ASSESSING CLIMATE CHANGE INDUCED DECLINES IN PONDS IN BRITISH

COLUMBIA'S SEMI-ARID GRASSLANDS

by

Aaron James Antonio Coelho

B.Sc. Thompson Rivers University, 2008

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

Master of Science

in

Environmental Science

Thompson Rivers University

Spring Convocation 2015

Thesis Examining Committee:

Wendy Gardner (PhD), Thesis Supervisor and Associate Professor, Natural Resource
Science, Thompson Rivers University

Tom Pypker (PhD), Thesis Supervisor and Assistant Professor, Natural Resource Science,
Thompson Rivers University

Nancy Elliot (PhD), Adjunct Faculty, Natural Resource Science, Thompson Rivers
University

John Buckhouse (PhD), External Examiner, Professor Emeritus, Oregon State University

ACKNOWLEDGEMENTS

To my supervisors, Wendy Gardner and Tom Pypker, by accepting me into the program they exponentially changed the course of my life for the better. Everything I have accomplished over the last two years would not have been possible without their support. They started out as my supervisors and are now my mentors, role models and friends. I could not have asked to be teamed up with anyone better, thank you.

To my father in-law and unofficial committee member, Reg Newman, who encouraged me to apply to the program. He brought out the best in me by challenging me to reach my potential. A truly uplifting spirit, he is the first to offer a compliment for good work and is an expert at squashing the doubt that creeps into the mind of every grad student. Thank you for your invaluable advice, document reviews and rescue from automotive break downs.

I would like to thank key people who were instrumental throughout this project. To my official committee member Nancy Elliot, thank you for providing GIS data, technical support and valuable comments on my writing. To John Dumesnil who helped survey my wells and piezometers on possibly the most miserable day of the year. Despite the non-stop pouring rain and our truck breaking down, his positive attitude and contagious smile never faltered. Thank you to Wendy and Russ Gardner for lending me their truck, "The White Death," for an entire season of field work. I am grateful to them for generously sacrificing their legendary truck to my cause.

Thank you to my family, Tony, Cindy and Trevor. I owe everything I am to my parents who have provided me with every opportunity to follow my dreams. They are the most generous and supportive people I have ever known and I am proud to be their son. To my brother, best friend and coolest guy I know, thanks for all the fun times and laughs, they kept me sane.

Most of all, I would like to thank my beautiful wife-to-be, Karen Newman, for believing in me. Without her support and sacrifices I would not have been able to seize this opportunity. She is the most selfless and caring person that I know.

Last but not least, to my furry little companion and all round best pal, Vader, field days would have been lonely without you. A final thank you to the Ranching Task Force of British Columbia for supporting and funding this project.

Supervisors: Wendy Gardner (PhD) and Tom Pypker (PhD)

ABSTRACT

In British Columbia (BC), the ranching community has expressed a concern with observed declines in the number and surface area of grassland ponds used as drinking water sources for cattle during grazing. This study evaluates the extent of the observed declines in BC's southern interior grasslands and determines the differences in groundwater – surface water (GW-SW) interactions between perennially and seasonally inundated ponds in the Lac du Bois grasslands. Using remote sensing techniques to compare historic and modern imagery, ponds from eight 100 km^2 sites were evaluated. From 1992 – 2012, the total number and surface water area of ponds decreased by 63% and 54%, respectively within the eight sites. Due to the effects of climate change on wetlands worldwide it is expected that changes in climate are responsible for these declines. A climate data analysis of ClimateWNA modelled data for the eight sites showed a significant increase in air temperature and potential evapotranspiration (PET) from 1900 – 2012 implying an increased evaporative demand on surface water. Precipitation also increased significantly over this time period. However, low snowfall is reported for the 1992 – 2012 time period showing that there have been decreased snowmelt inputs available for GW - SW recharge. The field study in Lac du Bois highlighted the importance of GW - SW interactions in maintaining pond surface water. Wells and piezometers were installed in and around two perennially inundated ponds and two seasonally inundated ponds. It was determined that the perennially inundated ponds receive a persistent input from the local groundwater system allowing them to sustain surface water despite high evapotranspiration rates in the summer months. Conversely, groundwater inputs to seasonally inundated ponds are either temporary or non-existent and therefore they are highly dependent on the amount of input from the spring melt and are more vulnerable to summertime evapotranspiration. Our results are consistent with other studies that show that climate change has contributed to significant losses in wetlands worldwide.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

BC = British Columbia

PET = Potential evapotranspiration

GIS = Geographic Information System

ClimateWNA = Climate Western North America

LDP = Lower dry pond (study site)

LWP = Lower wet pond (study site)

UDP = Upper dry pond (study site)

UWP = Upper wet pond (study site)

N = Upslope well

M = Middle of pond well

S = Downslope well

CHAPTER 1. INTRODUCTION

British Columbia (BC) grasslands represent 1% of the provincial land base, 95% of which are working rangelands (Wikeem and Wikeem 2004). Grasslands have provided economic and cultural services for centuries and are extremely valuable as a source of carbon sequestration, clean water and air and high quality low cost forage for the ranching industry (Wikeem and Wikeem 2004). Grasslands are classified as semi-arid and therefore, have limited sources of fresh water to support wildlife and cattle. In areas lacking a nearby river, stream or lake to supply water, fresh water is found mainly in closed-basin ponds that form in depressions in the terrain. Closed basin ponds take their name from operating as a "closed system" meaning that except for surface runoff and direct precipitation, there are no persistent surface inputs (i.e. streams, rivers) to feed them. In some cases, multiple ponds may be hydrologically connected with ephemeral streams but the basin as a whole remains closed with no outflow to other basins or water sources. Water mainly leaves the system by evaporation, groundwater recharge and uptake by wildlife, vegetation and cattle. These ponds are breeding grounds for water fowl and amphibians and are used as drinking water sources for cattle during grazing. Many of the hydrological processes controlling the water levels in ponds are sensitive to changes in climate (Hayashi and van der Kamp 2007). Recent climate change reports assert that semi-arid ecosystems are most vulnerable to increasing temperatures and changing precipitation patterns (MacKerron 2010; Stocker et al. 2013).

Recently, the ranching community has expressed a concern regarding an observed decline of closed-basin ponds in BC's semi-arid rangelands. However, to date, there is no official evaluation of changes in number and surface area of closed-basin ponds to support these observations. Moreover, there are limited weather data analyses and field studies to explain the observed change. This thesis aims to determine if there is a significant decline in the abundance of ponds. If significant declines are measureable, it will determine if they can be attributed to changes in climate. This study also endeavors to explore how groundwater – surface water (GW-SW) interactions differ in permanently and seasonally inundated ponds in the Lac du Bois grasslands. The remainder of this chapter will review British Columbia's grasslands, pond hydrology, climate change in the context of the hydrologic cycle and the objectives of this thesis.

British Columbia Grasslands

   Grasslands make up 1% of British Columbia's land mass and are found mostly in the central and southern parts of the province (Wikeem and Wikeem 2004). Within these regions the grasslands are located between the Coast and Rocky mountain ranges in and around the valleys and plateaus of major rivers such as the Fraser, Thompson, Chilcotin, Okanagan and Kettle (Figure 1.1). The rain-shadow effect from the Coast Mountains has the most pronounced effect on the climate of the interior plateau where annual precipitation is relatively low, ranging from 200 mm to 500 mm annually (Wikeem and Wikeem 2004). During the Pleistocene era, the interior plateau was covered by a large sheet of ice. As the ice melted, it's movement widened and straightened the pre-glacial valleys and a mantle of glacial till was deposited over the area (Daubenmire 1942; Tisdale 1947). This till constitutes the parent material for grassland soils (Van Ryswyk et al. 1966).
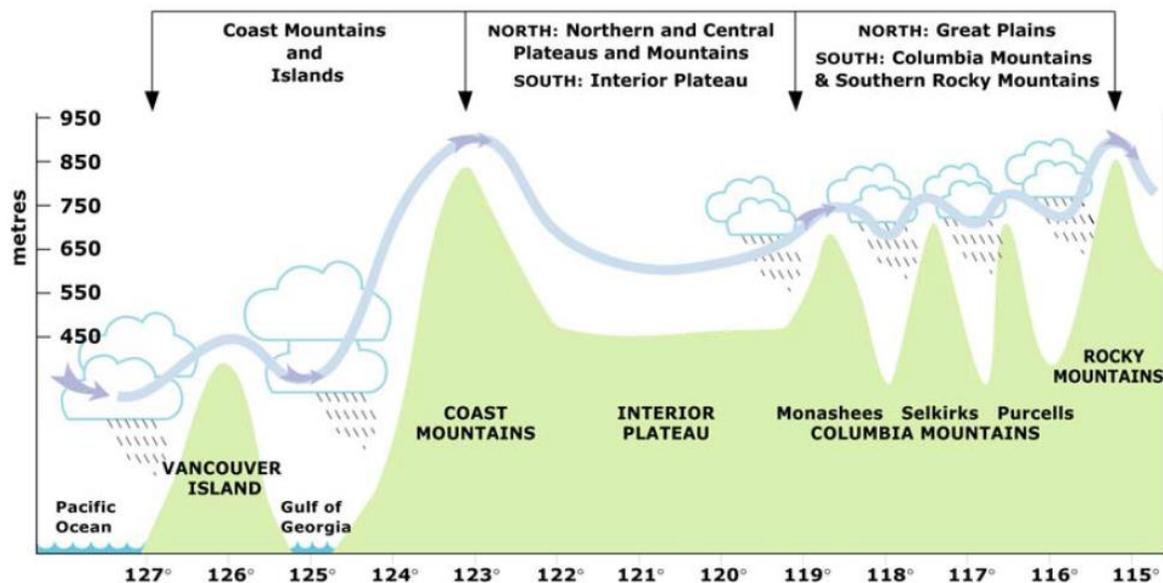
Figure 1.1: Longitudinal cross section of southern British Columbia (Williams 1982).

   Ecosystems in BC are divided into zones classified using the Biogeoclimatic Ecosystem Classification (BEC) pioneered by (Krajina and Brooke 1970) and expanded on by the BC Forest Service. The zones are distinguished using a combination of vegetation, climate and soil data (Pojar et al. 1987). There are a total of 16 BEC zones in BC which are classified into subzones and variants for specific sites. BC's grasslands are found mainly

within three BEC zones with similar climates: Interior-Douglas Fir (IDF), Ponderosa Pine (PP) and Bunchgrass (BG) (Gayton 2003).

Another commonly used classification system in the Okanagan and Cariboo regions separates sites by elevation (Table 1.1) (Tisdale 1947; Gayton 2003). This system is often useful within a site that varies greatly in elevation (e.g Lac du Bois grasslands). BC's grasslands are classified as semi-arid and are typically hot, dry and water limited (Wikeem and Wikeem 2004). At local scales the topography, aspect and elevation have a large effect on climate. For example, opposite facing slopes greatly differ in native vegetation due to differences in sun exposure. However, elevation typically has the greatest influence on species composition (Tisdale 1947). At higher elevations temperatures are cooler and precipitation levels are often higher than those at lower elevations. This results in distinct vertical regions that differ in climate, soils and vegetation (Tisdale 1947). In general, the dominant vegetation are grasses, grass-like plants, forbs and shrubs that grow in semi-arid conditions that are too dry to support forests (Wikeem and Wikeem 2004)

Table 1.1: The Tisdale grassland classification framework (Tisdale 1947).

Zone	Distribution	Dominant Vegetation
Lower Grasslands	Thompson River valley, from Kamloops to Lytton; southern third of Okanagan valley	Wheatgrass-Sagebrush
Middle Grasslands	Mid-slopes of Thompson and Okanagan Valleys, lower slopes of Nicola and Chilcotin Valleys	Wheatgrass-Bluegrass
Upper Grasslands	Upper slopes of Thompson, Okanagan and Nicola valleys	Wheatgrass-Fescue

The hydrologic processes in BCs grasslands are controlled by precipitation, which is mostly confined to snowfall from November to January and rainfall in June and July, with the rest of months being relatively dry (Wikeem and Wikeem 2004). The major source of water available for pond filling and plant life comes from melting snow packs that develop over the winter months (Hayashi and van der Kamp 2007). The depth and density of the snow pack is highly variable from year to year and has a large influence on pond recharge and summer flows (Hayashi and van der Kamp 2007). Evapotranspiration rates are directly

related to air temperature (Allen et al. 2006) and are highest during the hot and dry summer months, July to September. During this period potential evapotranspiration (PET) outweighs precipitation resulting in a net loss of water from grassland soils (van Ryswyk et al. 1966) and ponds (Riordan et al. 2006; Hayashi and van der Kamp 2007).

Pond Hydrology

Ponds are typically located in depressions within the landscape. Their characteristics cover a range of depth, size and permanence, each with a unique water budget influenced by hydrological processes. Changes in surface water levels are dynamic and controlled by the balance between inputs and outputs of water (Hayashi and van der Kamp 2007). The balance is sensitive to, and driven by changes in climate. For example, in semi-arid grasslands evaporation tends to outweigh precipitation in the summer months which can cause pond levels to drawdown or even completely dry out (Jolly et al. 2008). Climate also affects the balance through yearly variations in snowpack accumulation and the subsequent level of groundwater recharge during the spring melt (Barnett et al. 2005; Mote et al. 2005; Stewart et al. 2005). These hydrological processes are also complicated by their interaction with soil and vegetation. Therefore, anthropogenic changes to upland ecosystems, such as logging, cattle grazing and agriculture, which affect plant cover, plant composition and soil properties, can in turn affect the water balance of ponds within the watershed (Hayashi and van der Kamp 2007). For example, grazing animals affect plants by reducing cover and, in cases of mis-management, by changing plant species composition. Heavy grazing with excessive reduction in plant cover reduces the protective structure of the vegetation layer, allowing raindrop impact to damage the soil surface. This can cause soil erosion and reduce water infiltration. The amount of above-ground plant cover and plant composition also affects the amount and nature of below-ground biomass which directly affects soil organic matter. Soil organic matter is one of the key factors in formation and maintenance of many beneficial soil properties including water infiltration (Buckhouse and Coltharp 1976). Furthermore, heavy grazing, or grazing on saturated soils can lead to a compacted soil surface by hoof action (Bohn and Buckhouse 1985). This will increase surface runoff and may lead to reduced water quality because of increases in sediment reaching water bodies (Buckhouse and Gifford 1976). In a province known for its forests, mountains and abundance of water the grasslands

represent a rare ecosystem, rich in biodiversity and high quality rangeland and low in water availability. If grasslands are to provide water to the soil for plant growth and water to the surface in the form of ponds to support cattle during grazing and provide breeding grounds and drinking water to a variety of species, they must receive a consistent supply of precipitation.

The water level of a pond is governed by a balance of inputs and outputs and can be described mathematically as:

$$\Delta V = P + S_i + G_i - ET - S_o - G_o$$

Where ΔV is the change in storage, P is precipitation (rain and snow), S_i is surface inflow, G_i is groundwater inflow, ET is evapotranspiration which is the combination of direct evaporation from the pond surface and transpiration from the surrounding vegetation, S_o is surface outflow, and G_o is groundwater outflow (Kendall and McDonnell 1998). In this study, we are concerned with closed-basin ponds which operate as a closed system with no persistent input or output to or from other water sources (ie. lakes, rivers, streams) (Rains 2011). Therefore, the terms for surface water inflow (S_i) and surface water outflow (S_o) can be removed and the equation reduced to:

$$\Delta V = P + G_i - ET - G_o$$

The main input is subsurface and groundwater flow which can be traced back to precipitation in the form of rain and snow. However, the majority of rainfall in BC's semi-arid grasslands falls in June and July and is mostly absorbed by dry soils and immediately taken up by vegetation (Tisdale 1947; van Ryswyk et al. 1966; Wikeem and Wikeem 2004). Therefore, rain is secondary to the snow melt which can be considered the primary component of the precipitation term (Hayashi and van der Kamp 2007). The amount of water a pond receives from snow melt is dependent on the depth and density of the snowpack, the timing of the spring melt, soil infiltration rates and groundwater flow dynamics (Mote et al. 2005; Stewart et al. 2005; Jolly et al. 2008). These factors are mostly determined by climate. For instance, the presence of frozen soil beneath the snowpack combined with a fast melt

would limit soil infiltration and increase run-off into ponds (Chamberlain and Gow 1979; Hayashi et al. 2003). Conversely, a slow melt would increase the potential loss of snowpack to sublimation and increase the probability of thawed soils during the latter part of the melt both of which would decrease the water equivalent entering ponds (Chamberlain and Gow 1979; Hayashi et al. 2003; Mote et al. 2005). Snow melt also has a large influence on the groundwater table at both regional and local scales (Mote et al. 2005; Stewart et al. 2005), which in turn can affect the groundwater and surface water components of the pond water balance equation.

Ponds in semi-arid ecosystems have some level of input from precipitation and output from evapotranspiration but where they tend to differ most is in their groundwater - surface water (GW – SW) interactions. Therefore, it is possible to classify ponds based on these interactions. Theoretical and field studies have shown that GW - SW interactions can be broadly categorized into four types of flow regimes (Figure 1.2): (i) connected perched-precipitation pond – no groundwater input and surface water is lost by groundwater recharge to the saturated local groundwater system; (ii) disconnected perched-precipitation pond – similar to (i) but surface water is lost by groundwater recharge to an unsaturated deep regional groundwater system; (iii) groundwater discharge pond – receives water from the local groundwater system and no groundwater recharge; (iv) flow-through pond – gains water by groundwater discharge from some parts of wetland and loses water by groundwater recharge at other parts (Townley and Davidson 1988; Townley and Trefry 2000; Smith and Townley 2002).

