ASSESSMENT OF WATER AVAILABILITY WITHIN THE WINNIPEG RIVER DRAINAGE BASIN OVER THE PAST 2 MILLENNIA

SYNOPSIS: One of the main challenges of water management is projecting future water availability. The main objective of this proposal is to provide long-term data on the spatial patterns in water availability within the Winnipeg River Drainage Basin (WRDB) in northwestern Ontario over the last ~2000 years. This data can be used by water managers at Manitoba Hydro to more effectively predict and plan for changes in water availability in the future. Present-day climatic processes and orbital parameters are similar to those of the past two millennia, but climate records over this timeframe are extremely scarce. Long periods of drought can have significant impacts on surface-water availability, but the spatial and temporal patterns of such events are poorly known over adequate time frames in regions which rely on the water resources for power generation, and other societal demands. Analysis of past long-term drought conditions provide a view of the spatial extent and magnitude of past lows in water availability and thereby set the minimum level of change that should be anticipated under projected anthropogenic induced warmer conditions. This project will determine the susceptibility of the WRDB to synchronous droughts in northern and southern portions of the WRDB, and hence the sensitivity in water flow that currently accounts for ~40% of the energy generated by Manitoba Hydro. This data is important to determine if the last 100 years, and specifically the drought of the 1930s, is the appropriate scenario to base long-term planning. In order to adequately prepare for future extremes, long-term planning must be based on realistic estimates of historical lows in water availability (Turanli 2002). However, these long-term lows are currently only based on 80-100 year records, which are not representative of the full range in climate extremes (e.g., St. George and Nielsen 2002, Laird *et al.* 2003, Cook *et al.* 2007).

Although many regions of Canada are projected to have increased precipitation with increasing CO_2 conditions, there is great uncertainty in both the temporal and spatial distribution of future precipitation based on General Circulation Models (Schindler 1997, Hofmann *et al.* 1998, IPCC 2007). In the western prairie provinces of Canada, there are already significantly reduced flows of major rivers as a result of climatic warming and human water withdrawals (Schindler and Donahue 2006). However, further to the east, in the WRDB, mean annual flows have significantly increased since 1924, due primarily to increases in winter and spring discharge (St. George 2007). Based on this small temporal window, St. George (2007) concluded that potential future threats to water supply in the Canadian Prairies will not include the WRDB over the next few decades. Such a conclusion may be optimistic when hydrological changes are considered over a longer period of time, especially given the magnitude of the projected temperature increases. Even with an increase in precipitation, there will likely be less water availability due to increased evaporation and transpiration associated with higher air temperatures (Schindler 1997).

In our recent research (Premier's Research Excellence Award to Brian Cumming in conjunction with Manitoba Hydro) we developed new techniques to track changes in lake level in drainage lakes (i.e., lakes that have a surface outflow). Results from our main study site in northwestern Ontario (Lake 239 in the Experimental Lakes Area) document large fluctuations in lake level over the past ~3000 years including estimated declines in lake level of up to 5m, and a prolonged drop in lake level of ~2.0-2.5 m approximately 1500 years ago (Laird and Cumming, accepted). A 2-m decline in this lake represents a ~14% decrease in lake surface area and a ~18% decrease in lake volume; with a 5-m decline, lake surface area decreases by ~28% and volume decreases by ~ 40%. Confidences in these estimates are extremely high, since they are based on tracking changes in near-shore locations using three independent proxies of change in lake depth. However, empirical data from other lakes within the WRDB are needed to provide basin wide estimates of drought that can be used to estimate past precipitation conditions and infer declines in runoff through hydrological models.

Our current proposal seeks to provide an estimate of the spatial patterns of drought in the WRDB by identifying, and developing new sites to reconstruct changes in lake level from the Lake of the Woods watershed (southern region), and sites in the northern region of the WRDB (Red Lake and the Lac Seul watersheds). Such a network will allow the assessment of both within and between watershed variability; thereby providing a clear picture of the variability of lake-level declines across the WRDB. These empirically-based studies of past water availability will provide information for companies highly dependent upon water resources to more effectively plan for the future based on records that will encompass the full range of extremes pertinent to human society.

Few studies have specifically addressed long-term changes in water availability, particularly in regions that appear to have an abundance of water today. Canadian industry, particularly those that are heavily reliant on water resources (e.g., hydro and agriculture), will benefit from the new knowledge generated from this study by being able to plan strategically for water shortages. The benefits to the academic institution include the training of undergraduate and graduate students, increased collaboration with Canadian industry, and dissemination of research highly relevant to society. The scientific community will benefit through the further development of new techniques to quantify past and future water availability from lake-level analysis of drainage lakes that is applicable to many other regions.

