THERMOKARST LAKE CHANGES IN CONTINUOUS PERMAFROST ON THE TUKTOYAKTUK PENINSULA, WESTERN CANADIAN ARCTIC

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Abstract

Landsat remote sensor imagery from 1978-2001 and GIS software were used to classify thermokarst lake area and determine changes in lake coverage on the Tuktoyaktuk Peninsula in Northwestern Canada. Study area segments were constructed to examine total lake area changes for multiple lake class sizes between periods ranging from 1-22 years. Climatological data were obtained to compare trends in studied years to thermokarst lake growth factors including mean annual temperature, thaw temperature, and cumulative precipitation. Substantial lake area growth (up to 15%) and shrinkage (up to 11%) were detected, with growth occurring primarily between 1978-1992 and shrinkage between 1991-2001. These changes correlate strongly with cumulative precipitation data ($r^2 = 0.823$) and suggest that this is the primary factor influencing lake growth detectable on a large scale when relatively coarse resolution remote sensing is used. These results also suggest that long-term lake area changes are well masked by short-term climatological changes, contrasting recent studies showing sustained long-term changes attributed to Arctic climate change.

Key Words: Tuktoyaktuk, thermokarst, Arctic lake, remote sensing, Landsat, lake change

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CHAPTER 1 – INTRODUCTION

1.1 - Overview

Much of the northwestern Canadian Arctic landscape is heavily influenced by thermokarst lakes and ponds, which cover between 15% and 50% of total land area (Rampton, 1988., 2005, Burn, 2002). Thermokarst lakes form, coalesce with other lakes, and drain (often rapidly) over geologically short periods, with life-cycles often measurable in centuries (French, 1996). These characteristics make thermokarst lakes the primary influence on the landscapes they occupy (Fig. 1.1) (Frohn et al., 2005, French, 1996). The massive scope of thermokarst lake systems and their isolation make satellite remote sensing an ideal tool for further study. Recent remote sensing studies have been undertaken in northern Alaska by Frohn et al. (2005), in the Yukon by Duguay et al. (1999) and in Siberia by Smith et al. (2005), and provide a basis for comparison for this study.

Here I identify the extent of thermokarst lake coverage in northwestern Canada, focusing on the Tuktoyaktuk Peninsula. To examine changes I use both recent (2000/2001) satellite imagery and corresponding data from 1978/1979 and 1991/1992 using the IDRISI geographic information system to produce an appropriate comparison. The purpose of this analysis is to observe changes in total lake coverage for this period and to examine growth trends derived from these results in the context of regional climate factors.

1.2 - Thermokarst Lakes and Climate Change Feedbacks

Thermokarst lakes are the dominant feature in lowland periglacial environments, and are generally caused by the melting of ground ice in areas of high ice content (permafrost), subsidence of ground, and accumulation of water in shallow depressions (MacKay, 1997). Subsequent growth of thermokarst lakes is attributed to processes such as wind-driven wave erosion, slumping, and continual thawing at lake margins (French, 1996). Thermokarst lake sizes are highly variable, ranging from several kilometers to dozens of meters, but are typically shallow, seldom deeper than 3-4 meters, while being much more shallow at their littoral margins (MacKay, 1988).

Figure 1.1 – Thermokarst Lake Dominated Terrain

Figure 1.1. Thermokarst lake dominated terrain, near Barrow, Alaska. (Courtesy of S. Marshall, www.arcus.org)

As thermokarst lakes form and grow in part due to regional temperature fluctuations, overall growth in size and/or number of thermokarst lakes may prove to be a valuable indicator of changing Arctic climate. The 2004 Arctic Climate Impact Assessment (ACIA) noted that temperatures in the western Canadian Arctic and parts of Alaska have risen up to 3°- 4°C over the past 50 years, while overall Arctic precipitation has increased by approximately 8% in the past 100 years. Many other current studies also indicate various degrees of warming occurring in high latitudes (Chapin et al., 2005, Smith et al., 2005, Maxwell, 1997). Arctic tundra typically acts as a net carbon sink, with large volumes of organic material stored in frozen soils and permafrost of northern ecosystems (Oechel et al., 1993, Woo et al., 2000). Studies by Oechel et al. (1993) indicate that Arctic tundra has become a net carbon source as rising temperatures accelerate carbon release more rapidly than carbon fixation by local flora is increased. Melting of Arctic soils and permafrost may create additional carbon-contributing environments such as northern peatlands, which account for 30% of global soil carbon and 5 to 10% of global methane emission, despite occupying only 3% of land area (Blodau, 2002). Thermokarst lakes play a major role in melting large sections of permafrost and ice-rich Arctic soils, contributing to the positive feedback on atmospheric carbon dioxide already underway.

1.3 – Study Area

The Tuktoyaktuk Peninsula (Fig. 1.2) is on the northern coast of the Northwest Territories, bordering the Beaufort Sea This 40 km wide peninsula stretches from the hamlet of Tuktoyaktuk to Cape Dalhousie at its northernmost point. The Beaufort coastline is typically composed of unconsolidated, but ice-cemented, sediments, including mud, gravel, sand, and glacial diamict (Rampton, 1988). The landscape of the Tuktoyaktuk Peninsula is a distinctive combination of thousands of thermokarst lakes, as well as an abundance of pingos. Permafrost thickness generally ranges from 200-600 m in this region, and the overlying active layer ranges from 50 cm to 150 cm (Cote and Burn, 2002). Mean temperature recorded at the town of Tuktoyaktuk is -10.3°C and mean annual precipitation is 142 mm (Environment Canada, 2005). Elevations vary, but are typically less than 60 m RSL.

Figure 1.2 – Regional Study Area

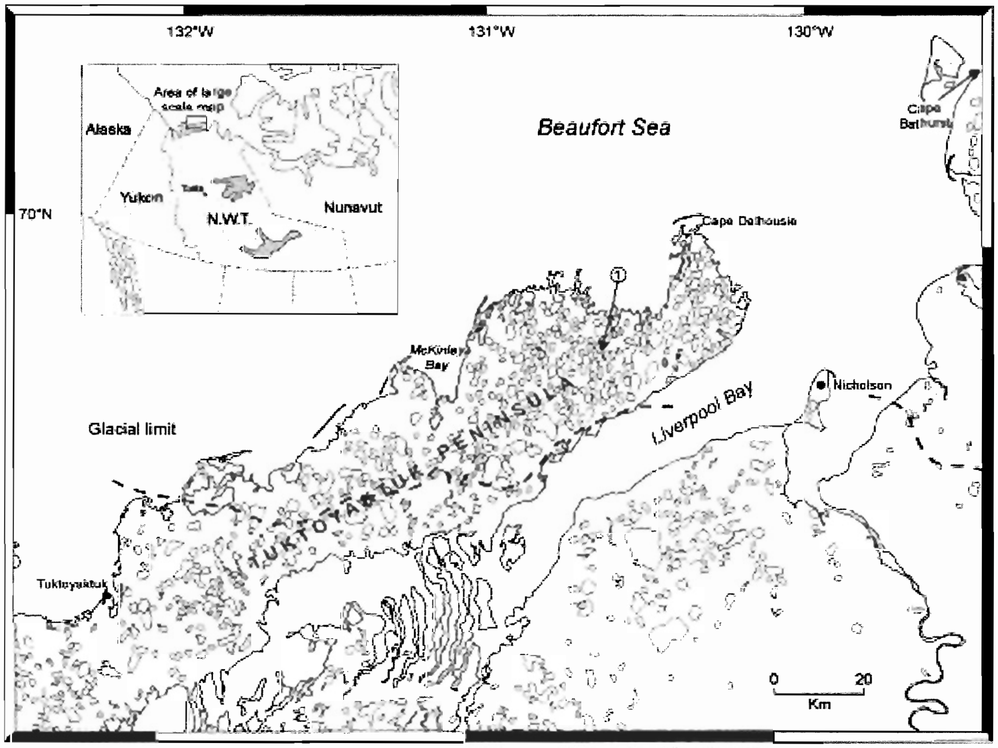


Fig. 1.2 - The Tuktoyaktuk Peninsula of Canada's Northwest Territories, From Cote and Burn (2002).

1.4 - Previous Studies

Numerous studies of this region and its accompanying permafrost and thermokarst features have been conducted, most notably by MacKay (1956, 1981, 1988, 1997, among others), Rampton, (1988), French (1996), and others (see MacKay, 1997, for an additional list of references). Of particular relevance to this study are three recent remote sensing projects. Frohn et al. (2005) recently employed Landsat-7 imagery and GIS software to conduct a detailed examination of thermokarst lake and drained thermokarst lake basin coverage. Their analysis found thermokarst lake coverage on the Alaskan Arctic Coastal Plain range from 20%, to as high as 40%, and coverage of the Alaskan Foothills and Seward Peninsula to be considerable as well (Frohn et al., 2005). Their study was a more detailed GIS analysis than is attempted here, and is a first for reliably identifying drained thermokarst lake basins using remote sensing, though it did not track changes in modern lake coverage.

Duguay et al. (1999) used Landsat data for a small area of the Old Crow Flats in the Yukon from 1973-1999, tracking changes in detected lake area. Both lake area increases and decreases were detected, while equivalent lake areas did not change significantly from 1986-1999.

Smith et al. (2005) recently undertook a remote sensing and GIS analysis of changes in lake coverage of over 10,000 large lakes across 515,000 km² of Siberia between 1973 and 1998. Their analysis showed a net decline in total lake coverage, with a 6% decrease in overall lake area. In continuous permafrost zones, however, Smith et al. (2005) note a 12% (13,300 ha) increase in total lake area and a 4% increase in total lake numbers (in lakes larger than 40 ha). Smith et al. attribute these changes to progressively increasing Arctic temperatures, a conclusion which will discussed in greater detail in Chapters 4 and 5. A similar method to Smith et al. (2005) is applied to the western Canadian Arctic in this study.

