Multiple Methods for Assessing the Sustainability of Shallow Subarctic Ponds in Churchill Region: Hudson Bay Lowland, Canada

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.
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Abstract

This thesis examines the occurrence of hydrologic variability in subarctic ponds within the Churchill region of the Hudson Bay Lowland (HBL) and investigates the utility of using remote sensing studies to characterize changes in pond surface area. The thesis also characterizes hydro-climatic change over the past ~60 years, and compares this to pond sustainability within the region of Churchill. A multiple-methods approach incorporating field research, simple water balance modeling and remote sensing is used to address these objectives.

Research findings demonstrate the occurrence of natural fluctuations in pond surface area and water levels in the Canadian subarctic. These fluctuations in pond water levels (and thus surface area) are caused by differences in antecedent hydrologic conditions prior to image capture and should not be considered representative of long-term regional climatic or landscape change. Differences in pond surface area due to variable antecedent hydrologic conditions were observed at three temporal scales: (1) within the same season in early and late summer, respectively (intra-seasonal variability); (2) differences between two successive years where hydrologic conditions contrasted throughout the season (inter-seasonal variability); and (3) differences between two successive years with similar antecedent hydrologic conditions but one year having a significant rain event (antecedent precipitation) immediately prior to image capture (antecedent precipitation).These temporary changes in pond surface area are easily detected using remotely sensed imagery and may produce unrepresentative estimates of pond surface area change. A comparison of modeled pond water levels and remotely delineated surface boundaries revealed significant pond changes caused by naturally induced hydrologic variability within the Churchill region. Resulting from a 4.5 - 11.8 cm variation in water depth, pond surface areas were significantly altered by antecedent precipitation (average: 3,711 m^2, range: 0 – 9,748 m^2), intra-seasonal variability (average: 2,049 m^2, range: 0 – 7,168 m^2) and inter-annual climatic variations (average: 1,977 m^2, range: 396 – 6,491 m^2). These noteworthy pond boundary and water level differences reinforce the importance of accounting for hydrologic variability when delineating representative pond coverage and sustainability. In order to accurately calculate pond sustainability from remote sensing imagery within the Canadian subarctic, acquisition dates, ground conditions and hydrologic context must be consistent or accounted for.

Contemporary pond sustainability findings reveal significant regional climatic change, changing pond hydrologic conditions and overall pond physical stability between 1947 and 2008. Specifically, the Churchill region experienced an increase in annual temperature (+0.03 °C/yr), annual precipitation (+1.28 mm/yr), annual rainfall (+1.97 mm/yr), annual evaporation (+0.80 mm/yr) and the length of the open water period (+0.18 days/yr), indicating that conditions are becoming warmer and wetter. Occurring at a rate of 1.37 mm/yr over the study period, changing atmospheric conditions caused a decrease in open water pond hydrologic deficits. During the open water period, pond features surveyed in the field exhibited a natural decrease in water levels and corresponding areal extent between break-up and late July followed by a natural water level increase (and pond areal extent) from early August until ice freeze-up. During the hydrologic recharge period, modeled pond water levels exhibited an increasing trend (August +0.72 mm/yr, September 0.51 mm/yr), which suggests ponds are filling closer to their maximum storage capacity prior to freeze-up. A remote sensing analysis of pond boundary modifications in mid-summer revealed no change in contemporary physical pond sustainability. Detected surface area changes from imagery were mainly attributed to naturally induced hydrologic variability.

Overall, this thesis suggests a new methodological approach for conducting remote sensing pond sustainability research within the arctic/subarctic environment. As well, this study determined the sustainability of shallow water features within the Churchill region of the Hudson Bay Lowland over the last ~60 years.

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Table of Contents

List of Figures

List of Tables

1.0 Introduction

“Despite geographic isolation, subarctic environments are subjected to a wide spectrum of environmental stressors (Schindler et al., 2006)”. Due to fragile ecosystem dynamics, several contemporary environmental changes have been linked to shifting atmospheric conditions (Rouse et al., 1997). Specifically, irregular pond biological communities, increased precipitation/evaporation ratios, prolonged ice-free seasons, permafrost degradation, increased summer temperatures and decreased frequency or extent of spring flooding have been documented throughout the subarctic environment (Rouse et al., 2007; Rouse et al., 2008; Stow et al., 2004). Increased rates of environmental change coupled with ecologically sensitive ecosystems have facilitated accelerated environmental transformations within the subarctic region and require further monitoring (White et al., 2007). Given the predominance of hydro-climatically induced environmental change within this region, hydrologically isolated open water features should be considered important bellwethers of climate change (Schindler et al., 2006).

Within the subarctic environment, shallow pond features are estimated to occupy between 15% and 50% of total land area (Duguay and Pietroniro, 2005) and significantly contribute to regional chemical, energy, biological and hydrological systems (Rouse et al., 1997; White et al., 2007). Therefore, changes in pond extent and distribution will significantly impact the regional ecosystems and alter biophysical regimes (White et al., 2007). Little is known regarding the fate of ponds in this region under a warmer climate, in spite of estimated environmental change within the Canadian subarctic (Environment Canada, 2009). This is an area where research is needed.

Growing concern related to the fate of open water systems coupled with significant atmospheric change estimates has provided a framework for several northern pond sustainability studies. However, imagery centred sustainability studies have revealed disparate results related to the fate of subarctic and arctic shallow water features. Relying on remote-sensing delineated changes in pond/lake boundaries, studies have concluded pond/lake degradation (Riordan et al., 2006; Smith et al., 2005; Stow et al., 2004;

Yoshikawa et al., 2003), expansion (Grippa et al., 2007; Smith et al., 2005) or multi-directional change (Labrecque et al., 2009). These contrasting results may suggest inconsistent research methods, geographically incomparable ground conditions or unconsidered independent variables.

Most notably, the influence and importance of naturally induced pond hydrologic variability is not inclusively considered within most previous remote sensing focused pond/lake sustainability studies. Hydrologic variability may temporarily alter pond water levels, boundaries and distribution within the subarctic environment, which may influence remote sensing pond delineation. Remote sensing imagery efficiently captures hydrologic ‘snap shots’ and may misrepresent normal ground conditions due to antecedent precipitation immediately prior to image capture, intra-seasonal water level fluctuations (i.e. imagery captured immediately following spring melt versus peak summer drying) or inter-annual hydrological anomalies (i.e. imagery captured during an abnormally dry or wet year). Since imagery based pond sustainability studies rely heavily on representative pond boundary delineation, it is imperative to determine the influence of previously unconsidered short-term hydrological variability.

Focusing primarily on Alaska, Siberia and western Canada, previous pond sustainability research has only considered portions of the northern landscape. Specially, very little research has investigated subarctic landscape morphology and contemporary hydrologic dynamics in central Canada. Within this region, the Churchill portion of HBL is characterized by glacial topography and the abundance of shallow open water features, which cover 25% to 40% of the landscape (Bello and Smith, 1990; Duguay and Lafleur, 2003; Macrae et al., 2004). Estimated changes in climatic conditions (Environment Canada, 2007) may have altered pond dynamics and produced landscape modifications within this region. As pond sustainability research findings are not transferable between similar locations, the livelihood of shallow open water features within the Churchill region is unknown. Therefore, contemporary hydro-climatic pond sustainability research should be conducted within the Churchill region in order to determine landscape stability and further enhance understanding of Canadian subarctic hydrologic dynamics.

1.1 Thesis Objectives

Given the above stated research gaps, the following questions will be addressed in this thesis:

1. **Can remote sensing techniques be employed to accurately detect surface area change within systems that experience high levels of hydrologic variability?**

   1a. Does naturally induced hydrologic variability over three temporal periods (*Immediate*: antecedent precipitation, *Short-term*: intra-seasonal water level fluctuation and *Longer-term*: inter-annual hydrologic differences) influence pond water levels and surface area in the Churchill region?

   1b. Are naturally fluctuating pond boundaries evident when delineating features using remote sensing imagery?

2. **Has contemporary pond surface area and hydro-climatic change occurred within the Churchill region over the past ~60 years?**

   2a. Has the Churchill region experienced hydro-climatic change between 1947 and 2008?

   2b. Accounting for naturally induced hydrologic variability, have pond boundaries changed between 1947 and 2008?

1.2 Structure of Thesis

This thesis contains two chapters which will form the basis of academic manuscripts upon completion of this thesis. The first chapter (Chapter 4) demonstrates the occurrence of short-term pond surface area/water depth fluctuations caused by natural hydrologic variability and analyzes the relationship between hydrologic conditions and accurate remote-sensing pond surface area delineation. The second chapter (Chapter 5) examines contemporary hydro-climatic and pond surface area change within the Churchill portion of the HBL between 1947 and 2008. Additionally, this thesis includes a general introduction (Chapter 1), literature review (Chapter 2), study site description (Chapter 3) and overall conclusion (Chapter 6) chapters which provide context, background, research justification and academic contributions.

2.0 Literature Review

Within the subarctic environment, shallow ponds represent abundant and significant landscape features (Bello and Smith, 1990; Duguay and Lafleur, 2003; Macrae et al., 2004). Often formed by glacial processes, these water features considerably influence regional hydrological, thermal, biotic and biogeochemical cycles (Rouse et al., 1997; White et al., 2007). Since subarctic ponds typically reside within areas of relatively impermeable ground, contemporary sustainability is heavily influenced by changing environmental conditions (Schindler et al., 2006). Therefore, isolated subarctic pond water budgets can be modeled using an atmospheric exchange equation throughout the open water period (Macrae et al., 2004; Yee, 2008). Hydrologic modeling of these features provides accurate estimates of pond water level fluctuation and overall contemporary sustainability (Oswald and Rouse, 2004). As well, remote sensing pond change detection techniques can provide tangible data which strengthens findings associated with hydrologic modeling within the subarctic environment (Duguay and Pietroniro, 2005). However, when conducting accurate pond sustainability research within the subarctic, several variables must be considered. Some of these variables include: imagery type, resolution, environmental impacts, feature size, seasonality and location (Duguay and Pietroniro, 2005). Overall, representative remote sensing pond sustainability research must incorporate regional water budget dynamics in order to provide hydrologic context for imagery and identify changing hydrologic conditions. Detecting contemporary pond hydrologic and surface area change within the Canadian subarctic provides excellent indication of regional environmental trends.

2.1 The Subarctic Landscape

Situated below the Arctic Circle (66°N), subarctic regions generally include northern Siberia, Canada and Alaska (Christopherson, 2004). Littered with lakes (larger than 38,000m² and/or maximum depth over 1m), ponds (less than 38,000m² and maximum depth less than 1m), pingos, palsas and peat plateaus, subarctic landscapes are strongly influenced by previous glacial activity (Ritter et al., 2002). Within this region, low-lying coastal areas situated above the northern tree line typically exhibit minimal vegetation coverage, flat topography (Dredge, 1992) and shallow soil profiles due to glacial scouring, ice wedging and bedrock outcrops (Ritter et al., 2002). Shallow ponds, which occupy significant portions of this region, are considered major landscape features (Yee, 2008).

2.1.1 Evolution and Distribution of Ponds within the Subarctic

Shallow water bodies are predominant landscape features and cover approximately 30% of the subarctic environment (Bello and Smith, 1990; Frohn et al., 2005; Grosse et al., 2005). Although hydrologic dynamics fluctuate due to regional conditions, coastal environments typically exhibit the largest concentrations of pond features while open forest zones experience the smallest (Lafleur et al., 1997). Differentiated by visual appearance and location, pond features within the subarctic region are classified as: thermokarst, depression or perched basin (Ritter et al, 2002; Walker and Harris, 1976; Woo, 1980). Thermokarst ponds are naturally circular, often oriented by prevailing winds and display blocky bathymetries while depression ponds are shallower, non-uniform and display gradual bathymetries (Arlen-Pouliot and Bhiry, 2005; Ritter et al., 2002). Although characteristically similar to depression ponds; perched basins are situated within areas of higher elevation (Walker and Harris, 1976). Regardless of visual differences, many shallow pond features within the subarctic environment experience similar origin, evolution and hydrologic dynamics.

Occupying closed depressions known as alas, subarctic thermokarst ponds typically originate from thawing ground ice conditions (Hopkins et al., 2006). Specifically, ponds most commonly develop as permafrost thaws and natural voids develop on the surface (Duguay et al., 2005). Isostatic rebound and beach ridge/sediment exposure additionally contribute to the formation of spatially significant topographical lows where water naturally pools and ponds frequently originate (Dredge, 1992). Less commonly, thermokarst features may form in response to local surface disturbances such as tundra fire or human interaction (Duguay et al., 2005). Overall, active layer depth, permafrost type, subsurface flow and local topography determine subarctic pond distribution and initial sustainability (Jorgenson and Shur, 2007).

Following initial formation, the presence of uninterrupted underlying permafrost, relatively impermeable soils and thin active layer depths support pond development (Prowse and Ommanney, 1990). Positive thermal hydrologic feedback loops further facilitate pond creation and expansion due to locally accelerated permafrost warming and expanded ice-free subcutaneous zones (Ritter et al., 2002). Initiated by strong winds, mechanical and hydrological erosion additionally contribute to accelerated pond development within the subarctic environment.

Once developed, these dynamic water features may transform as a result of marginal thaw subsistence, wind erosion, lateral mechanical sorting or subsurface thawing (Jorgenson and Shur, 2007; Katamuraet al., 2006). As well, surface area decline may result from internal drainage caused by talik formation, the development of integrated drainage networks, long term stream migration, human interaction or long term environmental change (Jorgenson and Shur, 2007; Yoshikawa et al., 2003). Although natural pond evolution requires lengthy temporal periods, environmental change may accelerate pond development and decay (White et al., 2007). Therefore, subarctic pond sustainability should be continually monitored in order to indicate environmental changes as well as shifting biogeochemical, hydrological and thermal cycles.

2.2 Significance of Ponds

Understanding the role and significance of subarctic water features is crucial when attempting to quantify the implications of changing landscape conditions. Particularly, subarctic ponds significantly influence regional biogeochemical exchanges (Macrae et al., 2004), contribute to local hydrologic/energy regimes (Rouse et al., 2008) and provide necessary seasonal habitats for various migratory species (Bello and Smith, 1990). Changing subarctic pond sustainability may facilitate shifts in regional biogeochemical, biotic, hydrological and thermal dynamics.

Throughout the open water period, thousands of migratory birds and aquatic mammals rely on Churchill water features for seasonal habitats (Bello and Smith, 1990), nutritional sustainability and nesting locations (Lemelin and Wiersma, 2007). Changing regional pond sustainability would cause decreased habitat quality, altered bird and mammal migratory patterns, decreased reproductive success, lowered migratory success rates and degrade various micro-organism pools (Wrona et al., 2006).

Subarctic water bodies are supersaturated carbon dioxide sources in some regions (Christensen et al., 2007) but not others (Macrae et al., 2004). In the Churchill region, these ponds store significant quantities of particulate organic carbon in underlying sediments (Macrae et al., 2004). Experimental findings reveal considerable atmospheric carbon oxidation due to prolonged sediment exposure caused by pond water level decline or fluctuation (Devito et al., 2005; Petrone et al., 2005). Released carbon dioxide from pond sediments facilitates an enhanced positive feedback loop, which may further initiate increased regional air temperatures, enhanced carbon sediment evasion and altered pond water levels (Wrona et al., 2006).

Documented as regional methane sources, subarctic ponds exhibit daily methane emissions between 10 to 20 mg CH_4 $d^{-1}m^{-2}$ (Roulet et al., 1994) and significantly increase atmospheric exchanges with rising water tables (Christensen et al., 2007). As shallow water features transform, methane fluxes shift to produce a positive feedback loop (Callaghan et al., 2004) which further accelerates localized climate change and chemical balance exchanges (Bartsch et al., 2007).

Shallow water features significantly contribute to regional thermal and hydrologic budgets throughout the summer growing season (Duguay and Lafleur, 2003). Specifically, ponds act as major melt-water reservoirs during the post-melt period and strongly influence atmospheric moisture conditions (Woo, 1980). During this period, evaporative processes dominate pond atmospheric exchanges (Browling et al., 2003) and latent heat transfers (0.75 Wm^{-2}) represent primary pathways for convective heat loss (Eaton et al. 2001). Altered pond sustainability would drastically impact regional active layer development, evaporation rates, catchment hydrology, surface moisture availability, latent and sensible heat fluxes, regional humidity, cloud formation and precipitation.

2.3 Subarctic Pond Hydrology

Shallow subarctic ponds typically follow a three-phase annual hydrological cycle which includes spring melt, post-melt and winter freeze (Figure 2.1). Comparatively, post-melt pond conditions are considered most significant for regional hydrological, ecological, and biogeochemical processes (Macrae et al., 2004; Rouse et al., 2008). Changing hydrological conditions during this period may lead to altered subarctic pond sustainability.

Typically initiated during June, spring pond ice degradation commences the open water period (Environment Canada, 2009; Macrae et al., 2004; Roulet and Woo, 1986; Rovansek et al., 1996; Walker and Harris, 1976). In comparison to surrounding larger lakes, small water features become ice and snow-free earliest and act as natural reservoirs for regional melt water (Woo, 1980). Initial permafrost active layer underdevelopment creates optimal conditions for meandering and non-channelized overland flow, which facilitates temporary connectivity of small water features within the landscape. During this period, pond water level rises to maximum storage capacity and surface ice degrades quickly (Macrae et al., 2004). Rapidly occurring, the spring melt period typically ranges from several days to numerous weeks (Figure 2.1) and concludes as ponds become geographically disconnected (Walker and Harris, 1976).

The post-melt period typically persists for three to four months (Walker and Harris, 1976) and is characterized by hydrologic disconnection, water level fluctuation and active layer development (Macrae et al., 2004; Oswald and Rouse, 2004). During this period, pond water levels become primarily controlled by atmospheric moisture exchanges while infrequent extreme rainstorms or conjunctive minor rain events temporally restore regional catchment connectivity (Environment Canada, 2008; Macrae et al., 2004; Quinton and Roulet, 1998). Within the Churchill region, ponds exhibit hydrologic deficit and recharge cycling during the post-melt period (Macrae et al., 2004; Yee, 2008).

Concluding the annual hydrologic cycle, winter freeze is characterized by pond ice generation (Woo, 1980) and occurs between September and October (Walker and Harris, 1976). Due to distinctly dissimilar energy balance regimes, small water features typically freeze prior to larger lakes (Eaton et al.,

2001) and become hydrologically insignificant until subsequent spring melt conditions reinitiate (Duguay and Lafleur 2003).

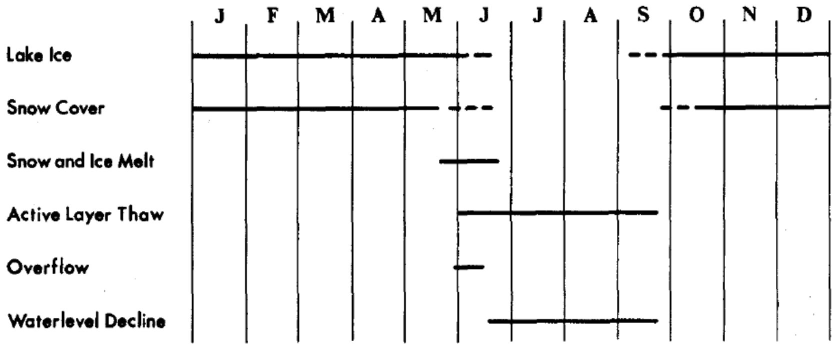


Figure 2.1 - Annual Hydrologic Cycle of a Small Perched Pond, Northern Alaska (Walker and Harris, 1976)

2.3.1 Influences on Pond Hydrology and Distribution

Numerous variables influence subarctic pond distribution and sustainability (Smith et al., 2007). Most commonly, permafrost extent, active layer depth, land cover type, sediment permeability, sub-surface hydrologic flow and atmospheric moisture exchanges impact regional pond dynamics. Shifting environmental and hydrologic conditions should initiate changes in subarctic pond sustainability.

2.3.1.1 Permafrost and Active Layer Depth

Thick permafrost coverage provides optimal ground conditions for subarctic pond development and sustainability. Permafrost acts as an impermeable layer, typically in conjunction with silt or clay soils, in order to pool precipitation and melt water near the surface (Dingman, 1994). Permafrost thawing may lead to terrain slumping, seepage and catastrophic drainage of surface water features within areas of discontinuous permafrost while enhanced thermokarsting is common within continuous permafrost regions (Smith et al., 2007).

Permafrost active layer development influences open water pond hydrologic dynamics. During the spring thaw season, thin active layer depths prevent melt water from dissipating and facilitate non-channelized surface hydrologic connectivity (Woo, 1986). Exhibiting progressively larger summer thicknesses, active layer depths rarely exceed 1m in areas of continuous permafrost and infrequently facilitate subsurface hydrologic interactions (Hinkle et al., 2005). Within the Churchill region, active layer thicknesses infrequently surpass 50 cm (Macrae et al., 2004; Rouse et al., 2008). Regions of shallow active layer growth typically coincide with impermeable underlying sediment, which creates relatively concrete ground conditions and increased surface saturation (Quinton and Roulet, 1998). These conditions are crucial for developing and sustaining subarctic ponds within the Churchill region.

2.3.1.2 Peatlands/Wetlands and Soil Type

Subarctic peatlands support high water table development, saturated ground conditions, decreased hydrologic mobility and pond sustainability (Roulet and Woo, 1986; Rovansek et al., 1996). Within wetland complexes, seasonally induced hydrologic fluctuations coincide with dampened subsurface responses and delayed surface moisture reactions. Near saturated peatland conditions coupled with major rain events may initiate surface runoff, subsurface flow and pond hydrologic gain. Following spring ice melt conditions, regionally uncommon major rain events are required to facilitate pond runoff contributions (Macrae et al., 2004). As well, dehydrated peatland complexes absorb atmospheric moisture, prevent surface water interactions and influence pond sustainability (Boudreau and Rouse, 1995). Churchill wetland complexes exhibit near surface volumetric soil moisture seasonally ranging from 67% to 85%, mean specific yield of 6.5% (Bourdeau and Rouse, 1995), porosity averaging 0.87 and high specific retentions (Roulet and Woo, 1986). These physical characteristics facilitate minimal catchment connectivity and pond hydrologic isolation.

Wetlands and shallow open water features typically thrive within areas of poorly drained soils (Bourdeau and Rouse, 1995). Marine silts and clays found near Churchill region create an impending barrier, ceasing seepage and allowing water to pool near the surface (Dredge and Motts, 2003). These outwash sediments are found within many water features and contribute to the hydrological storage capacity of hydrological inputs (Smith et al., 2007).

2.3.1.3 Surface and Sub-Surface Flow

Within the subarctic region, surface and subsurface flow is primarily controlled by wetland distribution, permafrost extent, bedrock position, rainfall intensity, water table location and sediment permeability (Haugen, 1982). During the major melt period, surface runoff initiates and pond maximum storage capacities are achieved (Yee, 2008). Subsequently, subsurface flow gradually diminishes to supply minimal pond hydrologic contributions throughout the summer growing season (Macrae et al., 2004, Roulet and Woo, 1986; Rovansek et al., 1996). However, subsurface lateral flow may temporally resume during major precipitation events (Walker and Harris, 1976; Woo and Mielko, 2007). Within the Churchill region, subsurface flow contributes between 2-5% of total pond hydrologic inputs and typically results from major rain events and major ice break-up (Yee, 2008). Therefore, post-melt pond hydrology is primarily controlled by atmospheric exchanges and exhibits minimal surface/subsurface influences (Macrae et al., 2004; Rovansek et al., 1996).

2.3.1.4 Precipitation

Annual precipitation varies significantly within the subarctic environment (Hinzman and Yoshikawa, 2003). Following the major melt period, precipitation contributions provide hydrologic inputs which solely sustain pond features. In the absence of precipitation, it is estimated that western Alaskan subarctic ponds would completely drain within one year (Yoshikawa and Hinzman, 2003). However, geographically unique precipitation ranges create regionally specific pond hydrologic fluctuations and long-term sustainability requirements.

Annual precipitation averages 416 mm and ranges from 214 to 618 mm within the Churchill region (Environment Canada, 2009). Macrae et al. (2004) analyzed several ponds within the Churchill region and determined that these features generally remained near storage capacity during an abnormally wet year while ponds contracted during a notably dry year. Therefore, varying amounts of precipitation can significantly alter the size and distribution of shallow water features and should be considered significant components of the local water balance.

2.3.1.5 Evaporation

Opposing precipitation, evaporation is considered the major hydrological output during the open water period. Evaporation rates are primarily controlled by available energy, water supply and the atmospheric vapour pressure deficit. Typically, evaporation counteracts 50 to over 100% of annual precipitation inputs within northern regions and often represents the dominant regional efflux process (Macrae et al., 2004; Prowse and Ommannay, 1990; Rovansek et al., 1996; Ryden, 1979; Walker and Harris, 1976; Woo, 1980; etc). More specifically, evaporation typically exceeds precipitation within the arctic and subarctic environment (Rovansek et al., 1996; Schindler and Smol, 2006). Subarctic pond evaporation annually averages between 200 mm (Boudreau and Rouse, 1995) to 383 mm (Yee and Bello, 2006) and significantly contributes to regional pond sustainability.

