



Permafrost Monitoring Protocol for the Arctic Network

Narrative

Natural Resource Report NPS/ARCN/NRR—2017/1396



ON THE COVER

Aerial view of a retrogressive thaw slump in the Noatak Valley, Alaska (upper photograph) and a closer view of ground ice exposed in the main scarp of the slump (lower photograph).

NPS photos by Ken Hill, 21 June 2010.

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Contents

	Page
Figures.....	v
Tables.....	vii
Abstract.....	ix
Acknowledgments.....	ix
1 Introduction.....	1
2 Ground Temperature Monitoring.....	5
2.1 Introduction	5
2.1.1 Monitoring of near-surface temperatures at ARCN climate stations	5
2.1.2 Monitoring of deep borehole temperature profiles.....	5
2.1.3 Monitoring active-layer depth	5
2.2. Sampling Design	6
2.2.1 Co-location of new sites with ARCN climate monitoring	6
2.2.2 Existing long-term deep borehole monitoring sites.....	6
2.2.3 Existing long-term active-layer monitoring sites	7
2.3 Deployment and Operation of Temperature Monitoring.....	8
2.4 Data Management, Analysis, and Reporting.....	9
2.5 Operational Requirements	9
2.5.1 Personnel	9
2.5.2 Equipment.....	9
2.5.3 Annual workload and field schedule	10
3 Mapping of thermal erosion features	11
3.1 Introduction	11
3.2 Sampling Design	13
3.2.1 Imagery properties.....	13
3.2.2 Timing and spatial distribution of samples	14
3.3 Data Processing	15
3.4 Analysis and reporting.....	16
3.5 Operational Requirements	18

Contents (continued)

	Page
3.5.1 Personnel	18
3.5.2 Equipment and supplies.....	18
4 Three-dimensional photographic modeling of selected thermal erosion features	19
4.1 Introduction	19
4.2 Selection of monitoring objects.....	19
4.3 Sampling.....	20
4.3.1 Photography.....	20
4.3.2 Ground control.....	20
4.4 Data analysis: model construction and analysis	21
4.5 Operational requirements	22
4.5.1 Oblique aerial photography	22
4.5.2 Vertical photography and airborne GPS.....	23
4.5.3 Data processing and reporting.....	23
5 Monitoring Ice-Wedge Degradation	25
5.1 Introduction	25
5.2 Study area selection.....	27
5.3 Imagery.....	28
5.3 Sampling.....	29
5.4 Data analysis and reporting	30
5.5 Operational requirements	33
Literature Cited	35

Figures

	Page
Figure 1. The National Park Service Arctic Inventory and Monitoring Network.....	1
Figure 2. Characteristic permafrost landforms.....	2
Figure 3. Mean annual air temperatures in ARCN (PRISM Climate Group 2009).....	3
Figure 4. Climate monitoring stations in ARCN.	6
Figure 5. Active-layer detachment failures (ALD) in the Noatak National Preserve	12
Figure 6. A retrogressive thaw slump in the Noatak National Preserve	13
Figure 7. Retrogressive thaw slumps mapped in ARCN and the proposed RTS monitoring area.	15
Figure 8. Suggested remapping areas for ALD, and ALD susceptibility in ARCN.	16
Figure 9. Mapping of thermal erosion features (erosion features related to permafrost thaw)	17
Figure 10. Oblique stereo-photographs of a RTS	21
Figure 11. 3D model of a retrogressive thaw slump	22
Figure 12. Low-center ice-wedge polygons.....	26
Figure 13. High-center polygon formed by degrading ice wedges.....	26
Figure 14. High-center polygons with marginal water-filled troughs due to ice-wedge degradation.....	27
Figure 15. Areas for monitoring ice-wedge polygons in KOVA and NOAT.....	28
Figure 16. Overview of the Lower Noatak Lowlands study area.	29
Figure 17. Example plot and computation of the water pixel position index.	31
Figure 18. Sectors of polygons as defined by the distance index.	32
Figure 19. Percent cover by water in ice-wedge polygon quarter sectors at two different times in the Ahnewetut Wetlands study area, Kobuk Valley National Park.	32

Tables

	Page
Table 1. Summary of ground temperature installations at ARCN climate stations	7
Table 2. Deep Permafrost Monitoring Boreholes in ARCN vicinity.	8
Table 3. Circumpolar Active Layer Monitoring (CALM) network monitoring locations in the ARCN vicinity.	8

Abstract

Permafrost underlies most of the Arctic Inventory and Monitoring Network (ARCN) and has been selected as a monitoring vital sign. Significant thaw of permafrost is considered likely with future climate change, and this thaw would have important ecological consequences, such as drainage of lakes, creation of new ponds, soil erosion, slumping, siltation of streams and lakes, release of greenhouse gasses, and changes in soil wetness and nutrient supplies leading to vegetation changes. Long-term monitoring of permafrost will focus on monitoring of ground temperatures and monitoring of permafrost-related landforms. Ground temperatures will be monitored at climate monitoring stations; this monitoring will help us understand the vulnerability of permafrost to thaw. Landform monitoring will track some of the outward effects of changes in permafrost on ecosystems. Landforms will be monitored with remote sensing in 3 different projects: 1) comprehensive mapping of bare-soil features produced by thaw of permafrost (active-layer detachment failures and retrogressive thaw slumps) on high-resolution satellite imagery; 2) intensive monitoring of selected retrogressive thaw slumps by three-dimensional modeling using small-format aerial photography; and 3) monitoring of ice-wedge degradation and other thermokarst features using high-resolution imagery.

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1 Introduction

Most of the Arctic Inventory and Monitoring Network (ARCN) is underlain by permafrost. Permafrost has been identified by collaborative effort as one of the “vital signs” of environmental condition that will be monitored over the long term in ARCN (Lawler et al. 2009). Permafrost is defined as ground (soil or rock, plus any included ice or organic material) that remains at or below 0 °C for at least two consecutive years (van Everdingen 2005), though in reality most permafrost has been frozen for thousands of years. Permafrost is continuous (covers more than 90% of the landscape) across most of ARCN, with discontinuous permafrost (local cover 50% to 90% of the landscape) in the low-elevation, southern portions of Kobuk Valley National Park (KOVA) (Fig. 1; Jorgenson et al. 2008b) and Gates of the Arctic National Park and Preserve (GAAR; Swanson 1995). ARCN is a showcase for permafrost-related landforms, including solifluction lobes, ice-wedge polygons, pingos, and thermokarst depressions (Fig. 2; Hopkins 1949, Hopkins and Sigafos 1951, Péwé 1975). The ice content of permafrost in ARCN, and consequent potential for subsidence if permafrost thaws, ranges from negligible in areas of exposed bedrock to very high in the lowlands with fine-grained deposits.

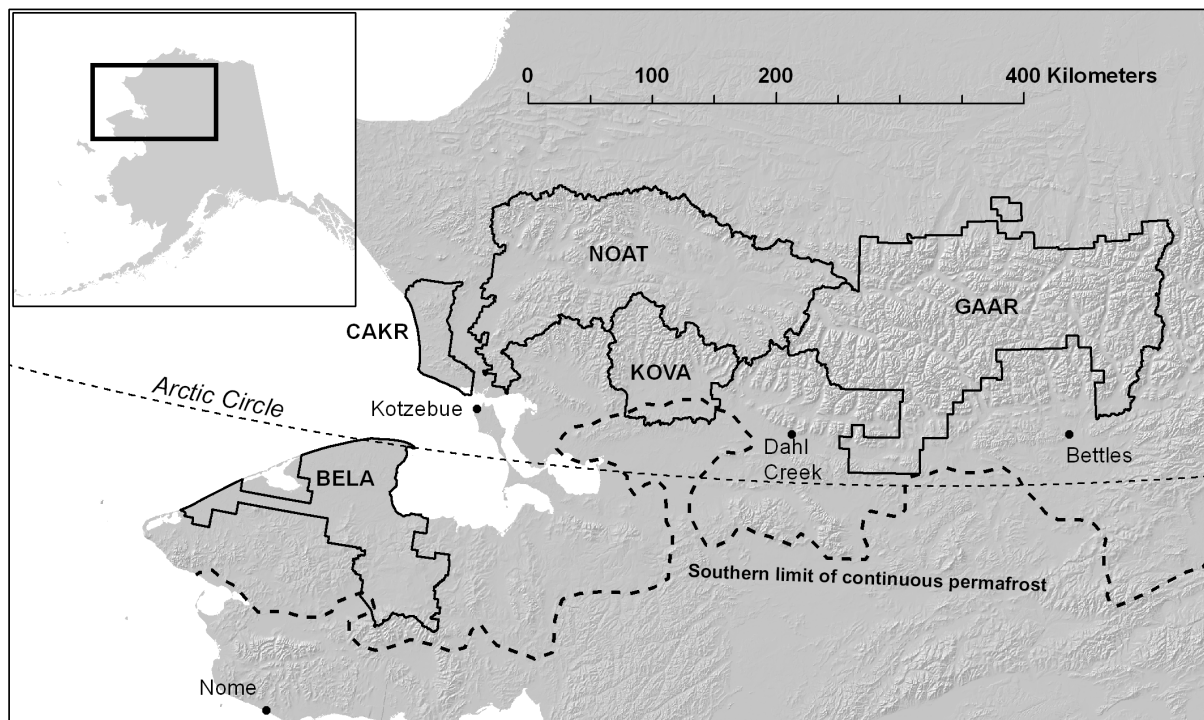


Figure 1. The National Park Service Arctic Inventory and Monitoring Network: Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Kobuk Valley National Park (KOVA), Noatak National Preserve (NOAT), and Gates of the Arctic National park and Preserve (GAAR). Permafrost is considered continuous where it underlies 90% or more of the landscape, and discontinuous where it covers 50-90% of the landscape (boundary from Jorgenson et al. 2008b).

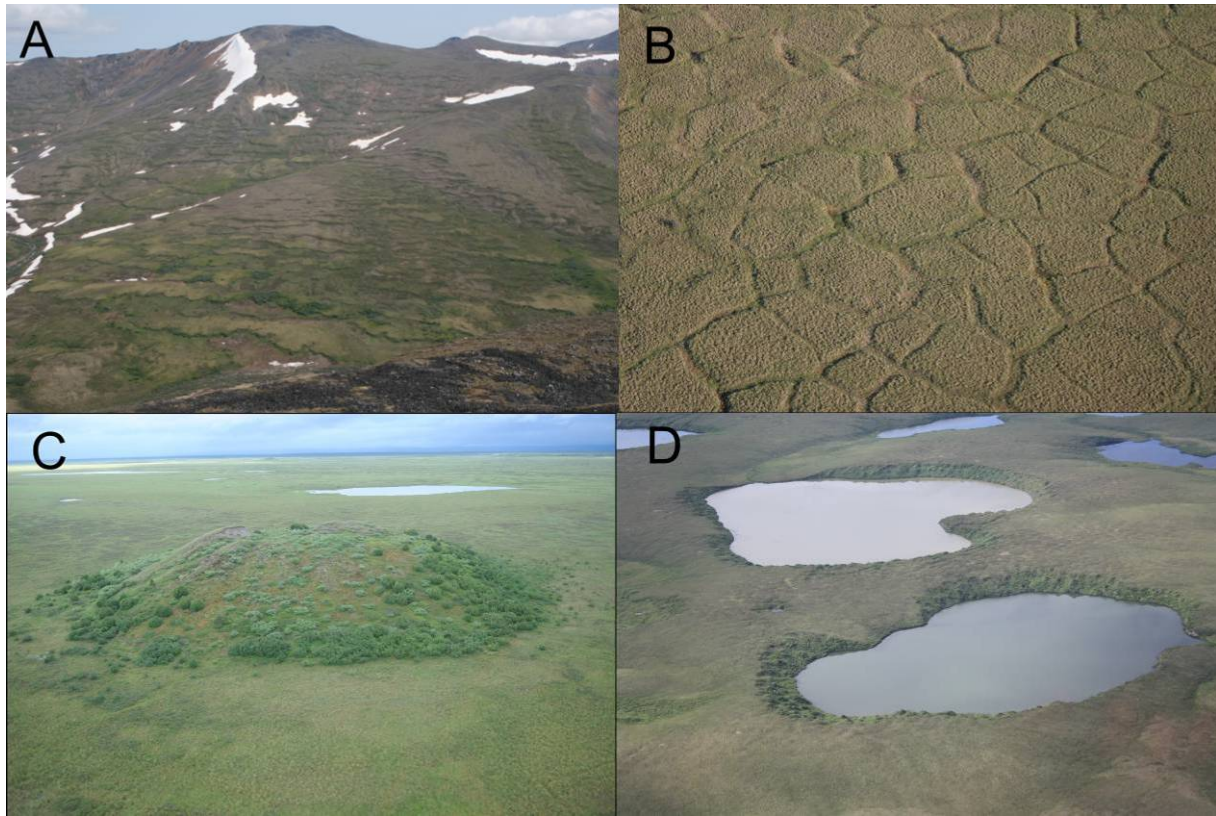


Figure 2. Characteristic permafrost landforms: (A) solifluction lobes (soil flowing downslope, marked here by horizontal lines of vegetation); (B) ice-wedge polygons; the size of the polygons is approximately 10 m; (C) pingo; and (D) thermokarst depression, occupied by lakes.