CHAPTER 2 – BACKGROUND

2.1 – Thermokarst Lakes

2.1.1 – Lake Characteristics

Thermokarst lakes are a common phenomena in lowland periglacial environments such as the Tuktoyaktuk Peninsula. These shallow rounded depressions contain circular to ellipsoidal ponds or lakes (French, 1996). While referred to as thaw lakes, thaw depressions, tundra ponds, and cave-in lakes in North American literature, they will be referred to here as thermokarst lakes following the *Multi-Language Glossary of Permafrost Terms and Related Ground-Ice Terms* (van Everdingen, 2005).These features may occupy 15-50% of total land area in flat lowland Arctic environments where silty-clay alluviums with high ground-ice or massive ground-ice contents are present (French, 1996, Burn, 2002).

2.1.2 – Growth and Morphology

The initial cause of thermokarst lake formation is simply melting of ground ice or local subsidence that allows accumulation of water in a depression (French, 1996). Initial melting occurs due to disruption of the thermal equilibrium of permafrost causing subsequent increase in the depth of the active layer. Potential reasons for this thermal disruption vary, and include regional climate change, polygonal ground development, or human activity such as disruption of vegetation cover (Harry and French, 1983). In areas where permafrost is thicker, thermokarst lake formation is often associated with existing ice-wedge polygons, where the depressed polygon centers promote formation of standing water (Harry and French, 1983).

Bodies of standing water then grow through continued melting of ice-rich soil and sediment both vertically (melting of permafrost at depth) and laterally (melting at lake margins), and often coalesce with adjacent ponds and lakes. Thaw of bordering permafrost and undercutting of shoreline vegetation causes retreat and collapse of banks (Fig. 2.1), creating smooth circular lakes in many cases (French, 1996). Shoreline erosion may be accelerated by the strength and direction of prevailing winds, creating circulation patterns which erode banks (Harry and French, 1983). Yearly growth from bank retreat has been measured at 15-20 cm per year in some areas, depending on water temperature, wind activity, and precipitation (MacKay, 1988).

Figure 2.1 – Thermokarst Lake Growth and Development

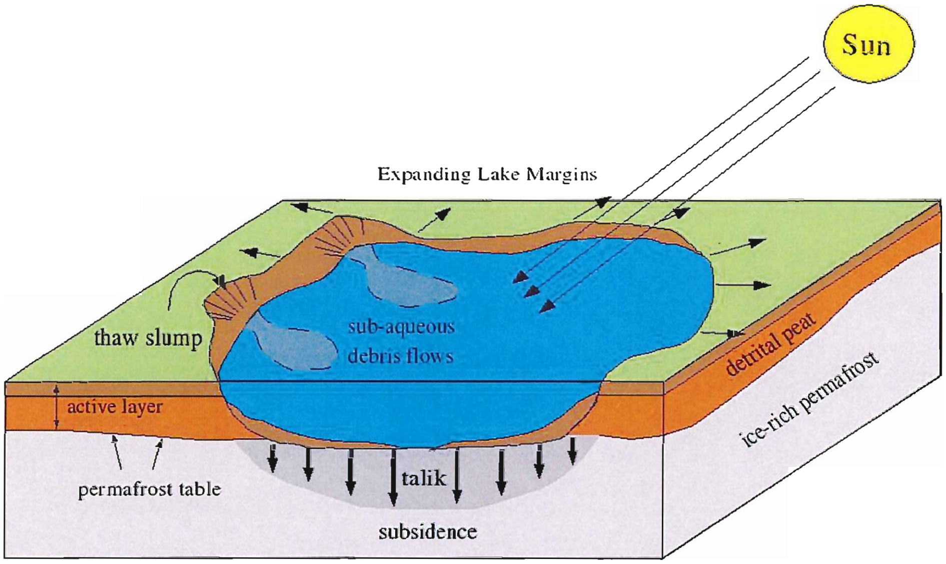


Figure 2.1 – Thermokarst lakes expand vertically through melting of ice-rich permafrost and laterally through melting of ice-rich sediment at lake margins or through undercutting of banks, often leading to thaw slumping.

Thermokarst lake size varies considerably, with more mature lakes typically less than 300 m in diameter, but reaching over 2 km in some cases. Thermokarst lakes are typically very shallow, rarely exceeding 3-4 m depth at their center, and generally less than 1 m in depth along lake margins (MacKay, 1997). This makes thermokarst lakes particularly sensitive to temperature and precipitation changes, as small changes in water level may alter total lake area considerably.

2.1.3 – Lake Attenuation and Drainage

Thermokarst lake growth often causes lakes to expand beyond the initial depression in which they formed. This may allow for coalescence with other lakes, greatly increasing their size. This process may also create access to a suitable drainage channel causing drainage into another suitable depression, or into a river, lake, or the ocean (French, 1996). Breached lakes, where contact with the coast occurs through drainage channel formation or coastal erosion, are common along the coast of the Tuktoyaktuk Peninsula (Cote and Burn, 2002, Cote et al., 2003). This process is aided by frequent storm-surge flooding which is common on the Tuktoyaktuk Peninsula (Environment Canada, 2000). Ice-wedge systems melting and erosion by lakes is a major cause of drainage channel formation. Lake drainage may be gradual, emptying over months or years, or catastrophic, emptying over days or hours (Marsh and Neumann, 1997, MacKay, 1988, Plug and Gardner, 2006). Drained basins are then re-vegetated and lake basins infill with silt and organic matter. In the case of catastrophic lake drainage, solifluction and mass-wasting may occur, moving material into the drained lake basin immediately. Either process may obliterate drained lake basins from the landscape over time. They may also serve as depressions for the eventual rebirth of future thermokarst lakes (Cote et al., 2003).

2.2 – The Tuktoyaktuk Peninsula

2.2.1 – Geology and Climate

The Tuktoyaktuk Peninsula consists of a thick wedge of Pleistocene marine and fluvial sediments rich in ground ice which have been modified by glaciation and thermokarst activity. Underlying the Quaternary deposits are Cretaceous and Tertiary bedrock (Rampton, 1988). Unconsolidated sediment forms a thick layer over most of the peninsula and bedrock outcrops are rare (Rampton, 1988). Elevations are low, typically less than 60 m RSL. Thermokarst lakes commonly occupy 30% of the land area, and rarely less that 15%. Much of the landscape is poorly drained and marked by irregular drainage patterns from thermokarst lake activity.

The Tuktoyaktuk Peninsula is an area of continuous permafrost, where more than 80% of land area is underlain by permafrost (Burn, 2002). The seasonally thawing active layer overlying the permafrost varies in thickness from 50-150 cm across most of the peninsula, while permafrost thickness ranges from 200-600 m (Cote and Burn, 2002, Rampton, 1988). Vegetation cover is relatively continuous in the Tuktoyaktuk Peninsula, and is comprised of sedge, shrubs, lichen, and moss (Rampton, 1988). Vegetation cover is an important factor in Arctic Lowland terrain because the type and density of plant cover determine the thickness of the active layer and the stability of ground ice (Carter et al., 1987).

The Tuktoyaktuk Peninsula is an Arctic Lowland environment, characterized by low air temperatures, short cool summers, long cold winters, and low precipitation (Carter et al., 1987). The annual average temperature for Inuvik, the closest monitoring station with recent annual average data, is -8.8°C, with monthly average temperatures ranging from -27°C to -28°C in January and February to 11-14°C in June and July. Mean annual air temperature has increased in this area by 1.7°C over the past century, the greatest recorded increase in Canada (Environment Canada, 2005). Average monthly temperatures remain consistently positive from June to September (Environment Canada, 2005). Annual precipitation is relatively low, averaging 140-160 mm, 35-50% of which typically falls as rain with the rest accumulating as snow (Carter et al., 1987). Rainfall is highest in August and late July, and normally falls gradually, with Inuvik reporting an annual mean of 144.3 days of precipitation (Environment Canada, 2005), though infrequent storms may rapidly deposit 20-30% of annual precipitation (Carter et al., 1987).

2.2.2 – Human Activity

The hamlet of Tuktoyaktuk on the southwest margin of the Tuktoyaktuk Peninsula has a population of 1000 (as of 1994) and is the only permanent settlement on the peninsula (Environment Canada, 2005). Most human activity in this area is centered around the hamlet of Tuktoyaktuk which serves as a transportation center supporting oil and gas exploration in the Beaufort Sea and previously served as an important transportation and maintenance hub for the Distant Early Warning (DEW) line of Canadian and American radar sites designed to provide warning of Soviet missile attack. With most oil and gas exploration focused on offshore resources and the MacKenzie Delta region the vast majority of the Tuktoyaktuk Peninsula is virtually untouched, though renewed interest in potential gas deposits may drive additional exploration in the near future (Indian and Northern Affairs Canada, 2005).

2.3 – Remote Sensing

2.3.1 – Utility of Remote Sensing in Northern Environments

Instrumentation sites in northern latitudes are sparse and poorly distributed, and their number are declining, making satellite remote sensing an ideal tool for studying many Arctic processes (Duguay and Pietoniro, 2005). Satellite imagery can be used to examine a wide variety of features on a massive scale, including "snow cover, glaciers and ice sheets, lake and river ice, permafrost and seasonally frozen ground, surface water and soil moisture, evaporation, and evapotranspiration" (Duguay and Pertoniro, 2005). In studies of northern hydrology remote sensing is quickly becoming a dominant tool which will only expand in value as several new satellite platforms are launched over the next five years (Duguay and Pertoniro, 2005).

2.3.2 – Principles of Remote Sensing

As explained by Lillesand and Kiefer (2000) the term *remote sensing* refers to any analysis performed with an instrument that is not in contact with the subject of the analysis. By this broad definition remote sensing includes every type of analysis from seismic surveys to visual inspection. The popular use of the term, however, generally refers to the use of electromagnetic energy sensors deployed from airborne and spaceborne platforms to assist in the inventorying, mapping, and monitoring of earth resources (Lillesand and Kiefer, 2000). Data from these sensors is often processed by geographic information system (GIS) software.