Within the Churchill region, annual evaporation typically ranges from 217to 383 mm and averages 307 mm (Bello and Smith, 1990; Yee and Bello, 2006; Yee, 2008). Over the summer months, this region is exhibits an atmospheric moisture deficit (Rouse, 1998). Overall, Churchill evaporative exchanges significantly counteract pond precipitation contributions and influence daily pond hydrologic conditions.

2.3.2 Hydrological Modeling

Hydrologic modeling provides estimates of pond dynamics and environmental change. Precise pond storage estimates often require regionally specific water balance equations, which consider atmospheric exchange, regional topography and surrounding moisture exchanges. Within the Churchill region, pond hydrologic modeling must include evaporation and precipitation contributions (Macrae et al., 2004; Yee, 2008). Therefore, pond water temperature modeling is required to derive pond evaporation exchanges, which are necessary to develop an accurate regional hydrologic model for Churchill region. Additionally, ice-phonology modeling provides estimates of pond open water duration and water balance dynamics.

2.3.2.1 Evaporation Modeling

Accurately modeling surface water evaporation enhances overall hydrologic estimates and provides necessary data for complex water budget equations. Hydrologists have proposed over 30 site-specific evaporation equations which include energy budget and/or aerodynamic dynamics and integrate empirical or semi-empirical variables (Winter et al., 1995). As well, each equation requires varying degrees of input data, field obtained information and geographic understanding (Mosner and Aulenbach, 2003). Pond hydrologic dynamics and regional data availability within the Churchill region suggest that the Oswald and Rouse`s (2004) evaporation model should provide reasonable estimates of evaporative exchanges.

Oswald and Rouse`s evaporation model (2004) utilizes Fick’s first law of diffusion (1855), where “a diffusing substance moves from where its concentration is larger to where its concentration is smaller at a rate that is proportional to the spatial gradient of concentration”. This method employs the mass transfer approach to estimate actual point evaporation over a water surface. Input values for this model include: daily average wind speed, daily average surface temperature, daily air temperature and average daily relative humidity. Oswald and Rouse (2004) incorporated these variables to derive actual evaporation using:

$$E = K_e \, u_z \, (e_0 - e_z) \qquad \textit{(Equation 2.1)}$$

where E is point evaporation, K_e is the coefficient of proportionality, u_z is the horizontal wind speed at height z, e_0 is the vapour pressure of saturated air at the temperature of the water surface and e_z is the vapour pressure of the air at height z above the water surface. Oswald and Rouse statistically derived K_e using collected field evaporation measurements and suggested that site-specific coefficients should be computed to produce optimal results. Overall, the mass transfer approach provides an estimate of actual point evaporation using easily obtained parameters and straightforward equations. However, the modeled E data is not intended to represent all ponds in the landscape as ponds in this region vary in their bathymetry/depth, size and underlying sediment characteristics and therefore their true E values. The modeled E data is intended to represent a hypothetical pond with a mean depth of 1 m. To calculate E_o, pond water temperatures were modeled using a physically-based thermodynamic model (CLIMo, Dugual et al., 2003) using climate station records for input data.

2.3.2.2 Ice Thickness and Water Temperature Modeling

Hydrologic models often require water temperature and ice thickness measurements to determine subarctic pond-atmospheric exchanges. The Canadian Lake Ice Model (CLIMo) was originally created as an adaptation of Flato and Brown's one-dimensional thermodynamic sea-ice model (1996) to simulate ice-phenology on shallow lakes in the arctic, subarctic and high boreal forest environments (Duguay et al., 2003). During ice-free periods, CLIMo additionally estimates pond surface and subsurface water temperatures. Utilizing daily average air temperature, daily average relative humidity, daily average wind speed, daily average cloud cover and daily average snow on the ground, CLIMo is fundamentally based on Maykut and Untersteiner's equation for one-dimensional unsteady heat conduction including penetrating solar radiation:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k \frac{\partial T}{\partial z} + F_{sw} I_o (1-\alpha) K e^{-K_z} \qquad \textit{(Equation 2.2)}$$

where T(z,t) is temperature within the ice or snow, t is time and z is depth measured positive downward from the upper surface. $\mathrm{C_p}$ is specific heat capacity, $\mathrm{F_{sw}}$ is downwelling shortwave radiative energy flux, $\mathrm{I_o}$ is the fraction of shortwave radiation flux that penetrates the surface, ρ is density, k is thermal conductivity, α is surface albedo, and K is the bulk extinction coefficient for penetrating shortwave radiation (Duguay et al., 2003). Calibrated to one meter maximum depths for ponds, CLIMo can be used to estimate pond ice break-up and freeze-up dates within the Churchill region. As well, calculated pond open-water durations and daily water temperatures with CLIMo enhance water balance modeling accuracy and provide necessary parameters to derive evaporation.

2.3.2.3 Subarctic Water Balance Modeling

Subarctic pond hydrologic budgets generally resemble a simple conservation equation, where:

$$Inputs - Outputs = Change\ in\ Storage \quad \text{(}\textit{Equation 2.3)}$$

This basic equation is considered a generalization of basic classical physics laws including: the conservation of mass rule, Newton's first law of motion and the first law of thermodynamics (Dingman, 1994). Although simple in theory, variables associated with each input and output component typically vary in complexity based on geographic location. Estimates of northern ice-free hydrologic storage change often require complex equations incorporating various hydrologic variables:

$$\pm r = P + GW_{in} + SW_{in} + C_{in} - E - GW_{out} - SW_{out} - C_{out} - \Delta V \qquad \text{(}\textit{Equation 2.4)}$$

where P is precipitation, GW is ground water discharge to and from the pond, SW is diffuse surface flow to and from the pond, C is unchannelized overland flow to and from the pond (typically during the major melt period), E is evaporation, ΔV is change in pond volume and $\pm$r is the residual or unaccounted hydrologic transfer (Dingman, 1994).

Subarctic pond hydrologic research confirms simple atmospheric exchange equations are sufficient for modeling pond water balances post the major melt period (Bello and Smith, 1990; Boudreau and Rouse, 1995; Browling et al, 2003; Lafleur, 1994; Macrae et al., 2004; Woo, 1980). Within the Churchill region, Macrae et al (2004) discovered a near 1:1 relationship between P-E values and daily pond level fluctuations. This near linear relationship (r^2=0.73) strongly indicates atmospherically controlled pond storage conditions during the open water period (Figure 2.2). Therefore, pond hydrologic dynamics within Churchill region are modeled using a modified version of Woo's (1980) equation:

$$P - E = \frac{ds}{dt} \qquad \textit{(Equation 2.5)}$$

where P is precipitation, E is pond evaporation and dS/dt is the change in pond storage. Resulting pond water balances should be coupled with field observations and remote sensing imagery analysis to determine as accurately as possible contemporary pond environmental and hydrological change.

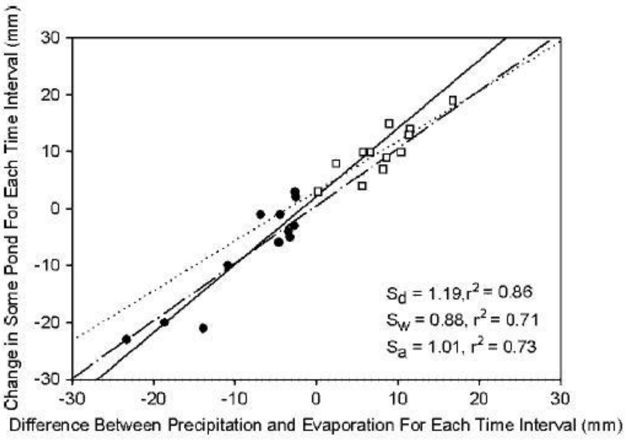


Figure 2.2 - Daily Pond Atmosphere Exchange Versus Observed Changes in Water Levels: The slopes (S) and respective coefficients (r2) are shown for drought (Sd), wet (Sw) and all periods (Sa) (Macrae et al. 2004)

2.4 Remote Sensing and Pond Surface Area Change

Due to geographic isolation, scattered hydrologic data collection coverage and incomprehensive historical climate datasets, remote sensing techniques are particularly well suited to detect contemporary subarctic pond boundaries and sustainability (Pietroniro and Leconte, 2005). Irretrievable using alternative methods, these cost and time saving techniques produce large-scale hydrologic landscape datasets and well capture ground conditions. However, remotely acquired imagery detects hydrologic ‘snap shots’ which may misrepresent average seasonal moisture conditions. In order to assure pond delineation accuracy, remote sensing methods must incorporate appropriate imagery selection, suitable classification techniques, representative environmental conditions and correct acquisition sensors (Jensen, 2007). Within the Churchill region, remotely derived pond sustainability research must incorporate understanding of the electromagnetic spectrum, water-atmosphere interactions, imagery acquisition influences and previously conducted studies. Additionally, remote sensing pond delineation studies within this region should consider pond size and distribution when selecting imagery resolution (Pietroniro and Leconte, 2005).

2.4.1 Surface Water and the Electromagnetic Spectrum

Varying in intensity, pond surface water absorbs significant portions of the electromagnetic spectrum (Jensen, 2007). As displayed in Figure 2.3, clear water absorbs nearly all received electromagnetic radiation between near and middle infrared wavelengths (0.74-2.5µm) and reflects minimal portions between violet to light blue or 0.4-0.73 µm (Schultz and Engman, 2000). Therefore, easily recognizable subarctic water features appear dark on near and mid-infrared remotely sensed imagery in comparison to the surrounding area (Henderson and Lewis, 1998). Within the Churchill region, optical imagery best captures pond feature tonal contrast.

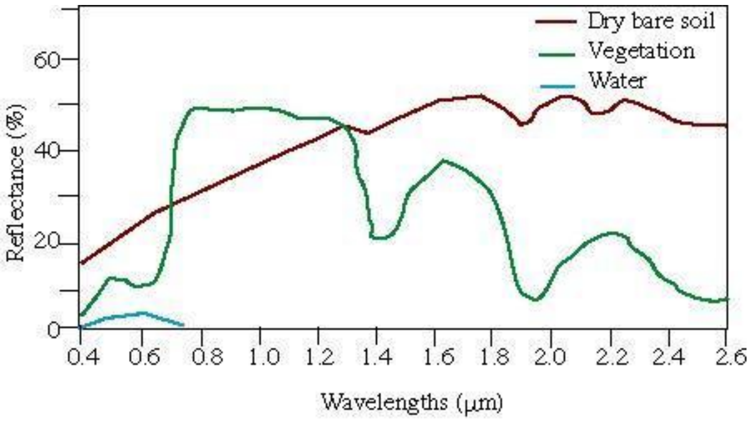


Figure 2.3 – Electromagnetic Spectral Reflectance Curve for Clear Water and Other Land Cover Conditions (Lillesand and Keifer, 1994)

Within the visible portion of the electromagnetic spectrum, clear water exhibits very low spectral reflectance. However, various environmentally induced conditions significantly alter landscape spectral signatures and, as a result, impact pond boundary delineation. These conditions arise due to pond characteristics, atmospheric conditions and surrounding landscape qualities. Specifically, optical imagery may capture spectral scattering due to high electromagnetic penetration within the blue/green portions (0.35 µm to 0.5 µm) of the spectrum. Under these conditions, electromagnetic radiation reaches shallow pond bottoms to produce lighter spectral signatures for sandy sediments and the reverse for clay sediments. Similarly, increased presence of pond chlorophyll or suspended pond sediments produce heightened reflectance between the green and near IR portions of the spectrum and results in ponds appearing lighter on optical imagery. Pond water depth influences electromagnetic signatures as deeper water bodies remain dark while shallow features may appear lighter (Duguay and Lafleur, 2003). Lastly, contrasting pond tonal signatures may become less distinct due to moist adjacent ground conditions. These conditions influence feature spectral signatures causing surrounding landscapes to appear darker. Table 2.1 summarizes these influences as well as various atmospheric contributions. Overall, accurate imagery-based pond boundary delineation requires consideration of atmospheric conditions, environmental circumstances and pond characteristics.

Table 2.1 - Variables which Influence the Return Signal Received by Optical Remote Sensing Instruments when Detecting Water Features (Dingman, 1994; Jensen, 2007)

<table>
<tr><th colspan="2">Variables Influencing Accurate Pond Boundary Delineation Using Optical Imagery</th></tr>
<tr><th>Variable that Influences the Signal</th><th>Response Found on Imagery</th></tr>
<tr><td>*Suspended Sediment in Water*</td><td>Increased suspension produces increased reflectance
– Pond look lighter</td></tr>
<tr><td>*Chlorophyll in Water*</td><td>More reflectance within the green and near IR portions of the spectrum and increased scattering
– Ponds looks lighter</td></tr>
<tr><td>*Underlying Sediment type of Shallow Water Bodies*</td><td>Sand – Ponds look lighter
Clay/Silt – Ponds remain dark</td></tr>
<tr><td>*Pond Water Depth*</td><td>Shallow pond features may facilitate spectral scattering due to high penetration
– Ponds look lighter</td></tr>
<tr><td>*Surface Roughness/Wind*</td><td>Increased wind produces Increased reflectance
– Ponds look lighter</td></tr>
<tr><td>*Clouds*</td><td>Ponds are shadowed and cannot be detected. Clouds influence the accuracy of automated delineation</td></tr>
<tr><td>*Presence of sunlight*</td><td>Without sunlight pond are undetectable</td></tr>
<tr><td>*Surrounding Area*</td><td>Features may cause shallows which could be misclassified as water
Saturated adjacent conditions may blur pond boundaries</td></tr>
<tr><td>*Atmospheric Scattering*</td><td>May create a dulling effect on the image
– Pond may blend with surrounding area</td></tr>
<tr><td>*Solar Angle (optical sensors)*</td><td><table>
<tr><td>Solar Inclination Angle</td><td>Albedo</td></tr>
<tr><td>60°</td><td>0.05</td></tr>
<tr><td>30°</td><td>0.1</td></tr>
<tr><td>10°</td><td>0.35</td></tr>
<tr><td>5°</td><td>0.6</td></tr>
</table>
Decreased solar angle – ponds look lighter</td></tr>
</table>

2.4.2 Imagery Classification Methods for Detecting Water Features

Classification techniques can significantly alter the categorization of land and water features from satellite imagery (Brown and Young, 2006). Due to inconsistent or inappropriate classification methods, pond surface areas may significantly increase or decrease and become disproportionate to the study area. Therefore, classification techniques require significant consideration when performing time-series comparative analyzes (Canty, 2007).

Images are typically classified using manual digitizing, unsupervised classification, supervised classification, shape-based techniques or a combination approach. Generally, method selection is dependent on sensor type, imagery quality, technician experience and software availability. As well, multiple studies have stressed the importance of employing multiple methods in order to accurately delineate water features (Grosse et al., 2005; Pietroniro et al., 2005; Brown and Young, 2006). Overall, classified satellite images should combine aerial photography and field validation in order to produce the most accurate results. Onscreen digitizing was selected and utilized for pond feature extraction throughout this thesis.

Onscreen digitizing utilizes fully interactive feature extraction methods where data is collected from previously scanned or captured images (Jensen, 2007). All types of georeferenced spatial data can utilize this form of feature extraction. Generally, information is collected as the user traces features from an original image to create a new layer or theme. The resulting data is georeferenced and easily overlaid on other datasets featuring the same location. Uniquely, this form of extraction relies solely on user interpretation and decision making, while specific pixel characteristics are less significant (Pietroniro et al., 2005). Most commonly employed to delineate water features, this method easily omits classification error due to environmental influences. However, this universally applicable and straight forward method is associated with many drawbacks. Imagery extraction is subjected to individual rule making and may be associated with poor repeatability. As well, this method is extremely time consuming and may be considered impractical for large datasets. Lastly, with poor knowledge of the research site, features may be poorly understood and thus unknowingly misclassified. Therefore, a thorough understanding of the research site should accompany this method (Brown and Young, 2006).

2.4.3 Previous Remote Sensing Hydrologic Sustainability Research

Recent remote sensing hydrologic sustainability research has produced disparate trends regarding the sustainability of northern water bodies (lakes and ponds) (Table 2.2). Several studies have observed a long-term drying trend (Riordan et al., 2006, Smith et al., 2005; Stow et al., 2004; Yoshikawa et al., 2003), while others have concluded that water features are expanding (Grippa et al., 2007; Smith et al., 2005) or exhibiting multi-directional change (Labrecque et al., 2009). Riordan et al. (2006) assessed northern Alaskan lake/pond distribution from 1950 to 2000 and discovered a slight drying trend due to restricted subsurface hydrology. In contrast, Grippa et al. (2007) observed an unexplainable increase in lake/pond surface area within the Western Siberian Lowlands over a similar 23-year period. Overall, as shown in Table 2.2, the results acquired under similar landscape and climatic conditions suggest water features within the northern environment do not universally transform. Regionally specific pond boundary changes may relate to shifting climatic regimes, human interactions or landscape morphology and are not translatable to similar subarctic landscapes. Therefore, pond sustainability research that provides understanding of regional hydrologic dynamics does not translate to global predictions of landscape change.

Table 2.2 - Synopsis of Previous Northern Lake/Pond Sustainability Findings

Author(s)/Year	**Period**	**Recorded Surface Area Change by Permafrost Type** (= no change, - decreasing trend, + increasing trend * large water bodies)
Yoshikawa and Hinzman (2003)	1950-2000	(-) discontinuous permafrost landscape
Christensen et al. (2004)	1970-2000	(+)continuous permafrost landscape
Stow et al. (2004)	1905-1960	(-) discontinuous permafrost landscape
Smith et al. (2005)	1973-1998	(-) discontinuous permafrost landscape * (+)continuous permafrost landscape *
Klein (2005)	2000 -2002	(=)continuous permafrost landscape
Riordan et al. (2006)	1950-2002	(-) discontinuous permafrost landscape (=)continuous permafrost landscape
Walter et al. (2006)	1974-2000	(+)continuous permafrost landscape
Grosse et al. (2007)	1969-2002	(=)continuous permafrost landscape (not including Δ from human interaction)
Grippa et al. (2007)	1988-2002	(+) discontinuous permafrost landscape*
Plug et al. (2008)	1978-1992 1992-2001	(+)continuous permafrost landscape (-)continuous permafrost landscape (=) overall landscape
Labrecque et al. (2009)	1951-1972 1972-2001	(+)continuous permafrost landscape (-)continuous permafrost landscape (=) overall landscape

2.4.3.1 Issues Related to Previous Research

Although a multitude of previous studies have focused on the sustainability of northern open water features, various issues emerge when attempting to apply results to similar environments. These issues are related to location, feature size, imagery resolution, imagery capture dates and environmental consideration. Most notably, regional characteristics significantly impact pond distribution and sustainability. For example, permafrost extent and distribution alters pond hydrology and influences landscape morphology. In addition, regional topography and surrounding vegetation may affect hydrology and may produce disparate pond stability results regardless of similar climatic conditions. Therefore, comparisons of research findings across different landscapes should be applied with caution. Studies have been conducted in areas of both continuous and discontinuous permafrost, but most work has been conducted on larger lakes rather than small shallow water bodies. At present, the fate of Churchill water features is unknown.

Additionally, previous subarctic hydrologic sustainability studies reveal inconsistent pond water feature size classifications. Since larger open water features may respond differently to environmental changes over long term periods, results are not necessarily comparable to smaller water bodies (Duguay and Pietroniro, 2005). As well, larger lake sustainability studies typically utilize lower resolution imagery and focus on deriving landscape trends while pond boundary change studies require higher resolution imagery and detects small scale environmental transformations. Due to varying methods, objectives and underlying hydrology, pond/lake sustainability findings do not provide universal estimates of northern water feature change.

Lastly, imagery capture dates and environmental conditions can significantly alter pond stability findings. Several previous studies have attempted to account for this issue by selecting images with similar capture dates. However, these studies have not accounted for annual climate anomalies, seasonal/periodic water level fluctuations, imagery capture date conditions or the influence of antecedent precipitation. Each of these variables can significantly alter detected pond surface area and need to be considered prior to feature extraction. Therefore, resulting surface area change may result solely due to inter-annual hydrologic fluctuations. In order to accurately account for naturally induced surface area fluctuations, hydrological water level modeling must be conducted and linked to imagery capture dates (e.g. Labrecque et al., 2009). Overall, seasonal imagery context should be considered a very significant variable when attempting to determine and apply change detection results within the subarctic.

Although many studies have attempted to quantify changes in northern ponds/lakes throughout Alaska and Siberia, the long-term sustainability of small water bodies within the Canadian Subarctic is relatively unknown. Documenting the surface area and extent of these water features is crucial in understanding change within the northern environment. These evident research gaps are addressed throughout this thesis.

3.0 Study Site

3.1 General Research Location: Hudson Bay Lowland

Located within central Canada, Hudson Bay Lowland is considered the third largest wetland complex globally. Geographically confined by the Canadian Shield (west/south), Hudson Bay (north) and James Bay (east), this area is situated near the southern edge of continuous permafrost coverage and generally above the northern tree line. As displayed in Figure 3.1, open water features occupy a significant portion of the landscape.

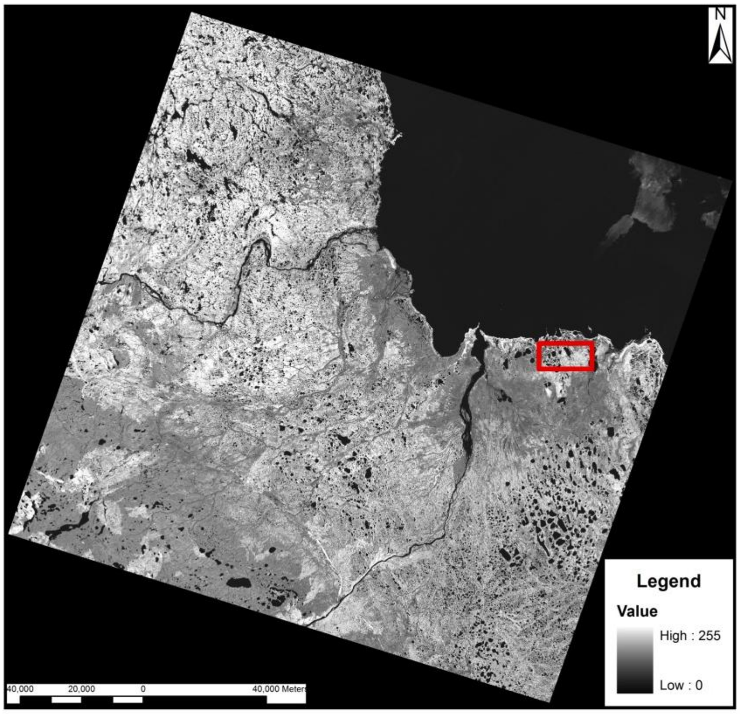


Figure 3.1 - Research Site, Hudson Bay Lowland Within Northern Manitoba: Specific location indicated with red square (Landsat 7 Image, 2000)

3.1.1 Climate

Ranging from -3°C (2006) to -10°C (1972), annual temperature averages -6.87°C within the Churchill region. June to September exhibit average monthly temperatures above 0°C, which contribute to maximum mean annual temperatures averaging -2.80°C. During the open water period, average mean temperatures hover around 7°C and range between 9°C (1948) and 4°C (1972). July has the highest recorded average monthly temperature (12°C) while September exhibits the coldest open-water air temperatures (6°C). The coldest monthly temperature, averaging -27°C, is recorded for January (Environment Canada, 2009).

Annual precipitation averages approximately 416 mm and ranges between 214 mm (1944) and 618 mm (1983). Over 60% of total annual precipitation consists of snowfall while the remainder is added as rainfall during the open water period. In total, 93% of the total average annual rainfall occurs within the open water period (averaged 230 mm). Minimal snowfall occurs between June and October (averaging 35 cm or 18% of total snowfall). During the open water period, August is considered the wettest month (averaging 65 mm) while June is the driest month (averaging 42 mm). However, facilitated by the major melt period, June exhibits saturated ground conditions and pond overflow (Environment Canada, 2009).

Annual average vapour pressure ranges between 0.1 kPa (December to April) and 1.1 kPa (July to September) with average values hovering near 0.5 kPa. Displaying increased values during the open water period (85 – 89%), daily humidity ranges from 71 – 79% annually. Average annual atmospheric pressure is 101.1 kPa within the Churchill region. Annual wind speed averages 21 km/h. The highest recorded monthly values occur in January, October and November (23 km/h) while the lowest values are recorded in July (17 km/h). Generally, winds are strongest during the winter months and lessen during the open water period. Wind direction is frequently recorded as westerly during winter and north-westerly throughout summer (Environment Canada, 2009).

