Spatial and temporal trends of snow cover properties in a large subarctic basin: implications for basin-wide, end-of-winter snow water equivalent estimates

By

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Abstract

Basin-wide snow water equivalent (SWE) is an important hydrologic variable. For large basins, SWE is often estimated using a sparse network of sites. In this study, historical snow surveys (1978-2017) conducted across the ~13,700 km^2 Snare River basin near Yellowknife, NWT, were analyzed to identify local and regional scales of variability as well as temporal trends. Two field seasons of enhanced surveys (2016/17) were conducted. Snow regimes were found to differ significantly between sites north and south of treeline. No statistically significant temporal trends in SWE were detected but snow depth was found to be increasing while snow density was decreasing. Surveys on lakes showed consistently lower SWE than in adjacent uplands by approximately 23%. North of treeline sites consistently contributed much greater error to basin-wide SWE estimates than sites to the south. The consistent regional differences were used to inform sampling strategies for each region.

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1 Introduction

1.1 Description of Problem

In the cold regions of the northern hemisphere the spring snow melt is the most significant hydrologic event of the year. How much water will be available for human and industrial consumption as well as power generation is partly the result of how much water is stored as snow at the end of the winter. Measuring snow in large, northern watersheds with few or no roads is difficult and costly. The Snare River basin (Figure 1.1), located north of Yellowknife, Northwest Territories (NWT), drains an area of almost 13,700 km^2 and supplies the water needed to provide power to half the population of the territory. This thesis aims to improve our understanding of the variation of snow across the basin and, in turn, our ability to estimate how much water is stored at the end of the winter. Additionally, this thesis will examine historical snow records to determine if there are changes, perhaps due to climate change, in the availability of this critical resource.

The volume of water per unit area of snow cover is known as the snow water equivalent (SWE). In northern watersheds, where snow represents a significant percentage of annual precipitation, an estimate of the total SWE before the spring melt begins is a critical input for hydrologic models and forecasting (Elder *et al*., 1989; Liston, 1999; Clark *et al*., 2011). SWE at a location can be estimated from the product of snow depth and snow bulk density. Both depth and density vary spatially across a landscape and temporally over the course of a year (Dickinson and Whiteley, 1972). The variation is due to a wide variety of factors including initial differences in deposition, landscape features, redistribution after deposition, and different rates and types of metamorphosis on the ground (Goodison, 1981). In addition to the total SWE, the

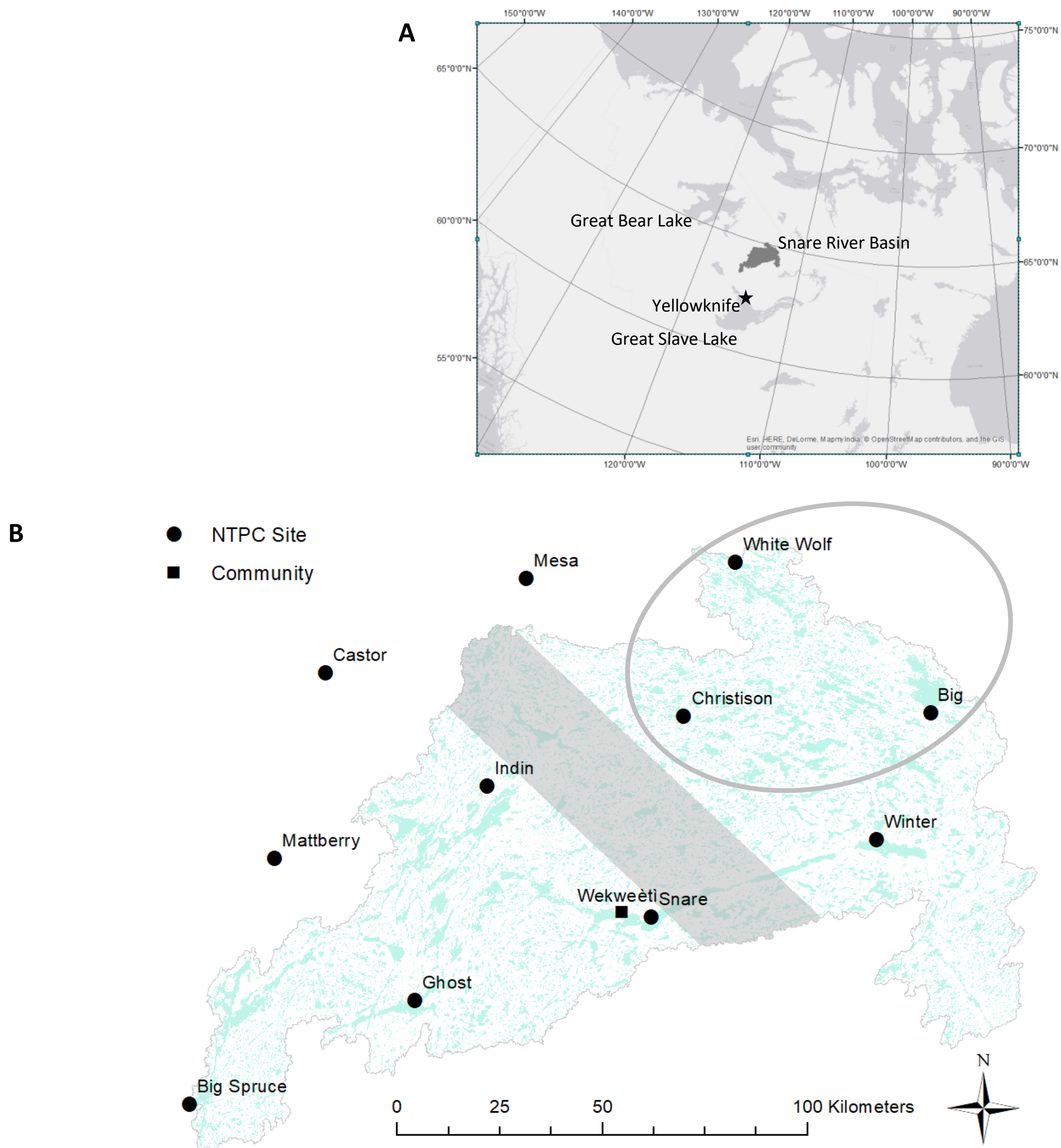

Figure 1.1 *(A) Location of the Snare basin and (B) historical NTPC snow survey sites. (A) The basin is located approximately 150 km north of Yellowknife, NWT. (B) shows the delineated watershed and the location of the 11 NTPC snow survey sites. Sites within the grey oval were added to the survey in 1995. The Big Spruce reservoir, and basin outlet, are located in the SW corner. The approximate location of the treeline is indicated by the gray band running across the basin from the NW to the SE. The Mattberry, Castor, and Mesa lake sites are located outside of the basin.*

distribution of snow depth and density across a landscape play a role in the timing and outflow of the spring melt (Elder *et al*., 1998; Clark *et al*., 2011). Despite its importance, SWE remains difficult to measure over large areas (McCreight and Small, 2014).

Long term changes in watershed SWE or other snow cover properties may alter the hydrology of a basin and the availability of melt water as a resource. Observations of northern snow cover made since 1967 have detected changes linked to climate warming (Serreze and Barry, 2011). Several studies have detected a decline in snow cover extent (IPCC 2013) and SWE (Sturm *et al*., 2017). Increasing Northern Hemisphere temperatures have both the potential to change snow regimes in northern areas and to be accelerated by changing regimes through changes in land albedo (Serreze and Barry, 2011).

To estimate basin-wide SWE, surveys of snow depth and density are often conducted throughout a watershed. In remote northern regions, sparse SWE observation networks result in substantial error to estimates of basin-wide SWE (Steppuhn, 1976; Rees *et al*., 2014). Since SWE is determined by both depth and density, it is important to understand how each of these components contribute to SWE variability across the landscape. Since 1978, the Northwest Territories Power Company (NTPC) has conducted an annual snow survey in the Snare basin before the spring melt. The purpose of the survey is to estimate end-of-winter, basin-wide SWE. This estimate is the main input variable for an empirical model used by the company to predict spring flow volumes.

Various studies have shown that snow cover properties such as SWE, depth and density vary with landscape characteristics such as slope, aspect, elevation, and the presence of vegetation and lakes (Woo and Marsh, 1978; Goodison, 1981; Hannula *et al*., 2016). In particular, large differences have been noted between Arctic, subarctic, and northern boreal forest snow cover. Open areas, north of treeline, tend to have snow cover that is shallower, denser, and contains more water than forest covered areas. (Derksen *et al*., 2014; Hannula *et al*., 2016). The Snare basin can be roughly split into two main landscape types or regions, north and south of treeline. The treeline shown in Fig. 1.1 is only an approximation, the actual treeline is an ecotone that gradually changes from relatively dense boreal forest in the south to shrub covered, open tundra in the north. Within each region there is a wide variety of terrain types with varying vegetation cover and topography. In both regions numerous lakes and rivers cover approximately 21% of the area.

1.2 Research Objectives

The purpose of this thesis is to analyze spatial variation and temporal trends in snow cover properties, and to improve understanding and statistical characterization of the end-of-winter SWE distribution in this large, subarctic basin. Findings will be used to improve sampling and estimation of the basin-wide average SWE, which is required every spring by NTPC for hydropower management operations. Data from NTPC historical snow survey (1978-2017) are examined along with enhanced snow survey data collected in 2016/17. Specific objectives and corresponding research questions are as follows:

1. Quantify the spatial variation of snow cover properties across the Snare basin.
    a. Does the historical record show two different snow regimes in tundra and forest environments?
    b. What relations between snow cover properties and latitude, elevation, and distance from treeline can be detected from the historical record?

2. Analyze the historical record for statistically significant temporal trends in end-of-winter snow cover properties.
    a. Is there a detectable change in the end-of-winter, basin-wide SWE between 1978 and 2017?
3. Quantify the confidence intervals around the mean, basin-wide SWE estimate associated with the current sampling scheme and statistically analyze alternative sampling strategies.
    a. What are the errors associated with the current SWE estimate?
    b. What number of sites and number of samples per site are needed to achieve SWE estimates between 5% and 20% with 95% confidence?
    c. Can basin-wide SWE estimates can be improved applying empirical spatial models of snow cover properties?

1.3 Significance

Hydropower generated in the Snare system is the main source of electricity for the city of Yellowknife and supplies power to over 50% of NWT residents. Estimates of end-of-winter, basin-wide SWE are important for effective management of the reservoir. In years when there is insufficient water the territory must rely on diesel power generation. The spring snow melt is the largest hydrologic event of the year and represents the bulk of water available for power generation. In 2014 and 2015 there were extremely low water levels in the Snare system which reduced hydro-power generating capacity, resulting in high expenditures on diesel. The NTPC empirical model of spring flows, which relies on the annual snow survey, did not predict these extreme low water levels. Work by Richardson (personal communication, 2018) showed that the annual snow survey is less effective at predicting flows than a single snow gauge, located at

Yellowknife Airport, over 150 km south of the basin. The poor results obtained from using the SWE estimate as a predictor suggest that other hydrologic factors may play more important roles than expected and/or the SWE estimate needs to be improved.

The applicability of this study is not limited to the Snare basin. An improved understanding of the snow cover differences across the treeline has potential application in any watershed near the forest and tundra boundary. Understanding how snow cover properties vary with large scale terrain differences is important for improving passive-microwave remote sensing of SWE. Temporal changes in snow properties at this boundary could be an indicator of climate change or climate change induced vegetation changes.

1.4 Thesis Structure

This thesis is structured in a traditional format. Chapter 2 reviews the scientific literature related to the measurement of snow cover properties and how point measurements are used to estimate basin-wide SWE. Chapter 3 describes the study area, the physical geography of the Snare basin, and the research methods used. Chapter 4 presents the results of the historical analysis as well as interpretation of the enhanced surveys. Chapter 5 discusses the significance of the results and suggests alternative sampling protocols that may provide improved basin-wide SWE estimates. Chapter 6 summarizes the conclusions and recommends future research.

2 Literature Review

2.1 The Importance of Snow Water Equivalent

The volume of water per unit area of snow is known as the SWE. SWE at a point can be determined by measuring the snow depth and snow bulk density. SWE at that location can then be calculated using the following relation

$$SWE = d \times \rho \quad [1]$$

where SWE is snow water equivalent, d is depth, and ρ is the bulk density of the snow cover. However, for hydrologic forecasting it is often the total volume of water stored within an entire watershed that is of interest, not SWE at a single point. SWE point measurements therefore, must often be extrapolated to estimate basin-wide SWE. Any attempt to estimate basin-wide SWE from point measurements necessarily involves the scaling of the measurements and introduces uncertainty into the estimate (Bloschl, 1999). This is complicated by the fact that simple snow cover properties (depth, density, SWE) can vary greatly over very short distances and within very short time periods (Dickinson and Whiteley, 1972; Elder *et al*., 1989; Bloschl, 1999; Yang and Woo, 1999). Additionally, snow density not only varies across a landscape but vertically at any given point (Sturm *et al*., 2010). The horizontal and vertical variation is due to a wide variety of factors including topography, surface properties, energy exchange, initial deposition, ablation, and redistribution (Stepphun and Dyck, 1974; Adams, 1976; Goodison, 1981; Sturm *et al*., 1995; Elder *et al*., 1998; Sexstone and Fassnacht, 2014; Hannula *et al*., 2016).

An understanding of the spatial and temporal distribution of snow accumulation, and its corresponding SWE, is important for a wide variety of practical and environmental research reasons. In areas where snow represents a significant percentage of annual precipitation, which is generally true at high latitudes, SWE is a critical value needed for hydrologic forecasting (Elder *et al*., 1989; Lindstrom *et al*., 1997; Bergstrom and Graham, 1998; Lopez-Moreno *et al*., 2013). During the winter, snow plays an important role in ecology (Watson *et al*., 2006; Rees *et al*., 2013), frost penetration (Lindstrom *et al*., 2002), and recreation (Burakowski and Magnusson, 2012). In many areas the spring snow melt is an important source of drinking water (Carroll *et al*., 1989) as well as being critical for agriculture (Barnett *et al*., 2005), hydropower generation, and industry (Carroll and Cressie, 1997). SWE is important for hydrologic models (Clark *et al*., 2011), energy and mass balances, climate models (Liston, 1999), and the calibration of remote sensing techniques (Derksen *et al*., 2014). In addition to knowing the mean basin-wide SWE and using it to estimate the total volume of water stored across a basin, the physical variation in the distribution plays an important role in determining the magnitude of melt that arrives at a basin outlet as well as the timing of outflow (Elder *et al*., 1998; Luce *et al*., 1998; Clark *et al*., 2011). On a larger scale, snow, with its relatively high albedo, serves as a critical component in the earth's energy balance (Groisman *et al*., 1994).

The Intergovernmental Panel on Climate Change (IPCC 2013) states that mean surface air temperatures (SAT) can be expected to increase by 1.5° C by the year 2100, and that Arctic SAT are expected to increase at a greater rate. Typical studies show that the Arctic SAT have risen by a factor of close to 2 times the global mean (Serreze *et al*., 2009; Bekryaev *et al*., 2010; Screen and Simmonds, 2010; Serreze and Barry, 2011). Due to this warming, snow cover properties in the Arctic and subarctic are not only changing rapidly but changing at different scales as well (Bokhurst *et al.*, 2016). The increasing temperatures have both the potential to change snow regimes in northern areas and be caused by changing regimes through alterations of land albedo (Serreze and Barry, 2011).

Several studies have found that snow cover extent (SCE) and SWE are in decline in the Northern Hemisphere (NH). The IPCC found that SCE in the NH declined at a rate of 1.6% per decade for the period 1967 to 2012 (IPCC 2013). Brown *et al*. (2010) incorporated a variety of remote sensing data and in-situ measurements to study SCE in the Arctic and found a decline of 14% for the period 1967-2008 as measured in May. Using similar datasets to Brown *et al*. (2010), Brown and Robinson (2011), found that for the period 1922 to 2010, NH SCE has declined by 11% as measured in April. Based on satellite observations from 1967-2015 Kunkel *et al*. (2016) determined that SCE declined in much of the NH, particularly in western North America.

Using GlobeSnow and NSIDC data Li *et al*. (2014) found a decline in NH SWE in the months of December to March over a 32-year period beginning in 1979. Jeong *et al*. (2017), also using GlobeSnow data, found that for the period from 1980- 2012 there was a statistically significant decrease in SWE in some areas (eastern North America and east Eurasia) yet an increase in other areas (parts of Eurasia). A study of passive microwave SWE data over a similar period (1979 - 2007) by Gan *et al*. (2013) found decreasing SWE trends particularly in Canada. Broad scale studies of snow in the NH do not agree on the quantitative value of the decline in SWE, and some fail to detect the decline at all, but the bulk of evidence suggests a decline is occurring (Kunkel *et al*. 2016).

In addition to changes in the snow cover extent, the onset of the spring melt and the peak flow timing of the annual hydrograph have been shown to have moved earlier in the year by between one and four weeks across western North America (Stewart *et al*., 2005). Studies in the western United States have shown a shift towards earlier melt times by several weeks over the last 50 years, explained partially by warmer spring temperatures (Regonda *et al*. 2005; Clow, 2010).

Sturm *et al*. (2017) point out that though many questions about snow trends remain, snow resources are in decline, and that further research is critical and timely. With respect to the NTPC and the Snare basin specifically, a change in snow melt volume, timing, or year-to-year variability could have implications for reservoir management. The current power system was built on the assumption that water availability was relatively consistent each year and was at levels sufficient to sustain Yellowknife and other surrounding smaller communities. In general, changes to SWE volumes and/or melt timing could have economic as well as environmental consequences (Sturm *et al*., 2017).

2.2 Spatial Variability of Snow Cover Properties

SWE varies across a landscape at a range of spatial scales (Clark *et al*., 2011). Though much research has been done to understand snow distribution, it remains an unsolved problem and is an ongoing area of research (Dozier *et al*., 2016; NASA, 2017). Spatial differences in initial deposition of snow are an important factor in determining the variability of SWE (Goodison, 1981). An extensive review by Clark *et al*. (2011), for guiding distributed snow models, discussed how different factors are of varying importance depending on the spatial scale the model is designed to work at. For example, temperature gradients due to latitude (watershed scale: 100 – 10 000m) *vs* redistribution by wind in the lee of a ridge (hillslope scale: 100 m) *vs* preferential deposition around a single tree (point scale: 1m). Other researchers have come to the similar conclusions. For example, a large set of snow depth, SWE, and density measurements from Finland were analyzed by Hannula *et al*. (2016) for use in comparison with airborne data. Similar to Clark *et al*. (2011) the variation of the three different snow cover properties were found to be different at different scales. Using variogram analysis to understand the different snow distribution processes and scales is difficult because snow cover properties are usually observed using point measurements spread sparsely across a basin (Bloschl, 1999). This is complicated by the fact that the basin can often be many orders of magnitude in scale larger than the measurement area or snow survey transect (Bloschl, 1999).

Landscape features (forests, shrubs, meadows, pastures, ponds, topography etc.) play a large role in the distribution of snow (Goodison, 1981; Steppuhn and Dyck, 1974; Adams, 1976). Similar landscape features within a basin often have similar frequency distributions of depth, density, and SWE (Stepphun and Dyck, 1974). Even in a landscape with little vegetation and relatively little relief, such as some areas of the Arctic tundra, there can be a large difference in snow cover distribution (up to 75%) between landscape features such as lakes, flat tundra, and plateaus (Rees *et al*., 2007). However, relations between landscape type and snow distribution found in one region are not necessarily transferable to other regions and perhaps not even between all years in the same region due to variation of annual climate and climate extremes (Adams, 1976).

A wide variety of studies (Table 2.1) have investigated the factors that control the observed variability in density, SWE, and depth. The studies in Table 2.1 took place in varying locations, were for different purposes, and were conducted in different ways and at different scales. They are not easily comparable. While there are many overlaps between the studies, Table 2.1 supports the concept that the importance of different factors on the variation of SWE, density, and depth changes with scale and location.

Table 2.1 *Factors investigated with respect to the variation of SWE, snow density, and depth across a landscape. 'Variable' refers to which of the three properties were investigated. 'Area' refers to the size of watershed studied, length of transect, number of sites, or spatial scale of the study.*

Variable	**Factors Investigated**	**Location**	**Area Note**	**Authors**
All	landscape features	Yukon, Saskatchewan, Alberta	17 km^2, 36 km^2	Steppuhn and Dyck (1974)
All	vegetation	Peterborough, Ontario	2.06 km^2	Adams (1976)
SWE	landscape features	Cold Creek Basin, Southern Ontario	60 km^2	Goodison (1981)
All	wind, precipitation, air temperature	Alaska	1300 km transect	Sturm *et al*. (1995)
density	net radiation, slope, altitude	Blackcap Basin, California	92.8 km^2	Elder *et al*. (1998)
SWE, density	wind, latitude, vegetation	North Slope of Alaska	4 watersheds (2.2km^2, 142 km^2, 471 km^2, 8140 km^2)	Kane and Berezovskaya (2007)
depth (rate of change)	proximity to large body of water, elevation	United States	continental	Mizukami & Perica (2008)
density	season, location, altitude, depth	Swiss Alps	37 sites across Switzerland	Jonas *et al*. (2009)
density	location (climate), snow depth, day of year	Canada, Switzerland, United States	northern hemisphere	Sturm *et al*. (2010)
SWE	Depends on scale. Dominant: drifting, vegetation, freezing levels, elevation, melt energy	Review includes many areas. Detailed analysis of basin in Southern Alps of New Zealand	30 km^2	Clark *et al*. (2011)
density (rate of change)	wind, melt-refreeze, compaction, metamorphism due to temperature gradient	United States, Australia, former Soviet Union	continental	Bormann *et al*. (2013)
density, depth	elevation, solar radiation, slope angle, terrain curvature	valley in the Spanish Pyrenees	1-2 km^2 areas	Lopez-Moreno *et al*. (2013)
SWE, density	day of year, SD, UTM easting, elevation	Cache la Poudre Basin, Northern Colorado	1493 km^2	Sexstone and Fassnacht (2014)
density	snow depth, elevation, degree days > 0 °C, wind days when $T < 0$°C and wind > 2ms^{-1}	Norway	sites spread across more than 10° of latitude	Bruland *et al*. (2015)
All	land cover, wind, topography	Finland (taiga and tundra areas)	70 km^2 and a separate 20 km transect	Hannula *et al*. (2016)

2.3 Relations Between and Variation of Snow Cover Properties

In some locations SWE has been found to be strongly correlated to depth (Adams, 1976; Jonas *et al*., 2009; Sturm *et al*., 2010). Adams (1976) found a correlation coefficient of 0.8-0.9 between SWE and depth (depending on the year) in a study conducted near Peterborough, in eastern Ontario. SWE and depth have been found to have a non-normal, skewed right, distribution while density has been found to be normally distributed (Jonas *et al*., 2009; Sturm *et al*., 2010). Some researchers find that density of the entire snowpack tends to increase as the depth increases, meaning there is a covariance between density and depth (Sturm *et al*., 2010; Bormann *et al*., 2013). However, others such as Lopez-Moreno *et al*. (2013) found no such relation. Pomeroy and Gray (1995) found no relation between depth and density for snowpacks under 80 cm and only a weak relation in deeper snow. This corresponds closely with findings from Stepphun (1976) who found only a weak relation between depth and density when depth was less than 85 cm. Thin layers of snow are more likely to have very different SWE and density since they could consist entirely of a light dusting of new snow or a wet layer of slush (Jonas *et al*., 2009).

Snow depth has been found to vary much more than density and in some cases by a range of up to four times as much (Dickinson and Whiteley, 1972; Steppuhn and Dyck, 1974; Steppuhn, 1976; Bruland *et al*., 2015). If, as has been shown, the variability of snow cover density is conservative compared to depth, efficient estimates of SWE can be made by taking fewer density than depth measurements (Steppuhn, 1976; Elder *et al*., 1991; Jonas *et al*., 2009). If bulk density can be estimated using a model, then depth measurements alone can be used to estimate SWE (Section 2.7).

An analysis of seven years of SNOTEL data from the western United States by Mizukami and Perica (2008) found that not only is density conservative compared to depth and SWE for a given site but that it is also less variable year-to-year. A study by Rees *et al*. (2007) in the Arctic tundra had similar findings. Elder *et al*. (1991) noted density varies less than depth and SWE particularly towards the end of the winter. Similarly, a study in the Pyrenees mountains found that snow density was less variable in April, when the snow cover had essentially accumulated for the year, than at other times during the winter (Lopez-Moreno *et al*., 2013).

2.4 Measuring Snow Cover Properties

Mobile point measurements of SWE are typically done using snow tube cores and/or snow pits. Typical techniques for using a snow tube are described by Hannula *et al*. (2016) and Rovansek *et al*. (1993). A metal, cylindrical tube is weighed empty, then inserted into the snow to the ground. A depth measurement is recorded. The tube is removed with the snow core inside and weighed again. Using the depth and the change in mass the SWE and density are calculated. There are several sources of error associated with snow tube cores but Sturm *et al*. (2010) point out that some studies show an underestimation while others an overestimation making any systematic correction difficult. As describe by Kane and Berezovskaya (2007) the snow tube often penetrates an organic layer under the snow. This layer is useful, for holding the snow in place as the tube is lifted. The vegetation plug is removed once the tube is horizontal so its mass is not recorded. Ideally, depth is recorded before the tube is driven into the vegetation layer. Snow tube coring represents a mobile observation system, there are also location fixed observation methods such as a snow pillow (Dozier *et al*., 2016). However, snow pillows and other fixed methods suffer from having to be placed in easy to access locations (not necessarily representative) and having limited coverage (Dozier *et al*., 2016).