Permafrost is maintained by a climate with cold mean annual temperatures. It exists in the zone between the active layer (the surface layer that thaws each summer, typically 0.3 to 1.5 m thick) and the point at depth where geothermal heat maintains above-freezing temperatures. This zone ranges from just a few meters to hundreds of meters in thickness (Jorgenson et al. 2008b). Mean annual ground temperatures in permafrost are generally several degrees warmer than mean annual air temperatures (Brown 1973). Thus for permafrost to exist, mean annual air temperatures must generally be a few degrees below freezing. In Alaska, permafrost is present nearly everywhere in the landscape where mean annual air temperatures are lower than -5°C , but as temperatures increase above -5°C permafrost becomes restricted in area; it is essentially absent where mean annual air temperatures are above 0°C (Jorgenson et al. 2008b). Mean annual air temperatures in ARCN at the present range from about -3°C to -12°C , with the coldest values occurring in the northern and higher-elevation areas (Fig. 3).

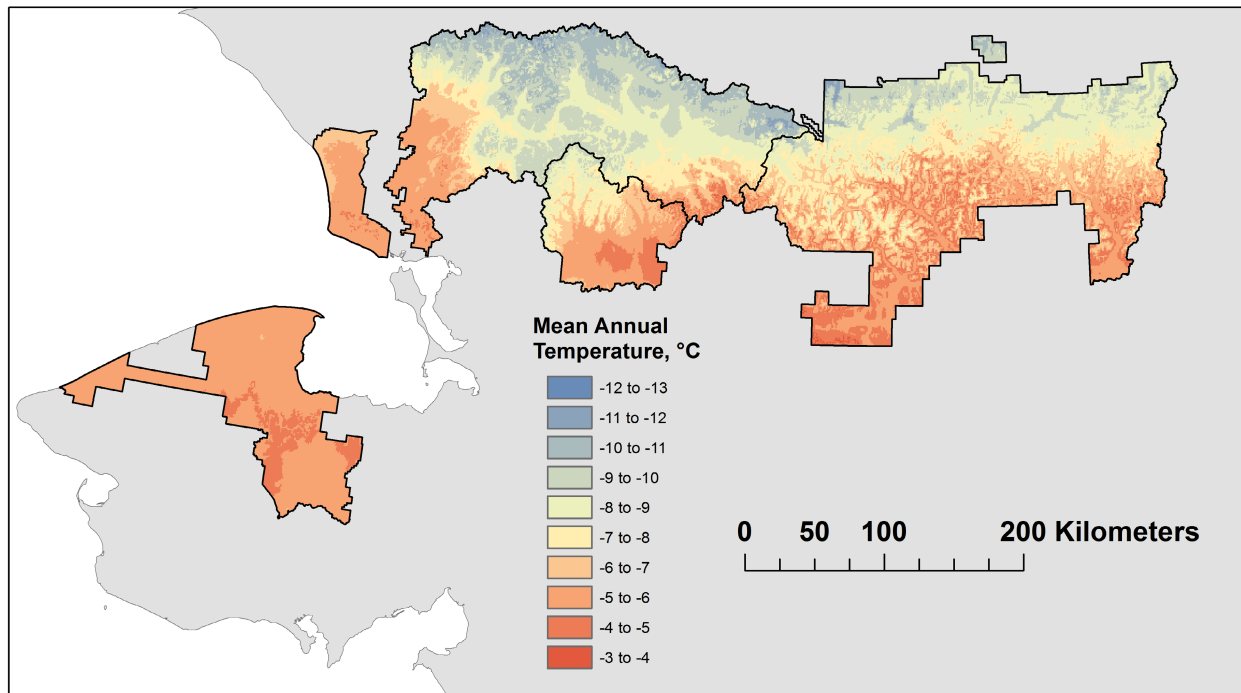


Figure 3. Mean annual air temperatures in ARC (PRISM Climate Group 2009).

Climatic warming will probably lead to permafrost thaw in ARC. Predictions based on the best available global circulation models are that mean annual temperatures in ARC in the 2010-2019 decade will average 2 to 3 °C higher than historical (1971-2000) norms, and the difference will increase to 3-4 °C by mid-century and 5-7 °C by the end of the century (PRISM Climate Group 2009, SNAP 2014). If these predictions prove correct, permafrost will become unstable and begin to thaw over large areas of ARC (Panda et al. 2016). Thaw of ground ice typically proceeds very slowly, such that complete loss of permafrost in ice-rich terrain would take centuries to millennia to be completed (Burn 1998). But the local effects of even incipient permafrost thaw can be dramatic (Jorgenson and Osterkamp 2005, Jorgenson et al. 2001a) and there is evidence that degradation of permafrost in response to climatic warming in Alaska has already begun (Osterkamp and Romanovsky 1999, Jorgenson et al 2006, 2008a.). Land subsidence due to thaw of ground ice is known as thermokarst (Czudek and Demek 1970, Jorgenson et al. 2008a). With 5-6 °C warming, the mean annual air temperatures in the very ice-rich permafrost terrain in the lowlands of BELA and KOVA would rise above 0 °C and destabilize most of the permafrost. Judging from the depth of existing thaw basins in these areas, this could result in subsidence of at least 2 m over large areas. BELA has some thick, very ice-rich, silty deposits with the potential to subside over 20 m if permafrost thaws (Shur et al. 2009). Thawing of permafrost can also result in landslides, notably active-layer detachment failures (Lewkowicz and Harris 2005, Lewkowicz 2007) and retrogressive thaw slumps (Burn and Lewkowicz 1990, Lacelle et al 2010, Swanson 2013a). Many new active-layer detachments were observed in the 2000 decade in ARC (Balser 2015, Swanson 2014).

Thawing of permafrost has important repercussions for ecosystems. Subsidence causes new lake and pond basins to form and existing ones to enlarge, while growth of gullies along thawing ice wedges

can breach a lakeshore and abruptly drain the lake. Slumping and erosion as sediments thaw can shed large amounts of sediments into streams and lakes (Bowden et al 2008, Lamoureux and Lafrenière 2009). Thaw of permafrost may also lead to release of methane and carbon dioxide, which over large areas could compound global warming (Walter et al. 2006). Loss of permafrost has important hydrological implications. Arctic soils are often wet due to perching of water on top of permafrost; loss of permafrost in principle allows better soil drainage and more infiltration (Hinzman et al. 2003), although this effect is confounded by subsidence and consequent ponding. Degradation of ice wedges can reduce ponding of water in polygon centers and enhance runoff (Liljedahl et al. 2012). These various changes in hydrology and soil temperature in turn affect nutrient cycling and vegetation communities (Chapin et al. 1995).

ARCN's long-term permafrost monitoring program has two main areas of emphasis: 1) monitoring of ground temperatures; and 2) monitoring of permafrost-related landforms (Osterkamp and Jorgenson 2009). The objective of the ground temperature monitoring is to track trends in the vulnerability of permafrost to thaw, while the objective of landform monitoring is to follow the outward effects of thaw. Monitoring of ground temperatures (Section 2) will be accomplished using temperature sensors at climate monitoring stations in ARCN, and by summary of ground temperature monitoring stations maintained by others near but outside park boundaries. Monitoring of permafrost-related changes in landforms will be by remote sensing: 1) mapping of thermal erosion features (erosion features related to thaw of permafrost) on high-resolution imagery (Section 3); 2) intensive monitoring of selected high-impact thermal erosional landforms using high-resolution aerial photography for three-dimensional surface modeling (Section 4); and 3) monitoring of ice-wedge degradation and other thermokarst features (Section 5).

ARCN's long-term permafrost monitoring program is described in detail in this narrative report. Standard Operating Procedures (SOPs) for this protocol are detailed in the SOP companion document (Swanson 2017).

Additional monitoring protocols related to permafrost are included in the ARCN Terrestrial Landscape Patterns and Dynamics vital sign (see <http://science.nature.nps.gov/im/units/arcn/index.cfm?rq=12&vsid=28>). The landscape vital sign includes monitoring of lake area dynamics and lake drainage, both of which are closely tied to permafrost dynamics. In addition, rates of coastal erosion, which are linked to permafrost in parts of ARCN, are being monitored as a part of the Coastal Erosion vital sign (<http://science.nature.nps.gov/im/units/arcn/vitalsign.cfm?vsid=7>).

2 Ground Temperature Monitoring

2.1 Introduction

2.1.1 Monitoring of near-surface temperatures at ARCN climate stations

Temperature sensors may be placed at various depths in the active layer and upper permafrost to a maximum depth of about 0.75 m using inexpensive hand tools with minor site impacts. These shallow soil layers undergo significant fluctuations on an hourly basis (near the surface) or seasonally (in deeper layers), but the mean stays roughly constant or declines slightly with depth down to the permafrost table (Burn and Smith 1988). Thus, even measurements at shallow depths in the active layer, if taken consistently throughout the entire year, can be used to estimate the temperature of the underlying permafrost and therefore judge its stability. This kind of temperature monitoring requires daily readings throughout the year. It is most useful if paired with atmospheric climate data, to help understand the relationship between the soil and air climate. In addition, soil and air climate monitoring equipment can share power supplies and data storage devices, and can be serviced by the same maintenance visits. Thus, shallow ground temperature profile measurement is most efficiently combined with atmospheric climate monitoring.

2.1.2 Monitoring of deep borehole temperature profiles

Temperatures may be measured from the surface to depths of 20 m or more in deep boreholes. Under a stable climate, mean annual temperatures should increase linearly with depth from the bottom of the active layer as a result of geothermal heat. Temperatures deviate from this trend under long-term warming or cooling. Deep boreholes in northern Alaska show positive departures from the expected values near the surface, indicating increasing temperatures in recent decades (Osterkamp and Romanovsky 1996, Osterkamp 2007). Deep boreholes require heavy equipment to create and thus are best located along road systems, which are essentially absent in ARCN. Thus, our work with this type of data will consist of summarizing data gathered by other workers from boreholes outside the parks on the road network (Osterkamp 2003). If in the future the road network is extended across NPS-administered lands in ARCN, ARCN could consider adding one or more deep permafrost temperature monitoring boreholes along such a road.

2.1.3 Monitoring active-layer depth

Active-layer monitoring requires annual visits at the time of maximum thaw (around 1 September). The logistical challenges associated with working in ARCN led us to choose not to establish any new active-layer monitoring sites, but instead to summarize active-layer depth data gathered by other workers in the ARCN vicinity. Researchers with the Circumpolar Active-Layer Monitoring program (CALM) make measurements annually with probes on systematic grids at many sites around the world (Fagan and Nelson 2016, <https://www2.gwu.edu/~calm/index.html>). Several CALM monitoring locations are near to ARCN and in fact are co-located with the deep borehole monitoring sites described above.

2.2. Sampling Design

2.2.1 Co-location of new sites with ARCN climate monitoring

Ground temperatures are measured at all active climate monitoring stations within ARCN. As a part of ARCN's Climate Vital Sign, a network of 17 new all-purpose climate stations in ARCN was established in 2012-2013 (Fig. 4, Table 1). Ground temperature upgrades were made to an existing USDA NRCS SNOTEL station in 2012 and to three existing Remote Automated Weather Stations (RAWS) in 2014. Plans are to visit these sites every year and maintain them indefinitely. The new station locations were chosen to be well distributed around the network, represent higher-elevation sites that currently lack data, and have appropriate local conditions for successful site operation. Details of the selection process may be found in Sousanes (2009).

