most drastic lake loss (Figure 8). In 2005 the portion of the BSLCP depicted in Figure 8 had 11 lakes larger than 100 ha (247 acres). Three of these lakes (one completely on private land, two mainly on private land but partly NPS) drained in 2006-2007, and four more (all on NPS land) drained in 2018-2019. Today only four of the 11 original lakes remain, three on NPS land and one mainly on private land but partly NPS.

The total water area mapped was greater by the “SWIR < 600” criterion than the DSWE criteria (Table 2). The “SWIR < 600” mapping showed a minimum water area around the year 2010 in many of the subsections that lacked a strong overall trend (Swanson 2019). These 2010 minima were not apparent on the results derived from the DSWE product, and more subsections showed a significant overall downward trend in water area by DSWE than by “SWIR < 600”.

Detection of lake drainage events was similar by the two water mapping methods. The count of drained lakes (Figure 6) and area lost by drainage in BELA by year (Figure 7) by the DSWE and “SWIR < 600” criteria were quite similar.

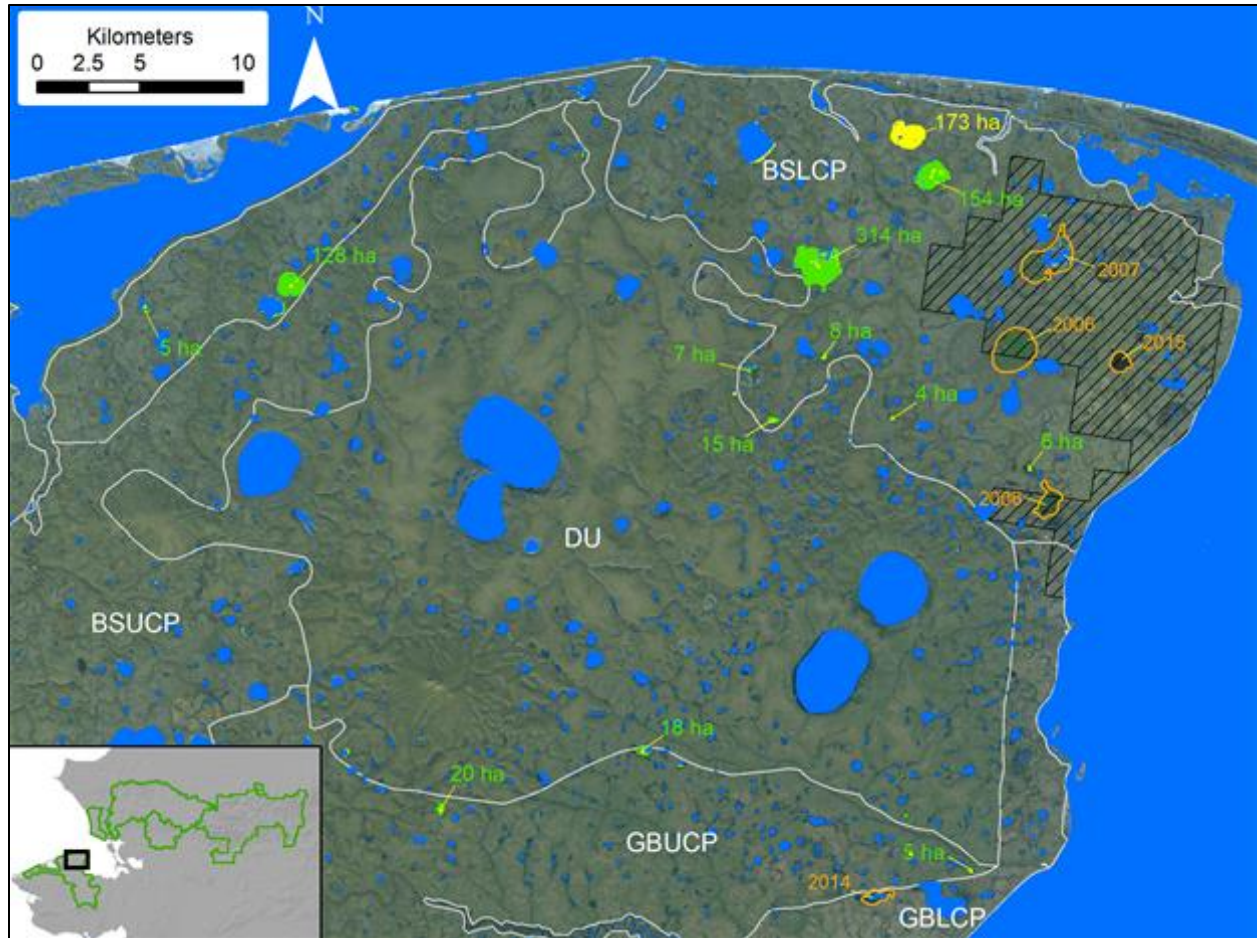


Figure 8. Lake loss in northeastern BELA. Areas that lost water between 2017 and 2018 are shaded in green, and areas that lost water from 2018 to 2019 are shaded in yellow. Lakes over 5 ha in area that drained in 2018-2019 labeled with the area lost, in hectares. Large (>50 ha) pre-2017 drained lakes are outlined and labeled with the year in orange. The white lines outline ecological subsections (Jorgenson 2001) used as analysis areas: BSLCP – Bering Straits Lower Coastal Plain, BSUCP – Bering Straits Upper Coastal Plain, DU – Devil Uplands, GBLCP – Goodhope Bay Lower Coastal Plain, GBUCP – Goodhope Bay Upper Coastal Plain. A large parcel of private land is hatched. The background image is from 2010 (Alaska Geospatial Council 2011).

Discussion and Conclusions

The results presented here show that the trends observed in our previous analysis (Swanson 2019) are continuing: the area of lakes and ponds declined in many areas, and the most rapid loss occurred in regions of thermokarst lakes where lakes drained through outlets created by permafrost thaw. The thaw of these new outlets is likely the result of the record warm temperatures of the past 5 years, probably in combination with high snowfall that produced high spring water levels in the lakes and ponds (Swanson 2019). The thaw-lake plain in northern BELA lost the most lake area. Similar permafrost and climatic conditions are present on the thaw-lake plains elsewhere in ARCN, and there is no reason to believe that these other areas will be immune to drainage events in the coming years.