Depth is typically measured by placing a graded rod (snow probe) into the snow and recording the depth. Other methods can be used such as a Magnaprobe, a device made by Snow Hydro, which automatically records depth and GPS coordinates (Hannula *et al*., 2016). Although snow depth measurements are simple to take, some researchers have noted that the transition between the bottom of the snow and the ground is often filled with organic material which can be penetrated by the rod leading to overestimates of depth (Berezovskaya and Kane 2007). According to Berezovskaya and Kane (2007) this problem is particularly relevant in the Arctic tundra and can cause an overestimation of SWE by as much 20% when a combination of depth and density measurements are used (Section 2.5). They add that using snow core measurements alone can underestimate SWE because the snow tube may not capture snow located in a mixed layer of organic material and snow at the bottom of the snowpack. As with SWE there are also fixed location depth observation methods such as ultrasonic sensors or stakes and cameras (Dozier *et al*., 2016).

Measuring SWE takes much more effort than measuring depth (Dickinson and Whiteley, 1972; Sturm *et al*., 2010; Bruland *et al.*, 2015). The equipment and training to measure depth is much simpler than that required by SWE measurements (Elder *et al*., 1989). According to Sturm *et al*. (2010) depth measurements can be done at a rate of 20 times that of SWE and the measurements require less equipment and less skill. Since density measurements take more time they may be less economical under some circumstances (Dickinson and Whiteley, 1972). To increase efficiency many surveys, particularly of large basins, take many more depth measurements than SWE (Sexstone and Fassnacht, 2014).

A range of other snow measuring methods and techniques exist including neutron probes, cosmic radiation probes, gamma ray probes, time domain reflectometry, snow forks, ground penetrating radar, and passive microwave detection (Lundberg *et al.*, 2010).

2.5 Double Sampling

As mentioned above, many researchers have noted that density tends to vary less than depth. Therefore, several attempts have been made to specify a ratio between depth and density measurements which balances the error in the resulting SWE estimate.

Stepphun (1976) proposed a central depth sampling method. Working in the prairies with snow covers of less than one meter it was shown that a few density measurements taken at a central depth (mean, mode, or median depth) could produce a SWE estimate that deviated from a more thorough SWE sampling scheme by only a few percent. Operationally, this means a fast depth survey is taken, then SWE measurements are done at the chosen central depth while a more thorough depth survey is being conducted.

Dickinson and Whiteley (1972) examined the resulting standard error when the ratio of depth to density measurements was increased. The study was conducted in the Grand River Basin in Southern Ontario. They found that the standard error term of the SWE estimate approached 10% as the measurement ratio reached approximately 4:1 (depth:density). Considering the error common in other hydrologic variables this was considered reasonable. It was pointed out that if a more accurate estimate is needed, more measurements of each type could be taken while keeping the ratio of 4:1 to ensure the most economical survey is conducted. The 4:1 ratio was found to be roughly the same in forested and unforested areas except during the melt season.

Many studies simply state the ratio or strategy of balancing depth and density measurements. For example, extensive double sampling done by Kane and Berezovskaya (2007) on the North Slope of Alaska was done with a 10:1 ratio. This was justified simply by stating that it is a more time efficient method. Bruland *et al*. (2015) varied the ratio at their convenience but kept it between 10:1 and 20:1. Clark *et al*. (2011) took only one density measurement per transect, while each transect contained an average of 78 depth measurements. Typical older studies mention a standard 10 point course which is 1 transect or loop with 10 SWE measurements, an effective ratio of 1:1 (Goodison, 1981; Dickinson and Whitely, 1972).

Rovansek *et al*. (1993), considering time as a proxy for cost, attempted to work out the most efficient ratio of depth to density measurements. They determined that a double sampling program can produce a SWE estimate with less variance than measuring depth alone. Using data from the North Slope of Alaska they arrived at a ratio of 14:1 as the most efficient in their area of study. They suggest that depth measurements be taken surrounding the SWE measurement in a circle or as a transect starting at the SWE measurement.

2.6 SWE at Different Scales

Bloschl (1999) describes one of the fundamental problems of estimating mean snow cover properties as interplay between the actual scale of the physical process that distributes the snow and the scale of the point measurements themselves which include spacing (distance between points), extent (length of transect), and support (the size of the measuring tool). Typical values of the three scale factors with respect to snow survey transects are 100 m, 1 km, and 10 cm respectively (Bloschl, 1999).

The measurement techniques described above along with the double sampling methods mentioned are aimed at measuring depth, density, and SWE in a single, relatively small, location.

To estimate basin-wide SWE a method must be used to scale the measurements up to an area that could be several magnitudes larger. Stepphun (1976) notes that "*A limited number of observations spread over such large area has long been a source of error in SWE estimates*". The simplest method, currently being used in the Snare basin, is to take a mean of all the measurements. Sampling can also be done in different representative landscapes and then weighted by area (Goodison, 1981). Bocchiola and Groppelli (2010) describe a model that uses historical snow measurements, current measurements, remotely sensed snow cover area, and kriging to create SWE maps. A wide variety of statistical and physically based models exist to estimate total SWE and SWE distribution (Bavera *et al*., 2014).

An economical estimate of basin-wide SWE, derived from direct measurements, should rely on two key concepts according to Stepphun and Dyck (1974):

1. Stratification by landscape type.
2. A double sampling scheme which relies on the fact that density varies less than depth.

Several other studies suggest that conducting snow surveys in characteristic landscape types throughout a basin and then area-weighting them is an effective way to estimate basin-wide SWE (Stephhun and Dyck, 1974; Adams, 1976; Woo and Marsh, 1978). Also, while total basin SWE is important for forecasting, its non-uniform disappearance also contributes to melt quantity and timing (Elder *et al*., 1998; Clark *et al*., 2011) which means that distribution maps of SWE can also be important inputs to hydrologic models.

To help parameterize snow characteristics over even larger areas Sturm *et al*. (1995) developed a set of six snow classes: tundra, taiga, alpine, maritime, prairie, and ephemeral. They acknowledge previous snow classification systems and provide a table summarizing 14 previous systems, the earliest from 1946. To develop their own system, Sturm *et al*. (1995) used a large data set that included observations from a 1300 km transect in Alaska that spanned three mountain ranges and included a large variety of climate zones. A map of the northern hemisphere was produced indicating likely snow classes to be found in each 0.5° x 0.5° long grid cell. The Snare basin is shown as being entirely within the taiga classification, but near the southern edge of the tundra. Taiga snow is described as deposited with a low temperature, low precipitation, and low wind speed resulting in a snow cover that is 30 – 120 cm deep, containing more than 15 layers, and having a typical bulk density of 0.26 g cm^{-3}. Tundra snow is deposited under similar conditions but with greater wind speed resulting in a snowcover with fewer layers, less depth, and a typical bulk density of 0.38 g cm^{-3}. By characterizing different snow covers in this way Sturm *et al*. (1995) state that it enables researchers to extrapolate information beyond what is measured such as using depth measurements as a proxy for SWE. This is important for research in large inaccessible areas such as the Snare basin where measurements are limited and costly to make.

2.7 Density Models

Several researchers have developed models to estimate basin-wide SWE by collecting depth measurements and using modelled density. Estimating SWE in this fashion can be justified by the fact that depth varies more than density, is easier to measure, and improvements to technologies such as LiDAR and Structure from Motion could drastically increase the number of depth measurements being taken (Sexstone and Fassnacht, 2014; Bruland *et al*., 2015). Furthermore, density at the end-of-winter tends to vary even less than it does throughout the season (Lopez-Moreno *et al*., 2013), making end-of-winter density models more accurate than those applied during the season. While density varies less than depth it can still vary significantly, changing throughout the season due to melt and refreeze events, wind, gravity, and other mechanisms of metamorphism (Bormann *et al*. 2013). Density tends to increase over the year but not at the same rate each year (Dickinson and Whiteley, 1972).

The studies described below were conducted in different locations, over different scales, and sometimes for different purposes. They are not easily comparable. Sturm *et al*. (2010) pointed out that even though a strong relation between SWE and depth has been noted many times and, in many locations, there have not been many formal attempts to estimate SWE from depth data. Since then several formal attempts have been made that take alternative approaches or attempt to improve upon the existing models.

A density model developed by Sturm *et al*. (2010) is based on the following equation

$$\rho_{h,DOY_i} = (\rho_{max} - \rho_{o})[1 - \exp(-k_1 \times h_i - k_2 \times DOY_i)] + \rho_o \qquad [2]$$

Where ρ_{h,DOY_i} is the estimated density, h_i is the snow depth, DOY is the day of the year, k_1 and k_2 are densification parameters, and ρ_{max} and ρ_o are the maximum and initial densities determined by the snow classes mentioned above. The fact that a relation between depth and density exists is accounted for with the h_i term while the k_2 term accounts for the densification of the snow with time. Broad climate variables are taken into account by using the snow classes. The model was developed using over 25,000 measurements from Canada, Switzerland, and the United States.

Jonas *et al*. (2009) developed a model, with data from the Swiss Alps, based on the concept that a few depth measurements along with a model for density could be used to estimate SWE with as much accuracy as a single SWE measurement. They point out that this is important due to the fact that SWE measurements cost more to make. The research showed four factors with a measurable effect on density: season, depth, altitude, and region. The model uses regression analysis and look up tables to estimate density given only the four variables listed. They conclude that using the model with several depth measurements produced a SWE value as representative as taking a SWE measurement. They also suggest that regional effects were limited enough that the model could be used in other locations with a similar climate.

The Sturm *et al.* (2010) and Jonas *et al.* (2009) models mentioned above both assume a positive relation between depth and density. However, McCreight and Small (2014) as well as Pistocchi (2016) have pointed out that, at times when a fresh layer of light snow is deposited, the relation could temporarily be negative, meaning the Sturm and Jonas models are not suitable for short time steps such as a day. Pistocchi (2016), using measurements taken in South Tyrol, Italy, compared the Sturm and Jonas models with an even simpler model to estimate density (ρ) based on the following equation:

$$\rho = \rho_0 + K(DOY + 61) \qquad [3]$$

where DOY represents the day of year, ρ_0 = 200 kg m^{-3}, and K = 1 kg m^{-3} day^{-1}. Pistocchi (2016) concluded that in the absence of sufficient data to calibrate the Sturm and Jonas models the simplified model produced results that were comparable. The 1 kg m^{-3} day^{-1} used in the above equation contrasts with the findings of Mizukami and Perica (2008) which found the densification rates across the western US to be closer be 2 kg m^{-3} day^{-1}.

Bormann *et al*. (2013) used data from the US, the former USSR, and Australia to model snow densification rates and to predict spring density. Nine variables were considered with each of the snow classes developed by Sturm *et al*. (1995) along with an Australian class. The best predictors of densification rates and spring density changed with the snow classes. For the taiga class, minimum and maximum temperatures, maximum snow depth, and latitude were found to be the best combination. For the tundra class, minimum temperature, mean daily melt freeze events, precipitation, and a varying dynamic term were found to be the best predictors.

Bruland *et al*. (2015) state that the Sturm model, through its classes, only takes general climate into account and not year-to-year variability. In a study conducted in Norway, they attempted to determine if meteorological data added to the Sturm model could better predict density. By testing multiple combinations of different meteorological factors, they concluded that the most important factors to include in the Sturm model were depth, elevation, positive degree days, wind days when $T < 0°C$ and wind $> 2\ ms^{-1}$. The authors suggest that the model is useful anywhere weather station data are available.

All the above models rely on the relatively low variability of density across a basin, particularly at small spatial scales. However, a comparison of six depth-density models and direct measurement models (from 1000 SWE measurements) in a 207 km^2 alpine basin in Montana found that depth-density models varied around a mean by over 14% while direct measurement models varied by only 1% (Wetlaufer *et al*. 2016).

3 Methods

3.1 Study Area

The Snare basin is located in the North Slave region of the NWT (Fig. 1.1) and is part of the larger Mackenzie River basin. The area's primary terrestrial zone is the Taiga Shield which is characterized by shallow, coarse soils (Environment Canada, 2001a) as well as numerous lakes and streams. The hydrologic regime is largely driven by the large amount of surface storage in lakes and wetlands (Wedel *et al*., 1992) as well as the fact that the basin is within the zone of discontinuous permafrost. Vegetation is primarily sparse, open forest and open shrub tundra. Mean annual daily temperature in Yellowknife is -4.3 °C and mean annual precipitation is 289 mm (Environment Canada, 2016). Three Water Survey of Canada gauges are located within the basin (07SA002: Snare River below Ghost, 07SA004: Indin River above Chalco Lake, 07SA008: Snare River above Indin Lake). A large proportion of the annual precipitation is stored as snow resulting in spring melt being the most significant hydrologic event of the year. The hydrographs are characteristically subarctic, nival regimes. The basin can be broadly categorized into two regions, north and south of treeline (Fig. 1.1). The treeline is not a distinct boundary but an ecotone running roughly from the northwest to the southeast. The area of the basin is approximately 13,700 km^2 with roughly 52% north of treeline and 48% to the south.

Figure 3.1 shows typical landscapes north and south of treeline in the Snare basin, as well as in the transition zone. Trees tend to be more densely distributed and taller in the more southerly parts of the basin with a mixture of spruce, larch, pine, and birch. Further north, the forests are sparser and contain mainly black spruce. The landscape north and south of treeline

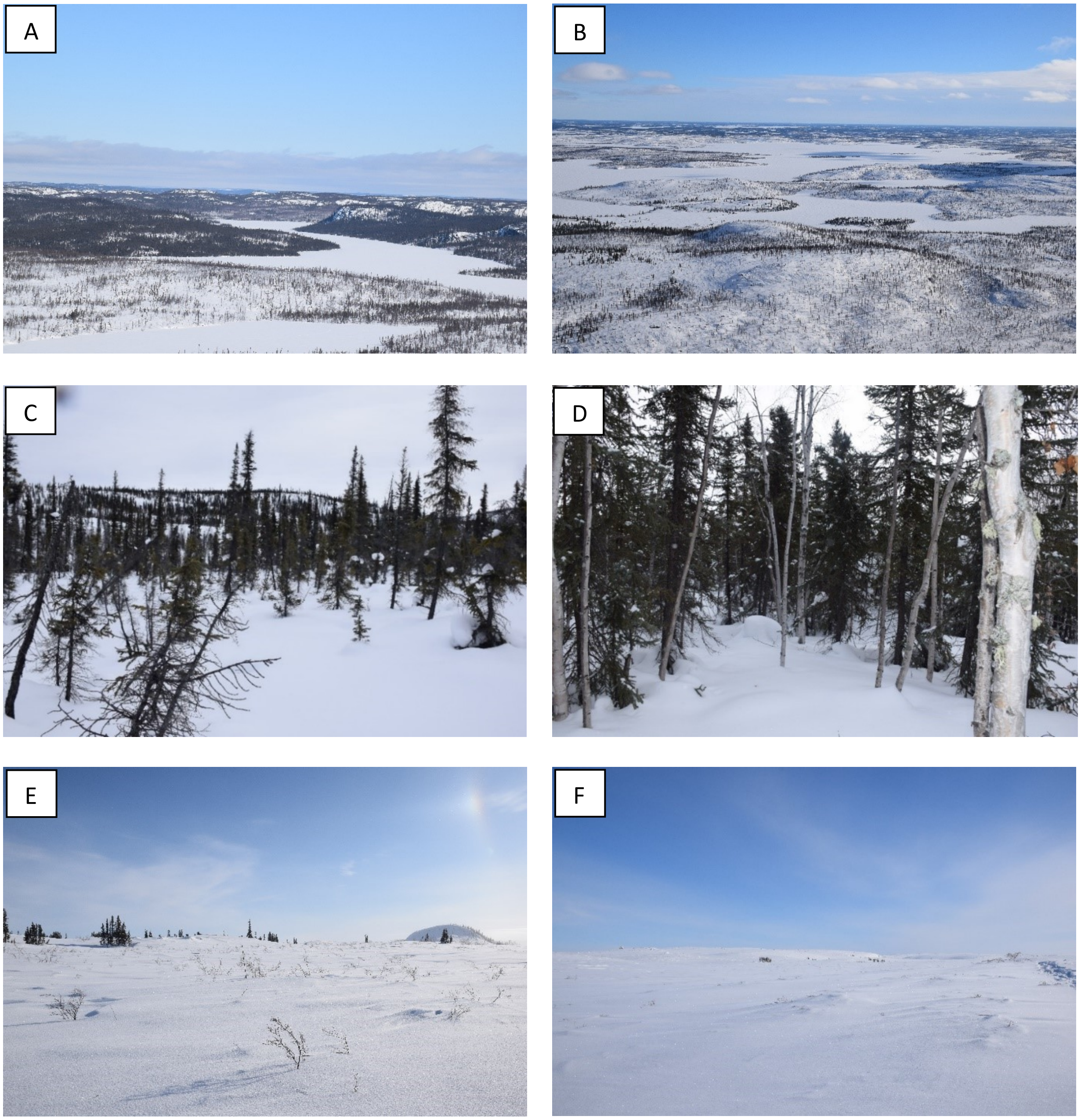

Figure 3.1 *Typical landscapes and forest cover within the Snare basin. (A) Near site B10 showing the significant relief seen in some areas particularly in the south. (B) Near site B7 showing the rolling hills and sparse forest cover typical over large areas within the basin. (C) Typical forest cover close to the treeline. (D) Typical forest cover in the southern region. (E) Typical landscape north of treeline with tree clumps and shrubs showing above the snow. (F) Typical barren landscape in the far north of the basin, with shrubs still showing above the snow.*

varies across the basin ranging from large relatively flat areas to areas with substantial relief. Rolling hills, ridges, small cliffs, eskers, and exposed rock are common. The elevation within the watershed ranges from 215 m to 511 m above sea level. Numerous large and small lakes and ponds cover roughly 22% of the landscape both north and south of treeline. Large areas, some hundreds of km^2, show evidence of past forest fires.

The basin drains into the Big Spruce reservoir located near the southwest corner of the watershed. Discharge from the Big Spruce reservoir enters the Snare Hydro system which consists of four dams and a total generating capacity of 30 MW. Along the Snare River there is potential for an additional 33 MW of power, however NTPC has no plans to add generating capacity. The Snare Hydro system supplies power to approximately half the residents of NWT.

The basin is within the traditional territory of the Tłı̨chǫ First Nation. The only community located in the basin is Wekweètì, which has a population of approximately 140. Travel to, and within, the basin is difficult. There are no all-season roads, making summer access fly-in only. Two airstrips are located within the basin, one at the community of Wekweètì and the other at Snare Falls. The Snare Falls airstrip is located beside one of the NTPC dams and has road access to the rest of the Snare Hydro system. In winter, an ice road connects Yellowknife to the Snare Hydro system as well as Wekweètì. However, the winter ice road is open for only a short period of time, and only provides access to a limited portion of the basin. The winter ice road is often closed and not maintained past the end of March, therefore travel for snow surveys, often conducted in early April, is only feasible by helicopter or ski plane.

3.2 Study Period and Available Data

Data from snow surveys conducted by NTPC from 1978 – 2017 will be referred to as 'historical' data. Data collected as part of Carleton University's 2016/17 field campaigns, which included additional measurements at NTPC sites as well as surveys conducted in additional locations, will be referred to as 'enhanced' snow survey data.

3.2.1 Historical Data

NTPC began conducting snow surveys in 1978 at eight sites (Fig. 1.1). Three additional sites (Big, Christison, Whitewolf) were added in 1995. All eleven sites, with minor exceptions, were surveyed from 1995 to 2017 (Appendix A). Of the eleven sites, six are located south of treeline and five to the north. The three sites added in 1995 are all located north of treeline. Previous to that year the survey was heavily biased towards the southern region. The Mattberry, Castor, and Mesa lake sites are located outside of the basin. Table 3.1 gives the latitude, longitude, and other quantitative descriptors of each NTPC site. Table 3.2 gives a qualitative description of each NTPC site.

Ten of the NTPC sites were visited by Twin Otter over the course of a typical survey day. The use of a ski-plane necessitates the sites being near relatively large lakes. At each site the surveyors walk off the lake into the uplands and take 10 SWE measurements along a looped transect that varies in length from 130 m to 275 m (Fig. 3.2A and Table 3.1). Measurements were taken using an ESC-30 snow tube (See section 3.2.4). At each location where a SWE measurement was taken the snow depth was recorded as well. Snow density was calculated from the recorded SWE and depth using equation [1]. In forested sites there was a large shore marker showing the start of each transect and 10 signs attached to trees (Fig. 3.2B) showing where specific measurements should be taken. At tundra sites measurement locations were indicated by numbered steel posts (Fig. 3.2C). Not all individual measurement signs and posts were present. In these cases, surveyors used GPS coordinates. The Big Spruce lake site, which is accessible from the dam site, was typically visited within a few days of the main survey.

Table 3.1 *NTPC historical sites. MASL (Mean Elevation Above Sea Level). 'Length' indicates length of transect. '2016 Depth' and '2017 Depth' indicate number of snow depth measurements taken along the transects during enhanced surveys. 10 SWE measurements were taken over the length of the transects in both 2016 and 2017. '2017 Lake Depth' and '2017 Lake SWE' indicate number of snow depth and SWE measurements taken on adjacent lakes during enhanced surveys. 'Treeline Distance' refers to the approximate distance of the site from the treeline.*

Site	Latitude (dd)	Longitude (dd)	MASL (m)	Length (m)	2016 Depth	2017 Depth	2017 Lake Depth	2017 Lake SWE	Treeline Distance (km)
Big Spruce	63.5167	-116.0000	225	NA	0	0	0	0	123
Ghost	63.8775	-115.0688	291	220	73	87	230	10	71
Mattberry	64.0885	-115.9548	260	202	54	111	137	14	63
Snare	64.2018	-114.0390	360	230	108	57	162	11	21
Indin	64.3785	-115.0260	300	180	61	45	106	10	18
Winter	64.4970	-113.1792	363	275	134	109	191	11	27
Castor	64.5148	-115.9885	297	215	90	34	140	9	19
Christison	64.6410	-114.1637	440	180	91	119	134	10	23
Big	64.8008	-112.9258	430	130	120	132	0	0	60
Mesa	64.8445	-115.1383	374	250	83	63	144	13	28
Whitewolf	65.0045	-114.1055	437	170	91	37	173	10	61

Table 3.2 *Qualitative description of NTPC sites.*

Ghost	Located on the west side of a northern arm. Sparse spruce and tamarack forest. Relatively flat with significant microtopography. First part of transect is a wetland.
Mattberry	Located on the west shore. Dense mix of birch and black spruce. Site is on a significant east facing slope.
Snare	Located on the north shore of small bay. Sparse black spruce with some birch and jack pine. Transect rises 14 m above lake.
Indin	Located on the west shore. Transect circles open wetland but stays in the forest. Sparse black spruce.
Winter	Located on the north shore. Mostly open but with clumps of black spruce nearby. Site is exposed to the lake with no significant change in elevation from the lake and only a thin treeline barrier between the transect and the lake.
Castor	Located on narrow passage between two parts of Castor Lake. Dense spruce and birch. Relatively steep slope with most of the transect 20 m above lake.
Christison	Located on the northeast shore. Relatively flat open tundra. Clumps of trees in distance and shrubs showing above the snow.
Big	Located in the northeast corner of the lake. Open tundra with no visible trees. Shrubs showing above snow throughout. Transect runs up and over a steep ridge/esker.
Mesa	Located on north shore. Largely open tundra with shrubs showing. Transect starts flat but climbs a ridge during the second half. One SWE measurement is taken near a clump of spruce.
Whitewolf	Located on the north shore. Open tundra with no visible trees. Some shrubs showing. Transect is straight line up a ridge.