A variety of satellite sensor platforms have operated since the early 1970's designed to emit and/or detect electromagnetic energy ranging across the spectrum, from visible light (0.4-0.7 μm wavelength) and near-infrared/infrared(~0.77-1000 μm wavelength) to microwaves and radar (1mm-30cm wavelength) (Lillesand and Kiefer, 2000). Satellite remote sensors detect the reflected energy incident on a given earth surface (or shallow sub-surface) feature, the magnitude of which is dependent on the magnitude of incident energy, reduced by scattering and absorbtion and by the atmosphere and feature being studied. The resulting data are based on spectral reflectance, forming spectral response patterns to be interpreted by the user (Lillesand and Kiefer, 2000). Optimally, satellite remote sensing is used in conjunction with other methods of observation, such as aerial photography or ground-level field studies, though this is often difficult in large areas of undeveloped terrain, such as Arctic regions.

2.3.3 – Landsat

The Landsat program began in 1967 as an attempt to determine the feasibility of satellite remote sensing of earth resources. Landsat-1, launched in 1972 was the first unmanned satellite specifically designed to acquire data about earth resources on a systematic, repetitive, multispectral basis (Lillesand and Kiefer, 2000). Landsat satellites operate within the optical spectrum, from approximately 0.3-14 μm, including UV, visible, and near-, mid-, and thermal infrared wavelengths. Three generations of increasingly capable Landsat platforms have been deployed since 1972, from Landsat-1 to the current Landsat-7. A combination of satellite generations must be employed to observe change over any period greater than 7-8 years. Capabilities and limitations of each will be discussed briefly, as data from each generation was used in determining thermokarst lake changes in the Canadian Northwest.

Landsats 1-3 comprise the initial generation of satellites and were equipped with a Multispectral Scanner (MSS) and return beam vidicron (RBV) cameras, though the RBV were plagued with problems and their data are not generally used. The MSS covered 185-km swaths of the earth in four wavelength bands, two in the visible spectrum and two in the near infrared spectrum, returning data in 79 m by 79 m cells (Lillesand and Kiefer, 2000).

Landsats 4 and 5 represent the second generation of satellites, and were equipped with a Thematic Mapper (TM) sensor suite which could acquire data in seven bands, expanding the wavelength range to include the full visible light spectrum to thermal infrared. Ground cell size is reduced to 30 m by 30 m and geodetic position was improved due to an upgraded ground tracking system (Lillesand and Kiefer, 2000).

Landsat-7, launched in 1999, is the most recent (and last planned) addition to the program and is equipped with an Enhanced Thematic Mapper plus (ETM+) sensor suite which includes a panchromatic band operating in the 0.5-0.9 μm range with a spatial resolution of 15 m. Data collected from this sensor can be used in combination with other 30 m TM bands to produce color images with a ~15 m resolution with sufficient processing. An additional thermal IR band was also included (Lillesand and Kiefer, 2000). Landsat-6, jokingly referred to as a Pacific seabed sensor, suffered a launch failure in 1993.

CHAPTER 3 – METHOD

3.1 – GIS Analysis

3.1.1 – Data Acquisition

Data for this study were collected from Michigan State University's landsat.org, where Landsat data from all three satellite generations were available for the Canadian Northwest. Six Landsat scenes were selected based on data availability, providing partial coverage of the Tuktoyaktuk Peninsula from 1978/1979 and complete coverage from 1991/1992 and 2000/2001. These were the only available images which provided sufficient coverage of Tuktoyaktuk Peninsula for all three satellite generations spanning 21-23 years. All the Landsat scenes used were acquired between June 28th and September 19th (Table 3.1) of their respective years during periods of negligible cloud cover.

Table 3.1 – Landsat Scene Characteristics

Path	Row	Reference System	Date (d/m/y)	Platform
67	11	WRS-1	06/07/78	Landsat-2
71	11	WRS-1	10/08/79	Landsat-2
61	11	WRS-2	18/07/92	Landsat-5
63	11	WRS-2	28/06/91	Landsat-5
61	11	WRS-2	09/09/00	Landsat-7
63	11	WRS-2	19/09/01	Landsat-7

Table 3.1 – Landsat image characteristics used in this study. Image locations use the Worldwide Reference System (WRS) for Landsat satellites, which assigns a path and row number to each image.

The Landsat-2 scene from 1979 (p71 in the WRS-1 reference system) is of lower quality than the other scenes, containing a small area of cloud cover over the lower Tuktoyaktuk Peninsula as well lines and isolated pixels of missing data. Total missing data comprises approximately 2-3% of the scene.

3.1.2 – Imagery Specifications

All the images used were processed between 1990-2002 by the Earth Satellite Corporation (1998) and were orthorectified to eliminate geometric distortions inherent in transferring information from three dimensions to two dimensions, yielding map-accurate images. MSS images were converted to the Universal Transverse Mercator (UTM) projection (UTM-8) and the World Geodetic System 1984 (WGS84) ellipsoid model using geodetically accurate TM imagery as a reference, making this imagery consistent with imagery from subsequent Landsat generations. This processing reduced MSS imagery pixel size from 80 m to 57 m and improved positional accuracy (Table 3.2).

Table 3.2 – Effects of image pre-processing

Satellite	*Sensor*	*Raw Resolution (m)*	*Processed Pixel Size (m)*	*Absolute Positional Accuracy (RMS) (m)*
Landsat-2	MSS	80	57	100
Landsat-5	TM	30	28.5	50
Landsat-7	ETM+	15, 30, and 60	14.25, 28.5, and 57	50

Table 3.2 – Processed pixel size as compared to raw sensor resolution. Post-processed accuracy is improved, particularly in the case of MSS data. Multiple pixel sizes for ETM+ data reflect multiple bands used by the Landsat-7 platform. Bands in common with MSS and TM imagery have a 28.5 m pixel size, while the panchromatic band possesses a 14.25 m pixel size.

3.1.3 – Initial Processing

Each image was imported into the IDRISI Kilimanjaro GIS software. Each image band was then enhanced to improve contrast, performing a linear stretch with saturation set at 3%, effectively grouping the highest and lowest reflectances and increasing the contrast of the remaining data proportionally. The resulting images were then classified by unsupervised classification using the IDRISI CLUSTER module. This module examines all the available Landsat bands (from visible light to near-infrared) in order to isolate dominant spectral response patterns. CLUSTER uses a histogram peak technique of cluster analysis. CLUSTER stretches each band of the original image into a number of grey levels and creates a histogram of reflectance values with one dimension for every band selected (1-7 dimensions). It then identifies peaks in distribution of reflectance values and assign all pixel reflectance values to the nearest peak, creating classes. In the broad classification used for this analysis a class must contain a higher frequency of values than all of its non-diagonal neighbors. The resulting classes (typically 4-9) were then reclassified to combine all signatures that occurred on land (barren land, flora types, drained lake basins) and all those representing water (deep water, sediment-rich water, or ice coverage) to create a binary image consisting of water and non-water. This reclassification was performed by by visually comparing the CLUSTER image with a true-colour equivalent produced by combining the three visible light bands from each image.

3.1.4 – Defining the Study Area

Binary images from each time period produced by the initial processing were combined (concatenated using the CONCAT module) into a mosaic showing the available study area from each period. Each mosaic was divided into distinct areas of interest by constructing polygons to isolate them. These overall areas were too large to allow use of the GROUP module to analyze them for individual objects, requiring that each study area be subdivided into two or more parts. Areas were subdivided along scene boundaries, ensuring that each section represents only one time period. This allows for a comparison not only of thermokarst lake changes over the 21-23 year period, but also for comparisons of the areas common to multiple images within the same time period. This provided a means to assess consistency in later (1991/1992 and 2000/2001) time periods, as some images from the same period were taken up to one year apart and range from June 28th (Arctic spring) to September 19th (fall). Five study areas were created in total. Table 3.3 describes the nature and purpose of each study area.

Table 3.3 – Study Area Components

Study Area	Satellite Paths Used	Dates Available	Area (km²)	Purpose
MSS Lower Tuktoyaktuk	p71, p63	1979, 1991, 2001	1880	Full range lake change comparison
MSS Upper Tuktoyaktuk	p67, p61	1978, 1992, 2000	3370	Full range lake change comparison
Central Tuktoyaktuk	p63,p61	1991/1992, 2000/2001	3910	Short term (1 year) lake change comparison
TM/ETM+ Lower Tuktoyaktuk	p63	1991, 2001	7120	Recent lake change comparison over maximum available area
TM/ETM+ Upper Tuktoyaktuk	p61	1992, 2000	4210	Recent lake change comparison over maximum available area

Table 3.3 – Study area characteristics. Five zones of interest were examined. Lower and Upper MSS zones allowed for a lake change analysis over the longest period but using the smallest amount of the Tuktoyaktuk Peninsula. Lower and Upper TM zones comprised the entire peninsula, but analyzed only 8-10 years of change. The center of the Tuktoyaktuk peninsula common to paths 61 and 63 for TM/ETM+ imagery was used to compare short-term change, particularly to assess the impact of using scenes taken several weeks apart in the relevant season. Total area of the Tuktoyaktuk Peninsula (from TM/ETM+ combined images) is ~7500 km².

While the entire Tuktoyaktuk Peninsula is the study area for all TM/ETM+ data (Fig. 3.2), MSS imagery contains a large gap in the central Tuktoyaktuk Peninsula where the available Landsat-2 paths did not join or overlap (Fig. 3.1). This gap was used to separate the primary study areas of the lower and upper Tuktoyaktuk Peninsula. A binary mask of each area (combining all land and water in the section) was created so that everything outside of these zones could be eliminated from subsequent images, allowing comparison of these two areas in all time periods.

3.1.5 – Isolating Thermokarst Lakes

Study area section polygons from each period were isolated following their selection and further processed to eliminate water signatures that were not (or not likely) thermokarst lakes. All distinct objects within these water/non-water polygons were first grouped. A dominant group in all images is ocean. Bodies such as breached lakes, estuaries, and rivers were considered part of the ocean where connectivity with the ocean was detectable. This group was eliminated from the final image.

