Final Report

Identification

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Project Title: Disappearing and flooding prairie lakes: Solving an aquatic whodunnit

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Supporting Organization: Natural Resources Canada
Saskatchewan Watershed Authority

Public Summary of Outcomes and Benefits to Canada

"Prairie residents often lament their shrinking and disappearing lakes, remembering a shoreline now hundreds of metres away from the beaches where they paddled as children. Speculation about a dwindling water supply appears frequently in the media, with shrinking glaciers and a warming climate cast as villains that threaten prairie agriculture, the economy, and a sustainable supply of freshwater for public consumption." (EnvironmentCanada, 2006).
"For cabin owners at Waldsea Lake, it's time to move it or lose it. Literally. With record rains in 2010 and a heavy snowfall this winter, water levels are expected to rise further on Waldsea Lake, which first experienced major flooding in 2007. The government has decided it's done repairing the temporary berms erected to protect the cabins and cabin owners will be asked to move their buildings to a new location. Waldsea Lake Regional Park will be closed and the berms will eventually erode." (The Star Phoenix, 2011)

As noted in the above quote from Environment Canada's Online News Magazine (EnviroZine), receding lake levels in the Prairies are a problem, no doubt made more noticeable by the fact that the lakes in this relatively dry region of Canada are heavily used for recreation, agriculture, and industry. Although few historical records extend back more than just a few decades, it is clear that the general trend within the Canadian Great Plains over the past four to five decades is toward lower lake levels. These declining lake levels present a multitude of associated environmental concerns due to increased salinity and changes in natural processes in the basins.

Although declining water levels are noteworthy, it is also evident the entire Great Plains region cannot currently be characterized by diminishing lake levels. Since the 1990's, many lakes located in broad areas of the northern Great Plains have experienced exceptionally high stands. When high lake levels occur in closed basins the immediate and long term repercussions can be just as devastating to the local communities and economy as low water levels, as is today so graphically illustrated in the Waldsea Lake area.

Management of water resources in this region must recognize and accommodate large variances imposed by natural fluctuations and trends over the longer term, and episodic drought and flooding caused by anthropogenic stresses over the short term. Effective management at the local and regional levels requires not only collaboration among agriculturalists, developers, industrialists, outdoor enthusiasts, and environmentalists, but, most importantly, a scientific knowledge base and a sound understanding of the impact of climate change on lacustrine and wetland hydrology of the prairies.

This project examined the stratigraphic records of five closed-basin lakes in Saskatchewan in order to reconstruct the history of lake levels over the past 2000 years. Although these lakes have experienced recent dramatic water level changes, in each case the modern changes are well within the range of natural variability caused by climatic fluctuation over the past several thousand years. It is highly probable that future climate change in the Prairie region, as predicted by various global warming scenarios, will result in much more significant fluctuations in closed-basin lakes of Alberta, Saskatchewan, and Manitoba. Thus, with this enhanced understanding of the long-term history of lake level fluctuations, water resources managers must prepare for the lakes of the Prairie region to exhibit more dramatic fluctuations than have been observed in the past half century.

Progress Towards Objectives/Milestones

To what extent were the objectives of the grant achieved? Rate your answer on a scale from 1 to 7.

Not at all — Somewhat — To a great extent

○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ● 6 ○ 7

Report on Progress

Preface

As per NSERC instructions, this Report on Progress is to comprise a maximum of 7 pages covering: **(i)** description of project objectives, **(ii)** description of progress made toward these objectives, **(iii)** justification for any deviations from original objectives, and **(iv)** description of significance of results. In summary, this two year project fully accomplished nearly all of the original objectives, the deviations from the original were minor and did not negatively affect the research results, and the results are significant as based on the number of scientific presentations at international conferences (12) and manuscripts (9) being published and prepared as part of the project. Although recruitment of HQP as part of this project was difficult, the project benefited from the participation of 1 Ph.D. and 1 M.Sc. student, and 2 senior undergraduate students. These students have or are in the process of preparing theses derived from data acquired in this project.

Introduction and Background of Project

Water is one of the most critical resources affecting the prosperity of the southern Canadian Prairies. In much of the vast region of the northern Great Plains there are well documented water supply/demand imbalances [1-5], which have been strongly influenced by historic climate variability. Thus, any future climate change for this region, such as the trends predicted by various Global Circulation Model simulations, will have a significant and probably adverse impact on water availability. In short, water in the Great Plains region of western Canada is an essential resource that is vitally important to economic development, environmental health and social stability.

Despite inherent difficulties and limitations in applying large-scale GCM simulations to relatively small scale and more local investigations, a large body of research suggests that projected warming in western Canada will adversely affect water quantity, which will ultimately lead to water quality problems [6-10]. Clearly, future water availability and drought frequency/duration are exceedingly important topics in terms of the agricultural production and economics of western Canada, and therefore have received much attention from government agencies and academic researchers. In contrast, there has been surprisingly little research on adaptations to climate change impacts on the ecosystem resources of western Canadian lakes [11]. This Prairie region contains literally millions of lakes and wetlands [12,13], which serve a critical role in waterfowl and wildlife habitat, recreation, and an array of economic and social pursuits. The vast majority of these lakes occupy small closed basins that respond dramatically to changes in climate, groundwater, and drainage basin and landscape modifications.