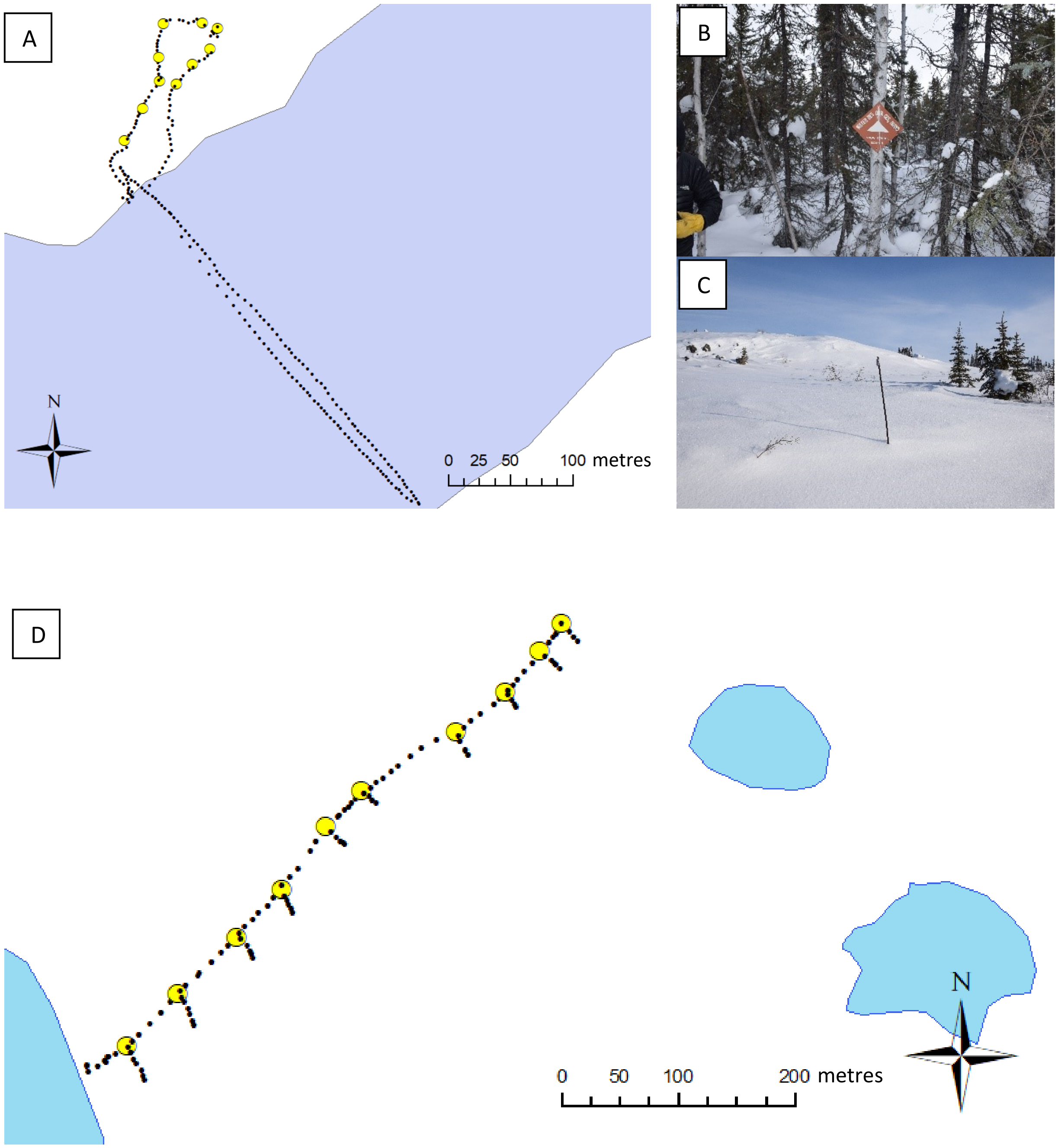

Figure 3.2 *(A) Typical NTPC transect (Mattbery Lake). Yellow circles show locations of SWE measurements taken in 2017. Black circles show locations of enhanced depth measurements. Blue shapes show the location of lakes. (B) Snow course markers located along forested NTPC transects. (C) Snow course markers located in tundra sites. (D) Typical enhanced snow survey site transect (site B1, 2016).*

The Big Spruce lake site is surveyed using different equipment and by a different team of people. The dates of the main survey have ranged from March 25th to April 15th (Appendix F).

For this study, two different datasets of the NTPC historical measurements were used. Each year the mean SWE at each site was calculated from the 10 individual measurements. These mean values were recorded in different ways since 1978 but are currently stored in a spreadsheet known by NTPC as the ‘operational spreadsheet’. This spreadsheet has a near complete record of the mean SWE for all sites and years since 1978 (Appendix A). The operational spreadsheet does not include the individual measurements, and therefore has no information regarding depth, density, or the variation of SWE at a site in a given year. This dataset will be referred to as the ‘mean SWE’ data.

The second dataset will be referred to as the ‘individual measurements’. For the years 1978 – 2005 these were entered into a database as part of a project for the Department of Indigenous and Northern Affairs Development (DIAND). For the years 2006 – 2017 the data were transcribed from scanned copies of the original NTPC field notes. There are several sites and years where the original field notes were lost and therefore no individual measurements can be found (Appendix A).

As a quality control measure, mean SWE values from the operational spreadsheet were checked against the mean of the individual measurements for all sites and all years. Several discrepancies were found by checking values against original NTPC field notes. Staff from the Water Resources Division of The Government of Northwest Territories (GNWT) performed the same analysis and all errors and were checked against their work. Corrections were made to the operational spreadsheet and DIAND database. In 2016, an equipment error was discovered by

NTPC which had resulted in incorrect SWE measurements from 2005 – 2015. The error was corrected before the 2016 survey was completed and therefore the correction was not applied to the 2016/17 data. Details about the error and the correction applied are reported in Appendix D.

3.2.2 Enhanced Snow Surveys

Objective 2, examining temporal trends in snow cover properties, was addressed using the historical data described above. Data from enhanced surveys, described below, was used with the historical data to address objectives 1 and 3. Enhanced surveys consisted of three components: extensive depth measurements taken along the NTPC transects (Fig. 3.2), surveys of lakes adjacent to NTPC sites, and surveys of new sites that included SWE and extensive depth measurements. All additional sampling beyond the standard NTPC surveys was constrained by time, cost and weather conditions. When accompanying the NTPC surveys all additional surveying had to be completed in the same amount of time used by NTPC surveyors.

To address objectives 1 and 2 the following sampling was intended to be completed in both 2016/17. Researchers from Carleton as well as GNWT staff were to accompany the NTPC survey and do the first two components of the enhanced surveys. Extensive depth measurements were to be taken at a ratio of 5:1 or 10:1 (depth:SWE) depending on timing and terrain. Lakes were surveyed while the upland survey took place, allowing for comparison between the two landscape types. Finally, two days of funding for travel by helicopter was secured to travel to ten new sites, five to the north and five to the south of treeline. These sites were chosen to be representative of smaller scale landscape types found within each of the two broad regions. The helicopter allowed for landings on smaller lakes, in open areas, and closer to ridgetops and hilltops. These types of locations were not accessible to the NTPC survey. South of treeline, NTPC sites were heavily forested despite open areas making up close to 50% of the non-lake landscape. Visiting different terrain types, particularly those far from large lakes, would allow us to test whether NTPC sites were biased towards certain snow cover characteristics due to their locations.

3.2.3 Enhanced 2016 Field Data and Sites

Weather and logistical problems prevented the 2016 enhanced survey from being conducted as described above. Staff from the Water Resources Division of GNWT were able to take 905 additional depth measurements along 10 of the NTPC site transects using a Magnaprobe on April 4th (Table 3.1). Myself, Dr. Murray Richardson, and GNWT staff were also able to visit 6 additional sites on March 31st, three north of treeline and three south of treeline, taking 72 SWE measurements as well as 1218 depth measurements (Table 3.3). The six additional sites visited are referred to as A1-A3 (located north of treeline) and A4-A6 (south of treeline). The location of the sites relative to existing NTPC sites can be seen in Fig. 3.3. Table 3.3 shows the coordinates, number of measurements, and other quantitative characteristics of the sites. Table 3.4 contains a qualitative description of the sites.

3.2.4 Enhanced 2017 Field Data and Sites

The 2017 enhanced survey was conducted as described in section 3.2.2, although exact ratios of depth to density measurements were not always followed. The NTPC survey was conducted over two days (March 28th and 29th) to give staff time to repair survey signs (Fig. 3.2). Extensive depth measurements were taken along the transects (Table 3.1). Lake surveys were conducted on adjacent lakes at 9 out of 10 NTPC sites (Table 3.1). The Big Lake site was not visited due to poor weather. The upland part of the Big Lake site survey was completed the next day, but there was insufficient time to complete the lake survey. In total 1417 additional depth

Table 3.3 *Quantitative descriptions of the 2016 enhanced sites. MASL (Mean Elevation Above Sea Level). 'Length' indicates length of transect. 'Depth/SWE #' indicate the number of each type of measurement taken. 'Treeline Distance' refers to the approximate distance from the site to the treeline.*

Region	Site	Latitude (degrees)	Longitude (degrees)	MASL (m)	Length (m)	Depth #	SWE #	Treeline Distance (km)
North	A1	64.5226	-113.3317	427	310	137	11	24
	A2	64.5453	-113.7360	448	410	331	14	20
	A3	64.5249	-114.3541	417	680	404	11	8
South	A4	64.1506	-114.8186	359	420	160	12	39
	A5	64.0828	-114.5595	366	480	140	16	41
	A6	63.6466	-114.5258	292	240	46	8	86

Table 3.4 *Qualitative descriptions of 2016 enhanced sites.*

A1	Straight transect. Began on a small lake, passed through a narrow band of trees near the shore, up an open ridge. Shrubs showing above snow.
A2	Straight transect. Began at the top of an open ridge. Down a slope, through small valley, over a smaller ridge and down to smaller lake. Open tundra with some shrubs showing. Small clumps of trees.
A3	Open tundra. Down a slope, across an open plain, down another slope. Tops of shrubs showing, sparse clumps of trees. No large lakes in area.
A4	Began at a small lake. Traversed through a dense forest, up a hillslope, across a forested plain, and then to a different lake. Forested, spruce and birch.
A5	Straight transect. Began in an open wetland. Traveled up and over a small hill which was sparsely forested. Returned to another flat wetland.
A6	Straight transect. Began in an open wetland. Then through a sparse forest. Slight elevation gain into the forest.

and 98 additional SWE measurements were taken at the 10 NTPC sites.

10 additional sites were visited as part of the enhanced snow survey and are referred to as B1-B5 (north of treeline) and B6-B10 (south of treeline). The location of the sites relative to the watershed and the existing NTPC sites are shown in Fig. 3.3. Table 3.5 shows the coordinates, number of measurements taken, and other quantitative characteristics of sites B1-B10, while Table 3.6 contains qualitative descriptions. A total of 2330 depth and 100 SWE measurements were taken at the 10 additional sites (Table 3.5).

3.3 SWE Measurements

SWE measurements during the historical sampling were made using a variety of snow core tubes. Measurements taken in 2016/17 used an Environment Canada ESC 30 (30 cm^2 area) snow sampler manufactured by Geo Scientific Ltd. Aluminum models were used in 2016 and clear Lexan models were used for all sampling in 2017. The following procedure was used for measuring snow depth and SWE with a snow core. Before each measurement the tube was visually inspected, any remaining snow or dirt was removed. A spring scale with SWE (cm) markings was used to measure the weight of the empty snow tube. This 'empty' weighing procedure was repeated every 5 measurements. The tube was inserted vertically in the snow until it reached the ground. The snow depth was read and recorded from graded markings on the side of the tube. If possible, the tube was then 'screwed' into the soil below, creating a plug of dirt which held the snow in the tube as the tube was lifted vertically. In the case of sampling on rock or ice surfaces the tube was tilted horizontally to prevent snow from falling from the bottom. When possible the snow around the tube was dug away so the surveyor could visually

Table 3.5 *Quantitative descriptions of 2017 enhanced sites. MASL (Mean Elevation Above Sea Level). 'Length' indicates length of transect. 'Depth/SWE #' indicate the number of each type of measurement taken. 'Treeline Distance' refers to the approximate distance from the site to the treeline.*

Region	Site	Latitude (degrees)	Longitude (degrees)	MASL (m)	Length (m)	Depth #	SWE #	Treeline Distance (km)
North	B1	64.2846	-112.4533	433	520	370	10	15
	B2	64.6333	-112.9325	418	560	407	10	42
	B3	64.8902	-113.5042	444	470	344	10	59
	B4	64.5668	-113.7912	429	390	203	10	21
	B5	64.6063	-114.6558	388	580	115	10	11
South	B6	64.4060	-114.7835	350	380	119	10	12
	B7	64.3328	-114.1733	395	370	239	10	9
	B8	64.0227	-114.7102	358	250	248	10	50
	B9	64.0933	-115.2105	289	230	123	10	51
	B10	63.7894	-115.6466	286	470	162	10	89

Table 3.6 *Qualitative descriptions of 2017 enhanced sites.*

B1	Open tundra. A few small trees in area. Clumps of trees visible in distance. Lots of shrubs showing through snow. Not near a large lake. Transect was up and over a ridge.
B2	Open tundra. Few trees visible. Some shrubs showing. Up a slight slope, boulder field, along a ridge.
B3	Large open hilltop. Relatively flat, some boulders and open rock. Shrubs showing.
B4	Flat, open wetland. Shrubs showing. Adjacent to a large tree clump nearby.
B5	Flat, open area. A few small clumps of trees nearby. Shrubs showing.
B6	Very sparse, open mixed forest. Some topography. Part of a larger area showing evidence of a forest fire.
B7	Very sparse, predominantly spruce forest. Small elevation changes.
B8	Sparse, mixed forest. Relatively flat site. Partially wetland.
B9	Dense, tall, spruce forest. Steep northwest facing slope.
B10	Sparse, mixed forest. Only a slight elevation change. Part of a much larger, relatively flat area.

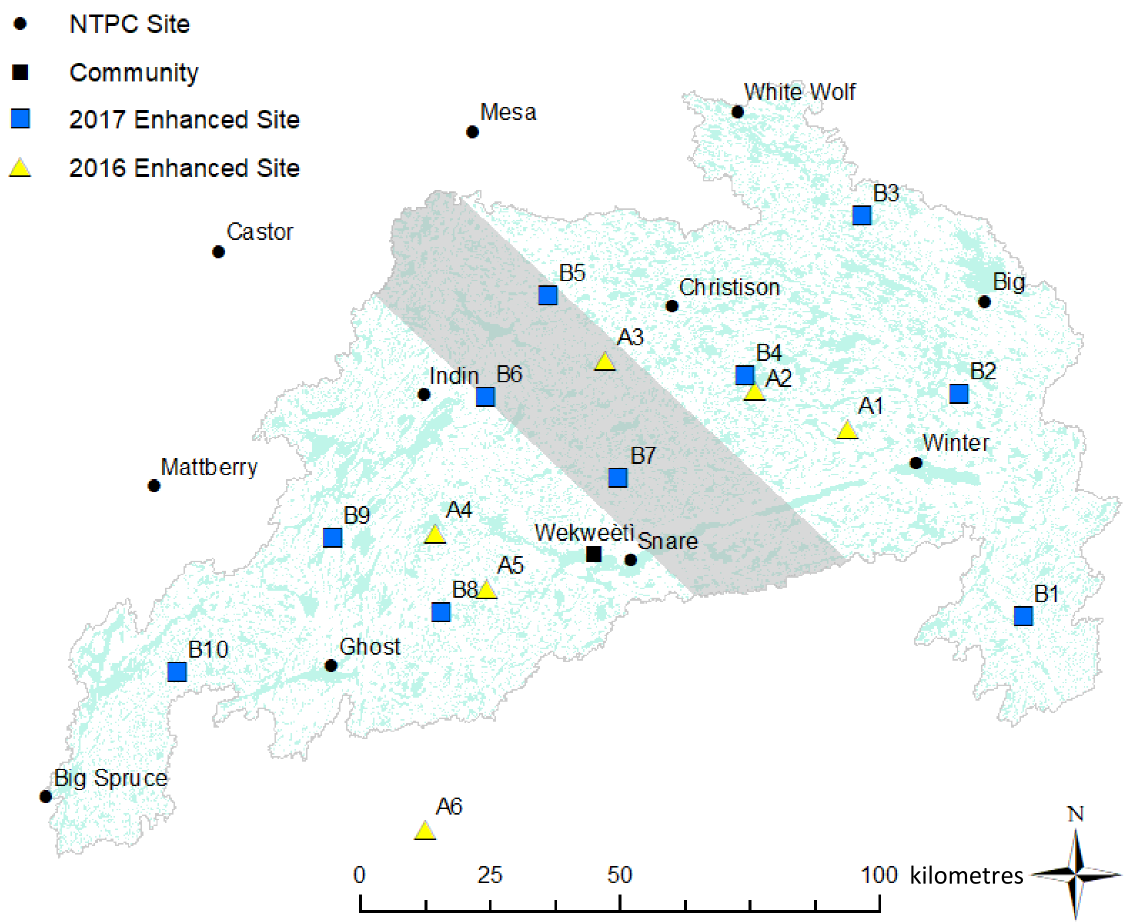

Figure 3.3 *Location of NTPC and 2016/17 enhanced survey sites. The approximate location of the treeline is indicated by the gray band.*

check that no snow was lost from the tube. The tube, now containing the snow core, was then held horizontally by the spring scale. If present, the plug of dirt was removed before the SWE reading on the scale was recorded. Depending on the nature of the snow and ground cover it was be difficult to keep all the snow in the tube as the core was lifted so the procedure described above was often repeated several times at a single location until the surveyors were satisfied that no significant amount of snow had been lost.

3.4 Depth Measurements

Snow depths were measured using a GPS Magnaprobe built by Snow Hydro. The probe is a steel rod with a circular plastic basket that can slide along the rod. The probe is inserted into the snow until it reaches the ground while the basket 'floats' on top of the snow. The steel rod is attached to a backpack which contains batteries, a Campbell Scientific CR800 datalogger, a GPS receiver on an antenna, and a keypad. A button at the top of the steel rod is pressed and the snow depth (distance from basket to the end of the rod) and GPS coordinates are automatically recorded. The probe emits a series of beeps each time to let the operator know that both depth and coordinates have been recorded. The probe can measure a maximum snow depth of 1.2 m. Observations took as little as 2-3 s to make and record. When snow conditions were suitable the operator could take measurements every few steps without breaking stride. When the snow contained hardened slabs, thick ice layers, or was close to the maximum depth then measurements took longer. However, the same factors increased the time required to make a SWE observation.

3.5 Analysis

Statistical analysis and figures for this study were completed using R and ArcGIS. Results were examined for inconsistencies that might indicate potentially unrepresentative data, particularly at the site level. The Mattberry, Castor, and Mesa lake sites are located outside of the basin and were potentially unrepresentative of the snow cover in their respective regions. Carleton researchers were not able to visit the Big Spruce site and no pictures were available. It was described by NTPC staff as being similar to the other southern sites but with relatively denser forest cover. It is located in the extreme southwest of the basin. Other possible unrepresentative sites were identified as the analysis was conducted. In all cases, the analysis below was conducted with and without the identified sites to understand their effects, if any, on the findings.

3.5.1 Historical Data Analysis

Historical data was analyzed at the site, region, and basin scales. Mean and coefficient of variation (C_V) values were calculated for each site and region between both 1978 - 2017 and 1995 - 2017. The addition of three new northern sites in 1995 makes the period 1995 – 2017 more suitable for comparing the regions (See section 3.2.1). Stratification by landscape was only done at the regional scale (north and south of treeline) since this data set was not designed to test differences between finer resolution landscape units. The R^2 values between SWE and depth were calculated for each site over the historical record and then calculated again lumped by region. R^2 values were calculated using 1st and 2nd order linear regression. Plots were made of each individual measurement showing SWE and depth values stratified by region with a line of best fit plotted for each region. Regional probability distributions of SWE, depth, and density were produced, and skew values were calculated. Correlation matrices between sites over the complete historical record for SWE, depth, and density were produced. One tailed t-tests (Welch's) were performed between the two regions for snow depth, snow density, and SWE data to determine if regional differences were significant.

To examine temporal trends, linear trend analysis was conducted on the mean depth, density, and SWE values at the site, region, and basin scales. The analysis was also completed for the two time-frames mentioned above. Linear trend analysis was also conducted on the R^2 value between SWE and depth for each site and for each region.

Linear trend and multi-regression analysis were conducted on each year of the historical data between latitude, elevation, and distance from treeline and mean SWE, depth, and density values to test if these three geographic variables were strong and/or consistent predictors of the snow cover properties. This analysis was repeated with a two-factor linear model where SWE, depth, and density were tested against the variable 'region', which included only the values 'north' and 'south'. This analysis was done using the *linear model* function in R which treats a model with a single categorical covariate as a one-way ANOVA. In general, trends were considered significant if $p < 0.05$. However, in some cases, such as attempting to determine the existence of a trend over many years or across many sites, a higher threshold of $p < 0.1$ was considered significant.

3.5.2 Enhanced Data Analysis

Mean and C_V of SWE, depth, and density for all upland sites from the enhanced surveys in 2016/17 were calculated. Values were pooled by region and compared to the regional differences seen in the historical data. Linear trend analysis was conducted between latitude, elevation, and distance from treeline and mean SWE, depth, and density values using sites from both the enhanced surveys and NTPC surveys. Pooling the NTPC and enhanced data created a dataset with n = 16 (2016) and n = 20 (2017). All multi-variate combinations of the three geographic variables were tested against the historical data year-by-year and against the pooled enhanced and NTPC data in 2016/17.

Depth profiles of transects that crossed between lakes and uplands were produced. The mean and C_V of snow cover properties on the 9 lakes sampled in 2017 were calculated and compared to the values found in the adjacent uplands during the NTPC survey. A similar analysis was conducted with the limited 2016 lake data. Lake data was also pooled by region with mean and C_V values compared between the regions and their respective upland values.

Enhanced surveys in both the north and south regions were conducted at sites which had different terrain characteristics from NTPC sites (Table 3.2 and Table 3.4). The mean and C_V of snow cover properties for these sites were calculated individually and pooled by region. These results were compared to the values calculated in their respective regions and years. This enabled a comparison of NTPC site snow cover characteristics with a broader range of terrain types within each region.

3.5.3 Snow Survey Optimization

Confidence intervals (CI) around the basin-wide SWE estimate for each region were calculated in three ways. The first assumed each individual measurement taken at each site was independent. The second assumed a large amount of spatial autocorrelation within each site by treating only the means of each site as independent, thus reducing the effective sample size by a factor of approximately ten. The third method used bootstrapping. This involved estimating the CI by finding the mean of a probability distribution of 1000 CI's generated by random sampling of the dataset. This was repeated within sites, between sites, and basin-wide. With the bootstrapping method, the relative contributions of inter- and intra-site variability to the error in basin-wide estimates could be quantified to better elucidate optimal sampling design strategies. Bootstrapping facilitates CI calculations for non-parametric distributions, small sample sizes, comparisons between sampling schemes with different samples sizes, and more complex sampling schemes such as varying the ratio of depth to density measurements (Watson *et al.*, 2006).

2017 data was used to estimate how many sites need to be visited to achieve basin- and region-wide SWE estimates within 5% and 10% of the best-case mean (mean of all sites) with 95% confidence. The 95% CIs were calculated using a bootstrap method. The mean SWE at each of the 19 sites surveyed in 2017 was sampled with replacement and the basin and region SWEs were calculated. The number of samples was increased from 1 to 80 with the procedure repeated 1000 times for each sample size. At the site level, the 2017 data was used to estimate how many measurements need to be taken to achieve a site SWE estimate within 10%, 15%, and 20% of the best-case mean with 95% confidence. A bootstrap method was also used for this analysis. The best-case mean used all density measurements and all enhanced survey depth measurements. In this case, the samples were taken randomly from both the density and depth measurements allowing different ratios to be tested.

Optimal sampling ratios of depth:density were calculated for each site and region. This was done using a method adapted from Rovansek *et al.* (1993). The calculation is based on the concept that depth is a less expensive indirect measurement of SWE. This method uses the following equation

$$\frac{n_{den}}{n_d} = \sqrt{\frac{c_d}{c_{den}} \frac{s_p^2}{\left(s^2 - s_p^2\right)}} \qquad [3]$$

where the ratio $\frac{n_{den}}{n_d}$ represents the optimal measurement ratio of density:depth, $\frac{c_d}{c_{den}}$ is the cost ratio of depth:density, s^2 is the variance of SWE, s_p^2 is a term related to the variance of SWE in relation to density and depth. The cost ratio is based on the time required to complete one depth measurement *vs* one density measurement. For this analysis a cost ratio of 20:1 was assumed based on work by Sturm *et al.* (2010). Field experience has shown that this is a conservative value when using a magnaprobe and depending on measurement spacing and terrain characteristics. Often upwards of 25 or more measurements can be taken. The optimal ratio represents the sampling ratio that best balances the different C_V's of the two properties and the different costs associated with each measurement.

The optimal sampling ratios described above do not indicate the absolute number of depth or density measurements that should be taken, only the ratio between them. To determine the number of measurements needed to achieve specific error objectives a bootstrap method was used. This method randomly sampled from 1 to 30 density measurements from a site, with replacement, as well as a corresponding number of depth measurements from the enhanced surveys. The ratios of depth:density measurements tested were 1:1, 11:1, and 20:1. A ratio of 11:1 was chosen based on the results of the optimal ratio calculation using the Rovansek *et al.* (1993) method described above. The number of density measurements needed to achieve site-level SWE estimates within 10%, 15%, and 20% of the best-case estimate with 95% confidence were determined. The best-case SWE estimate at the site-level was calculated using all available depth and density measurements.

3.5.4 Density Model

Two simple density models were tested to estimate the differences between snow surveys conducted with only depth *vs* depth and density measurements. In the first case, the mean basin-wide SWE was calculated for each year from 1978-2017 by weighting the mean site values by region area. This is different from the typical method used by NTPC and helps compensate for the fact so few northern sites were surveyed in the early part of the record. Snow density was estimated by using the historical basin-wide mean density, an estimate of Taiga snow density from Sturm *et al.* (2010), and the historical regional mean densities. Annual means were plotted against estimated mean SWE values calculated using the three different density estimates. In each case the mean of only depth measurements at each site was calculated and then the mean depth was found for each region.

In the second case it was assumed that NTPC would continue to measure density at the existing sites and new sites would only involve depth measurements. SWE at enhanced sites was estimated using only the depth measurements taken at the sites and the mean regional density from NTPC sites. This depth-only SWE estimate was compared to the best-case SWE estimate which included the depth and density measurements.

4 Results

4.1 Spatial Variation of Snow

4.1.1 Statistical Summary of Regional Snow Cover

A statistical summary of the historical snow measurements at each NTPC site is presented in Table 4.1. Means and coefficients of variation (C_V) for three snow cover properties (SWE, snow depth, snow density) are shown. Sites are grouped by region (north and south of treeline), with means for both regions presented at the bottom of the table along with percentage differences between them. With limited exceptions, Table 4.1 shows that each region within the basin has a distinct and consistent set of snow cover properties. Winter Lake and Big Spruce lake were identified as potentially unrepresentative of their respective regions.