Elimination of rivers and river fragments with no connectivity to the ocean required constructing new layers which defined the areas and perimeters of each object. These layers, once overlayed using division, produced a map showing each object's ratio of perimeter to area. Initial attempts found that this approach did successfully identify rivers, but also identified some lakes, particularly those with very small pixel sizes, giving them large perimeter-to-area values. Smaller objects were excluded prior to creating a mask to isolate rivers and any lakes connected to them, as well as fragments of rivers or other structures such as large ox-bow lakes. These features are very rare on the Tuktoyaktuk Peninsula, and this procedure did not identify many objects.

Figure 3.1 – MSS Imagery Coverage, 1978-1979

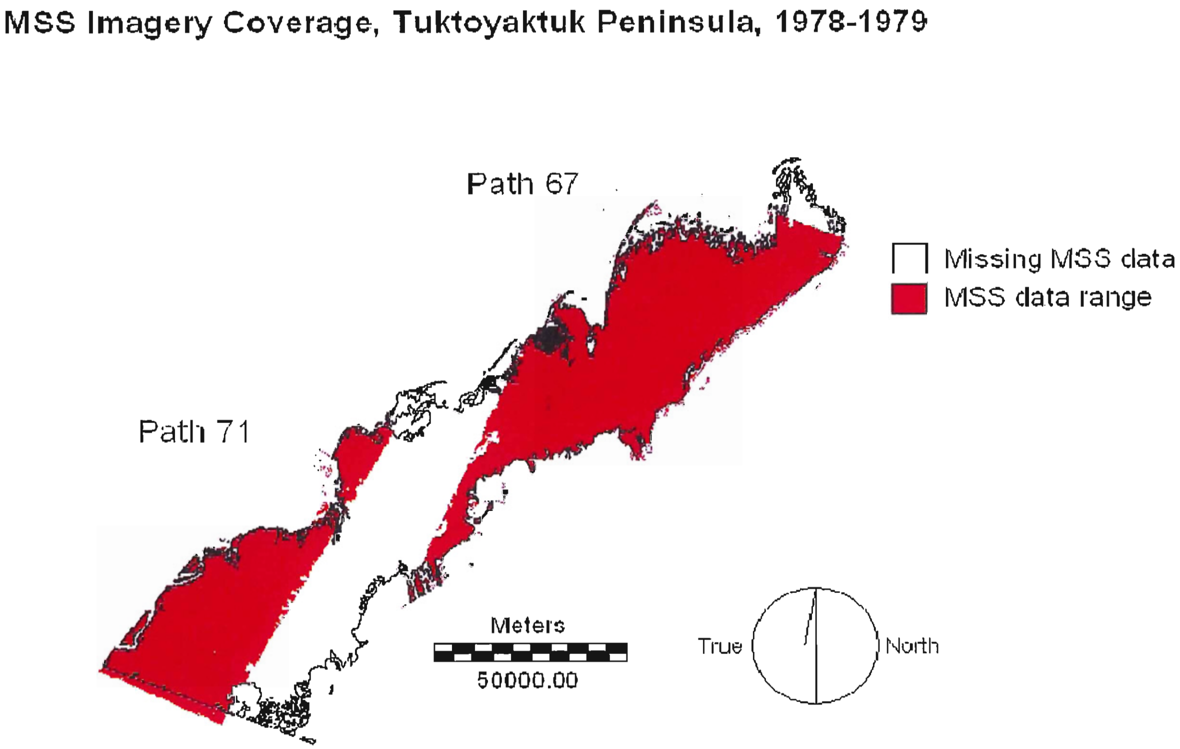
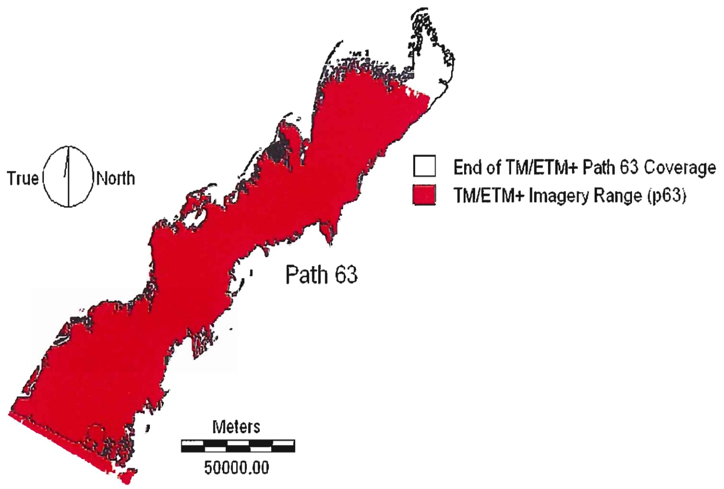


Figure 3.1 – Available Landsat-2 MSS imagery scenes did not join, leaving a segment of the central Tuktoyaktuk Peninsula as well as the northern tip without data. The areas shown in red were isolated and used to create masks applied to subsequent data in order to compare changes occurring in area of data coverage from all periods.

Figure 3.2 – TM/ETM+ Imagery Coverage, 1991-2001

TM/ETM+ Coverage, 1991-2001, Path 63



TM/ETM+ Imagery Coverage, 1992-2000

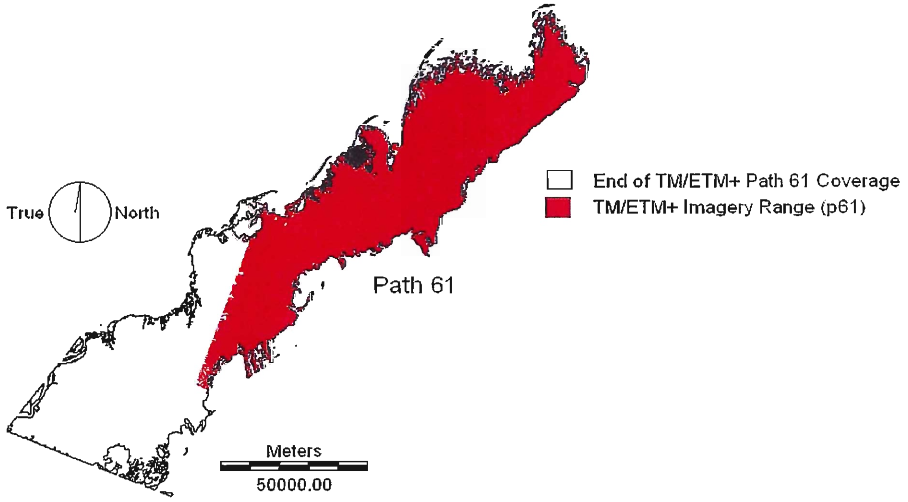


Figure 3.2 – Both paths for TM/ETM+ data cover the majority of the Tuktoyaktuk Peninsula. The overlapping data was compared between paths to examine change over single year periods.

Several other areas of the classified images of the Tuktoyaktuk Peninsula appeared inconsistent with thermokarst lake coverage, such as areas of swamp/wetland or partially inundated terrain near the coast. Eliminating these areas without removing all other small objects required manually excluding each area by drawing a polygon around each suspected swamp/wetland area and then using the polygon as a mask. Additional polygon masks were employed to mask coastal lakes where connectivity to the ocean was inconsistent between images. When image comparisons were made and coastal lakes were noted to suddenly appear or disappear between images these areas were examined on true-colour composites and excluded if necessary. This process was repeated for other ambiguous features. After applying these masks to every image the resulting cells classified as water are believed to be thermokarst lake cells in most instances, though the actual identity of very small water areas remains somewhat uncertain. Single and small multi-pixel water areas are often removed from parts of the results to improve the likelihood of dealing with thermokarst lakes more exclusively.

3.1.6 – Lake Classes and Area Comparison

After grouping all water object and excluding those inconsistent with thermokarst lakes the area of each object was determined individually (using IDRISI's AREA module). Objects were then reclassified into four area classes of small to increasingly large lakes. The AREA module was again used to reclassified lake class images to produce layers indicating the total area for all lakes in each class. Scenes from different times were not directly compared (no overlay operations were used).

Table 3.4 – Lake Area Classes

Lake Class	Area Range (m^2)	Pixel Range (MSS) (pixels)	Pixel Range (TM) (pixels)
Class 1	0.1 – 12996	1	1-4
Class 2	12996 – 263169	2-9	4-36
Class 3	263169 – 1299600	9-20	36-80
Class 4	1299600 – > Ocean	20 - > Ocean	80 - > Ocean

Table 3.4 – Area and pixel breakdown of the four lake classes used. Class 1 zones are subsequently referred to as class 1 water area rather than lake area, because classification uncertainty is greatest for these objects. Class 4 lakes comprise any lake above 1,299,600 m^2.

3.1.7 - Lake Area Change

A second analysis was performed on images for each study area to examine areas of lake growth and shrinkage between various time periods. Original water/non-water maps were used and reclassified to produce binary images of water and non-water. Images between periods were then added (overlayed) producing compositions with lake area common to both images, lake area found only in the older image (lake shrinkage) and lake area found only in the newer image (lake growth). The AREA module was then used to calculate the total area of each of the three possible classes.

3.2 – Sources of Error

3.2.1 - Resolution and Classification Error

A primary source of potential error in all aspects of this analysis is sensor resolution. The preprocessed Landsat MSS images have a cell size of 57 m, while Landsat 5 and 7 data have a 28.5 m cell size. Because the CLUSTER module assigns values based on the closest histogram peak some pixels may be classified as one class but contain some portion of another, as a pixel that represents an area covered by 51% water should be classified as a water pixel. Some error is likely to occur at all water pixels bordering non-water pixels. Assuming any water/non-water pixel border is correctly classified then the potential error at any boundary is up to half of the area of each border pixel. A 57 m border cell will be considered to have a water area <1624.5 m^2 if it is classified as water and >1624.5 m^2 if it is classified as land. Correspondingly, the accuracy of area values calculated for any lake is dependent on its overall size and perimeter. Figure 3.3 demonstrates the potential discrepancy between calculated area and actual area. In practice this error is minor as these errors cancel when using large data sets assuming the error is random and water content is not being systemically inflated or underestimated (Lillesand and Keifer, 2000). Error in lake area sizes in this study are highest in the lower size classes, and unlikely to be significant in the upper size classes. Table 3.5 describes the potential error for each of the size classes used in the overall lake area study.