Receding lake levels in the Prairies are a problem, no doubt made more noticeable by the fact that the lakes in this relatively dry region of Canada are heavily used for recreation, agriculture, and industry. Although few historical records extend back more than just a few decades, it is clear that the general trend within the Canadian Great Plains over the past ~40 years is toward lower lake levels [14,15]. Similarly, in the shorter-term, 70% of the lakes in the Great Plains region of Alberta that are monitored by Alberta Environment have had mainly below normal levels for the past five years [16]. These declining lake levels present a multitude of associated environmental concerns due to increased salinity and changes in biogeochemical processes dominant in the basins [17,18].

Although declining water levels are noteworthy, it is also evident the entire Great Plains region cannot currently be characterized by diminishing lake levels. Since the 1990's, many lakes located in broad areas of the northern Great Plains have experienced exceptionally high stands [19-22]. When high lake levels occur in closed basins the immediate and long term repercussions can be just as devastating to the local communities and economy as low water levels.

Any strategy for water resources management in this region must recognize and accommodate large variances imposed by natural fluctuations and trends over the longer term, and episodic drought and flooding caused by anthropogenic stresses over the short term [23]. Effective management at the local and regional levels requires not only collaboration among agriculturalists, developers, industrialists, outdoor enthusiasts, and environmentalists, but most importantly a scientific knowledge base and a sound understanding of the impact of climate change on lacustrine and wetland hydrology of the prairies. Unfortunately, with a few notable exceptions [24-28] very little is known about natural long term hydrological changes in most areas of the Canadian Great Plains. This paucity of data and conceptual framework greatly limits our ability to accurately predict the influence of projected climatic fluctuations in the longer term and the effect of anthropogenic (cultural) stresses over the short term.

Project Objectives and Progress Toward Accomplishing Project Objectives

In the absence of adequate historical information, paleoenvironmental analyses are required to evaluate the role of climate and natural variability in regulating hydrological and lake level conditions of the lakes in the northern Great Plains. Examination of these records are necessary to determine whether the lakes experienced prolonged periods water levels that were either significantly higher or lower than today under the full range of natural conditions that existed before human occupation and modification of the landscape. To understand and reconstruct the often complex paleohydrological dynamics of lakes in the Great Plains, use of a multiple-indicator paleoenvironmental approach is essential. Reliance on only one or a few stratigraphic components (such only siliceous microfossils or mineralogy alone) is unlikely to provide a scientifically-defensible lake level history. Consequently, multiple independent lines of evidence from a variety of proxy indicators are required to establish a reliable lake level history and to assess the role of climatic variability in observed and interpreted hydrological changes.

The sediment in closed-basin lakes of the northern Great Plains provides information about the water level, salinity, and natural environmental fluctuations. The deposits in these lakes may also contain a detailed history of anthropogenic stress during post-settlement time. Even small changes in virtually any element of the hydrological budget of the salt lake basins are often reflected rapidly and directly by physico-chemical, sedimentological and/or geobiological fluctuations. Indeed, the fact that these salt lakes are essentially closed hydrological entities provides a unique opportunity to evaluate the complexity of various geological, hydrological, and geochemical interactions. The main objective of this project is to formulate a comprehensive ~2000-year record of the magnitude and frequency of water level changes and corresponding ecological fluctuations in four lacustrine basins in the Canadian Great Plains.

The specific objectives of this research project and the status and progress toward accomplishing these objectives during the two years of NSERC support are as follows:

Objective 1. Retrieve sediment cores from Manito, Antelope, Waldsea, and Deadmoose lakes. Completed as planned. A total of 8.6 m of sediment core was retrieved and analyzed from these lakes as part of this project. As a result of consultation with one of the partners, sediment cores were also collected from Lenore Lake, north of the Waldsea-Deadmoose chain. Because the emphasis of this project was on the past several thousand years only, core acquisition was limited to less than 2 m in all the basins. Sediment core samples and data were also provided by the Geological Survey of Canada from their Palliser Triangle Global Change Project. A total of 84 man-days was spent in the field on core collection. In addition to sediment core collection, various other samples and data were collected while in the field, including water samples for geochemistry, biological, and isotope analyses, water pH, temperature, depth, O_2 saturation, salinity, and conductivity. All water samples collected for analyses were pretreated according to APHA Standard Methods protocols [29]. Untreated water, sediment, and biological samples collected for microscopic, geochemical, and mineralogical analyses were stored at 4^oC (or frozen) until subsequent analysis.

Objective 2. Acquire samples of carbonate microbialites and tufas from Manito Lake. Completed as planned. A total of approximately 100 samples (and associated environmental data) of microbialites and hardgrounds were collected from 16 locations in the basin and analyzed as part of this project. In addition to sample collection, monitoring stations were installed at three locations in order to evaluate changes in modern microbial mat growth, productivity and population composition over a multiyear framework. The samples ranged from below present-day lake level up to an elevation of ~20 m above lake level. Many of these samples collected from Manito are large (to one meter in length), intact microbialite structures and tufa columns, which were subsampled at millimeter to centimeter scales after splitting and cutting in the laboratory. A total of 70 man-days was used to collect samples from the Manito Lake basin.