(a) Connected Perched-precipitation Pond

(b) Disconnected Perched-precipitation Pond

(c) Flow-through Pond

(d) Groundwater Discharge Pond
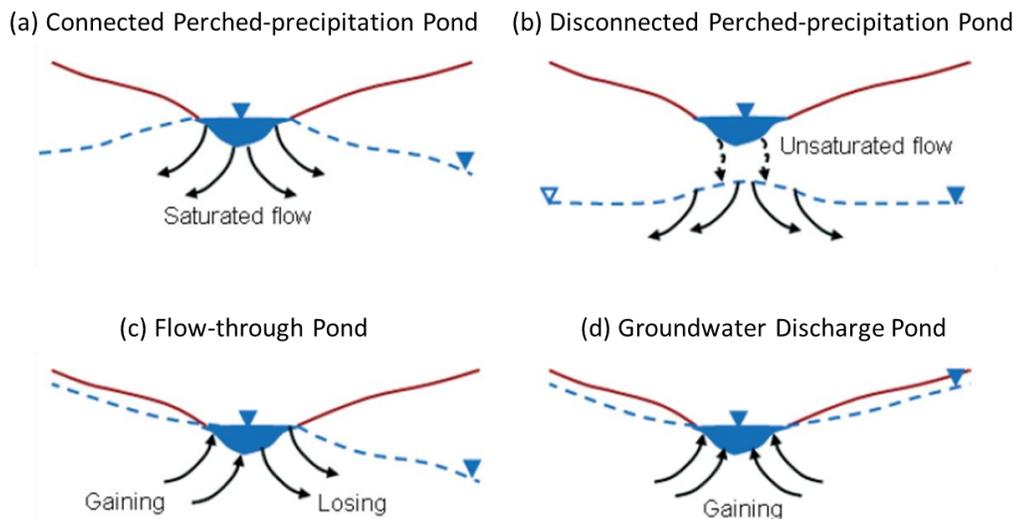
Figure 1.2: Conceptual groundwater flow paths to and from a (a) connected perched-precipitation pond, (b) disconnected perched-precipitation pond, (c) groundwater discharge pond and (d) flow-through pond (Jolly et al. 2008).

Groundwater inputs and outputs are important components of the pond water balance equation especially with respect to pond permanence. A ponds connection to groundwater is strongly influenced by local geomorphology (i.e. location within a landscape) and the relative pressure heads between groundwater and surface water (Rosenberry and Winter 1997; Jolly et al. 2008). A deep pond found within a low lying depression is more likely to have groundwater input compared to a shallow pond found within a relatively flat depression. The latter tend to be perched-precipitation ponds; type (i) or (ii) that are seasonally inundated. Their surface water originates from snow melt and often has a large surface area to volume ratio. Without any further, significant inputs, the surface water is lost by groundwater discharge and evapotranspiration. Conversely, the groundwater discharge and flow-through ponds, type (iii) and (iv) have either seasonal or perennial groundwater inputs which extend the permanence of their surface water. The extent and term of the groundwater input to these ponds depends on the relative height of the groundwater table to the surface area of the pond, the relative pressure heads and how they fluctuate throughout the year (Jolly et al. 2008).

The degree of interaction between groundwater and surface water at local scales is often dependent on the condition of the regional water table (Rosenberry and Winter 1997; Van der Kamp and Hayashi 1998; Jolly et al. 2008). The depth and density of the snow pack development in the winter determines the amount of water added to the entire system during

the spring melt including the level of flows in areas where there is groundwater discharge to the surface (Mote et al. 2005; Stewart et al. 2005). This is also important for areas where groundwater discharge is seasonal because more water equivalent can result in discharge continuing later into the dry season. Therefore, groundwater recharge from spring snowmelt is an important factor in maintaining surface water throughout the year.

Climate Change and the Hydrologic Cycle

Global average air temperature increased during the 20th century and most assessments indicate a strong possibility of further warming in the future (Houghton et al. 2001; Houghton 2009). In Western North America, a 2 – 5 °C increase is predicted in the next century (Cubasch et al. 2001; Spittlehouse 2008). It is expected that increased air temperature will lead to increases in evapotranspiration and precipitation and an overall intensification of the water cycle (Loaiciga et al. 1996; Huntington 2006). Predictions associated with this intensification at mid-latitudinal areas of North American include shorter winter seasons, larger winter floods, drier and more frequent summer weather and overall enhanced hydrologic variability (Loaiciga et al. 1996; Huntington 2006). Semi-arid ecosystems are projected to be most vulnerable to increasing air temperature and variations in precipitation patterns (MacKerron 2010; Stocker et al. 2013). Deteriorating conditions for water storage and water supply are predicted for semi-arid climates that are dependent on snowmelt (Loaiciga et al. 1996; Barnett et al. 2005; Mote et al. 2005; Stewart et al. 2005).

Snow pack represents a key component of the hydrologic cycle in Western North America. One of the primary consequences of climate warming is the reduction in snow accumulation and the water supplied by snow melt (Stewart et al. 2005). At high elevations in grassland watersheds, storage of water in the winter snowpack and its release in spring and early summer is especially important for semi-arid climates where demands are the greatest (Loaiciga et al. 1996). Changes in the amount of precipitation near the end of winter tend to affect the size of the snowpack and the volume of run-off (Stewart et al. 2005). Alternatively, temperature increases can affect the timing of the run-off which in turn will influence flows in the summer and fall (Mote et al. 2005).

Climate change is expected to change the timing of hydrological processes in BC (Leith and Whitfield 1998). These changes include earlier snowmelt, lower late summer –

early fall flows and higher early winter flows. The implications of these hydrological changes include increasingly long and dry summers and possible water shortages in the late summer (Leith and Whitfield 1998). This is consistent with other studies in Western North America which found that increasing air temperature is affecting spring streamflow timing (Cayan et al. 2001; Mote et al. 2005; Stewart et al. 2005). The warming trends also affect precipitation and exacerbate this affect. Winter warming results in an increased fraction of the precipitation to fall as rain which in turn affects the size of the snowpack and timing of the spring melt (Stewart et al. 2005). Studies of changes in snowpack extent and depth over the last 50 years in Western valleys and plains have reported significant declines (Karl et al. 1993; Scott and Kaiser 2004). A recent climate change study in British Columbia reported a 0.71 °C increase in air temperature and a 0.5% decrease in precipitation from 2001 – 2009 (Wang 2013). If these current trends continue, it is likely that we can expect significant losses in snowpack and changes toward earlier streamflow timing (Mote et al. 2005; Stewart et al. 2005).

There is an abundance of evidence that suggests ongoing and future changes to the hydrological cycle in response to climate change (Loaiciga et al. 1996; Cayan et al. 2001; Barnett et al. 2005; Mote et al. 2005; Stewart et al. 2005; Huntington 2006). The projected declines in snowpack and earlier streamflow timing will have profound consequences for water availability in climates that depend on spring snowmelt, like BC's semi-arid grasslands. Springtime snowmelt is historically the most predictable part of the hydrologic cycle and is relied upon to supply 50 – 80 % of the annual flow volume in Western North America (Stewart et al. 2005). A decrease in this supply could have consequences that include potential declines in snow water equivalent available for groundwater and surface water recharge during the spring melt, declining regional groundwater tables that may affect groundwater – surface water interactions and increased evaporative demand on surface water and thus, accentuate the typical seasonal summer drought.

Thesis Objectives

The research scope of this thesis was determined based on input from The Ranching Task Force of British Columbia, The Ministry of Forests, Lands and Natural Resource Operations and Thompson Rivers University. This collaborative approach allowed the

project to be built around the observations and concerns of the ranching community. It also helped identify knowledge gaps, facilitate data collection of aerial images, Geographic Information Systems (GIS) layers and weather data and provide access to field study sites.

The ranching community of British Columbia has observed pond declines in BC's grasslands. Pond declines have been quantified in other ecosystems (Smith et al. 2005; Riordan et al. 2006; Umbanhowar et al. 2013) but there is a gap in the evaluation of pond declines in the semi-arid grassland ecosystems of BC. There is also limited knowledge of hydrologic processes pertaining to ponds in semi-arid ecosystems, particularly GW – SW interactions (Jolly et al. 2008) and their effects on pond permanence.

The Specific objectives of this thesis are:

1. Quantify the decline of closed-basin pond number and surface area in BC's semi-arid grasslands from the 1990s to the 2010s.
2. If significant declines are identified, determine trends in weather variables that explain the declines.
3. Measure the differences in GW – SW interactions between permanently and seasonally inundated ponds in the Lac du Bois grasslands.
4. Determine if groundwater connectivity affects the response of ponds to rainfall events.

Literature Cited

Allen RG, Pruitt WO, Wright JL, Howell TA, Ventura F, Snyder R, Itenfisu D, Steduto P, Berengena J, Yrisarry JB. 2006. A recommendation on standardized surface resistance for hourly calculation of reference ET o by the FAO56 Penman-Monteith method. *Agricultural Water Management* 81:1–22.

Barnett TP, Adam JC, Lettenmaier DP. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438:303–309.

Bohn CC, Buckhouse JC. 1985. Some responses of riparian soils to grazing management in northeastern Oregon. *Journal of Range Management* 38 (4):378–381.

Buckhouse JC, Coltharp GB. 1976. Soil moisture response to several levels of foliage removal on two Utah ranges. *Journal of Range Management* 29 (4):313–315.

Buckhouse JC, Gifford GF. 1976. Water quality implications of cattle grazing on a semiarid watershed in southeastern Utah. *Journal of Range Management* 29 (2):109–113.

Cayan DR, Dettinger MD, Kammerdiener SA, Caprio JM, Peterson DH. 2001. Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society* 82:399–415.

Chamberlain E, Gow A. 1979. Effect of Freezing and Thawing on the Permeability and Structure of Soils. *Engineering Geology* 13:73–92.

Cubasch U, Meehl GA, Boer GJ, Stouffer RJ, Dix M, Noda A, Senior CA, Raper S, Yap KS. 2001. Projections of future climate change. , in: JT Houghton, Y. Ding, DJ Griggs, M. Noguer, PJ Van der Linden, X. Dai, K. Maskell, and CA Johnson (eds.): Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel:526–582.

Daubenmire RF. 1942. An ecological study of the vegetation of southeastern Washington and adjacent Idaho. *Ecological Monographs* 12:53–79.

Gayton D. 2003. British Columbia grasslands: monitoring vegetation change. Kamloops, BC: FORREX.

Hayashi M, van der Kamp G. 2007. Water level changes in ponds and lakes: the hydrological processes. *Plant Disturbance ecology: the process and the response* 311–339.

Hayashi M, van der Kamp G, Schmidt R. 2003. Focused infiltration of snowmelt water in partially frozen soil under small depressions. *Journal of Hydrology* 270:214–229.

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) (2001) Climate change 2001. The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Houghton JT. 2009. Climate change: The Complete Briefing. Cambridge University Press, Cambridge, UK.

Huntington TG. 2006. Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology* 319:83–95.

Jolly ID, McEwan KL, Holland KL. 2008. A review of groundwater–surface water interactions in arid/semi-arid wetlands and the consequences of salinity for wetland ecology. *Ecohydrology* 1:43–58.

Hayashi M, van der Kamp G. 1998. The groundwater recharge function of small wetlands in the semi-arid northern prairies. *Great Plains Research: A Journal of Natural and Social Sciences.* Paper 366.

Hayashi M, van der Kamp G. 2003. Comparing the hydrology of grassed and cultivated catchments in the semi-arid Canadian prairies. *Hydrological Processes* 17:559–575.

Karl TR, Groisman PY, Knight RW, Heim Jr RR. 1993. Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *Journal of Climate* 6:1327–1344.

Kendall C, McDonnell JJ. 1998. Isotope Tracers in Catchment Hydrology. Elsevier Science, NewYork.

Krajina, RJ, Brooke RC. 1970. Ecology of western North America. Edited by V.J. Krajina. Department of Botany, University of British Columbia, Vancouver.

Leith RM, Whitfield PH. 1998. Evidence of climate change effects on the hydrology of streams in south-central BC. *Canadian Water Resources Journal* 23:219–230.

Loaiciga HA, Valdes JB, Vogel R, Garvey J, Schwarz H. 1996. Global warming and the hydrologic cycle. *Journal of Hydrology* 174:83–127.

MacKerron DK. 2010. Global Warming: The Complete Briefing. By J. Houghton. Cambridge: Cambridge University Press, UK. pp. 438.

Mote PW, Hamlet AF, Clark MP, Lettenmaier DP. 2005. Declining mountain snowpack in Western North America. *Bulletin of the American Meteorological Society* 86:39–49.

Pojar J, Klinka K, Meidinger DV. 1987. Biogeoclimatic ecosystem classification in British Columbia. *Forest Ecology and Management* 22:119–154.

Rains MC. 2011. Water Sources and Hydrodynamics of Closed-Basin Depressions, Cook Inlet Region, Alaska. *Wetlands* 31:377–387.

Riordan B, Verbyla D, McGuire AD. 2006. Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. *Journal of Geophysical Research: Biogeosciences*111.

Rosenberry DO, Winter TC. 1997. Dynamics of water-table fluctuations in an upland between two prairie-pothole wetlands in North Dakota. *Journal of Hydrology* 191:266–289.

van Ryswyk A, McLean A, Marchand LS. 1966. The climate, native vegetation, and soils of some grasslands at different elevations in British Columbia. *Canadian Journal of Plant Science* 46:35–50.

Scott D, Kaiser D. 2004. Variability and trends in United States snowfall over the last half century. Preprints, 15th Symp. on Global Climate Variations and Change, Seattle, WA, *American Meteorological Society* CD-ROM, 5.2.

Smith AJ, Townley LR. 2002. Influence of regional setting on the interaction between shallow lakes and aquifers. *Water Resources Research* 38:10–1.

Smith LC, Sheng Y, MacDonald GM, Hinzman LD. 2005. Disappearing Arctic lakes. *Science* 308:1429–1429.

Spittlehouse DL. 2008. Climate Change, impacts, and adaptation scenarios: climate change and forest and range management in British Columbia. BC Min. For. Range, Res. Br., Victoria. BC Tech. Rep. 045.

Stewart IT, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. *Journal of climate* 18:1136–1155.

Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM. 2013. Climate change 2013: The physical science basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5). Cambridge Univ Press, New York.

Tisdale EW. 1947. The grasslands of the southern interior of British Columbia. *Ecology* 28:346–382.

Townley LR, Davidson MR. 1988. Definition of a capture zone for shallow water table lakes. *Journal of Hydrology* 104:53–76.

Townley LR, Trefry MG. 2000. Surface water-groundwater interaction near shallow circular lakes: Flow geometry in three dimensions. *Water Resources Research* 36:935–948.

Umbanhowar C, Camill P, Edlund M, Geiss C, Durham W, Kreger D, Molano W, Raskob C, Stocker M, Tvera A. 2013. Contrasting changes in surface waters and barrens over the past 60 years for a subarctic forest-tundra site in northern Manitoba based on remote sensing imagery. *Canadian Journal of Earth Science* 50:967–977.

Wang T. 2013. Projecting future distributions of ecosystem climate niches in British Columbia. *Journal of Ecosystems and Management* 13.

Wikeem B, Wikeem S. 2004. The Grasslands of British Columbia. The Grasslands Conservation Council of BC, British Columbia.

Williams WD. 1999. Conservation of wetlands in drylands: a key global issue. *Aquatic Conservation: Marine and Freshwater Ecosystems* 9:517–522.

**CHAPTER 2. EVALUATION OF THE DECLINE IN NUMBER AND SURFACE
AREA OF CLOSED-BASIN PONDS IN BRITISH COLUMBIA'S SEMI - ARID
GRASSLANDS**

Introduction

British Columbia's (BC) grasslands have a hot and dry climate and therefore have a limited surface water supply. Closed-basin ponds represent a major source of fresh water in these ecosystems, and changes in their water levels are controlled by a balance of water inputs and outputs. Climate change may have a considerable effect on the hydrological processes governing the water balance. Snow melt run-off constitutes the major input to these ponds and is dependent upon the depth and density of the snowpack at the time of melt (Barnett et al. 2005; Hayashi and van der Kamp 2007). Evaporation constitutes the major form of output from closed-basin ponds and is directly related to air temperature (Allen et al. 2006; Hayashi and van der Kamp 2007). If evaporation exceeds precipitation and surface/subsurface water inputs, then the ponds experience a net loss of water.

Since the 1940s temperatures have increased 1-2 °C in the northwestern part of North America (Karl et al. 1993; Lettenmaier et al. 1994; Vincent and Gullett 1999; Folland et al. 2002). Environmental changes associated with a warming climate have been documented and include glacial retreat (Pelto 2008), declining mountain snow pack (Mote et al. 2005) and earlier stream peak discharge (Stewart et al. 2005). In BC, a recent study reported a 0.71 °C increase in temperature accompanied by a 0.5 % decrease in precipitation from 2001 – 2009 (Wang 2013). Currently, it is unknown how these changes are affecting the water balance in BC's grassland ponds.

In BC, industry professionals have commented on pond loss in the southern interior grasslands (J. Guichon, personal communication, September 2012, R. Frolek, personal communication, September 2012). These observations are consistent with reports of declining surface water and numbers of ponds in other areas around the world. Over a 50–60 year period, a study in subarctic Alaska reported a 5-50% decrease in number and area of lakes (Smith et al. 2005; Riordan et al. 2006) while another study in the subarctic tundra of Manitoba found a 30% decrease in number of water bodies (Umbanhowar et al. 2013). These studies, and others (Oechel et al. 2000), suggest that increases in potential evapotranspiration

(PET) may explain the observed drying trends. While current literature focuses on increases in PET to explain pond declines it is also useful to look at changes in input, specifically snow packs and spring melts (Barnett et al. 2005).

Although declines in closed-basin ponds have been noted by industry professionals in BC there are no data on the extent of pond loss. Also, recent climate change in BC has been documented (Wang 2013), but there are limited data on trends that are specific to grassland ecosystems. This study intends to quantify the change in closed-basin pond size and number in BC's southern interior grasslands from the 1990s to 2010s and determine possible correlations with changes in air temperature, precipitation patterns, potential evapotranspiration (PET) and water balance.

Methods

Study Sites

Eight 100 km^2 semi-arid grasslands sites in the southern interior of BC were selected to evaluate the decline of closed-basin ponds in BC's grasslands. The sites were selected because they represent a range of grasslands in BC's southern interior (Figure 2.1). The sites differ slightly in mean annual temperature and precipitation, but all are considered semi-arid grassland ecosystems (Table 2.1). Bordered by the Coast mountains to the west and the Monashee, Selkirk, Cariboo and Purcell mountains to the east, the climate of the interior plateau is influenced by a rain shadow effect and the movement of Pacific Maritime, Great Basin Desert and Artic air masses (Tisdale 1947). These combinations produce high summer temperatures and moisture deficits and cold wet winters with summer to winter temperature differences exceeding 25 °C (Valentine 1978; Wikeem and Wikeem 2004). The grasslands are found where the conditions are the driest, in the valleys and plateaus created by the Fraser, Thompson, Chilcotin, Okanagan and Kettle rivers. Typically, temperatures decrease while precipitation increases along an elevation gradient from the bottom of the valleys upward to the plateaus (Tisdale 1947; Van Ryswyk et al. 1966).