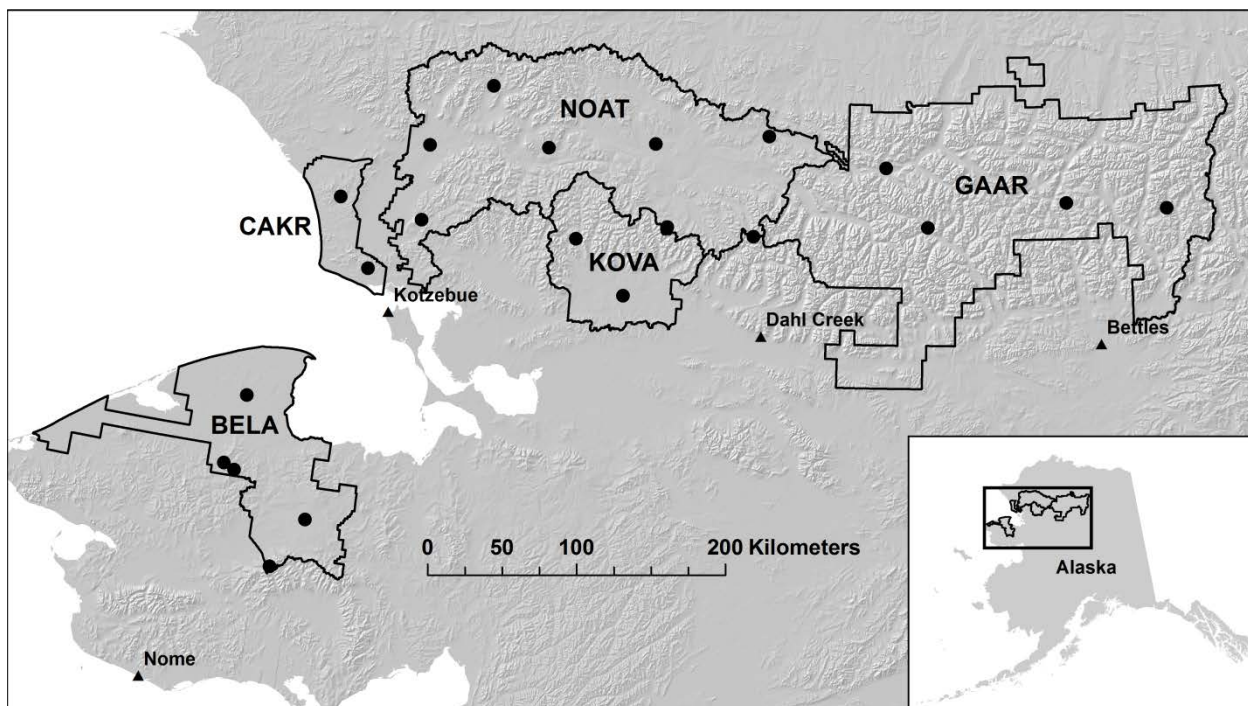


Figure 4. Climate monitoring stations in ARCN. These include 17 NPS climate stations, three RAWS climate stations, and one NRCS SNOTEL station.

Ground temperature sensors are integrated into the system of sensors on the weather station, such that they are operated using the same power source and data are managed with the air climate data. We have installed temperature sensors at standard depths (10, 20, and 50 cm) at all NPS climate stations and upgraded existing RAWS stations with soil temperature sensors.

2.2.2 Existing long-term deep borehole monitoring sites

Deep borehole locations were chosen by accessibility (most are along the north-south Dalton highway) and to be representative of various major environments along a north-south transect across Alaska (Osterkamp 2003, Global Terrestrial Network for Permafrost <http://gtnpdatabase.org/boreholes>, http://permafrost.gi.alaska.edu/sites_list/,

<https://www.aoncadis.org/home.htm>). Several of these deep borehole long-term temperature monitoring sites are highly relevant to ARCN (Table 2).

2.2.3 Existing long-term active-layer monitoring sites

The CALM network (<https://www2.gwu.edu/~calm/>) has several long-term active-layer monitoring locations in the vicinity of ARCN (Table 3).

Table 1. Summary of ground temperature installations at ARCN climate stations

NPS Unit	Climate Site	Latitude, dec. degr.	Longitude, dec. degr.	Altitude, m	Setting	Number of Sensors ¹
BELA	Devil Mountain	66.29590	-164.52058	87	Tussock tundra	3
BELA	Ella Creek	65.27522	-163.82012	707	Barrens	3
BELA	HooDoo Hills RAWS	65.58583	-163.40806	144	Tussock-low shrub tundra	3
BELA	Midnight Mountain	65.82033	-164.54274	691	Dwarf shrub tundra	3
BELA	Serpentine HS	65.85256	-164.70868	158	Low shrub tundra	3
CAKR	Mt. Noak	67.14143	-162.99453	247	Dwarf shrub tundra	4
CAKR	Tahinichok	67.54990	-163.56624	294	Dwarf shrub tundra	4
GAAR	Chimney Lake	67.71420	-150.58500	1128	Dwarf shrub tundra	4
GAAR	Killik Pass	67.98350	-155.01300	1329	Dwarf shrub tundra	3
GAAR	Pamichtuk Lake	67.76630	-152.16420	956	Tussock or dwarf shrub tundra	3
GAAR	Ram Creek	67.62430	-154.34460	1250	Dwarf shrub tundra	3
KOVA	Kavet RAWS	67.13861	-159.04361	22	Spruce-tall shrub	3
KOVA	Salmon River	67.45990	-159.84125	385	Dwarf shrub tundra	3
NOAT	Asik	67.47488	-162.26643	405	Dwarf shrub tundra	3
NOAT	Howard Pass	68.15602	-156.89582	628	Dwarf shrub tundra	3
NOAT	Imelyak	67.54482	-157.07744	1103	Dwarf shrub tundra	3
NOAT	Kaluich	67.57338	-158.43172	735	Dwarf shrub tundra	3
NOAT	Kelly SNOTEL	67.93300	-162.28300	94	White Spruce forest	3
NOAT	Kugururok	68.33331	-161.37588	311	Low shrub tundra	3
NOAT	Noatak RAWS	68.07083	-158.70417	91	Tussock tundra	3
NOAT	Sisiak	67.99458	-160.39606	556	Dwarf shrub tundra	4

¹Sensors are at 10, 20, and 50 cm depth. Sites with 4 sensors have an additional sensor at 75 cm depth

Table 2. Deep Permafrost Monitoring Boreholes in ARCN vicinity¹.

Borehole Number	Borehole Name	Depth, m	Year Established	Latitude, dec. degr.	Longitude, dec. degr.	Elevation, m
U26	Galbraith Lake *	75	1985	68.47741	-149.50242	823
U27	Chandalar Shelf *	63	1985	68.06907	-149.58042	976
U29	Coldfoot	64	1983	67.23727	-150.16144	335
U38	Kotzebue	29	1982	66.85182	-162.60433	20

¹Osterkamp (2003); Global Terrestrial Network for Permafrost <http://gtnpdatabase.org/boreholes>, http://permafrost.gi.alaska.edu/sites_list/

Table 3. Circumpolar Active Layer Monitoring (CALM) network monitoring locations in the ARCN vicinity¹.

Site code	Site Name	Year Established	Latitude, dec. degr.	Longitude, dec. degr.	Landscape	Vegetation
U14	Galbraith Lake *	1996	68.48333	-149.5	Broad glaciated mountain valley	Graminoid-moss tundra and graminoid, prostrate-dwarf-shrub, moss tundra (wet and moist nonacidic)
U15	Chandalar Shelf *	1996	68.06907	-149.58042	Glaciated mountain terrace	Alpine meadow with low shrubs
U11A	Imnavait Creek 1 km grid	1992	68.5	-149.5	Glaciated foothills	Tussock-graminoid, dwarf- shrub tundra and low-shrub tundra (moist acidic)
U26	Ivotuk 1 km grid	2000	66.85182	-162.60433	Glaciated foothills	Tussock-graminoid, dwarf- shrub tundra and low-shrub tundra (moist acidic)
U28	Kougarok	1999	65.45	-164.61667	Glaciated foothills	about 70% tussock tundra w/moss, about 20% shrubs, mostly on south facing slope and creek bottom, usually low and fairly sparse except creek bottom

¹See <https://www2.gwu.edu/~calm/index.html>

2.3 Deployment and Operation of Temperature Monitoring

The equipment to be used at initial deployment are Campbell Scientific soil temperature sensors at ARCN climate stations and Forest Technology Systems sensors at RAWs stations. Soil temperature and moisture probes have also been installed at the USDA-NRCS Kelly SNOTEL snow and climate monitoring site in NOAT (see <http://www.wcc.nrcs.usda.gov/snow/>). The soil temperature sensors that are integrated with the ARCN climate stations were deployed during initial setup of the stations. A soil description of a profile similar to where ground temperatures are being monitored, by standard

U.S. Department of Agriculture methods (Soil Survey Division Staff 1993), will be completed during a maintenance visit in the first few years of operation.

2.4 Data Management, Analysis, and Reporting

Soil temperature data from the NPS and RAWs climate stations are transmitted by telemetry and stored at the Western Regional Climate Center (<http://www.wrcc.dri.edu/index.html>) along with the other climate data (Sousanes 2006 and unpublished updates). Climate data are also retrieved annually from stored memory at the stations, to fill in gaps due to missed telemetry transmissions. Soil temperature data gathered at USDA-NRCS SNOTEL sites are available from the NRCS National Water and Climate Center, <http://www.wcc.nrcs.usda.gov/nwcc/inventory?category=soil>. Data are currently quality checked by the ARCN climate monitoring staff and transferred to the NPS Aquarius database (Hill et al. 2017). This quality check consists of automated checking for values that exceed thresholds (-65° F and +110° F) and a visual inspection of a time-series plot for obvious errors. The Campbell Scientific model 107 temperature probe does not require periodic re-calibration (Campbell Scientific 2016). The “zero curtain” effect provides us with an opportunity to verify the calibration. During the annual cycle between the soils' thawed and frozen states, most of our soil sensors record a period of a few days in the spring and fall when the temperature is nearly constant between -1° and 0° C, corresponding to the time when liquid water and ice coexist in the soil. For sensors that are working properly, the zero curtain should be in this range and similar in temperature to other years.

At five-year intervals the soil temperature data from climate monitoring stations in ARCN, along with temperature and active-layer thickness data from the stations outside of ARCN and maintained by other observers, will be summarized in a report. Temperature data analysis will include computation of descriptive statistics on an annual basis (mean, maximum, minimum temperatures, freezing and thawing degree-days) for each sensor. Multi-year trends in means for a site can be tested using linear regression or Mann-Kendall trend test (Helsel and Hirsch 2002, Marchetto 2015).

Of particular interest at the reporting phase will be extrapolation of any trends observed at the climate stations to the larger area of ARCN. This extrapolation will be accomplished initially by assigning trends observed at the monitoring stations to zones in ARCN with similar climate, as judged from the PRISM modeling (PRISM Climate Group 2009).

2.5 Operational Requirements

2.5.1 Personnel

Deployment of the integrated soil temperature sensors at the climate stations was accomplished by the NPS Physical Scientists installing the climate instruments. Annual maintenance of the soil sensors is by NPS personnel. The soil description will require an additional person trained in that task and about 1 hour's time. The 5-year reporting should be completed by a worker trained in permafrost science who is able to interpret probable causes and implications of any trends observed.

2.5.2 Equipment

Initial installation required simple hand digging and boring equipment, sensors, data loggers, and batteries. After initial installation, equipment costs beyond what is required for the climate station as a whole will be minimal and consist of replacements for any failed sensors (about \$100 each).

Because the soil temperature monitoring relies on data loggers and batteries shared with other sensors, some of the cost of these items may be shared with the Climate and Weather vital sign (Hill and Sousanes 2015).

2.5.3 Annual workload and field schedule

Sites are accessed from the staging areas of Bettles, Dahl Creek, Kotzebue, and Nome (Fig. 4). Typically two days are required to travel to and from the staging area. Initial installation required approximately 1 day per site. Annual maintenance visits can be accomplished at the rate of several per day by the personnel performing the climate station maintenance (Hill and Sousanes 2015).

3 Mapping of thermal erosion features

3.1 Introduction

Thaw of permafrost can lead to subsidence, mass movement of material on slopes, and exposure of bare soil to erosion by water. Erosion that occurs by a combination of thawing permafrost and mechanical transport of material is called "thermal erosion" (van Everdingen, 1998). Two types of thermal erosion landforms are of particular interest because they can expose extensive areas of bare soil: active-layer detachment failures (or "active-layer detachments", ALD, Lewkowicz and Harris 2005, Lewkowicz 2007) and retrogressive thaw slumps (RTS, Burn and Lewkowicz 1990, Lantuit and Pollard 2008, Balser 2015).