The difference in total water area mapped by the USGS DSWE methods and the simpler “SWIR < 600” method is due to the fact that the DSWE “moderate- and high-confidence water” classes used here exclude some of the wetland and mixed land-water (i.e. shoreline) pixels captured by the “SWIR < 600” criterion. These pixels are probably available to some degree from the DSWE product’s “potential wetland” class, and one could re-run this analysis to include the DSWE wetlands, and compare the results to “SWIR < 600”. However, the more stringent DSWE “moderate- and high-confidence water” raster are entirely suitable for locating drained lakes and examining overall lake (as opposed to wetland) area trends.

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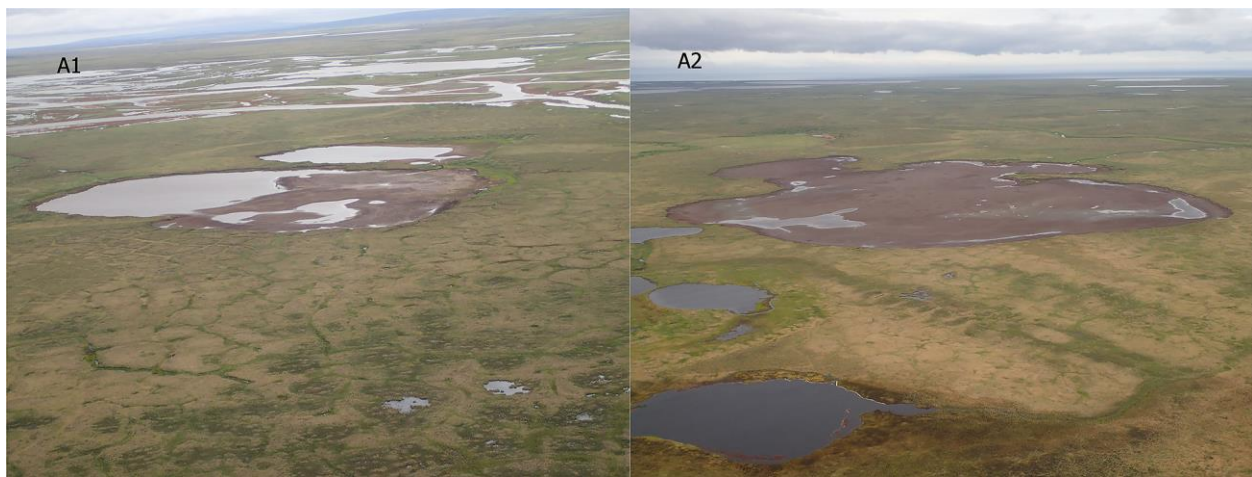
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Appendix A: Oblique aerial photographs of newly drained lakes from 2019

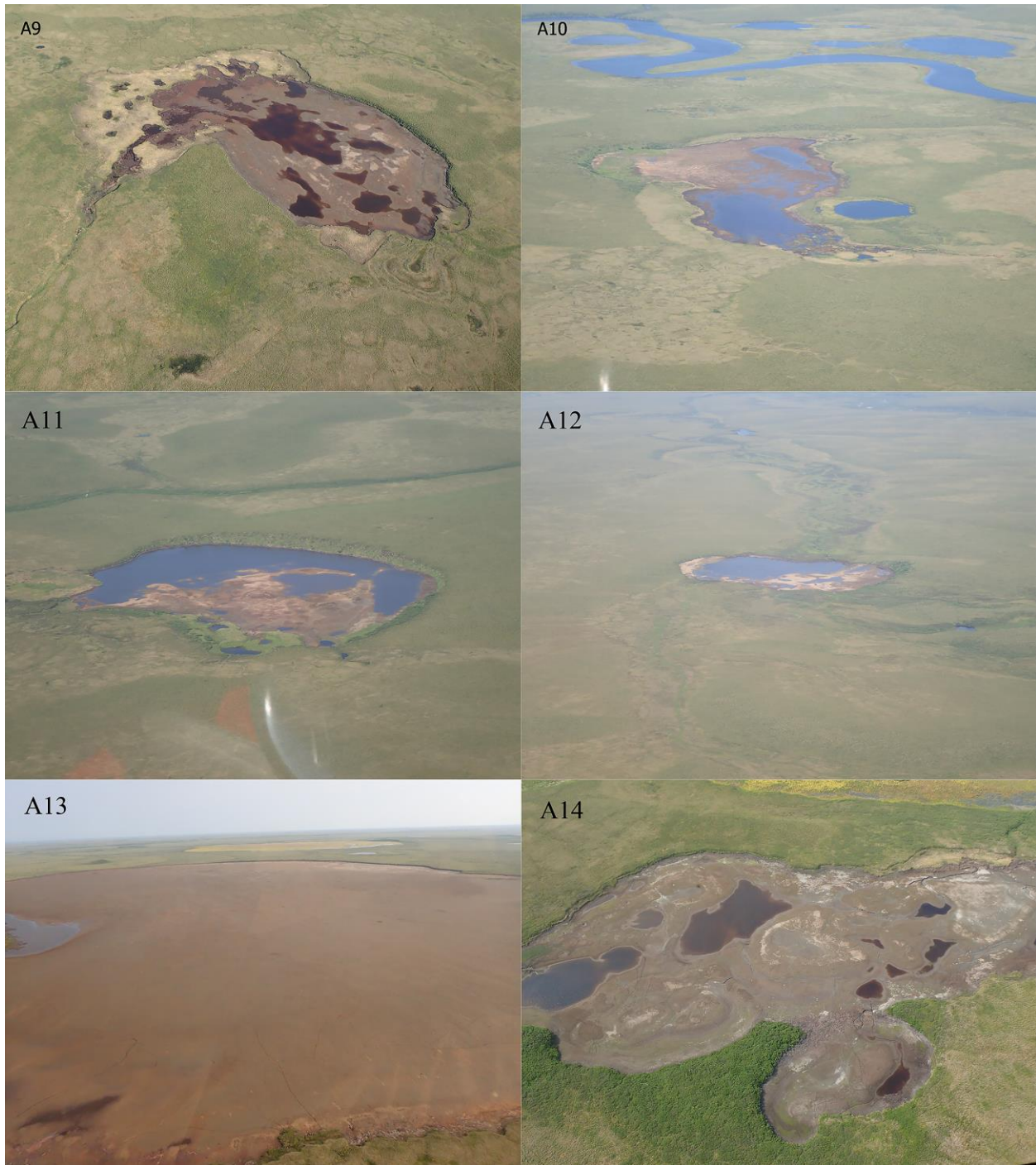
This Appendix contains oblique aerial photographs of lakes that had mud exposed in July 2019 as a result of lowered water levels (figures A1 through A14). These photos were taken opportunistically by the author in July 2019 as a part of other projects in northern BELA and do not represent a systematic effort to locate all of the drained lakes present. The locations of the camera for each photo (taken from the camera's internal GPS) are shown in Figure A15, along with the locations of lakes that my analysis of satellite image data later showed to have drained in 2019. Dates, locations, and orientations of the cameras for these photos are given in Table A1. Some photos are of the lakes that were identified as drained by the satellite image analysis (A2, A8, A10, A11, A13), while the others were not, probably because the amount of drainage visible on the available Landsat images had not progressed far enough to meet the criterion for a “drained lake” (loss of 50% of surface area). The vast majority of lakes in northern BELA were filled to bankfull in 2019, and those showing exposed mud flats often had an obviously eroded new outlet visible during a cursory fly-by. Thus even the partial drainages depicted here are probably due to thermoerosion of new outlets and not simple evaporative drying.