3.1.2 Physical Characteristics

The Churchill region exhibits typical Canadian subarctic climate, physical characteristics and land cover (Christopherson, 2004). Table 3.1 provides a synopsis of landscape attributes characteristic to the study site. Most notably, Hudson Bay Lowland morphology is significantly influenced by historical glacial activity. Due to retreat of the Laurentide Ice sheet approximately 8,000 years ago (L. Dredge, 1992), the northern portion of the Lowland exhibits characteristically flat terrain and gradually slopes (<1 m per km) towards Hudson Bay (Dredge and Mott, 2003). Experiencing 11.4 (±0.7) mm of isostatic uplift annually (Wolf et al., 2006); this region has exhibited significant water level decrease (approximately 150 m) and the development of peatland (Dredge, 1992). Major relief features, such as patterned ground, peat plateaus, palsas and thermokarst ponds, originated from glacial deposits and landscape scaring. In addition, several hydrologically sensitive landscape features occupy the region. These features include bogs, fens, peatlands and small water bodies.

Table 3.1 - Physical Landscape Characteristics in Churchill Region, (Duguay et al., 2002; Geological Survey of Canada, 2008; Lafleur et al., 1997; Macrae et al., 2004; Yee, 2008)

Variable	Description of Variable for Churchill Region
Relief	Flat – gently sloping towards Hudson Bay (1m km^{-1})
Land cover Types	Tundra, Peatlands, Forest Transition, Open Forest
Bedrock	Ordovician and Silurian Limestone
Soil Type	Marine Silts and Clays overlying tills
Peat Deposits	10-100cm (Gradually deeper proceeding inland)
Permafrost Terrain	Patterned Ground, Peat Plateaus, Palsas, Thermokarst Ponds
Permafrost Thickness	Continuous (30-61m)
Active Layer Depth	30-100cm

Generally, permafrost coverage ranges from continuous (30- 60 m thickness) within the northern portion of the Hudson Bay Lowland to discontinuous near the southern limit (Nelson, 1986). Permafrost degrades significantly with distance from Hudson Bay (Rouse et al., 1997). The Churchill region exhibits continuous permafrost and active layer depths typically ranging from 30 cm in peat plateaus to 1 m within the inland open forest region (Lafleur et al., 1997; Yee, 2008). Within the coastal region, active layer depth averages between 40 and 50 cm (Macrae et al., 2004). Excluding glacial relief features comprised of outwash deposits, marine silts and clays above Ordovician and Silurian limestone bedrock predominantly shape the landscape. Bedrock outcrops are evident and scattered throughout the region. An evident layer of peat topsoil, sustained by poorly permeable soil/bedrock conditions, ranges in thickness between 10 to 100 cm (Duguay et al., 2002) and gradually increases with distance from the coast (Lafleur et al., 1997).

Within the Churchill region, landscape topography and shoreline proximity primarily control vegetation cover. Facilitated by increased active layer depth, improved coastal wind protection and thicker soil profiles, vegetation height increases with distance from the shoreline. Trees found in the region include dwarf birch (betula glandulosa), nine willow (Salix) species, and larch (Larix laricina). Across the tundra landscape, peatland surface cover is dominated by lichen-heath communities that are comprised of a combination of various macro-lichen species (e.g. Cladina, Cetraria), sedges (Carex), and vascular plants (e.g. Empetrum nigrum, Vaccinium vitis-idaea). Generally, peatlands surrounding the ponds are polygonal peat plateaus, throughout which, hummocks and hollows can be found. Many of these hummock areas host lichen-heath communities while the hollows support various Carex species. Near the southern portion of the Lowland, various aspen (populus tremula), birch (betula), balsam (abies balsamea) and spruce (Picea) cover the landscape (Scott, 1996).

3.2 Specific Research Location: East-Central Churchill Region

Specifically, the selected 50 km² research site is located within the northwest portion of the Hudson Bay Lowland and east of Churchill, Manitoba (93°54’51.71” W, 58°45’06.75” N to 93°40’49.21” W, 58°41’08.65” N). Several constructed and landmark features reside within the study area. Situated near the centre of the research site, the Churchill Northern Studies Centre as well as an abandoned rocket range, gravel pit and several intersecting gravel roadways influence regional hydrology and topography. As well, constructed tundra buggy tourist routes and parking lots have significantly altered the natural landscape within the western portion of the research site. Lastly, water pumping, elevated gravel roadways and manually routed catchments have contributed to hydrologically altered ground conditions.

3.2.1 Land Cover & Water Features

Evident throughout the research site, open water features range in size, proximity and location. In total, small water features occupy between 15 - 50% of the Churchill landscape, with estimated averages of 25% (Macrae et al., 2004) to 40% (Bello and Smith, 1990). Within this region, shallow ponds and lakes occupy approximately 32% of the tundra zone, 24% of the forest–tundra zone and 7% of the open forest zone (Lafleur et al., 1997). These land cover classes are distributed in gradual transition from east to west towards Hudson Bay. Duguay and Lafleur (2003) and Lafleur (1997) documented an abundance of shallow water features in the tundra zone and a gradual decreasing trend with proximity to the northern treeline. As well, larger ponds typically reside within the transition zone, while smaller catchment pools occupy the tundra region. The exact percentage of pond occupancy is unknown within the region. Previous research suggests average mean pond/lake depth ranges between 1 m in the tundra zone, 1.4 m in the transition zone and 1.8 m in the open forest zone (Duguay and Lafleur,2003). As well, ponds rarely exceed an average water depth of 1 m (Macrae et al., 2004, Duguay et al., 2003). The greatest variability in size and depth was found in the transition zone (Duguay and Lafleur,2003).

For the purpose of this research, open water features exhibiting surface area boundaries between 400 and 40,000 m^2 and water levels less than 1 m deep were considered ponds. As well, ponds must completely freeze during the winter months and begin the open water period at maximum hydrological capacity. These size distinctions were established based on previously published water sustainability research (Bello et al., 1990, Duguay et al., 2005, Duguay et al., 2002, Macrae et al., 2004). Due to shallow water depths and the presence of strong winds, pond water temperatures exhibit isothermal status post the major melt period.

4.0 Results and Discussion: The Occurrence and Influence of Natural Hydrologic Variability on Remote Sensing Pond Surface Area Change Detection Studies in the Hudson Bay Lowland, Canada

4.1 Introduction

Shallow open water features occupy a significant portion of the Canadian subarctic landscape (Bello and Smith, 1990; Macrae et al., 2004; Duguay and Pietroniro., 2005) and notably influence regional chemical, energy, biological and hydrological systems (Rouse et al., 1997; White et al., 2007). Often sustained by ombrotrophic peatlands, these systems exhibit water balances dominated by atmospheric exchanges after the major snowmelt period (Woo, 1980; Bello and Smith, 1990; Boudreau and Rouse 1995; Browling et al., 2003; Macrae et al., 2004). Given the anticipated sensitivity of pond-atmospheric exchanges to climate change, shifting pond surface area and distribution may indicate regional environmental change (Gorham, 1991; Hinzman et al., 2005; Schindler and Smol, 2006; White et al., 2007).

Due to documented climatic change within some areas of the subarctic, there is growing concern over the fate of open water systems. Several remote sensing studies have produced contrasting results regarding the long-term sustainability of subarctic/arctic shallow water features. Previous studies have concluded pond/lake degradation (Stow et al., 2004, Yoshikawa and Hinzman, 2003, Riordan et al., 2006, Smith et al., 2005), expansion (Smith et al., 2005, Grippa et al., 2007) or multi-directional change (Labrecque et al., 2009). However, many of these studies have not considered pond/lake physical characteristics, antecedent hydrologic conditions or annual climatic influences.

Facilitated by hydrologic sensitivity to atmospheric conditions, changes in pond sustainability have been directly linked to regional climate change (Hinzman et al., 2001; Schindler and Smol, 2006; Smol and Douglas, 2007; White et al., 2007). These highly variable systems are controlled by diurnal hydrologic exchanges, which may generate continuous fluctuations in water levels. Antecedent hydrologic conditions may significantly impact pond surface area and consequently impact the accuracy of pond sustainability results.

The purpose of this study was to examine the occurrence of pond water level and surface area fluctuations caused by naturally induced hydrologic variability within the Churchill region of the Hudson Bay Lowland (HBL) and characterizes the influence of these conditions on remote sensing pond surface area delineation. Specifically, the following two questions were addressed: (1) Does naturally induced hydrologic variability over three temporal periods influence pond water levels and surface area in the Churchill region? (2) Are naturally fluctuating pond boundaries evident when delineating features using remote sensing imagery? Three examples of hydrologic change were used to characterize the effects of antecedent conditions on pond surface area: (a) short-term variability within the same season (intra-seasonal water level fluctuations: 1956); (b) a comparison of two successive years (200, 2001) what had similar antecedent hydrologic conditions with the exception of the occurrence of a significant rainfall event immediately prior to image capture in one year; and (c) a comparison of two years (2000, 2006) with contrasting antecedent conditions (wet Versus dry).

4.2 Study Area and Pond Selection

The general study site (Figure 4.1), located east of Churchill, Manitoba (58°45’N, 94°04’W), west of Hudson Bay and within the northern portion of Hudson Bay Lowlands, was selected as a 50 km^2 rectangle near the southern limit of continuous permafrost (Duguay et al., 2002) and the northern limit of the treeline (Bello and Smith, 1990) (93°54’51.71” W-93°40’48,21” W and 58°45’05.75” N-58°41’08.65” N). This site was selected based on historical hydrologic/climate data availability, accessibility, the abundance of pond features, geographic gaps in pond sustainability research and previously established hydrologic conditions.

Within this region, the terrain is flat and gently sloping towards the north shore at 1 m/ km^{-1} with 11.4mm (±0.26) of isostatic uplift occurring annually (Wolf et al., 2006). Glacial deposits comprise all major regional relief features and the soil profile typically consists of peat overlaying silts and clays of marine origin (Dredge, 1992). Active layer depth ranges from 40 – 150cm within the region (Lafleur et al., 1997). The study area crosses three major ecological zones: open tundra, forest tundra transition and open forest (Duguay et al., 2002). Detailed descriptions of the Churchill region are provided by Bello and Smith (1990), Dredge (1992), Duguay and Lafleur (2003), Duguay et al. (2002); Duguay et al. (2003), Macrae et al. (2004), and Chapter 3 (General Study Site).

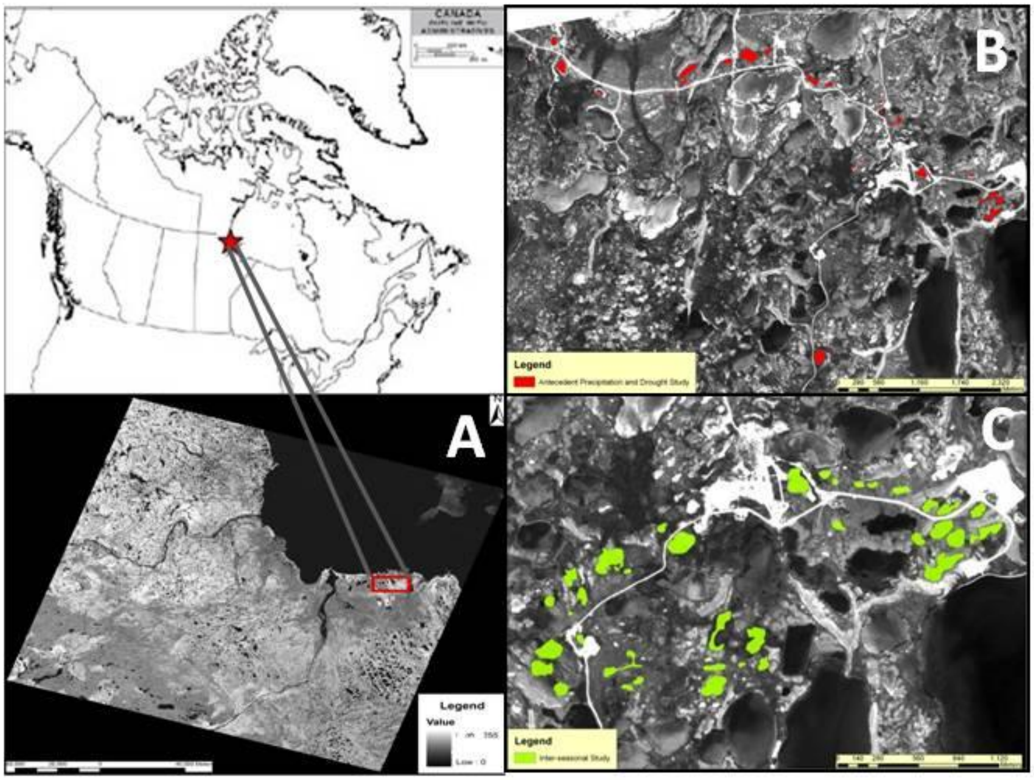


Figure 4.1 - Study Site: (A) Extent of Study Site, Southwest of Hudson Bay and East of Churchill, Manitoba, Canada, (B) Red circles depict 29 Ponds Selected to Examine the Impact of Inter-annual Hydrologic Anomalies and Antecedent Precipitation, (C) Green circles depict 37 Ponds Selected to Evaluate the Influence of Intra-seasonal Hydrologic Variability (Landsat, 2006; NAFL 1956)

The Churchill region exhibits a 30-year mean annual temperature of -6.9°C, with lowest mean monthly recorded temperatures occurring in January (-26.7°C) and warmest mean monthly temperatures occurring in July (12°C). Annual total precipitation averages 416 mm, with over 60% falling as snow

(Environment Canada, 2004). Averaging 230 mm, approximately 93% of the total average annual rainfall occurs within the open water period.

Within the Churchill Region ponds occupy between 15% - 50% of the landscape and are estimated to average between 25% (Macrae et al., 2004) and 40% (Bello and Smith, 1990). For the purpose of this study, ponds were defined as any water feature exhibiting surface area between 400 - 40,000 m^2 and a maximum depth less than 1 m. Size and depth distinctions were determined based on previous northern pond studies(Bello and Smith, 1990; Duguay et al., 2002; Macrae et al., 2004; Duguay et al., 2005). Selected ponds were organized into four size classes including: puddle ponds (400 m^2 to 5,000 m^2), small ponds (5,001 m^2 to 10,000 m^2), medium ponds (10,001 m^2 to 20,000 m^2) and large ponds (20,001 m^2 to 40,000 m^2).

Within each image, subsets of ponds were selected for comparison to characterize changes in pond surface area. Specific ponds were selected based on imagery overlay, image quality, feature size (to represent the physical landscape) and field collected data. Unfortunately, due to imagery availability, a consistent subset of ponds could not be used for all comparisons. One subset of 29 ponds was selected to examine the impact of inter-annual hydrologic variability and antecedent precipitation. A second subset of 37 ponds (many of which overlapped with the subset of 29 that was used for inter-annual comparisons) was selected to evaluate the influence of intra-seasonal hydrologic variability (Figure 4.1).

4.3 Data Sources and Methodology

Within this study, field based methods were used in order to establish the occurrence of hydrologically induced intra-seasonal/ inter-annual water level and surface area change while hydrological modeling and remote sensing analyses determine the impact of these naturally induced hydrologic fluctuations on the accuracy of remote sensing pond shoreline delineation. Specifically, field measurements and photographs captured over multiple dates within and amongst selected years were examined to characterize the fluctuation of pond shorelines. Findings were supported by pond hydrologic modeling and surface area change predictions.

4.3.1 Field Observations

Daily pond water levels and surface area observations were collected during a 32-day field campaign from July 21st to August 21st 2008. Pond water height measurements were collected from two locations daily and cross-referenced to minimize the influence of device slump due to thawing permafrost conditions. Corresponding pond surface area changes were captured at the same location using controlled photography. Additionally, several pond characteristics were surveyed in order to establish a representative understanding of pond structure, dynamics and model surface area change. These characteristics included: peat ridge heights (30 ponds), maximum capacity surface area (40 ponds), current pond surface area (100 ponds) and pond bathymetry (30 ponds). Inter-annual surface area change of a representative pond within the study site was documented using controlled photography between 2005 and 2008 (Pond LeeAnn, unofficial name). Churchill Northern Studies Research Centre staff captured annual pond surface area images on approximately the same date for three consecutive years and one additional year. Resulting imagery was coupled with modeled water level change in order to provide hydrological context for each imagery capture date.

4.3.2 Climate Analysis & Water Balance Modeling

Precipitation, air temperature, humidity, wind speed and snow cover were obtained from Environment Canada for 1956, 2000, 2001 and 2006 (‘Churchill A’ Weather Station). These parameters were used as input into the Canadian Lake Ice Model (CLIMo) (Duguay et al., 2003), for the purpose of deriving the timing of freeze-up and break-up dates, open water season duration, and surface water temperature. The resulting surface water temperature values during the open water season were utilized to determine evaporation using the Oswald and Rouse model (2004).

The Oswald and Rouse (2004) mass transfer equation, which adopted Fick’s first law of diffusion (1855), was used to obtain evaporation values using the equation:

$$E = K_e u_z \, (e_o - e_z) \qquad \textit{Equation 4.1}$$

where E is point evaporation, K_e is the coefficient of proportionality, u is the horizontal wind speed at height z, e_o is the vapour pressure of saturated air at the temperature of the water surface and e is the vapour pressure of the air at the height z above the water surface. A value of 0.81 was used for K_e, which was derived statically using published values for summer evaporation rates from ponds collected over a 4 year period in the Churchill region (Boudreau and Rouse, 1995; Petrone and Rouse, 2000; Yee, 2008). Figure 4.2 displays the strong relationship between modeled and field collected evaporation data ($r^2 = 0.94 – 0.99$). Results from this model provide an average estimate of point evaporation for shallow water features within the region. However, derived data does not directly translate to all pond features due to varying bathymetries, pond dynamics and underlying sediment.

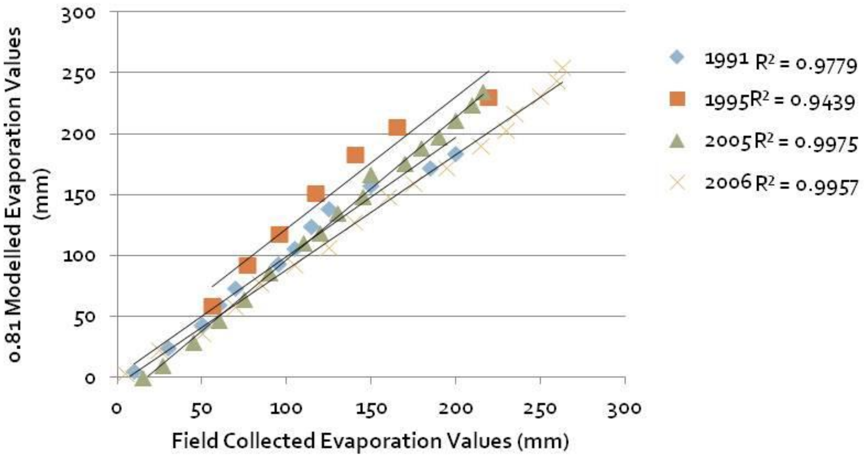


Figure 4.2: Scatter Plot Comparing Modeled Evaporation Data Derived from the Oswald Equation (2004) using a Ke Value of 0.81(Boudreau and Rouse, 1995; Petrone and Rouse, 2000; Yee, 2008)

Precipitation and evaporation predominantly control pond water levels post the major melt water period within the Churchill region (Macrae et al., 2004; Prowse and Ommanney, 1990). Surface and subsurface flow contribute to the overall water balance during major rain events; however, these are relatively uncommon during summer months within the Churchill region (Environment Canada, 2004). Therefore, the pond water balance may be modeled using the equation:

$$\Delta = P - E \qquad \textit{Equation 4.2}$$

where Δ is change in pond water storage, P is precipitation and E is evaporation. As well, it is assumed that pond water levels begin at bankfull storage post the major melt period and oscillate due to atmospheric exchanges until freeze-up. It was understood that overland flow commenced during all instances where total cumulative precipitation exceeded evaporation and any additional water was lost to the surrounding area. Pond water balances were determined for each imagery capture year using Environment Canada precipitation data and Oswald and Rouse (2004) evaporation data. These data sources provide general water balance values that may not directly translate to individual pond conditions due to topography, hydrologic networks and unique bathymetries. Pond surface area change was estimated using a combination of field collected data and modeled water balance calculations. Calculated modeled water balance changes for each temporal period were subtracted or added to average seasonal water level measurements (Field Season 2008) in order to estimate pond water levels upon imagery capture. A linear equation reveals moderate correlation ($R^2=0.4$) between pond surface area and depth measurements within the Churchill region. Estimated pond shoreline positions were determined by combining water level estimates with calculated surface area to depth ratios. Resulting modeled pond surface area values are compared in order to establish estimated antecedent hydrologically induced pond shoreline change under various environmental conditions.

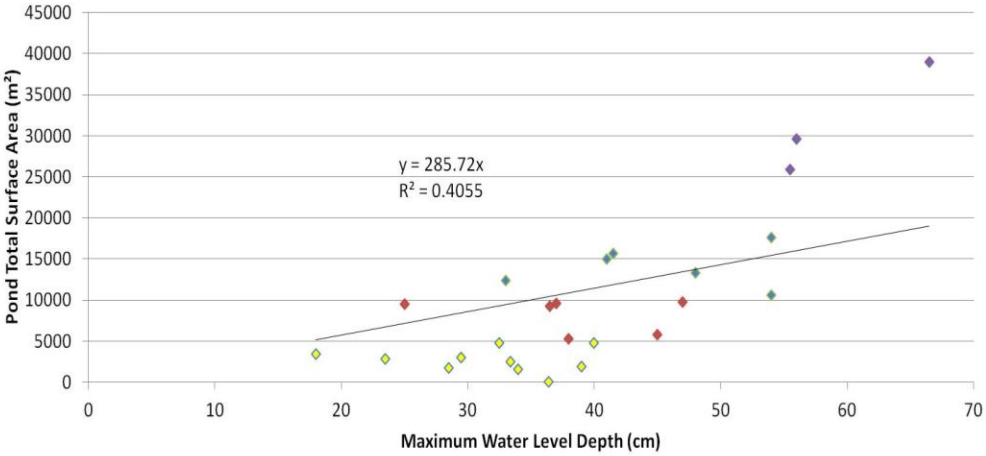


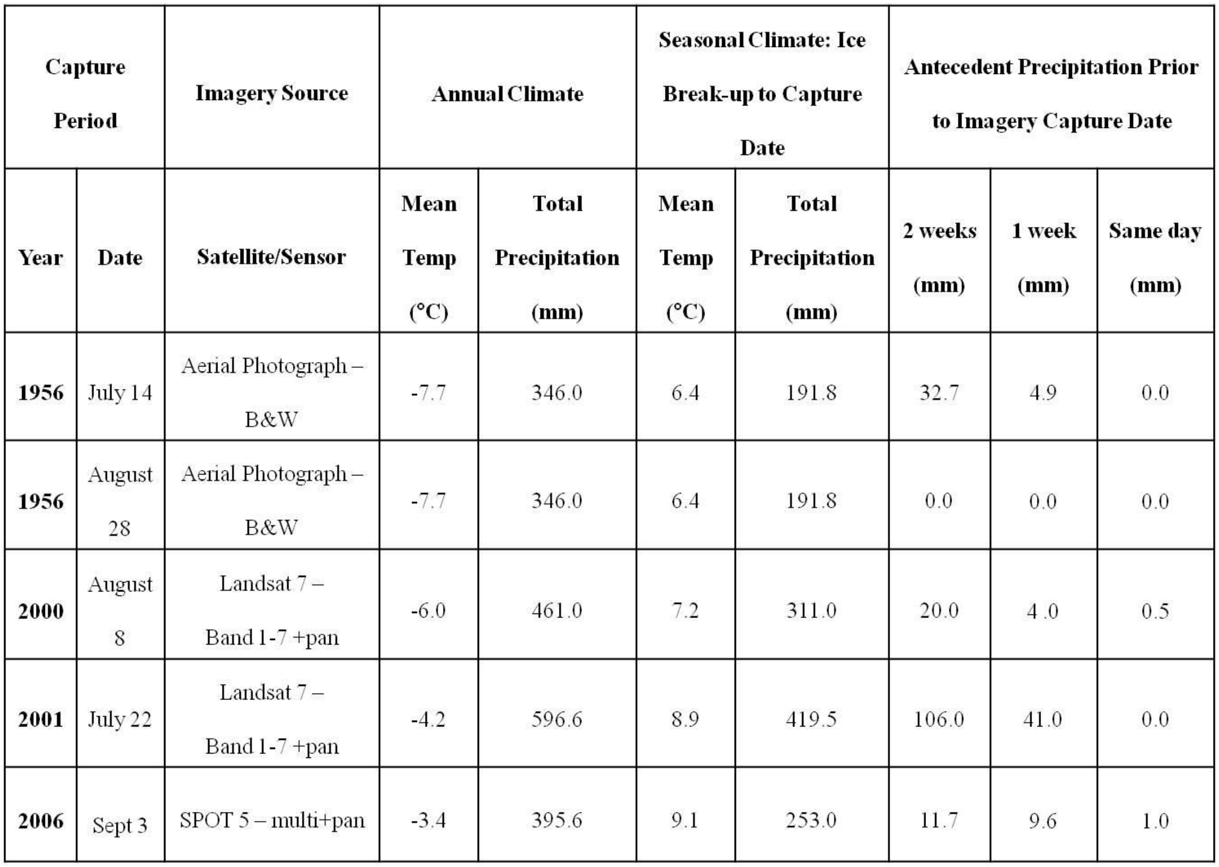
Figure 4.3 - Relationship between Pond Surface Area and Water Level Depth: Churchill region. Pond features are classified by size class: Orange markers = puddle ponds, Red markers = small ponds, Blue markers = medium ponds Purple markers = large ponds

4.3.3 Remote Sensing Imagery Analysis

Five remote-sensing acquired images (2 air photos, 2 LANDSAT 7 and 1 SPOT) were selected to represent varying hydrologic conditions within the Churchill region. For the purposes of this study, only cloud-free imagery captured within the latter portion of the open water period and exhibiting either intra-seasonal/inter-annual water balance fluctuations or large antecedent precipitation events were considered.