Class 1 water area is likely to be the most erroneous, and may often correspond to area of high moisture content or other standing water (swamps and wetland) rather than actual lakes (Lillesand and Kiefer, 2000). Area was recalculated to exclude class 1 water area where it exceeded 1.5% of total lake area and where it changed between periods by more the 20%, as seen in most results tables presented in Chapter 4. In other instances the effect of class 1 water area on total lake area change is not substantial.

Figure 3.3 – Classification Uncertainty

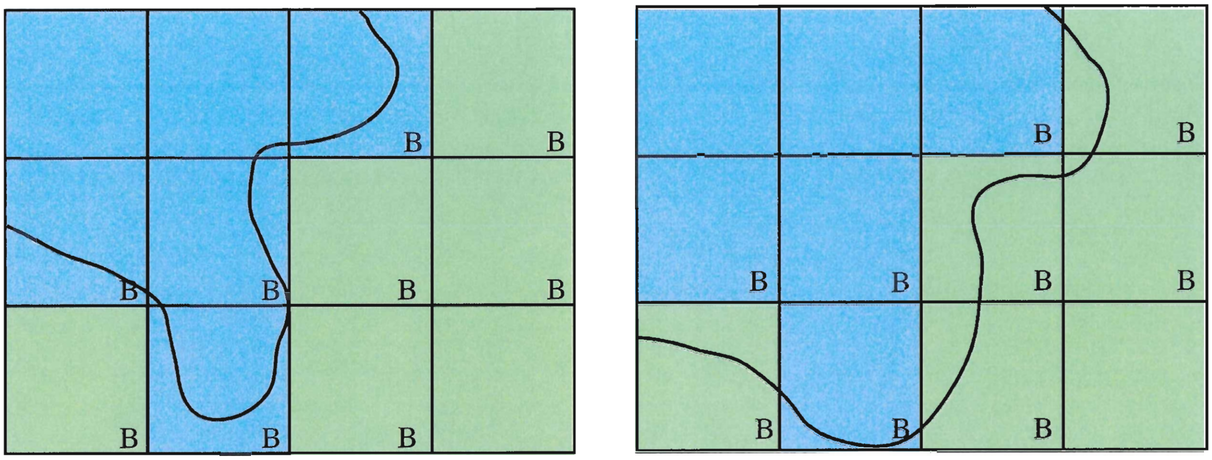


Figure 3.3 – Sensor resolution causes a coastline area like those above (wavy line) to be represented as water (blue) or non-water (green) depending on the dominant characteristic within each cell. These lake fragments have very different areas, but would be classified as shown in raster GIS. In this example, potential area error for each cell bordering another cell type (shown with B's in bottom right corners) may be up to 1624.5 m² (at 57m resolution). While the GIS system used would classify the lake fragment above as 19,494 m² (6 pixels at 57m resolution) its true size based on this pixel count could range from 34,115.5 m² to 4873.5 m² if every border cell was evenly divided between water and non-water (9 border cells +/- 1624.5 m² per cell for potential uncertainty).

Table 3.5 – Size class uncertainty for MSS data

Size Class	Area (m²)	Border Cells (square lakes)	Potential Uncertainty (m²)	Percentage uncertainty
Class 1: Min.	3.25 E+03	9	1.30 E+04	400
Max.	1.30 E+4	12	1.95 E+04	300
Class 2: Min.	1.30 E+04	12	1.95 E+04	300
Max.	2.92 E+05	24	3.90 E+04	14.8
Class 3: Min.	2.92 E+05	24	3.90 E+04	14.8
Max.	1.30 E+06	40	6.50 E+04	5.00
Class 4: Min.	1.30 E+06	40	6.50 E+04	5.00
Max.	3.25 E+11	804	1.31 E+06	4.02 E-04

Table 3.5 – Areal uncertainty as it decreases with size class. While error associated with class 1 and 2 lakes is significant, error for class 3 and 4 lakes (which constitute most of the area calculated) is much less important. Calculations above assume square lakes, underestimating total border area and decreasing uncertainty. Cancellation of errors by averaging over large areas of lake border is not considered, making these errors worst-case estimates. For TM/ETM+ imagery (with 28.5m pixel size) uncertainty is exactly 1/4 that of MSS imagery.

3.2.2 – Resampling Error

In order to calculate lake area change between periods it was necessary to convert MSS data to the 28.5 m pixel size found in subsequent TM data. The IDRISI RESAMPLE module constructs a larger grid (copied from the Landsat-7 scenes) and fits the the previous data to it by developing a series of polynomial equations to describe the spatial mapping of data from the original grid to the desired grid. This processes was greatly simplified in this case because all images use the same coordinate system and the new resolution was exactly double that of the original when converting Landsat-2 data. This effectively quartered every cell, converting each 57 m by 57 m pixel into four 28.5 m by 28.5 m pixels. In order to assess the effect of resampling the MSS data on lake area calculations total lake area was calculated for all study area MSS data before and after resampling. The original total lake area of 1454.073 km² changed to 1453.785 km² when resampled. This difference of 0.02% is assumed to be insignificant, particularly when compared to the uncertainty inherent in the sensor resolution. In the case of Landsat-5 data, only the grid size was changed. As the actual cell size was identical to the Landsat-7 data the grid size change merely added empty cells to the image background, leaving the actual data unaltered.

3.2.3 - Positional Accuracy

Uncertainty in actual position may be an important source of error for lake change calculations where data from different periods were overlayed in processing. The Landsat MSS data used has an absolute positional accuracy of 100 m RMS, while TM imagery has an absolute positional accuracy of 50 m RMS (Earth Satellite Corporation, 1998). While precise positional accuracy is not needed to calculate overall lake area within a single image it may be a source of systematic error when comparing multiple images. When images are overlayed for the lake change analysis, lake growth and shrinkage are recorded where lakes no longer overlap. Positional inconsistency between two images may cause an unchanged lake to appear offset in two different images, creating the appearance of lake area simultaneously increasing on one Landscaptelake margin and decreasing on the opposing margin. This should not affect net lake change, as positional errors will cancel in this analysis, but may create an impression of greater lake change activity than is warranted. In some lake change map compositions (Fig. 3.4) there is evidence of multiple lakes which appear to have reduced in area along one margin while correspondingly increasing along the opposing margin. In other instances growth or shrinkage envelopes the entire lake, while other lakes show no change, suggesting that this potential error is small and not entirely systemic.

Figure 3.4 – Positional Error and Lake Change

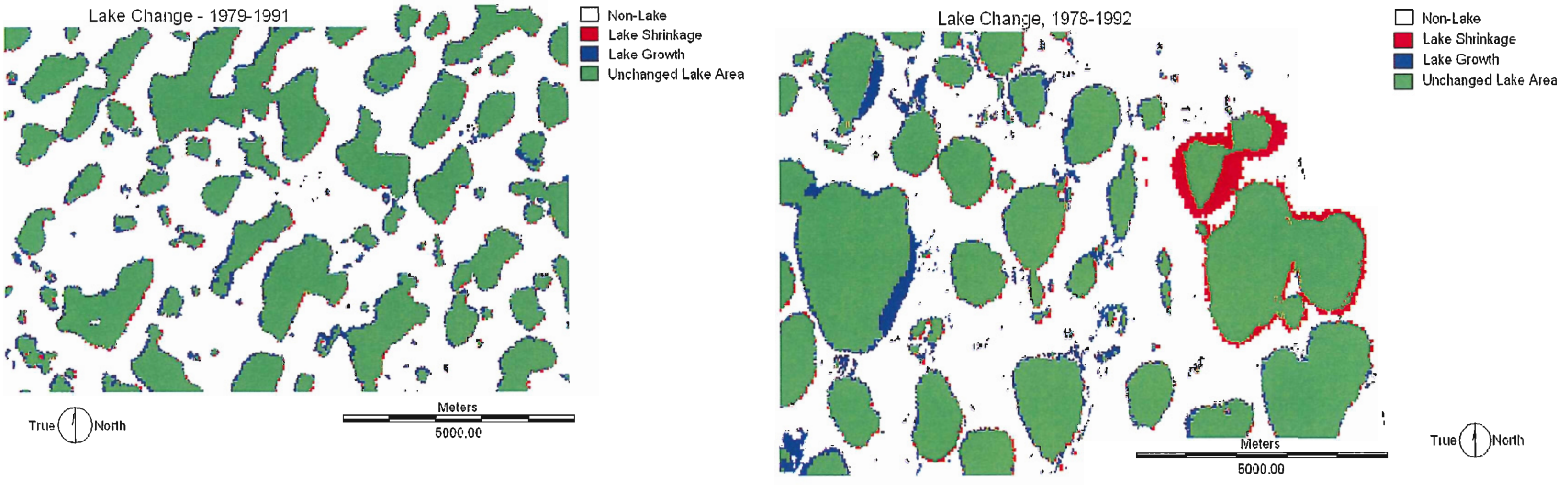


Figure 3.4 – Both images above are a comparison of 1978/1979 MSS imagery to 1991/1992. Imagery in the upper (right) and lower (left) Tuktoyaktuk Peninsula are for the MSS data range (Paths 67 and 71). The left image shows indications of positional error offsetting lakes and exaggerating lake change. Shrinkage (red) in the left image is consistently seen on the south-east lake margin with corresponding growth on the north-west margin. This can also be seen to a lesser extent in the right image, but this effect is dwarfed by other lake changes, with some lakes growing or shrinking along their entire margin. In the right image the large growth seen in the two large western lakes may be due to a water level increase covering shallow lake shelves that were not submerged in 1978. In the north-east section of the left image an example of the missing data lines found in Path 71 can be seen as a series of growth (blue) pixels cutting through several lakes in a NE-SW direction.