Figures A1-A2. Oblique aerial photographs of lakes in northern BELA with mud exposed due to lowered water levels.



Figures A3-A8. Oblique aerial photographs of lakes in northern BELA with mud exposed due to lowered water levels.



Figures A9-A14. Oblique aerial photographs of lakes in northern BELA with mud exposed due to lowered water levels.

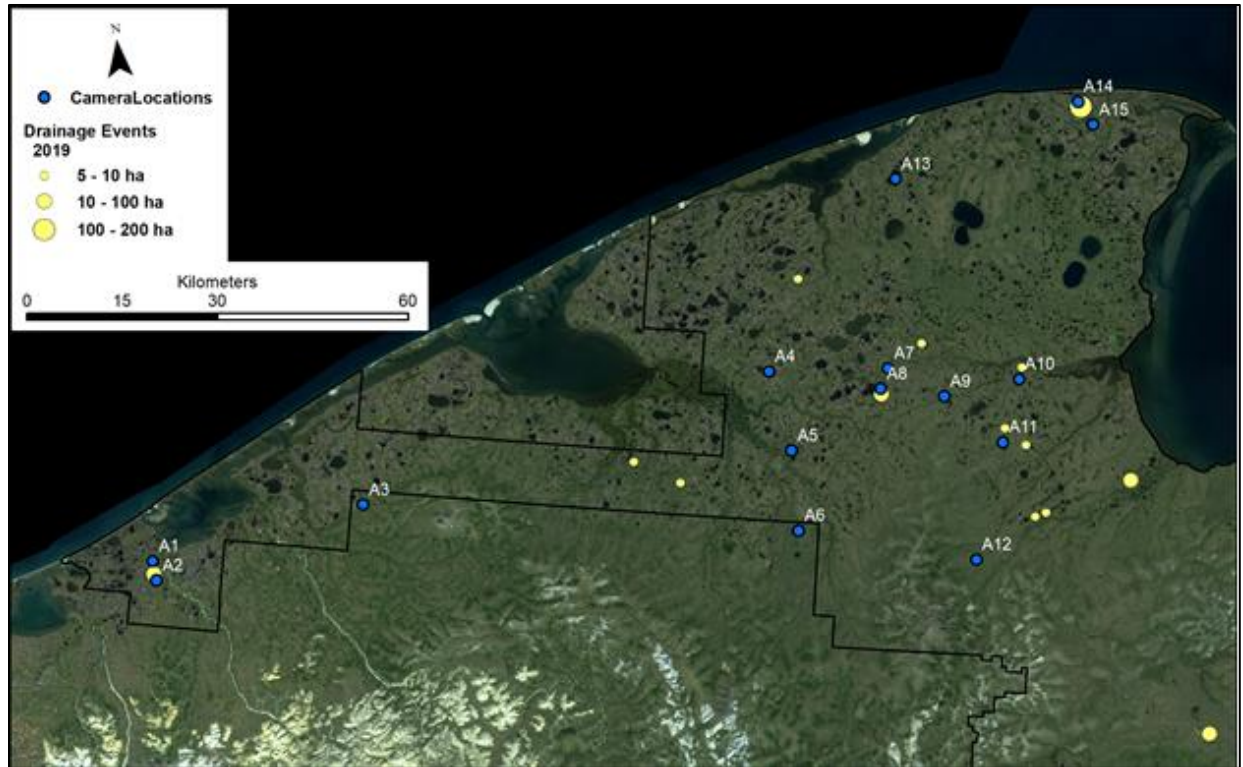


Figure A15. Camera locations for the photographs in Figs. A1 through A14.

Table A1. Camera date, time, location, and orientation for Figs. A1 through A14

Figure	Source File	Date Time	Camera Latitude, °	Camera Longitude, °	Camera Direction, °
A1	P7040160.JPG	2019:07:04 14:21:07	65.83113	-167.226	53
A2	P7040167.JPG	2019:07:04 14:23:04	65.80457	-167.207	334
A3	P7060603.JPG	2019:07:06 18:14:04	65.93694	-166.523	336
A4	P7070627.JPG	2019:07:07 09:33:31	66.16701	-165.154	316
A5	P7070625.JPG	2019:07:07 09:28:24	66.05767	-165.059	340
A6	P7070619.JPG	2019:07:07 09:22:43	65.94531	-165.018	332
A7	P7101008.JPG	2019:07:10 19:57:44	66.18132	-164.741	137
A8	P7101011.JPG	2019:07:10 19:59:01	66.15241	-164.762	141
A9	P7070798.JPG	2019:07:07 18:17:14	66.14663	-164.541	97
A10	P7100933.JPG	2019:07:10 17:10:12	66.17625	-164.282	71
A11	P7100930.JPG	2019:07:10 17:06:45	66.08641	-164.327	57
A12	P7100928.JPG	2019:07:10 16:59:23	65.91838	-164.399	87
A13	P7100951.JPG	2019:07:10 17:27:18	66.57277	-164.124	107
A14	P7100943.JPG	2019:07:10 17:25:17	66.54067	-164.067	327

Appendix B: Observations of revegetation on lakes drained in 2018.