Objective 3. Establish a sediment chronology. Completed as planned. Sediment core and sample chronology was established by radiometric dating. Radiocarbon dating of both plant remains and endogenic carbonates was performed by accelerator mass spectrometry (AMS) at Keck-Carbon Cycle AMS facility (KCCAMS; University of California Irvine) and Beta Analytic Radiocarbon Dating Laboratories (Miami, Florida). Radiocarbon dates were calibrated to calendar years before present (cal. yrs BP) by the probability distribution method using Calib Radiocarbon Calibration 5.0.2 and the INTCAL04 calibration set [30]. To establish recent (~150 years) core chronologies, sediment samples were analysed for radioactive isotopes (^{210}Pb, ^{137}Cs) at the Environmental Radiochemistry Lab, Department of Fisheries and Oceans.

Objective 4. Delineate and map geomorphological and shoreline indicators of high water stands in each basin. Completed as planned. Standard field mapping methods and techniques [31] were used to map shoreline geomorphic features in each basin. This mapping effort was most successful in the basins in which present day water levels are relatively low (i.e., Manito and Antelope).

Objective 5 Evaluate long-term fluctuations in texture, petrography, bedding and sedimentary structures, mineralogy, organic content, and sediment geochemistry, and interpret these changes with respect to hydrologic and limnological fluctuations in the basins; and Objective 6 Assess recent, short-term changes relative to changing land use characteristics and/or specific human events. Completed as planned. All sediment cores and samples collected as part of this project were transported to the University of Manitoba where they were subsampled at various intervals. The highest resolution sampling occurred for the laminated microbialites (stromatolites) from Manito Lake. For these samples, sub-millimeter to millimeter spacing could be achieved, approaching sub-annual to annual resolution. Subsampling of sediment cores was dictated by (i) the nature of the analysis and the physical amount of material required, and (ii) anticipated resolution as suggested by the chronostratigraphy and the nature of bedding features. Clearly, highest resolution could be achieved with cores having fine laminations; lower temporal resolution occurred in sequences having no observable bedding. The best sample resolution for core material collected in this project is approximately annual for the recent part of the recovered sedimentary sequences; the normal resolution for sediment older than about 100 years is decadal.

In the laboratory, cores and samples were subjected to a series of analyses using well-established experimental protocols as summarized in various published methodological papers and handbooks [32-37]. Physical and sedimentological analyses emphasized bedding features and sedimentary structures, mineralogical composition and petrography, moisture and organic matter contents, and texture and fabric. The rationale and importance of this suite of analyses to lake level history studies are discussed by Dean et al. [38], Kemp et al. [39], Last [40,41], Schnurrenberger et al. [42] and Teller and Last [43]. As reviewed by Last and Vance [44] and Kemp [45], these physical features and data yield critical information about past limnological and hydrological conditions in the basin and catchment. For example, sedimentary structures provided unambiguous information about the physical and chemical structure of the overlying water mass, the nature of the sediment transporting mechanisms, and the level of energy at the depositional site - factors which were quantitatively related to basin depth and lake-level fluctuations. Non-annual laminae (from Waldsea and Deadmoose), cryptalgal laminae and mat structures (from Manito), and graded bedding and current-generated laminae (from Antelope) formed the basis of much of the preliminary paleoenvironmental interpretations from these four basins.

In contrast, the Lenore Lake and portions of the Antelope sequences exhibited no observable sedimentary structures. However, study of the various textural and fabric parameters in Lenore and Antelope sediments lead to important quantitative information about: i) provenance of the deposits, ii) the mechanisms responsible for transport of the material, iii) past physical and chemical conditions at the depositional site, and iv) paleoclimatic and paleohydrological conditions within the surrounding watershed. Unfortunately, interpretation of textural data is not always unambiguous, thus requiring that these fundamental measurements be incorporated within the multiple-indicator approach.

Knowledge of the minerals comprising the inorganic components of these lake sediments provided information related to the genesis of the sediments, transport mechanisms, and past limnological, hydrological and climatic conditions. The various mineralogical and petrographic analyses undertaken in this project allowed us to quantitatively decipher a tremendously wide array of paleoenvironmental and paleohydrological conditions. Following the rationale presented by Last & Ginn [46], Last [41], Henderson and Last [47], Last and Sauchyn [48] and Teller and Last [49], the relative chemical stabilities of the allogenic fraction of the cores (i.e., clay minerals, quartz, detritial carbonates, feldspars, and ferromagnesian minerals) allowed us to calculate the chemical weathering intensity in the drainage basins. Stratigraphic variation in these weathering intensity values were then related to paleoprecipitation and temperature in the specific watersheds.

More specific and quantitative paleohydrological information was derived from the endogenic and authigenic mineral fractions. Stratigraphic variation of the carbonate species (calcite, Mg-calcite, aragonite, dolomite, hydromagnesite, ikaite, monohydrocalcite, dypingite, and nesquehonite) was used to reconstruct past Mg/Ca ionic ratios, pH, and salinity of the lake water following the interpretive techniques outlined in Last [41], Last & Vance [50], Campbell et al. [51] and Last et al. [52] . The endogenic carbonate microcrystal morphology and fabric was used to evaluate water column stratification, depth and paleochemistry following the methodology of Last et al. [53], Last & Vance [44], and Greengrass et al. [54]. The endogenic evaporitic minerals identified in the sequences allowed us to reconstruct the relative ionic activities of the major dissolved cations and anions in the lakes following the methodologies discussed in Shang [55], Shang & Last [56] and Greengrass et al. [54].