BACKGROUND: Projecting future water availability is one of the main challenges of water management. Given the difficulty of this task, one of the first steps is to better understand what extremes are possible, and the probability and spatial extent of these extremes. This knowledge is essential to develop a framework to manage water resources, since knowing the extremes in past water availability allows a clearer view of possible future conditions. Given the enormous size of the Winnipeg River Drainage Basin (WRDB), changes in one region may not be representative of changes in another region. We propose to develop and apply techniques to assess the spatial and temporal variability in water availability in the southern and northern watersheds of the WRDB. This work will develop new approaches that were initially investigated in conjunction with Manitoba Hydro from 2003-2007 as part of Cumming's Premier's Research Excellence Award from the province of Ontario. As part of this award, we developed an approach based on analysis of several indicators preserved in sediment cores that can be used to quantitatively determine declines in lake level. This multi-proxy paleolimnological approach utilized the biological, chemical and physical signals preserved in lake sediments to reconstruct past lake conditions and infer conditions in the surrounding environment (e.g., Laird & Cumming, accepted). We propose to further develop and apply these paleolimnological techniques to clearly establish within region and between region changes in lake levels and water availability over the past ~2 millennia in the WRDB.

Analyses of sedimentary cores from lake basins can extend our view of climatic variability and extremes back in time. This extended view is extremely important for future management of water resources because numerous studies have indicated that the climate variability witnessed during the 20th century is not representative of the full range in extremes (e.g., St. George and Nielsen 2002, Laird *et al.* 2003, Cook *et al.* 2007, Laird and Cumming accepted). For example, in the Red River Valley of southern Manitoba, tree-ring analyses indicate that a century-long period of generally arid conditions prevailed from ~ AD 1670 to AD 1775 (St. George and Nielson 2002). Tree-ring analysis within the WRDB over the past 220 years indicates that summer droughts were more persistent during the 19th and 18th century, with the longest interval of warm, dry summers occurring in the 1880s and early 1890s (St. George *et al.* in review). Our recent findings from the Experimental Lakes Area (ELA) (Reconstruction of Hydrological Variability and Extremes in northwestern Ontario, PREA/Manitoba Hydro grant, Final Report July 2007) indicated that the period around the 1890s had some of the lowest lake levels of the past ~1500 years with average declines of 0.8 m, whereas before ~1500 years ago declines of > 2m were common (Laird and Cumming accepted). Recurrent drought also occurred during the 1880s and 1890s in the Great Plains of North America, other areas of the North American west, as well as other midlatitudes around the globe, being linked by persistent La Niña-like sea surface temperatures (SSTs) in the tropical Pacific (Cook *et al.* 2007).

Our detailed lake-level analyses from ELA provide a starting point of understanding hydrological changes in the WRDB. Spatial variability in total annual precipitation during the 20th century is large in the WRDB (e.g., Fig. 1), with correlations between the sites varying from 0.27 to 0.66 (Table 1). Decadal-scale periods of low precipitation also vary tremendously across the WRDB. For example, Kenora indicates low precipitation in the 1930s, 1950s and 1980s, whereas, Fort Frances has low precipitation in the 1920s and 1950s, and all sites indicate at least parts of the 1980s as having low precipitation (Fig. 1). Because of this inherent spatial variability in precipitation additional records of past conditions are required before a general picture of water availability across the basin can be drawn. Multiple records of past lake levels can help to detail the frequency and severity of past extremes on a spatial basis, thereby providing a regional picture of hydrological variability that would be of interest to long-range water planners at Manitoba Hydro.

Increases in mean annual temperature of 0.5-0.6 ºC have occurred since the 1900s across much of Ontario (Smith *et al.* 1998). Data from Kenora, in northwestern Ontario indicates that there has been a highly significant increase of ~1.2 ºC since 1900 (Fig. 2). Projected increases in mean annual temperatures in Ontario from Global Circulation Models (GCMs) suggest an average increase of 1ºC to 2ºC (IPCC 2007). Evaluating province-wide long-term trends in precipitation is more difficult than temperature due to the inherently high spatial variability and the difficulties associated with accurately measuring precipitation (IPCC 2007). Although many regions of Canada are projected to have increased precipitation under increasing atmospheric CO_2 concentrations, there is great uncertainty in both the temporal and spatial distribution of future precipitation based on GCMs (Schindler 1997, Hofmann *et al.* 1998, IPCC 2007). A series of carefully developed paleolimnological records can provide empirical data on past water levels and as a consequence provide a realistic range of variation in water availability. This data is essential to determine if the last 100 years and specifically the drought in the 1930s is the appropriate gauge for planning for future extremes. Estimates of past lake levels, along with estimates of past climatic conditions (e.g., precipitation and evaporation) from regional pollen and vegetation data can then be used in a hydrologic budget model to provide estimates of past declines in runoff (e.g., Yang and Teller 2005).

