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Methods to assess natural and anthropogenic thaw lake drainage on the western Arctic coastal plain of northern Alaska

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[1] Thousands of lakes are found on the Arctic Coastal Plain of northern Alaska and northwestern Canada. Developed atop continuous permafrost, these thaw lakes and associated drained thaw lake basins are the dominant landscape elements and together cover 46% of the 34,570 km^2 western Arctic Coastal Plain (WACP). Lakes drain by a variety of episodic processes, including coastal erosion, stream meandering, and headward erosion, bank overtopping, and lake coalescence. Comparison of Landsat multispectral scanner (MSS) imagery from the mid-1970s to Landsat 7 enhanced thematic mapper (ETM+) imagery from around 2000 shows that 50 lakes completely or partially drained over the approximately 25 year period, indicating landscape stability. The lake-specific drainage mechanism can be inferred in some cases and is partially dependant on geographic settings conducive to active erosion such as riparian and coastal zones. In many cases, however, the cause of drainage is unknown. The availability of high-resolution aerial photographs for the Barrow Peninsula extends the record back to circa 1950; mapping spatial time series illustrates the dynamic nature of lake expansion, coalescence, and drainage. Analysis of these historical images suggests that humans have intentionally or inadvertently triggered lake drainage near the village of Barrow. Efforts to understand landscape processes and identify events have been enhanced by interviewing Iñupiaq elders and others practicing traditional subsistence lifestyles. They can often identify the year and process by which individual lakes drained, thereby providing greater dating precision and accuracy in assessing the causal mechanism. Indigenous knowledge has provided insights into events, landforms, and processes not previously identified or considered.

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1. Introduction

[2] The Arctic Coastal Plain (ACP) of northern Alaska and northwestern Canada is relatively flat, low-relief tundra underlain by continuous permafrost. By any definition, it is a wetland. Permafrost at depth prohibits infiltration of snow meltwater, and surface drainage is limited on the gently sloping planar surface. Thaw lakes and associated drained thaw lake basins (DTLBs) are the primary landscape elements. A recent analysis of a Landsat 7 enhanced thematic mapper (ETM+) mosaic [*Hinkel et al.*, 2005; *Frohn et al.*, 2005] of the ACP west of the Colville River (152°–162° W longitude) estimates that about 20% of the 34,570 km^2 area is covered with lakes and ponds (13,214 water bodies >1 ha) and an additional 26% is identified as DTLBs. Much of the remaining land surface is affected by thaw lake processes, but the basins are so old and overlapping that individual features can no longer be clearly discerned [*Hinkel et al.*, 2003; *Eisner et al.*, 2005]. The ACP can therefore be considered a palimpsest of younger generation lakes and DTLBs superimposed on even older basins.

[3] Analysis of existing climate records, combined with results from modeling and observational data, suggests that the greatest rate of warming is expected to occur at high northern latitudes due to increasing concentrations of radiatively active gases [*Serreze et al.*, 2000; *Houghton et al.*, 2001; *Keeling and Whorf*, 2004; *Chapin et al.*, 2005]. This would likely cause a widespread deepening in the active layer (seasonal thaw layer) above permafrost. Recently, *Lawrence and Slater* [2005] have proposed that by 2100, only 10% of the current 10.5 million km^2 of permafrost will remain within 3.4 m of the ground surface. Although this estimate may be extreme, there is consensus that permafrost will experience widespread degradation in the next century

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[*Anisimov and Nelson*,1997; *Zhang et al.*, 2003; *Sazonova et al.*, 2004]. *Jorgenson et al.* [2006] has documented extensive permafrost degradation in Arctic Alaska over the past 25 years.

[4] Differential thaw of near-surface permafrost, resulting in an irregular landscape surface, is known as thermokarst. Thermokarst favors pond and lake formation, whereas a deeper active layer could promote lake expansion and drainage by thawing the ice-bonded sediments that form the lateral confines of the thaw lake. In ice-rich sediments, warmer soil temperatures would cause regional subsidence of the ground surface as near-surface permafrost thaws. This would be manifested as an expansion of the lake margin, merging of lakes, and an increased incidence of lake drainage. Permafrost in many areas of the western Arctic Coastal Plain (WACP) is highly susceptible to thaw subsidence owing to the large ice fraction [*Pollard and French*, 1980; *Brown et al.*, 2001]; soil cores collected near Barrow indicate that the volume of pore ice and ice lenses or veins averages 50–75% in the upper 2 m of the permafrost [*Sellmann et al.*, 1975], and ice wedges may contribute an additional 10–20%.