On 10 July 2019 the author and P. Neitlich visited the three large lakes in northeastern BELA that drained in 2018. These are shaded in green in Figure 8 and labeled as “128 ha” (upper left of Figure 8), “314 ha” (upper right) and “154 ha” (upper right), indicating the area of water lost. Here I will refer to the lakes by these numbers. This Appendix presents a summary of observations and photographs from that visit. At each lake I took a Trimble GPS point that we differentially corrected to sub-meter precision (Table B1). From this point I took 4 photographs at approximately cardinal directions and estimated plant species cover in the point vicinity.

Table B1. Location data for reconnaissance plots on 3 lakes that drained in 2018^A

Description	Date	Time	Longitude, °	Latitude, °	Horizontal Precision, m
Lake 154	7/10/2019	04:42:59pm	-164.0793193	66.55075723	0.3
Lake 314	7/10/2019	05:16:02pm	-164.1961969	66.49786991	0.3
Lake 128	7/10/2019	06:11:33pm	-164.7541805	66.45565449	0.2

^ARecord Longitude and latitude are differentially corrected GPS; WGS 1984.

Drained Lake 128

This lake appeared from the air to be uniformly green with new vegetation, except for some bare mud patches mostly around the margins (Figure B1). On-the-ground examination of the green area showed it to be a nearly solid lawn of *Equisetum scirpoides* (Figure B2). An estimate of the cover by species near the photo point (Figure B2) was: *Equisetum scirpoides* 75%, *Acrophila fulva* 2%, *Senecio congestus* <1%, *Salix* cf. *glauca* <1%, *Rorippa palustris* <1%, bare mud 5%.



Figure B1. Aerial view of drained lake 128.

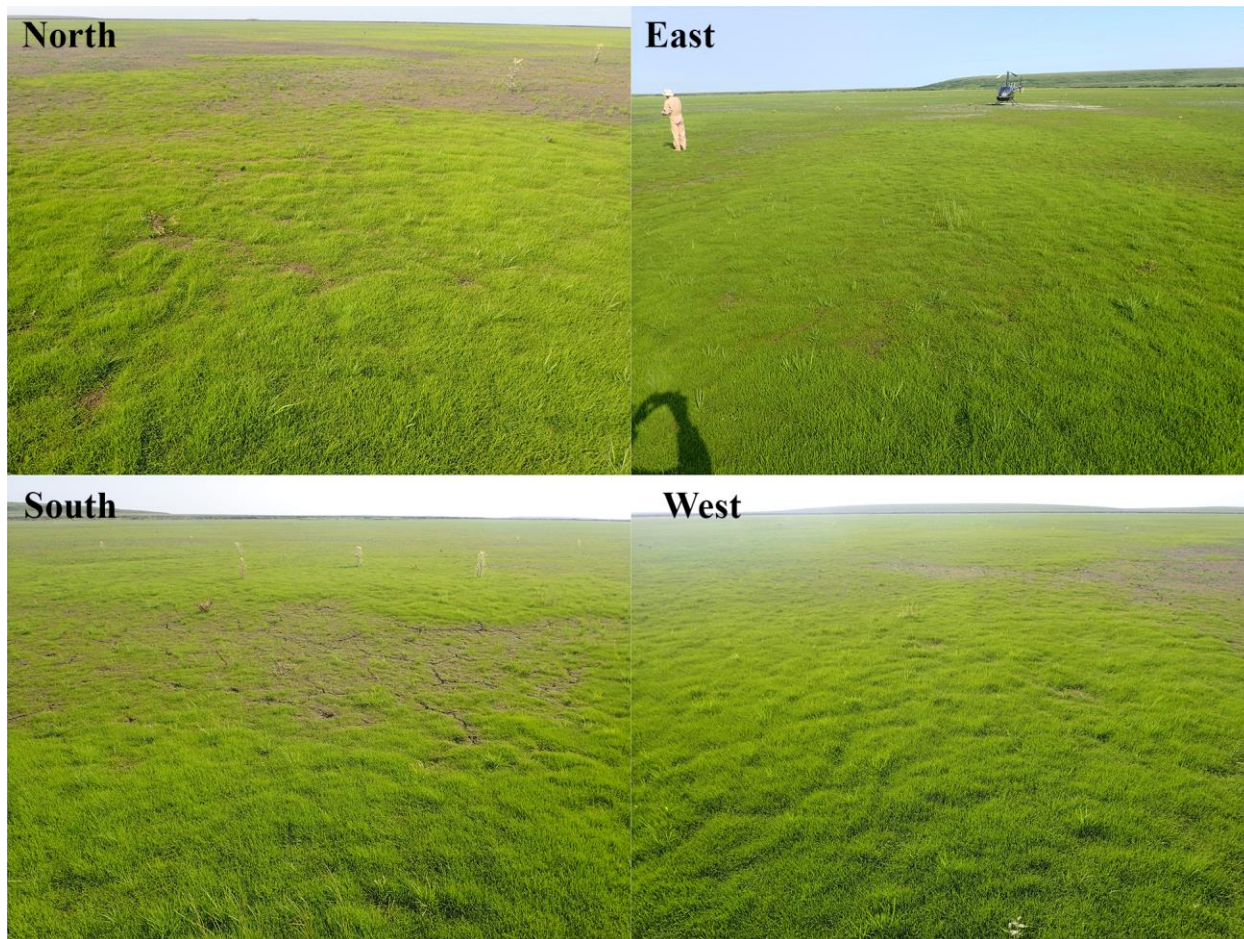


Figure B2. Cardinal direction photos from the GPS point in drained lake 128.