Numerous glaciation events during the Pleistocene era shaped the present topography of the region, and left behind glacial till which makes up the parent material for most grassland soils (Van Ryswyk et al. 1966). At local scales, grassland terrains are often complex with steep elevation gradients. Within sites, the grasslands are often classified as

lower, middle and upper depending on dominant vegetation and climatic variables (Tisdale 1947). The major types of soils belong to the chernozemic order but tend to shift towards vertisols in and around depressions in the terrain where water collects and forms closed-basin ponds (Van Ryswyk et al. 1966). The type of chernozems range from brown in the lower grasslands to dark brown in the middle grasslands and black in the upper (Van Ryswyk et al. 1966; Valentine 1978). The soil type and moisture content determine the dominant vegetation types which include big sagebrush (*Artemisia tridentata*), bluebunch wheatgrass (*Pseudoroegneria spicata*) and rough fescue (*Festuca campestris*).
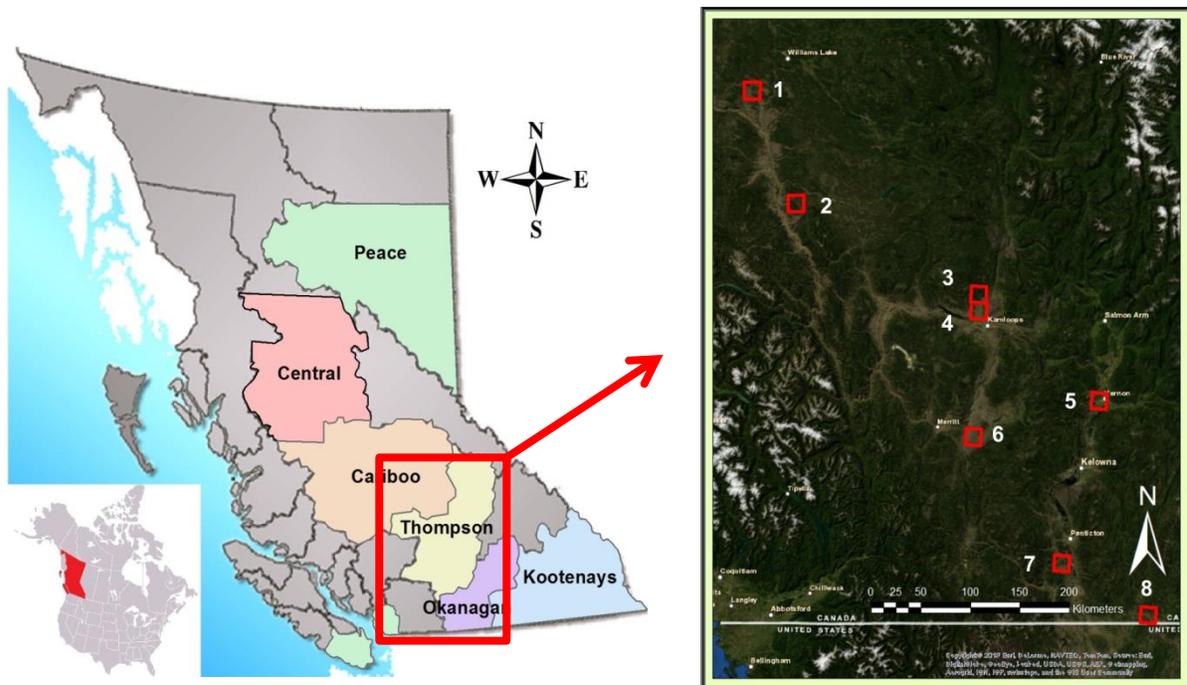
Figure 2.1: Map showing the locations of the eight 100 km^2 semi-arid grassland sites in BC. 1 – Becher's Prairie, 2 – China Lake, 3 – Lac du Bois North, 4 – Lac du Bois South, 5 – Vernon Commonage, 6 – Hamilton Commonage, 7 – White Lake, 8 – Midway.

Table 2.1: Site names, coordinates, elevation, number of water bodies and mean annual temperature and precipitation taken from Climate Western North America (ClimateWNA) data from 1901 – 2012.

Site Number	Site Name	Center Point Coordinates	Elevation Range (lowest pond to highest pond	Elevation used in ClimateWNA (m asl)	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)	Number of Water Bodies
1	Becher's Prairie	122°28'18.2789"W 51°57'19.9076"N	960 - 980	970	3.4	404	46 (17 wet in 1990s)
2	China Lake	122°4'33.3474"W 51°20'43.8589"N	1060 - 1140	1100	3	403	38 (19 wet in 1990s)
3	Lac du Bois North	120°25'1.063"W 50°50'52.8183"N	700 - 960	900	4.8	466	40 (38 wet in 1990s)
4	Lac du Bois South	120°24'55.5842"W 50°45'28.2344"N	720 - 880	800	5.8	348	83 (78 wet in 1990s)
5	Vernon Commonage	119°19'30.5019"W 50°15'23.618"N	620 - 800	700	6	378	30 (27 wet in 1990s)
6	Hamilton Commonage	120°27'51.3789"W 50°3'25.0191"N	1040 - 1240	1180	4	448	83 (57 wet in 1990s)
7	White Lake	119°39'55.4431"W 49°20'40.4304"N	540 - 1200	700	6.4	405	15 (15 wet in 1990s)
8	Midway	118°52'47.6779"W 49°2'49.932"N	940 - 980	950	5.1	379	11 (8 wet in 1990s)

Image Acquisition and Rectification

Images from three time periods between 1992 and 2012 were obtained for each site with a minimum of 6 years of separation between images (Table 2.2). Multiple images sources were used both in processing (orthorectified rectified and unrectified) and type (aerial photos and satellite images). Orthorectified aerial photo compilations were used for the intermediate time period, 2004 or 2005, for each site. The orthorectified photos were also used for the initial time period for 6 of the 8 sites and for the most recent time period for 4 of the 8 sites. The photos were flown in July, have a scale of 1:20000 ft (1 ft = 0.3048m) and a spatial resolution of 1m. The most recent images for 4 of the 8 sites were satellite images. The images were either 2010 – 2011 high resolution (WorldView-1) pan sharpened black and white images (0.5 – 1.0 m resolution) or high resolution (WorldView-2) 4-band near-infrared-red-green-blue (NIR-R-G-B) images (0.5 – 1.0 m resolution). Historic water bodies for 2 of the 8 sites, Becher's Prairie and China Lake, were based on multiple unrectified aerial photos with the same scale and resolution as the compilations mentioned above.

All images were displayed using the NAD83 BC Albers projection because it preserves area and therefore results in more accurate analysis of the surface area of water bodies (Iliffe and Lott 2008). The unrectified aerial photos were rectified and georeferenced to the modern imagery using ArcMap 10.1 (Environmental Systems Research Inc. 2011). A minimum of 7 control points (trees, roads and other distinctive features) were used per photo based on methods by Sannel and Brown 2010. A second order polynomial transformation was used for each photo and root mean square error (RMSE) ranged from 0.7 to 1.3 m.

Table 2.2: The type and date of images taken at three different time periods for eight semi-arid grassland sites in British Columbia.

Study Site	Initial Imagery	Intermediate Imagery	Most Recent Imagery
Becher's Prairie	Aerial photos. July 1995	Orthorectified aerial photo compilation. July 2005	Orthorectified aerial photo compilation. July 2011
China Lake	Aerial photos. July 1992	Orthorectified aerial photo compilation. July 2004	Orthorectified aerial photo compilation. July 2011
Lac du Bois North	Orthorectified aerial photo compilation. July 1997	Orthorectified aerial photo compilation. July 2004	Orthorectified aerial photo compilation. July 2011
Lac du Bois South	Orthorectified aerial photo compilation. July 1997	Orthorectified aerial photo compilation. July 2004	Orthorectified aerial photo compilation. July 2011
Vernon Commonage	Orthorectified aerial photo compilation. July 1997	Orthorectified aerial photo compilation. July 2004	WorldView-2 Satellite Imagery. May 2011
Hamilton Commonage	Orthorectified aerial photo compilation. July 1996	Orthorectified aerial photo compilation. July 2004	WorldView-1 Satellite Imagery. July 2010
White Lake	Orthorectified aerial photo compilation. July 1995	Orthorectified aerial photo compilation. July 2004	WorldView-1 Satellite Imagery. July 2011
Midway	Orthorectified aerial photo compilation. July 1995	Orthorectified aerial photo compilation. July 2005	WorldView-2 Satellite Imagery. July 2012

Pond Selection and Water Body Digitization

Within each site, all wet and dry ponds in the 1990s were identified manually by visual analysis of the initial imagery. To assist in pond identification both the GeoBase National Hydro Network (NHN) Water and Contour Lines (1:20,000) reference layers were used. All wet and dry ponds within each site were then assigned a unique number. The numbered ponds were used for the analysis of change in total number of wet ponds by comparing their status in the initial and most recent images.

To obtain an estimate of change in surface area of water within each site, eight randomly selected ponds were used per site. To be accepted for analysis, each pond had to: 1) contain water in the initial images and 2) be larger than 0.1 ha. Delineation of water bodies

was done by manually digitizing visual pond boundaries (Riordan et al. 2006; Sannel and Brown 2010; Umbanhowar et al. 2013). Although there are automated methods for digitizing water bodies, based on computerized spectral analysis of images, they introduce inaccuracies (Sannel and Brown 2010). For example, shadows can be classified as water bodies and spectral analysis programs are challenged with accurately distinguishing shorelines containing vegetation. While manual delineation is more accurate it is also far more time consuming. The shorelines of each water body were traced using ArcMap 10.1 (Environmental Systems Research Inc. 2011). A polygon was created for each pond at each of the three time periods. ArcMap was then used to calculate the area of each polygon. No formal ground truthing was conducted.

Pond Number Analysis

To determine the change in number of water bodies from the 1990s to 2010s the initial and most recent imagery were compared. The intermediate imagery was used only to establish a trend in the surface area analysis. Each uniquely numbered pond per site was analyzed individually. First, the status of the ponds was determined to be either wet or dry in both the initial and most recent images (Figure 2.2). If the ponds contained any amount of water they were considered wet. Although in some cases the surface area of a pond may have changed, its status was considered unchanged if any amount of water was present. Hence, if there was a noticeable decrease in surface area it was not captured in this portion of the analysis. The results are reported as the percent change in number of ponds containing water between the 1990s and 2010s images for each site.

1992 - Wet   2010 - Dry
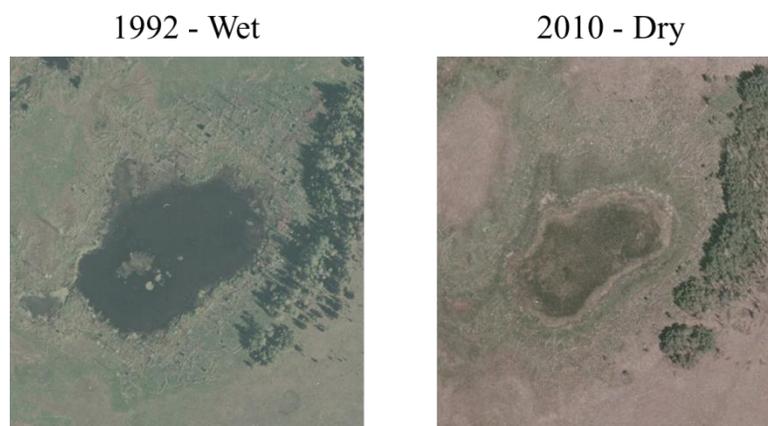
Figure 2.2: Example of a pond from the Becher's Prairie site that was wet in 1992 and dry in 2010.The total number of ponds containing water in each site in the 1990s were compared to the 2010 images to determine change in status (wet/dry).

Pond Surface Area Analysis

To reveal trends in changing surface area, imagery from three time periods (1990s, 2000s and 2010s) were analyzed. Surface areas were estimated using ArcMap to create a time series for each of the eight randomly selected ponds at each site (Figure 2.3). For each site, the change in water surface area was then determined between each time period.

Figure 2.3: Example of a pond from the Lac du Bois North site that showed a steady decline in water surface area from 1997 – 2011. Once boundaries were digitized, areas were compared to calculate change across the three time periods.

Weather Data Acquisition and Analysis

Weather data for each site were obtained from ClimateWNA modelling software (Wang et al. 2012). Directly measured data from Environment Canada weather stations were not used because of limited time ranges, missing data and distance from the eight sites. ClimateWNA software allows users to query pin point locations and retrieve statistically accurate time series data (Cannon et al. 2012). It has been used in a variety of research applications including forest ecology and management (Cortini et al. 2012), water resource management (Moore et al. 2013) and climate science (Gray and Hamann 2013). The weather data provided by ClimateWNA coupled with historic and modern imagery presents an opportunity to study selected areas remotely.

ClimateWNA software predicts monthly, seasonally and yearly climate variables for pin point locations from 1901 – 2012. The algorithms used in the model are developed from baseline data generated by PRISM which is an approach that incorporates weather station data, digital elevation models and expert knowledge (Daly et al. 2002; Wang et al. 2012). ClimateWNA improves on the estimates of temperature using downscaling techniques.

The center point coordinates and the mean elevation were used in ClimateWNA to generate weather data from 1901 – 2012 for each of the eight sites. Also, the same data was trimmed to include only the time frame covered by the images. For this data set we included the two years prior to the earliest image to capture the legacy effect on the hydrology of the sites from years past. From the Climate WNA data, PET was calculated using the Thornthwaite method (Thornthwaite 1948). Mean annual total precipitation and PET were used to calculate annual water balance (P – PET). Linear models were used to look for significant temporal trends in weather variables for both sets of data. (Riordan et al. 2006).

Results

Change in Pond Number

The total number of closed-basin ponds decreased in all sites from the 1990s to 2010s, ranging from -78.2 to -28.9 percent (Table 2.3).

Table 2.3: Total number of ponds with surface water in the initial imagery compared to the most recent imagery inventoried by study site.

Study Site	Initial Imagery 1992 - 1997	Most Recent Imagery 2010 - 2012	Percent Change
Becher's Prairie	17	8	-52.9
China Lake	19	8	-57.9
Hamilton Commonage	57	13	-77.2
Lac du Bois North	38	27	-28.9
Lac du Bois South	78	17	-78.2
Vernon Commonage	27	13	-51.9
White Lake	15	6	-60.0
Midway	8	5	-37.5
Totals	259	97	-62.5

Change in Pond Surface Area

All eight study sites had a reduction in area of closed-basin ponds, ranging from -87.5 to -19.4 % (Table 2.4). The majority of the decline occurred between the initial imagery (1990s) and the intermediate imagery (2004, 2005). Four of the eight sites had slight

increases in surface area from the intermediate imagery to the most recent imagery. The other four sites had a continued reduction in surface area, albeit much less than the previous interval.

Table 2.4: Estimates of the total surface area (ha) of eight ponds per site at three time periods.

Study Site	Initial Imagery 1992 - 1997	Intermediate Imagery 2004 - 2005	Most Recent Imagery 2010 - 2012	Percent Change (1990s - Most Recent Estimate)
Becher's Prairie	16.9	11.9	13.6	-19.4
China Lake	13.6	4.9	5.5	-59.5
Hamilton Commonage	12.4	1.5	1.6	-87.5
Lac du Bois North	14.8	11.4	9.2	-38.0
Lac du Bois South	8.7	2.0	1.9	-78.2
Vernon Commonage	9.8	3.0	3.1	-68.7
White Lake	16.0	15.6	7.8	-51.4
Midway	4.0	2.8	1.6	-59.8
Totals	96.4	53.2	44.3	-54.1

Weather Data Trends 1901 - 2012

For all sites, we found significant linear trends in ClimateWNA-modelled mean annual temperature ($p < 0.001$), total annual PET ($p < 0.02$) and annual degree days below zero ($p < 0.001$) (Table 2.5). Mean annual temperature increased at an average of 0.11 °C per decade. Total annual PET also increased at an average of 1.77 mm per decade. The ten year running means for PET at each site were positive and significant ($p < 0.001$) (Figure 2.4). Annual degree days below zero decreased at an average of 21.5 degree days per decade. Only two sites, Lac du Bois North and Vernon Commonage had significant ($p < 0.03$) positive trends in annual water balance (Precipitation – PET). Per decade, both increased by 5.01 mm and 6.10 mm, respectively.

There were inconsistent trends with regard to precipitation. Total annual precipitation (rain + snow) averaged a 5.3 mm increase per decade for six of the eight sites ($p < 0.03$). The sites that did not experience statistically significant increases were White Lake ($p = 0.065$) and Midway ($p = 0.07$). There was no significant trend in total annual snowfall at these sites (Figure 2.5). However, from 1901 – 1996 the eight sites averaged 17.75 (max = 21, min 14) years where snowfall was greater than one standard deviation of the mean and 4.75 (max = 8,

min = 2) years where snowfall was greater than two standard deviations of the mean. Conversely, from 1997 – 2012 there was not a single year where snowfall was above one standard deviation of the mean. Moreover, during this fifteen year period the average number of years for the eight sites where snowfall was above the mean was 2.125 (max = 4, min = 0).

Table 2.5: Linear temporal trends in mean annual temperature, degree days below zero, total annual precipitation, total annual potential evapotranspiration (PET) and annual water balance (P – PET) based ClimateWNA data from 1901 – 2012.