[5] Several recent studies have used remote sensing techniques, field work, and historical records to determine if the abundance or net surface area of lakes has changed in the past few decades in response to atmospheric forcing. Substantial changes have been noted, but the direction of change is ambiguous. Some researchers report lake expansion and growth [*Osterkamp et al.*, 2000; *Jorgenson et al.*, 2001; *Christensen et al.*, 2004; *Payette et al.*, 2004], while others find lake shrinkage or disappearance [*Yoshikawa and Hinzman*, 2003; *Stow et al.*, 2004]. *Smith et al.* [2005] examined a large geographic area ($\sim$515,000 km^2) in western Siberia containing about 10,000 large lakes ($\geq$40 ha), and found both patterns have occurred since the early 1970s. Geographically, lake expansion prevailed in the continuous permafrost zone to the north but lake disappearance dominated in the discontinuous permafrost zone in the south. *Smith et al.* [2005] proposed that thawing permafrost may explain both phenomena; thermokarst development caused lake expansion in areas of continuous permafrost while thawing permafrost enhanced groundwater infiltration that triggered abrupt lake drainage in discontinuous, sporadic and isolated permafrost zones.

[6] The analysis of climate-induced changes in lake dynamics is not solely an academic exercise. Lakes are important water supplies for community, municipal and industrial purposes. Lakes release large quantities of carbon-based gases to the atmosphere [*Kling et al.*, 1991; *Zimov et al.*, 1997], and strongly impact the surface energy balance because they absorb substantially more solar energy than the surrounding terrestrial surface and are a primary source of evaporative flux to the atmosphere. Arctic lakes and wetlands provide essential habitats for fish, birds and mammals [*Berkes and Jolly*, 2001]. Enhanced drainage or flooding of these lakes is therefore of concern to indigenous Arctic communities who rely on subsistence hunting and fishing, practices that underlie Iñupiaq culture and heritage. The WACP study area includes portions of the National Petroleum Reserve-Alaska (NPRA), a region recently reopened to oilfield development which entails construction of ice roads across the tundra surface using water pumped from lakes.

[7] In this study, we will compare available multispectral scanner (MSS) satellite imagery from the mid-1970s to ETM+ imagery from 2002, and examine the pattern of catastrophic lake drainage across the WACP. Specifically, we will identify lakes that have experienced significant reduction in surface area over the period. In a similar manner, aerial photos from circa 1950 will be used to examine changes in lakes over the period 1949–2002 at a much higher level of spatial detail. These image sources will enable us to estimate the rate of lake morphometric change over time. By accessing indigenous knowledge held by Iñupiaq elders and hunters, we can often identify the operative drainage process and pinpoint the drainage date. Lakes in some areas have been intentionally or inadvertently impacted by direct human activity, and it is necessary to separate such events from those triggered by natural processes.

2. Background and Study Area

[8] The Arctic Coastal Plain physiographic province is a relatively low-elevation, low-relief surface that rises gently from the shores of the Arctic Ocean. It is bounded (at $\sim$120–200 m asl) to the south by the Arctic Foothills, which is the northern piedmont of the Brooks Range. The Arctic Coastal Plain is characterized by deep permafrost, poor drainage, tundra vegetation, and numerous shallow lakes with elliptical shapes that exhibit strong north-south orientation of the long axis [*Wahrhaftig*, 1965; *Sellmann et al.*, 1975]. The surficial geology is ice-bonded Quaternary marine, fluvial and aeolian sediments atop slightly dipping Cretaceous sedimentary rock. The sediments reflect the effects of seven to eight marine transgressions that occurred during the late Cenozoic [*Dinter et al.*, 1990; *Brigham-Grette and Carter*, 1992; *Brigham-Grette and Hopkins*, 1995; *Brigham-Grette*, 2001], as evidenced by ancient shorelines, dunes and wave-cut scarps that can be traced discontinuously across the region. The ACP has been tectonically stable for at least the last 125 kyr, so the altitude of these shorelines have not appreciably changed [*Dinter et al.*, 1990] and they can be used to subdivide the ACP into subregions.

[9] The Outer Coastal Plain (0–23 m asl) is an area inundated by marine transgressions from 58 to 75 ka [*Brigham-Grette and Hopkins*, 1995; *Brigham-Grette*, 2001]. Composed of surficial marine silts and sands, it covers about one third of the entire ACP physiographic province [*Hinkel et al.*, 2005]. Thaw lakes on the Outer Coastal Plain tend to be large, shallow and highly elliptical [*Sellmann et al.*, 1975; *Jeffries et al.*, 1996]. Inland is the more extensive and older Inner Coastal Plain (23–120 m asl), a region of rolling topography with surface aeolian sand containing small, deep lake basins with relatively steep margins and deep thaw pools [*O'Sullivan*, 1961; *Williams et al.*, 1978; *Williams*, 1983; *Hinkel et al.*, 2005]. Average lake size is much smaller and lake density is substantially lower on the Inner Coastal Plain. Although lake areal coverage is fairly constant across the WACP at about 20%, there are far fewer DTLBs on the Inner Coastal Plain (19% of area)