Drained Lake 314

This lake had extensive areas of sparsely vegetated mud (Figure B3). The species composition was similar to the other lakes we visited, but with much lower plant cover. Near the photo point (Figure B4) the cover by species was: *Eleocharis acicularis* 5% (1 patch); *Senecio congestus* 1%, *Arctophila fulva* 1%, *Rorippa palustris* <1%, *Equisetum scirpoides* <1%, unidentified moss <1%, bare mud 95%. The mud had desiccation cracks and a probable salt crust. The *Eleocharis palustris* had an unhealthy brownish color in places (see Figure B4, south), presumably due to desiccation or soil chemical issues (e.g. salinity). There were curving parallel lines of mollusk shells deposited along shorelines during the lake's recession, and seedlings of *Rorippa palustris* were concentrated there, suggested a floating seed source. We observed fairly dense stands of *Hippuris vulgaris* near the lake margin that probably represent pre-drainage stands.



Figure B3. Aerial view of drained lake 314.

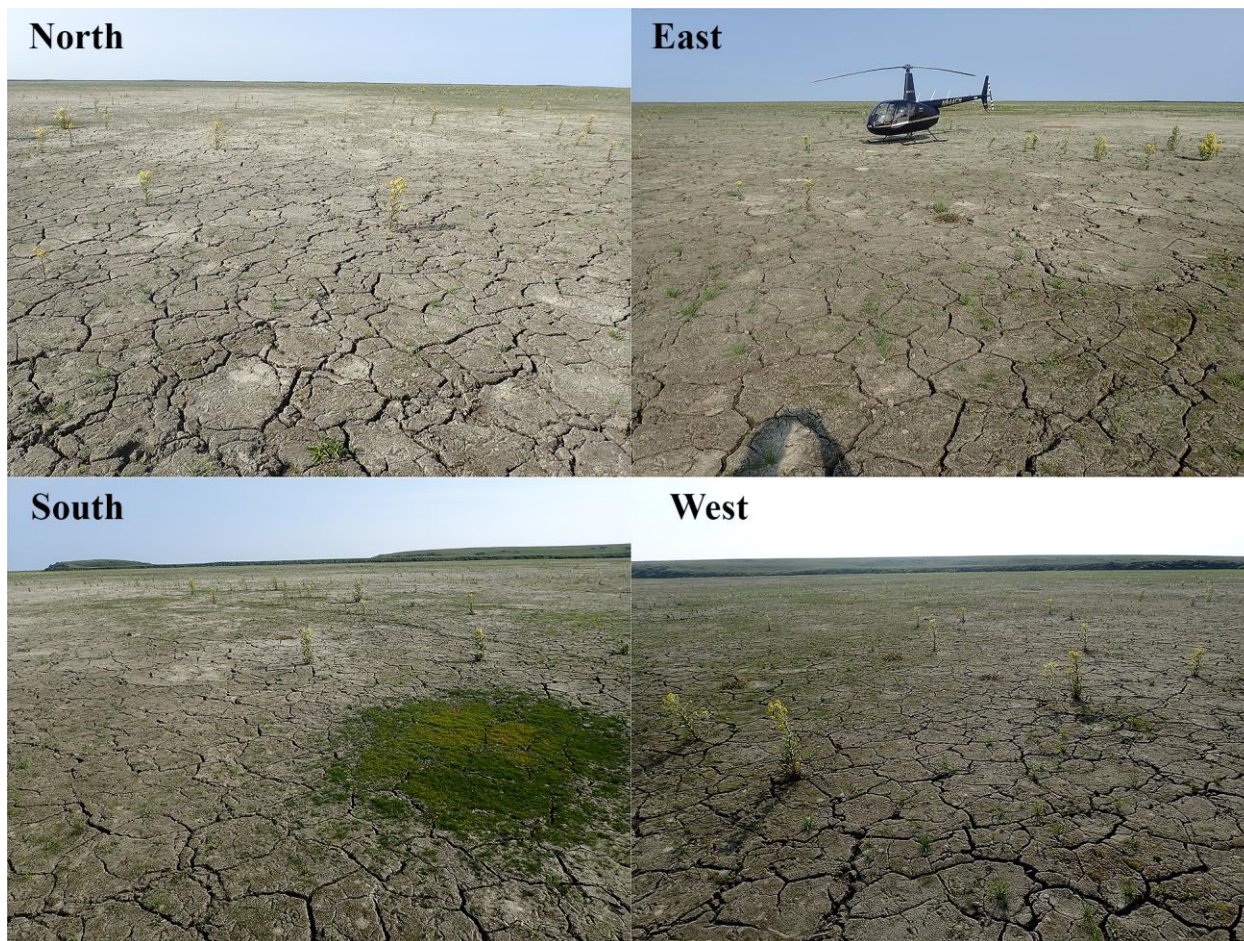


Figure B4. Cardinal direction photos from GPS point in drained lake 314.

Drained Lake 154

This lake appeared bright yellow from the air due to a profusion of flowers (Figure B5). On-the-ground inspection revealed these to be *Senecio congestus*, over a dense sod of *Eleocharis acicularis* (Figure B6). The *Senecio congestus* was denser nearer to the former lakeshore (Figure B6) than at the GPS photo point more in the center of the former lake (Figure B7). The plant cover by species near the GPS point was *Eleocharis acicularis* 90%, *Senecio congestus* 8%, *Rorippa palustris* <1%, bare mud 3%.