Over the forty-year historical record, the mean SWE of the northern sites was 17% higher, the mean depth was 13% lower, and the mean density was 24% higher. Comparing only the period 1995 - 2017, the mean SWE of northern sites was 12% higher, mean depth was 12% lower and, mean density was 27% higher. There is a large amount of variation in the regional differences in mean snow cover properties from year to year, but northern SWE was greater in 19 out of the 23 years from 1995 - 2017, mean depth was lower in 20 out of 23 years, and mean density was higher in 22 out of 23 years.

Density measurements are nearly normally distributed when pooled or disaggregated by year, region, or site. One tailed t-tests (Welch's) between northern and southern density measurements for each year show that the difference in means was significant at a $p < 0.05$ level in 22 out of 23 years. T-tests between regional, annual SWE and depth measurements were less certain and show significant differences ($p < 0.05$) in 10 and 12 years respectively. However, the

Table 4.1 *Statistical summaries of historical snow survey data (1978-2017; n=40) by site and region, including mean and C_V. Rows 'Mean South' and 'Mean North' show the mean regional values. Included at the bottom are the percentage differences in means for the period 1995-2017 and the number of years, of those 23, when the value of the difference had the same sign as the mean difference. R^2 indicates the coefficient of determination between SWE and depth. Winter Lake is not included in the mean values.*

			SWE (cm)		Snow Depth (cm)		Density (g cm^{-3})	
	Site	R^2	Mean	C_V	Mean	C_V	Mean	C_V
South	Big Spruce	0.33	10.3	0.28	51.7	0.28	0.21	0.36
South	Ghost	0.52	10.3	0.28	52.8	0.23	0.20	0.21
South	Mattberry	0.50	9.5	0.29	51.6	0.23	0.19	0.21
South	Snare	0.49	11.0	0.26	53.7	0.19	0.21	0.20
South	Indin	0.57	10.9	0.29	58.7	0.21	0.19	0.20
South	Castor	0.60	11.3	0.27	57.8	0.19	0.20	0.18
North	Winter	0.89	7.6	0.77	34.9	0.61	0.21	0.27
North	Christison	0.88	11.3	0.74	44.5	0.52	0.24	0.28
North	Big	0.92	12.2	0.86	44.5	0.71	0.26	0.28
North	Mesa	0.88	12.6	0.67	51.5	0.51	0.23	0.25
North	Whitewolf	0.87	13.3	0.66	48.5	0.49	0.26	0.23
	1978-2017							
	Mean South	0.50	10.6	0.28	54.4	0.22	0.20	0.23
	Mean North	0.89	12.4	0.73	47.3	0.56	0.25	0.26
	% Diff.	77	17	163	-13	152	24	15
	1995-2017							
	% Diff.		12		-12		27	
	Years		19		20		22	

assumptions of the tests are violated with northern depth and SWE having significantly different frequency distributions from southern measurements. Assumptions of equal variance were also frequently violated year-to-year. As an alternative, a one tailed paired t-test was performed on the annual difference in means of SWE and depth between northern and southern regions. The null hypothesis was rejected in each case indicating there is a real difference between the regions with northern SWE being greater ($p < 0.0001$), and northern depth lower ($p < 0.0001$).

The mean C_V of SWE in the northern sites was 163% greater than in the southern region. Northern site C_V, including the Winter Lake, fell within a range of 0.66 to 0.86 while the southern sites fell between 0.26 and 0.29. The higher C_V of SWE in the north was largely the result of differences in C_V of depth between the regions. The C_V of depth in the north was 152% greater than in the south and fell into two distinct, non-overlapping ranges (South: 0.19 - 0.28; North: 0.41 - 0.71). A smaller part of the higher northern C_V of SWE is explained by difference in the C_V of density. C_V of density for northern sites had a mean of 0.26, 15% greater than the southern sites. Removing the Big Spruce Lake site increased the difference to 30% greater in the north. The C_V of density at the Big Spruce site has a value greater than at any other site in the north or south.

In summary, spatial variability of snow depth was considerably higher for sites north of treeline, whereas spatial variability of snow density was only slightly higher. As a result of these relative differences, spatial variability of SWE was considerably higher for northern sites compared with southern sites.

The coefficient of determination (R^2) between SWE and depth, shown as R^2 in Table 4.1, was significantly different between the regions. The R^2 of the northern sites varied across a narrow range from 0.87 to 0.92 while the southern R^2 was lower and varied through a wider range of 0.33 to 0.60. The Big Spruce site was again a potential outlier, in this case with an R^2 much lower (0.33) than any other site. With Big Spruce removed, the mean R^2 in the north was 66% greater than in the south.

Figure 4.1 shows SWE plotted against depth for each available individual snow survey measurement taken from 1978-2017, with Fig. 4.1A (n = 1807) showing southern sites and Fig.4.1B (n = 1020) showing northern sites. Both SWE and depth can be seen to vary across a larger range in the northern sites. A second order line of best fit is plotted in red on both (A) and (B) with R^2 values of 0.55 ($p < 0.0001$) and 0.90 ($p < 0.0001$) respectively. These results indicate that there is a very strong relation between SWE and snow depth in the northern sites and a much weaker, though still significant, relation in the south. This geographic phenomenon is directly associated with the relative differences in variability of depth *vs* density between northern and southern sites, as described above.

Probability distributions of SWE, snow depth, and density, broken down by region, are shown in Fig. 4.2. All three snow cover properties in the south had relatively symmetric distributions with skews of 0.33, -0.02, and 0.21 respectively. Northern sites however, while having a relatively symmetric density distribution (skew: 0.11), had a moderate, positively skewed depth distribution with a skew of 0.71. Northern SWE was highly positively skewed (skew:1.4). The high skew of SWE in the northern sites is likely due to the strong relation between SWE and depth seen in Fig. 4.1B.

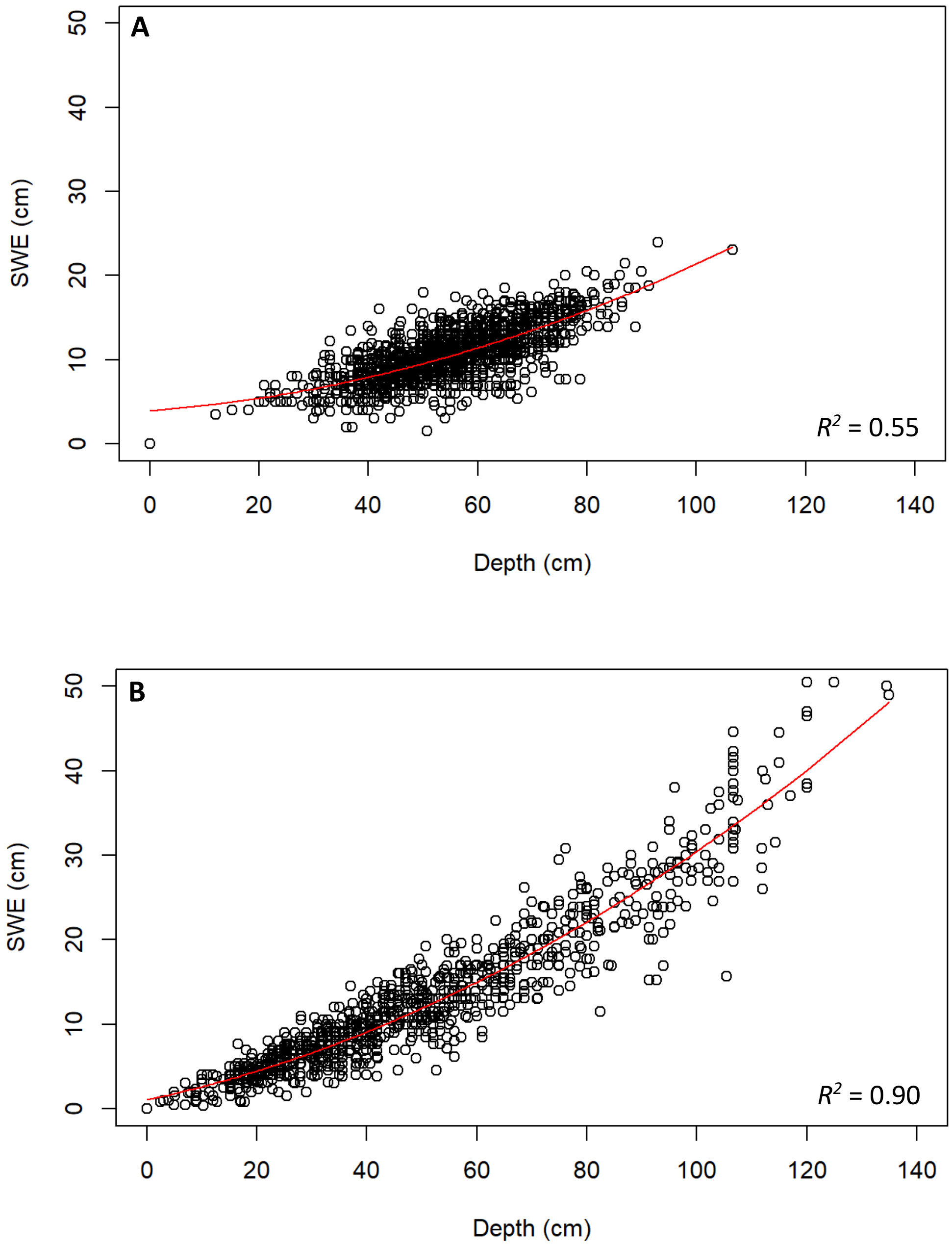

Figure 4.1 *SWE vs snow depth (1978-2017). (A) (n=1807) shows the southern sites (Big Spruce removed). (B) (n=1020) shows northern sites (Winter Lake removed). Northern sites have a much greater range of both depth and SWE. Red lines show 2nd order lines of best fit with (A) R^2 = 0.55 and (B) R^2 = 0.90. The vertical alignment of some measurements is an artifact of the maximum depth some snow tubes are capable of measuring.*

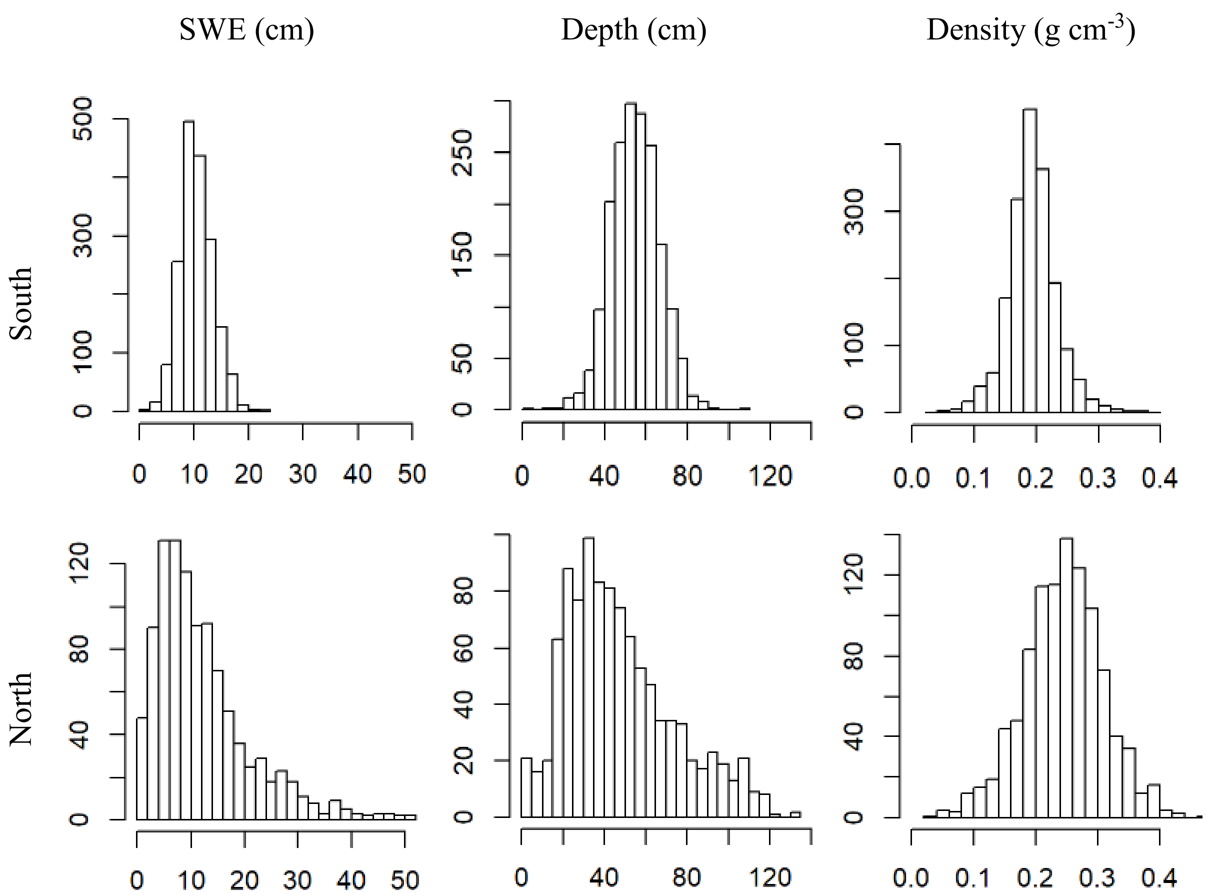

Figure 4.2 *Probability distributions of SWE, depth, and density by region, using historical survey data (1978 – 2017). Northern skew – SWE: 1.4, depth: 0.71, density: -0.11. Southern skew – SWE: 0.33, depth: -0.02, density: 0.21.*

4.1.2 Inter-Site Correlation

Analysis of the year-to-year inter-site correlation of annual mean SWE at each site showed a significant difference between northern and southern sites, with southern sites highly correlated with each other and northern sites much less so. Figure 4.3A shows a correlation matrix of the annual mean SWE values for the 11 NTPC sites from 1978-2017. The five main southern sites (within the solid black box) are well correlated with each other, with a minimum coefficient of 0.75. The sixth southern site, Big Spruce, is somewhat correlated with the southern sites, with a coefficient ranging from 0.48 to 0.61. No coefficients above 0.75 were found between any of the northern sites or between any northern and southern sites. The mean of the inter-site correlation coefficients is 0.38 between northern sites and 0.37 between northern and southern sites.

The regional difference in inter-site correlations of SWE are a result of differences in depth variability, rather than density. Depth shows a similar pattern to SWE (Fig. 4.3B) with strong differences in inter-site correlations for northern *vs* southern regions. The five main southern sites have a mean correlation of 0.84, this drops to 0.75 when Big Spruce is included. The mean of the correlation coefficients was 0.38 between northern sites and 0.37 between northern and southern sites. Inter-site variability of snow density within each region was relatively high but there was no distinct regional difference. Mean correlation coefficients for southern and northern regions were 0.58 and 0.59 respectively. The density correlation between northern and southern sites was 0.37.

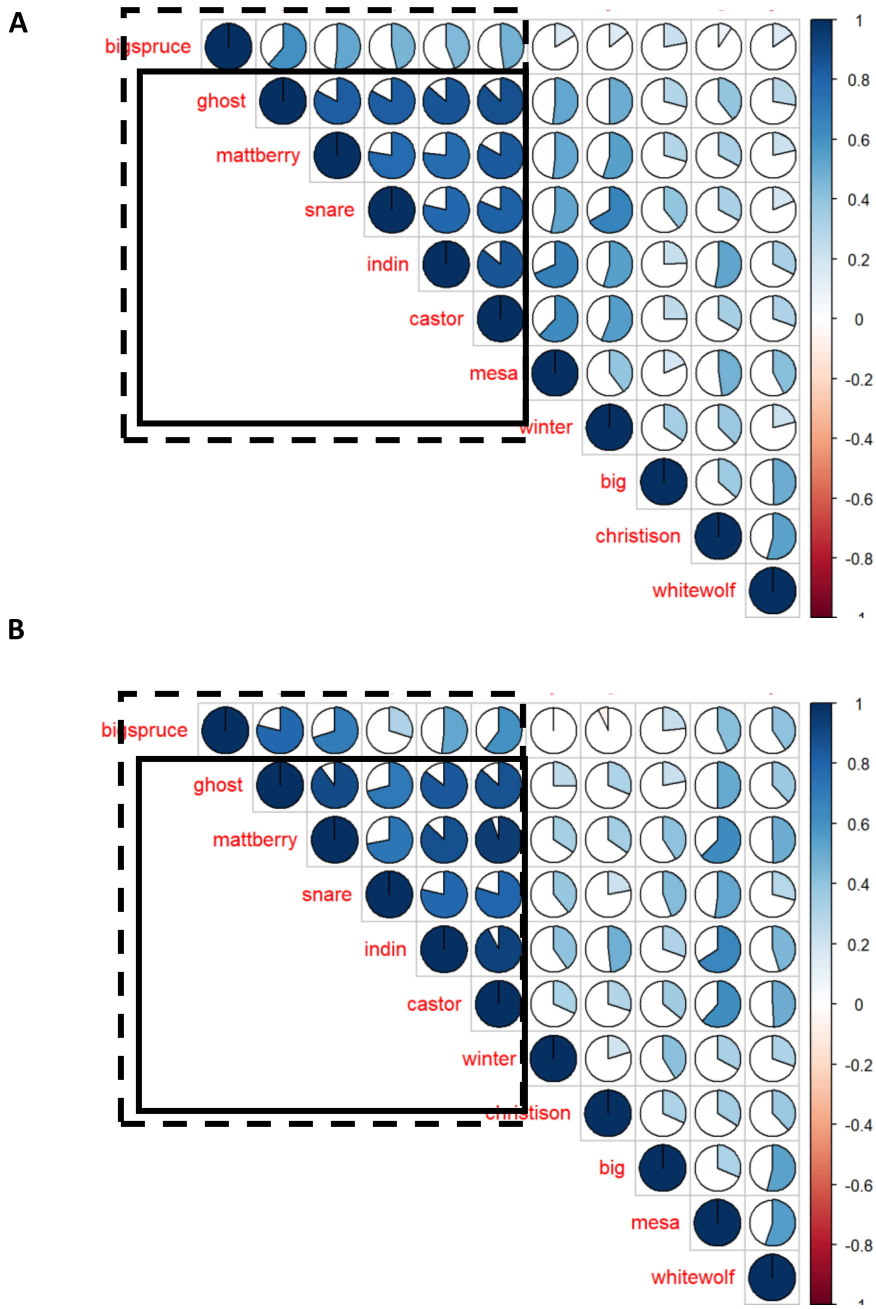

Figure 4.3 *Correlation matrices showing mean annual SWE (A) and mean annual snow depth (B) between sites over the historical record, 1978-2017. Solid black box shows the 5 main southern sites. Dashed box includes the 5 main southern sites as well as the Big Spruce site. Colour coding and the portion of the pie charts that are shaded both represent the correlation between pairs of sites.*

4.1.3 2016 and 2017 Enhanced Survey Data

Sections 4.1.1 and 4.1.2 indicate that the historical record shows clear differences in snow cover properties between the two regions. One purpose of the enhanced surveys of 2016 and 2017 was to collect data in a similar fashion to NTPC but at additional sites within each region and compare the enhanced survey results with NTPC results and historical findings. If the historical regional differences noted above were not found in the enhanced survey or enhanced survey results were not similar to NTPC results for that year, it may indicate that NTPC sites are biased towards particular snow property characteristics relative to other sites in the basin. Table 4.2 shows a statistical summary of results from the enhanced surveys. Summary statistics of NTPC surveys are also included for comparison. Results from the enhanced surveys broadly agree with the regional differences in the historical record and from NTPC surveys.

The mean SWE of the enhanced surveys was within 6% of NTPC surveys in both regions and in both years. The mean SWE of the enhanced surveys in the northern regions was greater than the southern regions by 12% and 33% in 2016 and 2017 respectively. These are similar to the differences seen in NTPC surveys in those years (15% and 37%) and within the range of typical historical differences. The C_V of SWE in the enhanced surveys was also similar to the respective NTPC results in both regions, in both years, and reflected the historical trend of higher SWE variability in the northern half of the basin. The enhanced depth results for both mean and C_V follow NTPC results closely and are similar to historical results. Mean density also followed historical trends, being greater in the northern region in both years. The C_V of density is typically higher in northern regions, this was seen in 2017, in the 2016 NTPC survey, but not in the 2016 enhanced survey. The R^2 value between SWE and depth in enhanced surveys agreed with the differences seen in the historical record with southern values significantly lower than

Table 4.2 *Enhanced 2016 and 2017 survey data summaries with same year NTPC summaries for comparison. R^2 values represents coefficient of determination between SWE and depth. NTPC and enhanced surveys in 2017: n =50. Enhanced surveys 2016: n = 30.*

				SWE (cm)		Depth (cm)		Density (g cm^{-3})	
			R^2	Mean	C_V	Mean	C_V	Mean	C_V
2016	South	NTPC	0.43	9.6	0.28	59	0.14	0.16	0.22
		Enhanced	0.56	9.2	0.30	58	0.15	0.16	0.22
	North	NTPC	0.94	12.8	0.63	55	0.49	0.21	0.27
		Enhanced	0.89	12.6	0.59	57	0.48	0.22	0.20
2017	South	NTPC	0.40	10.9	0.15	63	0.09	0.17	0.12
		Enhanced	0.71	11.2	0.21	59	0.15	0.19	0.16
	North	NTPC	0.86	12.2	0.74	55	0.49	0.21	0.33
		Enhanced	0.93	12.9	0.67	52	0.58	0.24	0.20

those seen in the north. The enhanced surveys suggest that NTPC sites are not biased in either the northern or southern regions.

4.1.4 Latitude, Elevation, and Distance from Treeline

Using both historical and enhanced snow survey data, three geographic variables, latitude, elevation, and distance from treeline, were considered as potential continuous predictors of snow properties across the Snare basin. If SWE, depth, or density can be shown to correlate strongly with these properties they could have potential use in any improved sampling and/or modelling scheme for the basin. The period 1995-2017 was used to test the relation between the three geographic variables and three snow cover properties.

Results of linear trend analysis between each property and each variable for each year, are shown in Table 4.3. Mean R^2 values for SWE and depth ranged from 0.21 to 0.37. Less than half of the years tested exhibited statistically significant trends ($p<0.1$). Slopes typically agreed with the general findings of more SWE in the north and lower depth in the south. These relations are not strong or consistent enough to be used for modelling. Density R^2 values ranged from 0.39 to 0.54 and had much higher percentages of significant years.

Results of a two-factor linear model comparing elevation, latitude, and distance from treeline and the categories North and South are shown in Table 4.3 under *Region*. The mean R^2 values give an indication of how much variance can be explained using a simple model of north and south of treeline rather than a gradual continuous variable. Results for all three snow cover properties indicate that a simple two factor model is at least as good a predictor. The two-factor density model showed the best results with a mean R^2 value of 0.54, a mean p-value of 0.09, with significance at the $p<0.1$ level in 78% of years.

Table 4.3 *Linear trend analysis, year-by-year, of SWE, depth, and density vs latitude, elevation, and distance from treeline. Winter Lake data was removed. 'Region' refers to the results of the two-region categorical model.*

		Latitude	Elevation	Treeline	Region
SWE	Mean R^2	0.26	0.27	0.28	0.28
	Mean p-value	0.25	0.29	0.27	0.28
	% years p < 0.1	39	43	52	43
	% years positive slope	83	83	83	
Depth	Mean R^2	0.21	0.37	0.27	0.34
	Mean p-value	0.36	0.22	0.29	0.20
	% years p < 0.1	20	52	23	48
	% years negative slope	74	83	60	
Density	Mean R^2	0.39	0.54	0.48	0.54
	Mean p-value	0.14	0.12	0.11	0.09
	% years p < 0.1	61	67	83	78
	% years positive slope	87	97	87	

Similar analysis was done for the years 2016 and 2017 where a larger dataset that includes NTPC survey sites and enhanced surveys is available. Results are shown in Table 4.4. Statistically significant results are highlighted. SWE was significantly correlated with latitude, elevation and distance from treeline in 2016 with high R^2 values ranging from 0.52 – 0.72. However, the relations were not replicated in 2017. Density was well correlated with latitude, elevation and distance from treeline in both 2016 and 2017 with R^2 values ranging from 0.33 to 0.74. In general, the enhanced data supports the results from the historical data with density being the best predictor and a simple two region model explaining as much variance as any of the continuous geographic predictors.

Multivariate regression analysis was performed on the SWE, depth, and density relations with all three physiographic characteristics. While R^2 values improved slightly, mean p-value and number of years with significant models ($p<0.1$) did not substantially change. The strong multicollinearity between latitude, elevation, and treeline complicate the analysis and make selecting appropriate variables for a model problematic. Multivariate regression did not significantly improve upon the R^2 value of 0.54 found using the two-factor model with density.