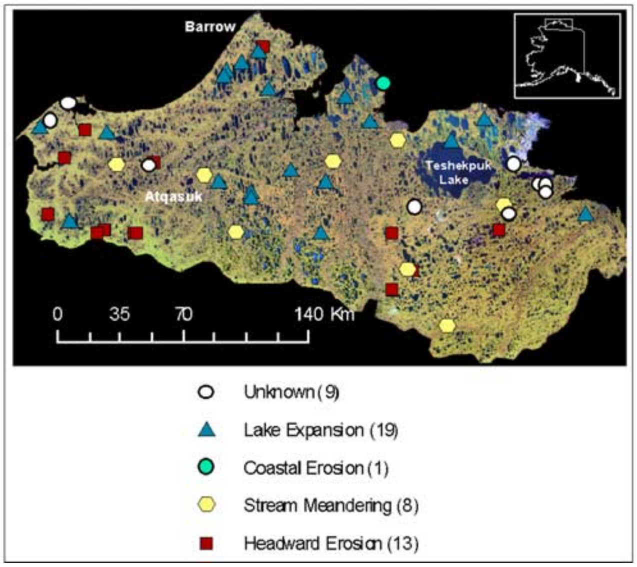

Figure 1. Mosaic of seven Landsat 7 ETM+ scenes (bands 543 RGB) showing the study area which ranges from 69.6 to 71.3 N latitude and 150.9 to 160.1 W longitude. Symbols represent lakes that drained over the ~25-year period, along with inferred or suspected cause.

compared to the Outer Coastal Plain (47%) [*Hinkel et al.*, 2005].

[10] Thaw lakes appear to go through sequential stages of pond formation and coalescence, lake expansion by thermoerosion processes, and concurrent basin deepening over time by permafrost thaw and consequent ground subsidence beneath the lake [*Carson and Hussey*, 1962; *Black*, 1969; *Billings and Peterson*, 1980; *Harry and French*, 1983]. Lake initiation has been linked to regional deepening of the active layer and thermokarst development in ice-rich permafrost during the postglacial period 8–15 kyr [*Ritchie et al.*, 1983; *Mackay*, 1992; *Burn*, 1997], although alternative models have recently been proposed [*Jorgenson and Shur*, 2007]. The final stage entails lake drainage. In the standard thaw lake cycle model, drainage marks the end of the lacustrine phase and a return to terrestrial conditions.

[11] Lake drainage can occur in response to bank overflow, erosion concentrated in ice wedge networks, coastal erosion, or headward erosion by streams [*Hopkins*, 1949; *Walker*, 1978; *Hopkins and Kidd*, 1988; *Mackay*, 1988, 1992]. Depending on local conditions, the lake may completely empty over a short time period (catastrophic drainage) or may gradually lose water and only partially empty. In many cases, the establishment of a drainage link between two lakes results in the lowering of the water level in one lake and rising of the water level in the other. *Mackay* [1988] estimates that 1–2 lakes in the Tuktoyaktuk Peninsula of northwest Canada drain suddenly each year. Other evidence indicates that lake drainage occurs indirectly by geomorphic and climatic factors that are not well understood. For example, *Brewer et al.* [1993] noted that numerous lakes drained in the warm summer of 1989 near Prudhoe Bay, but attributes this to bank overspill from above-normal lake levels caused by heavy summer precipitation.

3. Landsat Methods and Results

[12] The MSS mosaic (not shown, but very similar to Figure 1) was constructed from five individual scenes collected between 1974 and 1977 (Landsat 1 and 2). Scenes were selected if they were cloud-free and were taken during the summer months. All five scenes were reprojected to UTM zone 5N, and all four MSS bands were mosaicked to cover the WACP. Numerous lake spectra samples were collected, and a mask was created to identify all water bodies. Rivers, estuaries and inlets were identified and manually eliminated from the mosaic. Lakes in raster format were converted to vector-based shapes, and shape metrics were calculated within eCognition® application software. These include the geographic centroid of the lake, area, length, width, length/width ratio, elliptic fit, asymmetry, shape index, and main direction of the major axis. Only lakes exceeding 10 ha (31 pixels) in size were retained in the MSS mosaic, which covers 34,570 km^2 of the WACP and has a pixel size of 60 m.

[13] The Landsat 7 ETM+ mosaic (30 m resolution) was constructed in a similar manner using seven cloud-free summer scenes collected between 2000 and 2001 for the same region of the WACP. Bands 5,4, and 3 (RGB) were used to create the mosaic shown in Figure 1. Shape metrics were calculated and indicate that there are 7418 lakes (>10 ha, or 111 pixels) on the WACP that cover 19.7% of the land area. However, this includes the anomalous Teshekpuk Lake; at 836 km^2, it is larger than the next biggest lake (58.3 km^2) by a factor of 14. If Teshekpuk Lake is excluded from the analysis, there are 7417 lakes covering 17.3% of the WACP.

[14] A histogram and descriptive statistics of lake size are shown in Figure 2. The pattern demonstrates the predominance of small water bodies; 65.6% of the lakes are smaller than 50 ha (0.5 km^2), 17.6% of the lakes are larger than 100 ha (1 km^2), and 0.7% of the lakes exceed 1000 ha (10 km^2) in area. The nonnormal size distribution is also reflected in the difference between the mean (81 ha) and median (31 ha) values.

[15] To identify lake drainage events on the WACP, the ETM+ lake polygon shape file was subtracted from the MSS lake shape file. The difference represents those lakes that experienced significant changes in areal extent over the 25 year period which, at this temporal scale, can be considered a catastrophic event. For the purposes of this study, a reduction in area of at least 25% defined a significant drainage event. A total of 50 lakes (>10 ha) met this criterion (Figure 1). Thus an average of 2 lakes drained each year over the entire study area.