Active-layer detachments occur on vegetated slopes with an ice-rich layer roughly 0.5 to 1 m below the surface, near the boundary between the permafrost and the active layer. During unusually warm weather the ice-rich layer thaws, producing a mud slurry that lubricates the flow of an elongate strip of surface soil and vegetation downslope (Fig. 5). The root mat typically holds the surface layer more-or-less intact, such that the surface layer slides as a unit and accumulates as a winkled mass on the footslope. The slide leaves an elongated region of bare soil exposed on a slope, which can lead to erosion of soil into streams (Bowden et al. 2008, Lamoureux and Lafrenière 2009).

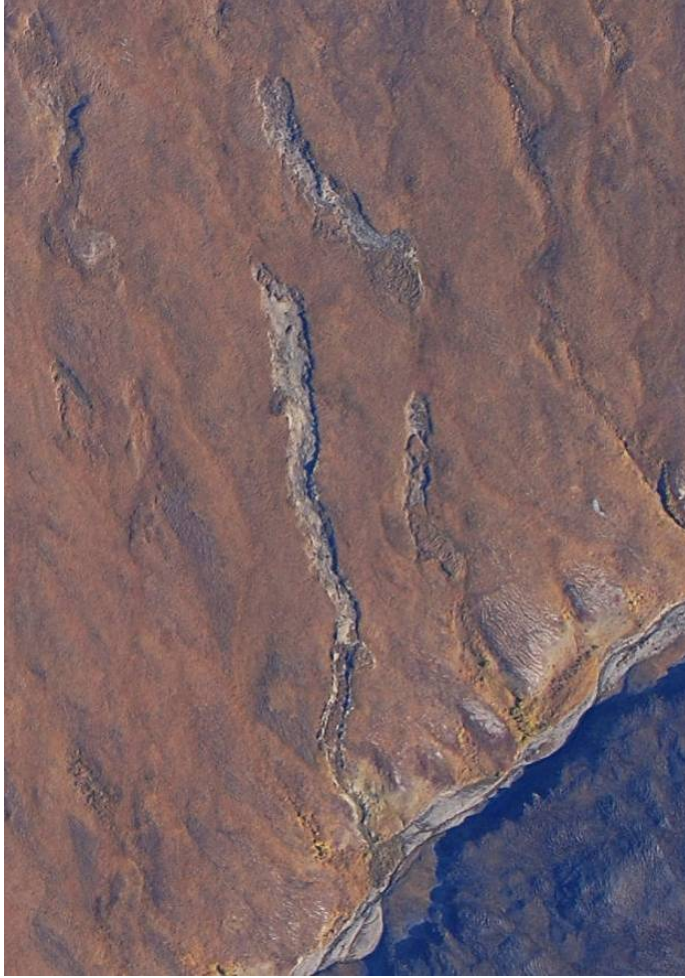


Figure 5. Active-layer detachment failures (ALD) in the Noatak National Preserve (lat 68.251°, lon - 157.904°). The grayish strips on this photograph are bare soil exposed by downhill sliding of the vegetation and an approximately 1-m thick layer of thawed soil over permafrost. The largest ALD pictured is about 300 m long and 25 m wide.

Retrogressive thaw slumps occur where a cut-bank in ice-rich permafrost advances into undisturbed ground. Material in the steep bank thaws, falls or slumps onto the adjacent slump floor, and then is partially transported away by water erosion or sliding. RTSs often begin as escarpments produced by shoreline or fluvial erosion and then advance away from the shore by thaw and slumping, sometimes shedding large amounts of sediment into the adjacent water body (Fig. 6). Very ice-rich material of substantial thickness (e.g., a meter or more), continuity, and lateral extent is needed to produce an RTS. In ARCN most true RTS are in the Noatak Valley (NOAT and GAAR) and the northern foothills of the Brooks Range (GAAR) on late-Pleistocene glacial moraines (Swanson 2014).



Figure 6. A retrogressive thaw slump in the Noatak National Preserve. The escarpment at the upper end of this slump is advancing into undisturbed tundra as the ground thaws, material falls onto the slump floor, and slides downhill.

The purpose of this project is to monitor the area of bare soil exposed across ARCN as a result of ALD and RTS. These bare soil areas are both important because they represent the most extreme disturbance cause by thaw of permafrost, and they are relatively easy to map because their unique properties contrast strongly with adjacent vegetated areas. These unique properties allow us to use a semi-automated mapping method that is feasible over large areas. This method was used in the ARCN-wide ALD and RTS mapping effort of Swanson (2010, 2012a, 2014)

3.2 Sampling Design

3.2.1 Imagery properties

Because the features of interest may be as narrow as 5-10 m, high-resolution imagery with 1 m pixel size or smaller is needed. Both the visible color and near infrared bands (NIR) are needed for best differentiation of vegetated and bare-soil areas. We mapped ALD and RTS across the entire network (Swanson 2014) using IKONOS imagery (Geoeye 2010) from 2006-2009. IKONOS imagery

includes blue, green, red, and near infrared bands at 4 m resolution, pan-sharpened to 1 m resolution. The imagery was orthorectified using the best available digital elevation model (DEM), the 60 m resolution U.S. Geological Survey (USGS) National Elevation Dataset (NED) DEM (<http://ned.usgs.gov/>).

The frequency and spatial scheme of resampling will be influenced by image cost and availability. At the present time, high resolution satellite imagery is available at no charge to government agencies through the US Geological Survey's CRSSP (Commercial Remote Sensing Space Policy) program (<http://crssp.usgs.gov/>). NPS may enter requests for imagery coverage through the CRSSP Imagery-Derived Requirements (CIDR) Entry Tool (<http://CIDR.cr.usgs.gov/>). This system is designed to deliver imagery for compact, individual areas of interest (and not, for example, many systematically dispersed scenes or all of ARCN). Thus we will limit our re-surveys to priority areas as described below.

3.2.2 Timing and spatial distribution of samples

Retrogressive Thaw Slumps. For RTS, surveys repeated at an interval of about 10 years are adequate to capture trends, because individual RTS can grow for a decade or more and require a similar amount of time to revegetate (Bartleman et al. 2001). RTS usually occur in the same general area year after year, so repeat surveys can be restricted to known susceptible areas based on the initial comprehensive survey by Swanson (2014). The smallest rectangular area that captures at least half of the RTS area (57%) in ARCN, based on the initial survey, runs from latitude 67.5° to 68.2°N and longitude 155° to 158°W (Fig. 7). This rectangle covers about 12% of ARCN and will require considerably less imagery and time to complete than the original survey in 2014. The latter was based on complete coverage of ARCN with high-resolution imagery, which we have no guarantee of repeating, and was too time-consuming to repeat regularly (requiring about 200 hours of analyst time for the mapping work alone). If either image acquisition or processing becomes significantly easier and faster in the future, the study area could be expanded beyond the rectangle in Fig. 7. Some large RTS occur outside of this area and are being monitored intensively as a part of the project described in section 4 below.

Active-layer Detachments. The same method is used to map ALD and RTS, and thus a periodic re-survey of ALD will be made in the RTS study area proposed above. However, ALD occur in large numbers as distinct events (Carter and Galloway 1981, Lewkowicz and Harris 2005); many revegetate in just a few years and become difficult to map using exposed bare soil (Swanson 2014). Thus our periodic RTS surveys are likely to miss an ALD event, and some areas of high ALD susceptibility are not included in our RTS monitoring area. Thus we recommend re-mapping of ALD in selected areas as soon as possible after any future ALD event, as indicated by informal observations of ALD. Annual flights for climate monitoring station maintenance (Fig. 4) bring observers from ARCN over much ALD-susceptible terrain where such observations can be made. No hard-and-fast rule to guide the decision to conduct an ALD survey is proposed here, because it will depend on currently unforeseeable conditions that include: the perceived severity of the event, cost of the imagery, funding, image availability, and personnel availability. Two proposed ALD re-mapping areas are suggested in Fig. 8, based on the susceptibility of terrain to ALD from Swanson (2014). A

leaf-on image from the summer immediately following the ALD event would be optimal, but our previous experience shows that imagery from the second summer after an event is still quite good, and images up to 5 years after the event can be used if needed.

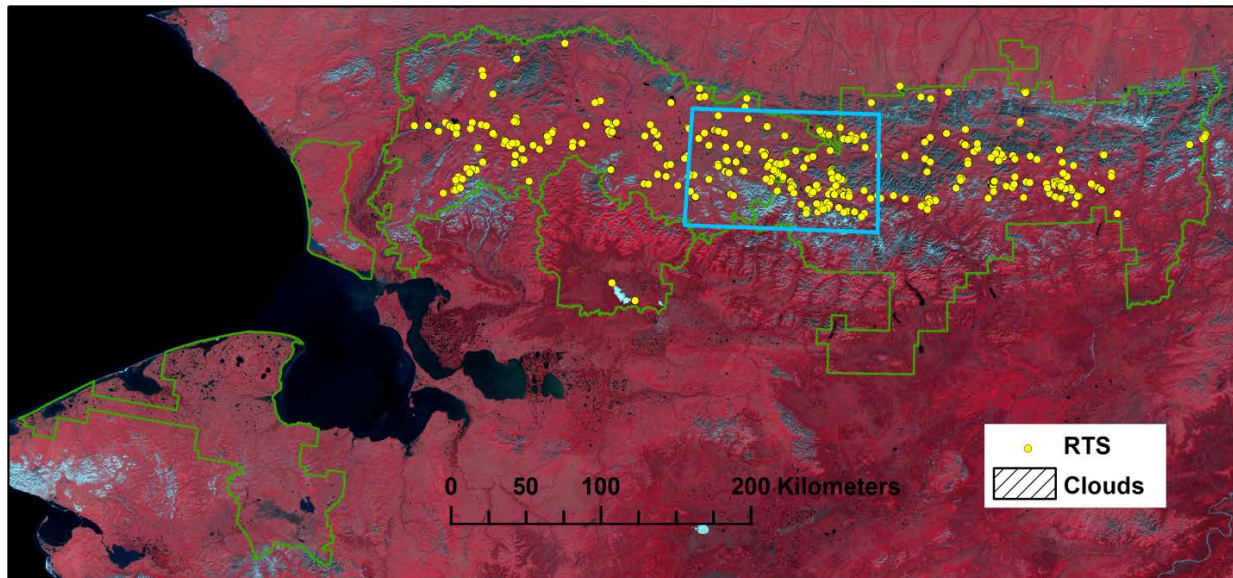


Figure 7. Retrogressive thaw slumps mapped in ARCN and the proposed RTS monitoring area. This rectangle (latitude 67.5° to 68.2°N and longitude 155° to 158°W) covers about 12% of ARCN and contained 57% of the area of RTS mapped in Swanson (2014).

3.3 Data Processing

Hundreds of ALDs and RTSs have been identified in ARCN, thus automation of the mapping process is desired. Spectrally ALDs and RTSs differ little from other bare soil areas such as river sandbars or scree slopes, so complete automation of mapping by spectral characteristics is not possible at the present. Water bodies also usually have a low NDVI. We determined that ALDs and RTSs can be visually identified and marked by mouse-click on high-resolution satellite imagery quite rapidly for large areas, but manually digitizing of their boundaries is quite slow due to their complex outlines. Thus we developed a partially automated mapping process whereby features are manually identified but boundaries are drawn by machine (Fig. 9).

Our automated process for drawing boundaries of bare-soil areas is based on normalized difference vegetation index (NDVI). NDVI is defined as $(NIR - red)/(NIR + red)$, where NIR and red are the reflectance values for the near infrared and red spectral bands, respectively. NDVI is positive for vegetated areas and negative for bare soil and other unvegetated areas (Tucker and Sellers 1986). Normalized difference vegetation index (NDVI) is computed using the high-resolution imagery. The NDVI image is smoothed by a median filter, which reduces speckling while maintaining sharp boundaries. A threshold value is chosen for NDVI that separates bare from vegetated areas, and polygons are created to encompass areas with NDVI lower than the threshold.