The purpose of this proposal is to select key sites within the WRDB from which analyses of lake sediments, along with the further development of our multi-proxy techniques, can provide a picture of long-term patterns in lake levels. The WRDB is a pivotal region of focus because it is adjacent to the semi-arid Great Plains, which is considered a transitional region between the humid east and arid west (Cook *et al.* 2007). Because of this geographical closeness, at least parts of the WRDB have often been synchronous with arid periods of the west (e.g., 1880s-1890s, 1930s, 1980s) and thus is a key region of the more typically humid east to determine the long-term susceptibility to drought. Analysis of these records will allow the assessment of the degree of spatial and temporal variability of water availability within the WRDB basin, thereby putting the 20th century variability within a long-term context. The estimates of lake level can then be used to infer past precipitation and runoff conditions using hydrologic models.

DETAILED PROPOSAL

Introduction: Findings from our analyses from a sediment core from Lake 239 at the ELA indicated that large declines in lake level occurred during the past ~3000 years. The drainage system of Lake 239 (Rawson Lake) flows into Lake of the Woods, which flows into Lake Winnipeg via the Winnipeg River. The lake level of Lake 239 (one of the primary reference lakes at ELA since its inception in 1968) had declines averaging 1 to 3m during the past several thousand years, as well as significant increases (Fig. 3). The largest period of decline was up to 5m with an average of ~2.0-2.5 m; a 2-m to 5-m decline results in a ~14-28% decrease in lake surface area and a ~18-40% decrease in lake volume. However, given the vast size of the WRDB, additional sites are needed to assess changes in lake level both within and between regions within the WRDB. **Below, we provide a brief summary of the techniques we would continue to develop to estimate lake-level changes at several key sites and the implications this could have on hydrological resources within the WRDB**.

T*echniques for estimating past lake levels in drainage lakes:* The strongest evidence of past changes in lake level in small drainage lakes can be preserved in near-shore sediment cores (Dearing 1997, Battarbee 2000) through a technique similar to the Digerfeldt method. The Digerfeldt method is a technique used to track sedimentary units across a transect of cores sampled from the shore towards the center of the lake (Digerfeldt 1986). Our analyses are based primarily on the algal (plant) remains of diatoms and scaled chrysophytes. Diatoms are single-celled plants that preserve well in lake sediments because of their siliceous cell walls, and are very sensitive indicators of chemical and physical changes in lake conditions (e.g, Smol 2008). Some chrysophyte species have siliceous scales that are preserved in lake sediments and high abundances of scales relative to diatoms are indicative of increases in lake depth due to the preference of scaled chrysophytes for open-water habitats. Because material preserved in the sediment cores can be dated through various methods (e.g., ^{210}Pb and ^{14}C analyses), the analysis of lake sediment cores can provide a view into the past.

We use a multiple indicator approach to infer lake level, with our primary analyses based on the diatom assemblages preserved in the sediment cores, along with values of the proportion of chrysophyte scales to diatoms, and estimates of organic matter (OM) content. A quantitative model to infer lake level was developed from ELA Lake 239 from the analysis of the diatom assemblages in surficial sediments (Fig. 4) along a depth gradient from near-shore littoral communities to deeper planktonic diatom communities (e.g., Fig. 5a, Moos *et al.* 2005). This method of determining the relationship of diatoms to depth within the study lake has often been proven to provide stronger predictive models for depth reconstruction than analysis of the distribution of diatoms across a suite of lakes along a depth gradient (e.g., Laird and Cumming accepted). For Lake 239, the diatom-inferred depth model provides a very good estimate of observed depth below a depth of ~ 13m (Fig. 5b). This model was used to infer changes in lake level through time from the diatom assemblages preserved in near-shore cores taken at a current depth of ~13 m. The sediment core retrieved from ~13m was selected for detailed analysis due to its proximity to the ecotonal variations that are present in the surficial samples from 13m and shallower (Fig. 5a). This technique is excellent at quantitatively estimating declines in lake level, but may not accurately detect large increases in lake level based on this core alone. The proportion of chrysophyte scales to diatoms can be used as a qualitative indicator of the boundary between the littoral (shallow near-shore) and pelagic (deeper central) lake zones (Fig. 5a). In addition, changes in percent organic matter (OM) content in sediments can be used to indicate changes in the boundary between the littoral and pelagic zone (Fig. 5c). Large changes in OM occur at the boundary of the nearshore littoral zone (Shuman 2003) and analysis of OM in lake sediment cores can provide a means of tracking past changes in the sediment limit or depositional boundary depth (i.e., the lower edge of the littoral zone) as it moves toward the center of the lake during declines in lake level (Dearing 1997).