[16] Most lakes (>75%) that drained were less than 100 ha (1 km^2) in size (Figure 2). As expected, drained lakes were predominately smaller, with decreasing frequency of larger lakes. The median lake size to drain was about 0.4 km^2 in area, while the largest was nearly 8 km^2. As shown in Figure 3, most lakes drained completely. Only 12% of the lakes experienced less than a 50% reduction in surface area, while 64% were at least 90% drained.

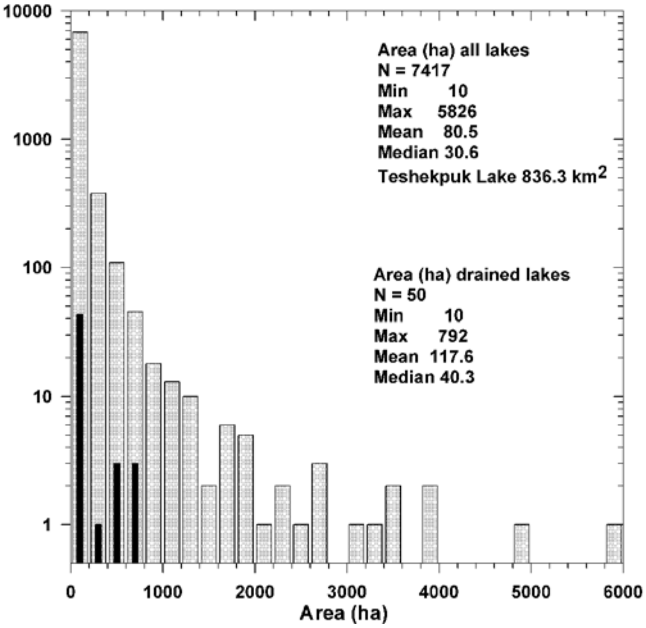

Figure 2. Histogram and descriptive statistics of lake area (ha) for all lakes on ETM+ mosaic for the WACP in 2002 (excluding Teshekpuk Lake), shown in stippled bars. The 50 lakes that drained over the time period are shown as solid bars. Bins are 200 ha wide.

[17] The analysis indicates that only 0.027% of extant lakes experience catastrophic drainage on an annual basis. Although the drainage rate of two lakes per year is the same as that observed by *Mackay* [1988] on the Tuktoyktuk Peninsula, the WACP study area is larger by a factor of six and contains far more lakes. Furthermore, the geographic setting of the WACP differs substantially from Mackay's study area, which has higher relief and lakes developed in glacial sediments [*Rampton*, 1988]. Over the 25 year time period, the total amount of water surface impacted was less than 1% of the total. Thus compared to northwestern Canada, lakes in the WACP region appear to demonstrate more stability.

[18] The analysis described above is limited in several regards. First, it serves only to bracket the drainage event between the two image acquisition dates. Second, it is not possible to identify the drainage mechanism except in a few obvious cases. For example, it is likely that the lake near the coast in Figure 1 drained due to coastal erosion. Coastal erosion rates in this area for the period since 1950 range from 1 to 10 m yr^{-1} [*Brown et al.*, 2003; *Manley*, 2004; *Jorgenson and Brown*, 2005], so it is feasible that the approximately 40 m separating the lake margin from the shore was eroded over the 25 year period. Similarly, lake expansion and coalescence can be deduced when the terrestrial divide between proximal lakes disappears during the time period; often one lake drains while the adjacent lake shows evidence of shoreline expansion. Further, lakes near large streams probably drained due to stream meandering and migration of the cut bank. Thus a high-energy geographic setting provides the basis for identifying some causative drainage processes.

[19] Other drainage mechanisms include headward erosion of streams and bank overtopping during periods of high water; both tend to be concentrated in the troughs of ice wedge networks. Identifying the effects of these mechanisms is far less certain because they tend to be episodic and site-specific. For example, drainage is often initiated during periods of high lake water level resulting from rapid or copious snowmelt, heavy summer precipitation, or damming of the lake outlet by drifting snow [*Mackay*, 1988; *Brewer et al.*, 1993]. Rising water encounters low-lying ice wedge troughs between polygons, channeling surface flow. In some cases, flow in thermal contraction cracks causes thermomechanical erosion of wedge ice at depth, and causes rapid lake drainage by subsurface flow [*Mackay*, 1988; *Marsh and Neumann*, 2001]. In the scenarios described above, the new drainage outlet does not necessarily or typically coincide with any preexisting or original lake outlet and, to a degree, such events can be identified on the satellite time series as a new drainage outlet. Conversely, a nearby stream may be apparent in the MSS image prior to lake drainage. On the ETM image, the lake has drained and the same stream appears as the drainage outlet where it forms the highest-order stream in the incised dendritic drainage network developed within the DTLB. In this case, we might suspect that headward erosion triggered drainage since this appears more likely than erosion in ice wedge troughs. By examining the geographic setting of each lake, we have attempted to identify the process by which the 50 lakes drained; this classification is shown in Figure 1. However, it is simply not possible to positively identify the causative drainage process for every lake using satellite imagery. Thus the cause of drainage remains unknown and unclassified for about 20% of the events, and is subjective for an additional 25% of the cases.