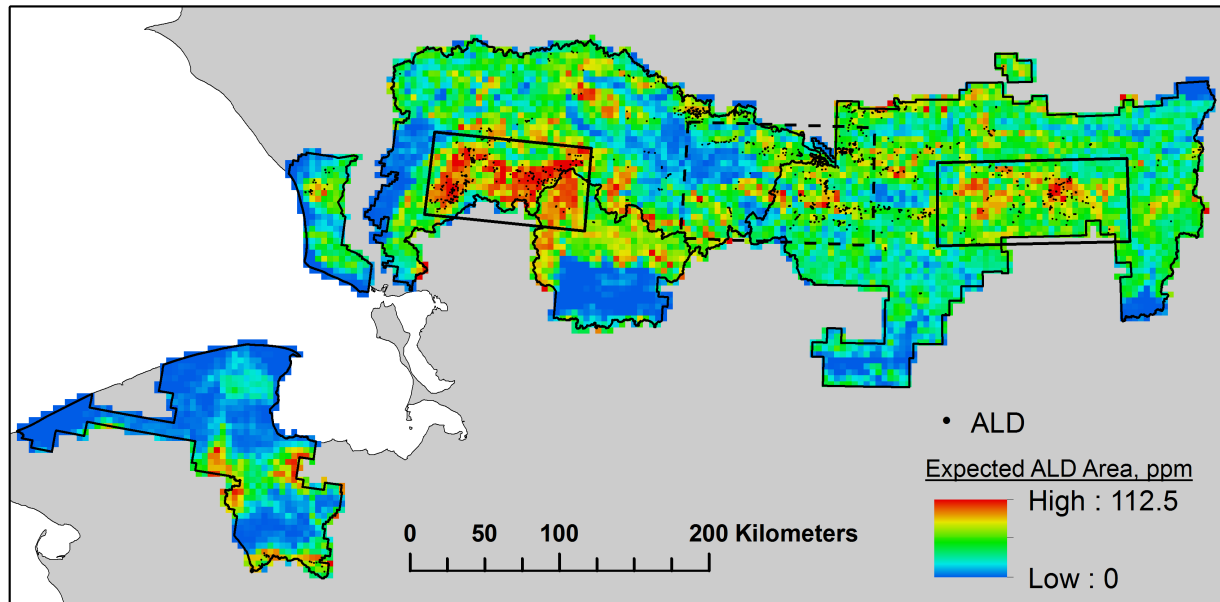


Figure 8. Suggested remapping areas for ALD, and ALD susceptibility in ARCN. The expected density of ALD (in proportion of area times 10^6 , i.e. ppm area) was based on the observed relationship between ALD and slope steepness, with areas of unsuitable vegetation types masked (Swanson, 2014). Dots mark observed ALD locations. The center (dashed) rectangle is the RTS monitoring area (Fig. 7). The two solid rectangles mark the suggested ALD monitoring areas. They have coordinates 67.5° to 68°N, 159.5° to 162°W (left, 6000 km²) and 67.5° to 68°N, 151° to 154°W (right, 7000 km²).

ALDs and RTSs are identified by systematically searching the high-resolution imagery with a grid overlay at 1:20,000, zooming to 1:5,000 to 1:10,000 in all places where erosion features are observed or suspected. All bare soil areas identified as ALDs or RTSs are digitized as points. Rugged mountains dominated by bedrock and rubble may be searched rapidly, as the likelihood of occurrence of ALDs and RTSs there is low. Flat lowlands may also be search rapidly, as ALDs and RTSs occur there only occasionally, on river- or lakeshore bluffs.

Finally, the points representing active ALDs and RTSs as identified by the visual inspection of the imagery are overlaid on the set of all unvegetated polygons mapped by the NDVI process to extract only the polygons representing ALDs and RTSs.

3.4 Analysis and reporting

From the polygon map of ALDs and RTSs we can tabulate the number of thermal erosion features present in study area, and the total area that they cover, for the image date. The number and area of these features may be analyzed in relation to recent weather history and environmental factors such as landforms and vegetation. We expect the data from the new ARCN climate stations to be particularly helpful in future data interpretation.

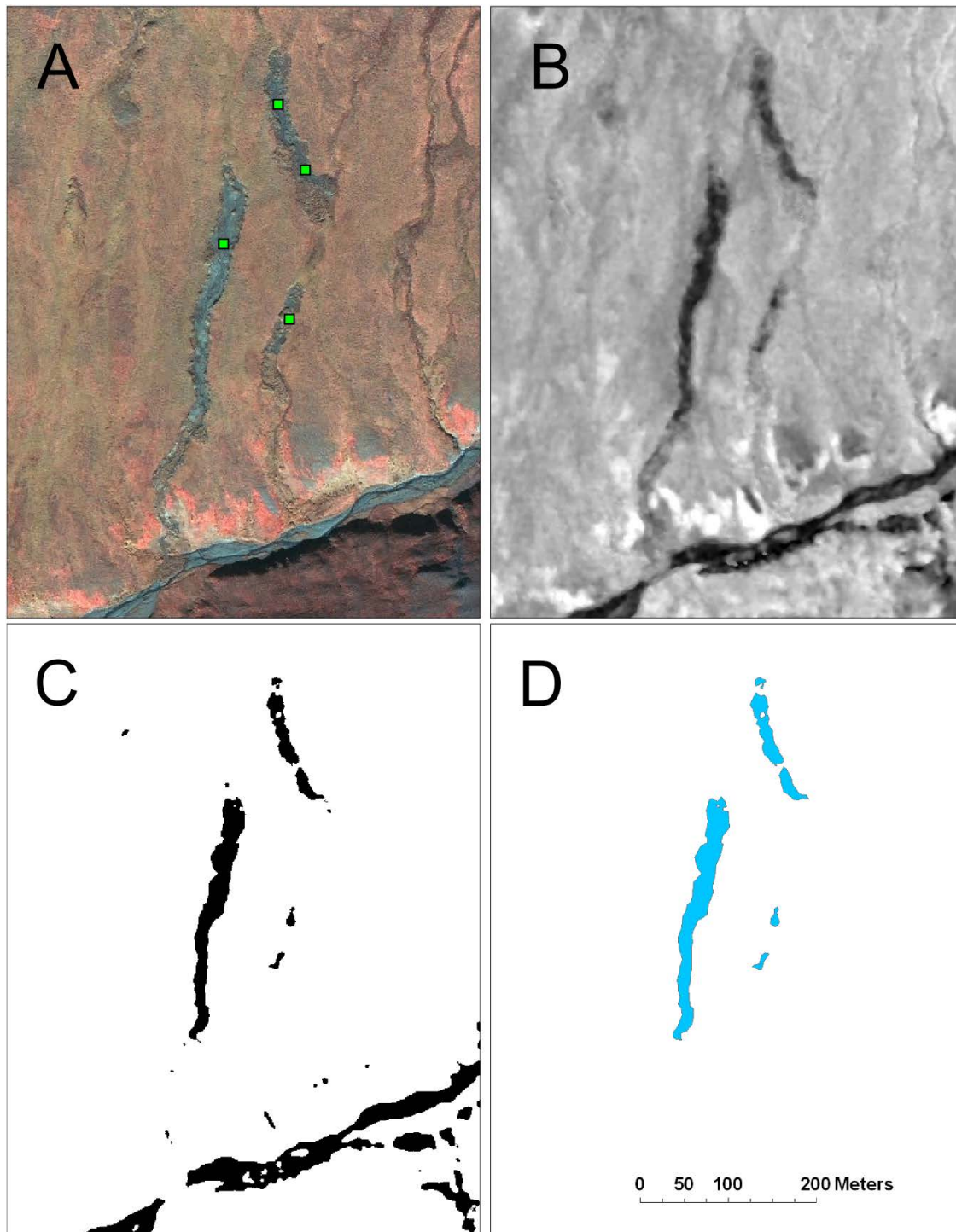


Figure 9. Mapping of thermal erosion features (erosion features related to permafrost thaw). A) IKONOS image with color-infrared color scheme and 3 ALDs marked manually with points. B) NDVI of the IKONOS image. C) NDVI image thresholded to differentiate bare soil (black) from vegetated areas (white). D) Polygons produced by conversion of the thresholded image to a polygon layer and intersection with points in (A). (163.880°W, 67.540°N).

3.5 Operational Requirements

3.5.1 Personnel

Mapping of ALDs and RTSs requires a person trained to recognize these features on imagery and with good GIS skills to perform the image processing, notably the ability to perform ArcMap geoprocessing using the Python scripts provided in the SOPs (Swanson 2017).

In the Swanson (2014) survey all of ARCN was covered by approximately 500 high-resolution image tiles (about 12 by 15 to 20 km each). These can be visually scanned for ALDs and RTSs at an average rate of about 2 to 3 tiles per hour, including some additional time for file management, or about 500 km²/hour. Thus it would take about 20 hours to complete the RTS monitoring area (Fig. 7) and about 30 more hours to complete the two ALD monitoring areas (Fig. 8). To prevent fatigue and maintain quality, this manual work should be restricted to half days. Image processing (computing NDVI) also takes substantial time but can be performed in the background or at night. Additional time for reporting will take an additional two or three weeks of half-time work every 10 years for the RTS study area, and a similar amount of time at undetermined intervals for the ALD re-surveys.

3.5.2 Equipment and supplies

The image analysis may be performed using computer equipment and Geographic Information System (GIS) software that is standard for NPS natural resource employees. Suitable imagery is the crucial supply required. This must be cloud-free, high-resolution (1 m pan-sharpened or finer), multispectral (including near infrared, red, and green bands), georeferenced, and terrain-corrected.

4 Three-dimensional photographic modeling of selected thermal erosion features

4.1 Introduction

The most dramatic thermal erosion features (erosion features resulting from permafrost thaw) in ARCN are retrogressive thaw slumps (RTSs). RTS can expose several hectares or more of bare soil and shed thousands of tons of material into water bodies (e.g., Barnhart and Crosby 2013). Numerous RTSs have been identified in ARCN (Balser 2015, Swanson 2014). We have selected especially large or high-impact RTS for intensive monitoring by detailed three-dimensional (3D) modeling and analysis of changes over time.

The 3D form of RTS is monitored by stereo photogrammetry: the analysis of geometric relationships between features on photographs taken from different perspectives. Multiple overlapping, low-altitude, aerial photographs of each feature are acquired on a single date and used to construct a detailed 3-D surface model, controlled by ground survey or accurate aerial camera coordinates. Photography is repeated in successive years and new 3D models constructed. Changes over time in the volume of material lost and area of disturbed, unvegetated surface may then be computed by comparing the 3D models from different dates.

Prior to 2014, 3D monitoring was accomplished using oblique aerial photographs shot from the window of an airplane or helicopter, and scaled by ground survey (Swanson and Hill 2010, Swanson 2012b, 2013a). Recent advances in GPS and photogrammetry have made it possible to create similar models using low-altitude vertical photographs coupled with airborne GPS, without ground survey (Nolan et al. 2015). We recently converted to the latter system because it has similar accuracy and saves the cost required to complete the ground surveys. Oblique photos taken through an aircraft window may still be used in the future by registering them to 3D models produced with airborne GPS. The SOPs provided in the companion document (Swanson 2017) document both the methods based on oblique photos and ground survey in 2010-2014, and the current system based on aerial GPS and vertical photography.

4.2 Selection of monitoring objects

Subjects of intensive 3D monitoring are chosen from the larger set of features mapped as described above in section 3 or reported to us by park staff and visitors. Of the hundreds of erosion features identified by the mapping process, we expect over the long term to maintain intensive monitoring of about ten features. Selection is based on size and potential effects on other resources, especially water quality and associated aquatic life, cultural sites, and visual impacts along frequently traveled routes. For example, an erosion feature shedding large amounts of sediment into the Noatak River might be chosen over a larger feature in a remote location not adjacent to a water body. Most features that will be monitored are RTSs, because these have the potential to grow to large size (e.g., over 1 ha) and depth (several meters or more) and thus produce large amounts of sediment; also, they are frequently found adjacent to water bodies. River or lakeshore bluffs that are actively eroding by gullies may also be included, in addition to true RTS. River or lakeshore cutbanks that are eroding by typical fluvial erosion or wave action will generally not be monitored, nor will erosion features along

the marine shoreline, as these are covered under a separate vital sign. Generally, active-layer detachments will not be intensively monitored either, unless they develop into a RTS or have exceptionally large impacts due to subsequent erosion.