The major geochemical proxies (major and trace elements and $\delta^{13}C$ and $\delta^{18}O$ of both endogenic inorganic carbonate and biogenic fractions) were used to track past changes in lake water balance, water composition, and source. Stable carbon and oxygen isotope systematics of carbonate minerals have been studied for decades and the utility of these isotope studies to lake studies is well documented [57-61]. In particular, the tandem approach of using stable isotope analyses in conjunction with trace and major element geochemistry of the endogenic carbonates in the lakes was most instrumental in helping to constrain the paleolimnological and hydrological reconstructions.

Finally, although the elevated salinities and very high alkalinities in the study lakes limited the application of diatom and ostracode assemblages to identify fluctuations in lake water salinity and composition, a limited examination of organic carbon and nitrogen and their stable isotopic ratios organic matter was undertaken. These data provided valuable information on the source of the organic matter in the sediments and thereby gave insight into past lake levels and paleohydrology.

Objective 7. Examine the periodicity of stratigraphic and geomorphic/shoreline changes and relate any changes to causal mechanisms. Completed as planned. In addition to simple 'visual' examination of the stratigraphic variations in each basin, the sequences were subjected to a variety of time series statistical analyses in an effort to identify non-evident periodicities or persistant patterns that could be interpreted with respect to possible external forcing mechanisms such as regional climatic fluctuations or solar intensity variations. The physical and geochemical data consist of series of observations which can be described in terms of self-affine fractals. Self-affine fractal is statistically similar to $f(rx,r^H y)$, where H quantifies the roughness of self-affine fractal and is known as the Hurst exponent. The trace of the record is a curve with fractal dimension $D=2-H$, $0<H<1$. When the Hurst exponent H is greater than 0.5, the series record is persistent: that is, an increasing or decreasing trend in the past favors an increasing or decreasing trend in the future. The increments in this case are positively correlated. If $H < 0.5$, the record is anti-persistent; the increments are negatively correlated and the data themselves seem to be highly "noisy". The Hurst exponent equal to 0.5 suggests a statistically random process. Two methods were used to measure the Hurst exponent of our core and microbialite data: the power spectrum method and the width method. The power spectrum method gives the fractal characteristics of data as a whole, and the width method gives the fractal characteristics of the data depending on length or time scale. Periodicity of the time series data can then be established by calculating a measure of likeness between members of the series: i.e., the series is compared with itself in consistent positions and a correlation coefficient is calculated between corresponding intervals.

Objective 8: Examine any regional pattern in the changes in sediment histories and relate these changes to either natural factors or to anthropogenic environmental modifications. Work is in progress and is approximately 60% completed. Placing our lake level histories into a regional context and integration of our results with other published paleolimnological and paleohydrologic studies is an obvious necessary final step in this research project. Although this final synthesis and integration must await the completion of the graduate theses that are currently in progress, it is evident even at this point that there are broad similarities in the interpreted lake histories over the past two millennia (e.g., similar responses during the period ~1200 – 700 cal yr BP) which will likely be correlated with other sequences in the Great Plains. However, it must be emphasized that these lake basins were specifically chosen because they exhibited water level changes over the past several decades. In this respect, only the Manito sedimentary sequence appears to be responsive to these modern fluctuations.

Deviations From Original Objectives

Overall, this research project progressed as originally planned in terms of objectives and accomplishments. As summarized above, nearly all of the objectives were completed as planned. However, there were several modifications required as the project developed. (i) As a result of suggestions and consultation with Saskatchewan Watershed Authority, an additional basin, Lenore Lake, was added to the project. This entailed collection of two additional cores and approximately 170 additional analyses for mineralogy, texture, organic matter and geochemistry. (ii) Unusually warm weather conditions during the first winter of this project necessitated a delay in core acquisition. (iii) On the basis of poor results from a reconnaissance study of pore water geochemistry in Waldsea Lake, the investigation of pore water composition was abandoned. (iv) Fluid inclusions were not observed in any of the thin sections prepared as part of this project. (v) Finally, I was seconded as Department Head during the academic year of 2009-2010. This necessitated the extension of the final report for this project by one year.

Significance of Results

This project was a two-year field and laboratory research effort designed to integrate a variety of paleolimnological, sedimentological, and geochemical approaches in order to examine lake level oscillations and other lacustrine hydrological/environmental changes in selected basins in the Great Plains of western Canada. As originally proposed, the prime focus was to develop century and decadal-scale environmental histories of Manito, Antelope, Waldsea, and Deadmoose lakes in the time interval of 2000 years ago to the present. This was accomplished.

Space limitations do not permit a description of all our new data and results. Nine full manuscripts have already been published or submitted to refereed journals. Preliminary results of this project have been disseminated to international audiences through twelve presentations at scientific meetings. Two undergraduate theses have been prepared and two graduate theses (Ph.D. and M.Sc.) are in preparation. The partners for this two year strategic project were not finalized until the second (final) year of the research program and, thus, information workshops and meetings could not be arranged. However, all publications, theses, reports and presentations derived from this project will be collected upon completion and transmitted to the supporting organizations. Very briefly, the highlights of our data and interpretations include:

(i) Non-biological proxies have been successfully applied to deduce late Holocene fluctuations in various limnological parameters, including lake level and water chemistry, in closed-basin saline/hypersaline lakes. This is important because most biological proxies, traditionally used in fresher open systems, are often limited in highly saline, alkaline settings of the northern Great Plains.