4.1.5 Terrain Types within Regions

4.1.5.1 Lakes

Lakes make up approximately 22% of the landscape both north and south treeline. In both of the 2016/17 snow surveys depth and density measurements were taken on lakes adjacent to NTPC sites. Figure 4.4 shows two profiles of snow depth where a depth transect crossed from a lake to the adjacent upland. Figure 4.4A shows site A4 from the 2016 enhanced snow survey. Transect A4 began at a small lake, crossed a dense upland forest, and ended at a large lake. Figure 4.4B shows the Snare Lake transect from the 2016 NTPC survey. In both cases there is a

Table 4.4 *Linear trend analysis of relations between depth, density and latitude, elevation, and treeline for data collected from NTPC and enhanced surveys in 2016 and 2017. 2017: 195 individual measurements at 20 sites. 2016: 160 individual measurements at 16 sites. Highlighted cells are relations significant at the $p < 0.05$ level. SWE and density relations are positive, while depth relations are all negative.*

		SWE		Depth		Density	
		R^2	p	R^2	p	R^2	p
2016	Latitude	0.67	0.0002	0.01	0.79	0.65	0.0003
	Elevation	0.52	0.002	0.03	0.51	0.74	<0.0001
	Treeline	0.77	<0.0001	0.00	0.87	0.74	0.0002
	Region	0.50	0.003	0.04	0.45	0.71	<0.0001
2017	Latitude	0.05	0.34	0.10	0.18	0.25	0.03
	Elevation	0.10	0.19	0.20	0.05	0.49	0.001
	Treeline	0.09	0.22	0.17	0.08	0.43	0.002
	Region	0.12	0.14	0.16	0.09	0.47	0.001

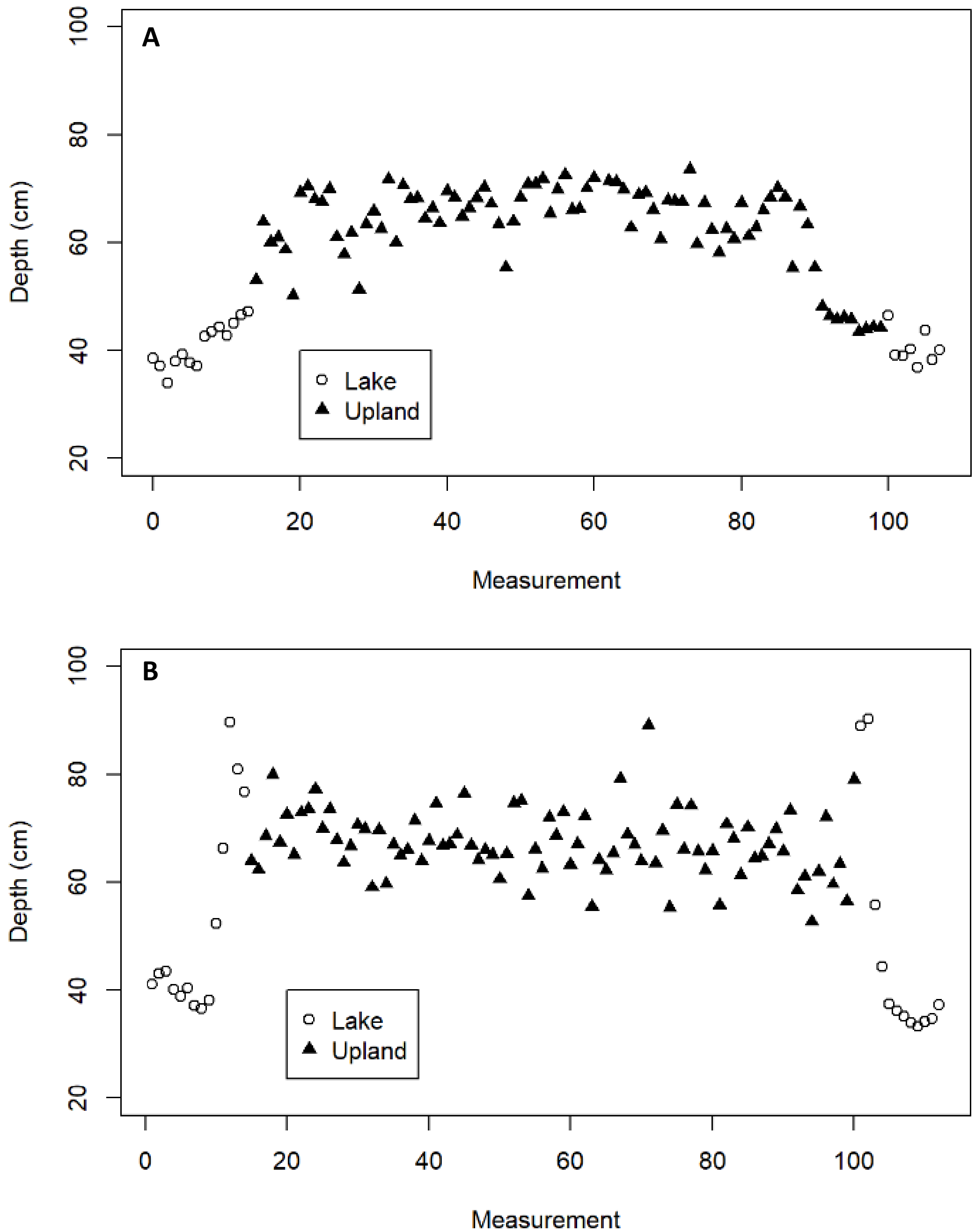

Figure 4.4 *Two examples of snow depth transects crossing from lakes to uplands and back to lakes. (A) 2016 Site A4. (B) 2016 Snare Lake.*

clear transition from low snow depth on the lake surface to higher snow depth in the uplands. Similar depth profiles were seen at all locations in 2016 and 2017 anywhere a transect crossed between lakes and uplands.

In 2016 depth measurements were taken on 9 lakes adjacent to NTPC sites. At each site extensive depth measurements were taken along the normal upland transect as well. Sample sizes on the lakes ranged from 5 to 31 with a mean of 13 and on the uplands from 40 to 99 with a mean of 64. Mean snow depth on lakes was lower than adjacent upland NTPC sites in all cases, with a mean of 44% less and a range from 29% to 71% less. Depth measurements were also taken on lakes at the enhanced survey sites A1, A2, and A4 in 2016. Sample sizes were similar to the NTPC survey with much higher values in the uplands. The enhanced survey lakes had a mean snow depth 38% less than their adjacent uplands.

Limited SWE measurements were taken on lakes in 2016. A total of 6 measurements were taken at three of the enhanced survey sites (A1, A2, A4). The mean lake SWE measurements were 34%, 22%, and 29% lower than adjacent uplands, respectively.

In 2017, more systematic and thorough surveys were conducted on lakes. Extensive depth measurements were taken on nine lakes adjacent to NTPC sites with a mean sample size of 157 on lakes and 73 in uplands (Table 3.1). Figure 4.5A shows the difference in snow depth between the 9 lakes and their adjacent uplands. Lake snow depth was lower in every case. Lakes had a mean snow depth 38% lower than the uplands. Figure 4.5B shows the mean SWE of NTPC sites *vs* a similar survey conducted on the adjacent lakes. Lake SWE was lower at 8 of 9 sites, with Winter Lake being the exception. Lake surveys had a mean SWE 23% lower than adjacent uplands. Figures 4.5A and 4.5B show the 95% CIs around the depth and SWE means. The CIs

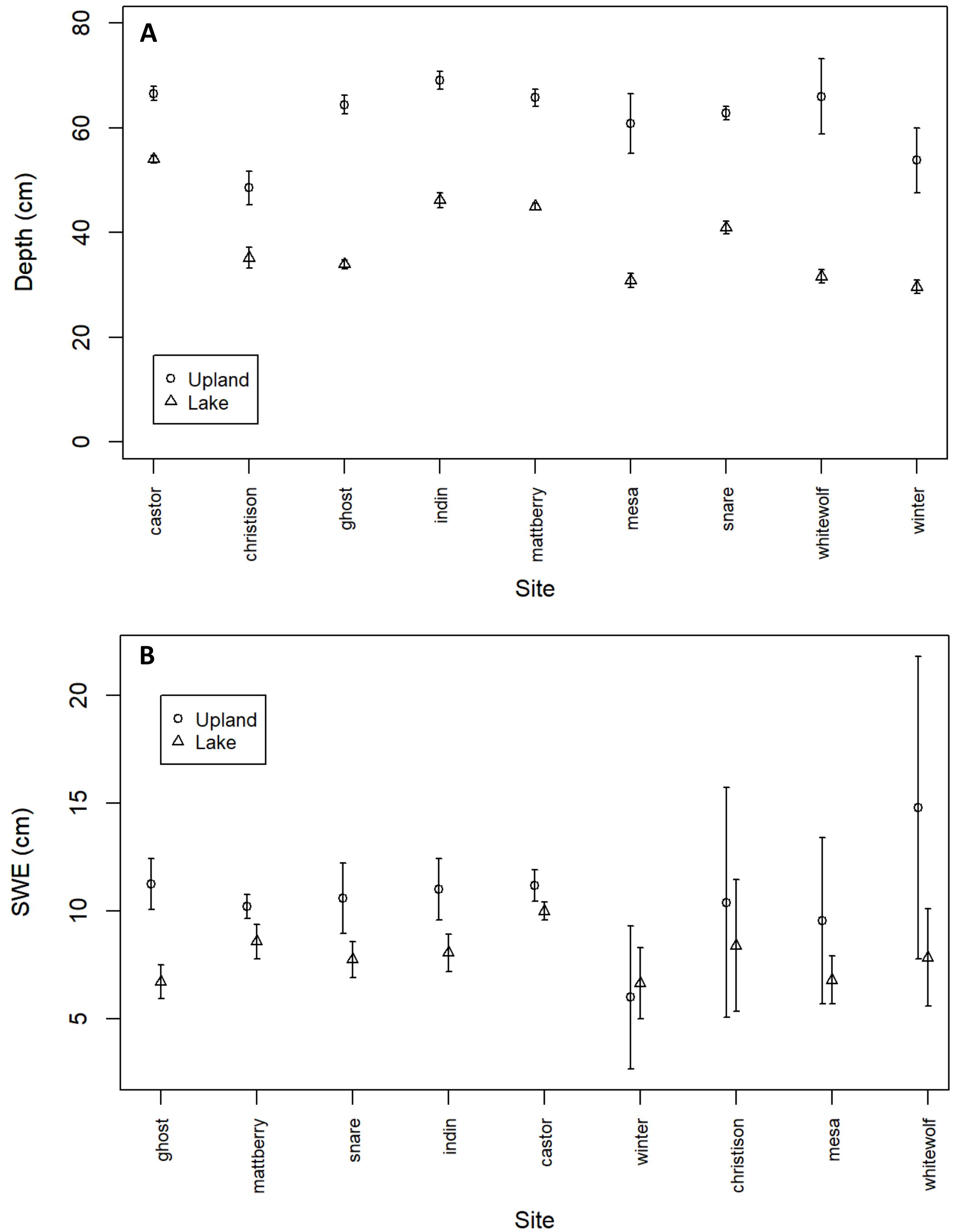

Figure 4.5 *Mean snow depth (A) and SWE (B) in uplands and on lakes at 9 NTPC sites in 2017. Vertical lines show 95% confidence intervals. The large confidence intervals at all sites in (B) compared to (A) reflect the lower number of SWE measurements taken compared to depth. Depth on lakes was lower in all cases with a mean value 38% lower. SWE was lower on lakes in 8 out of 9 cases with a mean value 23% lower.*

are larger in 4.5B which reflects the fact that much fewer SWE than depth measurements were taken during the surveys on both lakes and in the uplands. Due to the large CV of SWE at sites north of treeline there is much greater uncertainty in the SWE estimates resulting in overlap of the 95% CIs at northern sites. Density was greater on 7 out of 9 lakes than in the adjacent uplands by an average of 18%. Though the 2016 data is limited, it corroborates the differences in snow cover properties on lakes and uplands observed in 2017. Lake snow is roughly 1/5 more dense and 2/5 less deep, resulting in approximately 1/5 less SWE.

Table 4.5 shows the C_V of SWE, depth, and density, broken down by region, for the 2017 upland and lake surveys. The C_V's on lakes for all three snow cover properties are lower than in the adjacent uplands except for depth C_V in the southern region. Like the historical differences seen in the uplands (Table 4.1) the C_V's on lakes of all three properties are significantly higher in the north than in the south, however the increase is somewhat muted. This suggests that a factor other than vegetation at the exact location observations are made plays a role in the differences between the snow cover properties observed in each region.

4.1.5.2 Other Terrain Types

In addition to lakes, enhanced surveys included a wider variety of terrain types than the historical NTPC survey. Figure 4.6 shows the site mean SWE (A and B), depth (C and D), and density (E and F) from the 2016/17 NTPC and enhanced surveys. The dashed vertical lines separate the regions, with the southern region on the left of each plot and the northern region on the right. The dotted vertical lines in each region separate the NTPC survey (left) and the enhanced survey (right). The dashed horizontal lines show mean values in each of the sections delineated by the vertical lines. Winter Lake is shown on the plots as the solid triangle. It is not included in the mean calculations.

Table 4.5 *Mean and coefficient of variation of SWE, depth, and density on uplands and lakes in the 2017 survey.*

		South		North	
		Mean	C_V	Mean	C_V
SWE (cm)	Uplands	10.5	0.26	12.1	0.60
	Lakes	8.2	0.18	7.7	0.42
Depth (cm)	Uplands	61.7	0.15	59.1	0.38
	Lakes	44.7	0.20	32.1	0.32
Density (g cm^{-3})	Uplands	0.17	0.16	0.20	0.27
	Lakes	0.18	0.13	0.24	0.23

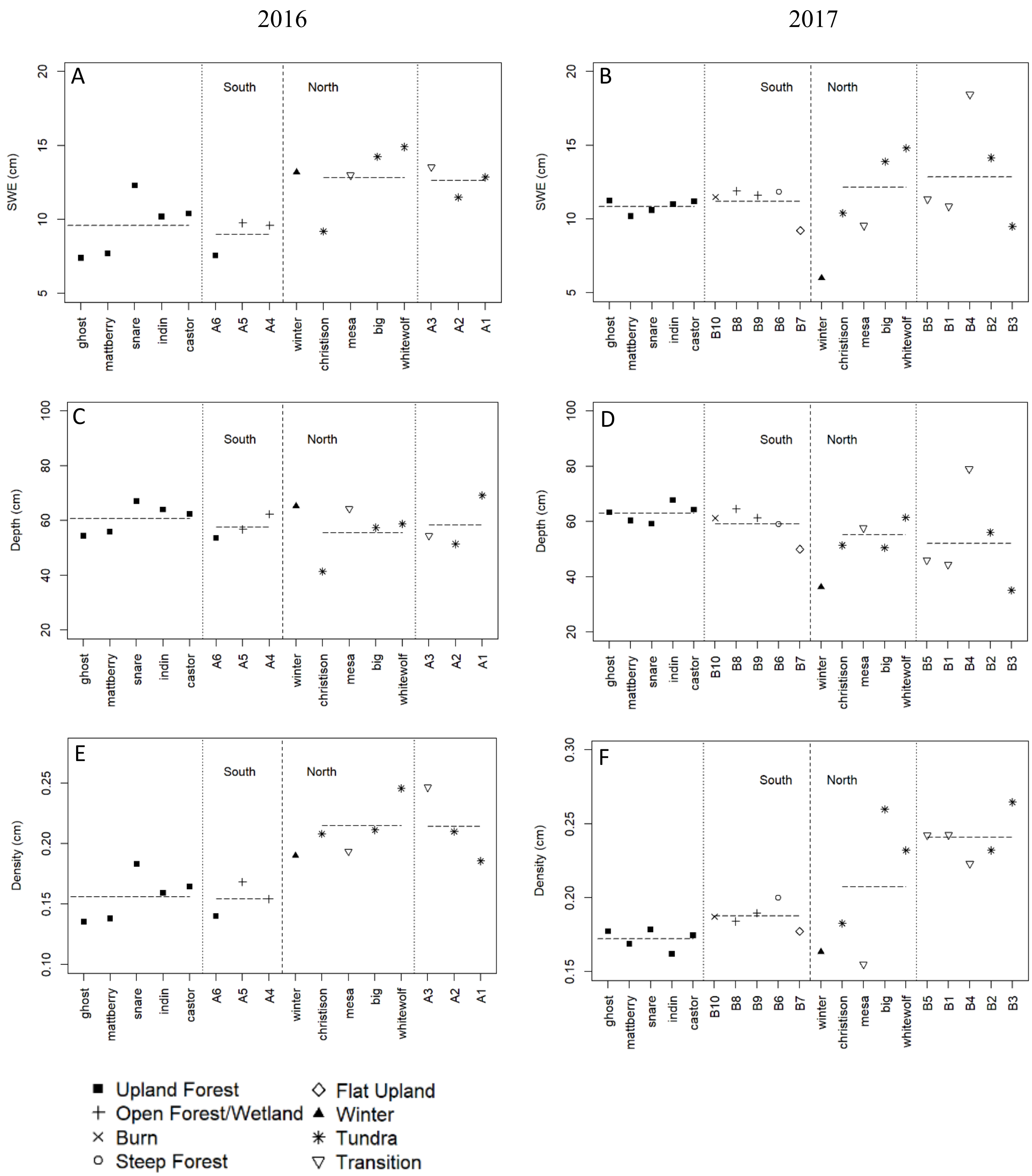

Figure 4.6 *Mean site SWE, depth, and density values from 2016 and 2017 NTPC and enhanced surveys.*

NTPC southern sites are labelled in Fig. 4.6 as *Upland Forest*. The enhanced southern surveys included open forest/wetland, recently burned forest, steep forest, and flat upland forested sites (see Tables 3.1 through 3.6). Since the northern region appears more uniform in winter, the enhanced sites and NTPC sites are divided into either barren or transition. However enhanced sites were different from historical NTPC sites as they were located on hilltops, in wetlands, near small lakes, or far from the influence of any lake.

Despite being conducted in different terrain types, the means of the 2016 and 2017 enhanced surveys in the southern half of the basin fall near their respective NTPC results in every case. The same is true in the northern half of the basin, except for density in 2017 (Fig. 4.6F) where the enhanced survey results were much higher. Historical data shows that the northern snow cover is shallower, denser, greater in SWE, and much more variable at multiple scales. The enhanced surveys support this in general, except for depth measurements in 2016 (Fig. 4.6C).

Broadly, data collected at enhanced survey sites in the southern region, in both 2016 and 2017, were similar to data collected at NTPC sites and typical of historical data, despite being collected in a much wider variety of landscape types. SWE C_V is typically 163% (Table 4.1) higher in the northern regions, yet enhanced survey sites, limited to just 3 in 2016 and 5 in 2017, still had the higher mean SWE values characteristic of their region. Northern enhanced survey density means also followed regional trends.

4.2 Temporal Trends

4.2.1 SWE Temporal Trends at the Basin, Region, and Site Scale

Figure 4.7A shows the basin-wide, end-of-winter annual mean SWE from historical records, 1978-2017, at all 11 NTPC sites. This is the method used by NTPC to determine end-of-winter SWE and are the values used in the empirical model to predict flow. The dashed line is a fitted linear trend line. There is no apparent increase or decrease in basin-wide SWE over the historical record.

The full historical record of annual mean SWE was also analysed for trends by region. No statistically significant trends over time were found using the mean of all southern sites, the mean of all northern sites, the mean of southern sites without Big Spruce Lake, or the mean of northern sites without Winter Lake. Area weighted means were also calculated using 52% area for the northern part of the basin and 48% for the southern part. This can change the annual mean SWE significantly in the case where six southern sites are used with only four northern sites. In no scenario at the basin or region scale was a statistically significant SWE trend found over the historical record, at the $p<0.1$ level.

Figure 4.7B shows the annual mean SWE separated by northern and southern regions from 1995 - 2017. In the north, there was no significant trend ($p<0.1$) over time, whereas SWE decreased at a rate of -0.12 cm yr^{-1} ($p=0.06$) in the south.

Linear trend analysis of the SWE records at the site scale detected only one statistically significant trend. Snare Lake SWE appeared to be in decline ($p = 0.035$). However, that trend was not detected in the 1995-2017 timeframe and was sensitive to data from 1984, when mean

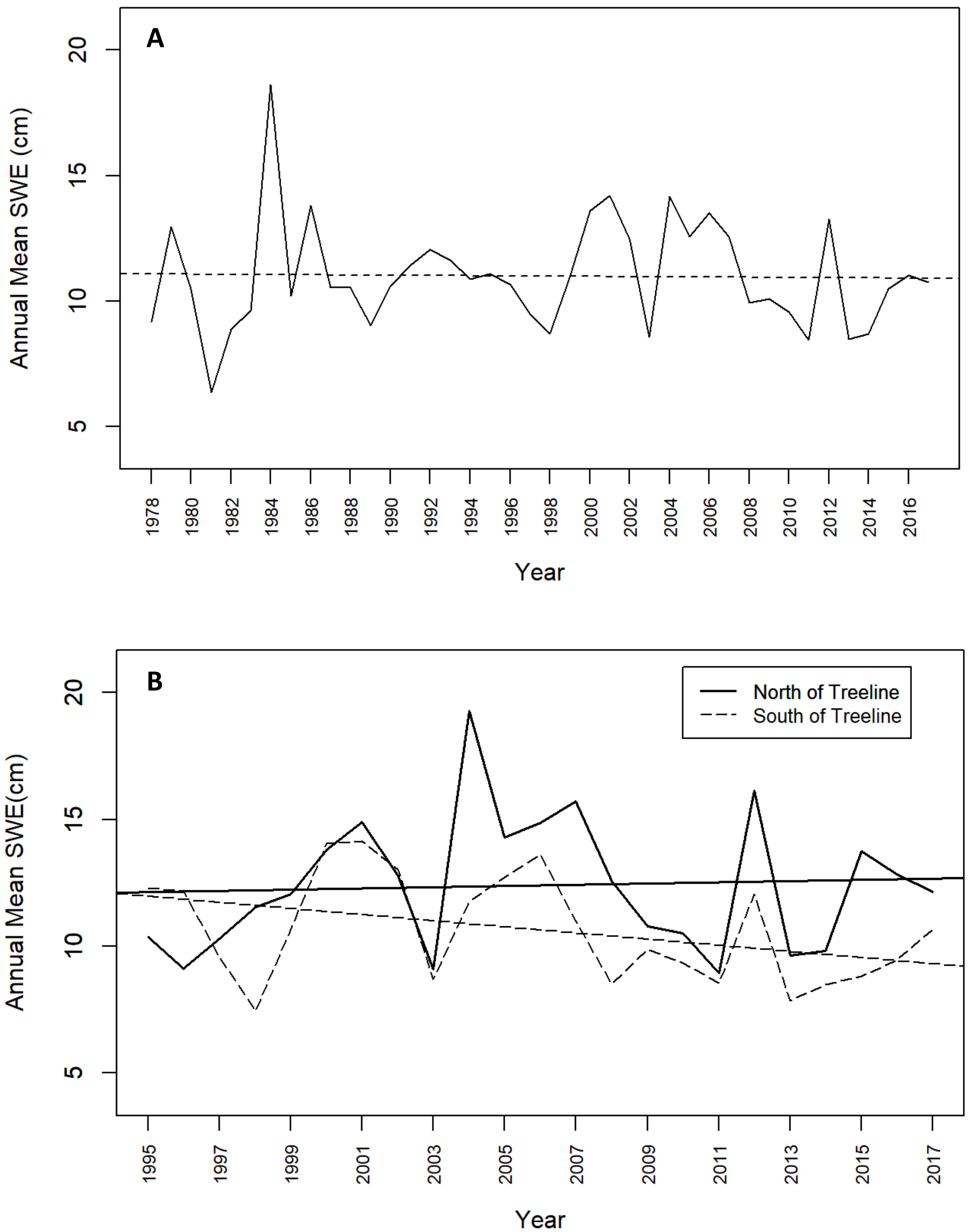

Figure 4.7 *SWE trends. (A) Basin-wide annual mean SWE calculated by taking the mean of the means of each site from 1978 - 2017. The dashed line is a fitted linear trend line. (B) Region annual mean SWE with Winter lake removed (1995 - 2017). The solid line is a fitted linear trend line for northern sites. The dashed line is a fitted linear trend line for southern sites with slope of -0.12 cm* yr^{-1} *(p=0.06).*

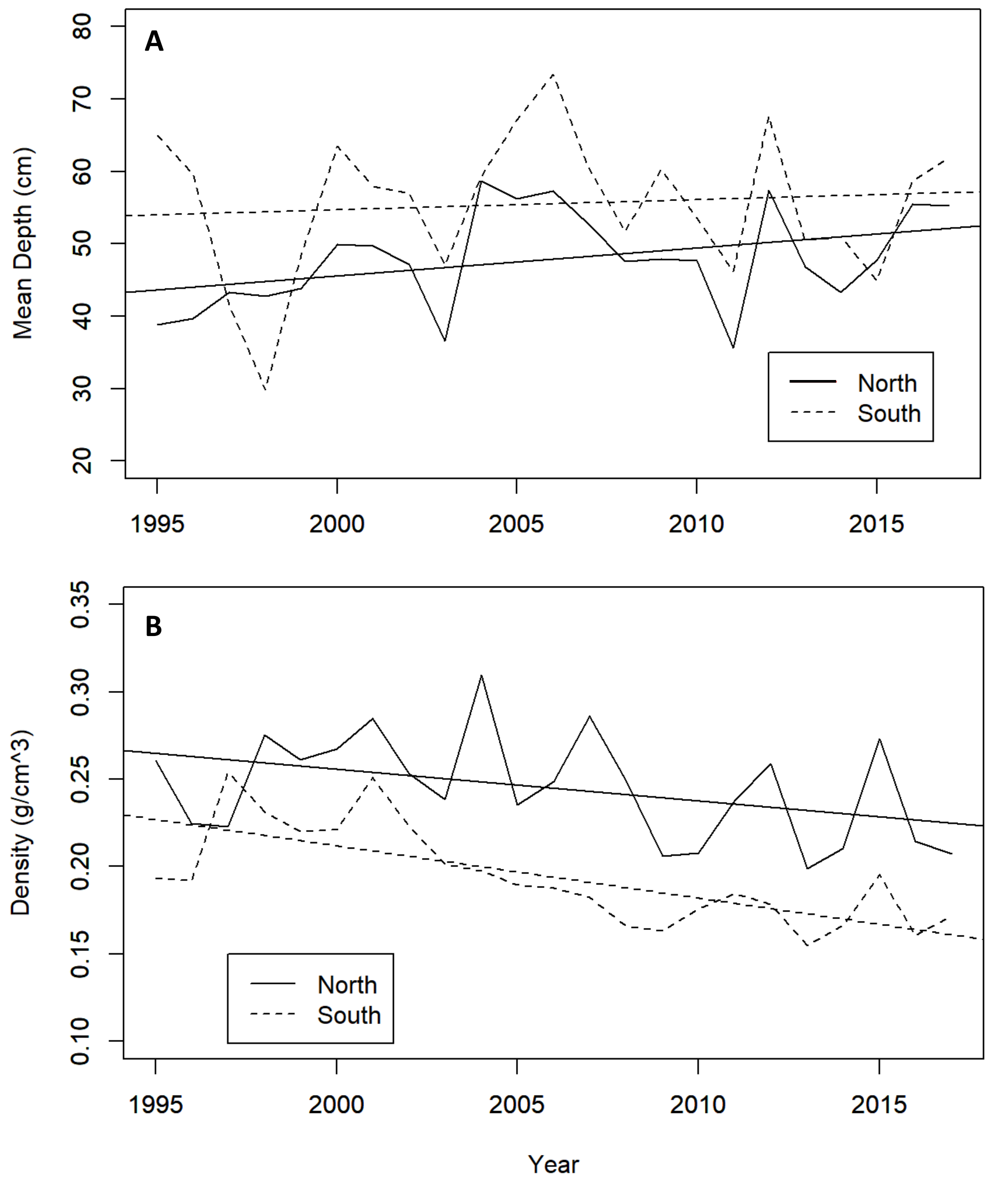

Figure 4.8 *Snow depth and density trends. (A) Annual mean depth by region (1995 - 2017). Southern slope is 0.30 cm* yr^{-1} *(p=0.09). Northern slope is 0.38 cm* yr^{-1} *(p=0.07). (B) Annual mean density by region (1995 - 2017). The southern trend has a slope of -0.003* yr^{-1} *with a (p < 0.001). The northern trend has a slope of -0.002* yr^{-1} *(p=0.06).*

SWE was particularly high across the basin. The trend was not significant at $p<0.1$ when the 1984 data were removed.