Figure B5. Aerial view of drained lake 154



Figure B6. Vegetation of drained lake 154, in area of dense *Senecio congestus* flowers. The sod below is *Eleocharis acicularis*. A pingo is visible in the background. Latitude 66.552105°, longitude -164.0792167°

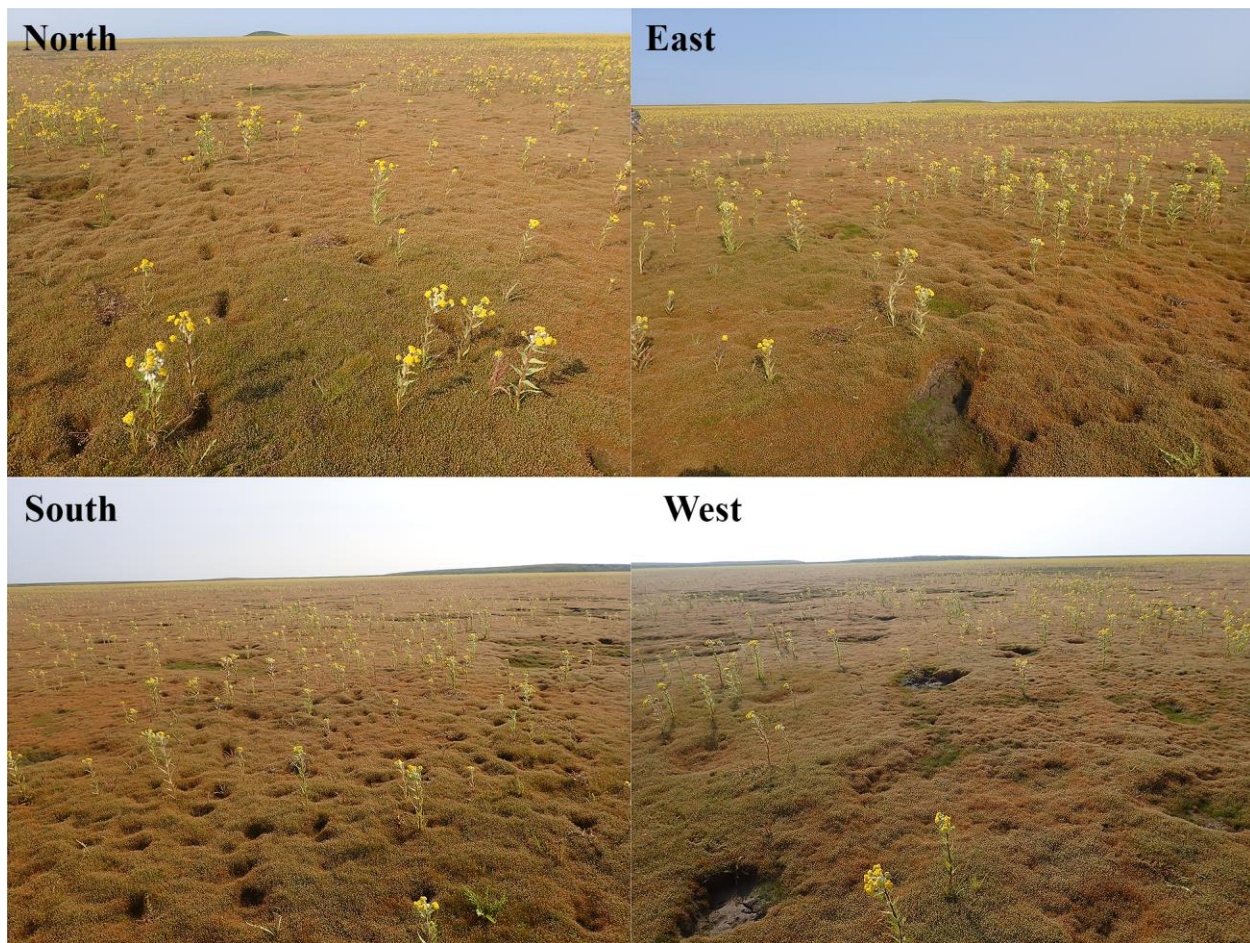


Figure B7. Cardinal direction photos from GPS point in drained lake 154.

Appendix C: Location Maps of Lake Analysis Subsections

Table C1. Subsection codes and names by NPS unit

NPS Unit	Subsection Code	Subsection Name
BELA	BSLCP	Bering Straits Lower Coastal Plain
BELA	BSUCP	Bering Straits Upper Coastal Plain
BELA	DU	Devil Uplands
BELA	GBLCP	Goodhope Bay Lower Coastal Plain
BELA	GBUCP	Goodhope Bay Upper Coastal Plain
BELA	IL	Imuruk Lowlands
BELA	KZL	Kuzutrin Lowlands
CAKR	ACP	Aukulak Coastal Plain
CAKR	IMP	Imikruk Plains
CAKR	KOP	Kotlik Coastal Plain
CAKR	LMN	Lower Noatak Moraine
CAKR	WUL	Wulik Lowland
GAAR	Alatna	Alatna River Valley
GAAR	Itkillik	Itkillik River Valley
GAAR	Killik	Killik River Valley
GAAR	Kobuk	Kobuk River Valley
GAAR	Koyukuk	Koyukuk River Valley
GAAR	Nigu	Nigu River Valley
GAAR	Noatak	Noatak River Valley
KOVA	AHW	Ahnewetut Wetlands
KOVA	AKP	Akillik Plain
KOVA	NIP	Nigeruk Plain
NOAT	AGU	Avingyak Glaciated Uplands
NOAT	IGU	Iggiruk Uplands
NOAT	KGU	Kavachurak Glaciated Uplands
NOAT	LNL	Lower Noatak Lowlands
NOAT	MNU	Middle Noatak Uplands
NOAT	NGL	Noatak Glaciated Lowlands
NOAT	NGU	Nigu Mountain Valley
NOAT	UNB	Upper Noatak Basin