Study Site	Mean Annual Temperature (°C)			Degree Days Below Zero			Total Annual Precipitation (mm)			Total Annual PET (mm)			Annual Water Balance (P – PET) (mm)		
	Slope	R^2	P	Slope	R^2	P	Slope	R^2	P	Slope	R^2	P	Slope	R^2	P
Becher's Prairie	0.010	0.129	0.000	-2.335	0.115	0.000	0.435	0.058	0.006	0.123	0.043	0.016	0.311	0.020	0.076
China Lake	0.011	0.149	0.000	-2.242	0.122	0.000	0.335	0.038	0.022	0.143	0.067	0.003	0.192	0.004	0.234
Hamilton Commonage	0.011	0.180	0.000	-2.280	0.136	0.000	0.477	0.042	0.017	0.161	0.092	0.000	0.318	0.012	0.127
Lac du Bois North	0.010	0.123	0.000	-2.076	0.097	0.000	0.644	0.063	0.004	0.143	0.060	0.005	0.501	0.034	0.029
Lac du Bois South	0.010	0.123	0.000	-1.992	0.096	0.000	0.461	0.052	0.009	0.165	0.073	0.002	0.296	0.015	0.105
Vernon Commonage	0.013	0.208	0.000	-2.101	0.135	0.000	0.832	0.152	0.000	0.267	0.171	0.000	0.610	0.069	0.003
White Lake	0.012	0.219	0.000	-2.090	0.171	0.000	0.395	0.022	0.065	0.235	0.142	0.000	0.160	-0.004	0.472
Midway	0.011	0.193	0.000	-2.056	0.154	0.000	0.337	0.021	0.070	0.177	0.093	0.000	0.161	-0.003	0.410
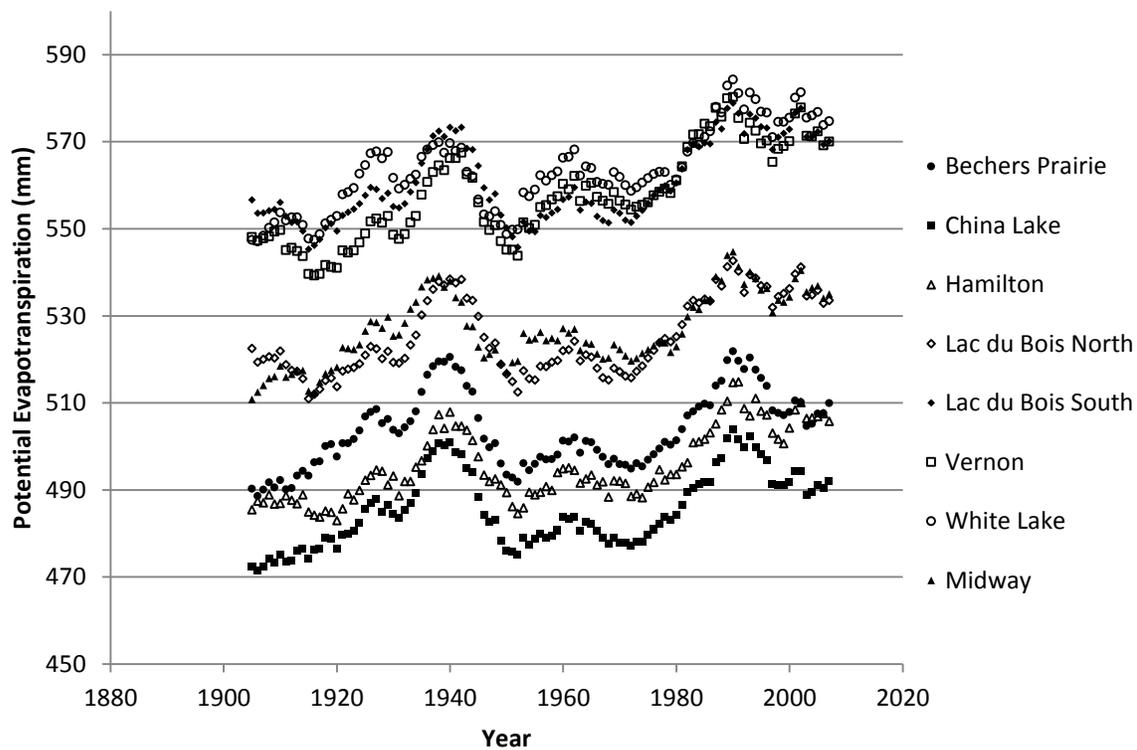
Figure 2.4: Ten year running means of potential evapotranspiration (PET) for long term ClimateWNA data from eight semi-arid grassland sites in BC. The linear trend since 1905 is positive and significant (p < 0.001) for all sites.
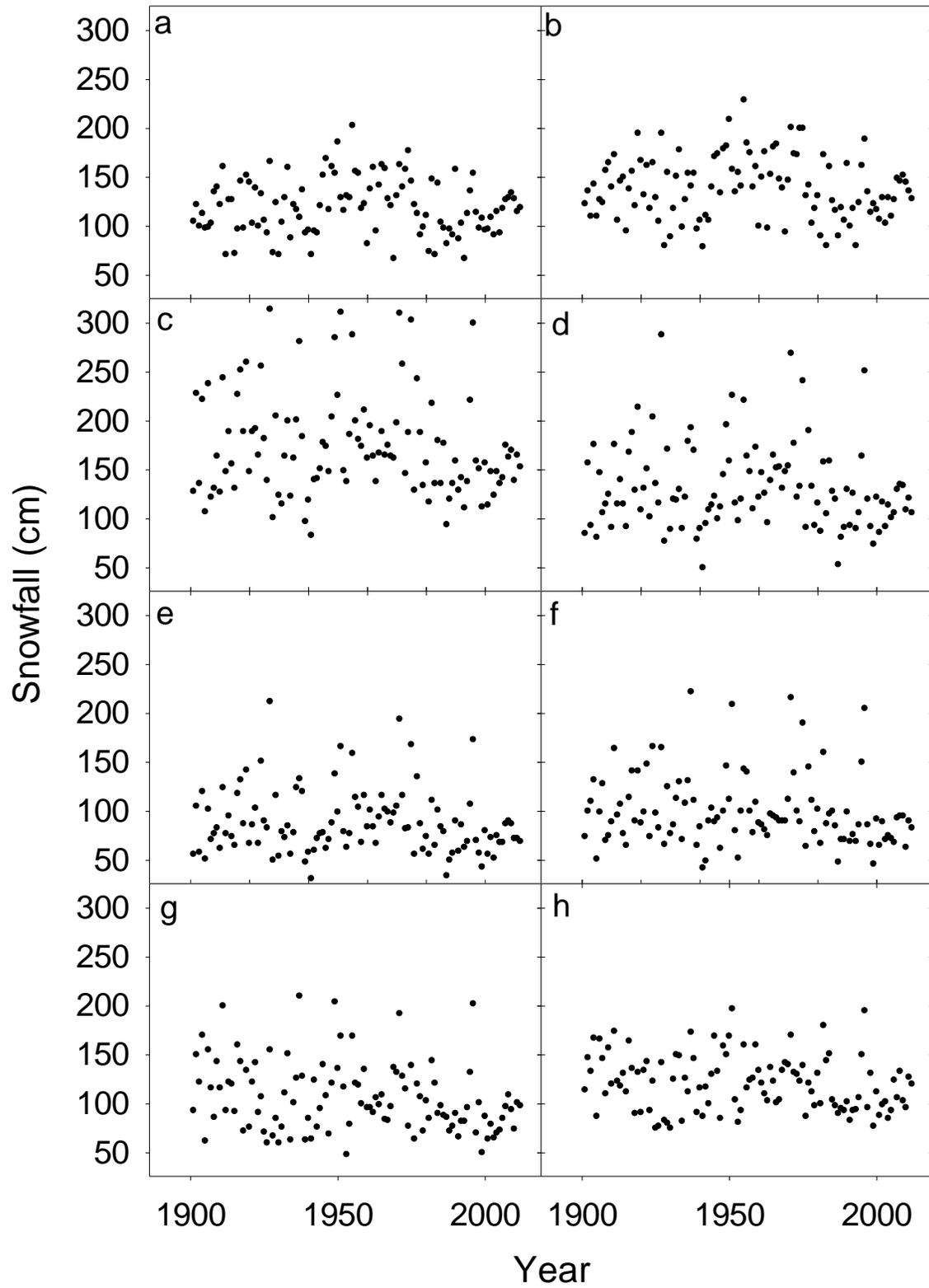
Figure 2.5: Total annual snowfall at eight semi-arid grassland sites in BC; (a) Becher's Prairie, (b) China Lake, (c) Hamilton Commonage, (d) Lac du Bois North, (e) Lac du Bois South, (f) Vernon Commonage, (g) White Lake, (h) Midway.

Weather Data Trends 1990 – 2012

        The following trends are based on ClimateWNA data from time ranges that correspond with the images used in the pond decline analysis. The data for each site starts two years before the first image to capture legacy effects and ends on the year of the last image. Unlike the long-term data set, there were no significant trends in mean annual temperature, total annual PET and annual degree days below zero (Table 2.6). Although there were no further significant increases during this period these variables did maintain higher levels relative to the past.

        We found a significant ($p < 0.05$) linear decrease in total annual precipitation (rain + snow) in five of the eight sites (Table 2.6). For those five sites, total annual precipitation declined on average 8.78 mm per year. Four out these five sites had significant ($p < 0.04$) linear decreases in annual water balance. The fifth site, White Lake, also had a linear decrease in annual water balance ($p < 0.055$). The annual water balance for these five sites declined on average 8.83 mm per year.

        There were no significant linear trends in total annual snowfall at any of the eight sites.

Table 2.6: Linear temporal trends in mean annual temperature, degree days below zero, total annual precipitation, total annual potential evapotranspiration (PET) and annual water balance (P – PET) based ClimateWNA data from 2 years before the initial image to the most recent image for each site

Study Site	Mean Annual Temperature (°C)			Degree Days Below Zero			Total Annual Precipitation (mm)			Total Annual PET (mm)			Annual Water Balance (P – PET) (mm)		
	Slope	R^2	P	Slope	R^2	P	Slope	R^2	P	Slope	R^2	P	Slope	R^2	P
Becher's Prairie	-0.007	0.000	0.829	-2.270	0.000	0.767	-0.467	0.000	0.843	-0.786	0.007	0.302	0.319	-0.058	0.898
China Lake	-0.023	0.000	0.351	0.691	0.000	0.901	-1.515	0.000	0.405	-0.928	0.069	0.126	-0.587	-0.044	0.749
Hamilton Commonage	-0.019	0.000	0.643	3.561	0.000	0.672	-7.877	0.243	0.026	-0.243	0.000	0.801	-7.635	0.224	0.032
Lac du Bois North	-0.025	0.000	0.563	5.794	0.000	0.522	-10.701	0.336	0.009	-0.451	0.000	0.674	-10.250	0.305	0.013
Lac du Bois South	-0.028	0.000	0.522	5.645	0.000	0.514	-8.083	0.322	0.010	-0.510	0.000	0.650	-7.574	0.268	0.019
Vernon Commonage	-0.009	0.000	0.856	2.980	0.000	0.720	-11.311	0.506	0.0008	-0.081	0.000	0.949	-13.200	0.572	0.000
White Lake	-0.009	0.000	0.788	0.000	0.000	0.977	-5.930	0.176	0.042	-0.461	0.000	0.623	-5.468	0.152	0.055
Midway	-0.007	0.000	0.805	-0.183	0.000	0.975	-3.371	0.057	0.161	-0.526	0.000	0.506	-2.844	0.028	0.230

Discussion

Warming temperatures and changing precipitation patterns can result in alterations in terrestrial and aquatic ecosystems (Wilson and Nilsson 2009). How these changes affect regions where water availability is limited is of particular interest. In BC's semi-arid grasslands, closed-basin ponds are an essential source of water for wildlife and the ranching industry. From the intermediate to most recent time period water surface area stayed relatively the same and in some cases rebounded slightly (Table 2.4). The only exception to these trends was the White Lake site which experienced the majority of declines from 2004 – 2011. Overall, the majority of the reported declines correspond with some of the hottest and driest years in BC's recent history (Vincent and Mekis 2006; Pike et al. 2008; Whitfield and Stahl 2010) with a reported increase of 0.71 °C from 2001 to 2009 (Wang 2013).

Our results are consistent with other studies that report considerable declines in closed-basin ponds, albeit in different ecosystems. For example Umbanhowar et al. (2013) report a 21% decline in pond number in the subarctic tundra of Northern Manitoba and others have reported a 5 – 50% decline in pond surface area in the subarctic boreal region of Alaska (Smith et al. 2005; Riordan et al. 2006). During the summer months, outflows from arctic ponds are dominated by evapotranspiration (Marsh and Woo 1977). These studies suggest that increased evapotranspiration due to warming temperatures is one factor associated with long term drying (Oechel et al. 2000; Riordan et al. 2006; Smol and Douglas 2007). Undoubtedly the climate and certain aspects of pond hydrology in these subarctic regions differ to that of BC's semi-arid grasslands, but evapotranspiration remains a consistent and significant outflow for closed-basin ponds in other, more comparable, semi-arid ecosystems such as the prairies (Shjeflo 1968).

From 1901–2012, rising air temperatures resulted in an increase in evaporative demand on BC's semi-arid grasslands (Figure 2.4). Air temperature is directly correlated with PET (Thornthwaite 1948; Allen et al. 2006; McAfee 2013) and our data reveal an average increase of 0.11 °C per decade accompanied by average increase in PET of 1.77 mm per decade (Table 2.5). This temperature data is consistent with other studies that report increases of 1 – 2 °C over the last 70 years in western north American and BC (Karl et al. 1993; Lettenmaier et al. 1994; Vincent and Gullett 1999; Folland et al. 2002; Wang 2013). In

contrast, our short term (1990 - 2012) weather data analysis showed no significant trends in either air temperature or PET (Table 2.6), although the high variability and short time frame of these data may have masked trends. Certainly, PET is a factor involved in the drying of ponds but in semi-arid ecosystems it is normal to have PET outweigh precipitation inputs in the summer months (Van Ryswyk et al. 1966; Wikeem and Wikeem 2004). Despite the normally high evaporative demand, ponds did maintain a volume of water throughout the year at other times during the last century. Although there was no significant increase in PET and temperature over the last 20 years, there was a significant increase over the last century which suggests that PET and temperature have levelled off and remained higher relative to the past. These sustained increases were sufficiently high enough to expose ponds to excess evaporation which would represent a contributing factor to the reported declines.

The lack of large snowfall events resulting in smaller snowpack accumulation is also an important limiting factor. From 1901 – 1996 there were many years where snowfall was over one or two standard deviations from the mean (Figure 2.5). These large snowfall events would not only provide enough water to sustain many closed-basin ponds throughout the given year but would also have a legacy effect on subsequent years by recharging local and regional groundwater systems. From 1996 – 2012, there has not been a single snowfall event above one standard deviation of the mean. In fact, snowfall for these years fell mostly below the mean. This fifteen year gap without a large snowfall event is not unprecedented with respect to the eight sites. It is, however, the only time period between 1901 – 2012 where all eight sites have experienced sustained low snowfall at the same time. This lack of snowfall and snowpack accumulation would affect pond recharge on a year to year basis and also affect the long term recharge of regional and local groundwater (Hayashi and van der Kamp 2007).

As the main form of input in colder climates, snowmelt determines the volume of water that a pond receives to start the year. With less snow water equivalent available during the spring melt ponds may not receive enough water to counterbalance the evaporative demand in the summer months and therefore, will not sustain an above ground volume of water through July and August. This is especially true for shallow ponds which are most susceptible to the effects of climate change due to their relatively low water volumes and high surface area to volume ratios (Hayashi and van der Kamp 2007; Jolly et al. 2008).

The increases in total annual precipitation from 1901 – 2012 were not sufficient to counter balance the water loss from the ponds. Six of the eight sites had significant increases in total annual precipitation (rain + snow), with an average increase of 5.31 mm per decade. The fact that there were no significant trends in snowfall suggest that the precipitation increases are due to a significant increase in rainfall ($p < 0.01$) (data not shown). Rain is much less effective at adding water to ponds relative to snow melt. The most effective rainfall for pond recharge happens during the first couple weeks after the snowmelt in March when the soil is saturated, the vegetation isn't actively transpiring and PET is relatively low. This is considered secondary to the primary input of snowmelt. The majority of rain in BC's grasslands falls during June and July and is mostly lost as transpiration during plant growth (Tisdale 1947; Van Ryswyk et al. 1966; Wikeem and Wikeem 2004). The significant increases in precipitation and PET for this time period only produced significant changes in annual water balance at two sites, Lac du Bois North and Vernon Commonage, both increasing at 5 mm and 6 mm per decade, respectively. Despite the increasing trend in water balance at these sites they still experienced considerable pond number and surface water declines. Although the system may have been receiving more water it is not indicative of increased water to ponds.

In contrast to the long term weather data, from 1990 - 2012 five of the eight sites had significant decreases in total annual precipitation at an average of 8.78 mm per year. The same five sites also had significant decreases in annual water balance (P – PET) at an average of 8.83 mm per year (Table 2.6). Since there was no significant change in PET over this period, the change in water balance can be attributed to decreases in precipitation. Decreases in snow and rainfall during this period are consistent with other studies on BC's weather trends (Wang 2013). Interestingly, the two sites, Lac du Bois North and Vernon Commonage, both with significant increases in annual water balance in the long term data also show the highest decreases in annual water balance in the short term data set, 10 mm and 13 mm per year, respectively. These data correspond with other studies that have found this time period to include some of the hottest and driest in BC's recent history (Vincent and Mekis 2006; Pike et al. 2008; Whitfield and Stahl 2010; Wang et al. 2012). The annual water balance results are indicative of the environmental pressures affecting water availability in BC's grasslands and correspond with the reported declines in pond size and number. A study

of pond area in the Kenai Peninsula of Alaska found a 70 % reduction based on 1950 to 1996 aerial photography and concluded that the major mechanism was decreased water balance in a warming and drying climate (Klein et al. 2005).

Another potential factor that may have changed over the last 20+ years is the presence of frozen ground during the spring melt. If the ground is frozen during the melt, water will not be able to infiltrate the soil and more overland land flow would be available to fill the ponds. For the ground to remain frozen throughout the winter it would need to freeze in the late fall/early winter before any lasting snowfall. The snow would then insulate the ground which would remain frozen throughout the winter and during a considerable part of the spring melt. One potential indicator of the likeliness of this happening is degree days below zero. The weather data from 1901 – 2012 indicate a significant ($p < 0.001$) decline in degree days below zero at all eight sites with an average decrease of 21.5 degree days per decade (Table 2.5). These results are consistent with the increase in mean annual temperature. They suggest that it is less likely that these sites would have experienced the required cold snap in the most recent years relative to other time periods in the 1900s. With unfrozen ground, during the spring melt, there would be more water available for soil and ground water recharge and less available for pond filling

The weather data and pond decline data may also be an indication of widespread lowering of the water table (Riordan et al. 2006). There is evidence that suggests climate change will result in changes to the hydrological cycle (Loaiciga et al. 1996; Cayan et al. 2001; Barnett et al. 2005; Mote et al. 2005; Stewart et al. 2005; Huntington 2006). In BC, changes in the timing of hydrological processes are predicted (Leith and Whitfield 1998). These predictions include increasingly long and dry summers and possible water shortages in the late summer (Leith and Whitfield 1998). This may be directly related to declining regional groundwater tables that would affect groundwater – surface water interactions and thus, accentuate the typical seasonal summer drought. Therefore, a lowering of the water table could affect the ability of some closed-basin ponds to sustain a volume of water throughout the year.