4.2.2 Snow Depth and Density Trends at Basin and Region Scale

In addition to SWE it is also important to know if properties of the snow cover such as depth, density, or distribution are changing. Linear trend analysis was performed on the historical snow depth and density data at the basin and region scale. As with SWE, depth and density trends were tested with and without the Big Spruce and Winter Lake sites as well as with area weighted means. Using the full historical record (1978-2017), no statistically significant trends were found at the basin scale. At the region scale, the southern region was found to have a moderately declining density trend with a slope of -0.0006 g cm^{-1} yr^{-1} ($p=0.09$).

For comparison between northern and southern regions the analysis discussed above was repeated for the period 1995 - 2017. Figure 4.8A shows the annual mean depth from 1995 - 2017 broken down by region. Both regions show a positive trend in depth. The northern trend has a slope of 0.38 cm yr^{-1}, while the southern region slope was 0.2 cm yr^{-1}. Figure 4.8B shows a similar analysis for density from 1995 - 2017. Both regions show a decline in density over the the period. The northern trend has a slope of -0.002 yr^{-1} ($p=0.06$) while the southern trend has a slope of -0.003 yr^{-1} ($p<0.001$).

Grouping the sites by region and basin appears to show a small increase in snow depth and a small decline in density since 1995. The trends are not observed when the longer record is analyzed.

4.2.3 Snow Depth and Density Trends at the Site Scale

As described in section 4.2.2, moderate changes in the snow cover were detected during the period 1995-2017. These were calculated taking the mean of the means of each site in the entire basin or at the region scale. Table 4.6 shows trends in depth and density at the site scale. Out of 11 sites, 10 show a positive depth trend of which four (Winter, Big, Mesa, and Whitewolf) are significant ($p<0.1$). All four of these sites are in the northern half of the basin. The mean slope of the depth increase at the four significant sites is 0.5 cm yr^{-1} or approximately 1% yr^{-1} of historical mean depth. Out of 11 sites, 10 show a negative density trend of which five (Ghost, Winter, Castor, Big, and Whitewolf) are significant ($p<0.1$). Three out of these five sites are in the northern half of the basin. The mean slope of the density decline at these five sites is 0.0016 yr^{-1} or about 1% per year of the basin mean density.

4.2.4 Trends in relation between SWE and depth

Mean historical values of the R^2 between SWE and depth are shown in Table 4.1. Figure 4.9 shows the R^2 disaggregated by year and by site as well as region means. The R^2 of the southern sites varies through a much greater range than in the northern sites. The overall mean is 0.55 in the southern sites and 0.90 in the northern sites. The southern site mean shows no increasing or decreasing trend while the northern site mean shows a statistically significant declining trend with a slope of -0.002 yr^{-1} ($p = 0.009$). Northern sites also show increasing variation over the historical record.

4.3 Estimating Basin-Wide SWE

4.3.1 Current SWE Estimate Confidence Intervals

Considerable spatial variation was observed for SWE over the historical record both

Table 4.6 *Trends in depth and density at the site scale over the full historical record (1978-2017). Trends which are significant at the p < 0.1 level are highlighted. Depth slopes are bolded if positive. Density slopes are bolded if negative.*

		Snow Depth			Snow Bulk Density		
Region	Site	R^2	p-value	Slope (cm yr^{-1})	R^2	p-value	Slope (g cm^{-3} yr^{-1})
South	Big Spruce	0.08	0.146	**0.34**	0.10	0.116	**-0.002**
South	Ghost	0.04	0.212	**0.18**	0.08	0.076	**-0.001**
South	Mattberry	0.02	0.464	**0.12**	0.03	0.376	0.000
South	Snare	0.01	0.651	-0.06	0.08	0.102	**-0.001**
South	Indin	0.04	0.206	**0.19**	0.02	0.345	0.000
South	Castor	0.01	0.607	**0.07**	0.11	0.044	**-0.001**
North	Winter	0.13	0.031	**0.27**	0.25	0.002	**-0.001**
North	Christison	0.03	0.443	**0.19**	0.05	0.300	**-0.001**
North	Big	0.23	0.031	**0.71**	0.20	0.047	**-0.003**
North	Mesa	0.08	0.096	**0.20**	0.34	0.000	**-0.002**
North	Whitewolf	0.19	0.044	**0.63**	0.03	0.407	**-0.001**

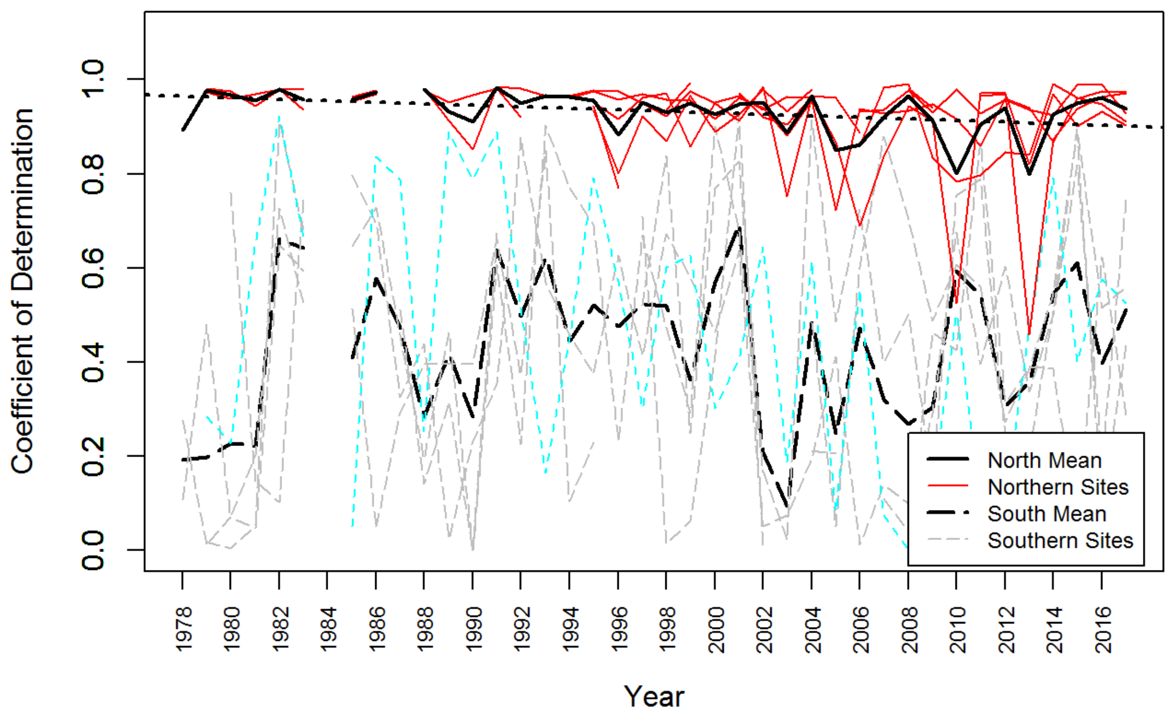

Figure 4.9 *Coefficient of determination (R^2) between SWE and snow depth (1978-2017). Red lines show individual northern sites with the solid black line showing the mean of all northern sites. Linear trend analysis performed on the northern means shows a declining trend with a slope of 0.002 yr^{-1} ($p = 0.009$). Gray dashed lines show individual southern sites with the black dashed line showing the mean of the southern sites. Southern sites vary through a much greater range than northern sites. The variation of northern sites appears to be increasing with time.*

within sites (intra-site) and between sites (inter-site). This large variation leads to errors and uncertainty in the SWE estimate at the site, region, and basin scale. Estimates of CIs depend on how many samples the survey is considered to have, which is not necessarily straightforward to determine due to the effect of spatial-autocorrelation at the intra-site scale. One strategy to avoid this problem is to pool individual observations at each site and average them, thus treating the mean of each site as a single observation. In this case the number of samples, n, is small ranging from 8 – 11 in each year, resulting in wide CIs. Ignoring the issue of spatial autocorrelation and considering all observation from each site to be independent, results in n values an order of magnitude higher. This reduces estimates of standard error and narrows CIs.

To address these issues, 95% CIs were calculated in different ways. Table 4.7 shows the mean annual 95% CI as a percentage of mean SWE for three different scenarios, broken down by region. In scenario 1 observations were pooled at the site scale such that the average of each site was treated as a single observation. This scenario can only be run from 1995 - 2017 since the number of northern sites, excluding Winter Lake, were as low as 1 before 1995. As expected, with such low sample sizes, the 95% CI as a percentage of mean SWE is high, with values of +/- 26% and +/- 45% in the southern and northern regions respectively. Scenario 2 runs for the entire historical record (1978-2017) and assumes that each individual measurement is unique. As with scenario 1 the 95% CI as a percentage of mean SWE is much higher in the north (23%) than in the south (5.4%). CIs for scenario 1 and 2 were based on the normal approximation and calculation of standard error from sample standard deviation and sample size.

Scenario 3 uses a bootstrap method to estimate the mean annual 95% CI as a percentage of mean SWE for each region, and for the entire basin. It also separates the contribution of error to the region- and basin-wide estimates that comes from both intra- and inter-site variation. Bootstrap estimates of total (intra- plus inter-) 95% CI as a percentage of mean for the southern and northern regions both fall between the scenario 1 and 2 estimates, and were 10% and 25% respectively. The basin-wide estimate is +/- 17%. Separating by region and intra- *vs* inter-site sources of variability indicates where the largest sources of sampling uncertainty are in the calculation of basin-wide SWE. The largest 95% CI as percentage of mean is found in the northern region with the inter-site and intra-site CIs of 18% and 17% respectively. Inter- and intra-site CIs in the southern region were much lower at 4% and 9% respectively.

To examine if the relative contribution of error between the northern and southern sites have been relatively constant over time, the 95% CI as a percentage of mean SWE for 1995 - 2017 is plotted in Fig. 4.10. In this case the analysis is broken down by year and assumed each individual measurement is independent as in scenario 2. N values range from 40 – 60. CIs in the north are consistently higher than in the south and neither region shows a significant increasing or decreasing trend.

4.3.2 Sample Optimization

Results from using the bootstrap method indicate that the number of sites required to estimate the mean SWE within 10% was 15 for the entire basin. Running the same analysis for the regions independently resulted in 6 sites for the southern region and 20 for the northern. The higher number of sites required in the northern region reflects the large difference in CV of SWE between north and south of treeline. The number of sites required to estimate the mean SWE within 5% was 69 for the entire basin, 20 for the southern region, and 75 for the northern region. These results indicate that the current sampling scheme of five sites in each region (six in the south with the Big Spruce lake site included) is likely close to achieving an estimate with CIs

Table 4.7 *95% CI intervals of SWE as a percentage of mean SWE (1978-2017). Scenario 1 assumes each site mean represents a single measurement (n varies from 4-6). Scenario 2 assumes each individual measurement is independent (n varies from 40 to 60). Scenario 3 uses a bootstrap method with 1000 repetitions.*

Scenario	1	2	3		
Region	%	%	Intra (%)	Inter (%)	Total (%)
South	26	5.4	9	4	10
North	45	23	17	18	25
Basin	16	11	13	11	17

of +/- 10% of mean SWE in the southern part of the basin but not in the north or for the entire basin.

At the site level both the number of density measurements and the ratio of depth to density measurements was examined. Optimal ratios of depth to density measurements were calculated and results are presented in Appendix B. Southern and northern ratios were consistent across sites within each region and over time. The mean southern ratio was 5:1, while the mean northern ratio was 11:1. In 2016/17 extensive depth measurements were taken along the NTPC transects (Appendix C). Using the extensive depth measurements in addition to the 10 NTPC SWE measurements changed the site SWE estimates by a mean of 7.5%.

Table 4.8 shows the number of density measurements needed at depth:density ratios of 1:1 and 11:1 to achieve site level estimates within 10%, 15%, and 20% of best-case means with 95% confidence. The current sampling scheme of 10 depth measurements, with no additional depth, results in 95% CI's less than 10% at all sites in the southern part of the basin except Snare lake. 95% CI's are much higher in the northern part of the basin, exceeding 20% using the current sampling scheme.

4.3.3 Density Models

The C_V of density was found to be lower than the C_V of depth, particularly in the north of the basin (Table 4.1). Coupled with the fact that depth is easier and faster to measure than density, a possible strategy for improving the SWE estimate at a site might be to use the available time to take extensive depth measurements and estimate density. Results of analysis in section 4.1.4 indicate modelling density with a simple division between regions may be the most effective.

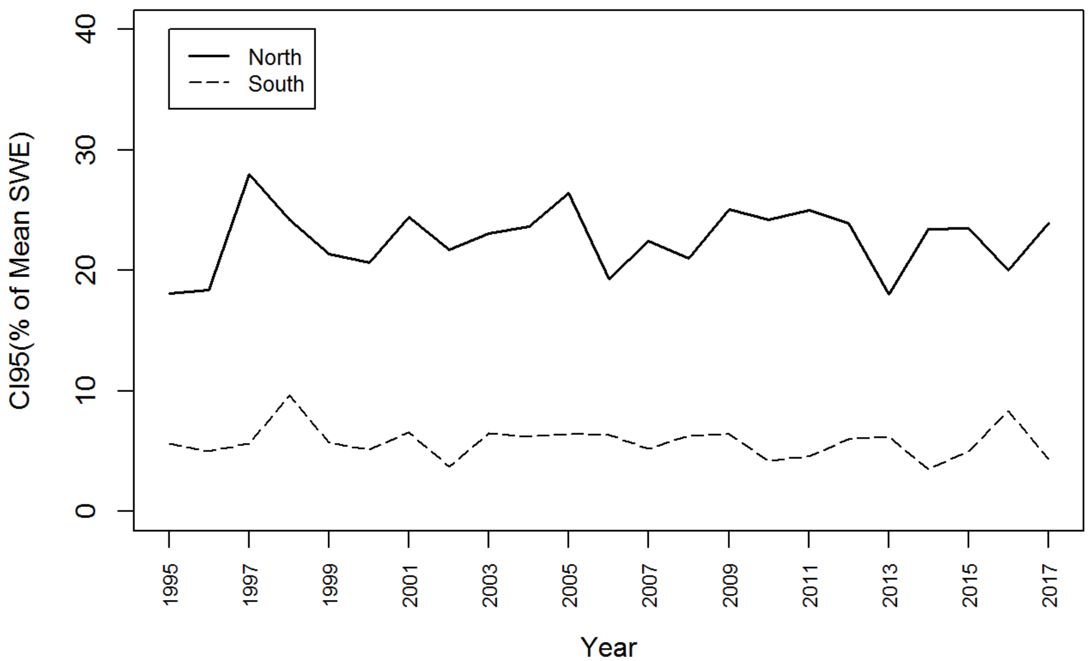

Figure 4.10 *95% CI as a percentage of mean broken down by region and year. Assumes each individual measurement is independent as in scenario 2 of Table 4.7 (n varies from 40 to 60).*

Table 4.8 *Number of density measurements needed to achieve estimates within 10%, 15%, and 20% of the "best-case" estimate with 95% confidence. The "best-case" SWE estimate is calculated using 10 density measurements and all extensive depth measurements taken at that site in 2017. Results are presented at two depth:density ratios: 1:1 and 11:1. The values indicates the number of density measurements that need to be taken.*

		10%		15%		20%	
	Ratio	1:1	11:1	1:1	11:1	1:1	11:1
Region	Site						
South	Ghost	9	3	4	2	3	1
South	Mattberry	7	2	4	1	2	1
South	Snare	14	13	7	7	4	4
South	Indin	8	6	4	3	2	2
South	Castor	4	2	2	1	1	1
North	Winter	>30	>30	>30	24	>30	14
North	Christison	>30	>30	>30	21	21	14
North	Mesa	>30	25	>30	12	18	8
North	Whitewolf	>30	21	27	11	16	6

This study first tested using a single density estimate for the entire basin or two estimates, one for each region. The mean density of all historical measurements was 0.212 g cm^{-3} for the entire basin and 0.194 g cm^{-3} and 0.246 g cm^{-3} for the southern and northern regions respectively. Accounting for the additional northern sites added in 1995 changes the northern mean density by less than 1%. Sturm *et al.* (1995) classify the area of the Snare basin as taiga and suggest using a mean density of 0.217 g cm^{-3}. Figure 4.11 shows the complete historical record with the mean, basin-wide SWE estimate (solid black line) calculated by weighting the area of the basin considered to be north and south of treeline and using only the measurements taken in each region. The dashed lines represent the estimated basin-wide SWE using only depth measurements and the historical, basin-wide, mean density, the Sturm *et al.* (2010) estimated density for taiga forest, and the historical, region-wide, mean densities. For those three scenarios, the depth based SWE estimate was reasonably well correlated to the SWE measurement estimate with R^2 values of 0.64, 0.64, and 0.66 respectively. The absolute percent difference between the two estimates was 9.8%, 8.8%, and 8.5% for each scenario respectively. The range of differences between the two estimates was from 0% to 22%, 20%, and 21%.

A second simple density model, as described in section 3.5.4, involved using the current survey methods to estimate density at new sites. For the years 2016/17 the mean density in each region was calculated and used in equation [1] with the mean depth of the extensive depth measurements taken at the enhanced survey sites. This estimated SWE was compared to the best-case SWE estimate which included 10 density measurements and the extensive depth measurements. At a site level the, depth-only estimated SWE had a mean absolute difference from the best-case estimate of 10% (Range: 2-21%). As expected, the model performed slightly

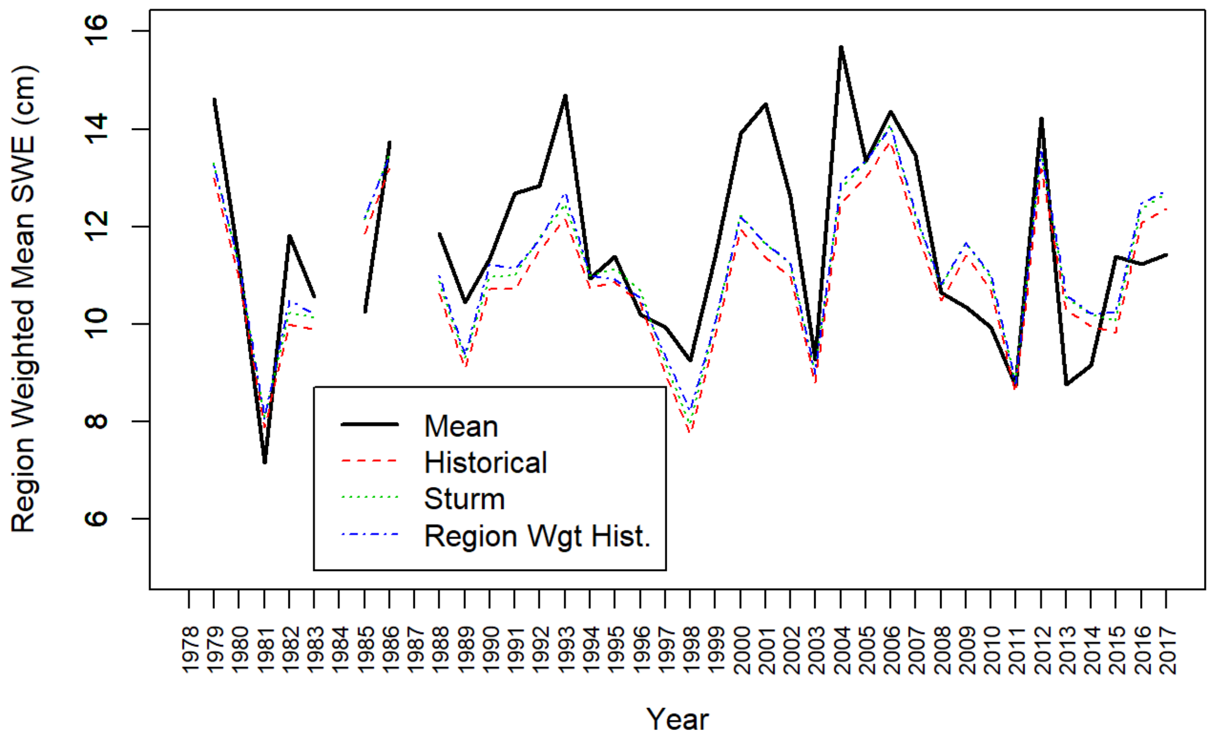

Figure 4.11 *Estimated basin-wide SWE using only depth measurements and mean densities, estimated using three different methods. Solid black line shows the area weighted basin-wide SWE estimate using SWE measurements. Dashed red line shows estimated SWE using depth measurements and mean historical density. Dotted green line shows estimate SWE using depth measurements and Sturm et al. (2010) estimated taiga snow density. Dash-dotted blue line shows SWE estimate using regional (north vs south of treeline) long-term mean historical densities.*

better in the south with a mean absolute difference of 8% (Range: 3-15%) than in the north which had a mean absolute difference of 12% (Range: 2-21%). Figure 4.12 shows a bar plot of the depth-only estimated SWE compared to the best-case estimate for sites A1-A6 (2016) and B1-B10 (2017).