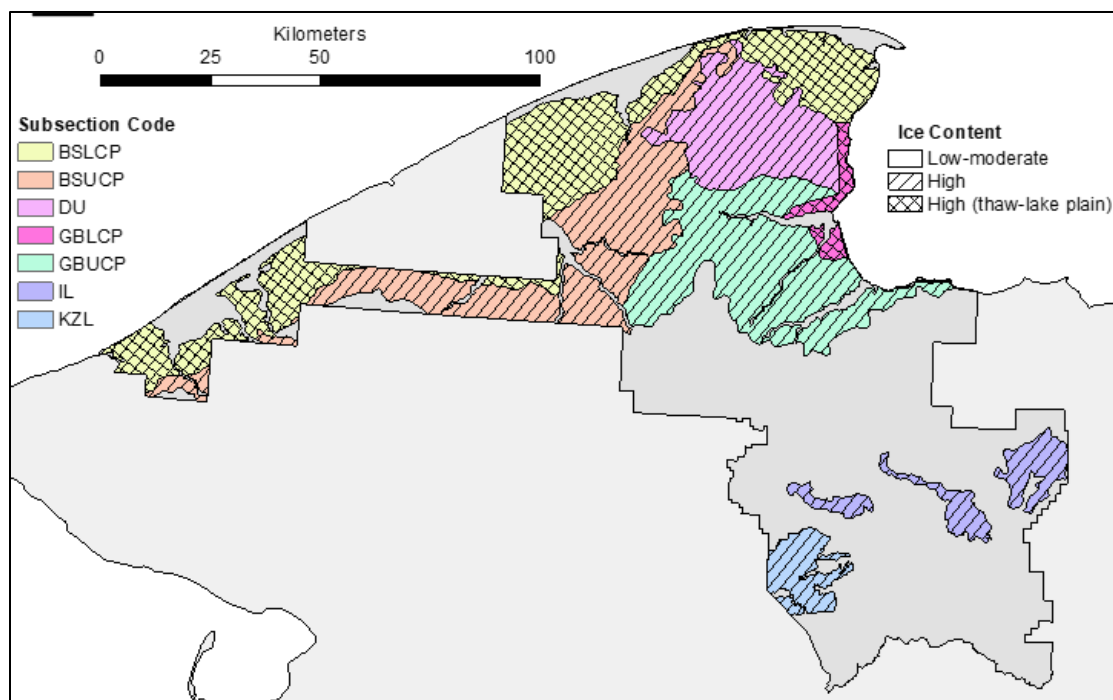


Figure C1. Lake analysis subsections in Bering Land Bridge National Preserve. See Table C1 for an explanation of the subsection codes.

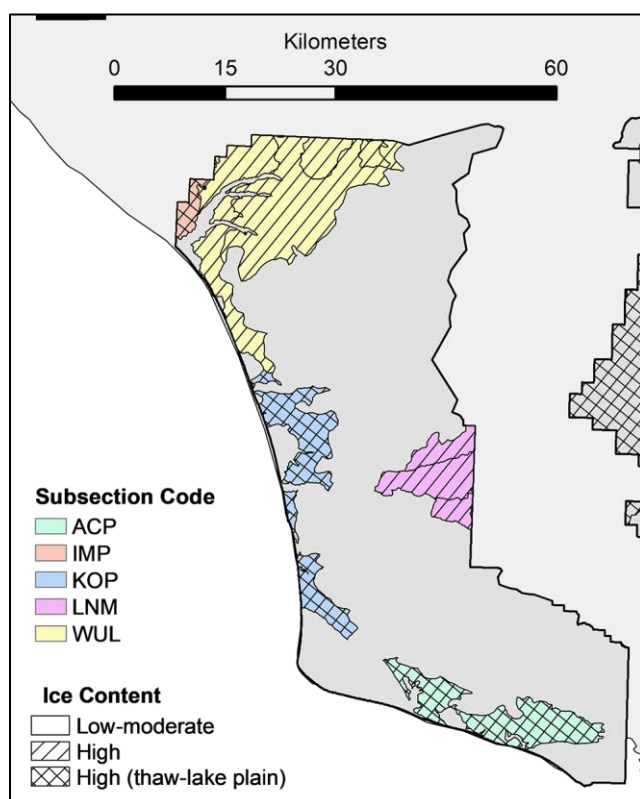


Figure C2. Lake analysis subsections in Cape Krusenstern National Monument. See Table C1 for an explanation of the subsection codes.

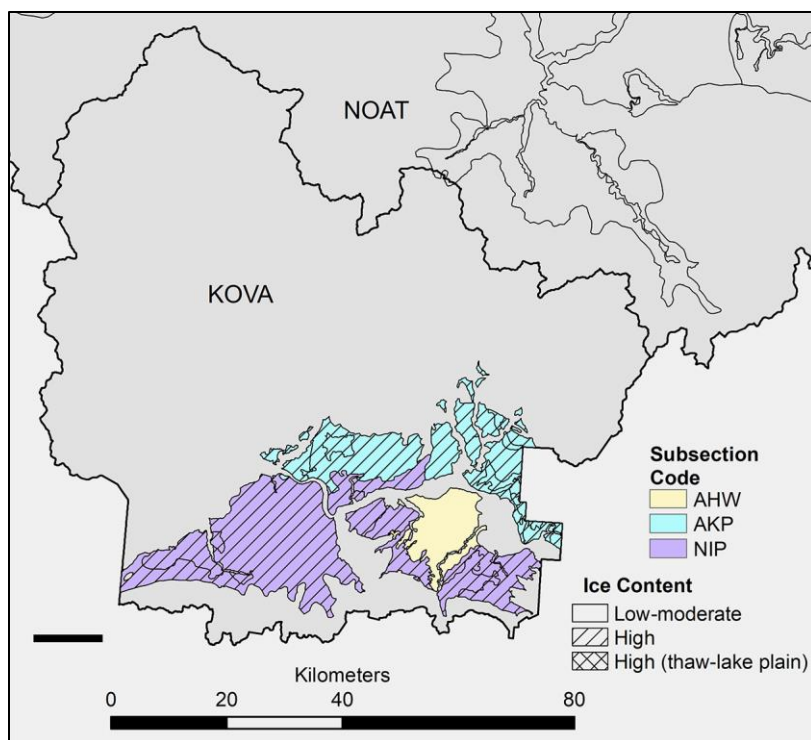


Figure C3. Lake analysis subsections in Kobuk Valley National Park. See Table C1 for an explanation of the subsection codes.