One limitation of this study is the length of time between the first and last images analyzed. Within such a narrow time frame it is possible that we have missed the potential cyclic nature of closed-basin pond filling and drying events. Also, due to the range of natural

variability of precipitation, if the first period in the time series was an unusually wet year, the observed trends could be due to a sampling artifact (Riordan et al. 2006). To build upon this study older images should be analyzed and compared to the ones used here. It would also be useful to look at images from years in the mid-1900s that fall in the gaps between large snowfall events and compare them to images from years during and after the large snowfall events. This targeted analysis may support our suggestion that declining snow packs are the mechanism driving declines in pond number and area. It could also identify other potential dry periods in the last century thus determining the possible cyclic nature of closed-basin pond filling and drying events.

If the ponds do have a cyclic nature it seems that they have been drying more and for longer than ever before in the last 15 – 20 years. The reduction in surface area and number of closed-basin ponds that we have documented in this study may be an initial signal of more widespread changes that are occurring throughout BC's semi-arid grasslands. If current climate trends continue further declines in closed-basin ponds are probable. These changes in water availability in BC's grasslands can have detrimental effects on the ecosystem services they provide. Of these services the most noteworthy are the loss of breeding habitats for amphibians and waterfowl and drinking water sources for cattle during grazing. Wildlife conservation officers and range managers should be aware of the current conditions and be prepared for further or sustained declines in pond number and surface area. The loss of closed-basin ponds is a threat to these valuable services and therefore there is a need to build upon this study and more fully assess historical trends, geographic scope and mechanisms of pond hydrology.

Literature Cited

Allen RG, Pruitt WO, Wright JL, Howell TA, Ventura F, Snyder R, Itenfisu D, Steduto P, Berengena J, Yrisarry JB. 2006. A recommendation on standardized surface resistance for hourly calculation of reference ET o by the FAO56 Penman-Monteith method. *Agricultural Water Management* 81:1–22.

Barnett TP, Adam JC, Lettenmaier DP. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438:303–309.

Cannon AJ, Neilsen D, Taylor B. 2012. Lapse rate adjustments of gridded surface temperature normals in an area of complex terrain: atmospheric reanalysis versus statistical up-sampling. *Atmosphere-Ocean* 50:9–16.

Cayan DR, Dettinger MD, Kammerdiener SA, Caprio JM, Peterson DH. 2001. Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society* 82:399–415.

Cortini F, Comeau PG, Bokalo M. 2012. Trembling aspen competition and climate effects on white spruce growth in boreal mixtures of Western Canada. *Forest Ecology and Management* 277:67–73.

Daly C, Gibson WP, Taylor GH, Johnson GL, Pasteris P. 2002. A knowledge-based approach to the statistical mapping of climate. *Climate research* 22:99–113.

Folland CK, Karl TR, Jim Salinger M. 2002. Observed climate variability and change. *Weather* 57:269–278.

Gray LK, Hamann A. 2013. Tracking suitable habitat for tree populations under climate change in western North America. *Climate Change* 117:289–303.

Hayashi M, van der Kamp G. 2007. Water level changes in ponds and lakes: the hydrological processes. *Plant Disturbance ecology: the process and the response* 311–339.

Huntington TG. 2006. Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology* 319:83–95.

Iliffe J, Lott R. 2008. Datums and map projections: For remote sensing, GIS and surveying 2nd edition. Whittles Publishing: Scotland, UK.

Jolly ID, McEwan KL, Holland KL. 2008. A review of groundwater–surface water interactions in arid/semi-arid wetlands and the consequences of salinity for wetland ecology. *Ecohydrology* 1:43–58.

Karl TR, Groisman PY, Knight RW, Heim Jr RR. 1993. Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *Journal of Climate* 6:1327–1344.

Klein E, Berg EE, Dial R. 2005. Wetland drying and succession across the Kenai Peninsula Lowlands, south-central Alaska. *Canadian Journal of Forestry Research* 35:1931–1941.

Leith RM, Whitfield PH. 1998. Evidence of climate change effects on the hydrology of streams in south-central BC. *Canadian Water Resources Journal* 23:219–230.

Lettenmaier DP, Wood EF, Wallis JR. 1994. Hydro-climatological trends in the continental United States, 1948-88. *Journal of Climate* 7:586–607.

Loaiciga HA, Valdes JB, Vogel R, Garvey J, Schwarz H. 1996. Global warming and the hydrologic cycle. *Journal of Hydrology* 174:83–127.

Marsh P, Woo MK. 1977. The water balance of a small pond in the High Arctic. *Arctic* 109–117.

McAfee SA. 2013. Methodological differences in projected potential evapotranspiration. *Climate Change* 120:915–930.

Moore RD, Nelitz M, Parkinson E. 2013. Empirical modelling of maximum weekly average stream temperature in British Columbia, Canada, to support assessment of fish habitat suitability. *Canadian Water Resource Journal* 38:135–147.

Mote PW, Hamlet AF, Clark MP, Lettenmaier DP. 2005. Declining mountain snowpack in Western North America. *Bulletin of the American Meteorological Society* 86:39–49.

Oechel WC, Vourlitis GL, Hastings SJ, Zulueta RC, Hinzman L, Kane D. 2000. Acclimation of ecosystem CO_2 exchange in the Alaskan Arctic in response to decadal climate warming. *Nature* 406:978–981.

Pelto MS. 2008. Impact of Climate Change on North Cascade Alpine Glaciers, and Alpine Runoff. *Northwest Science* 82:65–75.

Pike RG, Spittlehouse DL, Bennett KE, Egginton VN, Tschaplinski PJ, Murdock TQ, Werner AT. 2008. Climate change and watershed hydrology: Part I–Recent and projected changes in British Columbia. *Streamline Watershed Management Bulletin* 11:1–8.

Riordan B, Verbyla D, McGuire AD. 2006. Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. *Journal of Geophysical Research: Biogeosciences* 111.

van Ryswyk A, McLean A, Marchand LS. 1966. The climate, native vegetation, and soils of some grasslands at different elevations in British Columbia. *Canadian Journal of Plant Science* 46:35–50.

Sannel ABK, Brown IA. 2010. High-resolution remote sensing identification of thermokarst lake dynamics in a subarctic peat plateau complex. *Canadian Journal of Remote Sensing* 36:S26–S40.

Shjeflo JB. 1968. Evapotranspiration and the water budget of prairie potholes in North Dakota. U.S. Geological Survey Professional Paper 585-B. Washington DC: U.S. Government Printing Office.

Smith LC, Sheng Y, MacDonald GM, Hinzman LD. 2005. Disappearing Arctic lakes. *Science* 308:1429–1429.

Smol JP, Douglas MS. 2007. Crossing the final ecological threshold in high Arctic ponds. *Proceedings of the National Academy of Sciences* 104:12395–12397.

Stewart IT, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. *Journal of climate* 18:1136–1155.

Thornthwaite CW. 1948. An approach toward a rational classification of climate. *Geographical Review* 55–94.

Tisdale EW. 1947. The grasslands of the southern interior of British Columbia. *Ecology* 28:346–382.

Umbanhowar C, Camill P, Edlund M, Geiss C, Durham W, Kreger D, Molano W, Raskob C, Stocker M, Tvera A, et al. 2013. Contrasting changes in surface waters and barrens over the past 60 years for a subarctic forest-tundra site in northern Manitoba based on remote sensing imagery. *Canadian Journal of Earth Science* 50:967–977.

Valentine KWG, Sprout PN, Baker TE, Lavkulich LM. 1978. Soil Landscapes of British Columbia. British Columbia Ministry of Environment, Resource Analysis Branch, Victoria, BC.

Vincent LA, Gullett DW. 1999. Canadian historical and homogeneous temperature datasets for climate change analyses. *International Journal of Climatology* 19:1375–1388.

Vincent LA, Mekis E. 2006. Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. *Atmosphere-Ocean* 44:177–193.

Wang T. 2013. Projecting future distributions of ecosystem climate niches in British Columbia. *Journal of Ecosystems and Management* 13.

Wang T, Hamann A, Spittlehouse DL, Murdock TQ. 2012. ClimateWNA—High-Resolution Spatial Climate Data for Western North America. *Journal of Applied Meteorology and Climatology* 51:16–29.

Whitfield PH, Stahl K. 2010. RD (Dan) Moore, David L. Spittlehouse. Compendium of forest hydrology and geomorphology in British Columbia. BC Min. For. Range 66:47.

Wikeem B, Wikeem S. 2004. The Grasslands of British Columbia, The Grasslands Conservation Council of BC, British Columbia.

Wilson SD, Nilsson C. 2009. Arctic alpine vegetation change over 20 years. *Global Change Biology* 15:1676–1684.

CHAPTER 3. DIFFERENCES IN GROUNDWATER – SURFACE WATER INTERACTIONS BETWEEN PERENNIALLY AND SEASONALLY INUNDATED PONDS IN BRITISH COLUMBIA'S SEMI-ARID GRASSLANDS

Introduction

Ponds and other wetlands are essential because they provide drinking water and support biodiversity (Daily et al. 1997; Gopal and Junk 2000; Zedler and Kercher 2005). Over the last century a large percentage of wetlands have been lost worldwide (Williams 1999). In the absence of lakes and streams, closed-basin ponds are the main source of fresh water in British Columbia's (BC) semi-arid grasslands. One of the most noticeable differences between types of ponds is whether they are perennially or seasonally inundated. Perennially inundated ponds maintain a level of surface water throughout the year, whereas surface water is only temporary in seasonally inundated ponds. Perennially inundated ponds are a more reliable breeding ground for water fowl and amphibians and a more reliable source of drinking water for wildlife and cattle. Seasonally inundated ponds also provided similar services, but are more sensitive to climatic shifts and may be at risk due to climate change (Johnson et al. 2005). Currently there is limited understanding of the factors that govern the hydrologic functions of these wetland systems (Jolly et al. 2008). This knowledge is necessary to determine the differences between permanently and seasonally inundated ponds, predict the impacts of climate change and guide effective management of wetland systems in BC's semi-arid grasslands.

The dominant hydrological inputs and outputs of closed-basin ponds can influence their permanence and ecology (Ferone and Devito 2004). Closed-basin ponds may be strongly linked to regional or local groundwater systems (Jolly et al. 2008) and large-scale changes to regional aquifer hydrology may affect their ecological integrity (Dempster et al. 2006; Scibek et al. 2007). Studies of prairie potholes have shown that hydrogeological setting or landscape position can define the dominant recharge-discharge mechanisms, stage fluctuations and permanence of a wetland (Lissey 1971; Sloan 1972; Winter et al. 1989; Hayashi et al. 1998). Groundwater – surface water (GW – SW) interactions are strongly governed by local geomorphology (Jolly et al. 2008). In BC's grasslands, ponds form at low points in the landscape where alluvial depositional processes have created bases of low

hydraulic conductivity clay and silt (Wikeem and Wikeem 2004). These deposits can impede vertical groundwater movement between the aquifer and pond (Jolly et al. 2008) and consequently GW – SW interactions occur laterally at pond edges (Hayashi et al. 1998; Van der Kamp and Hayashi 1998). These interactions are strongly controlled by the relative groundwater and surface water pressure heads which can vary significantly over the short term (Rosenberry and Winter 1997). Short term variations include cases where evapotranspiration (Hayashi et al. 1998; Van der Kamp and Hayashi 1998) or snowmelt (Winter and Rosenberry 1995; Winter and Rosenberry 1998) have initiated reversals in groundwater flow direction. In colder climates, snowmelt is a main form of water input to closed-basin ponds and can have a large effect on the pressure heads governing the GW – SW interactions (Winter and Rosenberry 1998; Stewart et al. 2005; Hayashi and van der Kamp 2007). Therefore, the effect of climate change on precipitation patterns and snowmelt dynamics could influence changes in pond GW – SW interactions (Wurster et al. 2003).

The Lac du Bois grasslands in the southern interior of BC are cattle grazing rangelands where ponds have been used as drinking water sources for cattle since the early 20th century. Within these grasslands there are both seasonally and perennially inundated ponds. These ponds were formed by similar processes and are exposed to similar weather patterns. Despite these similarities, some ponds are able to maintain surface water year round while others are not. It is possible to classify the ponds into two basic types based on differences in hydrodynamics (Rains 2011). One type are perched-precipitation ponds, which have inputs of snow melt water and direct precipitation and outputs by evapotranspiration and groundwater recharge. They are seasonally inundated because surface water is perched above the water table and therefore, water is lost by both evapotranspiration and groundwater recharge. The second type are flow-through ponds which have inputs of snow melt water, direct precipitation and groundwater discharge and outputs by evapotranspiration and groundwater recharge. They are permanently inundated because of the consistent flow-through of groundwater (Hayashi and van der Kamp 2007; Jolly et al. 2008; Rains 2011).

Despite the well documented role of wetlands in the hydrological cycle (Bullock and Acreman 2003) there is a knowledge gap in the study of wetlands in semi-arid ecosystems (Jolly et al. 2008). In particular, GW – SW interactions were not the traditional focus in wetland environments but recently have been increasingly treated as part of the same system

(Hayashi and Rosenberry 2002; Sophocleous 2002). The objective of this study is to expand our knowledge of wetland hydrology in semi-arid ecosystems by determining if the GW – SW interactions between permanently and seasonally inundated ponds in the Lac du Bois grasslands differ and determining the effect of rainfall on these interactions. We hypothesize that the perennially inundated ponds are persistently connected to the regional groundwater, whereas the seasonal ponds are not. We also hypothesize that perennially inundated pond levels will respond more to rainfall than seasonal ponds because of their groundwater connections to the surrounding catchment.

Methods

Study Area

The study sites are located in the Lac du Bois Grasslands, a 15 000 hectare park in the Southern Interior of BC. Lac du Bois is a moderately grazed rangeland and closed-basin ponds are often used as watering sources for cattle. This area is ideal for studying closed-basin ponds on complex terrain due to the broad altitudinal scale and rolling hill topography. It is located west of the North Thompson River and north of the Thompson River. It has an elevation gradient of 300 – 940 m above sea level (asl) and complex rolling hill terrain formed from past glaciation events. The lower elevations, 300 – 600 m asl, are dominated by *Pseudoroegeneria spicata* (bluebunch wheatgrass), *Poa secunda* (Sandberg's bluegrass) and the shrub *Artemisia tridentata* (big sagebrush). The middle elevations, 600 – 800 m asl, have the same species as above with greater diversity and lower cover of sagebrush (Van Ryswyk et al. 1966). The upper elevations, 800 – 940 asl, are nearly void of big sagebrush and have continuous herbaceous cover dominated by *Festuca scabrella* (rough fescue) and many species of forbs. This area also contains clumps of *Populus tremuloides* (quaking aspen) and is bordered at the highest elevations by the *Pseudotsuga menziesii* (douglas fir) forest (van Ryswyk et al. 1966).

Four ponds in the Lac du Bois grasslands were selected for this study. Two of the ponds are located in the upper elevation grasslands and referred to as upper wet pond (UWP) and upper dry pond (UDP). The other two ponds are located in the middle elevation grasslands and referred to as lower wet pond (LWP) and lower dry pond (LDP) (Figure F8). Ponds were not selected from the lower grasslands because there were insufficient

permanently inundated ponds. Each pair consists of a perennially inundated pond (UWP and LWP) and a seasonally inundated pond (UDP and LDP) determined by direct observation in September 2013. The lower ponds (Kamloops, BC; 120°25'27"W, 50°45'8"N) are at an elevation of 680 – 720 m asl with a mean annual precipitation of 300 mm (van Ryswyk et al. 1966). The soil profile consists mostly of light brown chernozems on morainal blankets which tend to be dry, thin and well drained (van Ryswyk et al. 1966). The upper ponds (Kamloops, BC; 120°26'55"W, 50°48'22"N) are located at an elevation of 900 – 940 m asl with a mean annual precipitation of 500 mm (van Ryswyk et al. 1966). The general soil profile consists of mostly black chernozems on a morainal blanket with more gravely till that provides better water retention (van Ryswyk et al. 1966; Gayton 2003). In and around the ponds there are low permeability surficial deposits consisting of solonetzic or vertic type soils (K. Watson, personal communication, January 2013).

Well and Piezometer Installation

Piezometer heads (Solinst, Georgetown, Canada) were fitted with two meter long black steel pipe (1.91 cm). Well points (3.175 cm stainless steel) were fitted with PVC pipe (3.175 cm) that had been slotted and wrapped in mosquito mesh. All wells and piezometers not submerged in water were inserted into pre-drilled holes and then sealed at ground level with bentonite clay. The holes were drilled with a power auger (5.08 cm) to a maximum depth of 2 m. Wells and piezometers installed in water were tapped into place using a post pounder.

Wells and piezometers were installed along a single transect through each pond (Figure F8). The orientation of each transect was based on where drainage was most likely to occur which was determined from examination of topography maps and GIS hydrology layers. Two piezometers were installed inside each of the four ponds. By installing two piezometers side-by-side at different depths, the vertical hydraulic gradient can be calculated (Post et al. 2007; Sara 2010). For the perennially inundated ponds, the piezometers were installed approximately 5 - 10 m from the northern shoreline to provide easy access for data collection. For the dry ponds, the piezometers were installed in the estimated center point of the depression. Along with each pair of piezometers, a well (M) was installed to monitor

pond stage height. Additional wells were installed upslope and downslope of each pond. Two offshore wells were installed at each pond; one was installed upslope (N) off the northern shore line and the other downslope (S) off the southern shoreline (Figure 3.1). The elevations and locations of all wells and piezometers were surveyed using a Pentax Total Station (Model PTS 605).

Figure 3.1: Images of four ponds in the Lac du Bois grasslands showing approximate well (blue dots) and piezometer (orange dots) locations; (A) upper wet pond (UWP), (B) lower wet pond (LWP), (C) upper dry pond (UDP), (D) lower dry pond (LDP) and (E) the spatial relationship between UWP and UDP.