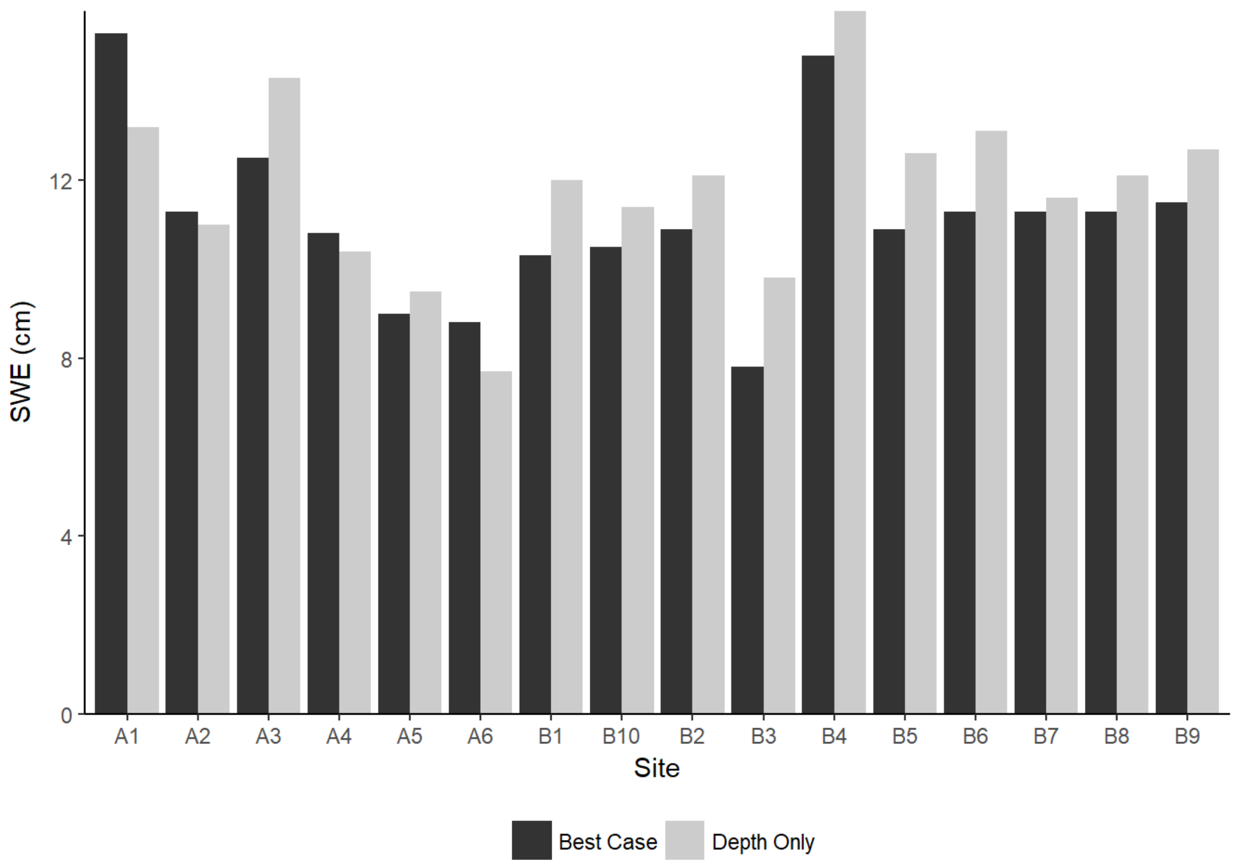

Figure 4.12 *Depth-only estimated SWE at enhanced survey sites (gray bars) compared to best-case (black bars) estimate. Depth-only estimate uses mean regional density from NTPC sites and mean of enhanced depth measurements at enhanced sites. Best-case uses enhanced depth measurements and 10 density measurements from enhanced sites.*

5 Discussion

5.1 Spatial Variability of Snow Cover Properties in the Snare Basin

Analysis of the historical record and enhanced surveys indicate that there are two distinct snow regimes within the Snare basin. Snow in the northern region has greater SWE, is shallower, denser, and more variable at the intra-site scale (indicated by higher C_V) and at the inter-site scale (indicated by poor correlations between sites). The correlation between SWE and snow depth is much stronger in the north. SWE and snow depth distributions in the north were positively skewed, while they were nearly symmetrical in the south. The differences observed are consistent across sites within each region and over time. The findings broadly support the differences noted in other studies between the snow regimes in open and forested areas (Steppuhn and Dyck, 1974; Adams, 1976; Pomeroy and Marsh, 1997; Derksen *et al*., 2012; Hannula *et al*., 2016).

The enhanced surveys conducted in 2016 and 2017 largely support the differences between the regions described above. The choice of the original locations for NTPC historical sites, and the three added in 1995, was somewhat arbitrary. They appear to have been chosen based on a grid and are spread out evenly across the area in and near the Snare basin (Fig. 1.1). They were not chosen, with perhaps the exception of north and south of treeline, to represent the different terrain types within the basin. The southern sites are all relatively densely forested and have moderate topography. Physically, they do not represent the large areas of shrubs, more open forest, flat forest, wetlands, and steeper areas that are also found in the south. In 2016/17 there were 3 and 5 enhanced sites in each region respectively. The sites were chosen specifically because they were dissimilar to NTPC sites. The NTPC survey covers only a small fraction of the landscape. Each region is approximately 7000 km^2, making each survey site of 10 SWE measurements, spread out over a few hundred metres, represent an area of 1400 km^2. Still, in both years, and both regions, the enhanced survey observations were close to their respective NTPC survey observations in those years and to the historical differences in terms of the R^2 between SWE and depth and the mean and C_V of SWE, depth, and density. The different snow regimes at the large regional scale (north *vs* south of treeline) appear to contribute more to the overall variance in snow cover properties than the smaller scale differences associated with terrain types, except for lakes, within each region. This is consistent with various broad scale classification systems for snow that indicate ranges of depth and density likely to be found in different landscapes such as taiga forest or open tundra (Sturm *et al*., 1995).

The Winter lake site was identified as unrepresentative of the region it was located within (Table 4.1). SWE values at the site were significantly lower in almost all years than all other northern sites and typically lower than southern sites as well. However, the CV of the snow cover properties at Winter lake were like other northern sites. These two findings show that the snow cover at the Winter lake site is more similar to the snow cover found on lakes north of treeline than uplands. While it was not possible to conclusively identify any particular reason why the site was different from the rest it was noted that the site was relatively flat and had an open transition from the lake to the upland with no protective barrier of vegetation or significant change in elevation.

5.1.1 Differences in Snow Cover Properties Between Forested and Tundra Regions

The results indicate that there is a difference in the magnitude of the snow cover properties between the regions. While northern snow is shallower, it is also denser. The increase in density is larger than the decrease in depth and results in greater SWE. Any comparisons between north and south must consider the addition of three northern sites in 1995 and whether or not Winter and Big Spruce lakes are representative of a portion of the landscape within their region. To mitigate the effects of these data issues, statistical analyses was conducted with and without the potential outlier sites and over two different time frames: 1978-2017, and 1995-2017. In all cases, northern snow was shallower by approximately 10%, denser by approximately 25%, and contained approximately 15% more water.

Many studies have compared the accumulation of snow in adjacent open and forested areas. In forested landscapes a large portion of falling snow (up to 60%) is intercepted by the trees and then a portion of that (up to 40% of original snow fall) sublimates back to the atmosphere rather than unloading to the ground (Pomeroy and Gray, 1995; Storck *et al*., 1999; Jost *et al*., 2007; Lopez-Moreno *et al*., 2008). These studies were generally done in more southern forests with denser canopies as opposed to the open and sparse forest at the very northern edge of the boreal forest. In this context, the 15% less SWE in the southern half of the Snare basin makes sense if the sparse forest intercepts less than the 50%-60% of snowfall reported by Lopez-Moreno *et al*. (2008) or Pomeroy and Gray (1995). The greater density and shallower snow cover observed also agrees with previous findings regarding the difference in snow cover properties between open and forested snow cover (Sturm *et al*., 2010; Hannula *et al.*, 2016).

Large snow losses due to sublimation caused by wind redistribution, up to 75%, have been reported in tundra areas (Tabler, 1975; Benson, 1982; Pomeroy and Marsh, 1997). Tundra snow is typically reported as shallow, often 40 cm or less (Sturm and Liston, 2003; Derksen *et al*., 2010; Derksen *et al*., 2014) and relatively dense due to the effects of wind. The studies of tundra snow cited above were conducted in locations where the snow depth typically exceeds the height of the vegetation. The northern half of the Snare basin is well vegetated with at least some shrubs visible above the snow at all sites. This is a critical factor in the interaction of snow, vegetation, and wind driven redistribution and sublimation (Clark *et al.*, 2011). The northern half of the Snare basin may reflect a transition zone between the edge of the boreal forest and the more northern tundra. The southern canopy is still intercepting some portion of the snow allowing greater initial accumulation on the ground in the northern region. The high shrubs allow a certain amount of wind redistribution, increasing snow density and decreasing depth, but not enough to cause the high rates of blowing snow sublimation observed at more northern sites. A band of high snow accumulation along the forest-tundra transition has been reported previously (*e.g.*, Pomeroy *et al.*, 1995) and detected by passive microwave remote sensing (Derksen *et al.*, 2005).

There is a clear difference between the density of snow in the two regions of the Snare basin with density increasing from 0.19 g cm^{-3} in the south to 0.25 g cm^{-3} in the north. Rees *et al*. (2007) reported a mean density of 0.293 g cm^{-3} at Daring Lake, a site located at a similar latitude to the northern part of the Snare basin but further north of treeline. The Sturm *et al*. (2010) classification system estimates tundra snow density at approximately 0.3 g cm^{-3}. Sturm and Liston (2003) estimated mean snow density in the Arctic Coastal Plain, Alaska to be between 0.28 g cm^{-3} and 0.29 g cm^{-3}. The band of high shrub area in the northern half of the Snare basin could be a zone of transitional density (0.25 g cm^{-3}) between the lower densities of the southern forest covered region (0.19 g cm^{-3}) and the higher densities normally found in the northern tundra (~0.29 g cm^{-3}).

In addition to differences in the magnitude of mean snow cover properties, the results show that northern sites have significantly greater variation of SWE, depth, and density (Table

4.1). This supports previous studies that have found higher C_V's of SWE in open areas than within forested areas (Pomeroy *et al*., 1998). At the regional level, the higher variability of the snow cover north of treeline, shown in the correlation matrices in Fig. 4.3, support previous findings that forest covered landscapes exhibit more large-scale homogeneity than open areas which are prone to greater wind distribution (Essery and Pomeroy, 2004; Derksen *et al*. 2014; Hannula *et al*., 2016). Implications of the greater variation of snow cover properties in the north at the site and regional scales are discussed in Section 5.3.

Many studies have shown that snow depth varies more than density (Dickinson and Whitely, 1972; Stepphun, 1976; Elder *et al*., 1991; Bruland *et al*., 2015). This greater variation is used as one of the justifications for snow surveys to be conducted using many depth samples with relatively few density assays (Sturm *et al*., 2010; Clark *et al*., 2011). Typically, depth is found to have a higher C_V than density. For example, Derksen *et al*. (2014), working at Daring Lake, found C_V's of depth and density of 0.50 and 0.16 respectively. The C_V's found in the northern part of the Snare were similar to those found at Daring Lake, with the C_V of depth (0.56), much greater than the C_V of density (0.26) (Table 4.1). However, the typical greater depth C_V was not found in the southern region where mean C_V's of depth and density were 0.22 and 0.23 respectively. The depth C_V in the forest is at the high range of what has been reported in previous studies (Lopez-Moreno *et al*., 2011; Hannula *et al*., 2016). Enhanced surveys from 2016 and 2017 had typical greater depth than density C_V in the north, but lower depth C_V in the south.

The absence of higher depth than density variation in the southern part of the basin differs from the findings of many studies. However, snow studies are often conducted at alpine, prairie, tundra, and more southern boreal forest sites, rather than the relatively open canopy forests found at the northern edge of treeline. Additionally, the C_V of density is sometimes not reported due to an insufficient number of measurements at a site compared to depth (Hannula *et al*., 2016).

A significant relation between depth and SWE was found in both the southern (R^2=0.55) and northern (R^2=0.90) regions. The large difference in these R^2 values is an indication of the different physical snow regimes operating in each region and has implications for how each half of the basin should be sampled and modelled (See sections 5.3 and 5.4). The strong relation in the north was consistent across all sites and varied little when tested for in individual years. The high R^2 between SWE and depth in the northern region, and upward curved 2nd order relation, is similar to other studies (Adams, 1976; Jonas *et al*., 2009; Sturm *et al*., 2010). The low R^2 value found for the southern region is uncharacteristic of previous studies.

The probability distribution of snow cover properties in the historical record were consistent within each region and over time. Density was found to be close to normally distributed in both regions. Depth, and therefore SWE, were positively skewed in the northern region and relatively normal in the south (Table 4.2). The similar distribution of depth and SWE are an indication of the strong relation between them (Fig. 4.1). The inter-site consistency within each region supports previous research showing that different sites within a certain landscape type will have similar probability distributions (Stepphun and Dyck, 1974). Several previous studies, across a variety of landscapes, have shown that density is typically close to normally distributed, while depth tends to be positively skewed (Derksen *et al*., 2008; Jonas *et al*., 2009; Sturm *et al*., 2010; Bruland *et al*., 2015). As described by Hannula *et al*. (2016), the skewed distribution of depth is due to the fact that snow can be scoured by wind to a lower limit of 0 but can accumulate in an unbounded fashion. The lower likelihood of redistribution by wind in the forest may account for the more normal depth distribution, however this is contrary to the skewed depth and SWE that is typically reported.

It is important to note, for the development of sampling strategies, that though northern sites were poorly correlated with each other in terms of the magnitude of SWE and depth (Fig. 4.3) there was a high level of inter-site consistency with respect to many of the statistical properties (Probability distributions, R^2 between depth and SWE, C_V of SWE, depth, and density) observed both north and south of treeline. This suggests that it is appropriate to use different sampling strategies in each region.

5.1.2 Geographic Predictors of Snow Cover Properties

The results presented in Table 4.3 show that none of the three geographic variables tested (latitude, elevation, distance from treeline) were significant predictors of SWE or depth given the data available. While the relations between the variables typically supported the findings of higher SWE and lower depth in the north (in terms of sign), the R^2 values were low and the relations were significant ($p<0.1$) in less than 50% of the years tested. Relations between the three geographic properties and density were stronger, with R^2 values as high as 0.54, but still often not significant ($p<0.1$). Several previous studies have used relations between snow cover properties and elevation, latitude and longitude (Jonas *et al*., 2009; Bormann *et al*., 2013; Sexstone and Fassnacht, 2014; Bruland *et al.*, 2015) to model SWE. However, as with many snow studies, these were conducted largely in alpine areas. Additionally, the models tend to work in conjunction with detailed meteorological data that is not available in the Snare basin. The simple two-region model of density explained as much variation as any of the continuous predictor variables. Again, the different snow regimes at the large regional scale appear to be more dominant than the smaller scale changes in geographic properties.

5.1.3 Landscape Unit Predictors of Snow Cover Properties

The fundamental problems with snow sampling in the Snare basin are size and access. This is not unique to the Snare basin; any large watershed is going to suffer from access problems. Even a small basin of a few km^2 cannot necessarily be thoroughly sampled every year, given the possible changes in snow accumulation due to deposition, terrain, vegetation, and climate. A commonly adopted, and well-studied, solution to this problem is a stratified sampling scheme based on differences in terrain type (Stepphun and Dyck, 1974; Woo and Marsh, 1978). Two representative studies using this strategy are Woo and Marsh (1978) and Rees *et al*. (2007) who divided their respective study sites into 9 and 12 categories. The categories used often include divisions such as slope angles (several ranges) and aspects (N, E, S, W). In the Snare basin these would have to be doubled to include terrain categories north and south of treeline. This quickly results in an unmanageable number of sampling sites. Any terrain type chosen would have to be sampled at several locations to ensure there is consistency in type, and then repeated over several years to ensure some temporal consistency. It is unknown at this time if a finer scale subdivision of terrain sampling units would contribute to improved SWE estimates.

The results presented in Table 4.2, Table 4.4, and Fig. 4.6 indicate that the broad regional differences have a greater influence on the snow properties one would expect to find in any location than the locally different terrain types. This appears to be true at least at the scale of the snow survey transects. Open areas, flat forests, burned forests and steep forests in the southern regions had snow cover properties similar to each other and to NTPC sites. In the north, the R^2 and C_V were relatively constant across the region, though the magnitude of SWE was not.

Given the limitations of smaller scale stratified sampling discussed above, the poor results of models using geographic properties discussed in section 5.1.2, and the similarity of snow cover properties at enhanced and NTPC sites within each region, it does not seem worthwhile to attempt to stratify the Snare basin into more detailed terrain types using the data from this study. The most promising approach with this data set, and future sampling that is similar to the current NTPC method, may be simply to stratify by the two main regions with the addition of lakes, discussed below, as a separate terrain type. Future studies, with more detailed terrain classifications, may change this approach.

Lakes cover approximately one fifth of the landscape, so a difference in SWE between lakes and uplands could have a significant effect on basin-wide SWE estimates and water balance calculations. Several studies have shown that SWE on lakes is significantly lower than on adjacent uplands in areas north of, or near the treeline (Sturm and Liston, 2003; Derksen *et al*., 2005; Derksen *et al.*, 2008; Rees *et al*., 2014). Three contributing reasons for lower SWE values on lakes are snowfall before freeze-up, lack of vegetation and topography to trap blowing snow, and the formation of snow ice (Sturm and Liston, 2003). The 23% lower SWE observed on lakes in 2017 would lower the basin-wide SWE estimate by 5.1 percent.

Lake snow in enhanced surveys was found to be shallower, denser, and have lower SWE than adjacent uplands. This is consistent with the studies mentioned above. Ratios of snow depth, snow density, and SWE on lakes relative to adjacent uplands for this study and three others (for comparison) are shown in Table 5.1. Due to the large CV of SWE north of treeline and the low number of SWE samples taken there is a large amount of uncertainty around the SWE estimates. This makes comparisons of lake and upland SWE north of treeline less certain than comparisons of SWE south of treeline or depth throughout the basin (Fig. 4.5).

Rees *et al*. (2014) working at Daring Lake (NWT), found lake snow depth was consistently and significantly lower than in flat uplands, however they did report lake snow was slightly deeper than exposed, vegetation free plateaus. The study by Sturm and Liston (2003) referred to in Table 5.1, was also entirely tundra based (Alaskan Coastal Plain) but was similar to this study in that concurrent surveys were taken on lakes and in the adjacent uplands. Derksen *et al*. (2005) (Table 5.1) took extensive measurements south and north of the treeline in a transect stretching from Thompson to Churchill, Manitoba. These three studies, and the two years of enhanced snow data from the Snare basin, suggest there is consistently less SWE on lakes than in adjacent uplands by a mean of 23%.

Consistent differences were found in the variability of all snow cover properties between northern and southern regions in NTPC historical data from upland sites, as inferred from C_V's (Table 4.1). For all three snow properties C_V's were higher in the north. Similar results were seen on lakes where all C_V values were higher in the north than in the south (Table 4.5).

5.2 Temporal Trends in Snow Cover Properties

A key objective of this thesis was to determine if there was a detectable long-term trend in basin-wide SWE. A decline in SWE at the end of the winter could have repercussions for hydro-management and future planning for NWT. In general, no significant increase or decrease in the amount of SWE stored on the landscape at the end-of-winter was detected. However, some changes to snow cover properties were found.

Remote sensing data from several studies have shown a general decline in Northern Hemisphere (NH) SWE over the period roughly coinciding with NTPC historical snow survey (Gan *et al*., 2013; Li *et al*., 2014; Jeong *et al*., 2017). The magnitude of the decline in SWE and

Table 5.1 *Ratios of snow cover properties found on lakes compared to uplands. The ratio expresses the mean fraction of the property (SWE, depth, density) found on lakes vs adjacent uplands.*

	Depth	Density	SWE
April 2016 Snare Basin, NT	0.58	-	-
April 2017 Snare Basin, NT	0.62	1.18	0.77
2004-2010 Rees *et al*. (2014) Daring Lake, NT	-	-	0.86
March 2005 Derksen *et al*. (2005) Churchill, MB	0.51	1.37	0.89
March/April 2001, 2001 Sturm and Liston (2003) Alaskan Coastal Plain	0.56	1.21	0.72

the applicability of the studies at a smaller scale is uncertain but there is a general understanding that SWE is in decline in the NH (Kunkel *et al.*, 2016; Sturm *et al.*, 2017). In the Snare basin, no statistically significant ($p < 0.1$) linear trends of increasing or decreasing SWE were detected at the basin or region scale when incorporating the full historical record. While a decline in SWE was detected in the southern part of the basin over the period 1995 - 2017, it was not seen over the longer record. At the site level, the single indication of a possible change in SWE, a decline at the Snare Lake site, was not significant when analyzed over the later period of 1995 - 2017, or with the removal of a single data point. The results of linear trend analysis of the historical record at three different scales, over two-time periods, and with and without the potential outliers show no long term trends in SWE. The studies cited above are on a much broader scale than the data from the historical Snare basin survey. The lack of evidence of a decline in SWE in the Snare basin may indicate that even for a relatively large basin (~13,700 km^2) hemispheric- and continental-scale findings are not applicable for hydrologic modelling or operational planning. A study by Derksen and MacKay (2006) which incorporated 25 years (1978-2002) of passive microwave data and in-situ SWE data highlighted the possible existence of an area near the northern edge of the Canadian boreal forest where the snow cover appears to be resistant to the changes observed in snow cover in southern boreal forests, prairies, and more northern tundra.

It should be noted that due to the large errors associated with the current SWE estimate it is possible that a trend is present but went undetected. It is also possible that the change in survey date (Appendix E) has masked a trend in SWE. The mean survey date was moved 18 days earlier in the year in 2005. NTPC staff told us the date was changed because the onset of melt was sometimes occurring earlier in the season and due to concerns about the Twin-Otter ski plane getting bogged down in slushy snow on the more southern lakes (personal communication, 2016). No sudden change in snow depth, snow density or SWE was noted in the historical record in 2005.

While no long-term changes in SWE were detected, changes in annual snow depth and snow density were detected. The depth and density of snow cover play a role in the progression of the annual the spring melt and can, to some degree, alter the amount of outflow independent of the basin-wide SWE (Elder *et al.*, 1998; Liston *et al.*, 2002; Clark *et al.*, 2011). Changes in the variation of depth and density can also affect the rate of snow covered area decline during melt and thus the energy balance (McCartney *et al*. 2006) and resulting outflow. No significant increasing or decreasing trend in snow depth at the region or basin scale was detected over the full historical record. Increasing snow depth and decreasing density were detected across both regions in the period 1995-2017 (Fig. 4.8). Both trends were stronger in the northern region. Zhong et al. (2018) using depth data from across Eurasia also detected an increase in snow depth over the years 1966 - 2012. Ma and Qin (2012) (as cited in Zhong et al., 2018) detected a similar increase in China over the years 1957 - 2009. The upward trend in depth and downward trend in density cancel each other out with respect to SWE. R^2 values between SWE and depth (Table 4.9) in the north declined, while the variability of the R^2 values in the north increased (Fig. 4.9).

The three trends described above, increasing depth, decreasing density, and changing R^2, indicate that the snow cover characteristics of northern sites may be changing to something more similar to the snow cover found at southern sites. This could be an indication of a changing climate affecting temperature, weather patterns, and/or vegetation growth. Studies have shown that the amount of vegetation in the Arctic and subarctic shrub lands has been increasing in response to climate change (Sturm *et al*., 2001b; Hinzman *et al*., 2005; Tape *et al*., 2006). The vegetation data collected in this study was coarse, consisting only of a qualitative statement regarding the relative density of forests in the southern part of the basin and whether or not shrubs were visible above the snow in the north. Since vegetation has a significant effect on snow, changes in shrub height, complexity, or species could have an effect on how the snow collects and is redistributed. An increase in shrub growth causes more snow to be trapped and causes an increase in snow depth (Sturm *et al*., 2001; Liston *et al*., 2002; Hinzman *et al*., 2005;). The increase in snow depth is accompanied by a decrease in density due to a greater portion of the snowpack being depth hoar rather than tightly packed wind slab (Sturm *et al*., 2001; Liston *et al*., 2002). This increased depth and change in the proportion of snow type can alter the thermal properties of the snow which in turn impact melt rates, energy exchange with the ground, and basin outflow (Liston *et al*., 2002).

5.3 Scale and Landscape Stratification

Spatially extensive snow sampling of large watersheds of similar size to the Snare basin is rare, particularly in northern regions. For example, Clark *et al*. (2011) did a review of 50 studies dealing with the spatial variability of SWE. Only one paper examined a watershed of comparable area, while the rest had an average study area of less than 25 km^2. Woo (1998) stated that for basins up to 1000 km^2 (a full order of magnitude smaller than the Snare basin) it is not feasible to map snow distribution in detail but dividing the basin into similar units such as plateaus, gullies, and different facing slopes offers potential for basin-wide SWE estimates. Beyond 1000 km^2, remote sensing offers the only feasible approach, with ground data having "insurmountable difficulties" (Woo, 1998). However, remote sensing products such as passive microwave still require ground truthing, calibration, and are particularly problematic in areas with a high fraction of lake cover (Kelly *et al*., 2003; Derksen *et al*., 2008; Derksen *et al*., 2010; Dozier *et al*., 2016).

Given the high costs of sampling in a large sub-arctic basin and the absence of acceptably accurate remote sensing, stratification by landscape type offers a possible solution to improving SWE estimates. This is not a new concept, stratification by vegetation, radiation, and other factors has been thoroughly studied in smaller watersheds for some time (Stepphun and Dyck, 1974; Woo and Marsh, 1978). There are several difficulties with applying this approach to large basins. The consistency within and between a landscape type may not hold as distances between areas of that type move from a watershed to a regional scale (Stepphun and Dyck,1974; Bloschl, 1999). Furthermore, it is difficult to determine the actual differences in snow properties between types without extensive measurements. For example, Watson et al. (2006) investigated optimal sampling schemes for different landscape types within a heterogeneous watershed. A relatively small watershed (314 km^2) was divided into strata based on vegetation, slope, and radiation. A nested sampling scheme was used to deal with variations at difference scales. Nested triangles of measurements spaced up to 300 m were used. It was found that to determine the effects of vegetation and radiation, as separate from random effects, 27 and possibly up to 54 carefully placed snow cores were needed. This level of sampling, even 27 cores, far exceeds any reasonable amount that can be achieved in the Snare basin at a site. This is especially true given that typical stratification schemes would require a dozen or more types in the Snare basin per region and need to be tested over several years.

In the most general sense, the results of this thesis suggest that there are three practical landscape types for stratifying the Snare basin: north and south of treeline, and lakes. The historical record shows consistent differences in the magnitude of SWE and in other snow cover properties between the two main regions. The results of the enhanced surveys supported these differences with respect to magnitude and variation of snow cover properties despite differences in topography and vegetation cover. In addition to determining what landscapes to survey in a basin of this scale there is also the issue of determining the scale at which to sample an individual site. Estimating the error and the confidence intervals for the SWE estimate at the site- and basin-scale is complicated by the highly clustered nature of ground surveys across such a large region. Site scale transects are on the order of 100's of metres in length while sites visited by airplane or helicopter are typically 50 km to 70 km apart. NTPC historical transects range from 130 m to 275 m, these are at the scale of typical snow surveys (Pomeroy *et al.*, 2002). Watson *et al.* (2006), determined that 83% of random variation in snow cover in their study area occurred at a scale of 100 m.