CHAPTER 4 – RESULTS AND DISCUSSION

4.1 – Lower Tuktoyaktuk Peninsula (MSS data range, 1979-2001)

Total lake class area results for the section of Lower Tuktoyaktuk Peninsula available in the MSS data (and common to all time periods) is shown in Table 4.1.

Table 4.1 - Lake Areas – Lower Tuktoyaktuk Peninsula (Path p71)

Area	1979 (km²)	1991 (km²)	% Change (1979-1991)	2001 (km²)	% Change (1991-2001)	% Change (1979-2001)
Total Lake Area	410.82	468.77	+14.1	415.53	-11.4	+1.2
Class 4 Lake	212.17	245.21	+15.6	203.20	-17.1	-4.2
Class 3 Lake	140.73	159.05	+13.0	147.08	-7.5	+4.5
Class 2 Lake	55.32	61.06	+10.4	60.62	- 0.72	+9.6
Class 1 Water	2.60	3.45	+32.7	4.63	+34.2	+78.1
Total Lake Area (without Class 1)	408.22	465.3	+14.0	410.90	-11.7	+0.7

Table 4.1 – Total area for each lake class from each time period for the section of the lower Tuktoyaktuk Peninsula covered by MSS data from 1979. Total lake area increased substantially between 1979-1991 and decreased substantially from 1991-2001. A mild increase is recorded over the entire period.

Total area change in this study area was substantial. Class 1 water type saw the largest percentage of increase between periods, and was the only type to increase between 1991 and 2001. Some Class 1 area increase is expected between 1979 and 1991, as increased sensor resolution of the TM imagery should allow for lakes to be detected that are 1/4 the actual size of the smallest lakes detected by MSS imagery. From 1991-2001, however, the Class 1 area increase was greater than the increase from 1979-1991. ETM+ imagery is superior to TM imagery due to the added sensor bands on Landsat-7, but overall resolution for most bands between Landsat 5 and 7 remains 28.5 m.

The extent of Class 1 increase that can be attributed to sensor quality cannot be determined here, so lake area was recalculated without Class 1 water area, which reduced the overall change from 1979-2001. Large lakes (Class 4) saw the greatest change, both in lake area and percentage of total lake area. From 1991-2001 lake area reduction was due largely to reduction in Class 4 lake area, while other lakes types contributed much less substantially.

Results from comparing study area segments from each time period to analyze lake growth and shrinkage over time are summarized in Table 4.2.

Table 4.2 -
Lake Area Change Across All Lake Classes from 1979-2001: Lower Tuktoyaktuk Peninsula (p71)

	1979-1991	1979-2001	1991-2001
Unchanged Area (km²)	388.03	388.64	410.09
Lake Growth (km²)	80.86	47.94	6.37
Lake Shrinkage (km²)	22.61	41.00	57.67
Net Change (km²)	+58.25	+6.94	-51.30

Table 4.2 – Total lake area change between time periods in the section of the lower Tuktoyaktuk Peninsula covered by MSS data from 1979. Net change between 1979-1991 is substantial. Net change as calculated using MSS data is consistent with the net change recorded from 1991-2001, which employed only TM/ETM+ data.

As seen in Table 4.1, significant lake growth took place between 1979-1991 and significant shrinkage occurred from 1991-2001. Total lake area varies from Table 4.1 to Table 4.2. In most study area sections values for total area are consistent between lake area (from combined lake class data) and lake area change calculations. The 1979 MSS scene, however, showed evidence of missing data, including the lines of missing data mentioned in Chapter 3. This caused lake area growth after 1979 to be exaggerated, as any missing data from 1979 that fell within existing lake area in subsequent periods was classified as lake growth. In order to minimize this discrepancy some lost data areas were removed by masking them with polygons as described in Chapter 3. As a result, total lake areas from this analysis do not match those from Table 4.1 as closely as in subsequent results. Total area removed was approximately 1-3 km². Missing data affect total area calculations less significantly, as missing data is simply classified as background (non-water), rather than being classified as lake growth between periods. Because each time period was examined individually, the missing data only affect the 1979 lake area figures from Table 4.1, causing recorded values to be underestimated.

4.2 – Lower Tuktoyaktuk Peninsula (TM data range, 1991-2001)

Lake class area and lake change results from the entire lower Tuktoyaktuk Peninsula using more recent TM/ETM+ data are shown in Tables 4.3 and 4.4.

Table 4.3 - Lake Areas: Lower Tuktoyaktuk Peninsula (p63)

Area	1991 (km²)	2001 (km²)	% Change
Total Lake Area	2147.10	1958.53	- 8.8
Class 4 Lake	1360.07	1186.47	-12.8
Class 3 Lake	518.92	502.39	-3.2
Class 2 Lake	248.30	242.10	-2.5
Class 1 Water	19.81	27.57	+39.2
Total Area Without Class 1 Water	2127.29	1930.96	-9.2

Table 4.3 – Total lake areas from 1991 and 2001 show a reduction in total lake area, as seen in section 4.1. Total area is recalculated here without class 1 water area in consideration of potential error (Chapt. 3), increasing the percentage of area loss to 9.2%, which is more consistent with the results seen in Table 4.1.

Lake area changes over the entire lower Tuktoyaktuk Peninsula are consistent with those from the section available from MSS data, though area loss is less here. With no lost data total area is consistent between Tables 4.3 and 4.4, as combining unchanged area with growth or shrinkage (Table 4.4) produces the total lake area for the respective year as recorded in Table 4.3. As in the MSS data range lake area loss is driven by reduction of Class 4 lake area, while Class 1 water area increased.

Table 4.4 -
Lake Area Change Across All Lake Classes From 1991-2001: Lower Tuktoyaktuk Peninsula (p63)

	1991-2001
Unchanged Area (km²)	1902.31
Lake Growth (km²)	56.20
Lake Shrinkage (km²)	244.26
Net Change (km²)	- 188.06

Table 4.4 – Lake area change from 1991-2001 is consistent with lake area figures in Table 4.3 and the general trend of lake shrinkage from 1991-2001. Despite an overall reduction, lake growth during this period is still considerable, indicating a high level of activity between these periods.

4.3 – Upper Tuktoyaktuk Peninsula (MSS data range, 1978-2000)

Tables 4.5 and 4.6 show lake area and lake change results for the section of the upper Tuktoyaktuk Peninsula common to all three time periods. This area includes the bulk of the available MSS data. As in the lower Tuktoyaktuk Peninsula lake area increased substantially from 1978 to 1992. Lake area reduction from 1992 to 2000 is less than was calculated for the lower Tuktoyaktuk Peninsula.

Surface water is relatively simple and reliable to identify in remote sensing and should pose no difficulty for the MSS sensor suite (Lillesand and Kiefer, 2000). This is supported by net lake change figures calculated by comparing MSS and TM data which are consistent with net change as calculated using only TM/ETM+ data, as was also the case in Table 4.2. This indicates that there is no major discrepancy in the classification of thermokarst lakes between MSS data and TM/ETM+ data despite the improved resolution and senor bands of Landsat 5 and 7. Unlike the lower Tuktoyaktuk Peninsula data, lake area increased in most lake classes but was negative overall due to reduction of Class 4 lake area.

Table 4.5 - Lake Areas: Upper Tuktoyaktuk Peninsula (p67)

Area	1978 (km²)	1992 (km²)	% Change (1978-1992)	2000 (km²)	% Change (1992-2000)	% Change (1978-2000)
Total Lake Area	862.09	979.98	+13.7	951.92	-2.9	+10.4
Class 4 Lake	626.07	727.54	+16.2	681.03	-6.4	+8.8
Class 3 Lake	161.21	158.72	-1.5	169.57	+6.8	+5.2
Class 2 Lake	69.00	82.29	+19.3	84.90	+3.2	+23.0
Class 1 Water	4.81	11.43	+137	16.42	+43.7	241%
Total Lake Area (without Class 1)	857.28	968.55	+13.0	935.50	-3.4	+9.1

Table 4.5 – Total lake area over time for the upper Tuktoyaktuk Peninsula (MSS data range) increases from 1978-1992 and decreases from 1992-2000, as in previous calculations. Lake loss from 1992-2000 is less here than the lower Tuktoyaktuk Peninsula from 1991-2001. All lake classes increased in area from 1991-2000 this period except for the largest lakes which more than offset these gains. A second calculation is made without Class 1 water area, and shows a 9.1% total area increase over the entire period.

Table 4.6 - Lake Area Change from 1978-2000: Upper Tuktoyaktuk Peninsula (p67)

	1978-1992	1978-2000	1992-2000
Unchanged Area (km²)	832.10	809.48	895.02
Lake Growth (km²)	147.87	142.434	56.90
Lake Shrinkage (km²)	29.26	51.19	84.59
Net Change (km²)	+117.74	+90.53	-27.69

Table 4.6 – Lake growth from 1978-1992 and 1978-2000 were similar while lake shrinkage increased from 1978-2000, decreasing net growth. Net change figures are consistent between calculations based on MSS data and the 1992-2000 net change based on TM/ETM+ data only. Net change from 1978-1992 shows significant activity.

4.4 – Upper Tuktoyaktuk Peninsula (TM data range, 1992-2000)

Results shown in tables 4.7 and 4.8 are consistent with those from the more limited MSS data range, but show less reduction in lake area from 1992-2000. As in the MSS data range increases in smaller lakes are offset by area loss of Class 4 lakes.