4.3 Sampling

4.3.1 Photography

Photographs are shot with a high-quality digital single-lens reflex camera at a flight altitude low enough to obtain a photo resolution of 10 cm or better. Vertical aerial photographs are shot through a port in the floor of an airplane. A typical setup that we have used recently involves using a 24-mm lens and a camera with a full 35 mm sensor (Nikon D800) flying at about 260 m above ground level. This yields photographs with a footprint of about 400 m by 260 m and resolution of about 5 cm. About 70% photo overlap (between adjacent frames) and 55% sidelap is desired for model construction; this ensures that each point on the ground is covered by at least 6 photos. An electronic link between the camera's remote flash triggering device and an accurate GPS unit provides accurate (sub-meter) locational control of each photograph. The term "fodar" has been coined for this technique (see <http://fairbanksfodar.com/> and Nolan et al. 2015)

Oblique aerial photographs are typically shot at an angle of about 45° from the window or door of a helicopter or fixed-wing aircraft flying at an elevation of about 150 m (Fig. 10). Several passes may be made to be sure to cover the entire feature with overlapping photographs, including steep banks that are visible only from certain perspectives.

The frequency of repeat photography is flexible. As a general guideline, active features in relatively accessible locations should be visited every other summer. Features that become inactive may be dropped from monitoring and their revegetation can be followed using the high-resolution satellite imagery obtained every 10 years as a part of ARCN-wide mapping described in section 3 above.

4.3.2 Ground control

In the years 2010-2012, ground survey with a total station was used to locate 4 or more points marked on the ground with aerial targets. The aerial targets were left in place briefly during photography (and then removed) to obtain a true scale and position for the 3D model (Swanson and Hill 2010). The ground control survey required only about an hour, but helicopter transport was required to reach the site. Re-photographing the slumps in subsequent years could be done more cheaply by fixed-wing aircraft, without landing, and ground control was obtained by manual location of distinctive features on the images from both the surveyed and un-surveyed years. However, manual control point identification was slow and registration became steadily less reliable in subsequent years.

Starting in 2013, we are using new technology that calibrates the 3D models with accurate aerial GPS locations to produce models with "real world" (i.e. Universal Transverse Mercator, UTM) coordinates; this allows accurate automated registration of models from different dates (Nolan et al 2015). Models created from oblique aerial photos can be registered to the UTM-based models, so we may extend our time series back to 2010 and perhaps utilize *ad hoc* oblique photos shot in the future. While registration of these older photos still requires some manual work, software and workflow

improvements have made the manual steps feasible for the limited cases where this is required. Manual registration involves identifying common landmarks in the unregistered and UTM-registered models.



Figure 10. Oblique stereo-photographs of a RTS. Two successive photos from a line of photographs taken from a helicopter while flying past a slump. The three-dimensional shape of the slump is constructed from the shift in features between the two views. A ground control point marked with a black-and-white “X” is visible near the lower left side of the slump in the left photograph.

4.4 Data analysis: model construction and analysis

The 3D models are constructed using photogrammetric software that determines the elevation of numerous points from their shift in position between photographs taken from different perspectives. The camera must be calibrated (its geometric properties and lens distortion determined) and common points (pass points) between each pair of photographs in a series must be identified. Modern software is able to automate these processes. Given the properties of the camera, the pass points, and real coordinates of either aerial targets, known landmarks, or the camera itself (from airborne GPS), the software can determine the position and orientation of the camera for each photograph.

The software then performs an automated search for numerous points common to the photographs and calculates their location and elevation. From these points and the camera locations the software

constructs a 3D surface as a triangular interpolated network (TIN) or a digital elevation model (DEM). The photographs can be overlaid on the 3D surface to produce striking 3D graphics that can be rotated, panned, and enlarged (Fig. 11). The analyst can also use the TIN or DEM to construct topographic cross-sections and compute the changes in slump volume between models for different dates. Because of the irregular time intervals between samples and the fact that growth occurs only during the summer thaw season, it is important to compare the amount of change to the sum of thaw degree-days that have accumulated between model dates (Swanson 2013a)

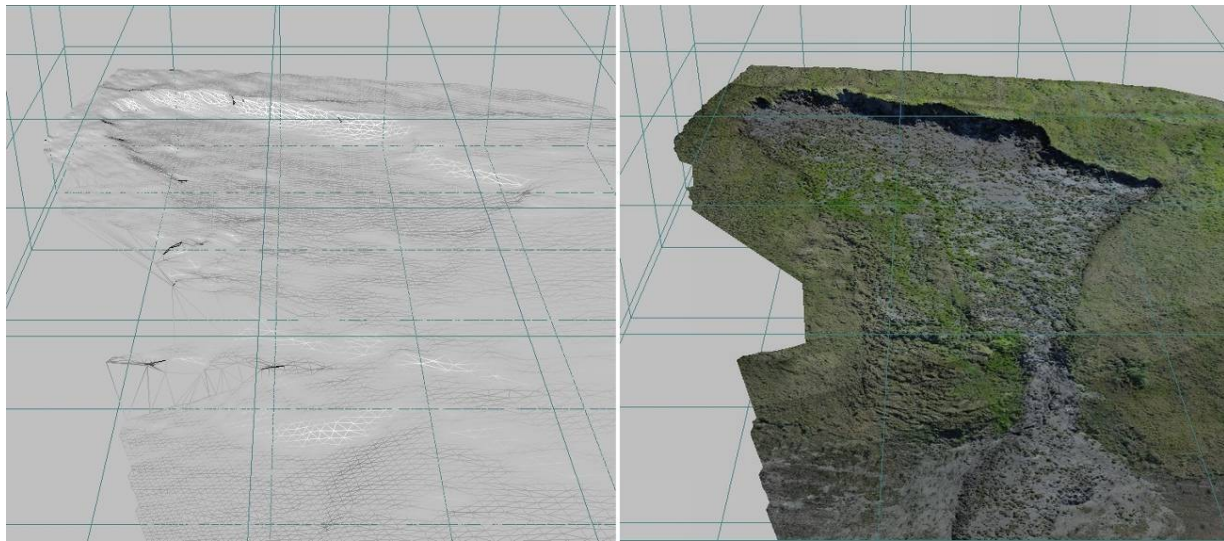


Figure 11. 3D model of a retrogressive thaw slump. A triangular interpolated network (TIN; left) is constructed from processing of stereo-photographs (Fig. 10). The photographs can be projected over the TIN to produce a realistic 3D model (right).

Elevations of models from different dates sometimes differ consistently by more than a few decimeters in places where change should not have occurred (i.e. in stable areas surrounding the slump). Fortunately, these errors are usually quite systematic over large areas. A correction raster can be constructed from the difference raster by simply removing areas where the elevation is known to have changed (i.e. the active part of the slump) and interpolating the correction across these gaps from the presumably stable surrounding areas.

4.5 Operational requirements

4.5.1 *Oblique aerial photography*

Ground survey with oblique photography was used in 2010-2012, but has since been replaced by vertical photos with airborne GPS locations as described above. However, new oblique photography could be utilized in the future through registration onto 3D models with GPS georeferencing. Oblique photography can be shot opportunistically by anyone flying in the area with a SLR camera and a fixed-focal length lens. Preferably the photographer will be able to open windows for improved photo quality. The flight time required is the transit time from the base to the site plus 3 or 4 passes at each location to shoot the photos. Monitoring sites are clustered in areas susceptible to slumping, and thus several can be completed together with short transit time. In good weather, up to 10 sites can be

covered in a day. Assuming use of NPS aircraft and 5-6 hours of flight time per day, cost in 2015 was approximately \$1500/day.

4.5.2 Vertical photography and airborne GPS

This system requires an airplane with camera port and mount, a GPS capable of sub-meter accuracy, and an electronic link to a high-quality digital SLR camera. The pilot must be trained and briefed in the use of GPS to determine the exact orientation of the flight lines. An on-board technician must be trained in the use of the camera and GPS. At the present time NPS does not have this expertise internally, and we will purchase the photos and processed products (digital elevation models and orthophotographs) commercially. Total cost is difficult to estimate because most of the cost is in ferry time between the base (most likely Fairbanks) and the photo locations, and standby for suitable weather, but \$20,000 every 2 to 4 years is a reasonable estimate. This cost may be lower if in the future NPS develops the ability to shoot and geolocate these photos.

4.5.3 Data processing and reporting

Data processing requires the PI or a technician skilled in the use of photogrammetric software. In the past this was Topcon Image Master software (www.topconpositioning.com), and currently is Agisoft Photoscan (www.agisoft.ru). Analysis of new photography with Image master required approximately one to two days per site, while with Photoscan or commercially acquired models it is less than one day. We have had success producing small models (50 or fewer photos) with Photoscan on a 2.66 GHz dual-core processor and 4 GB of RAM, but the manufacturer recommends at least a 3 GHz quad-core processor and 16 GB of RAM. Reporting of changes at each site photographed in a year should be compiled in an annual report that will take roughly a week to produce after modeling is complete. Given the dramatic nature of the graphics produced by this project, additional time should be allowed for reporting and development of interpretive products.

5 Monitoring Ice-Wedge Degradation

5.1 Introduction

Ice-wedge polygons are a striking and widespread feature of the Arctic landscape (Fig. 12). They form when frozen ground cracks due to contraction in the winter, the cracks fill with ice in the spring, and the resulting wedge of ice is preserved in permafrost (Lachenbruch 1962). After many years of cracking in approximately the same place, ice wedges can become a meter or more wide at the top. These ice wedges are vulnerable to thaw because they consist of nearly pure ice bodies near the surface and have little insulating overlying material. Warming climate or surface disturbance can cause them to thaw and produce surface subsidence. Jorgenson et al. (2006, 2015) reported significant degradation of ice wedges on the North Slope of Alaska since 1982.

A previous systematic study of historical aerial photographs and modern satellite imagery in ARCN suggested possible ice-wedge degradation, though the small number of lowland sites with polygons in that study caused the sample size to be too small for any conclusions about the trend (Swanson 2013b). The present protocol increases the sample size by targeting lowland portions of ARCN that have abundant ice-wedge polygons; it details the procedures used in Swanson (2016).

Actively growing ice-wedge polygons typically have a low ridge on either side of the wedge that is higher than the polygon center, hence the name “low-center ice wedge polygon” (van Everdingen 1998). In poorly drained permafrost lowlands, low-center polygons often have wet soils or standing water in the polygon centers, ringed by drier margins. These wet areas are readily visible as darker tones on aerial photographs and high-resolution satellite images (Fig. 12). A narrow shallow trough is often also present directly over the wedge. When an ice wedge melts, subsidence occurs over and adjacent to the wedge, i.e. around the polygon margins. Subsidence along the wedges can result in the formation of a “high-center ice-wedge polygon” (van Everdingen 1998; Fig. 13). Then the trough over the wedge can widen and deepen to the point of forming small ponds (Fig. 14). Flat or high-center polygons can also develop on dry sites with deep active layers and little ice accumulation in the permafrost (Romanovskiy 1977).

The presence or absence of ponds formed by ice-wedge degradation can be determined by examination of aerial photographs and satellite images. Our ice-wedge polygon monitoring protocol utilizes a random sample to assess the formation of small ponds by degradation of ice wedges in selected study areas across ARCN.

Mapping of small water bodies as an indicator of thermokarst has advantages and disadvantages. Water has unique spectral properties that make it relatively easy to map. Disadvantages of water as an indicator of thermokarst include: 1) shallow water and water with emergent vegetation has transitional properties. 1) water levels vary with season and weather; 2) pits and troughs are dynamic, and water can drain from a pit if an adjacent deeper one forms; and 3) vegetation can colonize and fill in troughs even though the ice wedges are still degraded.

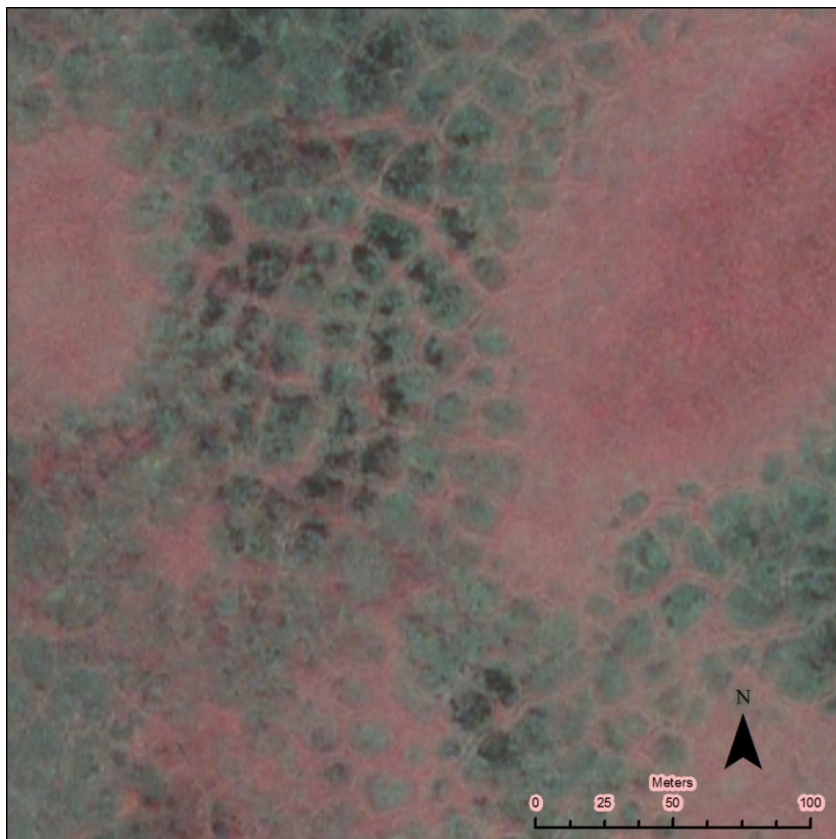


Figure 12. Low-center ice-wedge polygons. The polygons are darkest near the centers due to ponding of water there. IKONOS image, Noatak National Preserve.