5.4 Density Models

There are several reasons for investigating the potential of taking only depth measurements and estimating or modelling density: snow depth varies through a much larger range than density; snow depth is easier and faster to measure; LiDAR, structure for-motion, and other technologies may make mass snow depth information easier to obtain in the near future (Deems, 2013); and the inter-annual heterogeneity of density between different terrain types is less than with depth (Fassnacht *et al*., 2010; Sturm *et al*., 2010).

The first model tested applies an estimate of density to the snow depth measurements over the historical record. Using this simple density model results in a SWE estimate with a mean difference from the current sampling strategy on the order of +/- 10% with a maximum difference on the order of 20%. Considering the CI's reported in Table 4.7 this approach has potential. Sturm *et al*. (2010) reported a similar range of error (up to 26%) using a snow-class density model in three different locations using only DOY and snow depth. Another similar model by Jonas *et al*. (2009), in an alpine area using depth and altitude, was found effective giving SWE estimates within 1 standard deviation of +/- 16%. Working at a tundra site, Rees *et al*. (2007) found an R^2 value of 0.9 between measured SWE and SWE estimated with average density and measured depth. Sturm *et al*. (2010) make the key points that these relatively simple models are ideal for northern areas with limited populations, access, and meteorological data.

Correcting the density estimate with the relation between depth and density did not significantly improve the model. Pomeroy and Gray (1995) and Stephhun (1976) reported weak relations between depth and density when snow depth was less than 80 cm and 85 cm respectively. In the Snare basin historical record only 3.5% of measurements were above 80 cm in depth.

The next model investigated used the density data collected from NTPC sites in each region and applied it to the enhanced sites in 2016/17. Using depth data from enhanced sites and density from NTPC sites, SWE was estimated at enhanced sites with a mean absolute difference of 10% from the best-case estimate where all SWE measurements are used. The results were better in the south than in the north which is expected given the greater variation of snow cover properties in the north.

5.5 Recommendations for Annual Survey

The discussion below assumes that any proposed changes are in addition to the current sampling scheme. NTPC has been measuring SWE at 11 sites distributed across the basin using a consistent method for 40 years. While changes to the current sampling scheme might improve the chances of a more accurate SWE estimate, they may be outweighed by the disruption of a valuable, continuous historical record. The recommendations below, regarding depth to density sampling ratios depend on the assumption that depth measurements are taken with an automated probe and can therefore be taken relatively quickly. In situations where the C_V of density is not lower than depth, a higher number of depth measurements is still recommended due to their lower cost in time.

In general, open/tundra areas north of treeline exhibit greater variation in snow cover properties resulting in greater error. They should be sampled at more locations and more intensely than forested areas south of treeline. This is indicated by the CI's presented in Table 4.7 which give an estimate of the size of the error in the basin-wide estimate and the relative contribution from different sources. The concept that different terrain types require different numbers of samples and a different balance of depth and density is not novel. The consistent regional differences found in the historical record suggest that different approaches to sampling are appropriate for the northern and southern portions of the basin. In this context, the two important differences between the regions are the C_V's (Table 4.1) and the annual correlations between sites (Fig. 4.3). These two differences lead to different optimal ratios (Appendix B), density measurement requirements (Table 4.8), site number requirements, and error reducing priorities (Table 4.7). The enhanced surveys supported the findings in both 2016/17, particularly with respect to the variation of depth and density (Section 4.3.2). Therefore, it seems reasonable to approach sampling at any new sites with the optimal ratio found for the region the new site is within. This ratio is 5:1 depth to density in the south and 11:1 in the north (Appendix B). It should also be noted that regional differences noted above were found to be consistent over time (Fig. 4.7).

Given the large estimated errors shown in Table 4.7 there is a need to better characterize both inter- (in the north) and intra-site (in the north and south) variability by increasing the total number of sites visited across the basin, and by improving the sampling within each site.

Although this an obvious conclusion, the results indicate that there are more efficient approaches than simply adding to the number of sites and/or number of measurements per site. As stated previously, sampling in the Snare basin is complicated by two main issues: size and access. These two factors contribute to the high cost of travel within the basin and justify efforts to target additional sampling where it would be most effective.

At existing southern sites, the current system of taking 10 density measurements should result in an estimate of SWE that is generally within 10% with 95% confidence. The addition of extensive depth measurements will improve the estimate and is easily accomplished (Appendix C). At existing northern sites, the current method of 10 density measurements results in large errors. Even the addition of depth measurements at an 11:1 ratio only improves the estimates to approximately +/- 20% with 95% confidence (Table 4.8).

At the region scale, the error in the northern half of the basin is roughly double that in the south. The existing sampling scheme of 5 sites in the south (6 if the Big Spruce lake site is included) should result in a SWE estimate with a 95% CI of 10%. To achieve a similar level of confidence in the north would require the addition of 15 new sites to improve the inter-site error as well as extra density observations at each site to improve the intra-site error. When considering the entire basin, results indicate that the addition of 5 new sites should generate an estimate with a 95% CI of 10%.

It is likely impractical to add 15 new northern sites. However, a single additional day of surveying could easily add 5-10 new northern sites, particularly if a helicopter is used rather than a Twin-Otter. While the helicopters used for surveying have less range before needing to be refueled they have considerably faster landing and take-off times. Any new sites would be grouped only in the northern half of the basin and mitigate the loss of range. Considering the results presented in Table 4.7 and 4.8, the best approach would be to add as many northern sites as possible, take as many density measurements at each site as time allows, use an 11:1 ratio, and err on the side of more sites rather than more density measurements to get the broadest spatial coverage. Intra-site error in the north can be improved by increasing the number of density measurements at existing sites.

Taking the above suggestion to the extreme would mean taking only depth measurements at the new sites. Density could be estimated from the mean regional density from the NTPC survey in that year. Year-to-year density varies by less than depth in the north and almost 60% of the variation can be captured using the mean of NTPC sites. The results presented in section 4.3.3 show SWE errors on the order of 10% using this method. While still a considerable amount of error, using this method would help address the key problem of so few sites across such a large area.

Lastly, any survey conducted by plane, typically begins and ends on lakes, making them easy to access and requiring no additional travel time. Conducting surveys on lakes is typically faster than in the uplands, due to the ease of walking without vegetation or changing topography. If personnel are available to conduct the lake survey, then it should be done for at least several years to determine if the differences in SWE found in this study stay relatively constant. The high level of uncertainty of SWE estimates north of treeline indicates that more extensive SWE sampling needs to be done to improve the confidence of comparisons between lakes and uplands in that region.

In summary, suggested additions to the existing sampling scheme in order of priority are:

1. Add northern sites.
2. Take extensive depth measurements at both existing and new northern sites.
3. Increase the number of density measurements at northern sites.
4. Sample lakes while upland surveys are in progress.

6 Conclusion

The aim of this thesis was to quantify the spatial variation of snow cover properties across a large subarctic basin, look for evidence of temporal trends in end-of-winter snow cover, quantify the confidence intervals around the current sampling scheme, and analyse alternative sampling schemes to improve the basin-wide SWE estimates for hydropower operations.

The first objective was to examine the spatial variation of snow cover properties. The historical record clearly shows that there are consistent differences between the snow regimes in the two major regions of the Snare basin. The differences are consistent across sites, over time, and were confirmed by the more spatially extensive surveys completed in 2016/2017.

- Snow north of treeline is typically shallower (~13%), denser (~15%), and has greater SWE (~17%).
- Snow north of treeline is more variable at the site and region scale.
    - Site scale: The mean C_V of SWE, depth and density are greater in the north by approximately 163%, 152% and 15% respectively.
    - Region scale: Southern sites are relatively well correlated with each other year-to-year with a mean correlation coefficient of 0.75 as opposed to the lower coefficient of 0.38 in the north.
- Snow depth and SWE north of treeline have positively skewed distributions while snow properties in the south are all close to normally distributed.
- SWE and depth are highly correlated in the north (0.90) and much less so in the south (0.55).

Historical data and enhanced surveys indicate that there are relations between SWE and depth with elevation, latitude, and distance from treeline. However, the relations are weak and inconsistent year-to-year and therefore not likely useful for predictive models. The relation with density and the three geographic variables was stronger and more consistent. However, in all three cases a simple two-factor model using a northern and southern region explains as much variation as any continuous variable. Approximately 54% of the variation of density can be explained by using a simple two region model.

The enhanced surveys sampled a wider variety of terrain types than the NTPC historical survey. The mean and C_V of SWE, depth, and density from these new sites closely followed their respective regions. For example, open areas in the southern part of the basin had snow cover properties more like the forested parts than the open north. The similarity between NTPC and enhanced surveys in the south indicate that NTPC sites, though similar and not representative of the southern landscape, are not particularly biased. A similar conclusion can be reached in the north, but the greater variation of snow makes it less certain. At the scale of snow surveys conducted by NTPC (100's of m) differences in terrain such as vegetation and topography appear to be less significant than the broad regional differences.

The second objective was to analyze the historical record for temporal trends in end-of-winter snow cover properties. For the purposes of NTPC one of the more important aspects of this thesis was to determine if there was a detectable change in SWE at the end of the winter. This study found no detectable change in basin-wide SWE over the 40-year period. However, changes to the structure of the snow were detected, with northern snow becoming deeper and less dense. These changes are important to monitor since changing snow regimes could affect future optimal sampling design.

The third objective of this study was to quantify the error associated with the current SWE estimate, analyze the number of sites and samples per site needed to meet specific error objectives, and examine the application of a simple density model. Different assumptions result in a range of 95% CI's as a percentage of mean SWE of 5.4% - 26% for the south and 23% - 45% for the north. Using a bootstrap method to differentiate the contribution to the error at different scales resulted in CI's of 18% (north, inter-site), 17% (north, intra-site), 9% (south, intra-site), 4% (south, inter-site). The regional differences between the CI's reflect the greater variation in SWE in the north at both the site and region scale. The larger contributions of error in the north indicate the priority at which any new sampling should be done. Overall, the results of this study indicate that any additional resources used to improve the basin-wide SWE estimate should prioritize reducing the inter- and intra-site error in the northern region. Any additional resources used in the southern region should address the error associated with the site level estimate.

Including the Big Spruce Lake site there are currently 6 sites surveyed south of treeline. At 10 density measurements per site, the current sampling scheme is likely achieving a SWE estimate within 10% with 95% confidence for the southern half of the basin. Adding extensive depth measurements would improve the estimate at little cost and/or lower the number of SWE measurements needed. The extremely low inter-site error estimate within the southern half of the basin (Table 4.7) indicates that additional sites south of treeline are not likely required. Currently there are 5 sites sampled north of treeline. Analysis shows that an additional 15 northern sites would reduce the CIs to roughly 20% for the northern half of the basin and to below 10% for the basin as a whole. New northern sites, visited by helicopter, could be located in varied terrain types to help overcome any bias due to the current sites being located in upland areas adjacent to large lakes. The addition of extensive depth measurements at existing and new northern sites would significantly improve the CIs. Visiting 15 new sites would be prohibitive if they each required 10 density samples. A simple density model was tested by assuming mean densities from different sources which resulted in SWE estimates with no density measurements taken correlated to the current sampling scheme with an R^2 values of approximately 0.65. A second model was tested which assumed density at enhanced sites equal to the regional mean density at NTPC sites. This model generated SWE estimates at enhanced sites with an absolute mean difference of 10% from estimates with density measurements.

To better understand the spatial variation of snow within the basin there are several further research areas that could be investigated. The lower SWE values found on lakes should be investigated for several years to determine if the difference is close to a constant ratio. If more meteorological data could be collected, an improved density model in conjunction with more detailed depth data could be an effective way to estimate SWE.

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Appendix A - Available Data

Table A.1 *Mean SWE (cm) for each site and year. Big, Christison, and Whitewolf lakes were not surveyed until 1995. Dashes indicate missing data or when a survey was not conducted due to poor weather. Highlighted cells indicate where original field notes with 10 individual measurements of SWE and depth are not available and only the mean SWE is known.*

Year	Bigspruce	Ghost	Mattberry	Snare	Indin	Castor	Mesa	Winter	Big	Christison	Whitewolf
1978	8.3	8.6	10	9.7	6.7	11.9	12.8	5.5			
1979	10.4	12	12.4	15.1	13.9	14.1	16	9.8			
1980	8.4	10.4	6.8	13.4	9.2	13.8	11.8	10			
1981	7.1	5.6	4.1	6.5	6.9	6.4	8.3	6			
1982	7.9	7.8	8	10.1	9	7.6	14.9	5.8			
1983	9.2	8.8	8.9	10.3	10.5	10.8	11.3	7.3			
1984	13.4	19.5	18.1	19.8	19.8	19.5	18.7	20.2			
1985	11.9	10	9.2	13.4	11.2	10.5	9.7	5.7			
1986	11.8	15.3	15.7	15.5	14.8	16.4	12.7	8.4			
1987	6.8	8.1	11.2	10.9	10.5	12.2	12	12.7			
1988	12.2	10	8.5	12.7	8.8	10.2	13.2	8.7			
1989	9.7	8.5	8.6	9.8	9.3	9.1	11.7	5.5			
1990	6.6	11.3	8.8	12.8	11.7	10.6	12.3	10.7			
1991	12.4	12.5	10.6	11.5	11.2	12.5	13.5	7.2			
1992	12.5	13.2	11.5	13.4	12.9	13	12.5	7.5			
1993	8.3	10.8	9.3	12.1	12.2	12.9	17.2	10.2			
1994	11.8	10.9	10.9	12.5	10.5	11.5	10.6	8.2			
1995	13.3	12.3	10.8	11.1	12.9	13.3	12.7	6.8	9.8	8.7	10.2
1996	14.5	11.7	10.9	13.5	11.1	11.4	10.7	7.6	7.2	6.3	12.3
1997	8.4	8.9	9.1	10.1	11.1	9.9	10.4	6.3	-	11.6	8.9
1998	11	6.2	5.5	6.6	8	7.4	11	4.7	13.7	8.5	13
1999	9	9.6	10.2	11.8	11.7	11.6	13.7	8.1	12.7	12.5	9.3
2000	10.2	13.7	13	13.9	17.4	16.2	15.5	10.2	-	12.6	13.3
2001	15	14.5	10.9	13.8	15.9	14.7	13.9	11.9	13.2	19.4	13.1
2002	15.7	12.2	11.6	12.7	12.6	13.3	11.9	8.1	13.7	11.6	13.9
2003	9.2	9	7.6	6.9	8.9	10.5	11.3	5.7	7	7.7	10.4
2004	9.7	12.4	10.7	10.4	14.3	13	18.3	8.1	12.9	19.4	26.6
2005	11.6	14.4	8.4	12.3	15	14.6	16.3	4.7	13.2	11.5	16.2
2006	12.2	11.8	13.6	12.5	15.1	16.4	20.9	7.4	12.8	10.9	14.9
2007	12	10.5	9.9	11.7	11.3	10.6	15	9.2	17.3	14.7	15.9
2008	8.7	8	8.5	9	9.7	7.2	14.3	7.9	10.1	13.6	12.3
2009	13.4	9.9	10.4	8.3	7	10.2	8.5	8.8	12	8.9	13.7
2010	8.9	9.2	8.9	10.2	9.5	9.3	14.1	7.2	8.9	9.5	9.5
2011	8.1	9	8.6	8.5	8.1	8.9	9.2	6	7.7	10.8	8
2012	11.9	13.3	11.5	12.7	11	12	11.6	8.9	24.5	11.9	16.6
2013	7.9	7.5	6.2	7.9	8.9	8.7	8.7	7.7	9.8	7.9	12.1
2014	9.2	8.8	7.7	8.2	8.8	8.2	8.2	5.6	9.4	10.2	11.5
2015	9.8	6.9	8.5	8.8	9.1	9.8	9.8	7.5	13.9	13.2	18.1
2016	8.8	7.4	7.7	12.3	10.2	10.4	13	13.2	14.3	9.2	14.9
2017	9.6	11.3	10.2	10.6	11	11.2	9.6	6	13.9	10.4	14.8

Appendix B – Optimal Ratios

Table B.1 *Mean optimal number of depth measurements per density measurement (1978-2017). Calculated using double sampling method described in Rovansek et al. (1993). An assumption was made that 20 depth measurements can be made per density measurement (Sturm et al., 2010). Southern mean was 5:1 and all sites fall between 5:1 and 6:1. Northern mean was 11:1 and all sites fall within a range of 10:1 to 12:1. Disaggregating the data by year shows strong consistency, northern sites across the historical record have an optimal ratio of close to 11:1 while southern sites stay near 5:1.*

	Site	Mean Optimal Ratio (depth:density)
South	Ghost	5:1
	Mattberry	5:1
	Snare	5:1
	Indin	5:1
	Castor	6:1
	Mean	5:1
North	Winter	11:1
	Christison	11:1
	Big	12:1
	Mesa	10:1
	Whitewolf	10:1
	Mean	11:1
Basin	Mean	7:1

Appendix C – Extra Depth Measurements

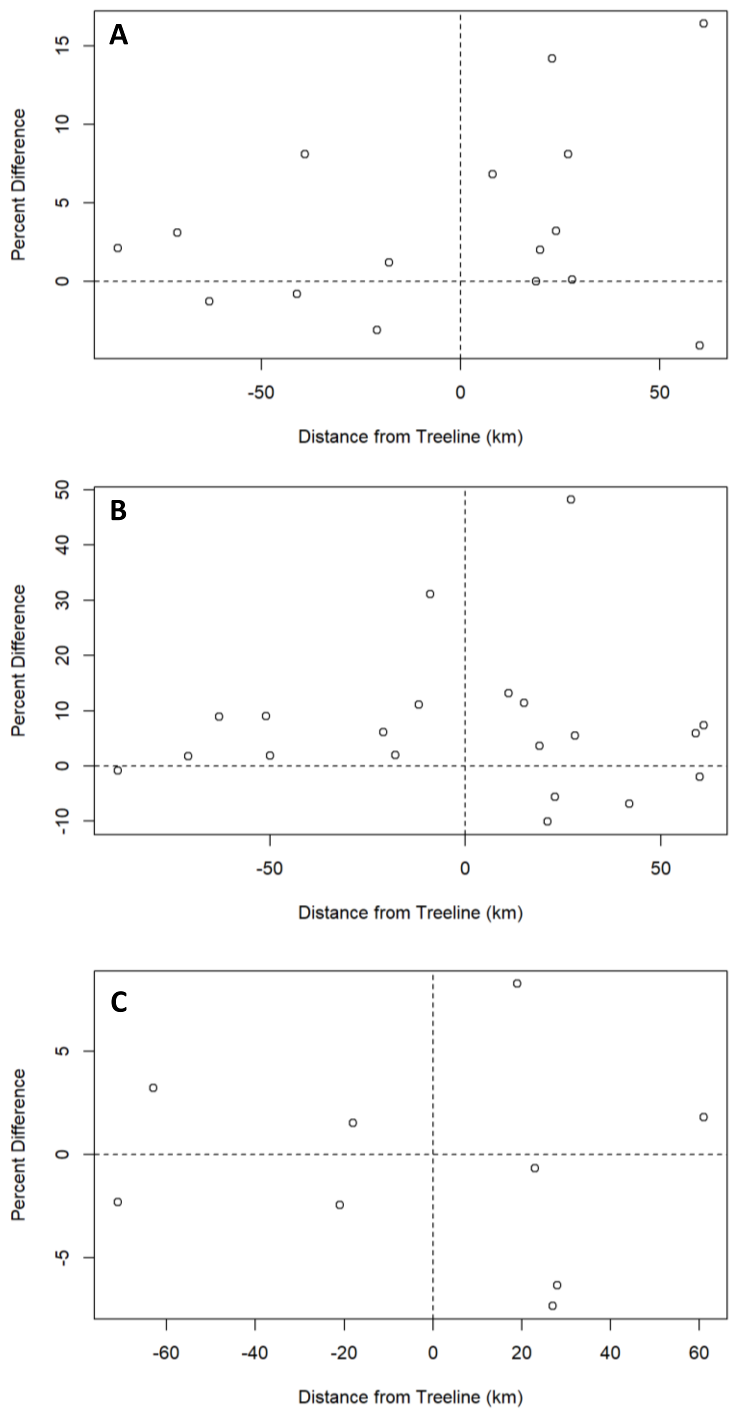

Figure C.1 *Percent difference between depth estimated at each site from 10 snow core measurements vs extensive depth measurements (n=37 to n=244). Points shown relative to distance from the treeline. Vertical dashed line shows position of treeline with positive* *distance to the right representing north. No relation between the magnitude of the percent difference and any geographic variable was detected. (A) 2016 Mean difference: 3.5%. Absolute mean difference 5% (Range: 0% to 16%). 12 out of 16 cases increased the SWE estimate. (B) 2017 Mean difference: 5%. Absolute mean difference 10% (Range: 1% to 48%). 15 out of 20 cases increased the SWE estimate. (C) 2017 Lakes Mean difference: -0.5%. Absolute mean difference 3.8% (Range: 0.7% to 8.3%).*

Appendix D – Data Correction

The following is a note contained in the NTPC operational spreadsheet:

A measurement error with the 2005-2015 surveys was identified during the 2016 survey. Previous surveys completed with NTPC's measuring equipment overstated the Snow Water Equivalent (SWE) by approximately 30%. This error was the result of a mismatch between the scale and tube combination - the scale was designed to be used with a tube having a narrower diameter than the one actually in use. The calculation on this sheet generates a "correction factor" that has been applied to the 2005-2015 survey results as of April 5, 2016. This correction factor was also applied to field measurements recorded at Bluefish and Big Spruce using NTPC's measuring equipment in March/April 2016. All remaining field measurements were taken using measuring equipment owned by ENR in 2016, and did not require correction. The control chart on the "uncorrected" tab was used as a tool in identifying the limits of the data range requiring correction - information provided by ENR indicated that the error years included 2006-2015, however, the state of the 2005 data was undetermined. A ten-year span of data believed to be correct (1995-2004) was used to define the system mean and upper/lower limits for the control chart. This date range was selected because the stations measured beginning in 1995 were generally the same as those included in the questioned year(s). Upper and lower limits were defined by a multiplier of 1.88 on the average annual variation. This methodology is expected to result in a data set with 95% of naturally occurring variation falling within the control limits. When these control limits were applied to the full 38-year data set, only two years prior to 2005 fell outside the control limits, 1981 and 1984. For a data set with 40 points, 2 points outside the control limits would represent the expected 5% normal variation. This evidence indicates that the sample size was sufficient to produce effective control limits for this data set. From 2005 onward, 4 out of 10 years (40%) were above the upper control limit, indicating a significant change in the system. The 2005-2007 years were all above the upper control limit. This allowed the "shift" in the recorded data to be pinpointed as having occurred starting in 2015. A correction factor based on the relative diameters of NTPC's snow measurement tube, and the tube diameter the scale is designed to be used with was calculated on this workbook tab. The resulting correction factor has been applied to all SWE data collected during the 2005 - 2015 surveys on the "Corrected" tab in this workbook.

Appendix E – Survey Date

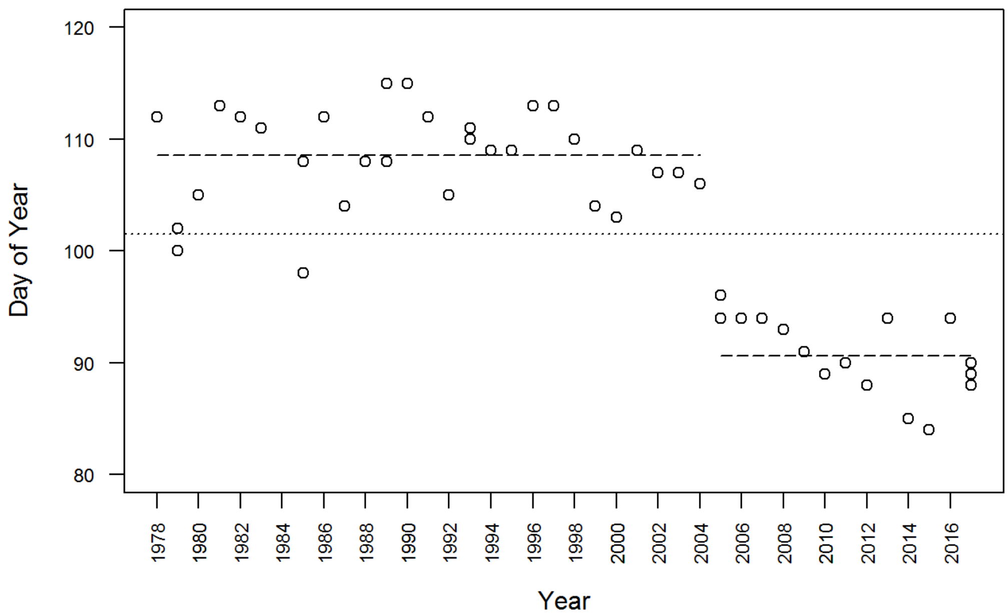

Figure E.1 *Day of year (DOY) the NTPC snow surveys were conducted between 1978 and 2017. Dotted line indicates the mean DOY (102). Dashed lines indicated the mean DOY from 1978-2004 (91) and 2005-2017 (109).*