Lakes which tend to preserve Digerfeldt's lines of evidence for lake-level change have been described as typically being small (< 50 ha), relatively shallow (< 10 m max depth) and have a catchment area to lake area ratio of < 5:1 (Dearing 1997). However, slightly larger lakes are also appropriate, especially if indicators such as diatoms and scaled chrysophytes are used. Lake 239 is ~56 ha and has a catchment to lake area ratio of 4.3. However, its maximum depth falls much outside of the typical 'Digerfeldt lake' at ~ 32 m. This suggests, that at least in the case of Lake 239, it is the clearly defined sedimentation limits, which we base on our analysis of OM and diatoms in surface samples along a depth transect, and the location of our near-shore cores along a relatively shallow underwater slope that proved successful. The location of these near-shore cores was critical to our study and was based on prior knowledge of sediment deposition provided by high-resolution acoustic (echo sounding) data profiles provided by Mike Lewis from the Geological Survey of Canada, in collaboration with personnel from the Manitoba Geological Survey. The acoustic profiles enabled us to choose an area that had the greatest near-shore sediment deposition with relatively gentle slopes. In addition, direct groundwater flow to Lake 239 is negligible (Schindler *et al.* 1996) and thus groundwater interactions likely did not complicate the lake-level reconstructions (e.g., Digerfeldt *et al.* 1992). We will continue to refine and develop both the quantitative inferences and the collaborating qualitative techniques for estimating lake-level changes in drainage basins using a variety of approaches. Our goals for further development include: 1) refining of the depth models; 2) develop methods that minimize the time of analysis; and 3) explore other proxy indicators preserved in the lake sediments.

Relating lake-level changes to water supply and runoff: Estimates of past lake levels, in conjunction with hydrologic models, can be used to infer past precipitation conditions (Barber and Finney 2000, Lewis *et al.* 2001) and estimates of past declines in runoff (Bengtsson and Malm 1997, Yang and Teller 2005). Estimates of past climatic conditions from vegetation and pollen data (e.g., evaporation, E; evapotranspiration, ET and precipitation, P) can be used as initial constraints in a water-balance model (Barber and Finney 2000, Lewis *et al.* 2001, Yang and Teller 2005) to determine climatic conditions that would maintain the lakes at the inferred lake levels (Barber and Finney 2000). Development of a modern hydrologic budget for a lake, along with estimates of past climatic conditions based on the lake levels and vegetation data, can then be used to estimate past declines in runoff (e.g., Yang and Teller 2005). Instrumental data, such as at the ELA suggests that 20^{th} century dry periods resulted in significant declines in runoff. For example, during the warm and dry 1980s runoff declined by ~37% at ELA and runoff represented as a % of precipitation declined from 40-50% to 15-30% (Schindler *et al.* 1996).

A series of past lake-level records within a watershed can provide information on the magnitude, frequency and coherency of low periods within a region, which can then be used to provide a more regional estimate of changes in water supply. Currently, in collaboration with Mike Lewis and colleagues, we are working on estimating the climatic conditions that resulted in the lake-level changes at ELA Lake 239 and will be using hydrologic models to infer the past changes in water supply from this data. A series of such estimates within the Lake of the Woods watershed and the northern basins of the WRDB will enable a better regional estimate of water supply changes.

***Research questions*:**

1) What were the spatial and temporal patterns of lake level and water availability within the WRDB over the past ~2000 years?
2) Are periods of low lake levels coherent among lakes within each of the southern and northern regions? (i.e., analysis of within region variability)
3) Are periods of low lake levels coherent between the southern and northern watersheds? (i.e., analysis of between region variability)
4) What implications do these findings have on future water resources in the WRDB?

***Research design*:**

1) Six lakes in the WRDB (Fig.6) will be selected for detailed analysis of the sedimentary record to estimate past extremes in water availability, with an emphasis on detecting the low periods. Three lakes will be selected within the southern Lake of the Woods watershed and three lakes from the northern region (Red Lake and Lac Seul watersheds).
2) Acoustic, echo sounding, data will be collected on these lakes and lake sediment cores will be collected in appropriate near-shore environments. Core location will be chosen to maximize the detection of declines in water level.
3) The cores will be analyzed for multiple indicators including diatoms, proportion of chrysophyte scales to diatoms, and percent organic matter. Lake specific transfer functions will be developed

to identify the depth of the current pelagic/littoral transition using diatoms, chrysophytes, organic matter and possibly other indicators. A diatom-based depth model will be used to quantitatively estimate changes in lake level. This information, along with bathymetry and volume estimates, will be used to estimate declines in lake volume.

4) Dating of the cores will be based on analyses of ^{210}Pb and ^{137}Cs analyses for the recent sediments. Chronology for older samples will be estimated from AMS ^{14}C dates on terrestrial carbon (e.g., needles, leaves, concentrated pollen samples).