Figure 13. High-center polygon formed by degrading ice wedges. In lowlands near the Kobuk River in KOVA, 67.096°N, 158.551°W.

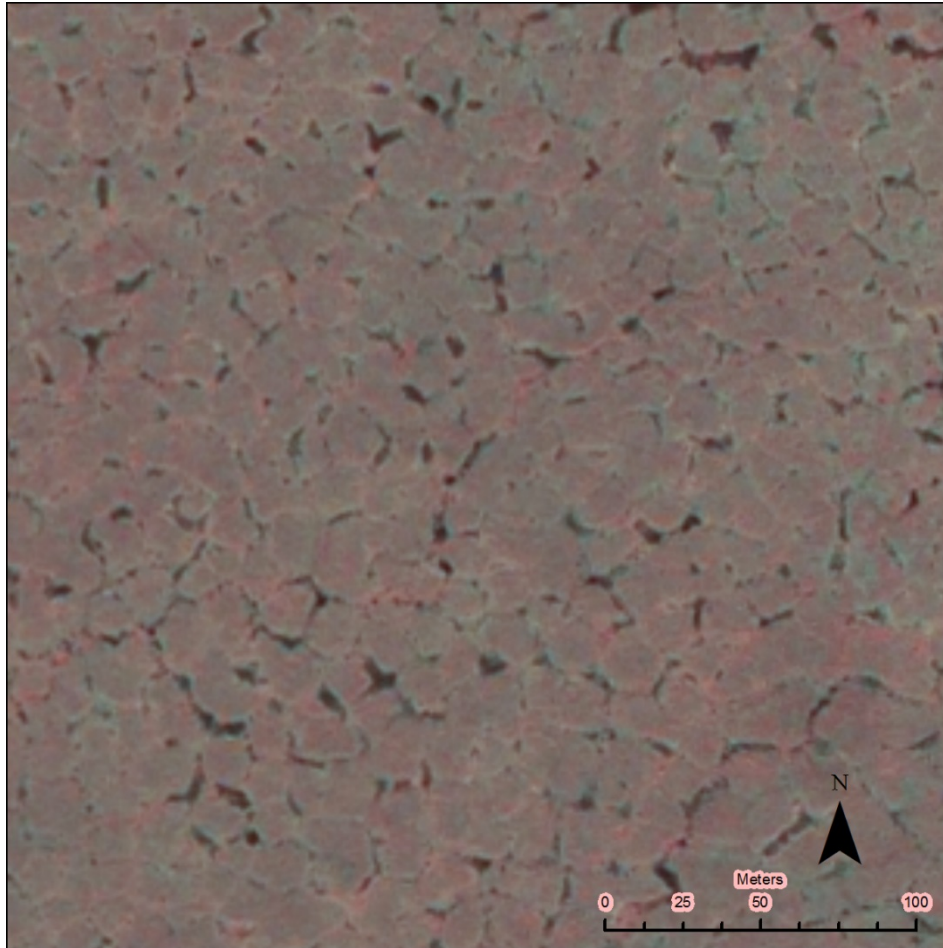


Figure 14. High-center polygons with marginal water-filled troughs due to ice-wedge degradation. IKONOS satellite image with color-infrared color scheme, Noatak National Preserve.

5.2 Study area selection

We use stratified sampling, targeting ecological subsections where the surface is dominated by ice-wedge polygons. In GAAR and NOAT, ice-wedge polygons are present in many lowland areas, but visible polygons occur mostly in patches of 1 km² or less; the exception is the Lower Noatak Lowlands subsection in NOAT (Jorgenson et al. 2001). The Lower Noatak Lowlands (LNL; Fig. 15) is a region of numerous thermokarst lakes and overlapping drained lake basins, with visible ice-wedge polygons on most of the land surface except in recently drained lake basins. In KOVA, ice-wedge polygons occur almost exclusively in the Ahnewetut Wetland ecological subsection (Fig. 15, Swanson 2001). These two subsections have historical (1951-52) aerial photographs with sufficient resolution to facilitate a retrospective study of ice-wedge degradation by comparison with recent (2006-09) high resolution satellite images. Thus, we have established specific monitoring plots and tested the monitoring protocol in these two areas (Swanson 2016).

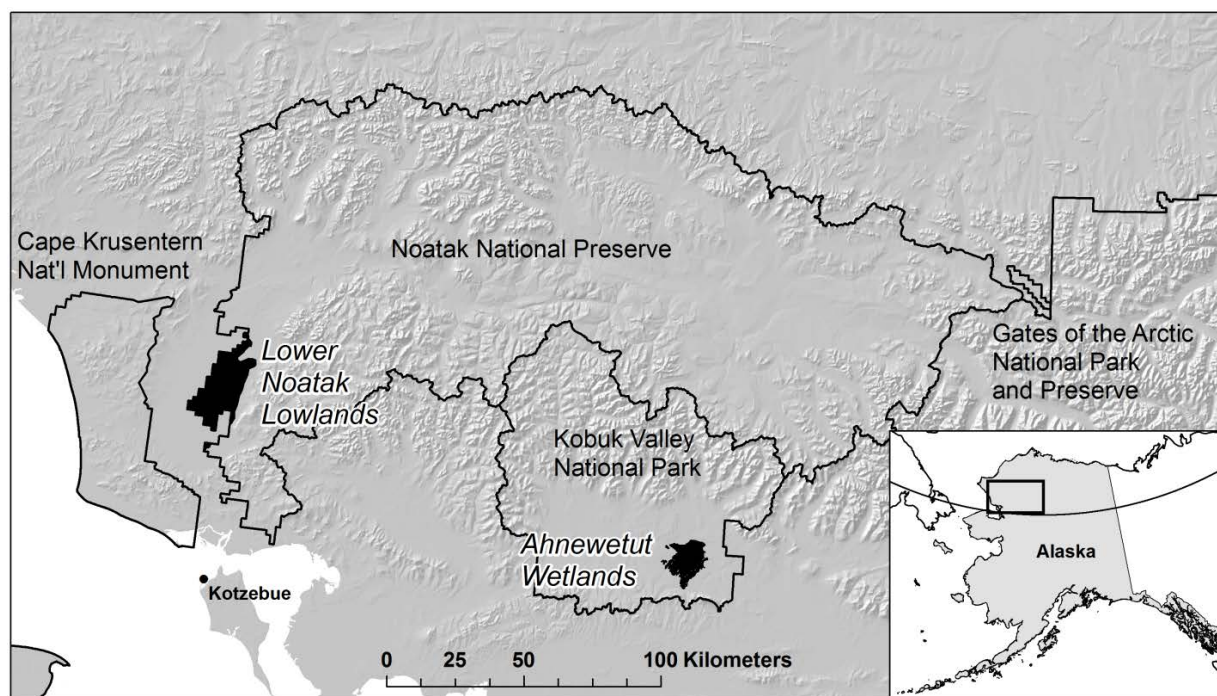


Figure 15. Areas for monitoring ice-wedge polygons in KOVA and NOAT.

Ecological subsections with the land surface dominated by ice-wedge polygons cover much of northern BELA, but historical aerial photographs there were judged to be inadequate and no monitoring has been carried out to date. Specific monitoring areas will be established in BELA at the next re-sampling, which is recommended to occur 10 years from the 2006-09 image period.

5.3 Imagery

Images with a resolution of about 1 m or better is required to discern ice wedge polygons and troughs. Historical imagery (1:20,000 scale panchromatic aerial photographs from around 1951-52) is available for the AHN and LNL study areas. (Historical panchromatic aerial photographs for the BELA study area are 1:40,000 and were judged not sufficient for our analysis.) The aerial photographs were scanned at 14 μm per pixel (1800 pixels per inch), which is close to the original grain of the photographs and results in a ground resolution of about 0.3 m for the panchromatic photos of 1:20,000 scale. The recent high-resolution IKONOS satellite imagery (Geoeye 2010) is from 2006-2009 and includes blue, green, red, and near infrared bands at 4 m resolution, pan-sharpened to 1-m resolution. Imagery in the future should be 1 m resolution or better and ideally with blue, green, red, and near infrared bands. Satellite imagery is orthorectified using satellite parameters and a digital elevation model (DEM). Aerial photographs are georeferenced to the satellite images with accuracy of 1 m or better using a projective transformation and numerous control points. This method is quicker than orthorectification and sufficiently accurate in lowland ice- terrain where topography is flat.

5.3 Sampling

Three hundred random 1-ha plots (56.42 m radius; Fig. 16) were placed in the AHN and LNL subsections. The centers of all visible ice-wedge polygons were digitized in the plots, and these centers were used to define the portion of the plot where ice wedges are present, which we refer to as "ice-wedge zones". Only the surface water within these zones is included in our analysis. Surface water is mapped by "thresholding", manually choosing an image value to separate water and land (Jorgenson et al. 2006, Liljedahl et al. 2016).

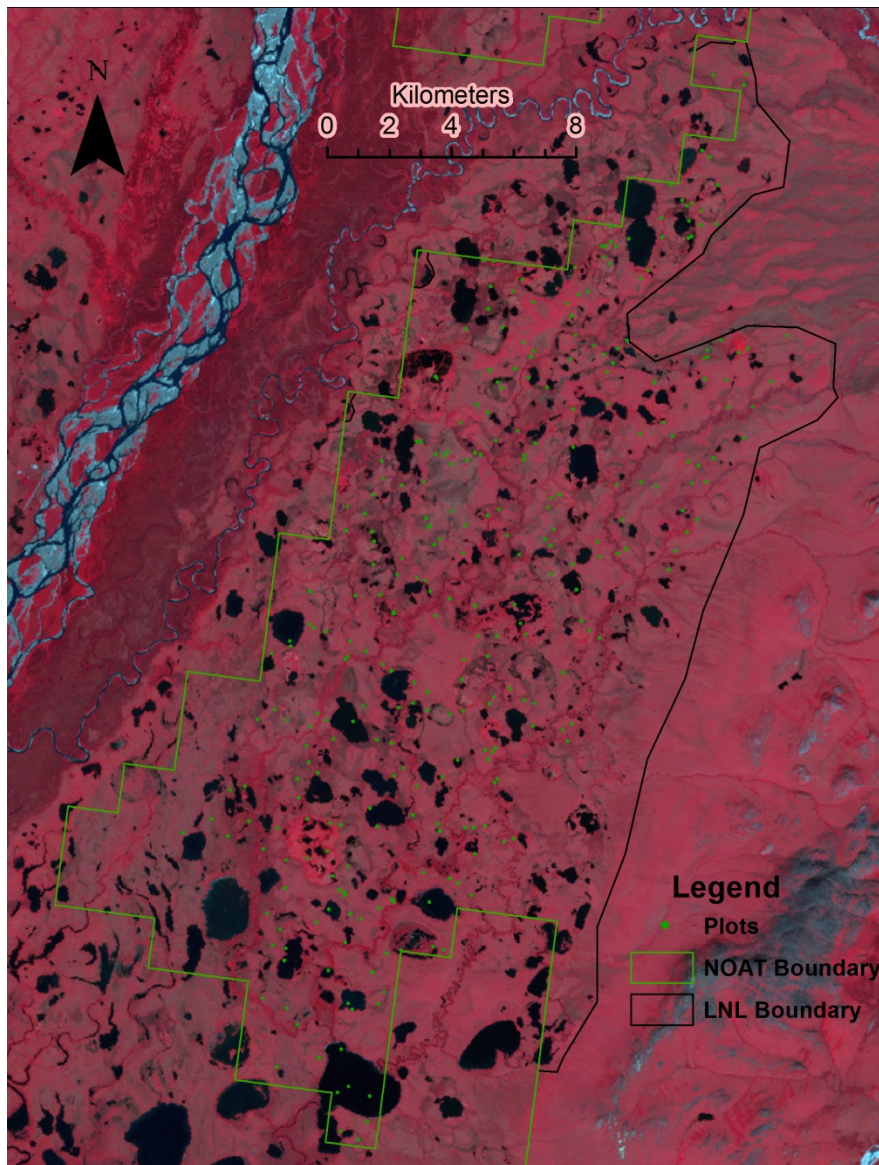


Figure 16. Overview of the Lower Noatak Lowlands study area. Remotely sensed plot locations are marked with green dots. The Noatak National Preserve boundary is shown in green and the Lower Noatak Lowlands (LNL) boundary in the Preserve is shown in black. Portions of the LNL without plots were omitted due to lack of 1950s-era aerial photographs. The background image here is a Landsat mosaic from the early 2000s, displayed in a color-infrared color scheme.