[20] The nonuniform spatial pattern in Figure 1 demonstrates the influence of high-energy settings on lake drain-

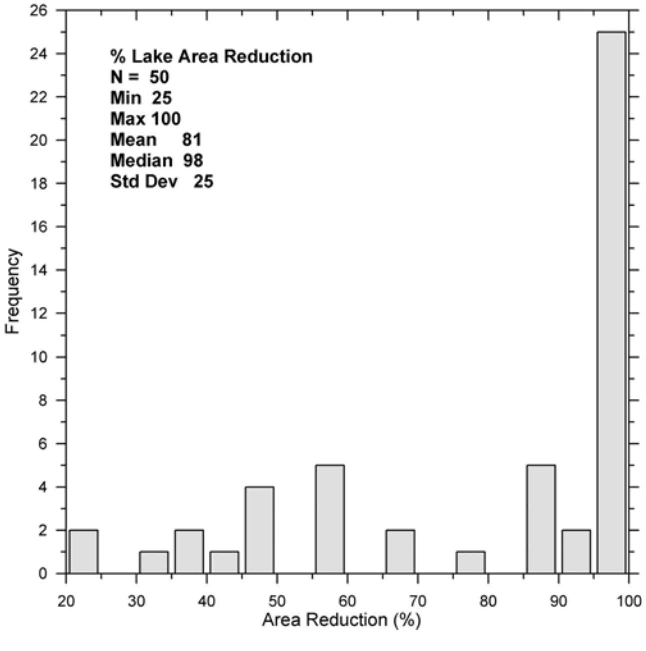

Figure 3. Histogram of surface area reduction (%) for the 50 lakes that drained over the time period.

age. Large meandering streams and associated tributaries can result in a corridor of lakes that drain catastrophically. Headward erosion of streams in those areas of high relief, such as marine cliffs and stream cutbanks, promotes nearby lake drainage. Similarly, bank erosion causes lake expansion over time. For this reason, lake coalescence is favored where lake density is high, such as on the Outer Coastal Plain. The spatial pattern of recently drained lakes is therefore not uniform, but is moderated by local processes and conditions.

[21] Several alternate methods can be used to address the limitations discussed above. First, aerial photographs are available for some regions that extend the coverage back to circa 1950, effectively doubling the period of record. In some cases, the greater spatial resolution of the photos allows the lake drainage processes to be inferred. Second, residents of the area have knowledge of drainage events that can help pinpoint the drainage mechanism and date. The examples below demonstrate how both can be used.

4. Aerial Photo Methods and Results

[22] To identify small-scale landscape changes it is necessary to examine imagery with resolution higher than that available with Landsat. Possible alternate data sources include recently available high-resolution orthorectified radar imagery (ORRI) and historical aerial photography. The Barrow Peninsula will serve as an example for this analysis.

[23] In 1955, the U.S. Geological Survey acquired vertical cartographic aerial photography for much of the ACP. The images for the Barrow Peninsula were captured in mid-August of that year. A total of 59 black and white aerial photographs (1:50,000 scale) were scanned. An average of 17 ground control points were selected on each aerial photo and, using a second-order polynomial, georeferenced to the ORRI acquired in 2002 [*Manley*, 2004]. The mean RMS error for all 59 photos was 1.32, with a maximum allowable RMS error of 3.00 for an individual ground control point. The resulting resolution of the photo mosaic was 5 m. The photomosaic was imported into eCognition®, histogram stretched, and processed with the multiresolution segmenter algorithm using a scale parameter of 10, shape factor of 0.1, color index of 0.9, and a compactness and smoothness of 0.5. This allows for the identification of lakes in the photomosaic using the manual image object fusion function. The lakes were exported as a polygon shape file, and those lakes at least 10 ha in area were analyzed.

[24] The coverage of the 2002 ORRI image of the Barrow Peninsula defines the study area shown in Figure 4. Modern thaw lakes were delineated from the 5 m resolution ORRI mosaic using automated classification techniques within eCognition®. The achieved accuracy was extremely high, with a mean best classification result of 0.99 for water bodies. The classified raster was converted to a feature shape file that contained two values; one value representing the lakes and the other representing the remainder of the Barrow Peninsula. Lakes were exported to a separate polygon shape file, and shape metrics calculated for each water body. Water bodies exceeding an area of 10 ha were selected and exported as a data set containing the number, area, and net extent of lakes on the Barrow Peninsula as of 2002. The 2002 lake shape file was overlain on the 1955 lake shape file to identify all lakes ($\geq$10 ha) that existed in 1955 but had decreased in surface area since that time.