(ii) Water level fluctuations greater than those experienced during the past half century have occurred in each of the study basins. Thus, the hydrological variation and resulting ecological changes in the study lakes witnessed during the past three to four decades are well within the range of natural variation observed during the past several millennia.

(iii) Climatic variability plays a dominant role in determining natural variations of hydrological and ecological conditions in the study basins.

(iv) Shoreline and nearshore organogenic structures (stromatolites, microbialites and associated hardgrounds) were considerably more valuable in creating high resolution reconstructions of lake conditions than offshore sediment cores. This was due mainly to the fact the sediments in the study basins, although finely laminated, are not varved. The laminated microbialites, in contrast, provided sub-annual to annual resolution records. Unfortunately, there have been very few reports of these laminated organogenic structures in the northern Great Plains.

The findings of this project increase general awareness about the sensitivity of lakes in western Canada and water resources of the northern Great Plains to climate change and the necessity of understanding impacts of paleoclimate change. Investigation of the sensitivity of climate-hydrology linkages and corroboration of past lake level changes as a result of climatic change is a new and exciting field of applied Quaternary research in Canada. The results of the project contribute additional perspective and confidence for advice on policy or decision-making by government programs on climate and hydrologic change in the Great Plains, a situation that is clearly in need of improvement as, for example, reviewed by Schindler [8] and Schindler and Donahue [7].

Important insight into long-term lake response under changed postglacial Prairie climates has already been obtained by several large multidisciplinary, multi-organizational projects such as the Geological Survey of Canada's Palliser Triangle Integrated Research and Monitoring Area [62-65] and the Lake Winnipeg Project [66-68]. However, few research programs have specifically targeted recent (past several millennia) lake level fluctuations in Prairie basins [26,69-72]. Indeed, Recent and late Holocene paleolimnological research in the Canadian Great Plains region has lagged behind other areas of North American, Europe, and Australasia [73,74]. Assessment of future lake level variability in the Canadian prairies has been largely based on extrapolation of historically-recorded climate-hydrologic variation. Water level and associated lacustrine ecosystem changes in the Canadian Plains are already seriously compromising societal interests by limiting commercial and recreational use of the lakes, adversely affecting shore infrastructure and nearshore habitat, and, in several cases, drinking water supply and quality. Thus, by better quantifying inferred high-amplitude paleoclimate changes, and modeling the hydrological response to them, the sensitivity of water levels to climate change can be more accurately reconstructed.

Finally, the results of this project contribute to enhanced evaluation of regional climate simulation models. Increases in atmospheric greenhouse gases will undoubtedly change the climate and hydrology of the Canadian Prairies [6,75]. It is generally assumed that temperatures will rise in the Prairie region, although there is much less agreement about the changes in other factors such as precipitation, runoff, and evapotranspiration. Most general circulation models and the higher resolution Regional Climate Models predict greater overall precipitation for the northern Great Plains [76-78]. Whether this will offset the moisture stress resulting from the increased temperatures is contentious. For example, in the Prairies of north-central United States, climate change due to a doubling of CO_2 levels is predicted to result in a reduction of wetlands by over 50% [79,80]. In contrast, Clair *et al.* [81] maintain that few wetlands and sloughs in the Canadian Prairies would be adversely affected under this scenario. Similarly, McGinn *et al.* [82] predict an overall increase in soil moisture for most of the Canadian Prairies region under 2xCO_2 GMC simulations. At best, it is evident that the climate simulation models demonstrate a high amount of variability in predicted future changes for both mean temperature and total precipitation [83]. The type of paleodata acquired in this project are clearly needed to test and better constrain the evolving GCM and RCM simulations [84].

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Problems Encountered

Identify the problems encountered during the research project. (Select all that apply.)

- [x] Technical or scientific problems
- [ ] Problems with direction of research or findings
- [x] Equipment and facilities
- [x] Staffing issues (e.g., availability of students, staff leaving project)
- [ ] Funding problems
- [ ] Partners withdrew from project
- [ ] Partners interaction issues
- [ ] No problems were encountered
- [ ] Other (specify)

Problems Encountered

If problems were identified, briefly describe them and the steps taken to resolve each one.

Staffiing Issues: The single most limiting problem encountered during this project was recruitment of graduate students. Although ultimately the project benefited from the participation of four students (1 Ph.D., 1 M.Sc., 2 undergraduate students), three of the four students did not join the project until well into the final year of this two year study. Graduate student recruitment in geological sciences at University of Manitoba during the 2008-2010 period was at an historic low, due mainly to attractive industry opportunities.

Equipment and Facilities: When the project was proposed I was assured of the use of in-house stable isotope analysis facilities. Unfortunately, these laboratory facilities did not come on line until early 2010. This lead to a delay in completing the project and also required modification of the original budget breakdown; some of the funds had to be diverted to help pay the 'extra' costs of using outside commercial laboratory facilities.