We also visually classify the polygon type on each 1-ha plot, and visually assess the presence or absence of water-filled troughs along polygon margins. The polygons on each plot as a whole are classified as low-centered (more than two-thirds of polygons had dark-colored centers), high-centered (more than two-thirds of polygons had light-colored centers), or mixed (both dark- and light-centered polygons present, neither are dominant). Water-filled marginal troughs or pits are considered "present" if any are found along polygon margins in the 1-ha plot. We do not attempt a significance test of the visual classification data, because the plots are not each equivalent samples from the population: the area of the ice-wedge zones within the plots varies widely, from not present to the full 1 ha.

5.4 Data analysis and reporting

The absolute area of water in the ice-wedge zones on the different sample dates may be compared directly to illustrate growth of ice-wedge troughs and pits. The simple area of water is most effective as an indicator of thermokarst in areas where relatively flat, dry polygons are converted by thermokarst into high-center polygons with marginal ponds. However, the boundary between water and land in polygonal terrain can be difficult to define, because ponds are shallow and have emergent vegetation. Thus, reasonable threshold values for mapping water will produce a range in the total area of water. In addition, intact low-center polygons may have considerable surface water present, and polygon degradation may lead to changes in its distribution more than absolute area. For this reason we do not rely completely on change in absolute area of water mapped, but also analyze the distribution of water relative to polygon centers. The location of each mapped pixel of water in relation to the ice-wedge polygons is determined by computing the distance index $i = 2a/(a + b)$, where a is the distance to the closest ice-wedge polygon center and b is the distance to the second closest ice-wedge polygon center (Fig. 17). This index is known to community ecologists as the Sørensen distance index (McCune et al. 2002) and it ranges from near 0 at the polygon centers (where a is small and b relatively large) to near 1 along polygon boundaries (where a and b are approximately equal).

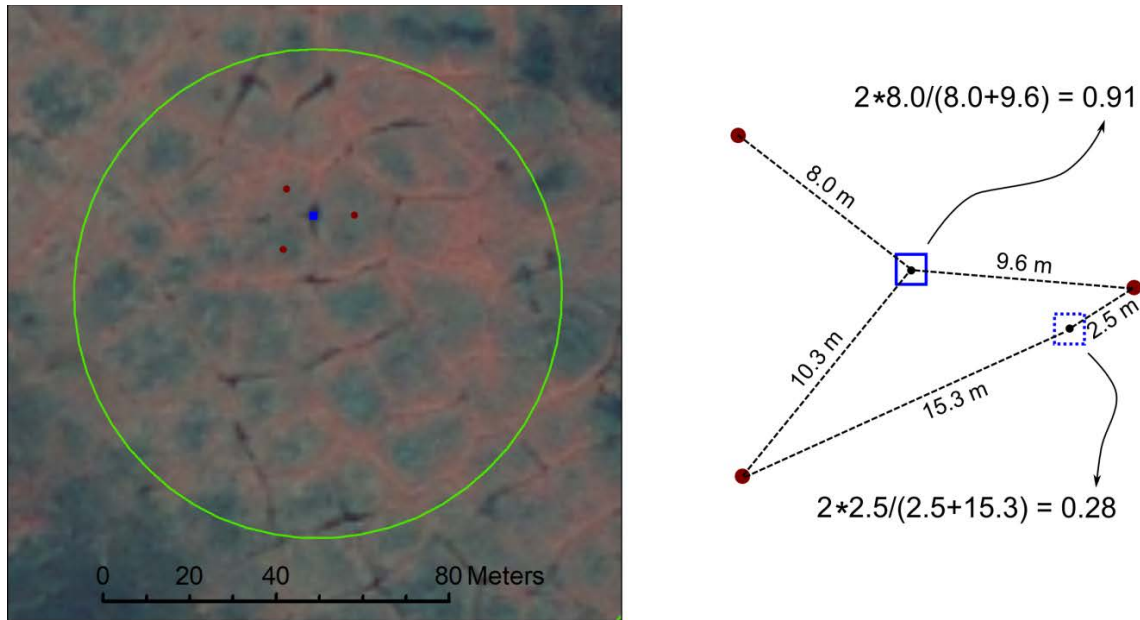


Figure 17. Example plot and computation of the water pixel position index. On the left is an example 1-ha plot (plot 63 in the Ahnetwetut Wetland monitoring area) with an example water pixel in blue on the polygon margins and three neighboring ice-wedge polygon centers. On the right, these features are magnified and the distance index is computed for this pixel (solid blue square) and a hypothetical pixel near one of the polygon centers (dotted blue square). The solid blue pixel near the polygon margins has a distance index of 0.91, while the dashed pixel near the right-most polygon center has an index of 0.28.

If the median index increases, then the proportion of water on polygon margins relative to water in the polygon centers has increased, suggesting ice-wedge degradation. The distribution of the distance index of water pixels in a study area on different dates is compared, and the significance of the difference determined by the Wilcoxon Rank-Sum test, corrected for clustering of the data by plots (Lumley and Scott 2013). The nonparametric Wilcoxon Rank-Sum test is used because the distribution of distance indices is typically strongly non-normal: it is skewed toward higher values (because of the larger area represented by higher indices, see below) and truncated at a value of one.

The location of ponds relative to polygon centers can be visualized by assigning them to "quarter sectors", as follows. Ten thousand random points were placed in the ice wedge polygon zones (portions of plots with polygons) in each of the AHN and LNL study areas, and the distance index was computed for each point. The quartiles (25th, 50th, and 75th percentiles) of these 10,000 points identify the distance indices corresponding to four equal-area sectors of the polygons ranging from the centers (zero to 25th percentile) to the margins (75th to 100th percentiles; Fig. 18). The quartiles were the same to the second decimal place for the two study areas. These quartiles are convenient for bar diagrams, to illustrate the proportion of water in polygon centers (indicating undisturbed low-center polygons) versus polygon margins (in marginal pits due to ice-wedge degradation (Fig. 19).

We also estimate the proportion of polygons with degraded ice wedges. Water pixels in the two marginal quarter-sectors (3 and 4 in Fig. 18) are tallied for each polygon center, and a polygon is counted as "having marginal pond(s)" if at least 5 m² of water pixels are present. The proportion of

polygons with these marginal ponds then approximates the proportion of polygons with degraded ice wedges.

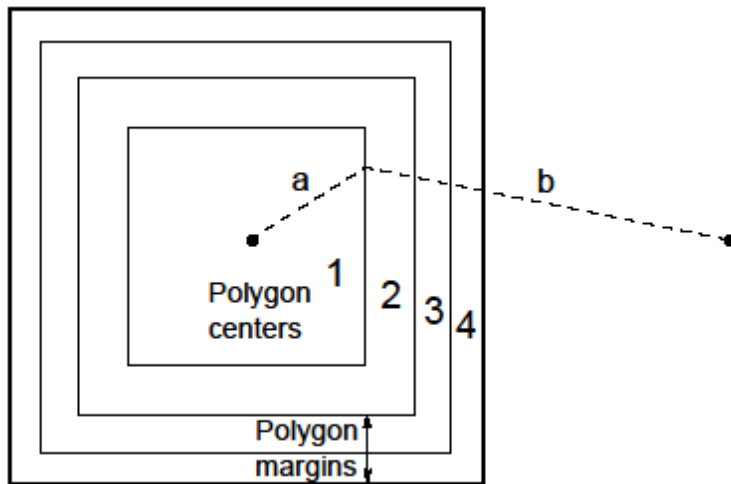


Figure 18. Sectors of polygons as defined by the distance index. The four numbered sectors of this schematic polygon have equal areas, each encompassing one-fourth of the area. The distance index $i = 2a/(a + b)$ determines the boundaries of each sector. Line a represents the distance to the nearest ice-wedge polygon center from the boundary between sectors 1 and 2, while line b is the distance from the boundary to the second nearest polygon center. Distance indices were computed for 10,000 random points in the ice-wedge polygons of each of the two study areas to determine the boundaries between quarter sectors, and the resulting boundaries were $i = 0.56, 0.75$, and 0.89 for both study areas. Sector 1 represents polygon centers, while sectors 3 and 4 represent polygon margins.

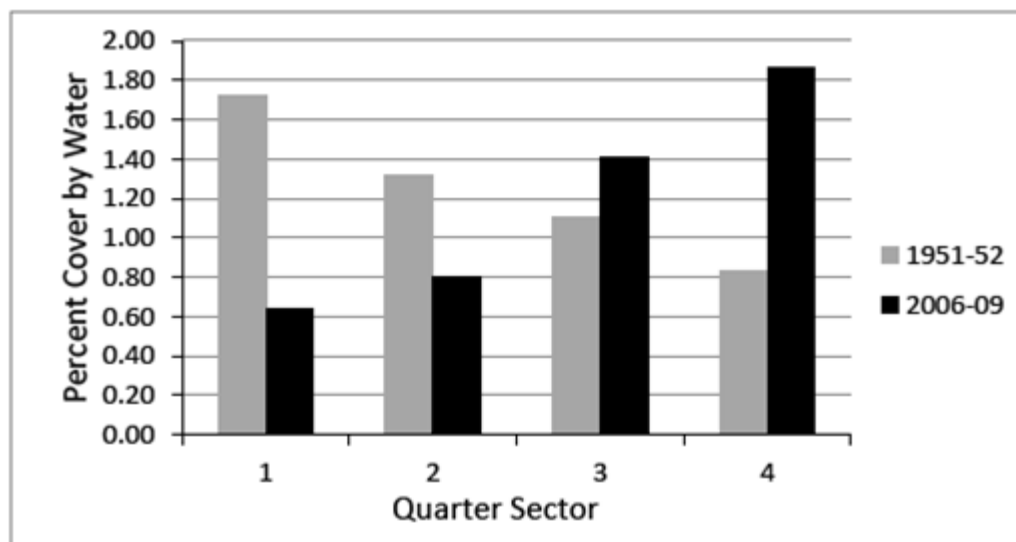


Figure 19. Percent cover by water in ice-wedge polygon quarter sectors at two different times in the Ahnewetut Wetlands study area, Kobuk Valley National Park. The area of water in polygon centers (quarter sector 1) declined from about 1.7 to 0.6% between 1951-51 and 2006-09, while the area of water at polygon margins (sectors 3 and 4) increased. The total water area was similar on both dates (1.2%).

5.5 Operational requirements

Re-sampling is recommended at a 10- year interval. Implementation of this protocol will require high-resolution (0.5 to 1 m) images covering about 300 km² (AHW), 350 km² (LNL), and perhaps 700 km² (BELA). Images should be from summer conditions (July-August; July 15 to Aug 15 if possible). Ideally the images should include red, green, blue, and near-infrared bands, to allow the best comparison with different kinds of 3-band historical images. At the present time, high-resolution satellite images are available at no charge to government agencies through the US Geological Survey's CRSSP (Commercial Remote Sensing Space Policy) program (<http://crssp.usgs.gov/>). NPS may enter requests for imagery coverage through the CRSSP Imagery-Derived Requirements (CIDR) Entry Tool (<http://CIDR.cr.usgs.gov/>).

The image analysis requires a worker with strong GIS skills, including using Python for ArcGIS geoprocessing. Familiarity with R or other statistical software is needed to run the Wilcoxon rank-sum test. Familiarity with databases is needed to append the data and perform some calculations. Image processing and manual classification of polygon type should require about one week per study area. Further data analysis and write-up should take another one to two weeks.

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