5) Estimates of lake level, along with our previous record from ELA Lake 239, will be used to provide estimates of variations and coherency in surface waters within and between each of the watershed regions (e.g., % changes in lake level and lake volume).

***Project work plan*: (see Activity Schedule)** The WRDB can be divided into 2 major sub-basins: 1) Lake of the Woods/Rainy River system in the south, and 2) English River system in the north which includes contributions from Lac Seul (Fig. 6). Lake of the Woods is the largest lake within the WRDB and thus sampling of lakes within its watershed would provide a key test area for how representative our findings at ELA are to lakes within this drainage area. In addition, we propose that we include another lake from ELA to determine how representative the results from Lake 239 are for the ELA region. Preliminary analyses have already begun on ELA Lake 442, a potential site for lake-level research identified in our previous work. At the conclusion of this project, we would have a total of four lakes from within Lake of the Woods watershed to provide an assessment of spatial variability in lake levels and past water availability. Three lakes in the English River system in the northern portion of the WRDB, within the Lac Seul and Red Lake watersheds, would also be selected to assess both within and between watershed variability. Lac Seul is the second largest lake within the WRDB and thus a key watershed to investigate. The Red Lake district is another important area because of the long-term monitoring data, and the large number of relatively undisturbed lakes. Sampling of the lakes in the north would be done in collaboration with the local First Nations, if applicable.

Year 1: Initial site selection within the Lake of the Woods watershed and the northern region watersheds (Red Lake and Lac Seul regions) will be based on lake size, geographic (and hydrologic) location and climatic sensitivity in conjunction with discussions with Manitoba Hydro (MILESTONE #1). Initial site selection of the northern region includes time to contact and arrange logistics with the local First Nations, if applicable. Research Associate, Kathleen Laird will be in charge of the initial site selection for all regions. The potential study lakes would be assessed using Google Earth, topographic maps and aerial photographs. From this, 4-6 lakes within each of the southern and northern regions would be chosen for exploration in the first field season. Initial ground truthing (e.g., assessment of maximum lake depth, ease of access) of all of the potential study lakes would determine the 3 lakes in each of the regions that would be investigated further (MILESTONE #2). Detailed bathymetric profiles will be developed and surface samples will be collected along multiple transects (MILESTONE #2). High-resolution acoustic reflection data will be collected from each of the selected lakes (MILESTONE #3). These data are important to determine the sampling locations that can provide high-resolution sediment records within each lake.

The surface-sediment samples collected along the multiple transects from each of the selected sites will be analyzed for organic matter, chrysophyte scales and diatoms, from which lake-specific quantitative models of lake depth would be developed (MILESTONE #4). This data, in combination with acoustic (echo sounding) data will determine the location within each of the lakes from which sediment cores would be retrieved in the second field season. Detailed analysis of sediment cores previously collected from ELA Lake 442 will be analyzed by Dr. Laird (MILESTONE #4).

Year 2: Sediment cores (short ~ 1 m gravity cores and longer piston cores) will be retrieved from each of the selected lakes in the southern and northern regions of the WRDB (MILESTONE #5). The gravity cores will be analyzed for diatoms, proportions of chrysophyte scales to diatoms and organic matter (OM) content (MILESTONE #6). Analysis of the diatoms preserved in the surface samples along a depth transect from each of the lakes (year 1) would be used to develop a lake-specific model for quantitatively estimating depth from down core diatom assemblages. OM and proportions of chrysophyte scales to diatoms would be used as additional indicators of lake level.

^{210}Pb dating analysis on the sediment cores will be carried out at Queen's and would provide a detailed chronology for the recent history (past ~150 years). Carbon dating of plant material or isolated pollen of bottom samples from the gravity cores (2 dates per master core from each lake) in Year 2 will determine the temporal length of these records (MILESTONE #6).

Year 3: Analyses of the sediment cores will continue, with the length of the cores analyzed being based on the preliminary carbon dating (MILESTONE #7). Further sampling for datable material from the gravity cores or piston cores will be based on the initial carbon dating outcomes in Year 2 (MILESTONE #7). Following the results of the additional carbon dates (3 additional dates per master core of each lake) a chronology for the last two millennia will be developed for each of the 6 lakes. Preliminary results will be presented to Manitoba Hydro (MILESTONE #7).

Year 4: Analyses of the sediment cores will be completed, compiled, written up in high-quality scientific journals, and presented to Manitoba Hydro (MILESTONE #8).

***Roles of students, research assistant and research technician*:** There is a large learning curve of our multi-disciplinary work, as a consequence the success of this project is dependent upon having a highly skilled researcher. Research Associate, Kathleen Laird would be in charge of the initial site selection for all regions (a critical component of the project), analyses of Lake of the Woods and ELA, and would help to oversee the student projects in the northern region. Dr. Laird will be in charge of analyzing 3 of the 6 lake records and will help oversee each of the student's research on the other three lakes. In conjunction with Dr. Cumming they will continue to develop methods to refine the depth models and develop methods to minimize the time of analysis, thereby allowing more lakes to be sampled or more samples to be analyzed to increase the temporal resolution.