Intra-seasonal hydrologic fluctuations were analyzed using 2 air photos captured in 1956 by means of a 9.5 mm black and white film at a scale of 35,000 using north and south orientation (Table 4.1). These images were scanned and resampled to 2 m resolution. One LANDSAT 7 image captured during 2000 was acquired and employed as a 'control/normal' within the antecedent precipitation and inter-annual studies. A second LANDSAT 7 image was selected based on significant antecedent precipitation prior to imagery acquisition (Table 4.1). Specifically, band 4 (0.76µm – 0.90µm) and the panchromatic band (0.50µm – 0.90µm) were chosen and merged based on strong contrast between water to land features and improved resolution. LANDSAT images were resampled to 15 m resolution. The remaining SPOT 5 image, which was selected to analyze varying inter-annual conditions, was captured in 2006 using four bands (Table 4.1). Of these, the red (0.61µm – 0.68µm) and near IR (0.78µm – 0.89µm) were extracted and merged with the panchromatic (0.48µm – 0.71µm) to create a 2.5 m resolution swath. Band 1 (green: 0.50 - 0.59 µm) was omitted due to moist ground conditions and the high sensitivity of this band to surface moisture. The red and near IR bands were merged with the panchromatic swaths in order to eliminate the influence of vegetation encroachment on pond boundary delineation. Additionally, a series of tone and texture rules were established in order to minimize the influence of this variable when manually digitizing pond features.

Table 4.1 - Summary of Imagery Acquisitions and Associated Climate/Weather Data: Churchill Region (1956, 2000, 2001, 2006)



Capture Period		Imagery Source	Annual Climate		Seasonal Climate: Ice Break-up to Capture Date		Antecedent Precipitation Prior to Imagery Capture Date		
Year	**Date**	**Satellite/Sensor**	**Mean Temp (°C)**	**Total Precipitation (mm)**	**Mean Temp (°C)**	**Total Precipitation (mm)**	**2 weeks (mm)**	**1 week (mm)**	**Same day (mm)**
1956	July 14	Aerial Photograph – B&W	-7.7	346.0	6.4	191.8	32.7	4.9	0.0
1956	August 28	Aerial Photograph – B&W	-7.7	346.0	6.4	191.8	0.0	0.0	0.0
2000	August 8	Landsat 7 – Band 1-7 +pan	-6.0	461.0	7.2	311.0	20.0	4 .0	0.5
2001	July 22	Landsat 7 – Band 1-7 +pan	-4.2	596.6	8.9	419.5	106.0	41.0	0.0
2006	Sept 3	SPOT 5 – multi+pan	-3.4	395.6	9.1	253.0	11.7	9.6	1.0

Following imagery collection, each image was scanned (air photos), orientated, orthorectified, cropped, amalgamated to create a mosaic, clipped to the study site and merged for band addition (LANDSAT7 and SPOT 5 images) in order to prepare for pond feature extraction. To aid with the extraction of ponds, 2008 ground-truthing data was overlaid onto each image. This process provided context for each image and acted as a guide for understanding imagery tones. Overall, 37 pond features from each air photo and 27 ponds from each LANDSAT 7 and SPOT images were on-screen digitized at a scale of 1:2,320 using ArcMap. Ponds were outlined using a set of rules regarding tone, size, shape, texture and orientation. In order to calculate digitization accuracy, a subset of 24 manually digitized surface areas from the 2008 SPOT image were compared with field collected surface area data. A comparative scatter plot revealed a strong relationship between the two data sets and an overall root mean square error of 172 m^2 (r^2=0.92). Therefore, the manual pond boundary delineation error for this study is assumed to be small.

The resulting polygons were overlaid and visually inspected for errors. Feature statistics were extracted and compared in order to determine feature growth or decay for each hydrologic study. Lastly, feature statistics were compared to estimated surface area change and modeled water level change to determine the influence of each variable on pond boundary delineation.

4.4 Results

4.4.1 Comparison of Field Observed Pond Surface Areas with Observed/Modeled Pond Water Levels

It was hypothesized that pond boundaries and water levels in Churchill region would fluctuate naturally within and between open water seasons and that pond characteristics would vary depending on antecedent hydrologic conditions as well as time of year. Controlled photography was used to establish the occurrence of variable pond surface areas while field collected and modeled pond water levels reveal the presence of corresponding water level fluctuation.

As displayed in Figure 4.4, pond Felix (unofficial name) experienced large surface area oscillations. Over the 29 day period, pond surface area visibly retreated under conditions where evaporation exceeded precipitation (August 7th to August 15th) and expanded due to rain events (July 23rd – 25th, August 2nd – 5th and August 16th - 17th). As well, Felix displayed similar surface area measurements under comparable water balance conditions (August 7th to August 19th). These documented short-term changes do not represent long-term changes in atmospheric conditions (Environment Canada, 2004). On the contrary, recorded shifts in pond surface area confirm the presence and impact of natural intra-seasonal hydrological variability on pond shape and size during the open water season. Similar pond surface area fluctuations were visually documented in surrounding water features during the 2008 field campaign. Therefore, intra-seasonal hydrological variability strongly influences the surface area of many regional ponds and must be considered when studying pond sustainability within this region.

July 31st 2008 August 7th 2008 August 15th 2008 August 19th 2008

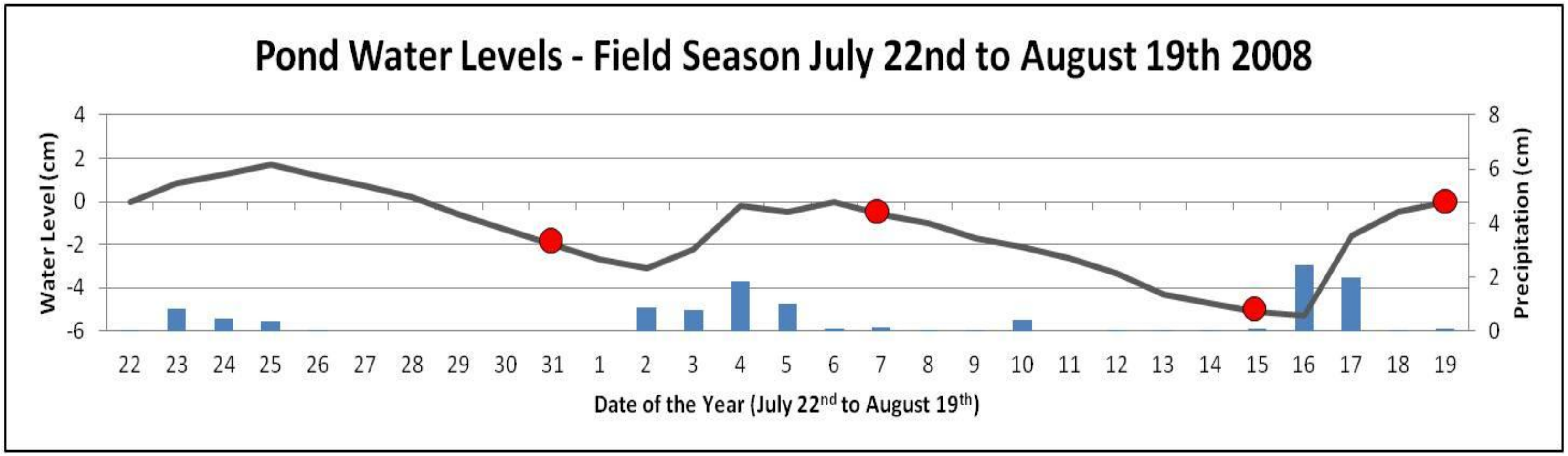


Figure 4.4 - Field Observed Water Level Fluctuations and Field Collected Photographic Surface Area Change (July 22nd-August 19th 2008), Pond Felix: Churchill Region. Red dots correspond with imagery capture dates featured above. Precipitation values are represented with blue bars.

Additionally, naturally induced inter-annual hydrologic variability is estimated to significantly impact pond surface area and manufacture unrepresentative short-term changes in pond sustainability measurements within the Churchill region. A 5-year imagery-based analysis of Pond LeeAnn (unofficial name) revealed significant fluctuations in pond size. As displayed through imagery in Figure 4.5, pond surface area notably expanded (2004-2005) then consistently retreated (2005 to 2008) to suggest significant pond shoreline variability. Based on the images alone, Pond LeeAnn has experienced considerable annual surface area change. As well, a comparable degree of change has been documented for surrounding water features (Fishback, 2008), which confirms the presence of shifting surface area conditions within the Churchill region. These contemporary inter-annual shoreline inconsistencies should correspond to changing water level conditions.

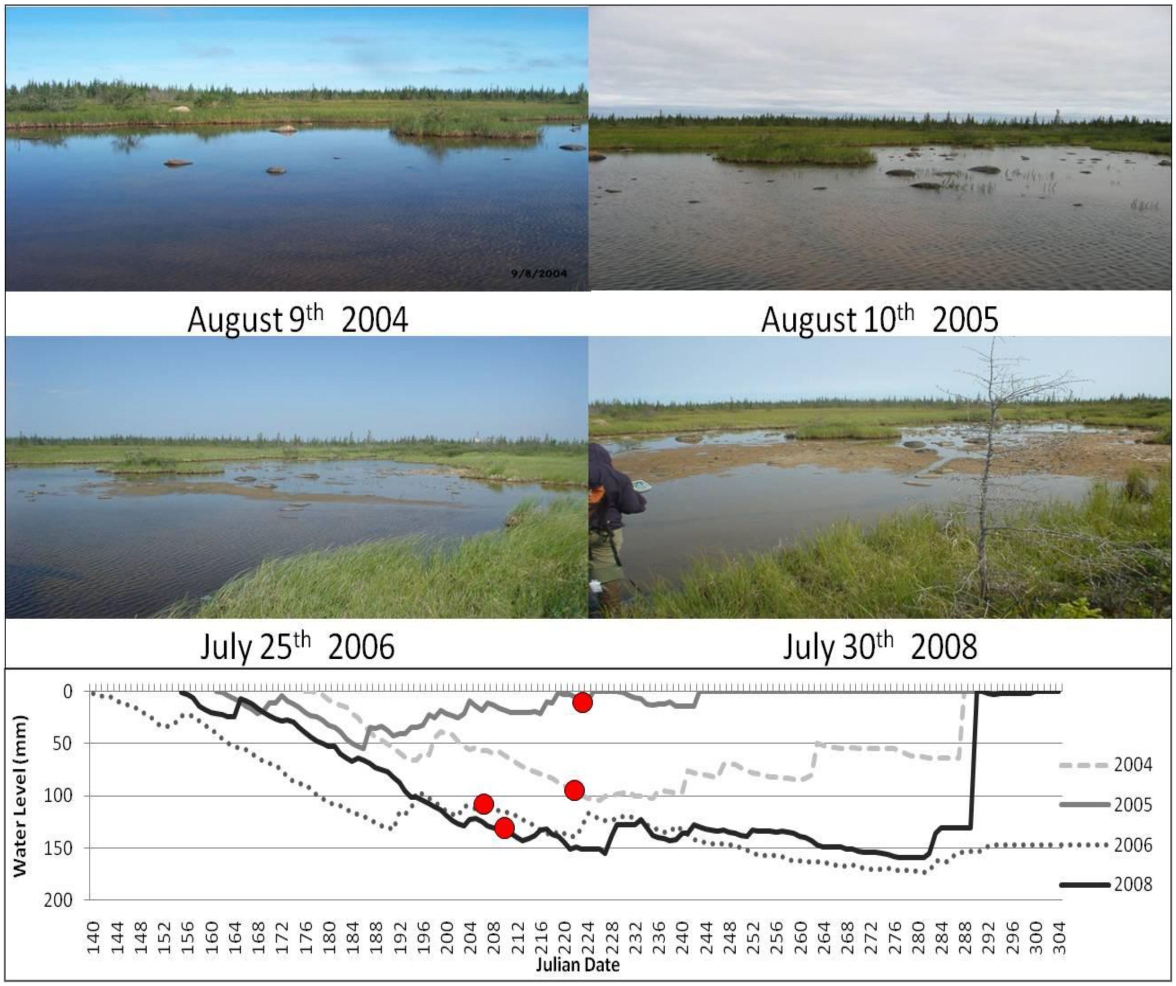


Figure 4.5 - Field Observed Inter-annual Pond Water Level Change Images and Modeled Water Level Position During Imagery Capture (2004-2008): Modeled water level positions during imagery capture dates are indicated with red dots (Pond LeeAnn, Churchill Region)

As was the case for pond surface areas (described above), it was hypothesized that pond modeled water balances would demonstrate large amounts of intra-seasonal change during the open water period. Indeed, daily field observations collected for a representative medium sized pond (surface area = 17,571 m²) over a 29-day period in 2008 revealed significant fluctuations in pond water levels. These oscillations generally coincided with regional weather patterns and were evident in surrounding water features (Figure 4.4). Generally, ponds exhibited a slight decrease in water levels under conditions where evaporation exceeded precipitation (dry period) and immediately rose following rain events. Figure 4.4 reveals the occurrence of fluctuating pond water levels, which were heavily controlled by intra-seasonal hydrologic variability (Pond Felix). Exhibiting a gradual decreasing trend as well as two periods of significant increase corresponding with major rain events (August 2nd and August 16th), water levels fluctuated by 7cm between July 22nd and August 19th. However, no significant water level change was evident between the first and last observation dates of the study period. Therefore, pond Felix`s water levels were seasonally variable and heavily controlled by atmospheric exchanges. These constantly fluctuating conditions translated to differences in pond surface area (Figure 4.4).

Similarly, in order to establish the influence of inter-annual water level variability on pond surface areas, daily water balances were modeled and cross referenced with imagery capture dates. As shown in Figure 4.5, results derived from connecting these data sources demonstrated significant inter-annual hydrologic variability and revealed no contemporary change in climatic conditions. Modeled water balance results suggested that the pond would exhibit a water level increase (and therefore an increase in surface area extent) between 2004 and 2005 (10cm) followed by a drying/shrinking trend from 2005 to 2008 (14cm total). Overall, pond surface area change documented from photographic imagery strongly coincides with modeled short-term water balance variability and suggests that inter-annual hydrological variability strongly influences pond surface areas within the Churchill region.

In summary, field observations collected between 2004 and 2008 have demonstrated the occurrence of hydrologic variability at both short and longer time scales, and have characterized the effects that this variability has on pond surface areas. These results have implications for remote sensing studies as naturally-occurring hydrologic variability may produce detectable changes in pond surface area, which may affect the interpretation and conclusions of studies using imagery analyses to detect pond sustainability.

4.4.2 The Influence of Natural Water Level Fluctuations and Surface Area Variability on Remote Sensing Pond Boundary Delineation

In order to establish the influence of naturally induced short-term hydrologic variability on the accuracy of image-based pond sustainability detection, several remote sensing based surface area change detection studies were executed in conjunction with water balance modeling. Variations in detected pond surface area were analyzed under three scenarios (within the same season and between hydrologically variable years) to determine the influence of these variables on accurately delineating pond sustainability. Results were separated by temporal scale to demonstrate the importance of characterizing antecedent conditions at different timescales when conducting remote sensing based pond sustainability studies.

4.4.2.1 Pond Surface Area Detection Under Conditions of Intra-seasonal Hydrologic Variability

Ponds in the Churchill region of the HBL follow a characteristic seasonal pattern in most years where ponds fill to capacity during melt and dry down throughout the summer season before refilling in autumn (Macrae et al., 1994; Rouse, 1998). Air photos taken of the same ponds early and late in the same season were compared to demonstrate the effects of seasonal drying on pond surface areas. As displayed in Figure 4.6A, results from a water balance study focusing on the 1956 open water period found considerable variation in seasonal water levels. Apart from major rain events, pond features were estimated to undergo significant and consistent water level decline during the entire open water season. Specifically, mid-season (July 8 capture date) pond water level depths were estimated on average to lie 5.3 cm below maximum storage. Attributed to intra-seasonal hydrological conditions, average pond water levels decreased by 11.8 cm between mid and late season, which resulted in a total estimated water level deficit of 17.2 cm on August 28 (second air photo capture date). According to calculated surface area to depth ratios, an 11.8 cm change in pond water levels should equate to an approximate pond surface area deviation of 3,371 m² or 37%. It is estimated that the selected subset of ponds of interest in this study should reveal a 12% to 100% change in total surface area on average. Therefore, intra-seasonal hydrologic variability should significantly alter pond surface area boundaries and impact the delineation remotely sensed feature detection.

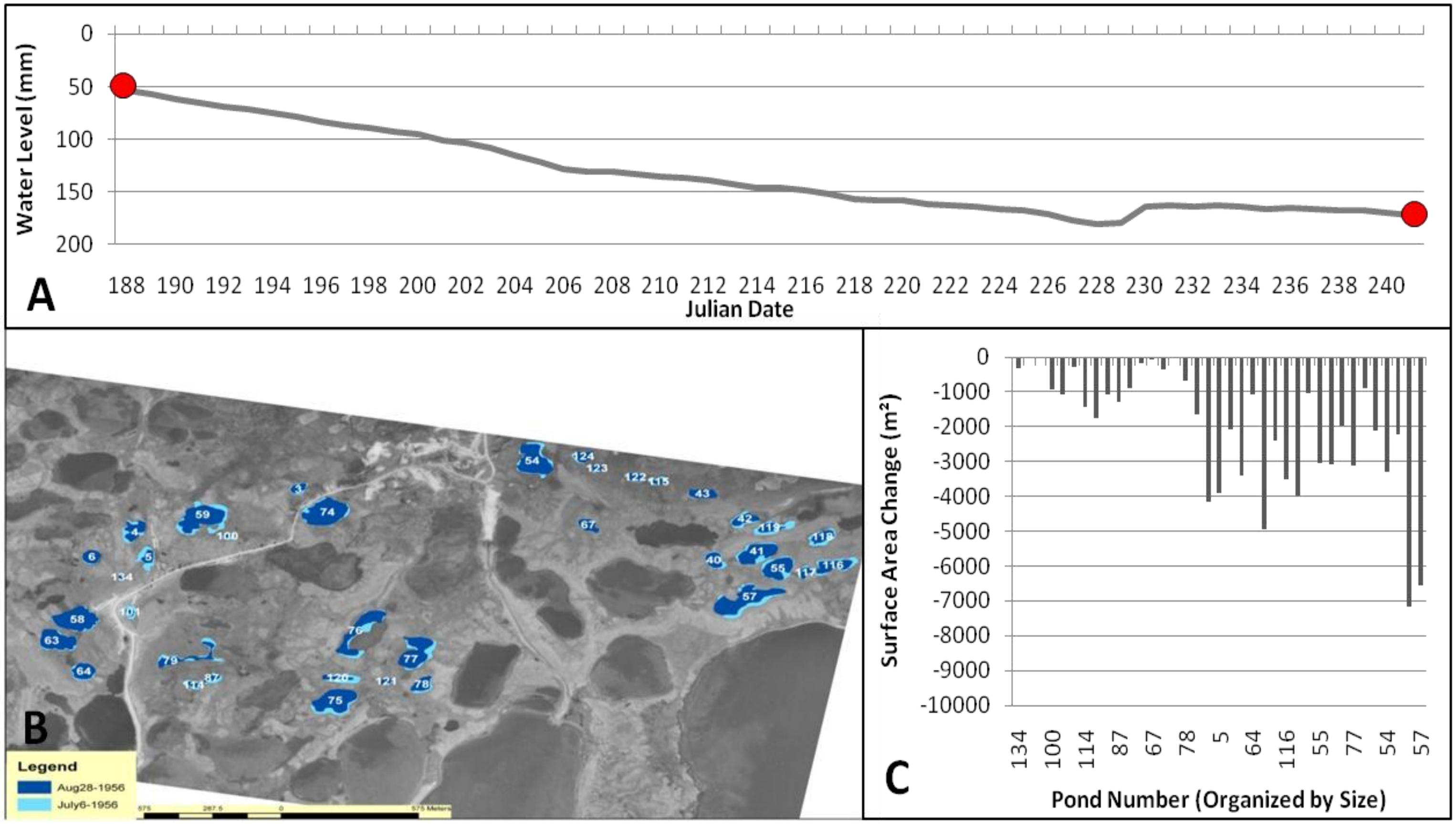


Figure 4.6 – (A) Modeled Pond Water Level Fluctuation During 1956: Red dots indicate water level position during air photo acquisition, grey line represents pond water depth below maximum capacity for 1956 (B) Results of Surface Area Change Detection Between Two Aerial Photos Captured in 1956 - Intra-seasonal Hydrological Variability (C) Change in Pond Surface Area between July 6 and August 28, 1956 (Churchill Region).

Pond surface area measurements from the two air photos captured on different dates in 1956 reveal contrasting conditions. As shown in Figure 4.6B, pond features displayed surface area retreat consistent with water balance estimates between July 6 and August 28. Given the absence of short term shifting climatic conditions (Environment Canada, 2004), it was determined that naturally induced intra-seasonal hydrological fluctuation influenced total pond surface area detection by 2,049 m^2 (0 – 7,168m^2) or 26% (0-66%) on average (Figure 4.6C). The largest surface area difference was observed within a larger pond and amounted to 7,168 m^2 (66% of the total pond surface area). The least significant detected shoreline change was observed within a puddle sized pond (400 – 5,000m^2) and accounted for 36 m^2 or 3% of the total surface area. Overall, within this study of 37 open water features, 34 ponds displayed considerable changes between the two dates examined while 3 remained relatively unchanged. Therefore, intra-seasonal hydrologic variability can significantly influence detected surface area size.

4.4.2.2 Pond Surface Area Detection Following Significant Antecedent Precipitation

Two images collected in successive years (2000, 2001) were compared. These years were similar hydrologically with one exception: several large precipitation events occurred in 2001 immediately prior to imagery acquisition. It was hypothesized that this significant antecedent precipitation would influence pond shorelines and water levels within the subset of ponds. In total, approximately 10.6 cm of rainfall fell during the two weeks prior to imagery capture July 22, 2001 (Environment Canada, 2004). Water balance modeling estimated the average pond water level depth at 0.2 cm lower than maximum storage during 2001 imagery capture (Figure 4.7 A). In contrast, the 2000 image was captured under conditions where pond water levels were approximately 10 cm below maximum storage; this produced an estimated 9.8 cm difference in pond water levels between acquisitions. Derived from calculated surface area to depth ratios, it is estimated that a 9.8 cm water level difference should relate to an average pond surface area change of 2,800 m^2 or 30% of pond area. Specifically, when comparing extracted surface areas from the 2000 (August 8) and 2001 (July 22) images, it is estimated that ponds should display an 8 to 34% change in total pond area.