[25] During this 47 year period, the total lake area on the Barrow Peninsula decreased from 21.3% to 20.9%. The number of lakes ($\geq$10 ha) declined by 30 (from 301 to 271), many from partial drainage that reduced the lake area below the 10 ha threshold (Table 1). The average lake size increased from 150 ha in 1955 to 160 ha in 2002, largely from lake coalescence. Of the 30 lakes that experienced shrinkage to less than 10 ha, thirteen have completely drained. Of these, eleven appear to have drained by natural causes (especially lake coalescence and stream erosion) and two drained as a result of direct human disturbance. Some lakes expanded; seven lakes that were below the 10 ha threshold in 1955 had grown to exceed the 10 ha threshold by 2002, and the operative process appears to be coalescence of smaller lakes and ponds.

[26] When examining the 1955 aerial photography, freshly exposed unvegetated sediments in six DTLBs suggested that lakes had drained just prior to photo acquisition. By viewing black and white aerial photos collected in July 1949, we determined that all had indeed been lakes at that time. This effectively adds six more completely drained lakes to our database for the Barrow Peninsula, bringing the total to 19. Further, five of the six were apparently drained as a result of human activity. Therefore, over the 53 year period (1949 to 2002), human activity has accounted for about 37% (7 of 19) of the completely drained lakes on the Barrow Peninsula; geographically, drained lakes are concentrated near the village of Barrow (Figure 4). Removing the human-impacted lakes from the database yields 29 lakes that have experienced shrinkage to less than 10 ha over the 53 year period. Given that the study area covers only about 6% of the WACP, this indicates a high incidence of drainage events which may reflect the influence of high lake density, large lake size, and the flat topography of the Outer Coastal Plain. Conversely, the high occurrence may be due to the direct or indirect effect of human activities that are not known or identified. It appears likely, however, that lake drainage rates will vary regionally in response to local conditions, and that the size, heterogeneity, and human history of the study area must be considered when reporting average rates.

[27] We have attempted to ascertain the purpose behind the drainage of the seven lakes directly impacted by human activities. First, we wished to determine if drainage was intentional or inadvertent. Footprint Lake, for example, was intentionally drained in 1950 (Figure 4). Some accounts suggest that it was drained to allow for the construction of a road to access the natural gas field near Barrow, while others maintain that drainage was to prevent flooding of natural gas wells [*Lewellen*, 1972; *Billings and Peterson*, 1980]. Whatever the reason, a ditch was bulldozed from the lake outlet to a nearby lagoon, and rapid partial drainage resulted. In the case of Black Lake, analysis of the aerial photography shows a linear drainage channel with sharp bends and long linear segments. This pattern can result from one of two mechanisms: intentionally bulldozing a ditch to promote lake drainage, or inadvertently destroying the thermally protective surface organic mat with a tracked vehicle (e.g., a bulldozer or weasel) and triggering localized