The three M.Sc. students will work in the northern region in order to expand the number of lakes and enable the assessment of both within and between watershed variability. These students, in addition to undergraduate students (funded through other sources), will explore other potential lake-level indicators under the supervision of Drs. Cumming and Laird. A Technical Assistant (50% time), is needed in years 2 and 3 because of the time consuming lab work required for preparing diatom samples, running organic matter measures, and processing samples for dating.

TEAM EXPERTISE: Professor Brian Cumming (see Personal Data Form 100), Director of the School of Environmental Studies and co-director of the Paleoecological Environmental Assessment and Research Lab (PEARL) will be in charge of the project and any hiring of personnel. Research Associate, Dr. Kathleen Laird will be the primary researcher of this project and will help to train the graduate and undergraduate students, and research technician. Dr. Laird was the primary researcher for our previous lake-level work at ELA and has conducted research in this field for over a decade, with 20 publications on the subject, including 2 in *Nature* and 2 in the *Proceedings of the National Academy of Science* (see Cumming's Personnel Data Form). Dr. Mike Lewis, Emeritus Scientist at the Geological Survey of Canada, a lacustrine geoscientist who has done extensive research in the Great Lakes and other large lakes resulting in 68 refereed journal papers (see attached C.V.), will be in charge of the seismic data collection and interpretation, and exploration of hydrologic models. Dr. Lewis was a Research Scientist with the Geological Survey of Canada for 32 years (13 of which were as a Senior Research Scientist) before becoming an Emeritus Scientist in 1997.

TRAINING OF HIGHLY QUALIFIED PERSONNEL: Three MSc students will be involved in field work and thus will obtain general training in lake and core sampling. There is also the potential to involve undergraduate students through other sources (e.g. internal funding from Queen's and/or summer NSERC) in field work and research related to this project. Personnel from the supporting organization will be invited to participate in the field work. The MSc students will each work on one of the three lakes in the northern region of the WRDB. At the request of Manitoba Hydro, preference will be given to highly qualified students from Manitoba. Students will also have the option of incorporating social implications into their theses. These students will gain training in a very multi-disciplinary field enabling them to work in many fields (e.g., science teachers, conservation authorities, park managers, environmental consulting companies, water-management positions, NGOs). With the continuing expansion of environmental issues, highly trained personnel in environmental assessment, and particularly in regards to water management, will continue to be in demand in Canada. The student's training will be further facilitated by involvement with Manitoba Hydro thorough various workshops.

Research Associate, Kathleen Laird, will continue to develop methods proposed in this project in conjunction with our previous ELA work, and will gain new knowledge through these endeavors. She will continue to develop methods which will be less time consuming to assess lake level in drainage lakes. Additionally, in collaboration with Dr. Cumming they will work to reduce the errors associated with the depth reconstructions by developing multi-proxy techniques to quantitatively infer lake depth. The research technician will be trained in many techniques, including core sectioning and description, dating methods, and sediment sampling and preparation for diatom and organic matter analyses.

VALUE OF THE RESULTS AND INDUSTRIAL RELEVANCE: Widespread drought was the main factor cited by Manitoba Hydro for reduced energy production and sales during the 2003-2004 fiscal year (Manitoba Hydro 2004). Water supply conditions were near the lowest recorded for much of Manitoba and northwestern Ontario, with precipitation levels in Lake of the Woods the second lowest in 100 years (Manitoba Hydro 2004). The recent multi-year drought in western North America, including the Canadian prairies, (~1998-2004, depending on specific location) resulted in severe lows in the water supply and in reservoir storage (Schindler and Donahue 2006, Cook *et al.* 2007). The economic consequences of these droughts, which were of short duration when compared to the pre-20th century megadroughts (Cook *et al*. 2007), was tremendous. For example, Manitoba Hydro became a net importer of electricity (Manitoba Hydro 2004), and the economic cost of the drought in the U.S. alone was in the billions of dollars (Cook et al. 2007).