Technical/scientific problems: The acquisition of sediment cores from saline and hypersaline lakes in the prairies is best accomplished using a stable coring platform provided by the winter ice cover. Unfortunately, unusually warm weather conditions during the winter of 2009 prevented the development of a suitable ice cover on these saline lakes. This necessitated a delay in core acquisition.

Research Team

Entry 1 of 5

Consent obtained: ● Yes ○ No
Name: William
Role: Applicant
If role is "Other", specify:

Contribution

Directed and supervised research project; took part in sample collection, analyses and interpretation; author or co-author of scientific manuscripts and conference presentations.

Entry 2 of 5

Consent obtained: ● Yes ○ No
Name: Ian
Role: Undergraduate Student
If role is "Other", specify:

Contribution

Assisted with sample and data collection from several of the study basins; summer field assistant; undertook B.Sc. Honours Thesis based on this project.

Entry 3 of 5

Consent obtained: ● Yes ○ No
Name: Adrian
Role: Undergraduate Student
If role is "Other", specify:

Contribution

Assisted with sample and data collection from several of the study basins; summer field assistant; undertook B.Sc. Honours Thesis based on this project.

Research Team

Entry 4 of 5

Consent obtained: ● Yes ○ No

Name: Jeff

Role: Graduate Student

If role is "Other", specify:

Contribution

Primary researcher on two of the study lakes and participated in sample and data collection for one of the other basins; author or co-author of scientific manuscripts and conference presentations; undertook M.Sc. thesis research based on this project.

Entry 5 of 5

Consent obtained: ● Yes ○ No

Name: Fawn

Role: Graduate Student

If role is "Other", specify:

Contribution

Primary researcher on one of the study lakes and participated in research data collection and interpretation for the other basins; author or co-author of scientific manuscripts and conference presentations; undertook Ph.D. thesis research as part of this project.

Training of Highly Qualified Personnel (HQP)

What types of interactions did the HQP have with the partners during the project? (Select all that apply.)

- [ ] HQP presented research results to the partners
- [x] HQP discussed the project directly with partners to obtain input
- [ ] Partners jointly supervised thesis projects of HQP
- [ ] HQP worked regularly in the partner's facilities
- [ ] HQP did not interact with the partners
- [ ] Other (specify)

Entry 1 of 4

Name: Adrian

Type: Undergraduate Student

If type is "Other", specify:

Start Date yyyy/mm: 2010/05

End Date yyyy/mm: 2011/04

Percentage (%) of time this individual spent on this project: 100

Percentage (%) of salary from this grant (NSERC and industry contribution): 0

Total person-months: 11

To the best of your knowledge trainee is: Do not know

If "Employed by Other", specify:

Entry 2 of 4

Name: Ian

Type: Undergraduate Student

If type is "Other", specify:

Start Date yyyy/mm: 2010/05

End Date yyyy/mm: 2011/04

Percentage (%) of time this individual spent on this project: 50

Percentage (%) of salary from this grant (NSERC and industry contribution): 0

Total person-months: 6

To the best of your knowledge trainee is: Employed in Industry

If "Employed by Other", specify:

Training of Highly Qualified Personnel (HQP)

Entry 3 of 4

Name:	Jeff
Type:	Master's Student
If type is "Other", specify:	
Start Date yyyy/mm:	2010/04
End Date yyyy/mm:	2012/05
Percentage (%) of time this individual spent on this project:	100
Percentage (%) of salary from this grant (NSERC and industry contribution):	0
Total person-months:	25
To the best of your knowledge trainee is:	Continuing Academic Training
If "Employed by Other", specify:	

Entry 4 of 4

Name:	Fawn
Type:	Doctoral Student
If type is "Other", specify:	
Start Date yyyy/mm:	2006/05
End Date yyyy/mm:	2011/09
Percentage (%) of time this individual spent on this project:	80
Percentage (%) of salary from this grant (NSERC and industry contribution):	50
Total person-months:	51
To the best of your knowledge trainee is:	Continuing Academic Training
If "Employed by Other", specify:	

Dissemination of Research Results

Refereed Journal Articles Submitted :	6
Refereed Journal Articles Accepted or Published:	3
Conference Presentations/ Posters:	12
Other (Technical Reports, Non-Refereed Articles, etc.):	3
How many of the publications, conference presentations, etc. identified above were co-authored with a non-academic partner?	0

Dissemination of Research Results

Refereed Journal Articles Submitted:

Last, F.M., Last W.M., Halden, N.M., Fayek, M. Occurrence and significance of a cold water carbonate pseudomorph in microbialites from a saline lake. (Nature)

Last, F.M., Last, W.M., and Halden, N.M. Microbially-mediated late Holocene dolomite in a saline lake from the Northern Great Plains of western Canada. (Sedimentology).

Last, F.M., Last, W.M., and Halden, N.M. Using microbialites as indicators of environmental change: a tale of two basins. (Palaeogeography, Palaeoclimatology, Paleoecology)

Last, F. M., and Last, W. M. Microbially mediated dolomite formation in saline lakes of western Canada. (Invited paper Microbes and microbial mat signatures in the sedimentary record, Special Issue of Sedimentary Geology).

Last, W. M. and Last, F. M., . Geolimnology of lakes in the Great Plains of Canada: An overview. (Invited paper Quaternary Research).