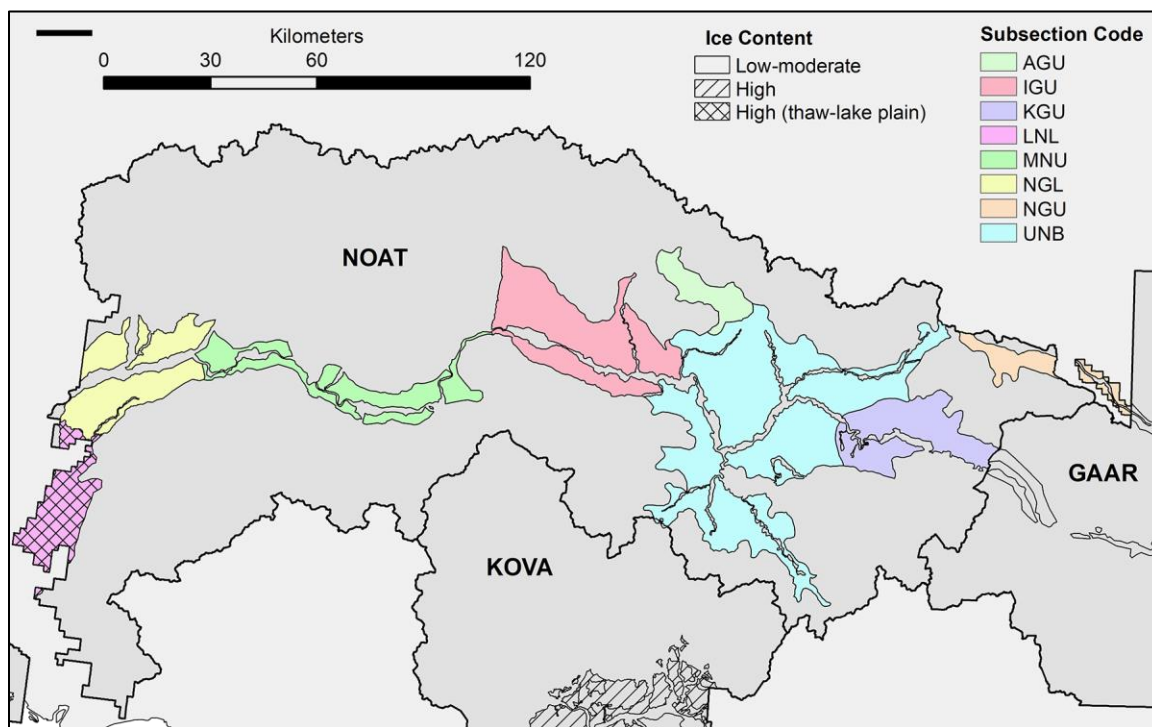


Figure C4. Lake analysis subsections in the Noatak National Preserve. See Table C1 for an explanation of the subsection codes.

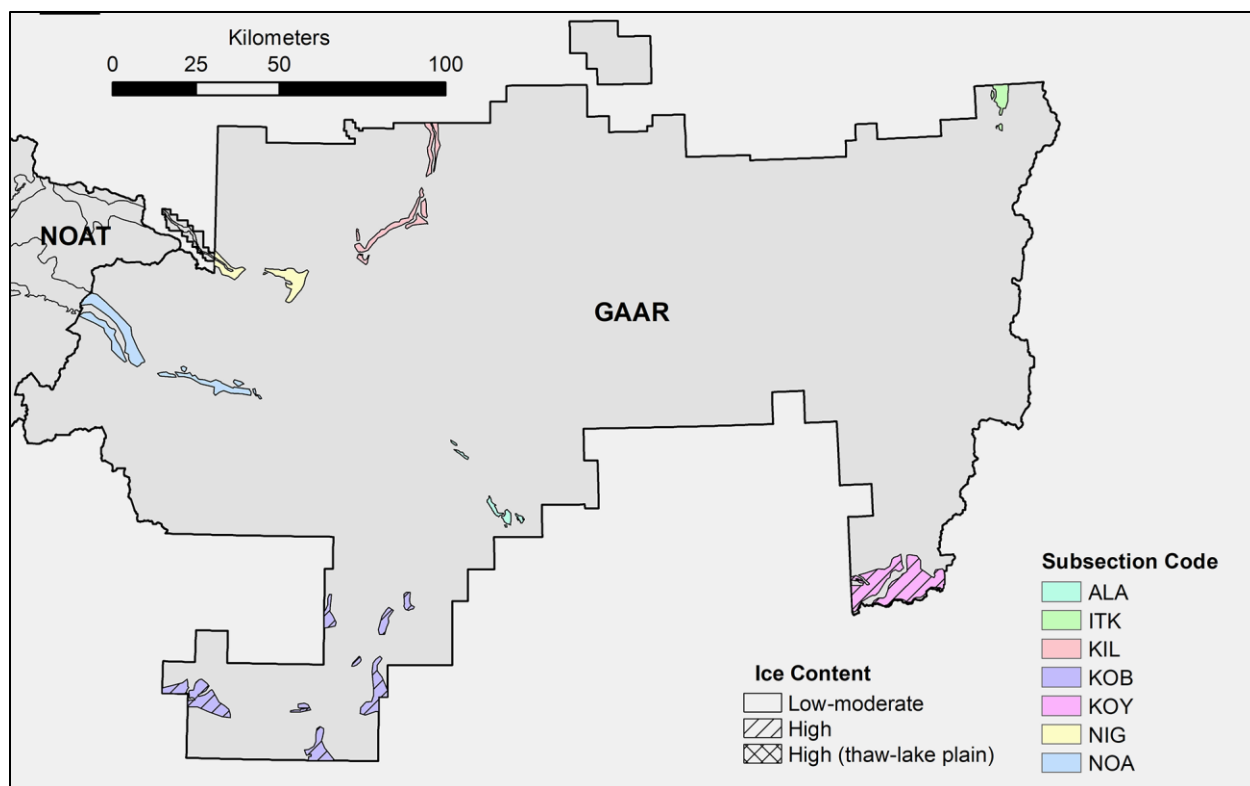


Figure C5. Lake analysis subsections in Gates of the Arctic National Park and Preserve. See Table C1 for an explanation of the subsection codes.

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NPS 953/167038, February 2020

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