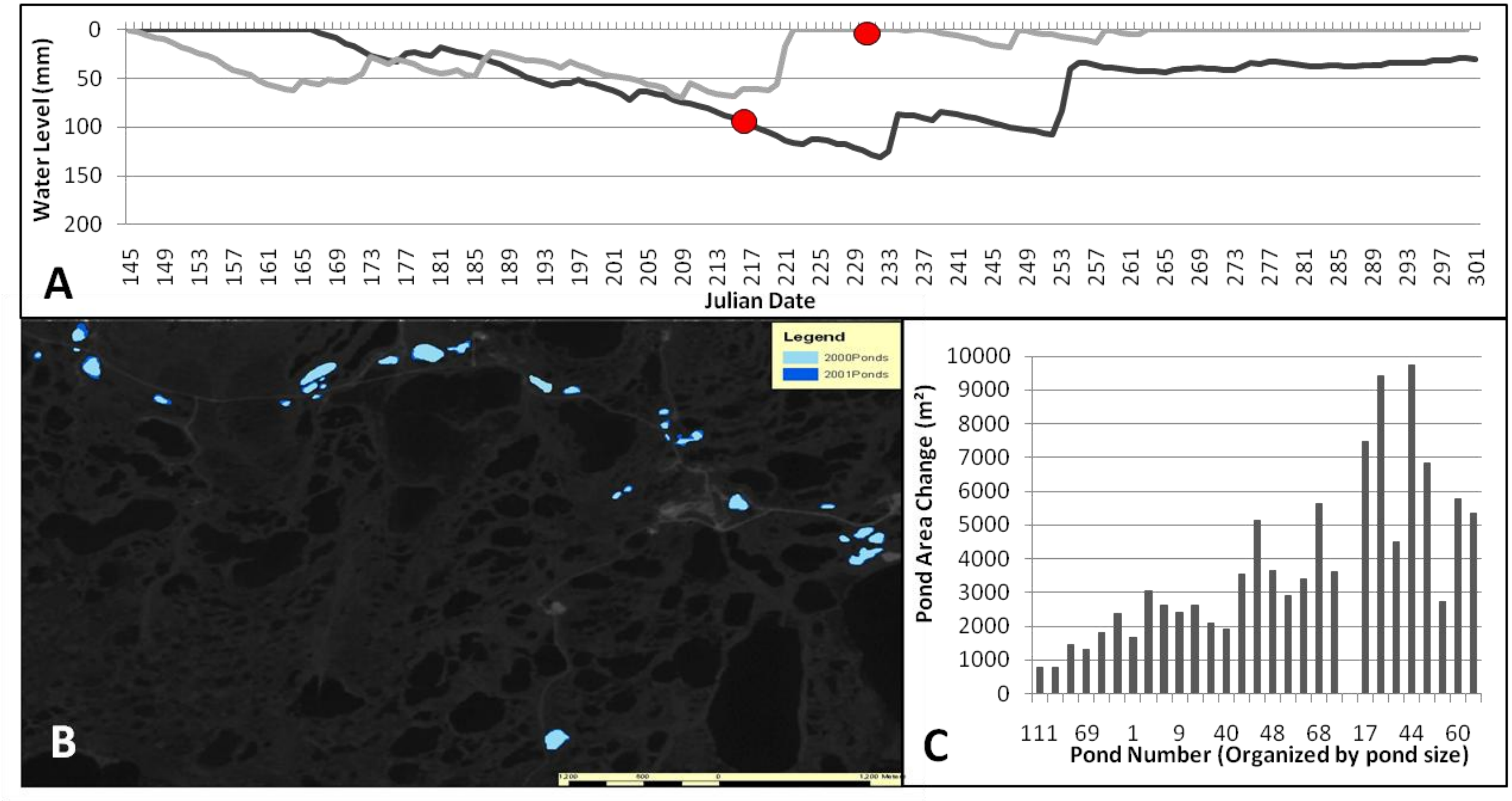


Figure 4.7 – (A) Modeled Water Level Fluctuations for 2000 and 2001: Red dots indicate water level position during imagery acquisition, Black line represents pond water depth below maximum capacity for 2000, Grey line represents pond water depth below maximum capacity for 2001 (B) Results of Surface area Change Detection Between Two Satellite Images Captured in 2000 and 2001 – Antecedent Precipitation Based Hydrological Variability (C) Change in Pond Surface Area between 2000 and 2001 images (Churchill Region).

A comparative remote sensing analysis focused on detecting the surface area of 29 ponds between 2000 and 2001, revealed the significant impact of antecedent precipitation conditions when attempting to establish representative estimates of pond area. All studied ponds exhibited surface area deviation between 2000 and 2001 images (Figure 4.7 B). On average, pond surface area changed by 3,711 m^2 (0 – 9,748 m^2) or 65% (0 – 172%) of the total average pond area. The highest surface area change was linked with a medium sized pond, which displayed a 9,748 m^2 surface area shift (Figure 4.7 C) or 172% increase in total surface pond area. The smallest surface area change was also observed within a medium sized pond, which experienced negligible influence of antecedent precipitation. Under conditions of heavy antecedent precipitation, many ponds filled to maximum capacity. As well, overland flow was established within many catchment areas causing pond edges to become blurred. Overall, antecedent hydrologic activity severely altered pond surface area coverage and created unfavorable conditions for pond boundary detection. Given the comparability of imagery capture conditions prior to the 2001 major rain fall event, it is determined that variances in pond surface area directly resulted from antecedent hydrological conditions. Therefore, antecedent precipitation can strongly impact surface area size as well as the correct delineation of pond features due to the surrounding saturated wetland conditions. These conditions should be considered when conducting long-term pond sustainability research as results may represent fluctuating pond conditions instead of long-term climatic or landscape change.

4.4.2.3 Pond Surface Area Detection Under Conditions of Inter-annual Hydrologic Variability

Finally, two images collected in different years to characterize the effects of inter-annual hydrologic variability on pond surface area. An analysis comparing 2000 and 2006 water levels derived from water balance modeling revealed evident hydrologic differences during the open water period. Aside from a two-week period occurring in late season (August 8 – August 22), pond water levels exhibited significant deviations and displayed an average difference of 7 cm throughout the open water period (Figure 4.8 A). Based on an analysis of climate data, the estimated water level variations are not attributed to shifting regional climate conditions (Environment Canada, 2008). Instead, naturally induced inter-annual hydrologic variability primarily provoked uncharacteristically warm pond conditions during the 2006 capture year; comparatively producing contrasting hydrologic conditions from the 2000 image. Specifically, water balance modeling estimated average water levels at 10 cm below maximum storage during 2000 imagery acquisition (August 6). In comparison, the 2006 image was captured under conditions where pond water levels were situated at roughly 14.5 cm below maximum storage. By comparing estimated water level deviations between 2000 and 2006 imagery capture dates, a 4.5 cm difference is evident and should produce an average total pond surface area change of 1,200 m² or 14%. The specific ponds selected for this study should exhibit an average surface area differentiation between 3 and 35%. Therefore, a remote sensing analysis should reveal variations in total pond surface area caused by inter-annual hydrologic variability.

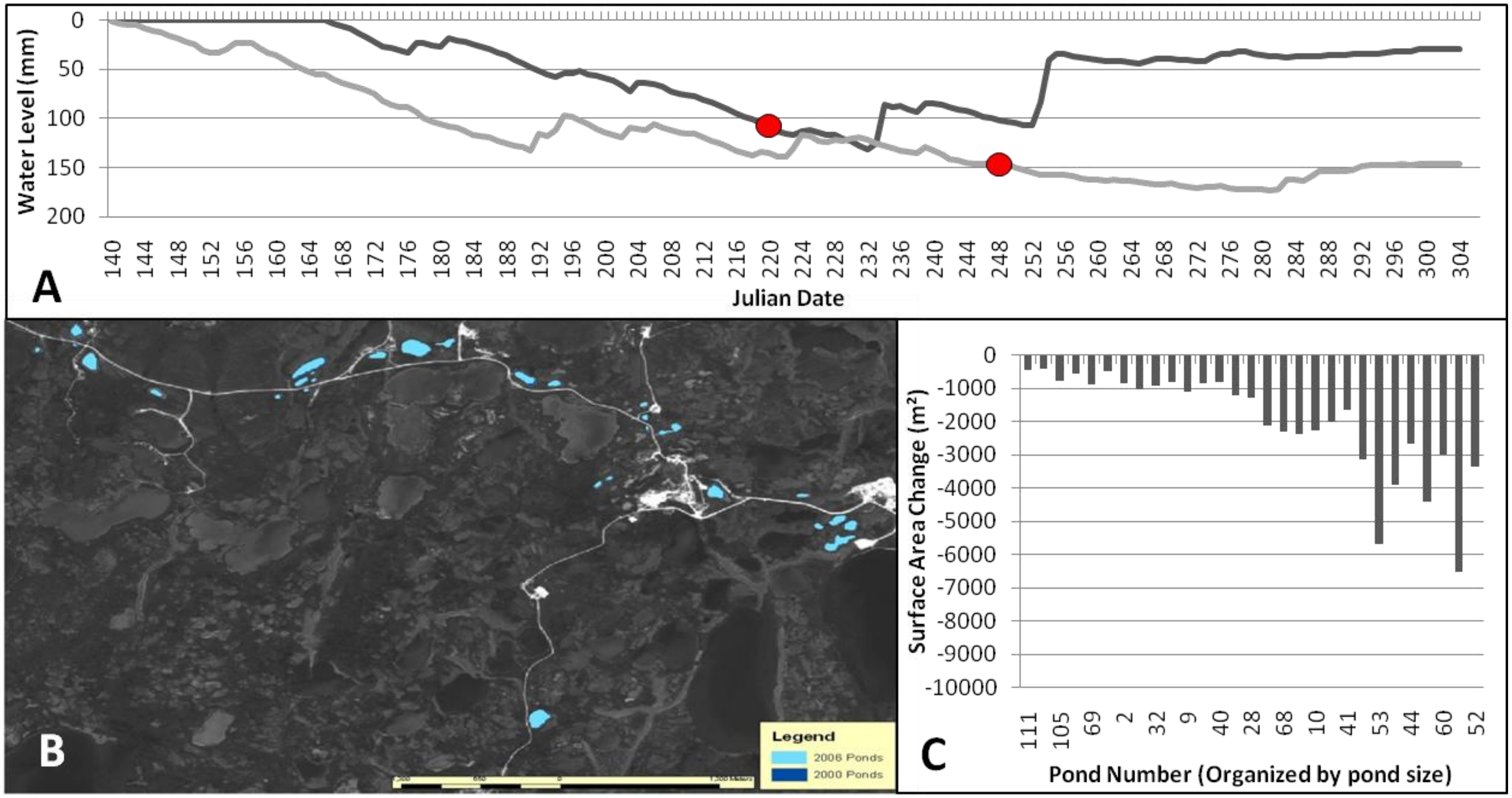


Figure 4.8 – (A) Pond Water Level Fluctuations for 2000 and 2006: Red dots indicate water level position during imagery acquisition, Black line represents pond water depth below maximum capacity in 2000, Grey line represents pond water depth below maximum capacity in 2006 (B) Results of Surface area Change Detection Between Two Satellite Images Captured in 2000 and 2006 – Wet vs. Normal Year (C) Change in Pond Surface Area Between 2000 and 2006 images, (Churchill Region).

Noteworthy delineation irregularities were observed when comparing remotely derived pond surface areas between 2000 and 2006. Amounting to a 28% change in average surface area, all studied pond features exhibited total surface area variations consistent with estimated inter-annual hydrologic water balance modeling. In total, an average pond surface area delineation difference of 1,977 m^2 was observed. As displayed in Figure 4.8 C, the largest surface area change was linked with a medium sized pond, which displayed a 6,491 m^2 surface area change or 60% decrease in total surface pond area. The least significant difference was observed in a large sized pond and amounted to a 392 m^2 decline or 10% change in total surface area. All pond features retained consistent shape and location characteristics that discounts landscape morphology as a contributing factor to these results. As well, antecedent hydrologic conditions were consistent during imagery acquisition providing an optimal environment to isolate inter-annual variability. Overall, inter-annual hydrologic variability drastically altered pond surface area coverage and impacted the proper delineation of all 29 pond features within the study. Therefore, inter-annual hydrologic variability alters pond surface area and can contribute to unrepresentative pond coverage delineation when conducting remote sensing imagery based studies. Comparative pond sustainability studies derived from remotely sensed imagery must consider inter-annual fluctuations in order to produce more accurate results.

4.5 Discussion

This study confirms that shallow water features within the Churchill region exhibit naturally induced hydrologic variability over three temporal periods: immediate, short-term (seasonally) and longer-term (annually). Corresponding fluctuations in pond water levels and surface area are linked to antecedent precipitation, intra-seasonal water level oscillations and/or inter-annual hydrologic variations. Accounting for each hydrologic condition is critical when acquiring imagery and conducting remote sensing pond sustainability research. Additionally, field-based observations provide vital knowledge of pond dynamics, site characteristics and aid imagery analysis. These findings provide methodological framework for future studies.

4.5.1 How to Account for Hydrologic Variability when Conducting Remote Sensing Pond Sustainability Studies

Shallow subarctic water features exhibit fluctuating short-range hydrologic conditions which are not representative of long-term climatic or landscape change. However, it is estimated that long-term shifts in pond sustainability can accurately indicate regional climatic change (Gorham, 1991; Schindler et al., 2006; Smol and Douglas, 2007). In order to accurately conduct pond sustainability research within the Canadian subarctic, fluctuating water level and surface area conditions dominated by naturally induced hydrologic variability must be considered. Even though specific methods required to accurately account for hydrologic variability will vary depending on research location, all remote sensing based studies should only include hydrologically comparable imagery. In order to produce accurate contemporary pond sustainability results, remote sensing imagery capture dates should coincide with similar antecedent conditions, intra-seasonal water level variability and inter-annual hydrological budgets.

Imagery captured immediately following major rain events should be considered unrepresentative. Additionally, precipitation conditions occurring weeks prior to imagery capture may collectively produce misleading pond surface area boundaries. Each research site will demonstrate unique antecedent precipitation thresholds which will affect pond storage. These thresholds vary depending on specific regional landscape and pond bathymetry conditions. Within the Churchill region, images obtained under conditions of recorded two-week antecedent precipitation above +/- one standard deviation from the average should be considered unrepresentative (below 1.8 cm or above 3.7 cm). These values were determined from Environment Canada weather data between 1947 and 2008.

Selecting imagery with similar capture dates will omit the influence of intra-seasonal hydrologic variability. However, due to the presence of cloud cover, undesirable environmental conditions and low frequency of imagery acquisition, the influence of naturally induced variations in pond water levels may become unavoidable. Under these conditions, simple water balance modeling coupled with calculated pond surface area to depth ratios will provide estimates of appropriate change detection thresholds. Given the uniqueness of daily pond dynamics and morphology, the influence of intra-seasonal hydrologic activity will vary annually amongst research sites. Although shallow open water features within the Churchill region generally follow a three-part hydrologic cycle during the open water period (Bello and Smith, 1990; Yee, 2008), modeled data reveals significant variation in cycle magnitude and fluctuation. Therefore, if selected imagery does not correspond with similar capture dates, pond surface area change detection thresholds should be calculated for each corresponding year.

Imagery captured under contrasting annual hydrological conditions should not be compared when conducting pond sustainability research. Variances in pond break-up dates, open water temperature or annual precipitation may give rise to unrepresentative pond water levels and could produce inaccurate pond sustainability results. Conducting a contemporary hydro-climatic study and isolating anomalous capture years will accurately account for inter-annual hydrological variability. Within the Churchill region, imagery capture years exhibiting annual temperatures (below -5.67°C or above 8.07°C), annual precipitation (below 319 mm or above 514 mm) or open water precipitation (below 191mm or above 335 mm) above +/- one standard deviation from the average should be considered unrepresentative.

Therefore, in order to conduct consistent remote sensing pond sustainability research, acquired images should exhibit similar (a) capture dates, (b) antecedent precipitation and (c) annual hydrologic conditions. If these conditions cannot be met, simple water balance modeling and surface area to depth ratios can be calculated to determine the influence of hydrologic variability on delineated pond boundaries and provide context for observed differences.

4.5.2 The Importance of Field-based Site Knowledge in Pond Sustainability Research

Field-based site knowledge strengthens remote sensing pond sustainability research. As observed within this study, field research supplemented imagery analysis and provided required variables to interpret the influence of naturally induced hydrologic variability. Proper understanding of pond physical characteristics as well as daily hydrological fluctuations is optimally acquired through on-site analysis and substantially strengthens imagery context.

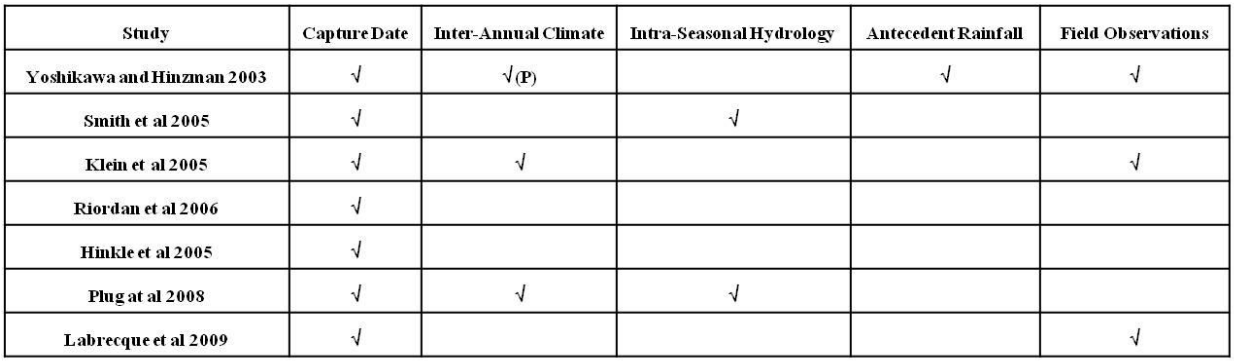
In order to accurately delineate pond boundaries, remotely sensed imagery must be partnered with an understanding of pond hydrologic dynamics as well as regional landscape morphology. Field observations provide essential information regarding pond bathymetries, hydrological catchments, ground conditions and human interactions, which significantly influence the interpretation of remote sensing imagery. As well, surveyed pond boundaries provide ground truthing and quality control measurements which strengthen georeferencing and pond delineation accuracy. Field observations provide meaningful context to collected imagery, which facilitates precise landscape categorization and minimizes analysis miscalculations.

Accounting for inconsistent naturally induced hydrologic variability between acquired images, simple water balance modeling and accurate surface area to depth ratios are required. However, several variables required to create these measurements rely on heavily field-based observations. Pond surface area and depth measurements must be manually collected and amalgamated to determine surface area to depth ratios. These values are site specific and cannot be inferred from previous studies. As well, simple water balance modeling requires in-depth understanding of site specific pond hydrologic dynamics and surrounding catchment conditions. Field research can provide daily water level fluctuation measurements and determine the hydrologic controls which influence pond water budgets. Lastly, calculated simple water balance results are strengthened by cross referencing values with field collected measurements.

4.5.3 Impact of Findings on Previous Remote Sensing Studies

Research findings suggest that subarctic pond/lake sustainability studies derived from remote sensing imagery must incorporate or correct for naturally induced hydrologic variability. An in-depth literature analysis discovered several influential remote sensing pond sustainability studies which seemingly did not account for all three sources of naturally induced hydrological error. Particularly, seven recent studies are evaluated in depth: Hinkel et al., 2005; Klein et al., 2005; Labrecque et al., 2009; Plug et al., 2008; Riodran et al., 2006; Smith et al., 2005 and Yoshikawa and Hinzman, 2003. Table 4.2 provides a synopsis of review findings.

Table 4.2 – Considered Components of Hydrologic Variability within Previous Northern Remote Sensing Change Detection Studies: 'P' indicates consideration for precipitation, 'Check mark' indicates variable was considered



Study	Capture Date	Inter-Annual Climate	Intra-Seasonal Hydrology	Antecedent Rainfall	Field Observations
Yoshikawa and Hinzman 2003	√	√(P)		√	√
Smith et al 2005	√		√		
Klein et al 2005	√	√			√
Riordan et al 2006	√				
Hinkle et al 2005	√				
Plug at al 2008	√	√	√		
Labrecque et al 2009	√				√

A study conducted by Hinkle et al. (2005), aiming to assess lake drainage through delineated boundary change in northern Alaska/Canada, attempted to account for hydrologic variability by acquiring images captured during the summer months. Intra-seasonal or inter-annual hydrologic variability was unobserved as well as antecedent conditions. Similarly, Yoshikawa and Hinzman (2003) selected imagery with similar capture dates with the purpose of identifying pond sustainability in southern Alaska. However, this study notably incorporated field surveying and accounted for antecedent precipitation/inter-annual precipitation variability when selecting imagery. Klein et al. (2005) and Riordan et al. (2006) studied pond sustainability within the Kenai Lowlands (south-central Alaska). While both studies selected imagery with similar capture dates, Klein et al. (2005) incorporated field surveys as well as open water temperature anomalies. Neither study considered antecedent rainfall or intra-seasonal hydrologic variability. Contrary to similar research, Smith et al. (2005) notably accounted for intra-seasonal hydrologic variability by selecting comparable capture dates in order to accurately delineate lake sustainability in northern Siberia. Regrettably, this study does not consider inter-annual climate variability or antecedent precipitation conditions. Most recently, Labrecque et al. (2009) conducted the first cross-disciplinary lake sustainability study which incorporated water balance modeling, field research and remote sensing analysis. Addressing spatio-temporal lake dynamics in northern Yukon, this study did not consider the influence of antecedent precipitation, intra-seasonal or inter-annual hydrologic lake variability or imagery capture conditions. Overall, Plug et al. (2007) most comprehensively accounted for lake hydrologic variability. This study cross referenced and considered the impact of intra-seasonal and inter-annual hydrologic variability on derived lake boundaries but failed to consider antecedent precipitation.

Through an analysis of previously conducted pond/lake sustainability research, it was determined that the comprehensive influence of naturally occurring annual climate variability, intra-seasonal hydrological fluctuations and antecedent rainfall have largely been unconsidered. Therefore, results presented from several previous studies may be unrepresentative of contemporary pond/lake sustainability.

4.6 Conclusion

Ponds within the Churchill region exhibit fluctuating water level and surface area conditions during the open water period. These irregular conditions originate from naturally occurring antecedent precipitation, intra-seasonal and inter-annual hydrologic variability and are unrepresentative of long-term climatic or landscape change. Remote sensing pond surface area studies within the Churchill region easily detect variances in water features coverage caused by these hydrologic conditions. Therefore, pond surface area measurements influenced by unaccounted hydrologic variability should be considered unrepresentative when conducting pond sustainability research. In order to more confidently estimate pond sustainability from remote sensing imagery within the Canadian subarctic, acquisition dates, ground conditions and hydrologic context must be consistent or accounted for when analyzing results. As well, remotely determined pond surface area change should be linked with water balance modeling and a field-based understanding of pond characteristics in order to provide holistic context for research findings. When applying these conclusions to previously conducted pond sustainability research within the region, several studies reveal methodological variations. Overall, remote sensing pond sustainability studies must be supported by climatic and weather analysis.

5.0 Results and Discussion: Detecting Contemporary Pond Sustainability Using Remote Sensing, Climate Analysis and Water Balance Modeling: Churchill Region, Canada (1947-2008)

5.1 Introduction

Northern peatlands and water features are anticipated to be highly sensitive to shifting environmental conditions (Gorham, 1991; Schindler and Smol, 2006). Specifically, shallow ponds occupy between 15 and 50% of the subarctic environment (Pietroniro and Leconte, 2005) and are highly responsive to changing climatic conditions (Hinzman and Yoshikawa, 2003; Smol and Douglas, 2007; White et al., 2007). These important bellwethers of atmospheric change (Schindler and Smol, 2006) significantly influence regional chemical, energy, biological and hydrological systems (Rouse et al., 1997; White et al., 2007). Therefore, shifting pond conditions have the potential to drastically influence regional ecosystems.

Found predominantly within ombrotrophic peatlands (Duguay and Pietroniro, 2005), pond features within the Canadian subarctic are predominantly controlled by atmospheric exchange following the major snowmelt period (Bello and Smith, 1990; Boudreau and Rouse 1995; Browling et al., 2003; Macrae et al., 2004; Woo, 1980). Surface and subsurface flow influence regional water budgets during major rain episodes (Yee, 2008); however, these events are relatively uncommon within the Churchill region of the Hudson Bay Lowland (Macrae et al., 2004). Consequently, ponds are hydrologically isolated from peatlands and exhibit water budgets which can be modeled using an atmospheric exchange equation (Bello and Smith, 1990; Boudreau and Rouse, 1995; Browling et al., 2003; Lafleur, 1994; Macrae et al., 2004; Woo, 1980). Due to small pond sizes, gradual bathymetries and hydrological sensitivity, changes in atmospheric exchanges can influence overall storage and may be good indicators of regional climate change (Hinzman et al., 2005; Schindler and Smol, 2006; Smol and Douglas, 2007; White et al., 2007).

Arctic climate change studies have revealed evidence of changing environmental conditions including: elevated regional air temperatures (Rouse et al., 2008; Kaufman et al., 2009), lengthened open water periods (Rouse et al., 2008), increased evaporation (Smol and Douglas, 2007) and localized permafrost degradation (Stow et al., 2004). However, few studies have linked the influence of shifting environmental conditions on northern pond sustainability or detected contemporary pond dynamics. Smol and Douglas (2007) observed lower pond water levels on Ellesmere Island, Nunavut (1983-2006), which directly coincided with observed increases in evaporation-to-precipitation ratios and increased air temperatures. It is not known if these shifting environmental occurrences and resulting changes in pond sustainability are consistent throughout northern Canada.

Due to geographic isolation, scattered hydrologic data collection coverage and incomprehensive historical climate datasets, remote sensing techniques are particularly well suited to detect contemporary subarctic pond sustainability (Duguay and Pietroniro, 2005). However, previous remote sensing pond/lake sustainability studies have produced incongruent results. Some researchers have documented decreasing trends in pond/lake surface area (Smith, 2005; Stow et al., 2004; Riordan et al., 2006; Yoshikawa and Hinzman, 2003) while others have concluded that ponds/lakes are increasing (Grippa, 2007; Smith et al., 2007) or exhibiting inconsistent change (Labrecque et al., 2009). These findings may suggest that regional water features are responding differently under similar climatic conditions, perhaps due to local controls. Attributed to geographical research gaps, it is not known if contemporary pond sustainability in the Hudson Bay Lowland has changed.