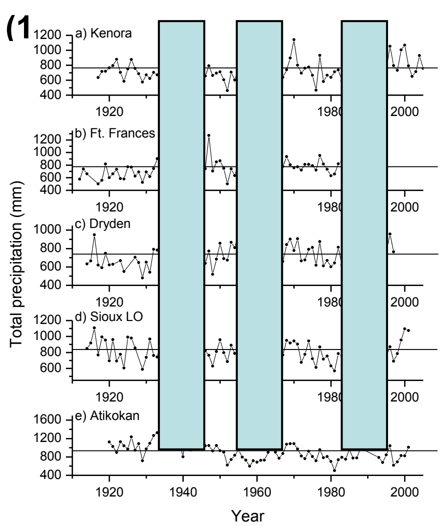
Given that drought can have such a tremendous impact economically, environmentally and socially, being better able to adapt for potential future lows in water availability is of extreme importance to industries dependent upon water resources, such as hydropower generation and agriculture. The first step in being able to better manage future water resources is to extend the instrumental climate record back in time to account for the full range in climate extremes that one may expect in the future. These records can then be used to more realistically prepare for future extremes under the likely increasing global temperatures. Our proposed lake-level records for the past ~2000 years in the WRDB will provide Manitoba Hydro with information on the spatial extent, duration and magnitude of droughts over an extended period of time that should encompass much of the natural extremes in drought conditions. These records can then be used to prepare an adaptation strategy based on extremes prior to the 20th century and thus help to reduce the economic losses.

BENEFIT TO CANADA: The development of the lake-level records proposed here will provide empirical data of what extremes in water availability were and as a consequence provide a minimum estimate of possible future conditions. This data will provide a view of spatial variability of water availability within the WRDB, providing information on the frequency, magnitude and duration of past lows in water availability. This is needed because numerous studies have indicated that the droughts of the 20th century were shorter and less extreme than those that occurred during the past few millennia. Furthermore, the 20th century represents only a small subset of the range in natural climatic variability, even in comparison to the last few centuries. Currently, most water-resource managers are relying on short (~80-100 years or less) instrumental records to provide estimates of lows and highs in the quantity of available water. However, because numerous studies indicate that these short instrumental records do not indicate the full range in extremes, then water resource managers are not adequately preparing future adaptation strategies for realistic extremes of low water availability. Our research will provide a clearer view of the spatial extent of aridity during the past ~2 millennia within the WRDB and consequently provide an important analog for the range of potential future variations in water availability. The WRDB is a pivotal region of focus because of its' geographical closeness to the transitional region between the humid east and arid west, and thus is a key region of the humid east to determine the long-term susceptibility to drought, since it often has been in sync with arid periods of the west.

Our research proposed here would provide valuable information for Manitoba Hydro, and other industries such as the Lake of the Woods Control Board, that are heavily reliant on water resources (95% of the current power for Manitoba is based on Hydro). In addition, our research will provide a means of better assessing past lake-level changes and water availability in drainage basins, which are the dominant type of lake in many regions of the world. Improved adaptation strategies need to be implemented for the full range in extremes of water availability. Few studies have specifically addressed long-term changes in water availability, particularly in regions today that appear to have an abundance of water. A better assessment of the extremes in water availability will enable companies heavily reliant on water resources (e.g., hydro and agriculture) to plan strategically for water shortages. In addition, strategic plans based on an integrated watershed management framework will incorporate not only the economic issues, but also the social and environmental issues related to future water resources. The students trained in this project will be able to work on water resource issues at many different levels (see Training Potential above.)

Table 1. Correlation coefficients of total annual precipitation between 5 climate stations in the WRDB, over the period of instrumental records from ~1920 to 2000.

	Kenora	Fort Frances	Dryden	Sioux Lookout
Fort Frances	0.36			
Dryden	0.62	0.56		
Sioux Lookout	0.52	0.39	0.66	
Atikokan	0.32	0.37	0.27	0.41



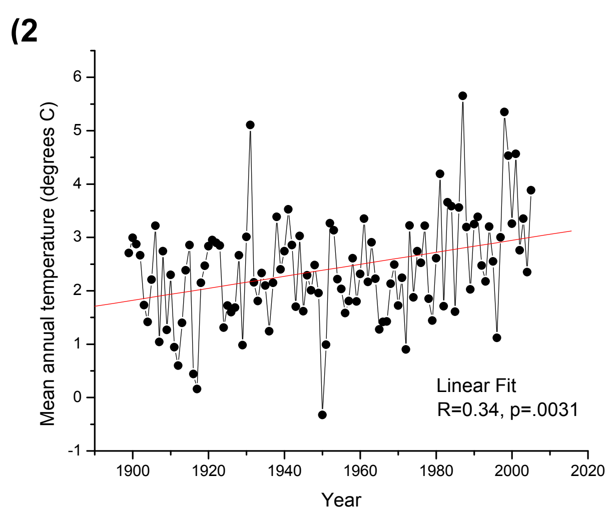
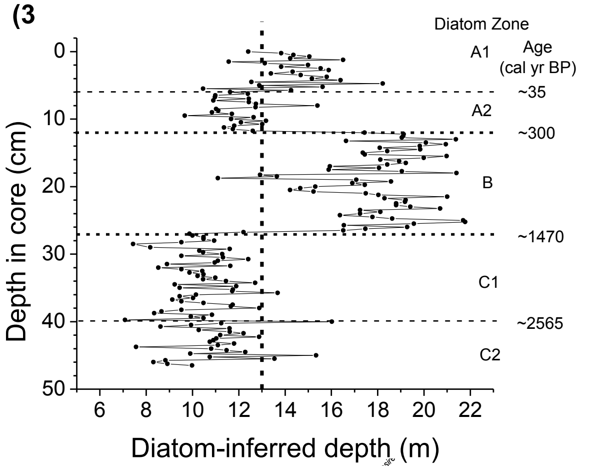