Data Collection

All wells and piezometers were measured manually from 8 March to 4 November 2014. Depth to water from the top of the wells and piezometers was recorded every 3-5 days during the spring (4 March to 29 April 2014), 1-2 times weekly from early spring to

midsummer (6 May to 7 July 2014) and once every 1-2 weeks from midsummer to early winter (21 July to 4 November 2014). Additional water depth data was measured hourly from 30 November to 4 November 2014 in four of the wells (one per pond) with pressure transducers (Hobo Levelogger, Onset Comp, Bourne, MA). For UDP and LDP the pressure transducers were installed in the middle wells (M). For fear of potentially losing the pressure transducers in the perennially inundated ponds, UWP and LWP, they were installed in the offshore wells (N). The height of the water table at the outer wells was graphed relative the stage height of the ponds. The vertical hydraulic gradient was calculated for all piezometer data points.

Precipitation and air temperature data from the Kamloops Airport were downloaded from Climate Services BC. Monthly average data from 2014 were compared to historical data (1951 – 2012). Also, daily precipitation events, greater than 4 mm, from spring through fall, were plotted against increases in water table height recorded by the pressure transducers during the the time of the rainfall events. The pressure transducer data 1-2 days after the precipitation event was subtracted from the data one day before the event to determine any changes in water table height associated with rainfall. The data were grouped by season, spring (March – May), summer (June – August) and fall (September – November).

Results

Air Temperature and Precipitation

In 2014 the average air temperature was higher than the average over the time period from 1951 – 2012. In particular, in 2014 the average temperature in January and December was 3.1°C and 2.1°C higher than the historic mean, respectively (Figure 3.2). The July and August temperatures were also higher than the historic mean, 2.0°C and 2.2°C, respectively. Total precipitation in 2014 (278 mm) was similar to the historic average yearly total (266 mm). However, precipitation from March through August totalled 184 mm in 2014 compared to the historic average of 133mm. Conversely, precipitation from January and February totalled 13 mm in 2014 compared to the historic average of 40 mm. Although the total precipitation was similar, in 2014 there was less precipitation as snow in the late winter and more precipitation as rain in the spring and summer compared to the historical means.
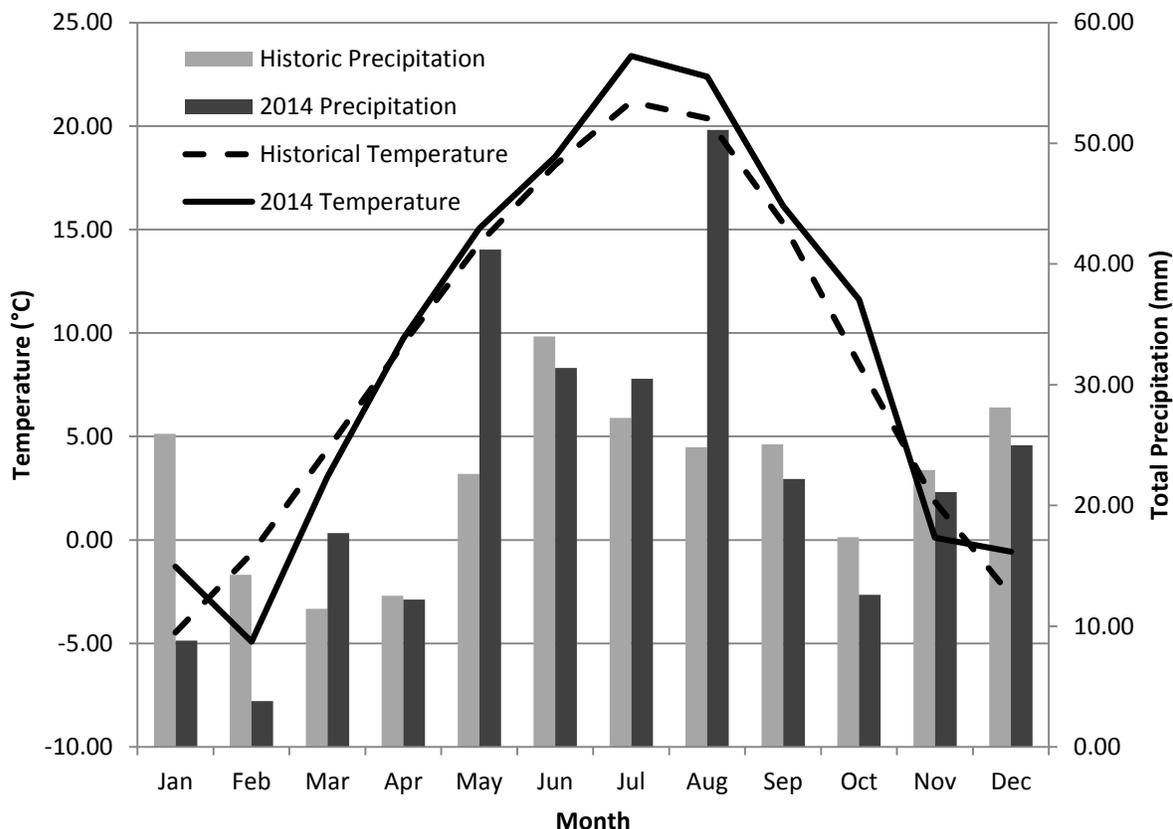
Figure 3.2: 2014 and historic (1951 - 2012) average monthly temperature and total monthly precipitation from the Kamloops Airport weather station.

Lower Dry Pond

The lower dry pond (LDP) was at its greatest depth during the measurement period immediately following the snow melt in mid-March. From, 15 March to 8 April 2014 water was above the surface of the soil, reaching a maximum depth of ~10 cm on 17 March 2014 (Figure 3.3). The water table in the middle of the pond was permanently below ground as of 8 April 2014 and for the remainder of the study. It fluctuated below ground during the first part of the growing season from 8 April to 22 May 2014 after which it steadily decreased throughout the summer and fall.

Prior to the snow melting in the spring, the water was down welling from the pond to the soil below (Figure 3.3; negative hydraulic gradient). After 14 March 2014 the water table height increased and the hydraulic gradient switched from negative to positive indicating that water was upwelling from below into the pond. At the same time the water table height

moved above the surface on 15 March 2014 and reached a maximum on 17 March 2014. Following 17 March 2014, the water table height and the hydraulic head decreased. On 8 April 2014 the water table dropped below the surface and on 28 July 2014 the hydraulic head became negative, indicating the water was now moving down the soil profile instead of up.

The water table height at N was initially below that of M, suggesting water was moving from M to N before and after the spring melt. When the pond was at its fullest in mid-March it was perched well above the local ground water table at N. In late May, the water table at N was higher than M, indicating that water was moving from N to M. However, this condition did no persist because on 7 July 2014 the water table at N dropped below M.

The downslope well (S) had a similar relative depth profile to that of N (Figure 3.4). It shows that as the water table at M rises to the surface during the snow melt it is perched above S. Similar to N, as the pond loses water in the spring at M the water table begins to level out with S below the surface. S stayed slightly higher or equal to M through the summer and fall.

The LDP stage height at the middle well appears to respond to precipitation in spring with large increases in stage height following precipitation events (Figure 3.5). However, the spring time increases in stage height were most likely due to the snowmelt and not direct rainfall. On the other hand, there is little to no response to the much larger precipitation events (ranging from 15 to 30 mm) that occurred during the summer.
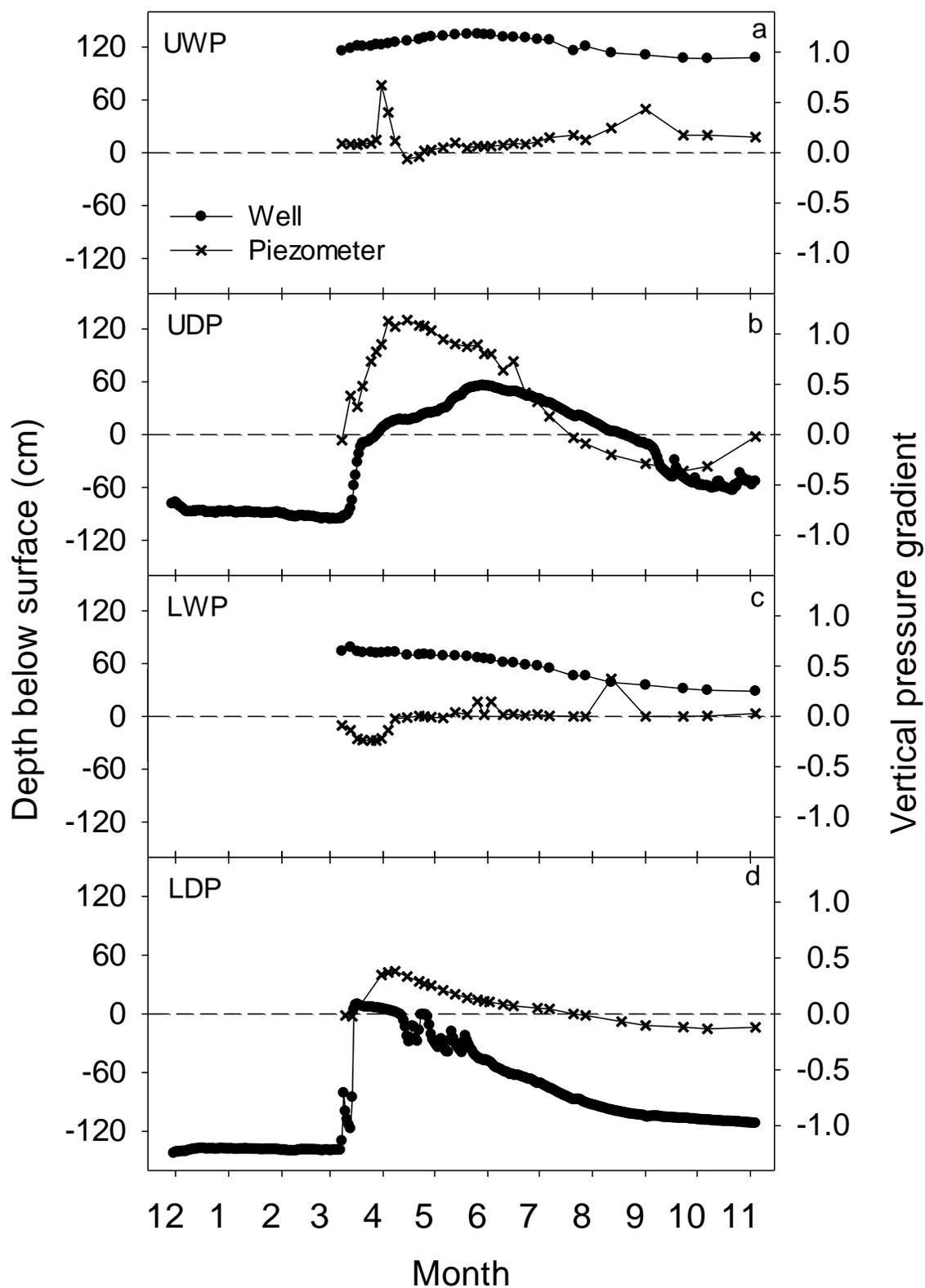
Figure 3.3: Depth of the water table at the middle wells (M) relative to the ground and the vertical pressure head gradient measure at M for all ponds.
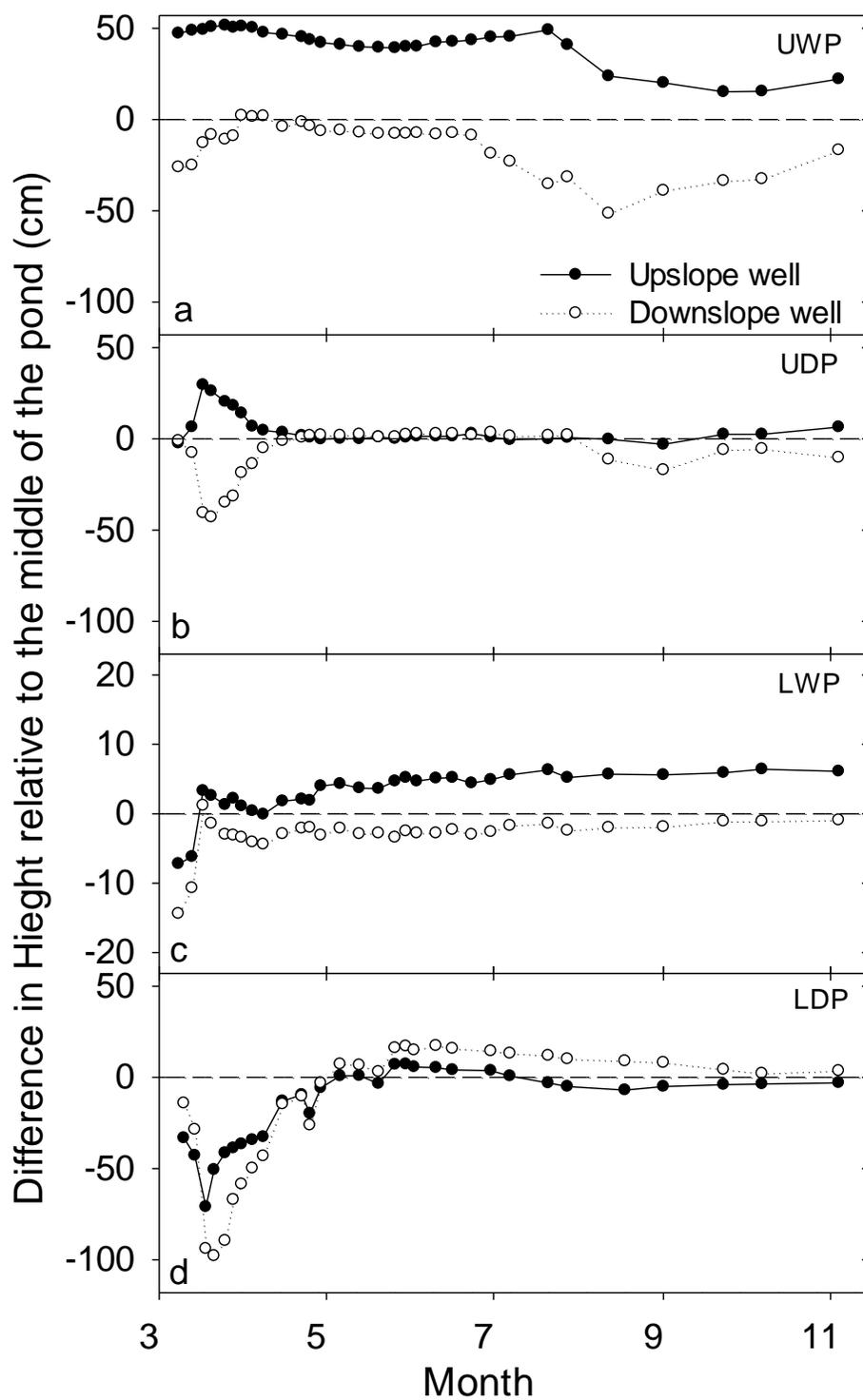
Figure 3.4: Depth of the water table of the upslope well (N) and the downslope well (S) relative to the middle well (M). Note: (c) has a different scale on the y-axis to better visualize the data.
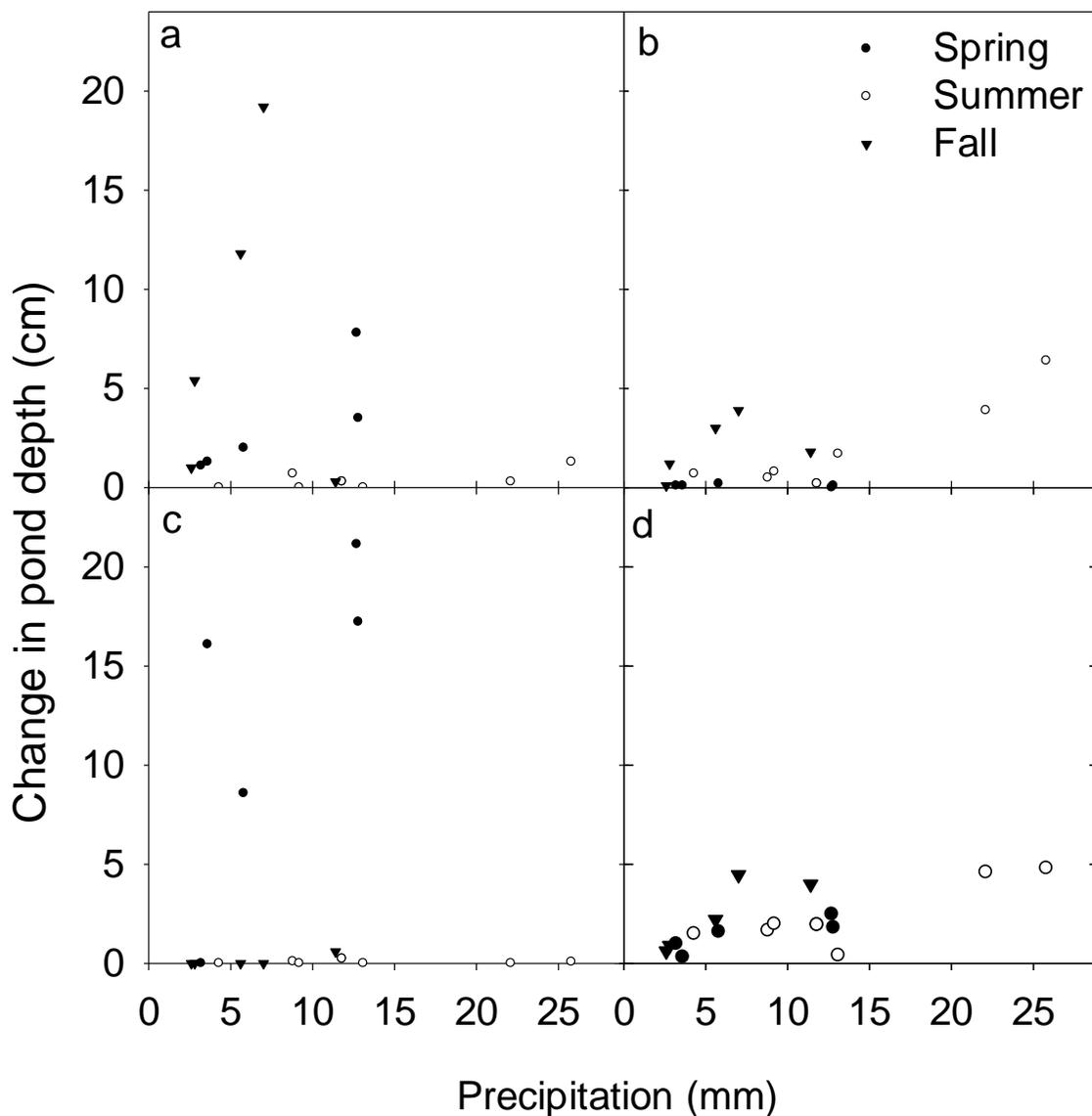
Figure 3.5: The change in water depth recorded by pressure transducers during and after daily precipitation events; (a) upper dry pond (UDP), (b) upper wet pond (UWP), (c) lower dry pond (LDP) and (d) lower wet pond (LWP).