Thus, the overall goal of this study was to characterize climatic trends and quantify contemporary pond surface area changes within the Canadian subarctic near Churchill, Manitoba. Specifically, (1) contemporary hydro-climatic change was examined using archived meteorological data and water balance modeling and (2) pond surface area change was quantified using an imagery analysis of remotely sensed SPOT (2008) and aerial photography (1947, 1956, 1972). Results were controlled to omit the influence of intra-seasonal hydrologic variability. Documenting pond sustainability within this region should provide enhanced understanding of northern climate change, hydrologic dynamics and landscape morphology.

5.2 Study Area

Located west of Hudson Bay and within the northern portion of the Hudson Bay Lowlands, the Churchill Region is characteristically representative of the subarctic landscape (Christopherson, 2004). Specifically, a 100km² site (58°45’05.75N, 93°54’51.71W and 58°41’08.65N, 93°40’48.21W), located east of Churchill Manitoba (58°45’N 94°04’W), was selected for this study (Figure 5.1). This area resides at the northern tree line and the southern limit of continuous permafrost (Duguay et al., 2002). Permafrost active layer depth ranges from 40 – 150 cm within the region (Lafleur et al., 1997).

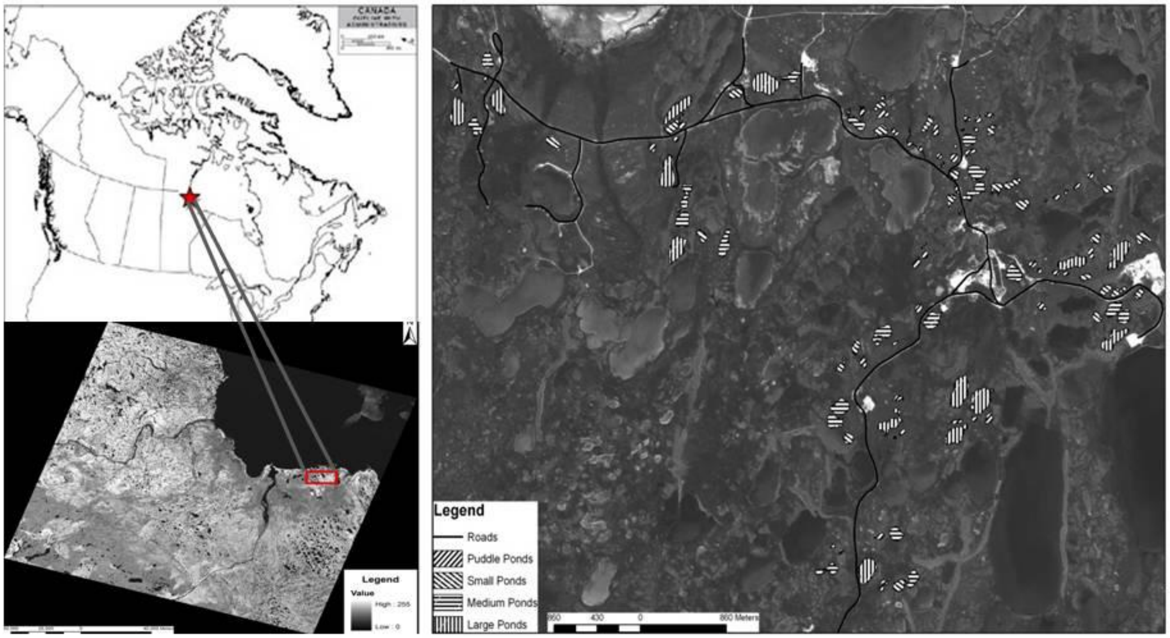


Figure 5.1 – Extent of Study Area, Southwest of Hudson Bay and East of Churchill, Manitoba, Canada (Puddle Pond= 400 m² to 5,000 m²; Small Pond =5,001 m² to 10,000 m²; Medium Pond =10,001 m² to 20,000 m²; Large Ponds =20,001 m² to 40,000 m²)

The Churchill region exhibits a 61-year mean annual temperature of -6.9°C, with lowest mean monthly recorded temperatures occurring in January (-26.7°C) and warmest mean monthly temperatures occurring in July (12°C). The open water period typically occurs between June and early October. Annual precipitation is 431 mm of which 61% occurs as rainfall (Environment Canada, 2004).

The regional landscape has been significantly influenced by the northern Laurentide Ice sheet retreat 8,000 years ago (Dredge, 1992). This area exhibits a slightly northern sloping (<1m per km), flat terrain with 11.4 mm (±0.26) of isostatic uplift occurring annually (Wolf et al., 2006). Glacial deposits form major relief features; patterned ground, peat plateaus, palsas and thermokarst ponds are ubiquitous across the landscape (Dredge, 1992). The soil profile generally consists of peat topsoil overlaying marine silts and clays, which rest above Ordovician and Silurian limestone (Macrae et al., 2004). Peat layer depth ranges from 10 – 50 cm and increases in depth with distance from the shore (Duguay et al., 2002). Three land cover zones are present within the study area. Distributed parallel from the coast, land cover gradually transitions from tundra to open forest with a dividing transition zone (Lafleur et al., 1997).

For the purpose of this study, ponds were defined as water features exhibiting a surface area between 400 m^2 and 40,000 m^2 and a maximum depth less than 1 m. Size and depth distinctions were determined with consideration of previous water sustainability studies and selected imagery characteristics (Bello and Smith, 1990; Duguay et al., 2002; Macrae et al., 2004). It is assumed that all ponds within the study site are hydrologically disconnected after the major melt period (Macrae et al., 2004; Yee, 2008). Specific pond features were selected based on size (to represent the physical landscape), accessibility, the omission of direct human influences and various safety concerns (visibility, nearness to vehicle, etc.). In order to represent pond size prevalence within the Churchill region, a larger number of puddle and small sized ponds were selected for this study. In total, 41 puddle ponds, 25 small ponds, 20 medium ponds and 14 large ponds were selected.

5.3 Data Sources and Methodology

Within this study, pond surface areas as well as hydro-climatic conditions were investigated in order to determine contemporary pond sustainability within the Churchill region between 1947 and 2008. Hydro-climatic variables considered included air temperature, evaporation, precipitation and open water period duration. These variables were combined to approximate pond water budgets and combined with surface area to depth ratios to estimate pond surface area change. Results were compared to remotely delineated pond surface area change derived from four images between 1947 and 2008. Additionally, multiple methods were employed in order to accurately detect and correct for unrepresentative short-term climate variability.

5.3.1 Detecting Hydro-climatic Change

In order to establish the occurrence of contemporary hydro-climatic change near Churchill, various methods were employed. The presence of changing climatic conditions was detected using historical climate data in conjunction with Mann Kendall and Sen’s slope trend analyses. Due to the influence of these variables on pond water budgets, air temperature and precipitation were specifically addressed. Pond hydrologic change was derived from simple water balance modeling and detected changes in open water duration. Lastly, findings were linked with pond surface area to depth ratios in order to establish estimated contemporary pond surface area change.

5.3.1.1 Climate Analysis

Historical air temperature and precipitation data were extracted from Environment Canada (1947-2008) and analyzed for annual, seasonal, monthly and daily change. In addition, these parameters were required within the CLIMo model (Duguay et al., 2003) in order to derive surface water temperature for the Oswald and Rouse evaporation model (2004). The CLIMo model was also employed to derive pond ice break-up and freeze-up dates. The presence of first order trends were tested using the non-parametric Mann-Kendall test. The magnitude/slope of each trend was predicted using the Sen’s method (Duguay et al., 2006). Results from this analysis provide climate context to water balance results and overall pond sustainability.

5.3.1.2 Water Balance Modeling

Precipitation and evaporation largely control pond water levels following the major melt period (Macrae et al., 2004; Prowse and Ommanney, 1990). Therefore, pond water budgets were derived using the following equation:

$$\Delta = P - E \qquad \textit{Equation 5.1}$$

where Δ is change in pond water storage, P is precipitation and E is evaporation. Precipitation values recorded at the Churchill airport were accessed through Environment Canada (Environment Canada, 2004) while evaporation values were derived using two models: Thornthwaite (1944) and Osward and Rouse (2004).

Due to poor availability of daily wind speed data, the Thornthwaite evaporation model (1944) was employed to calculate potential pond evaporation between 1947 and 1954, using the equation:

$$PET = d_l\, 16\, (10\, \frac{T_a}{I})^a \qquad \textit{Equation 5.2}$$

where PET is potential evaporation, d_l is day length in hours divided by 12, I is the sum of i (where i is the monthly heat index given by: $(\frac{T_a}{5})^{1.514}$, a is: $(6.75 * 10^{-7})I^3 - (7.71 * 10^{-5})I^2 + (1.79 * 10^{-2})I + 0.49$ (Stimulistics, 2003).

The Oswald and Rouse (2004) mass transfer equation, which is based on Fick's first law of diffusion (1855), was used to derive evaporation from 1955-2008 using the equation:

$$E = K_e u_z\, (e_o - e_z) \qquad \textit{Equation 5.3}$$

where E is point evaporation (mm), K_e is the coefficient of proportionality, u is the horizontal wind speed (m/s) at height z, e_o is the vapour pressure of saturated air at the temperature of the water surface and e is the vapour pressure of the air at the height z above the water surface. A value of 0.81 was used for K_e, which was derived statically using 4 years of field collected evaporation values for the Churchill region (Boudreau and Rouse, 1995; Petrone and Rouse, 2000; Yee, 2008). Specific methods for deriving K_e are found in Section 4.3.2.

Resulting water budget values were calculated to determine hydrologic trends using Mann Kendall and Sen.'s slope analyses. It is assumed that pond water levels begin at maximum capacity during the melt period and exhibit oscillations due to changing atmospheric condition until freeze-up (Macrae et al., 2004; Yee, 2008). In all instances, where total cumulative precipitation exceeded evaporation, overland flow occurred and all additional water was lost to the surrounding area. Maximum storage deficit, which is defined as the seasonal water level minimum, was determined by selecting the lowest cumulative water level during the open water period.

5.3.1.3 Modeled Pond Surface Area Change

Estimated contemporary pond surface area change was determined by combining field collected pond data and water balance results. Field collected bathymetry and surface area measurements (2008) were amalgamated to determine pond surface to depth ratios, based on a second order polynomial equation. Calculated pond water level changes were linked to the surface area to depth ratio in order to estimate contemporary pond boundary shifts with moderate confidence ($R^2 = 0.4$). Findings provide context for the remote sensing imagery analysis of pond surface area change. A further explanation of modeled pond surface area change methodology is provided in Section 4.3.2.

5.3.2 Detecting Pond Surface Area Change

To evaluate physical sustainability of pre-existing pond features, a comparative remote sensing analysis was conducted using three air photo mosaics and one satellite swath captured during mid-summer open water periods of 1947, 1956, 1972 and 2008. Ponds were manually delineated and compared to derive surface area change over July and August. Through the application of derived minimum change detection threshold values, findings were quality controlled to omit the influence of naturally induced hydrologic variability. Lastly, detected physical pond changes were compared with hydro-climatic patterns to characterize change. The establishment of new pond features was not examined within this study.

5.3.2.1 Remote Sensing Imagery Analysis

A total of 4 images (three sets of air photographs and one SPOT 5 panchromatic image) were selected between July 14, 1947 and July 22, 2008 to determine pond surface area change. Air photo mosaics included at least four images covering the entire study area, which were captured using 9.5 mm black and white film at a scale of 35,000 using north and south orientation. Adjacent photo overlay was at least 30%, which provided accurate mosaic creation. Air photos were resampled to 2 m resolution. Regarding the SPOT 5 image, red (0.61µm – 0.68µm) and near IR (0.78µm – 0.89µm) bands were extracted and merged with the panchromatic (0.48µm – 0.71µm) to create a 2.5 m resolution swath (2008). Band 1 (green: 0.50 - 0.59 µm) was omitted due to moist ground conditions and the high sensitivity of this band to surface moisture. The red and near IR bands were merged with the panchromatic swath in order to minimize the influence of vegetation encroachment on pond boundary delineation. Additionally, a series of tone and texture rules were established in order to minimize the influence of fuzzy pixel errors when digitizing pond features using air photos.

Following imagery collection, each image was scanned, orientated, orthorectified, cropped, amalgamated to create a mosaic, clipped to the study site, error corrected and merged for band addition (SPOT 5 image) in order to initiate pond feature extraction. Following this process, 100 pond features were manually on-screen digitized at a scale of 1:2,320 using ArcMap. Ponds were outlined using a set of rules regarding tone, size, shape, texture and orientation. In order to calculate digitization accuracy, a subset of 24 manually digitized surface areas from the 2008 SPOT image were compared with field collected surface area data acquired one week prior to imagery acquisition. A comparative scatter plot revealed a strong relationship between the two data sets and an overall root mean square error of 172 m^2 (r^2=0.92). The resulting polygons were overlaid and visually inspected for errors. Feature statics were extracted and compared in order to determine feature growth or decay between 1947 and 2008.

5.3.3 Accounting for Naturally Induced Hydrologic Variability

Pond water levels significantly fluctuate throughout the open water period due to naturally induced hydrologic variability. Due to summer hydrologic isolation of pond features within the Churchill region, daily precipitation and evaporation contributions impact pond water budgets and influence shoreline detection. These ‘weather initiated’ fluctuations in water levels are not representative of contemporary environmental change or pond sustainability. Therefore, to assure accurate contemporary pond sustainability findings, naturally occurring hydrologic variability must be considered. Within this study, the influences of unrepresentative pond water budget fluctuations were considered during imagery selection. As well, these findings created a minimum surface area change threshold required to characterize substantive pond transformations. Detected pond surface area change must exceed intra-seasonal water level fluctuation estimates in order to equate a shift in overall pond area.

5.3.3.1 Imagery Selection to Account for Inter-annual Hydrologic Variability and Antecedent Precipitation

Available open water remote sensing imagery was pre-selected based on similar capture dates and quality controlled for external atmospheric influences such as antecedent precipitation, annually anomalous conditions and intra-seasonal hydrological fluctuations to insure accurate comparability (Table 1). Images captured under conditions of calculated precipitation and air temperature values exceeding +/- 1 standard deviation from the mean (based on 61 year climate data) were considered moderately influenced by atmospheric fluctuations and deemed unfavorable to detect pond sustainability. As well, imagery associated with values exceeding +/- 2 standard deviations from the mean were omitted from the selection process. Excluding the August 8, 1972 mosaic, all selected images were captured during mid-summer, possessed similar annual/seasonal air temperatures and consistent antecedent precipitation (Table 5.1). Due to data availability constraints, the 1972 image was included within the study. Therefore, modeled water balances and remote sensing results should reveal an unrepresentative increase (1956 to 1972) than decrease (1972 to 2008) which must be omitted for overall pond sustainability results.

Table 5.1 - Summary of Imagery Acquisitions Characteristics and Associated Climate/Weather Conditions

Capture Period		Imagery Source	Annual Climate		Seasonal Climate: Ice Break-up to Capture Date		Antecedent Precipitation Prior to Imagery Capture Date		
Year	**Date**	**Satellite/Sensor**	**Mean Temp(° C)**	**Total Precipitation (mm)**	**Mean Temp (°C)**	**Total Precipitation (mm)**	**2 weeks (mm)**	**1 week (mm)**	**Same day (mm)**
1947	July 14	Aerial Photograph – B&W	-6.8	352.4	10.02	47.0	23.8	10	0.3
1956	August 28	Aerial Photograph – B&W	-6.5	322.4	11.33	59.1	0	0	0
1972	August 8	Aerial Photograph – B&W	-9.8	427.8	10.01	133.0	8.1	0.8	0
2008	July 22	SPOT 5 – multi+pan	-6.5	336.9	10.62	56.5	11.7	9.6	1

5.3.3.2 Intra-seasonal Hydrologic Variability

Following imagery selection, modeled pond water levels were derived for imagery capture years and compared with surface area to depth ratios in order to account for naturally induced intra-seasonal hydrologic fluctuations. Daily cumulative open water budgets were plotted for each capture year and cross referenced to determine potential differences in water level positions. Due to inconsistent capture dates, antecedent hydrologic conditions and annual climate contexts, open water hydrologic budgets varied between capture years. Figure 5.2 reveals significant variation in estimated water level position for each imagery capture date. When comparing estimated water levels between images, pond features notably exhibit an oscillating trend. Overall, it is estimated that intra-seasonal hydrologic fluctuations contributed to a 9.8 cm decrease (1947 to 1956), 13.7 cm increase (1956 to 1972), 9.3 cm decrease (1972 to 2008) and an overall decrease of 5.4 cm (1947 and 2008). These estimated water level differences, which inaccurately represent contemporary hydrologic change, must be considered when deriving pond sustainability findings.

From Year	To Year	Estimated Change in Water Depth (cm)
1947	**1956**	-9.8
1956	**1972**	13.7
1972	**2008**	-9.3
1947	**2008**	-5.4

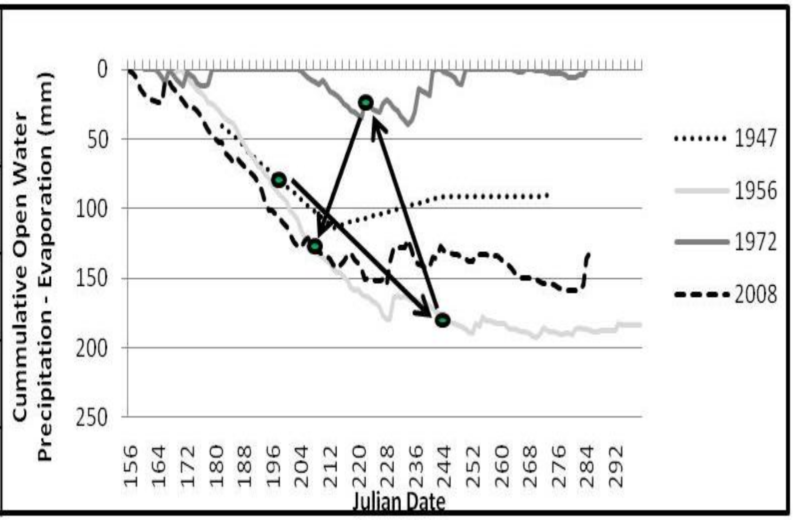


Figure 5.2 – Modeled Intra-Seasonal Pond Water Levels for Imagery Acquisition Years: Acquisition dates displayed with green dots, Black arrows suggest temporal direction of water level change between imagery acquisition dates.

5.3.3.3 Estimated Influence of Naturally Induced Hydrologic Variability on Pond Surface Area

Calculated hydrologic variability was amalgamated with derived surface area to depth ratios to determine the degree of surface area change which must be exceeded in order to conclude pond sustainability is shifting. Specifically, modeled pond water levels were combined with surface area to depth ratio to determine pond size estimates for each imagery capture date. Resulting values were compared to determine the degree to size change resulting from naturally induced intra-seasonal variation. These values represent the minimum change detection threshold required to conclude contemporary pond surface area change. Table 5.2 reveals significant surface area alterations associated with hydrological fluctuations between year capture periods. Overall, remotely delineated and compared pond surface area differences must surpass an average decrease of 2,057 m² (1947-1956), increase of 3,914 m² (1956-1972), decrease of 2,657 m² (1972 to 2008) or overall decrease of 800 m² (1947-2008) in order to accurately conclude ponds within the Churchill region are changing. However, ponds within the Churchill region exhibit irregular bathymetries, inconsistent sizes and various origins. Therefore, this derived threshold provides rough estimates of surface area change for average sized and shaped pond features within the study site.

Table 5.2 - Estimated Influence of Intra-Seasonal Variability on Pond Surface Area between Imagery Capture Dates: Minimum Surface area change threshold values for each imagery period (Churchill Region)

From Year	To Year	Estimated Change in Pond Surface Area Due to Naturally Induced Hydrologic Variability (m^2)
1947	**1956**	2,057 (5 – 100% decrease)
1956	**1972**	3,914 (10 – 400% increase)
1972	**2008**	2,657 (7 – 100% decrease)
1947	**2008**	800 (2 – 100% decrease)

5.4 Results/Discussion

Within this study, contemporary pond sustainability was detected using a multi-variable approach. Both external environmental indicators and pond physical attributes were analyzed to provide a comprehensive indication of contemporary stability between 1947 and 2008 within the Churchill region. Regional climate research reveals changing environmental conditions which may impact pond dynamics and modeled water balances estimate hydrologic sustainability. These results are combined with surface area to depth ratios in order to estimate potential surface area changes. Lastly, remote sensing change detection studies quantify pond boundary stability and reveal physical pond sustainability.

5.4.1 Changes in Climatic Conditions

The Churchill region exhibited climatic change between 1947 and 2008. As displayed in Figure 5.3, changing environmental conditions included altered temperature, precipitation, evaporation and open water duration. Total annual precipitation averaged 416 mm within the Churchill region and exhibited an approximate annual change of +1.28 mm/yr ($p= >0.1$) between 1947 and 2008 (Figure 5.3A). In addition, total open water precipitation averaged 254 mm and exhibited a substantial increasing trend of +1.91 mm/yr (p= 0.01). As precipitation increased, summer months received the largest extent of this addition, indicating regional conditions are becoming progressively wetter and pond features may expand. However, annual average temperatures exhibited increasing values which may counteract the hydrological impact of moistened conditions. In total, average annual temperature (-6.83°C) had experienced a significant increase of +0.03°C/yr (p= 0.01), while summer mean temperatures (+7.01°C) revealed similar increasing trends of +0.01°C/yr (p= 0.01) (Figure 5.3 B). Given the substantial increase in summer air temperatures, open water evaporation should increase and may offset any moisture additions available to the Churchill region.

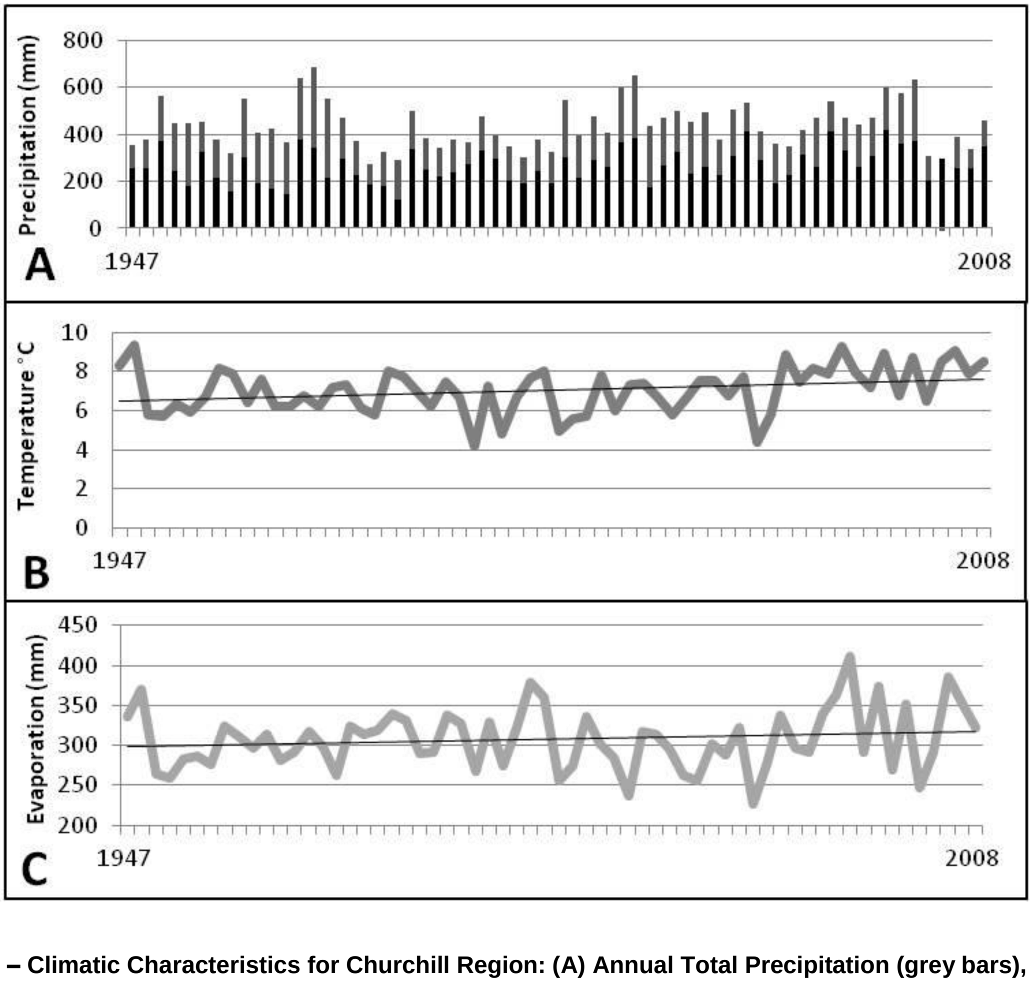


Figure 5.3 – Climatic Characteristics for Churchill Region: (A) Annual Total Precipitation (grey bars), Summer Total Precipitation (black bars), (B) Open Water Average Annual Temperature, (C) Annual Total Open Water Evaporation (1947-2008)

Between 1947 and 2008, annual open water evaporation values averaged 307 mm and increased at a rate of 0.8mm/yr (p= 0.1) based on a Mann Kendall trend/Sen's slope analysis. Although evaporation values are slightly increasing within the region, substantial variation is evident throughout the study period (Figure 5.3 C). As expected, evaporation values closely mimic and graphically resemble amplified temperature trends. Increasing evaporation trends should correlate with extended open water periods and altered pond hydrologic stability.