Witherow, R. A. and Lyons, W. B. The fate of minor alkali elements in the chemical evolution of closed-basin lakes. (Saline Systems)

Refereed Journal Articles Published:

Last, F. M., Last, W. M., and Halden, N. M. 2010. Carbonate microbialites and hardgrounds from Manito Lake, an alkaline, hypersaline lake in the northern Great Plains of Canada. Sedimentary Geology 225 (2010), pp. 34-49. (This paper was within the top 25 accessed article for the journal in 2010).

Cloutis, E. A., Grasby, S. E., Last, W. M., Léveillé, R., Osinski, G. and Sherriff, B., 2010. Spectral reflectance properties of carbonates from terrestrial analogue environments: Implications for Mars. Planetary and Space Science vol. 58, p. 522-537. (Although this paper does not address water level changes, it contains data collected as part of this project)

Last, W. M., and Ginn F. M., 2009. Water chemistry of saline lakes of the Northern Great Plains, western Canada., Geochemical News. Vol. 141

Published Abstracts of Conference Presentations:

Dowsett, A. 2011. offshore Holocene sediments from Manito Lake, Saskatchewan. Abstract, WIUGC Brandon, Manitoba.

Last, Fawn M., Last, William M., and Halden, Norman M., 2010. The Use Of Continental Saline Lake Microbialites As Indicators Of Holocene Environmental Change. Geol. Society of America, Annual Meeting, Denver. Geological Society of America *Abstracts with Programs*, Vol. 42, No. 5, p. 623

Last, William M. And Last, Fawn M., 2010. Antelope Lake, Saskatchewan: A Multidisciplinary Archive Of Late Holocene Hydrologic And Environmental Change In The Northern Great Plains Of Western Canada. Geol. Society of America, Annual Meeting, Denver. Geological Society of America *Abstracts with Programs*, Vol. 42, No. 5, p. 623

Read, Jeff**,** Last, Fawn M., and Last, William M., 2010. The Ups And Downs Of Lake Levels In The Northern Great Plains Of Western Canada. Geol. Society of

America, Annual Meeting, Denver. Geological Society of America *Abstracts with Programs*, Vol. 42, No. 5, p. 623.

Leslie, D., Witherow, R. A., Olesik, J., Welch, K. A., Lyons, W. B., and Last, W. M., 2010 Boron Concentrations In Saline Lakes: Great Basin, USA; Saskatchewan, Canada; And McMurdo Dry Valleys, Antarctica. Geol. Society of America, Abstracts with Program vol. 42, p. 303.

Last, W. M. and Ginn, F. M., 2009. Bio-mediated and abiotic dolomite formation in saline lakes of the northern Great Plains of Canada. Geochimica et Cosmochimica Acta Vol. 73, p.A725.

Ginn, F. M., Last, W. M. and Halden, N. M. 2009. Unraveling the microbialite web: Formation and diagenesis of laminated and massive carbonate sediments in saline lakes of North America and Australia. Geochimica et Cosmochimica Acta Vol. 73, p. A438.

Last, W. M. and Ginn, F. M., 2009. Modern and late Holocene dolomite formation in a continental hypersaline lake, western Canada. Program and Abstracts Volume, 27th Annual Meeting of International Association of Sedimentologists, p. 34

Ginn, F. M. and Last, W. M., 2009. Manito Lake microbialites: a record of changing environment and climate in the northern Great Plains of western Canada. Program and Abstracts Volume, 27th Annual Meeting of International Association of Sedimentologists, p. 84.

Ginn, F.M. and Last, W.M**.** 2008. Late Holocene Ikaite Pseudomorphs In a Saline Lake In the Northern Great Plains, Canada. Geological Society of America Abstracts with Programs. Houston, Texas. 40(6):399.

Last, W.M**.** and Ginn, F.M. 2008. A new Location of Modern lacustrine Dolomite Formation: Manito Lake, Saskatchewan, Canada. Geological Society of America Abstracts with Programs. Joint Meeting of The Geological Society of America Houston, Texas. 40(6):481.

Ginn, F. M. and Last, W. M**.,** 2008. Mineralogical and geochemical assessment of microbialites in a saline lake in the northern Great Plains of western Canada. ISSLR Conference, Salt Lake City.

Nonrefereed Reports:

Last, F. M., Carbonate microbialite formation in a prairie saline lake in Saskatchewan and an intermontane saline lake in Nevada: paleohydrologic and paleoclimatic implications Ph.D. Thesis (in preparation; anticipated submission date: July, 2011).

Read, J. Aragonite 13C and 18O stratigraphy of two saline, meromictic lakes in Saskatchewan. M.Sc. thesis (in preparation; anticipated submission date: March 2012).

Dowsett, A. E. I., 2011. Characterization and analysis of offshore Holocene sediments from Manito Lake, Saskatchewan. Unpublished thesis. University of Manitoba..

Read, J., Crystal morphology and size characteristics of Waldsea Lake sediments. Unpublished Report for GEOL 7489.

Dickie, I., 2011. Mineralogy and Late Holocene History of Lenore Lake, Saskatchewan. Unpublished thesis, Univeristy of Manitoba.