Lower Wet Pond

The lower wet pond (LWP) maintained a volume of water throughout the winter and immediately following the spring melt it reached a maximum on 13 March 2014. The small rise, 4.5 cm, it experienced during the spring melt only lasted a few days before the stage height dropped back to its previous level before the melt (Figure 3.3). Water remained above

the surface throughout the year despite a consistent drop that saw the water level decrease by 50 cm from 13 March to 4 November 2014.

Prior to the snow melt, the vertical pressure head at the M well location was slightly down gradient and became a stronger down gradient during the melt (Figure 3.3). It then leveled out at a gradient around zero in mid-April and remained around zero for the rest of the year except for a few up-gradient spikes at the end of May, early June and mid-August.

The depth of the water table relative to M at well N was below the pond stage height prior to the snow melt. Immediately following the melt the water table at N rose above that of the pond stage height and remained above from mid-March to early November (Figure 3.4). This indicates a consistent flow of water into the pond during spring, summer and fall from these locations.

Similar to N, the depth of the water table at S was below that of the pond prior to the snow melt. During the melt, the water level at S spiked above that of the pond indicating a flow of water into the pond during this period. However, immediately following the melt the water level at S dropped below the stage height of the pond and remained below from 25 March to 4 November 2014 (Figure 3.4). Therefore, the data indicates that this site has water moving from the north to the south for most of the year. For a brief period in the spring, the pond is receiving water from both the north and the south.

Precipitation events did correspond with increases in water table height at N during spring, summer and fall (Figure 3.5). The greatest increases resulted from fall precipitation and the large (15 to 30 mm) storms in the summer. The increased flows from the upslope groundwater table at N corresponded with a pond stage height response at M. Particularly, a few of the larger precipitation events in mid-June and near the end of July resulted in a leveling off the pond stage height that briefly interrupted the steady decline. This shows that rainfall capture in the ponds catchment temporarily increased groundwater flow to the pond.

Upper Dry Pond

The upper dry pond (UDP) represents a special case in which it has a strong hydrological connection to UWP, an adjacent, higher elevation pond (Figure F9). Despite this connection it is not perennially inundated. This pond is also the only one of the four that is extensively vegetated by water loving plants (e.g. bulrush, *Scirpus atrovirens*). Moreover,

due to the "bowl" like nature of the terrain and the relatively small pond area it was not possible to install the outer wells (N and S) far from shore with a 2 m depth limitation. Therefore, from the end of April to mid-august both N and S were within the surface water boundaries of the pond.

The water table at the middle well (M) in the upper dry pond rose 110 cm during the spring melt from 8 March to 8 April 2014 (Figure 3.3). The pond maintained surface water from 28 March to 19 August 2014 and reached a maximum depth on 26 May 2014. It then steadily declined throughout summer and fall with a slight rebound at the end of October finishing with a below ground water level ~ 30 cm higher than the start of the year.

The vertical pressure head was down gradient prior to the snow melt but quickly became up gradient during the melt and stayed up gradient until mid-July reaching its maximum on 15 April 2014 (Figure 3.3). After mid-July the vertical pressure became down gradient and continued to become stronger down gradient throughout the summer before increasing again in October.

The depth of the water table at N relative to M was similar prior to the snow melt. During the melt, the water table at N rose 30 cm above that of M indicating water was moving from N towards the pond (Figure 3.4). After 17 March 2014 the relative height of N to M declined until the levels again reached a similar depth around 29 April 2014. At this point N was within the surface water boundary of the pond. When the pond lost its surface water in mid-August the water table depth at N briefly dipped below that of M before rebounding during the fall and finishing above M.

In contrast to N, the water table at S fell 40 cm below that of M indicating water was moving from M towards S (Figure 3.4). Taken together with N, these results show a typical flow through pattern during 8 March to 22 April 2014. After 20 March 2014 the relative water table height of S to M began to rise until they reached a similar depth around 22 April 2014. At this point S was within the surface water boundary of the pond and its level remained even with M until the end of July. It then dropped below M and remained below for the rest of the study period.

The stage height of the upper dry pond showed no considerable response to rainfall events in the spring and summer (Figure 3.5). It appears to be more responsive to rainfall in the fall with increased water levels corresponding with rainfall events in mid-September and

the end of October. However, these responses also coincide with increased water levels in UWP which would have resulted in increased groundwater input from UWP to UDP.

Rainfall appeared to have no effect on the upper dry pond stage height during the summer months (Figure 3.5). Small increases in stage height ($1 - 8$ cm) were observed after medium depth ($5 - 15$ mm) rainfall events in the spring. The stage height appeared to be the most responsive to fall rain events even ones of low depth ($1 - 4$ mm). The fact that the stage height increased in the range of $5 - 20$ cm after only $1 - 4$ mm of rain suggests that the increases in pond level were due to increased flows from the upper wet pond.

Upper Wet Pond

The upper wet pond maintained surface water throughout the winter and experienced an increase in water level throughout the spring and reached maximum depth on 20 May 2014 (Figure 3.3). After 20 May 2014 the pond level began to decline and dropped 12 cm from 7 July to 21 July 2014. It then briefly increased in depth in response to the large (23 mm) storm event on 23 July 2014. The water level then continued to decrease throughout the summer and leveled out from mid-September to early November.

There was upwelling of water (positive vertical pressure gradient) throughout March, with a large positive spike on 30 March 2014, most likely corresponding to melt water from higher upland elevations. There was brief period of down welling in mid-April before returning to a positive upwelling that was maintained throughout the summer and fall. Although the pond declined in level throughout the summer, most likely, due to evapotranspiration and groundwater recharge,however the consistent upwelling suggests that these effects were to some extent minimized by consistent groundwater input to the pond.

The depth of the water table at N relative to the pond stage height at M was higher for the full study period measured (Figure 3.4). Although the relative water table depths fluctuated, the consistently higher water table at N suggests the pond is constantly receiving groundwater input from the upslope area which is consistent with the upwelling gradient reported at the M site.

In contrast to N, the depth of the water table at S was lower than that of M for the majority of the study period (Figure 3.4). The water level in S was similar to that of the pond after the snowmelt at the end of March. The water level then dropped approximately 7 cm

below that level of the pond and remained fairly consistent from the end of April to 23 June 2014. The water level relative to the pond then dropped considerably over the next 30 days, approximately 27 cm. It rebounded briefly after the 23 July 2014 storm and then continued to drop through mid-August after which it increased relative to the pond level throughout the rest of summer and fall. Taken together with N, these results are characteristic of a typical flow through pond in which there is groundwater input from upslope and groundwater output downslope.

The stage height of UWP responded to rainfall inputs. The pond stage height is increasing from 8 March to 26 May 2014 during which there were rainfall events. However, these increases are most likely due to the higher elevation snow melt inputs during this time. When the pond begins to decrease in late May it stabilizes for a brief two week period in which there were a couple moderate (5 – 15 mm) rainfall events (Figure 3.5). It also responded to the large storm on 23 July 2014 with a rise in pond stage height of approximately 6 cm. Also, the slowing of the decline in pond level from the end of the July through October appears coincide with periodic rainfall events during this period.

Similar to LWP and in contrast to UDP and LDP, UWP responds considerably to large summer precipitation events (Figure 3.5). The pond stage height increased noticeably after these events. The pond stage height also responded to fall precipitation but had little to no response to spring rainfall. Similarly to LWP, this is indicative of rainfall capture in the ponds catchment area translating into increased groundwater flows to the pond due to its connectivity to the groundwater system.

Discussion

Results from this study show that GW – SW interactions play an important role in the permanence of pond surface water and sensitivity to climate. Studies in the arctic, boreal plains and the prairies have classified ponds based on the relationship between the stage height of a pond and the surrounding water table (Lissey 1971; Sloan 1972; Winter and Rosenberry 1998; Ferone and Devito 2004; Rains 2011). In this study, two types of ponds were identified with respect to GW - SW interactions: perched-precipitation ponds and flow-through ponds. Pond type was determined by the relative water table level between the offshore wells and the stage height of the ponds. Similarly, a study of closed-basin

depressions in Alaska identified perched-precipitation and flow-through ponds by monitoring water levels in wells and piezometers installed in and around the ponds (Rains 2011). Here we found evidence that the LWP and UWP are perennial flow-through ponds and that the LDP is a seasonal perched-precipitation pond. UDP represents a special case. It is a flow-through pond when connected to groundwater flows from the UWP and is a perched-precipitation pond when not connected.

Perennially Inundated Ponds

It is evident that the perennially inundated ponds, LWP and UWP, receive consistent groundwater inputs. For the majority of the study period the water table at the upslope wells was higher than the water level of the pond. The maintained connection to the regional groundwater table represents a mechanism of maintaining surface water through the hot and dry summers and increased evapotranspiration that is common in semi-arid ecosystems (Tisdale 1947; Wikeem and Wikeem 2004; Nagler et al. 2007). These ponds also have a groundwater discharge component which is supported by the consistently lower water table depth downslope of the ponds. These GW – SW interactions are consistent with flow-through type ponds (Townley and Davidson 1988; Townley and Trefry 2000; Smith and Townley 2002). The piezometer data further support groundwater inputs. The vertical pressure head remained positive for most of the study period which suggests consistent upwelling of groundwater near the upslope shoreline of the ponds. Although the pressure head was mostly positive at these locations, it did fluctuate. Fluctuating head differences combined with local geomorphology can play a role in controlling the rates of exchange of groundwater and surface water (Huggenberger et al. 1998; Lamontagne et al. 2005). For instance, although perennially inundated and receiving inputs from upslope groundwater discharge, the LWP dropped 50 cm from March to November (Figure 3.3). This suggests that groundwater inputs to this pond were not significant enough to offset the outputs of groundwater recharge and evapotranspiration. This may be a sign that the regional water table has declined resulting in less groundwater discharge to the pond. Although these perennially inundated ponds appear to be less sensitive to seasonal weather due to groundwater connectivity, these groundwater connections may be at risk from long term changes to the hydrological cycle as a result of

climate change (Loaiciga et al. 1996; Cayan et al. 2001; Barnett et al. 2005; Mote et al. 2005; Stewart et al. 2005; Dempster et al. 2006; Huntington 2006; Scibek et al. 2007).

Further evidence to support the consistent groundwater connectivity to the LWP and UWP is the response to rainfall. Both ponds responded similarly to rainfall events in the spring, summer and fall. Groundwater levels and pond stage heights increased during and after rainfall events. However, the increases in pond level were disproportionate to the depth of rainfall. This suggests that rainfall in the catchment area increased subsurface and groundwater flows to the ponds. Therefore, these increases would not be possible without connectivity to the groundwater system. These observations are related to the fact that GW – SW interactions play a role in the rainfall-induced hydrological pulsing that drives the functioning of floodplain ecosystems (Amoros and Bornette 2002).

Seasonally Inundated Ponds

The seasonally inundated ponds, LDP and UDP, did not have consistent groundwater inputs during the study period. In the case of the LDP, it received a large influx of water from the snow melt in March. During the short period of time that it had surface water the water table at the outer wells was below the water level of the pond. Therefore, the pond was losing surface water to groundwater recharge. This relationship between the surface water and local groundwater is consistent with perched-precipitation type ponds (Townley and Davidson 1988; Townley and Trefry 2000; Smith and Townley 2002). The temporary surface water at LDP was due to snowmelt and it had no input at the surface from groundwater at any time during the study period. In contrast, UDP had temporary inputs from groundwater dependent on water levels in the UWP. From March to mid-August, the flow-through from the UWP maintained a groundwater level upslope of UDP that was higher than the water level of the pond. However, at the end of that time period the water level in the UWP dropped to a point where the groundwater flow to the UDP was disconnected. Also, during the majority of the study period the pond was losing water to groundwater recharge at the downslope location. Therefore, in mid-August, the UDP switched from flow-through to perched-precipitation and the surface water declined until the pond was completely dry. This type of pond is similar to the special-case flow-through pond described by Rains (2011).

The special-case flow through description is further supported by the change in vertical pressure head during the transition. While receiving groundwater input the vertical pressure head is positive and when the groundwater connection is cut off the vertical pressure head becomes negative. The rapid decline in surface water when both the LDP and UDP were in a perched-precipitation state confirms the importance of groundwater inputs to maintain surface water. These results also show that perched-precipitation ponds are dependent on snowmelt to collect temporary surface water. Therefore, the depth and density of the snowpack and snowmelt dynamics and timing will have a large effect on the volume of water received and the length of time surface water will persist. Consequently, perched precipitation ponds are very sensitive to changes in climate. Their reliability as drinking water sources for cattle at certain times of the year is at risk due to declining mountain snowpack and earlier streamflow timing (Loaiciga et al. 1996; Leith and Whitfield 1998; Barnett et al. 2005; Mote et al. 2005; Stewart et al. 2005; Huntington 2006).

As discussed above, pond water level response to rainfall can be an indicator of connectivity to the local groundwater system. In contrast, to the LWP and UWP, the LDP and UDP showed no response to the large (15 – 30 mm) rainfall events in the summer. The large responses to spring rain events coincided with the inputs being received by snow melt and therefore their true response to rainfall at that time cannot be determined. The below ground water table at UDP in the fall responded to precipitation which also coincided with higher levels in the UWP and increased groundwater flows. Without a consistent groundwater input connection perched-precipitation ponds do not gain significant volume from rainfall events.

Controls on GW – SW interactions in grassland ponds

Here we found evidence from monitoring wells in and around ponds that confirmed the LWP and UWP to be perennial flow-through ponds and the UDP to be a special case seasonal flow-through pond that is highly dependent on discharge from the upland UWP. We also determined that the LDP was a seasonal perched-precipitation pond. Consistent with other studies, we observed that local geomorphology has a strong influence on groundwater movement in and out of ponds (Lissey 1971; Sloan 1972; Winter and Rosenberry 1995; Van der Kamp and Hayashi 1998; Ferone and Devito 2004; Rains 2011).

The LDP is located in a large, flat area and any seasonal surface water is shallow with a high surface area to volume ratio. It has little to no interaction with the local groundwater system. It is completely dependent on snow melt and direct rainfall and subject to lateral groundwater discharge and high evaporative demand in the summer. It is therefore very sensitive to climate change which can affect precipitation patterns, snowmelt dynamics and evapotranspiration (Oechel et al. 2000; Folland et al. 2002; Wurster et al. 2003; Mote et al. 2005; Stewart et al. 2005). In contrast, the LWP and UWP are located in deep depressions with relatively steep surrounding embankments and likely have a lower surface area to volume ratio. They have constant interaction with the local groundwater system both as inputs and outputs which is consistent with flow-through type ponds (Van der Kamp and Hayashi 1998; Jolly et al. 2008; Rains 2011). The constant GW – SW interactions of these ponds make them less sensitive to changes in climate compared to perched precipitation ponds such as LDP. The balance between input and output of groundwater at these ponds is dynamic and is controlled by relative GW – SW pressure heads which can vary significantly over the short term (Rosenberry and Winter 1997). This was evident at both the LWP and UWP by the seasonal fluctuations observed in surface water level and groundwater level due to the spring melt and the dry conditions in the summer months. These fluctuations can vary from year to year based on climate variables and therefore these ponds are not completely protected from the effects of climate change. In fact, large scale changes to regional aquifer hydrology may affect the integrity of these type of ponds (Dempster et al. 2006; Scibek et al. 2007).

Future work looking more in detail at pond water balances is needed. Studies of catchment area and snow water equivalent in winter snow packs would be a valuable quantification of snow melt input. Also, measuring pond bathymetry and mapping surface area changes would quantify changes in surface water volume. Moreover, detailed weather data from locally installed weather stations could provide data for accurately measuring evapotranspiration. A more extensive network of wells and piezometers would provide more detailed information on local GW – SW pressure heads and interactions. This information could lead to determining the limiting factors affecting pond hydrology and how climate change may affect future surface water availability.

Literature Cited

Amoros C, Bornette G. 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. *Freshwater Biology* 47:761–776.

Barnett TP, Adam JC, Lettenmaier DP. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438:303–309.

Bullock A, Acreman M. 2003. The role of wetlands in the hydrological cycle. *Hydrology and Earth System Sciences Discussions* 7:358–389.

Cayan DR, Dettinger MD, Kammerdiener SA, Caprio JM, Peterson DH. 2001. Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society* 82:399–415.

Daily GC, Alexander S, Ehrlich PR, Goulder L, Lubchenco J, Matson PA, Mooney HA, Postel S, Schneider SH, Tilman D 1997. Ecosystem services: benefits supplied to human societies by natural ecosystems. Ecological Society of America Washington (DC).

Dempster A, Ellis P, Wright B, Stone M, Price J. 2006. Hydrogeological evaluation of a southern Ontario kettle-hole peatland and its linkage to a regional aquifer. *Wetlands* 26:49–56.

Ferone JM, Devito KJ. 2004. Shallow groundwater-surface water interactions in pond-peatland complexes along a Boreal Plains topographic gradient. *Journal of Hydrology* 292:75–95.

Folland CK, Karl TR, Jim Salinger M. 2002. Observed climate variability and change. *Weather* 57:269–278.

Gayton D. 2003. British Columbia grasslands: monitoring vegetation change. Kamloops, BC: FORREX.

Gopal B, Junk WJ. 2000. Biodiversity in wetlands: assessment, function and conservation. Vol. 2. Backhuys Publishers, Leiden.

Hayashi M, van der Kamp G. 2007. Water level changes in ponds and lakes: the hydrological processes. *Plant Disturbance ecology: the process and the response* 311–339.

Hayashi M, van der Kamp G, Rudolph DL. 1998. Water and solute transfer between a prairie wetland and adjacent uplands, 1. Water balance. *Journal of Hydrology* 207:42–55.