Table 4.7 - Lake Areas: Upper Tuktoyaktuk Peninsula (Path 61)

Area	1992 (km²)	2000 (km²)	% Change
Total Lake Area	1422.39	1399.48	-1.6
Class 4 Lake	1003.94	954.26	-4.9
Class 3 Lake	268.33	276.38	+3.0
Class 2 Lake	133.85	139.36	+4.1
Class 1 Water	16.27	22.48	+38.1
Total Area Without Class 1 Water	1406.12	1377.00	- 2.1

Table 4.7 – The TM data range for the upper Tuktoyaktuk Peninsula experienced less overall area change than the MSS data range. All the smaller lake classes increased in area but were offset by loss of lake area in the class 4 lakes. Total area is also shown recalculated without Class 1 water area.

Table 4.8 - Lake Area Change from 1992-2000: Upper Tuktoyaktuk Peninsula (Path 61)

	1992-2000
Unchanged Area (km²)	1312.13
Lake Growth (km²)	87.17
Lake Shrinkage (km²)	116.00
Net Change (km²)	-28.83

Table 4.8 – Net lake area change from 1992-2000 is similar for the TM data range and the MSS data range, despite the larger total lake area of the TM data range. While considerable activity appears to be occurring over this period little overall change occurred.

4.5 – Central Tuktoyaktuk Peninsula

Paths 61 and 63 for the TM/ETM+ imagery both provide coverage of the majority of the Tuktoyaktuk Peninsula, allowing short term comparison of lake area changes for the area common to both scenes from 1991/1992 and 2000/2001. From June 28th of 1991 to July 18th of 1992 very little change was detected. Table 4.9 describes both the area changes for each lake class and the growth/shrinkage over this period. Lake growth and shrinkage were both large compared to the actual net growth, with area changes offsetting one another. It is also possible that positional uncertainty has exaggerated these measurements to some extent.

Lake area change from September 9th of 2000 to September 19th of 2001 is greater than from 1991-1992. The -4.14% total area loss over this period (Table 4.10) is larger than the total area loss in the upper Tuktoyaktuk Peninsula over the 8 year period in Tables 4.5 to 4.8. These images are separated by 10 days seasonally, the closest of any image pairing used. Despite this a single year change of nearly 52 km² is recorded. This has implications for the effect of regional temperature and precipitation on observed lake area, which will be discussed in the next section.

Table 4.9 - Lake Area and Lake Area Change – 1991-1992: Common area (Paths 63 and 61)

Area	p63 - June 28th, 1991 (km²)	p61- July 18th, 1992 (km²)	% Change
Total Lake Area	1265.50	1269.57	+0.32
Class 4 Lake	873.29	872.82	-0.05
Class 3 Lake	251.01	254.35	+1.33
Class 2 Lake	127.85	127.64	-0.18
Class 1 Water	13.35	14.76	+10.1

Unchanged Area (km²)	1232.36
Lake Growth (km²)	37.19
Lake Shrinkage (km²)	33.14
Net Change (km²)	+4.05

Table 4.9 – Lake change from 1991-1992 appears limited, with a small increase in class 3 lake area driving a net area gain. Considerable lake growth and shrinkage appears to be occurring, but has produced a net change of only 4.05 km².

This single year area loss contributes to the discrepancy between area changes in the upper and lower Tuktoyaktuk Peninsula. The data for the upper Tuktoyaktuk Peninsula show considerably less lake area loss, but span only until September 9th, 2000. Data for the lower Tuktoyaktuk Peninsula span to 2001, and show much greater lake area loss over that period. The magnitude of lake area change over a single year suggests that this area is very sensitive to the factors influencing lake size.

Table 4.10 - Lake Area and Lake Area Change – 2000-2001: Common area (Paths 63 and 61)

Area	p63- Sept. 19th, 2001 (km^2)	p61- Sept. 9th, 2000 (km^2)	% Change
Total Lake Area	1153.48	1203.35	-4.14
Class 4 Lake	761.51	810.36	-6.03
Class 3 Lake	253.66	251.03	+1.05
Class 2 Lake	118.95	123.63	-3.53
Class 1 Water	19.36	18.33	+5.62

Unchanged Area (km^2)	1125.34
Lake Growth (km^2)	27.13
Lake Shrinkage (km^2)	85.29
Net Change (km^2)	-51.16
Percent Change	-4.25

Table 4.10 – Lake area changes from September 9th 2000 to September 19th 2001 are substantial, with a lake area net loss considerably greater than was seen in the lower Tuktoyaktuk Peninsula from 1992-2000. Significant decreases in both class 4 and class 2 lakes contribute to this overall loss. Very little lake area growth occurred over this period to offset lake shrinkage.

4.6 – Landscape Coverage

Table 4.11 shows the percentage of overall lake area covered by thermokarst lakes in each study area. On the Tuktoyaktuk Peninsula thermokarst lakes within the detection range used occupy 20-35% of the total land area, and increase in land area coverage toward upper peninsula. These figures are consistent with lake coverage as seen in studies by Rampton (1988) and Mackay (1997). Changes in total land area covered by thermokarst lakes are as high as 3% between several time periods.

Table 4.11 – Thermokarst Lake Area Coverage

Study Area	Land Area (km²)	Lake Area (km²) in each study year	% Lake Area in each study year
Upper Tuktoyaktuk Peninsula (MSS range)	3370	1978: 862 1992: 980 2000: 952	1978: 25.6 1992: 29.1 2000: 28.2
Upper Tuktoyaktuk Peninsula (TM/ETM+ range)	4210	1992: 1422 2000: 1400	1992: 34.3 2000: 33.2
Central Tuktoyaktuk Peninsula (TM/ETM+ range)	3910	1991: 1266 1992: 1270 2000: 1153 2001: 1203	1991: 32.4 1992: 32.5 2000: 29.5 2001: 30.8
Lower Tuktoyaktuk Peninsula (MSS range)	1880	1979: 411 1991: 469 2001: 416	1979: 21.9 1991: 24.9 2001: 22.1
Lower Tuktoyaktuk Peninsula (TM/ETM+ range)	7120	1991: 2147 2001: 1958	1991: 30.1 2001: 27.5

Table 4.11 – Thermokarst lake area change remains considerable between many time periods in terms of its coverage of total land area within the study area sections. Changes of up to 3% occur between several images and less than 1% in several others, particularly 1991-1992.

4.7 – Regional Climate

Climatological data from 1958-2005 were obtained for Inuvik, the closest monitoring station to the Tuktoyaktuk Peninsula with data available for the study period, situated approximately 60 km SW of the lower Tuktoyaktuk Peninsula (Environment Canada, 2005). Of primary importance to thermokarst lake growth and overall water levels are precipitation and temperature (Smith et. a., 2005). Based on the data obtained, figure 4.1 was created showing mean annual temperature, thaw temperature (mean temperature from June-August), and cumulative annual precipitation (from July of the previous year to July of the year in question) from 1970-2005. Values for the years where imagery was obtained are shown in table 4.12.

Table 4.12 – Climate conditions from imagery years

	1978	1979	1991	1992	2000	2001
Mean Temp. (˚C)	-8.18	-8.83	-8.88	-9.26	-8.49	-8.34
Thaw Temp (˚C)	6.40	10.65	9.48	9.05	7.80	8.03
Annual Cumulative Precipitation (mm)	153.6	113.9	189.7	190.4	183.0	145.5

Table 4.12 – Individual values for imagery years as shown in figure 4.1. Annual commutative is calculated from July of the previous year to July of the year in question. While mean temperature remains fairly consistent annual cumulative precipitation varies considerably between each time period.

Figure 4.1 and table 4.11 indicate that changes in cumulative precipitation may be a very important factor. Thaw temperature was relatively stable, with the exception of 1978-1979 where the largest increase over the 25 year period occurred. Mean annual temperature was consistent for the years studied, despite varying from -4.8˚C to -11.3˚C from 1970 to 2005. Table 4.13 compares changes in annual cumulative precipitation and lake area.