Fig. 1 Precipitation for WRDB climate stations, ordered from west to east. Blue boxes indicate droughts of the 1930s, 1950s, 1980s recorded at Kenora, ON. **Fig. 2** Temperature for Kenora. Solid line indicates the linear fit.

(3



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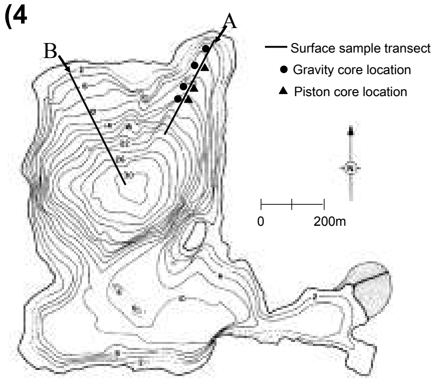

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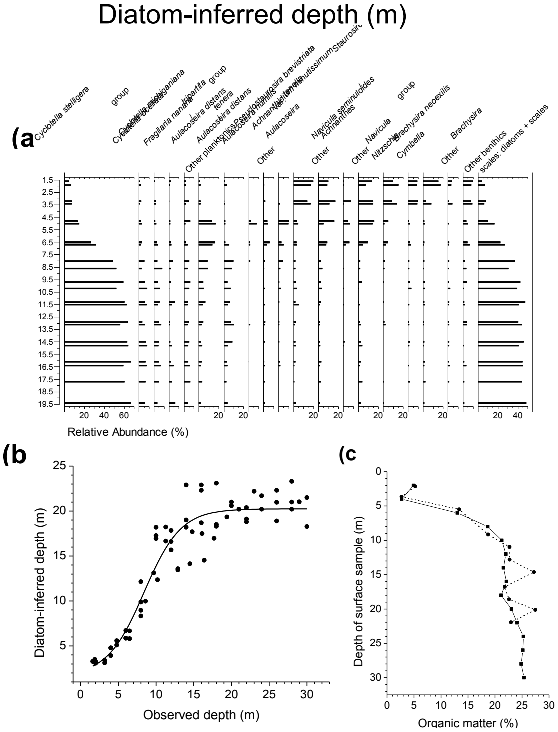

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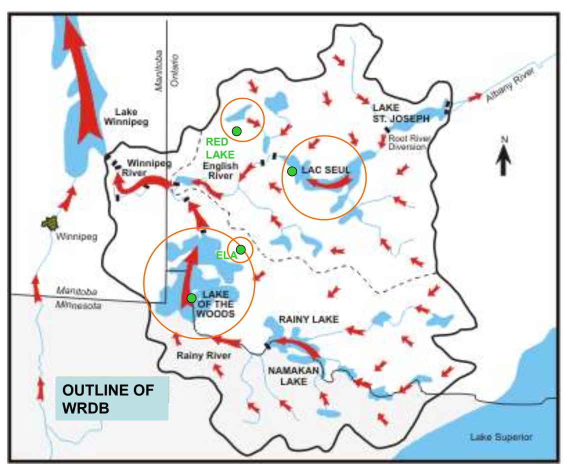

Fig. 3 Diatom-inferred depth from ELA Lake 239 for the past ~3000 years. Zones are based on a constrained cluster analysis of the diatom data. Ages are based on ^{210}Pb and radiocarbon dating. The vertical dashed line at 13m is the depth from which the core was taken. Hence estimates of change in lake depth are relative to 13m (e.g., inferred depths at 10m represent a 3 m decline in lake level. From Laird and Cumming accepted.

Fig. 4. Bathymetric map of Lake 239 indicating the location of surface samples and sediment cores. From Laird and Cumming accepted.

Fig. 5. (a) Dominant diatom taxa (>5%) found in the surface samples of Transect A. The last column is the proportion of chrysophyte scales to diatoms; (b) diatom-inferred depth versus measured depth, and (c) organic matter content of surface samples from Transect A (dashed line) and Transect B (solid line). Note the rapid change in assemblages occurring at a depth of 10-12 m in all indicators. From Laird and Cumming accepted.

Fig. 6. Location of the proposed research areas within the WRDB: 1) southern region- Lake of the Woods and ELA watersheds; 2) northern region - Lac Seul and Red Lake watersheds.