Hayashi M, van der Kamp G. 1998. The groundwater recharge function of small wetlands in the semi-arid northern prairies. *Great Plains Research: A Journal of Natural and Social Sciences.* Paper 366.

Hayashi M, Rosenberry DO. 2002. Effects of ground water exchange on the hydrology and ecology of surface water. *Groundwater* 40:309–316.

Huggenberger P, Hoehn E, Beschta R, Woessner W. 1998. Abiotic aspects of channels and floodplains in riparian ecology. *Freshwater Biology* 40:407–425.

Huntington TG. 2006. Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology* 319:83–95.

Johnson WC, Millett BV, Gilmanov T, Voldseth RA, Guntenspergen GR, Naugle DE. 2005. Vulnerability of northern prairie wetlands to climate change. *BioScience* 55:863–872.

Jolly ID, McEwan KL, Holland KL. 2008. A review of groundwater–surface water interactions in arid/semi-arid wetlands and the consequences of salinity for wetland ecology. *Ecohydrology* 1:43–58.

Lamontagne S, Leaney FW, Herczeg AL. 2005. Groundwater–surface water interactions in a large semi-arid floodplain: implications for salinity management. *Hydrological Processes* 19:3063–3080.

Leith RM, Whitfield PH. 1998. Evidence of climate change effects on the hydrology of streams in south-central BC. *Canadian Water Resources Journal* 23:219–230.

Lissey A. 1971. Depression-focused transient groundwater flow patterns in Manitoba. *Geological Association of Canada Special Paper* 9:333–341.

Loaiciga HA, Valdes JB, Vogel R, Garvey J, Schwarz H. 1996. Global warming and the hydrologic cycle. *Journal of Hydrology* 174:83–127.

Mote PW, Hamlet AF, Clark MP, Lettenmaier DP. 2005. Declining mountain snowpack in Western North America. *Bulletin of the American Meteorological Society* 86:39–49.

Nagler PL, Glenn EP, Kim H, Emmerich W, Scott RL, Huxman TE, Huete AR. 2007. Relationship between evapotranspiration and precipitation pulses in a semiarid rangeland estimated by moisture flux towers and MODIS vegetation indices. *Journal of Arid Environments* 70:443–462.

Oechel WC, Vourlitis GL, Hastings SJ, Zulueta RC, Hinzman L, Kane D. 2000. Acclimation of ecosystem CO_2 exchange in the Alaskan Arctic in response to decadal climate warming. *Nature* 406:978–981.

Post V, Kooi H, Simmons C. 2007. Using hydraulic head measurements in variable-density ground water flow analyses. *Ground Water* 45:664–671.

Rains MC. 2011. Water Sources and Hydrodynamics of Closed-Basin Depressions, Cook Inlet Region, Alaska. *Wetlands* 31:377–387.

Rosenberry DO, Winter TC. 1997. Dynamics of water-table fluctuations in an upland between two prairie-pothole wetlands in North Dakota. *Journal of Hydrology* 191:266–289.

van Ryswyk A, McLean A, Marchand LS. 1966. The climate, native vegetation, and soils of some grasslands at different elevations in British Columbia. *Canadian Journal of Plant Science* 46:35–50.

Sara MN. 2010. Site assessment and remediation handbook. CRC Press. Boca Raton, Florida, USA.

Scibek J, Allen DM, Cannon AJ, Whitfield PH. 2007. Groundwater-surface water interaction under scenarios of climate change using a high-resolution transient groundwater model. *Journal of Hydrology* 333:165–181.

Sloan CE. 1972. Ground-water hydrology of prairie potholes in North Dakota. US Government Printing Office Washington, DC, USA.

Smith AJ, Townley LR. 2002. Influence of regional setting on the interaction between shallow lakes and aquifers. *Water Resources Research* 38:10–1.

Sophocleous M. 2002. Interactions between groundwater and surface water: the state of the science. *Hydrogeology journal* 10:52–67.

Stewart IT, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. *Journal of climate* 18:1136–1155.

Tisdale EW. 1947. The grasslands of the southern interior of British Columbia. *Ecology* 28:346–382.

Townley LR, Davidson MR. 1988. Definition of a capture zone for shallow water table lakes. *Journal of Hydrology* 104:53–76.

Townley LR, Trefry MG. 2000. Surface water-groundwater interaction near shallow circular lakes: Flow geometry in three dimensions. *Water Resources Research* 36:935–948.

Wikeem B, Wikeem S. 2004. The Grasslands of British Columbia, The Grasslands Conservation Council of BC, British Columbia.

Williams WD. 1999. Conservation of wetlands in drylands: a key global issue. *Aquatic Conservation: Marine and Freshwater Ecosystems* 9:517–522.

Winter TC, Rosenberry DO. 1995. The interaction of ground water with prairie pothole wetlands in the Cottonwood Lake area, east-central North Dakota, 1979–1990. *Wetlands* 15:193–211.

Winter TC, Rosenberry DO. 1998. Hydrology of prairie pothole wetlands during drought and deluge: a 17-year study of the Cottonwood Lake wetland complex in North Dakota

in the perspective of longer term measured and proxy hydrological records. *Climatic Change* 40:189–209.

Winter TC, Valk A, others. 1989. Hydrologic studies of wetlands in the northern prairie. *Northern prairie wetlands* 16–54.

Wurster FC, Cooper DJ, Sanford WE. 2003. Stream/aquifer interactions at Great Sand Dunes National Monument, Colorado: influences on interdunal wetland disappearance. *Journal of Hydrology* 271:77–100.

Zedler JB, Kercher S. 2005. Wetland resources: status, trends, ecosystem services, and restorability. *Annual Review of Environment and Resources* 30:39–74.

CHAPTER 4. CONCLUSION

British Columbia's grasslands, although a small portion of the land (1%), provide a lot of value in terms of ecosystems services. In particular, they are a valuable source of forage for the ranching industry. In order to access this high quality, low cost forage, cattle require a nearby source of drinking water. Within this semi-arid ecosystem surface water is often limited. Historically, natural ponds that form in depressions in the terrain have been a dependable source of surface water. Recently the ranching community has expressed some concern regarding an observed loss of ponds in the grasslands. The research presented in Chapter 2 confirms these observations. Within eight 100 km^2 sites representing BC's southern interior grasslands there has been a 63% decline in total number of ponds and a 54% decrease in pond surface water area from the 1990s to 2010s. These results are consistent with other studies that have reported pond declines albeit in different ecosystems and over longer periods of time (Smith et al. 2005; Riordan et al. 2006; Umbanhowar et al. 2013).

The weather data analysis from Chapter 2 reveals some important factors related to the reported declines. An increase in air temperature over the last century and in particular, over the last 15 years, has increased the summer time evaporative demand on surface water. Furthermore, changing precipitation patterns have affected pond inputs. Increased rainfall and decreased snowfall is associated with a reduced amount of water volume in ponds. This suggests that the development of winter snow pack and the subsequent spring melt is the main contributor of water to the grassland ponds. These weather data trends are consistent with climate change models that predict increased air temperature and increased variability in precipitation (Houghton et al. 2001; Houghton 2009; Stocker et al. 2013). They are also supported by research in Western North America that reports declining mountain snow packs and earlier streamflow timing (Loaiciga et al. 1996; Leith and Whitfield 1998; Barnett et al. 2005; Mote et al. 2005; Stewart et al. 2005; Huntington 2006). Taken together, increased evaporation and decreased snow water input has likely affected the total amount of surface water in ponds and therefore reduced the potential for surface water to persist from spring through fall. However, not all ponds experienced the same degree of decline. In fact, some ponds have been shown to persist under the same climate conditions described above.

A field study detailed in Chapter 3 explores groundwater – surface water interactions to determine the differences between seasonally and perennially inundated ponds. This

chapter shows that not all ponds are the same in terms of their interaction with the local groundwater system. The degree in which a pond is connected to groundwater can determine how sensitive it is to the changing climate variables discussed in Chapter 2. Ponds that receive a consistent input of groundwater, such as LWP and UWP, are referred to as groundwater discharge or flow-through ponds. They tend to be found in deep depressions with steep surrounding embankments and are often perennially inundated. These ponds are less sensitive to changes in climate because they are less dependent on snow melt input and affected less by evapotranspiration due to typically low surface area to volume ratios and constant replenishment from groundwater. Conversely, ponds that are disconnected from the groundwater system, such as LDP, are referred to as groundwater recharge or perched-precipitation ponds. They are likely found in flat shallow depressions with low lying surrounding hills and are often seasonally inundated. These ponds are highly dependent on snowmelt to gain surface water and due to the typical flat terrain they often have a high surface area to volume ratio. These factors make them especially sensitive to the changes in climate variables discussed in Chapter 2. The groundwater – surface water interactions and the different pond types detailed in Chapter 3 are consistent with other pond hydrology studies (Rosenberry and Winter 1997; Van der Kamp and Hayashi 1998; Townley and Trefry 2000; Smith and Townley 2002; Hayashi et al. 2003; Ferone and Devito 2004; Jolly et al. 2008; Rains 2011).

The above examples represent the two extremes in terms of pond type but in reality there are a large portion of ponds that transition between types throughout the year, such as the UDP. A pond can be connected to groundwater during the spring when the water table is high but disconnected in the summer when the water table has lowered. Therefore, the permanence of these ponds is likely determined by the degree of recharge the regional water table receives from overall snowmelt to the watershed. Consequently, they are also quite sensitive to changes in climate and how those changes are affecting groundwater at large scale. Also, when the groundwater becomes disconnected in the spring/summer the ponds become subject to more noticeable losses by evapotranspiration which increases with increasing air temperature. Therefore, it can be assumed that the majority of grassland ponds are sensitive to changes in climate and this is supported by the results in Chapter 2 that reports the considerable decline in pond surface area an number over the last 20 years during

which snowfall has been low and air temperature has been high relative to the previous 90 years.

Other variables to consider outside of climate include land management, land use changes and range condition upland of grassland ponds. The majority of BC's grasslands are downslope from upland forested regions. Natural factors such as wildfire, losses of forests to mountain pine beetle, and anthropogenic factors such as clear cutting can affect the hydrology of the adjacent grasslands by altering upland precipitation capture and storage and timing of snow melt. This can lead to changes in the timing and quantity of stream and groundwater flow to downslope grasslands. Also, the conversion of upland grassland to agricultural land will also affect the hydrology of the adjacent grasslands. For example, conversion of native prairie to cultivation resulted in substantial increases in surface runoff for the first 4 years (Dragoun 1969). However, conversion of sagebrush to seeded grassland, the most likely practice in British Columbia, did not result in changes in runoff (Branson et al. 1981). Changes in range condition resulting from drought or poor grazing management can affect the plant composition and cover which may affect pond hydrology in the affected area. Grazing animals affect plants by reducing cover and in cases of mis-management by changing plant species composition. In turn, this will affect, snow accumulation, rainfall interception and soil infiltration dynamics (Buckhouse and Coltharp 1976). All of these variables are closely connected to the hydrologic processes within the ecosystem. Although this thesis is concerned with the effects of climate and large scale changes in grassland hydrology, these other factors should be considered when assessing hydrology at local scales.

This research reveals changes in surface water availability and associated climate variables in BC's grasslands. Due to the complex nature of ecosystems and hydrology there is more research that is needed to fill the gaps in this thesis and further support some of its findings. These include:

- A more comprehensive remote sensing study that looks at historic imagery from further back in time (ie. 50s, 60s). It should also look at images from multiple years between then and now to determine if pond declines are cyclical. Furthermore, images from years directly after large snowfall events should be compared to images from years preceded by long low-snow periods (e.g. 8 – 15 years). Other factors such as occurrence of frozen soils under the

snowpack and occurrence of sublimation during snowmelt are likely to be important as well. This would help support the idea that snowfall and the manner in which it melts is the limiting factor in determining pond persistence.

- A study that looks at modelled weather data, specific to BC's grasslands, that projects into the future to determine the degree of increase in air temperature and variability in precipitation. This could provide insight into potential increases in evaporative demand the ration of rain to snow. This would create awareness of future water conditions and prompt ranchers to be proactive in adaptation strategies.

- A field project looking at a detailed pond water budget. A study like this would reveal information on multiple important variables pertaining to pond hydrology and could be separated into multiple projects.

  o Using GIS and topography layers, map the catchment area of the pond being studied. Conduct snowpack surveys in the late winter by measuring snow depth and density along multiple transects within the catchment to determine the snow water equivalent available in the spring melt.

  o Setup an extensive network of nested wells and piezometers to map detailed groundwater flow dynamics and surface water interactions. This would provide insight in to how groundwater flows within the grasslands and provide more confidence in determining the ground water input and output components of the pond water balance equation.

  o Perform water chemistry analysis on pond water, groundwater and rainwater to further increase the accuracy of input and output values in the pond water balance equation.

  o Setup a weather station adjacent to the pond to capture detail meteorological information specific to the pond site. This should include measurements of rainfall, wind and net solar radiation. This data will allow the estimation of potential evapotranspiration from in

and around the pond and also provide precipitation input data from the catchment area.

- o Perform a bathymetric analysis of the pond to determine pond depth. GPS the shoreline of the pond at different time of the year to determine surface area changes. This information will allow the estimation of pond volume changes throughout the year.

- A field project, building on studies by Branson et al. 1981, looking at plant composition within a pond catchment area and how vegetation affects hydrology. This would include an analysis of snow trapping potential, rainfall interception and the effects on soil infiltration and runoff. This could also tie into looking at how different management regimes affect hydrology.

- A survey of BC's grasslands comparing present and historic range conditions and potential effects on hydrology. This would include land use changes (ie. agriculture, land development), changes over time to grazing management and changes to upland forested regions (ie. beetle kill, clear cutting). This could involve a correlation with the remote sensing data on changes in pond number and surface area.

This research creates awareness for the province of BC that water conditions in our grasslands are changing. It further supports climate change predictions that state that semi-arid ecosystems are at the greatest risk with respect to increasing air temperature and varying precipitation patterns. It affirms the observations made by ranchers that pond number and area has decline over the last 15 – 20 years and that ponds have become less reliable in terms of providing drinking water due to changes in surface water permanence from spring through fall. Furthermore, it shows that BC's grassland ponds can be categorized with respect to groundwater – surface water interactions in the same way that ponds in other ecosystems are classified. For ranchers, categorizing the ponds they depend on the most for cattle watering can provide insight to the risk associated with particular ponds with respect to future climate change. This information will allow them to be proactive in adapting to changing water conditions. They can seek out alternative water sources or ways of getting water to strategic locations. The information can also be used to lobby the government and other funding

agencies for support through research and the development of innovative adaptation strategies.

Literature Cited

Barnett TP, Adam JC, Lettenmaier DP. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438:303–309.

Branson FA, Gifford GF, Renard KG, Hadley RF. 1981. Rangeland Hydrology. Kendall. Hunt Publishing Co. Dubuque, IA.

Buckhouse JC, Coltharp GB. 1976. Soil moisture response to several levels of foliage removal on two Utah ranges. *Journal of Range Management* 29 (4):313–315.

Dragoun FJ. 1969. Effects of cultivation and grass on surface runoff. *Water Resources Research* 5:1078–1083.

Ferone JM, Devito KJ. 2004. Shallow groundwater-surface water interactions in pond-peatland complexes along a Boreal Plains topographic gradient. *Journal of Hydrology* 292:75–95.

Hayashi M, van der Kamp G. 1998. The groundwater recharge function of small wetlands in the semi-arid northern prairies. *Great Plains Research: A Journal of Natural and Social Sciences.* Paper 366.

Hayashi M, van der Kamp G, Schmidt R. 2003. Focused infiltration of snowmelt water in partially frozen soil under small depressions. *Journal of Hydrology* 270:214–229.

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) (2001) Climate change 2001. The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Houghton JT. 2009. Climate change: The Complete Briefing. Cambridge University Press, Cambridge, UK.

Huntington TG. 2006. Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology* 319:83–95.

Jolly ID, McEwan KL, Holland KL. 2008. A review of groundwater–surface water interactions in arid/semi-arid wetlands and the consequences of salinity for wetland ecology. *Ecohydrology* 1:43–58.

Leith RM, Whitfield PH. 1998. Evidence of climate change effects on the hydrology of streams in south-central BC. *Canadian Water Resources Journal* 23:219–230.

Loaiciga HA, Valdes JB, Vogel R, Garvey J, Schwarz H. 1996. Global warming and the hydrologic cycle. *Journal of Hydrology* 174:83–127.

Mote PW, Hamlet AF, Clark MP, Lettenmaier DP. 2005. Declining mountain snowpack in Western North America. *Bulletin of the American Meteorological Society* 86:39–49.

Rains MC. 2011. Water Sources and Hydrodynamics of Closed-Basin Depressions, Cook Inlet Region, Alaska. *Wetlands* 31:377–387.

Riordan B, Verbyla D, McGuire AD. 2006. Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. *Journal of Geophysical Research: Biogeosciences* 111.

Rosenberry DO, Winter TC. 1997. Dynamics of water-table fluctuations in an upland between two prairie-pothole wetlands in North Dakota. *Journal of Hydrology* 191:266–289.

Smith AJ, Townley LR. 2002. Influence of regional setting on the interaction between shallow lakes and aquifers. *Water Resources Research* 38:10–1.

Smith LC, Sheng Y, MacDonald GM, Hinzman LD. 2005. Disappearing Arctic lakes. *Science* 308:1429–1429.

Stewart IT, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. *Journal of climate* 18:1136–1155.

Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM. 2013. Climate change 2013: The physical science basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5). Cambridge Univ Press, New York.

Townley LR, Trefry MG. 2000. Surface water-groundwater interaction near shallow circular lakes: Flow geometry in three dimensions. *Water Resources Research* 36:935–948.

Umbanhowar C, Camill P, Edlund M, Geiss C, Durham W, Kreger D, Molano W, Raskob C, Stocker M, Tvera A, et al. 2013. Contrasting changes in surface waters and barrens over the past 60 years for a subarctic forest-tundra site in northern Manitoba based on remote sensing imagery. *Canadian Journal of Earth Science* 50:967–977.

APPENDIX

Figure A1: Photo of upper dry pond (UDP) on May 26th facing north.

Figure A2: Photo of upper wet pond (UWP) on May 20th facing south east.

Figure A3: Photo of lower wet pond (LWP) on May 20th facing north east.

Figure A4: Photo of lower dry pond (LDP) on May 20th facing south east.