Figure 4.1 – Key Climate Factors

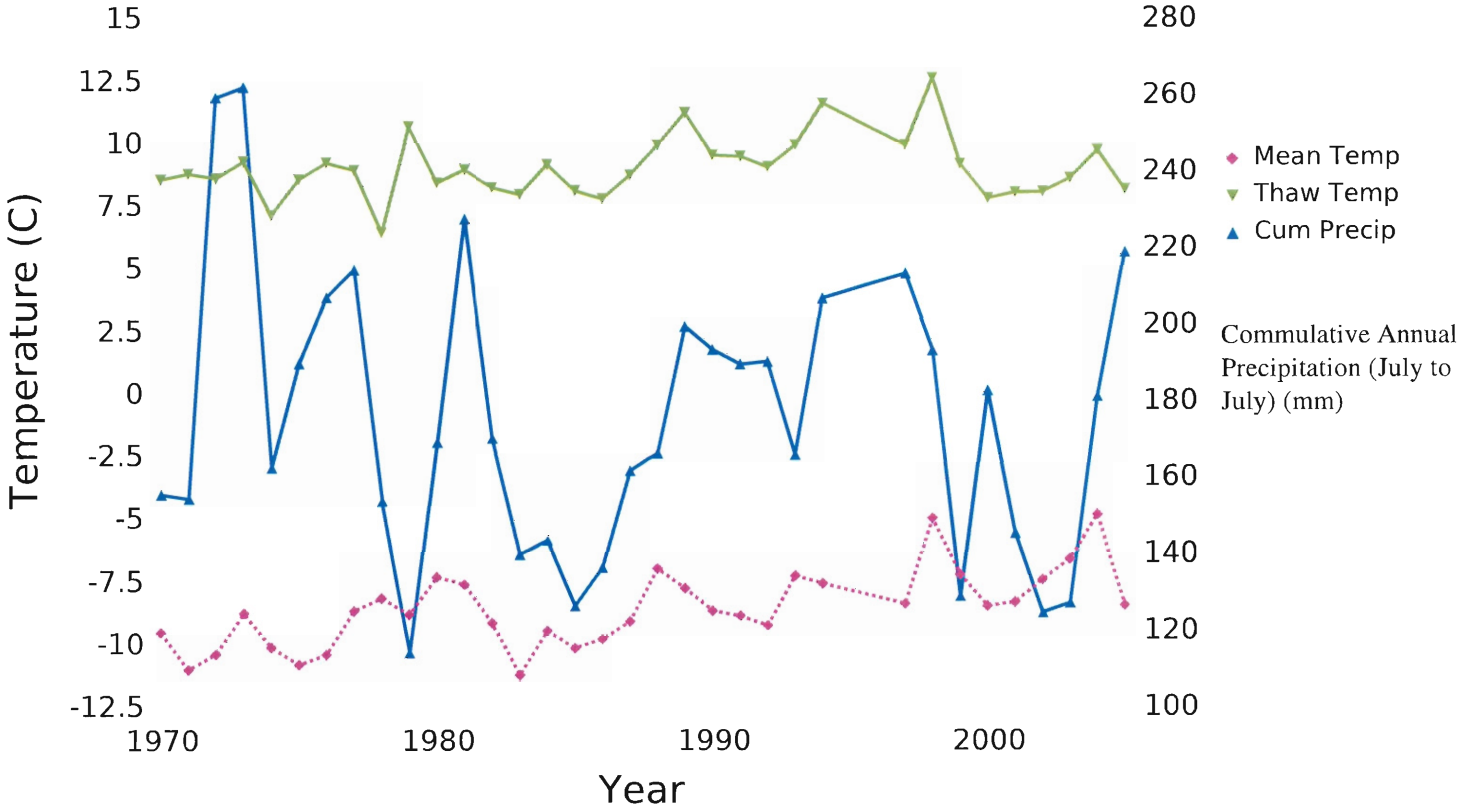


Figure 4.1 – Mean annual temperature and thaw temperature for permafrost are plotted for the time period studied, along with annual cumulative precipitation from July of the previous year to July of the year in question, with all precipitation converted to equivalent water volume (snow to liquid water). Mean annual temperature rises overall across this period, while precipitation fluctuates from below 120 mm to over 240 mm. Data from Environment Canada (2005).

Table 4.13 – Cumulative Annual Precipitation and Total Lake Area Change for each image pairing

Imagery Years	Annual Cumulative Precipitation Change (%)	Total Lake Area Change (%)
1979-1991	+66.5	+14.0
1979-2001	+27.7	+0.7
1978-1992	+24.0	+3.0
1978-2000	+19.1	+9.1
1991-2001 (p71)	-23.2	-11.7
1991-2001 (p63)	-23.2	-9.2
1992-2000 (p67)	-3.9	-3.4
1992-2000 (p61)	-3.9	-2.1
1991-1992	+0.4	+0.21
2000-2001	-20.5	-4.49

Table 4.13 – Imagery years are compared within the MSS data range except for the short term comparisons of 1991-1992 and 2000-2001. Both are shown as percentage changes from the earlier image in the pairing. Where cumulative precipitation was greater in a given year total lake area is shown to have increased, though the relative magnitude of these changes vary. Class 1 water area is not included in the total lake area change.

These data suggest a correlation between annual cumulative precipitation and total lake area change across these image pairings. The magnitude of these changes is inconsistent in some cases, such as from 1979-2001, where the second largest annual cumulative precipitation increase occurred while total lake area increased only 1.1%. Longer-term climate trends may account for some of this variation, as several consecutive wet or dry years prior to the years studied should impact total lake area. 1978 and 1979 occur in a period of progressive drying, while 1991-1992 were relatively wet years in a wet period spanning from 1989-1994 (and possibly to 1997, but data from 1995-1996 are missing). The period from 1999-2003 was relatively dry except for the year 2000 where annual cumulative precipitation jumped

42.1% over 1999. Figure 4.2 shows a plot of the data from Table 4.13 (without the repeat data from 1991-2001 and 1992-2002). Linear regression analysis of the plotted data produces a coefficient of determination (r^2) value of 0.823 indicating a strong relationship.

Temperature, rather than precipitation, is not noted by other authors examining thermokarst lake change as being the primary factor, and lake growth or shrinkage is attributed by Smith et al. (2005) to Arctic climate change. These results suggest that cumulative precipitation is considerably more important than is often discussed. Lateral expansion of thermokarst lakes is likely to be less significant in dry conditions where lake water levels fall below the current lake margin, while bank erosion, melting, and undercutting should be greatest in years where lake levels are highest due to precipitation. Precipitation may play a larger role in this study due to the employed methodology, as lake area may expand seasonally due to water-level changes while actual lake margins remain unchanged. This analysis detects both occurrences and combines them into overall lake area change, potentially making this analysis more sensitive to short-term and seasonal change than to any longer-term trend in overall lake change.

Figure 4.2 – Annual Cumulative Precipitation Change Vs Lake Area Change Between Studied Years

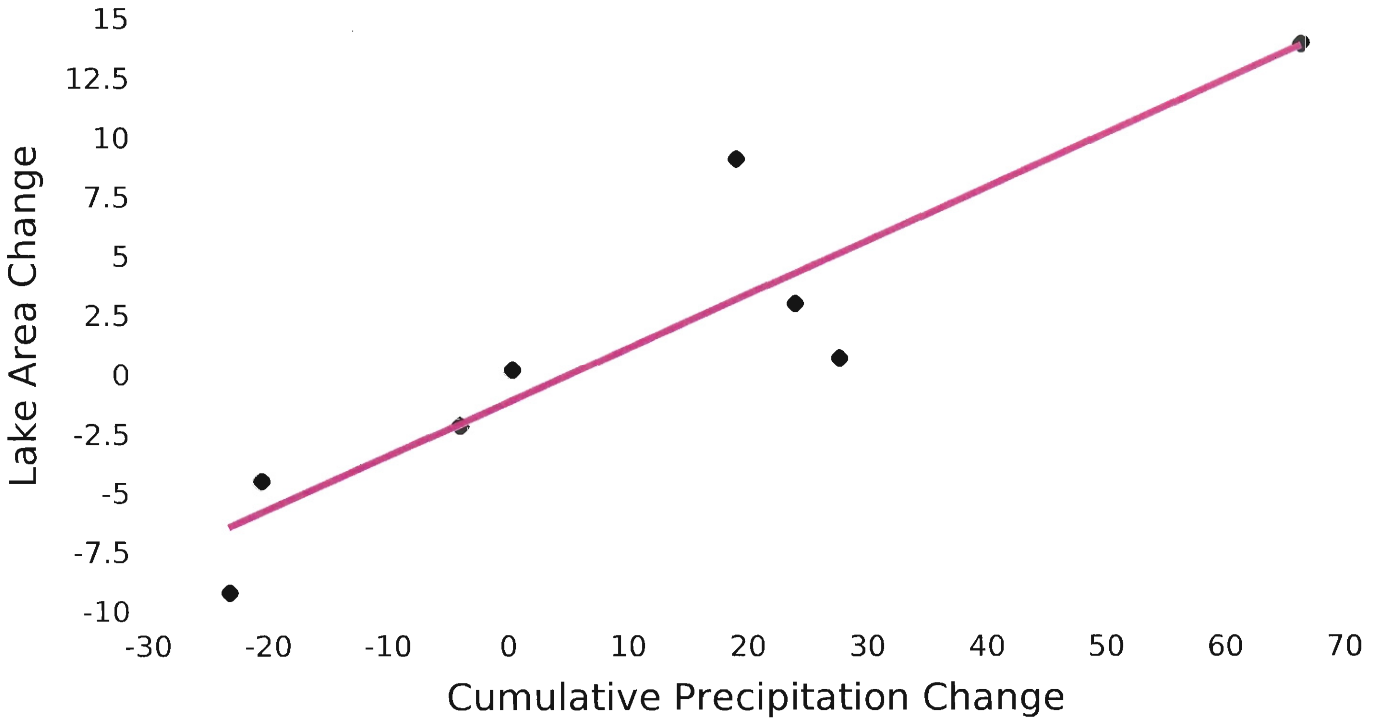


Figure 4.2 – Correlation of annual cumulative precipitation change (%) and lake area change (%) for study image pairings indicates a strong relationship between these variables. The linear regression line shown is based on the regression equation y (area) = 1.1565 + 0.2272 X (precipitation). r^2 for this regression is 0.823, with and p = 0.0019.

CHAPTER 5 – CONCLUSIONS

5.1– Lake Area Change

Total lake area changes for various sections of the Tuktoyaktuk Peninsula are substantial, ranging from a 14% increase in lake area from 1979-1991 to a subsequent area reduction of 11% from 1991-2001 in the lower Tuktoyaktuk Peninsula. Modest lake area growth was detected in the lower peninsula (0.7%) from 1979-2001, while a considerable area increase (9.1%) was detected from 1978-2000. As seen in Smith et al., 2005, thermokarst lakes in continuous permafrost appear to growing. This trend is not constant over the study period, however, with high levels of growth occurring from 1978-1992 partially offset by a large area reduction from 1991-2001. The magnitude of change seen over periods a short as a single year (-4.1% from 2000-2001) indicate that thermokarst lakes are highly sensitive to growth factors and fluctuate significantly.

5.2 - Regional Climate Effects

Climate data from the study period for the nearest weather monitoring station show a high variation of annual cumulative precipitation for the three time periods studied. Examination of lake area changes in compared images and annual cumulative precipitation changes over the same period show a strong correlation between calculated lake area and annual cumulative precipitation. Mean annual temperatures and thaw temperatures for the years studied were consistent while total lake area fluctuated substantially between study periods, indicating that this is not the primary factor influencing the changes recorded. In contrast to Smith et al. (2005), lake level rise due to precipitation rather than lake margin thawing is indicated to be the primary influence on thermokarst lake area change as detected by satellite remote sensing with relatively coarse resolution. Determining long-term trends in thermokarst lake behavior requires a more rigorous identification of actual lake margins, rather than the rapidly changing extent of water coverage. Decreased lake levels in years of low precipitation are likely to impede lake margin expansion by thawing, requiring a combination of warmer temperatures and high precipitation to drive significant thermokarst lake growth. Results from this study area using suggest that thermokarst lake level changes caused by short-term climate fluctuations mask longer-term trends in the increase or decrease of lake size.

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