Shallow pond features experienced changing open water conditions within the Churchill region. Generally, average pond ice break-up occurred on June 8 (JD159), while freeze-up began on October 25 (JD298). Annually, pond features experienced an average open water period lasting 139 days. Specifically, pond ice break-up occurred earlier (-0.12 day/yr, p= >0.1, or 7 days earlier from 1947 to 2008), while freeze-up occurred later (0.08 days/yr p= >0.1, or 5 days later from 1947 to 2008) and total open water duration progressively lengthened by +0.18 days/yr (p= >0.1) or 12 days between 1947 and 2008. Prolonged open water durations essentially facilitated conditions of extended precipitation as well as increased evaporation potential. Ponds should receive increased cumulative moisture transfers as well as altered water balances.

Overall, climatic conditions within the Churchill region are becoming warmer and wetter. Changing atmospheric conditions have facilitated an environment of increased evaporation rates and extended open water duration. Inevitably, shallow pond features have experienced altered hydrologic and environmental dynamics. Since Churchill ponds exhibit strong sensitivity to changing atmospheric conditions, such changes should produce altered pond hydrology and sustainability.

5.4.2 Changes in Hydrologic Conditions

Pond features within the Churchill region experience significant annual hydrologic deficits. On average, total open water evaporation exceeded total precipitation by 54 mm between 1947 and 2008 (Figure 5.4 A). However, pond hydrology within the Churchill region has changed to facilitate a gradual reduction of this deficit at an annual rate of +1.37 mm/yr (p=0.1). Although annual hydrologic deficits are evident, these circumstances may progressively transform into surplus conditions under sustained climate trends over a long-term period (approximately 40+ years). In addition, pond features are becoming less dry during the open water period and experience hydrologic recharge earlier. Seasonal maximum cumulative pond water retreat averages 12.2 cm and has reduced at a rate of 0.32 mm/yr (p= >0.1). Decreasing at a rate of 0.45 day/yr (p=0.1), these recorded lows are occurring earlier within the open water period. Therefore, ponds are experiencing decreased annual hydrologic deficits, increased recharge initiation and decreased maximum retreat values.

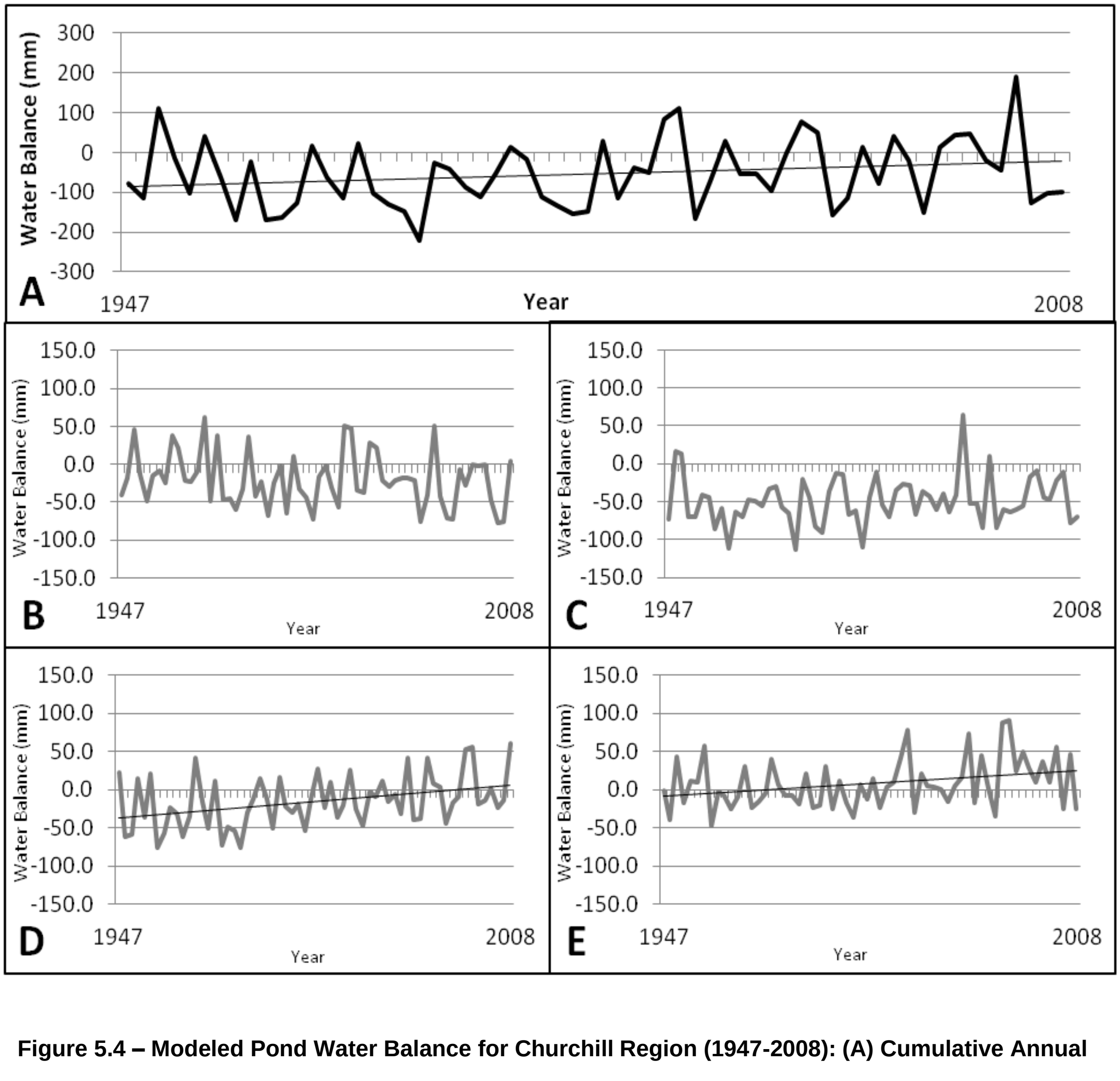


Figure 5.4 – Modeled Pond Water Balance for Churchill Region (1947-2008): (A) Cumulative Annual Atmospheric Exchange Driven Water Balance Values for Entire Open Water Period, (B) Cumulative Atmospheric Exchange Driven Water Balance Values for June, (C) July, (D) August and (E) September

Pond features within the Churchill region exhibit unique monthly hydrologic dynamics which do not coincide with detected annual trends. As noted by Macrae et al. (2004) and Yee et al. (2006) shallow open water features exhibit a distinct four-part hydrologic cycle which includes: break-up or maximum capacity, dry period or hydrologic deficit, wet period or recharge and freeze-up. Modeled monthly hydrologic budgets reveal similar deficit and recharge periods. As displayed in Figure 5.4 B-E, evaporation exceeded precipitation during June (-19.7 mm), July (-48.4 mm) and August (-15.4 mm), while precipitation typically exceeds evaporation during September (+8.1 mm). Consequently, ponds within the Churchill region typically fill to maximum capacity during the major melt period (June), exhibit lowering water levels until late July and recharge from August to freeze-up (late September to early November). Mann Kendall and Sen.'s slope trend analyses reveal a decreasing P-E deficit for August (0.72 mm/yr p=0.01) and September (0.51 mm/yr p=0.05). During these months, pond water levels have increased and should translate to larger detectable surface areas. Additionally, there is no significant trend in modeled pond water levels for June and July, which suggests pond boundaries have remained similar during these months. When compared, pond boundaries delineated under similar conditions may also exhibit the evidence of changing hydrological conditions.

5.4.3 Estimated Pond Surface Area Change

Although pond water levels and corresponding surface areas are highly variable and significantly influenced by seasonal hydrological cycling, annual average estimates suggest ponds have increased in size between 1947 and 2008. Hydrologic model results suggest that ponds have experienced a 7.2 cm increase in water levels, which translates to an average pond surface area increase of 2,761 m² or 30% percent before freeze-up within the Churchill region. Ponds should recharge closer to maximum capacity regardless of increased deficits during early summer. However, annual average surface area trends do not provide accurate application to monthly pond stability. Although ponds may become less dry before freeze-up, hydrologic modeling suggests pond surface area should reveal contradictory trends during June/July.

Given the timing of remote sensing imagery acquisition (July-August), annual average surface area trends do not provide accurate estimates of anticipated pond boundary delineation change. Due to differing capture dates, hydrologic conditions present on July 31st (average imagery acquisition date) most accurately represent average water level position during the acquisition period. Therefore, water balance estimates for July 31st between 1947 and 2008 provide hydrologic context to imagery findings. As displayed in Figure 5.5, no significant hydrologic trends are present (p= >0.1). Consequently, pond features within the Churchill region should reveal no significant surface area changes during the summer period around Jul 31st.

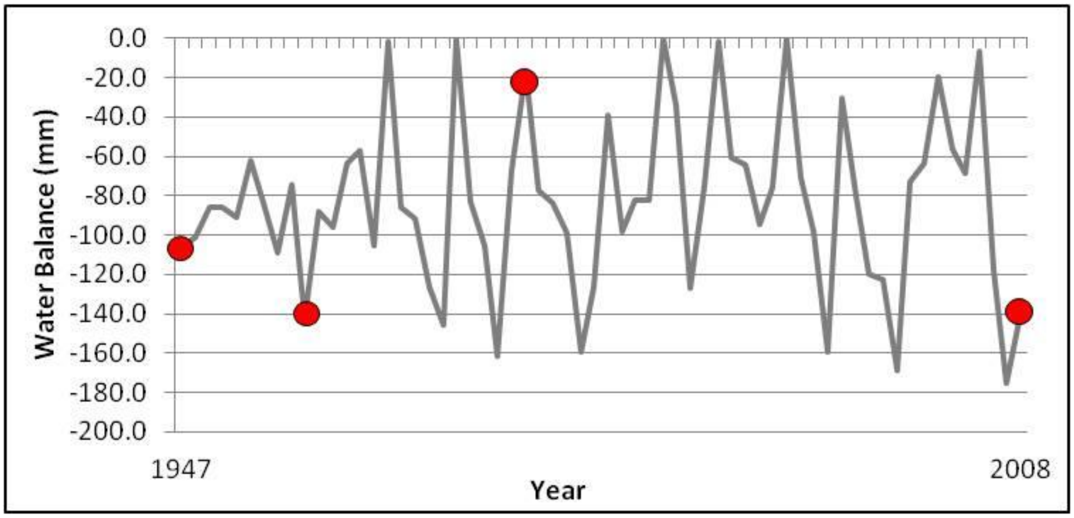


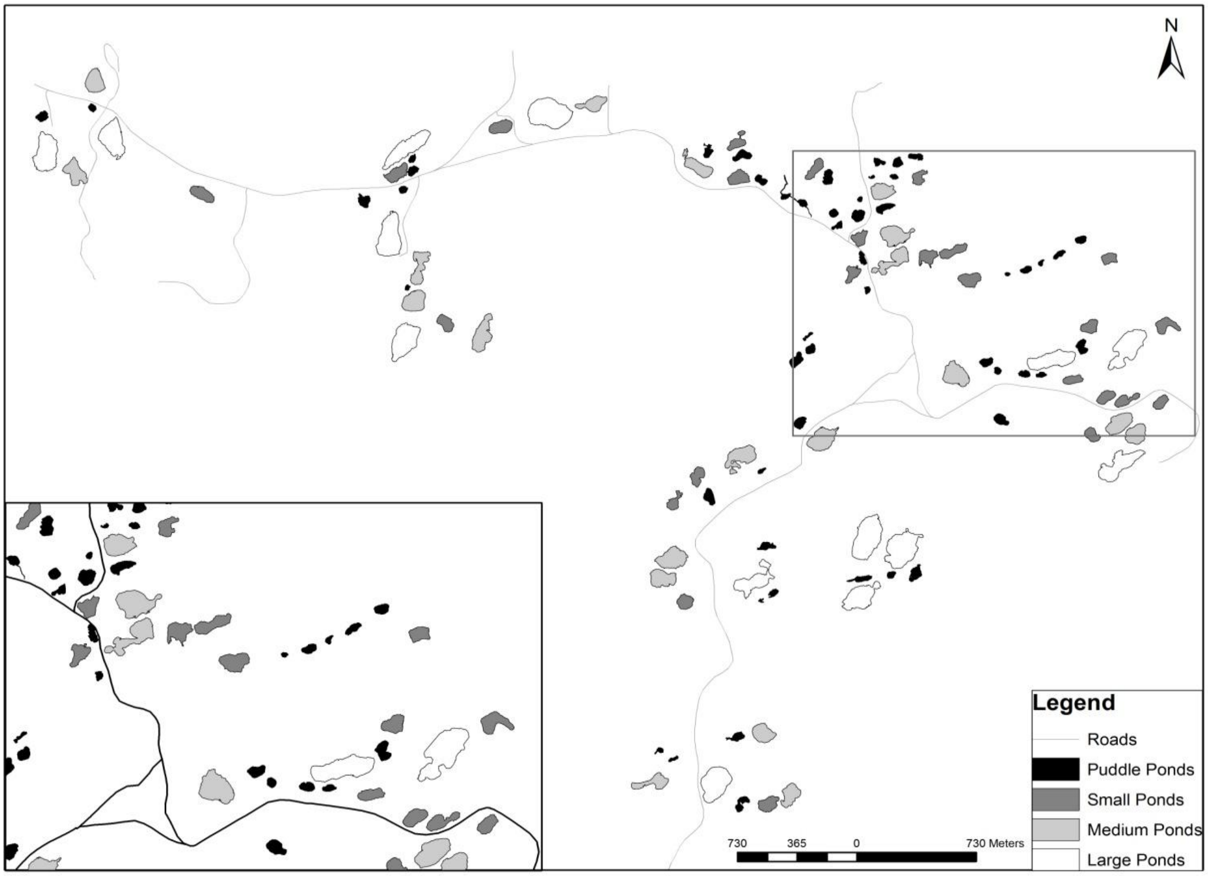
Figure 5.5 – Modeled Cumulative Pond Open-Water Hydrologic Balance for July 31st: Imagery capture years marked with red dots, 1947-2008 (Churchill region)

Due to inter-annual pond hydrologic variability, significant water level variation was modeled for mid-summer (July 31st) between 1947 and 2008 (Figure 5.5). These annually oscillating hydrologic values reveal the magnitude of naturally induced hydrologic fluctuations. As well, imagery capture years exhibit differing inter-annual pond hydrologic conditions. As displayed in Figure 5.5, modeled cumulative water balance reveals a comparative deficit (1947-1956), surplus (1956-1972), deficit (1972-2008) pattern and overall deficit between 1947 and 2008. This distinctive "high, low, high" hydrologic relationship should transform pond boundaries and skew representative pond delineation. Therefore, calculated minimum pond area change thresholds provide meaningful context to derived physical pond boundary measurements (Section 5.3.3).

5.4.4 Changes in Pond Surface Area

Ponds within the Churchill region experienced significant surface area change (Figure 5.6). Delineated features exhibited an average surface area decrease from 1947 to 1956 (-249 m² or 3%), followed by pond recharge exceeding initial boundary delineation between 1955 and 1972 (+427 m² or 5%). Subsequently, pond boundaries decreased from 1972 to 2008 (-668 m² or 8%), which facilitated conditions of overall average drying of 514 m² or 6% between 1947 and 2008. Although contemporary shoreline retreat was consistently documented for all ponds between 1947 and 2008, slight differentiations were observed throughout the temporal period based on size class. While puddle and small sized ponds mirrored estimated pond boundary changes, medium and large ponds displayed no significant change during 1947-1956 and 1956-1972 studies (Figure 5.6). These larger water features may have hydrologic stability due to subsurface hydrologic catchments or adjacent drainage which shifted between 1972 and 2008. Even though delineated pond boundaries revealed significant surface area change within the Churchill region, these results do not coincide with modeled contemporary hydrologic change.

As noted previously, pond boundaries were estimated to significantly fluctuate due to hydrologic variability. Pond areas were expected to reveal a distinct oscillating pond boundary pattern and an overall decreasing trend in surface area due to naturally induced hydrologic changes which are unrepresentative of long-term hydrologic shifts. Delineated pond feature changes closely mimic modeled natural hydrologic variability. These findings further solidify the significant influence of hydrologic variability on pond surface area and the challenge of detecting representative pond boundaries for sustainability research.

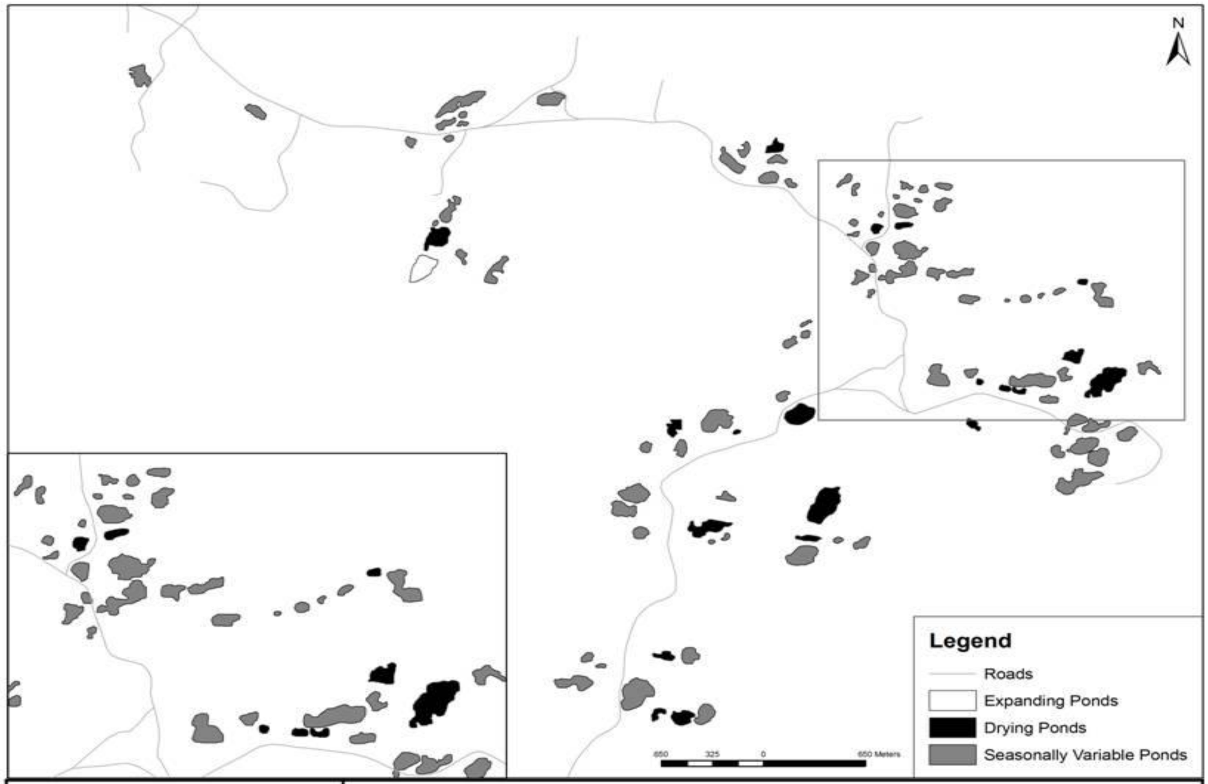


Average Change by Category					
Size	**Change**	**Period**			
		1947-1956	**1956-1972**	**1972-2008**	**1947-2008**
	Estimated Intra-seasonal Influence	Decrease	Increase	Decrease	Decrease
Puddle	Average (m^2)	-259.11	99.47	-405.19	-564.83
	% Change	-10% (-79 to 323%)	4% (-46 to 217%)	-16% (-50% to 39%)	-22% (-52 to 533%)
Small	Average (m^2)	-891.09	798.75	-800.64	-892.98
	% Change	-12% (-56 to 81%)	11% (-44 to 61%)	-11% (-19 to 11%)	-12% (-68 to 79%)
Medium	Average (m^2)	357.88	-291.60	-1587.77	-1521.49
	% Change	2% (-61 to 80%)	-2%(-22 to 98%)	-11% (-30 to 0%)	-10% (-40 to 28%)
Large	Average (m^2)	373.85	570.17	-2276.25	-1332.22
	% Change	1% (-19 to 12%)	2% (-13 to 19%)	-8% (-18 to 1%)	-5% (-10 to 18%)
All	**Average (m^2)**	**-249.08**	**437.49**	**-688.38**	**-514.59**
	% Change	**-3% (-79 to 323%)**	**5% (-46 to217%)**	**-8% (-50 to 39%)**	**-6% (-68 to 533%)**

Figure 5.6 – Remote Sensing Surface Area Change Detection Results for 100 Ponds Organized by Size Class: 1947-2008 (Churchill, Manitoba)

Omitting the influence of naturally induced hydrologic variability, remote sensing findings revealed no significant change in overall pond sustainability during mid-summer. Although overall average pond surface area change did not exceed the minimum threshold requirements necessary to conclude changing conditions, 33 features exhibited boundary decline between 1947 and 2008 which surpassed hydrologic variability influences. These contemporary landscape transformations were geographically scattered and potentially facilitated by altered catchment hydrology, human interactions or permafrost degradation. Between imagery capture years, 13 ponds decreased (1947-1956), 11 increased (1956-1972) and 14 decreased (1972-2008) beyond the minimum threshold values derived in Section 5.3.3.3. Although these temporary boundary changes do not provide conclusive evidence of shifting pond sustainability, it reinforces the inconsistent nature of pond features within the Churchill region. As well, these results reveal pond recharge potential and the influence of localized variables which facilitated these fluctuations.

Additionally, 21 pond features experienced consistent directional shoreline change throughout each imagery acquisition period (Figure 5.7). Geographically sporadic pond shoreline retreat was observed for 20 features while consistent expansion was evident for one feature within the study site. Although directional shoreline changes were evident, these changes do not consistently exceed the minimum required hydrologic threshold to omit the influence of naturally occurring pond fluctuations. Therefore, these pond changes may have resulted from hydrologic variability in conjunction with human interactions or digitizing error.



	Consistent Pond Shoreline Change		
Direction	**Drying**	**Wetting**	**Seasonally Variable**
Number of Ponds	20	1	79

Figure 5.7 - Ponds Exhibiting Consistent Directional Shoreline Change Between Each Capture Period: All Surface area change is below the minimum threshold required to omit hydrologic variability (Churchill, Manitoba)

Overall, pond features within the Churchill region experienced several isolated incidences of pond boundary change, while no overall shifts in pond physical sustainability were detected for mid-summer. Although these results may not accurately represent pond stability during early or late summer, overall physical pond sustainability is evident within the Churchill region.

5.5 Conclusions

This study employed a mixed method approach in order to analyze various indicators of overall contemporary pond sustainability within the Churchill region between 1947 and 2008. Results reveal regional climatic change, changing pond hydrologic conditions and overall contemporary pond physical sustainability. Specifically, atmospheric conditions within the Churchill region have become warmer and wetter while evaporation and open water duration have increased. These changing environmental conditions promoted pond water levels to remain similar during the drying phase and refill closer to initial maximum capacity during the recharge period between 1947 and 2008. As well, pond features exhibited similar water level conditions between break-up and late-July and water level increase from August until ice freeze-up. Although evaporation consistently exceeded precipitation within the region, pond annual hydrologic deficits gradually lessened. Under continued environmental conditions, ponds are estimated to ultimately expand in surface area. However, between 1947 and 2008 pond features revealed no contemporary change in delineated surface area. The majority of observed pond boundary fluctuations were directly caused by naturally induced hydrologic variability. This study further stresses the importance of considering hydrologic variability when aiming to conduct remote sensing pond sustainability studies.

6.0 Overall Conclusions, Contributions and Recommendations

Findings presented throughout this thesis suggest contemporary hydro-climatic change and pond sustainability within the Churchill region. Multiple methods were employed to quantify the influence of naturally induced hydrologic variability on representative pond shoreline delineation using remote sensing imagery within the Hudson Bay Lowland. Pond sustainability findings strengthen scholarly understanding of Canadian subarctic hydrologic dynamics while methodological analyses suggest a multi-method approach when calculating representative pond boundary change. Overall, this thesis provides meaningful academic contributions to the disciplines of hydrology, geomatics and climate change.