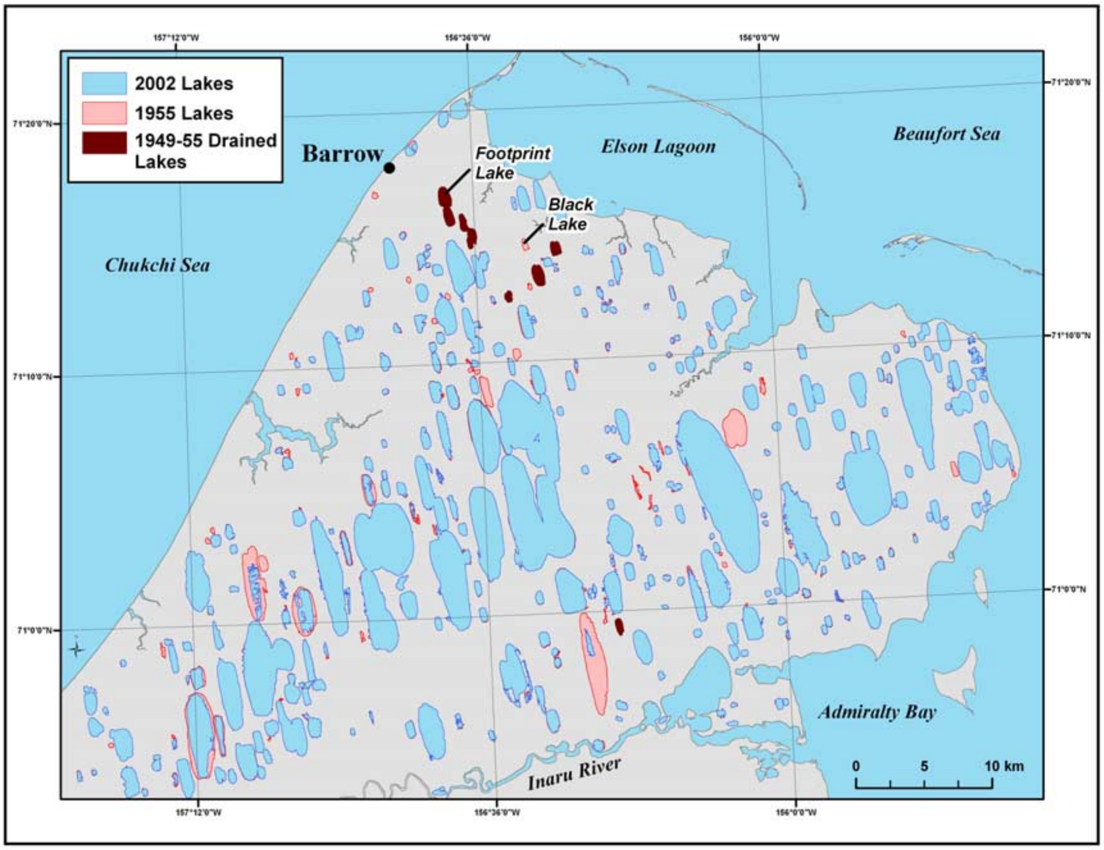

Figure 4. Lake comparison from 1949 to 2002 on the Barrow Peninsula. Lakes in light red are those classified from 1955 aerial photos, lakes in blue are from 2002 ORRI imagery, and lakes in maroon are those that drained between 1949 and 1955.

thermokarst in the ice-rich permafrost. Many of the drained lakes near populated sites have this signature, and resulted from activities of the USGS or the Naval Arctic Research Laboratory at Barrow in the post-WWII era. There is evidence in the form of vehicle tracks and oral histories to suggest that at some remote sites, lake drainage may have been triggered by seismic exploration vehicles, as discussed below.

[28] It is clear that drainage events triggered by direct human activities are important, at least in some areas of the WACP. To accurately assess drainage rates across the region, these events must be separated from those caused by natural processes. Local and indigenous knowledge is useful in ascertaining the timing and mechanism of both natural and human-induced lake drainage, as described in the next section.

5. Indigenous Knowledge Methods and Results

[29] A significant challenge in geomorphic research involves scaling between processes that operate at timescales ranging from annual to multimillennial. Standard methods of evaluating landscape evolution (e.g., palynology and radiocarbon dating) often lack the precision necessary for analysis at shorter temporal scales. Through community outreach efforts over the past few years, we have become increasingly aware of the potential for indigenous knowledge (IK) to bridge the gap between annual and centennial timescales. IK has proven to be a useful source of information about local effects of climate change, landscape processes, and recent changes in ecological communities [*Berkes*, 1999; *Stenmark*, 2002]. Local land users, especially hunters and elders practicing traditional subsistence lifestyles, are intimately familiar with their landscape and are cognizant of changes [*Cruikshank*, 2001; *Fox*, 2002]. These primary and secondary observations are particularly useful when they overlap and precede the availability of aerial photos. Since 2003, we have been interviewing Iñupiaq elders in the villages of Barrow and Atqasuk, and have been able to independently validate the timing of several significant landscape changes that are undetectable on remotely sensed image time series. Much of the information dis-

Table 1. Lake Drainage Events on the Barrow Peninsula Inferred From Time Series Analysis of Aerial Photographs and Satellite Images

Time Period	Total Shrunken Lakes	Completely Drained	Completely Drained: Human Induced
1955–2002	30	13	2
1949–1955	6	6	5
Total	36	19	7

cussed in the last section was obtained from interviews with local indigenous elders.

[30] These interviews were initiated, and interview protocols and methodologies were developed, in the spirit of collaboration. Local community leaders are independently concerned about and interested in climatic and landscape changes on the ACP, especially as they impact subsistence practices and local plant and animal species. A specific example of the value of these interviews for understanding lake dynamics is taken from an interview with Thomas Brower, Jr. An elder in the village of Atqasuk, Brower is highly regarded as a hunter and fisherman. During our initial interview, Brower identified a drained basin from the Landsat 7 image (Figure 1). He pointed to a DTLB, just off the Usuktuk River about 7 km northeast of Atqasuk. At the time, he had been net fishing in the river when he noticed water seepage from the upper part of the cut bank.

> Brower: That lake is empty (pointing to a DTLB on the satellite image).
> Interviewer: Do you know when that happened?
> Brower: 1980s. . .1989. I was boating right there. I see a little water come out, I watch it. I was setting my net down here (points downstream from the lake). About this high (raises his arm above his head) little bit (water) was coming out.
> Interviewer: What caused that?
> Brower: I don't know; a lot of ice in there.
> Interviewer: How long did it take to empty?
> Brower: Faster than anything. It's not really deep; it's shallow.

[31] With further questioning, Brower explained that excessive ice had piled up on the lake shore in the spring of 1989, and flowing melt water breached the narrow neck of land separating the lake from the stream cut bank. Drainage occurred within a day or two. As a corroboration of the timing, we bracketed the event Brower described with two Landsat images. The first shows an extant lake in 1985. The next available image, from 1992, shows a DTLB that had completely drained. Brower was thus able to pinpoint this event to the early summer of 1989. In addition, Brower was able to describe a naturally occurring drainage event, a rare occurrence that few people witness. His description of the initial drainage indicators, his obvious understanding of the conditions which led to the drainage, and the rapidity with which it drained, all point to the value of his observational skills and understanding of process.

[32] Local elders are also aware of the effects of human action on the landscape, and have corroborated our independent findings that human activity has contributed to lake drainage in recent decades. For example, three interviewees identified a DTLB near the Beaufort Sea, just north of Teshekpuk Lake, and told us that drainage occurred during the 1960s. Elders had summer camps near the area at the time, and stated that drainage was triggered by a seismic exploration vehicle making repeated trips to the lake. A 1955 aerial photograph shows an existing lake (Imagkruak, or "big water"). When we examined a 1979 aerial photograph (scale of 1:66,800) of the same area, it was apparent that the lake had been drained by a straight, artificial outlet channel. Without information of this kind, we might have assumed that the lake drained by natural processes given the proximity of the coast. Such nuances cannot be detected on satellite images, so IK helps us focus our efforts using the appropriate tool.

[33] IK has also provided new insights into operative drainage processes. Some elders have suggested that lake drainage preferentially occurs when winds are from the north; i.e., blowing down the long axis of the oriented elliptical lakes. This scenario is feasible because the fetch across the shallow lakes would be maximized under this condition. Storm surges would be enhanced at the southern end where lakes tend to narrow, and bank overtopping would be favored. Although this explanation is not accepted by all elders, it does provide us with alternative drainage mechanisms not previously considered.

[34] These examples demonstrate how indigenous knowledge can be used to supplement standard information sources to refine estimates of lake drainage dates, and to identify the operative drainage process. Some information suggests that, in the distant past, channels between lakes were dug or enlarged to ease boat portage in summer, but we lack geographic specificity to verify these claims.

[35] In an effort to determine the degree of agreement between the satellite-derived lake drainage map (Figure 1) and those drained lakes identified by village elders and hunters, we established a 75 km wide corridor between Barrow and Atqasuk. We considered this a sufficient distance because, like most people, the Iñupiaq tend to concentrate their subsistence and recreational activities near their homes and travel is restricted to walking, snow machine and ATV. The 26 people involved in the IK interviewing process to date identified about half of the lakes that have drained in this corridor; all were large lakes that had nearly completely emptied (>90%). Small lakes, and lakes that had only partially drained, were not identified. In addition, as distance from the village increased, fewer drained lakes were identified. This verifies our impression that land users are most knowledgeable about changes in the local landscape, but their geographic knowledge decreases with distance from their place of residence. This suggests that we must take care to specifically select hunters and elders who are familiar with certain regions of the ACP in order to ensure complete spatial coverage.

[36] We continue to interview hunters, fishers, berry pickers, and elders in villages on the ACP in order to acquire as much information about landscape changes as possible. This includes information on warm artesian springs, gas efflux sites, thermokarst and erosion processes, changes in stream hydrology, and alternative views of lake drainage and infilling. Given the advanced age of many of our interviewees and the changing lifestyle in the Arctic, there is a degree of urgency associated with this effort.

6. Conclusions

[37] A mosaic of Landsat 7 ETM+ scenes, collected between 2000 and 2001 for the western Arctic Coastal Plain, was compared to a Landsat MSS mosaic obtained in the mid-1970s. Fifty of the more than 7400 lakes with area exceeding 10 ha drained during the 25 year period. The drainage rate for this approximately 34,600 km^2 area is 1–2 lakes per year, which is similar to that observed on the Tuktoyaktuk Peninsula by *Mackay* [1988], but represents an area about six times larger. This indicates relative landscape stability, and suggests that there are many unknown factors influencing lake susceptibility to catastrophic drainage.

Such factors might include lake density and size, surficial material, ground ice content, distance from the coast, local topography, vegetation cover, and direct human impact.

[38] The spatiotemporal pattern of recent (post-1973) catastrophic lake drainage events suggests that drainage patterns are not uniform over space. Large meandering streams and associated tributaries can result in a corridor of lakes that drain catastrophically. Headward erosion of streams in those areas of high relief, such as marine cliffs and stream cutbanks, promote nearby lake drainage. Thus the spatial pattern of recently drained lakes is moderated by local conditions.

[39] Although Landsat images extend back to 1973, aerial photos exist for most of the North American arctic since circa 1950, doubling the temporal period of coverage. By carefully establishing ground control points, photo-overlay of the Barrow Peninsula demonstrates observed changes since circa 1950. In this area, the local hydrology has clearly been impacted by human activity; of the 19 lakes that completely drained during the period 1949–2002, at least seven were the result of intentional or inadvertent modification. Analysis of aerial photos and oral histories of local residents indicate that tracked vehicles bulldozed channels or created deep ruts that triggered localized thermokarst and ultimately resulted in lake drainage. At the same time, several lakes have formed or expanded. Warming air temperatures and a deeper active layer will likely cause ground subsidence, lake expansion, and lake drainage in regions of low relief. However, a similar effect can be achieved by increasing the precipitation/evaporation ratio since higher lake levels would result in bank overtopping and lake drainage. Separating these influences from each other, and from the effects of direct human activities, will pose a significant challenge to researchers.

[40] Our work with Iñupiaq collaborators and the insights gained from our interviews have provided this research with a valuable perspective. The fact that we have been able to corroborate their observations of specific events using remote sensing and aerial photography underscores the efficacy of their observations. We are continuing to interview indigenous people and other knowledge holders on the ACP in order to acquire as much information about landscape changes as possible. This information is geocoded and mapped in a GIS framework, and is returned to local communities for use as an educational and resource management tool.

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