In the first paper (Chapter 4), a methodological analysis examining the occurrence of pond water level and surface area fluctuations induced by natural hydrologic variability within the Churchill region has confirmed the presence of continually changing pond conditions. Oscillating pond boundaries caused by antecedent hydrologic conditions are detectable by remote sensing imagery and produce altered total pond surface area delineation. Thus, pond sustainability studies comparing shoreline changes during hydrologically varying conditions may present unrepresentative findings. Pond sustainability research must include the influence of antecedent precipitation, intra-seasonal hydrologic fluctuations and inter-annual hydro-climatic variability. In order to account for hydrologic variability, selected remote sensing images should exhibit consistent capture dates, pond conditions and hydrologic context. If imagery capture conditions are inconsistent, simple water balance modeling in conjunction with surface area to depth ratios should be employed to isolate and omit unrepresentative pond boundary changes caused by antecedent conditions. As well, field-based observations strengthen pond sustainability findings and provide essential quality control data. Cross referencing these findings with previous pond sustainability studies revealed methodological discrepancies and little consideration of hydrologic fluctuations. These conclusions suggest an innovative methodological approach which incorporates consideration for hydrologic variability when conducting subarctic/arctic remote sensing pond sustainability studies. In order to produce well rounded and conclusive results, future research should adopt a multi-disciplinary approach which incorporates hydrology, geomatics and climate change knowledge.

Adopting the proposed methodological approach, contemporary pond sustainability was determined for 100 ponds in the second paper (Chapter 5). Results reveal the compounding complexity of deriving accurate and representative changes in subarctic pond dynamics within the Churchill study area. Derived from a multi-method approach, findings suggest regional hydro-climate change and overall pond sustainability. Specifically, climate within this region exhibited gradually warming and wetting atmospheric conditions, which facilitated increased evaporation and extended open water durations. Given the sensitivity of northern environments, these changing atmospheric conditions may drastically influence regional ecosystems, biotic sustainability, chemical interactions and landscape morphology. Pond features within the Churchill region experienced decreased annual hydrologic deficits. These features gradually exhibited late-summer recharge ranges closer to maximum capacity which may eventually facilitate pond expansion beyond current boundaries. Thus, increased atmospheric moisture surpassed elevated evaporation contributions within the Churchill region. However, during the open water period pond hydrology revealed seasonally variable trends. Exceeding seasonal hydrologic cycling, ponds experienced decreasing water level trends during early-summer, no significant change mid-summer and an increasing trend during late-summer. Therefore, comparative temporal pond boundary analysis may produce three disparate results based on imagery capture dates within the open water season. If disregarded, hydrologic cycling in conjunction with naturally induced water level variability can drastically alter remotely delineated pond sustainability findings. Water balance modeling predicted pond boundaries should remain stagnant during the mid-summer imagery acquisition period. Quality controlled and corrected remote sensing results reveal similar findings. However, pond features experienced significant surface area fluctuations facilitated by naturally induced hydrologic variability, which further reinforce the importance of considering this variable. Therefore, accurate pond sustainability research within the Churchill region must consider (1) naturally induced hydrologic variability, (2) pond hydrologic cycling and (3) seasonally variable changing atmospheric conditions.

Findings of this thesis provide academic and social contributions related to several disciplines. Contributions associated with geomatics research include: (1) considering the influence of hydrologic variability when attempting to accurately delineate representation pond boundaries using remote sensing as a data source,; (2) proposing an innovative methodological framework, which includes field surveys, remote sensing and modeling, for conducting pond sustainability research within the Canadian subarctic that accounts for hydrologic variability; and (3) providing a critical analysis of previous remote sensing-based pond sustainability studies. Hydrology focused contributions include: (1) confirming the occurrence and prevalence of pond surface area and water depth fluctuations caused by antecedent precipitation, intra-seasonal oscillations and inter-annual variability within the Churchill region,; (2) reinforcing the significance of field-based research and hydrological calculations when conducting remote sensing pond sustainability research,; (3) providing evidence of changing annual and seasonal pond hydrologic conditions; and (4) revealing contemporary pond sustainability within the Churchill region. Lastly, thesis contributions related to climate change research include: (1) documenting contemporary atmospheric change within the Churchill region; and (2) creating linkages between atmospheric changes and environmental conditions.

Further pond sustainability research within the Churchill region may include:

- Deriving linkages between permafrost coverage and pond sustainability.
- Conducting paleo-limnological research to establish long-term pond sustainability.
- Determining the influence of land cover conditions on pond morphology and hydrologic dynamics.
- Developing a comprehensive hydrologic model which incorporates land cover, active layer depth, permafrost coverage, soil type, catchment area and human influences to estimate future pond sustainability under varying conditions.

Bibliography

(LSBU) London South Bank University. Water Structure and Science. 5 February 2008. 3 March 2008 <http://www.lsbu.ac.uk/water/>.

Adam, J, T Barnett and D Lettenmaier. "Potential impacts of a warming climate on water availability in snow-dominated regions." Nature (2005): 438 (7066): 303-309.

Arlen-Pouliot, Yann and Najat Bhiry. "Palaeoecology of a palsa and a filled thermokarst pond in a permafrost peatland, subarctic Québec, Canada." The Holocene 15.3 (2005): 408-419.

Bartsch, Annett, et al. "Satellite radar imagery for monitoring inland wetlands in boreal and sub-arctic environments." Aquatic Conservation-Marine and Freshwater Ecosystems 17.3 (2007): 305-317.

Bello, Richanrd and JD Smith. "The effect of weather variability on the energy-balance of a lake in the Hudson-Bay Lowlands, Canada." Arctic and Alpine Research 22.1 (1990): 98-107.

Boudreau, Dale and Wayne Rouse. "The role of individual terrain units in the water balance of wetland tundra." Climate Research 5.1 (1995): 31-47.

Browling, Laura, et al. "The role of surface storage in a low-gradient arctic watershed." Water Resources Research 39.4 (2003): SWC21-SWC213.

Brown, Laura and Kathy Young. "Assessment of three mapping techniques to delineate lakes and ponds in a Canadian High Arctic wetland complex." Arctic 59.3 (2006): 283-293.

Bruin, H and J Keijman. "The Priestley-Taylor evaporation model applied to a large, shallow lake in the Netherlands." Journal of Applied Meterology 19 (1979): 898-903.

Callaghan, Terry, et al. "Effects of changes in climate on landscape and regional processes, and feedbacks to the climate system." Ambio 33.7 (2004): 459-468.

Canty, John. Image analysis, classification and change detection in remote sensing : with algorithms for ENVI/IDL. Boca Raton: CRC/Taylor & Francis, 2007.

Christensen, T, et al. "A catchment-scale carbon and greenhouse gas budget of a subarctic landscape." Philosophical Transactions of the Royal Society A - Mathematical Physical and Engineering Sciences 365.1856 (2007): 1643-1656.

Christopherson, Robert. Elemental Geosystems. 4. Upper Saddle River: Pearson Education Inc., 2004.

Devito, K, et al. "A framework for broad-scale classification of hydrologic response units on the Boreal Plain: Is topography the last thing to consider?" Hydrological Processes 19.8 (2005): 1705–1714.

Dingman, Lawrence. Physical Hydrology. New York: Prentice Hall, 1994.

Dredge, Lynda and RJ Mott. "Holocene pollen records and peatland development northeastern Manitoba." Geographie Physique et Quaternaire 57.1 (2003): 7-19.

Dredge, Lynda. Field Guide to the Churchill Region, Manitoba. 53 vols. Geological Survey of Canada, 1992.

Duguay, Claude and Alain Pietroniro. Remote Sensing in Northern Hydrology. Washington, DC: American Geophysical Union, 2005.

Duguay, Claude and P Lafleur. "Determining depth and ice thickness of shallow sub-arctic lakes using space-borne optical and SAR data." International Journal of Remote Sensing 24.3 (2003): 475-489.

Duguay, Claude, et al. "Ice-cover variability on shallow lakes at high latitudes: model simulations and observations." Hydrological Processes 17.1 (2003): 3465- 3483.

Duguay, Claude, et al. "RADARSAT backscatter characteristics of ice growing on shallow sub-arctic lakes, Churchill, Manitoba, Canada." Hydrological Processes 16.8 (2002): 1631–1644.

—. "Recent trends in Canadian lake ice cover." 20.4 (2006): 781-801.

Eaton, A, et al. "Surface energy balance of the western and central Canadian subarctic: Variations in the energy balance among five major terrain types." Journal of Climate 15.11 (2001): 3692-3703.

Environment Canada. Churchill A - Historical Weather Data. 26 January 2004. 15 January 2008 <http://www.climate.weatheroffice.ec.gc.ca>.

—. Churchill A, Manitoba. 25 February 2009. 15 January 2008 <http://www.climate.weatheroffice.ec.gc.ca/climate_normals/>.

—. Churchill A, Manitoba. 25 February 2004. 15 January 2008 <http://www.climate.weatheroffice.ec.gc.ca/climate_normals/>.

—. Churchill UA - Historical Weather Data. 8 April 2004. 15 January 2008 <http://www.climate.weatheroffice.ec.gc.ca/climateData/>.

Fick, Adolf. "Ueber Diffusion." Annalen der Physik 170.1 (1855): 59–86.

Fily, M, et al. "A simple retrieval method for land surface temperature and fraction of water surface determination from satellite microwave brightness temperatures in sub-arctic areas." Remote Sensing of Environment 85.3 (2003): 328-338.

Fishback, LeeAnn. Pond Sustainibility and Water Level Fluctuations Within Churchill Region Jennifer Parrott. 10 August 2008.

Frohn, RC, KM Hinkle and WR Eisner. "Satellite remote sensing classification of thaw lakes and drained thaw lake basins on the North Slope of Alaska." Remote sensing and Environment 97.1 (2005): 116-126.

Gagnon, Alexandre and William Gough. "Climate change scenarios for the Husdon Bay region: An intermodel comparison." Climate Change 69 (2005): 269-297.

Geobase. Satellite Imagery. 3 February 2008. 3 February 2008 <http://www.geobase.ca>.

—. Satellite Imagery. 3 February 2008. 3 February 2008 <http://www.geobase.ca/>.

Geological Survey of Canada. Geoscience Data Repository. 10 Feburary 2008. 10 February 2008 <http://gdr.nrcan.gc.ca/index_e.php>.

Gorham, E. "Northern peatlands - Role in the carbon-cycle and probable responses to climatic warming." Ecological Applications 1.2 (1991): 182-195.

Grippa, M, et al. "Observations of changes in surface water over the western Siberia lowland." Geophysical Research Letters 34.15 (2007): No. L15403.

Grosse, Guido, et al. "The use of CORONA images in remote sensing of periglacial geomorphology: An illustration from the NE Siberian Coast." Permafrost and Periglacial Processes 16.2 (2005): 163-172.

—. "Thermokarst lakes: High-resolution distribution and temporal changes at three yedoma sites in Siberia." (2007): 1-6.

Haugen, R. "Climate of remote areas in north-central Alaska: 1975–1979 summary." 82.35 (1982): 110.

Henderson, Floyd and Anthony Lewis. Principles and Applications of Imaging Radar. Vol. 2. New York: John Wiley & Sons, 1998.

Hinkel, K, et al. "Morphometric and spatial analysis of thaw lakes and drained thaw lake basins in the western arctic coastal plain, Alaska." Permafrost and Preiglacial Processes 16 (2005): 327-341.

Hinzman, Larry and K Yoshikawa. "Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska." Permafrost and Periglacial Processes 14.2 (2003): 151-160.

Hinzman, Larry, J Jones and R Petrone. "Seasonal export of carbon, nitrogen, and major solutes from Alaskan catchments with discontinuous permafrost." Journal of Geophysical Research-Biogeoscience (2006): 111 (G2): Art. No. G02020.

Hinzman, Larry, et al. "Evidence and implications of recent climate change in northern Alaska and other arctic regions." Climatic Change 72 (2005): 251–298.

Hopkins, D, et al. "Controls on the distribution of productivity and organic resources in Antarctic Dry Valley soils." Proceedings of the Royal Society B.273 (2006): 2687 - 2695.

Jensen, John. Remote Sensing of the Environment: An Earth Resource Perspective. Ed. 2. Upper Saddle River: Prentice Hall, 2007.

Jorgenson, MT and Y Shur. "Evolution of lakes and basins in northern Alaska and discussion of the thaw lake cycle." Journal of Geophysical Research 112.F2 (2007).

Katamura, F, et al. "Thermokarst formation and vegetation dynamics inferred from a palynological study in Central Yakutia, Eastern Siberia, Russia." Arctic, Antarctic and Alpine Research 38.4 (2006): 561-570.

Kaufman, Darrell, et al. "Recent warming reverses long-term arctic cooling." Science 325.5945 (2009): 1236-1239.

Klein, Eric, Edward Berg and Roman Dial. "Wetland drying and succession across the Kenai Peninsula Lowlands, south-central Alaska." Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 35.8 (2005): 1931-1941.

Labrecque, S, et al. "Contempory (1951-2001) evolution of lakes in the Old Crow Basin, northern Yukon, Canada: remote sensing, numerical modeling, and stable isotope analysis." Arctic 62.2 (2009): 225-238.

Lafleur, Peter. "Annual variability in summer evapotranspiration and water balance at a subarctic forest site." Nordic Hydrology 25 (1994): 331-344.

Lafleur, Peter, AB Wurtele and Claude Duguay. "Spatial and temporal variations in surface albedo of a subarctic landscape using surface-based measurements and remote sensing." Arctic and Alpine Research 29.3 (1997): 261-269.

Lemelin, Raynald and Elaine Wiersma. "Perceptions of polar bear tourists: A qualitative analysis." Human Dimensions of Wildlife 12 (2007): 45-52.

Lillesand, Thomas and Ralph Kiefer. Remote Sensing and Image Interpretation. New York: John Wiley & Sons, 1994.

Macrae, Merrin, Richard Bello and Larry Molot. "Long-term carbon storage and hydrological control of CO2 exchange in tundra ponds in the Hudson Bay Lowland." Hydrological Processes 18.11 (2004): 2051-2069.

Mather, Paul. Computer processing of remotely-sensed images : an introduction. Chichester: Wiley, 2004.

Mosner, Melinda and Brent Aulenbach. "Comparision of methods used to estimate lake evaporation for a water budget of lake seminole, southwestern Georgia and northwestern Flordia." Proceedings of the 2003 Georgia Water Resources Conference (2003).

Nelson, Frederick. "Permafrost distribution in central Canada: Applications of a climate-based predictive model." Annuals of the Association of American Geographers 76.4 (1986): 500-569.

Oke, TR. Boundary Layer Climates. 2. New York: Routledge, 1987.

Oswald, Claire and Wayne Rouse. "Thermal characteristics and energy balance of various-sized Canadain Shield lakes in the Mackenzie River Basin." Journal of Hydrometeorology 5.1 (2004): 129-144.

Petrone, Richard and Wayne Rouse. "Synoptic Controls on the Surface Energy and Water Budgets in Subarctic Regions of Canada" International Journal of Climatology 20 (2000): 1149-1165.

Petrone, Richard, et al. "Effect of drought on greenhouse gas emissions from pond/peatland systems with contrasting hydrologic regimes, Northern Alberta, Canada." Dynamics and Biogeochemistry of River Corridors and Wetlands IAHS Publ. 294 (2005).

Pietroniro, Alain and Robert Leconte. "A review of Canadian remote sensing and hydrology, 1999-2003." Hydrological Processes 19 Sp. Iss..1 (2005): 285-301.

Pietroniro, Alain, Terry Prowse and D Peters. "Hydrologic assessment of an inland freshwater delta using multi-temporal satellite remote sensing." Hydrological Processes 13.16 (1999): 2483-2498.

Plug, L, C Walls and B Scott. "Tundra lake changes from 1978 to 2001 on the Tuktoyaktuk Peninsula, western Canadian Arctic." Geophysical Research Letters 35 (2008): 1-5.

Prowse, T.D. and C.S.L. Ommanney. Northern hydrology : Canadian perspectives. NHRI Science Report No., 1990.

Quinton, William and Nigel Roulet. "The spring and summer hydrology of the northern patterned fen." Arctic and Alpine Research 30 (1998): 285-294.

Riordan, B, D McGuire and D Verbyla. "Shrinking ponds in subarctic Alaska based on 1950-2002 remotely sensed images." Journal of Geophysical Research-Biogeosciences 111.G4 (2006): No. G04002.

Ritter, Dale, Craig Kochel and Jerry Miller. Process Geomorphology. 4. New York: McGraw Hill, 2002.

Roulet, Nigel and Ming Woo. "Hydrology of a wetland in the continuous permafrost region." Journal of Hydrology, 89 (1986): 73-91.

Roulet, T, et al. "Role of the Hudson Bay lowland as a source of atmospheric methane." Journal of Geophysical Research 99.D (1994): 1439-1454.

Rouse, Wayne, et al. "Climate-lake interactions." Woo, Ming-ko. Cold Region Atmospheric and Hydrologic Studies. Vol. 2. Springer, 2007. 139-160.

—. "Effects of climate change on the freshwater of arctic and subarctic North America." Hydrological Processes 11 (1997): 873-902.

Rouse, Wayne, et al. "The influence of lakes on the regional energy balance." Woo, Ming. Cold Region Atmospheric and Hydrologic Studies. The Mackenzie GEWEX Experience. Springer, 2008. 309-325.

Rovansek, Ronald, Larry Hinzman and Douglas Kane. "Hydrology of a tundra wetland complex on the Alaskan Arctic Coastal Plain, USA." Arctic and Apline Research 28.3 (1996): 311-317.

Ryden, Bengt Erik. High Latitude Hydrology on Processes and Water Budgets of Tundra Regions. Sweden: Lojdquist Tryckeri, 1979.

Schindler, David and John Smol. "Cumulative effects of climate warming and other human activities on freshwaters of arctic and subarctic North America." Ambio 35.4 (2006): 160-169.

Schultz, GA and ET Engman. Remote Sensing in Hydrology and Water Management. New York: Springer, 2000.

Scott, PA, et al. "Crown forms and shoot elongation of white spruce at the treeline, Churchill, Manitoba, Canada." 19.2 (1987): 175-186.

Scott, Peter. "Flora of Chuchill Manitoba." Edmonton: University of Alberta, 1996.

Simulistics Ltd. Thornthwaite equation to estimate potential evaporation (PET). Model. Loanhead, 2003.

Smith, Larry, et al. "Disappearing arctic lakes." Science 3008.5727 (2005): 1429-1429.

Smith, LC, YW Sheng and GM MacDonald. "A first pan-Arctic assessment of the influence of glaciation, permafrost, topography and peatlands on northern hemisphere lake distribution." Permafrost and Periglacial Processes 18.2 (2007): 201-208.

Smol, John and Marianne Douglas. "Crossing the final ecological threshold in high arctic ponds." PNAS Early Edition (2007): 1-3.

Stow, D, A Hope and D McGuire. "Remote sensing of vegetation and land-cover change in arctic tundra ecosystems." Remote Sensing of Environment 89.3 (2004): 281-308.

Thornthwaite, CW and HG Wilm. "Report of the committee on transpiration and evaporation. 1943±44." Transactions of the American Geophysical Union. 1944. 683-693.

Van der Werff, H and F Van der Meer. "Shape-based classification of spectrally identical objects." Journal of Photogrammetry & Remote Sensing 63 (2008): 251-258.

Walker, H and M Harris. "Perched ponds: An arctic variety." Arctic 29.4 (1976): 223-238.

Walter, K, et al. "Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming." Nature 443 (2006): 71-75.

Wessel, David and Wayne Rouse. "Modelling evaporation from wetland tundra." Boundary-Layer Meteorology 68 (1994): 109-130.

White, Daniel, et al. "The arctic freshwater system: Changes and impacts." Journal of Geophysical Research 112 (2007): 1-21.

Winter, T, d Rosenberry and A Sturrock. "Evaluation of 11 equations for determining evporation for a small lake in the north central United States." Water Resource Research 31.4 (1995): 83-993.

Wolf, Detlef, et al. "A reanalysis and reinterpretation of geodetic and geological evidence of glacial-isostatic adjustment in the Churchill region, Hudson Bay." Surveys In Geophysics 27.1 (2006): 19-61.

Woo, Ming-ko and Corrinne Mielko. "An intergrated framework of lake-stream connectivity for a semi-arid, sub-arctic environment." Hydrological Processes 21 (2007): 2668-2674.

Woo, Ming-ko. "Hydrology of a small lake in the Canadian high arctic." Arctic & Alpine Research 12.2 (1980): 227-235.

Wrona, Frederick, et al. "Climate change effects on aquatic biota, ecosystem structure and function." Ambio 35.7 (2006): 359-369.

Yee, Stanley and Richard Bello. "A seasonal water balance for a pond in a polygonal peat plateau in the Hudson Bay Lowlands." 2006. Arctic Net. December 2007 <www.arcticnet-ulaval.ca/>.

Yee, Stanley. "Water flow pathways to ponds and." Thesis: York University, 2008.

Yoshikawa, Kenji and Larry Hinzman. "Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska." Permafrost and Periglacial Processes 14 (2003): 151–160.

Appendix A:

Selected Previous Pond Delineation Research

Author	**Year**	**Location**	**Climate**	**Type of ground-cover**	**Type of imagery**	**Methods**	**Bands/Channels**	**Resolution**	**Pond Size**	**Focus**
Pietroniro et al.	1999	PAD, Canada	Subarctic	Sporadic	Visible	Landsat MSS	All	75m	80-1500km^2	Delineate water surfaces and Elevation
					Visible to near IR	Landsat TM	All	25m		
Duguay et al.	2002	Churchill, Canada	Subarctic	Continuous	Active Microwave	RADARSAT	C (HH)	25m	0.8-2km^2	Ice-Growth
Duguay and Lafleur	2003	Churchill, Canada	Subarctic	Continuous	Visible to near IR	Landsat TM	2	30m	-	Determine pond/lake bathymetry and depth
					Active Microwave	ERS-1	C (VV)	30m		
						Field Observation				
Yoshikawa et al.	2003	Council, Alaska	Subarctic	Discontinuous	Active Microwave	RADARSAT SAR	C	27m	<0.4km	Classification of terrain
						IKONOS		1m		Pond shrinking
						Aerial Photos				
Fily et al.	2003	Canada	Subarctic/Arctic	All	Passive Microwave	SSM/I	19 (HV) 37 (HV)	25km	-	Determine FWS
					Passive Microwave	SMMR	18 (HV) 37 (HV)			Determine FWS

Author	**Year**	**Location**	**Climate**	**Type of ground-cover**	**Type of imagery**	**Methods**	**Bands/Channels**	**Resolution**	**Pond Size**	**Focus**
Klein et al.	2005	South-central, Alaska	Subarctic	No Permafrost		Aerial Photos	-	1-3 m	-	Determine Long-term changes
						Field Observation				
Grosse et al.	2005	Northeast, Siberia	Arctic	Continuous	Visible	CORONA	-	2.5 m	6 m^2 (1 Pixel), 400 m^2	Delineate water surfaces
						Field surveys				Ground Truthing
Smith et al.	2005	Siberia	Arctic	Continuous, Discontinuous	Visible	Landsat MMS	NIR	80 m	>0.4 km^2	Delineate water surfaces
					Visible	MODIS	IR	250 m		
					Visible	RESURS-1	NIR	150 m		
Brown and Young	2006	High Arctic, Canada	High-Arctic	Continuous	Active Microwave	RADARSAT	C (HH)	7 m	>1 km^2	Delineate water surfaces
					Visible	Landsat 7	SWIR	30 m		
						Aerial Photos				
						Topographic Maps				
						Field surveys				Ground Truthing
Riordan et al.	2006	Central, Alaska	Subarctic	Continuous, Discontinuous		Aerial Photos		3 m	>2 km^2	Delineate water surfaces
					Visible to near IR	Landsat ETM+		30 m		
						Landsat TM		30 m		

Author	Year	Location	Climate	Type of ground-cover	Type of imagery	Methods	Bands/Channels	Resolution	Pond Size	Focus
Riordan et al.	2006	Central, Alaska	Subarctic	Continuous, Discontinuous		Aerial Photos		3 m	>2 km²	Delineate water surfaces
					Visible to near IR	Landsat ETM+		30 m		
						Landsat TM		30 m		
Grippa et al.	2007	Western, Siberia	Subarctic/ Arctic	Continuous, Discontinuous	Passive Microwave	SSM/I	37	25 km (pixel size)	Fraction of water	Water surfaces
Bartsch et al.	2007	Central, Siberia	Subarctic	Continuous	Active Microwave	ENVISAT ASAR	VV	150m	>8 km	Wetland monitoring
					Active Microwave	QuikScat	Ku	25 km		
					Aerial Photos	Historical GIS Data				Imagery context
Hinkel et al.	2005	Northern Alaska	Arctic	Continuous	Visible	Landsat MSS	All	60 m	100 m²	Thaw lake drainage
					Visible to near IR	Landsat ETM+	5,4,3	30m		
						Air Photos				
Grosse et al.	2007	Northern Siberia	Arctic	Continuous	Visible	Corona		2.5 m	30 m²	Thermokarst Lake Change
					Visible	Spot-5		2.5 m		
					Visible	IKONOS		1 m		
Plug	2008	Western Canada	Arctic	Continuous	Visible	Landsat TM	All	30 m	0.01 km - 1.2 km²	Tundra lake change
					Visible	Landsat MSS	All	60 m		
					Visible	Landsat ETM+	All	30 m		
Labrecque et al.	2009	Northern Yukon	Arctic	Continuous		Air Photos			>37 km²	Lake hydrologic change
					Visible	Landsat ETM+	All	30 m		