Intellectual Property Protection

Filing of patent applications:	Not applicable
Registration of copyright for computer software or databases:	Not applicable
Registration of copyright for educational materials:	Not applicable
Registration of industrial designs:	Not applicable
Filing for protection of trademarks:	Not applicable
Registration of integrated circuit topographies:	Not applicable
Filing of applications for plant breeders' rights:	Not applicable
Execution of non-disclosure or confidentiality agreements:	Not applicable
Other (specify):	Not applicable

Collaboration with the Partners

How was this research project initiated?

- [x] The university researcher approached the partners
- [ ] The partners approached the university researcher
- [ ] The government partner approached the university
- [x] There was a previous collaboration with the partners
- [ ] This is a new collaboration
- [ ] Other (specify)

Did this project arise from a grant funded by the NSERC Strategic Workshops Program? ○ Yes ● No

Did this project arise from a grant funded by the Interaction and/or Engage Program? ○ Yes ● No

Collaboration with the Partners

Briefly describe the process.

After the first year of this two-year NSERC SPG-SC program project, WML approached both the Saskatchewan Watershed Authority (SWA) and Natural Resources Canada (NRC) to inquire about partnership during the final year of the project. The choice of these two government organizations was straightforward: SWA has a direct and immediate practical interest in fluctuating water levels in closed basin prairie lakes in Saskatchewan, and in particular, Lakes Waldsea and Deadmoose, where high water levels during the past half decade have caused consider damage to property, facilities and rural infrastructure. Dr. John-Mark Davies has worked extensively on these two basins in addition to Lenore and other basins in the area. Natural Resources Canada has an obvious long-standing interest in climate change and its hydrological implications on the Prairies.

Both organizations responded positively to initial enquiries, and both indicated that they would be able to supply a considerable level of 'in-kind' support during the final year of the project as well as data and expertise/consultation as required.

Collaboration with the Partners

To what extent were the partners involved in the project? Rate your answer on a scale from 1 to 7.

Not at all | **Somewhat** | **To a great extent**

○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ● 6 ○ 7

In what way were the partners directly involved in the project? (Select all that apply.)

- [x] Partners were available for consultation
- [ ] Partners provided facilities
- [ ] Partners provided training
- [ ] Partners co-supervised students' theses
- [ ] Partners received training from university personnel
- [ ] Personnel from the partner organization received training from the university
- [x] Partners discussed the project regularly with the university team

  Average number of meetings per year: 1
- [ ] Partners were involved in the research
- [x] Other (specify)

  NRC kindly made available core samples; SWA assisted with sampling and provided data.

Collaboration with the Partners

Describe the partners' involvement and comment on the collaboration.

The support of both the Saskatchewan Watershed Authority and Natural Resources Canada was exceptional and critical for the successful completion of this project. During the second year of this NSERC SPG-SC program project SWA provided unpublished data and reports, and contributed important insight into the sample acquisition and encouraged us to broaden the scope of the project by investigating the stratigraphic record of Lenore Lake, immediately north of two of the original study basins. Dr. John-Mark Davies also assisting with field work during the final year of the project. Natural Resources Canada provided key core samples and unpublished data from the Geological Survey of Canada's Palliser Triangle Global Change Project (1991-1996).

Future Plans

What links are you maintaining with the partners? (Select all that apply.)

- [x] Collaborating with the partners on the same research
- [x] Collaborating with the partners on other research
- [ ] Collaborating with other partners on the same research
- [x] Continuing the research without partners
- [ ] No contact with the partners currently and none planned
- [ ] No contact with the partners currently but future collaboration planned

Future Plans

Describe any follow-up or related work that will be undertaken as a result of this project, who will be involved in this work (including partners) and how it will be funded.

One of the highest priority follow-up aspects to pursue will be acquisition of cores from more basins in the Waldsea-Deadmoose-Lenore area. Previous research on a nearby lake, Humboldt Lake, has indicated this lake is at the highest level in over 1000 years. However, this was not the case for Waldsea-Deadmoose or Lenore on the basis of our stratigraphic investigations. Likewise, Basin Lake, located at the 'end' of the chain of lakes in this area should be cored. Although our interpretations of water levels in Lenore Lake based on the initial coring did not reveal any significant water level or limnological fluctuations over the past 2000 years, this recent record should be placed in context by acquiring sediment cores spanning at least to 6000 yr BP.

I have a long-term interest in these study lakes; I and my research colleagues have been monitoring water levels, salinity and modern sedimentology in Antelope, Waldsea and Deadmoose lakes since 1980 and Manito Lake since 2005; we plan to continue limnogeological research on these basins.

Future Plans

Describe any additional links that the partners will maintain with the university.

It is anticipated that personnel from both partner organizations will continue to take an active role in graduate student research efforts in the Department through formal and informal advice, consultation, and thesis committees.

Knowledge and Technology Transfer

Research results transferred to the partners

- [ ] Through informal discussions
- [ ] Through reports provided to the partners
- [ ] As a result of the partners participating in the research
- [ ] Through formal publications
- [ ] Through patents
- [ ] Through licencing arrangements
- [ ] The research results have not been transferred to the partner
- [x] Other (specify)

Specific results of this project will be provided to the partners through publications and theses..

Research results being used and/or will be used by the partners

As a stimulus for future R&D:

To enhance the skills and knowledge of personnel in the partner's organization: Potential to be used

To improve an existing product:

To improve an existing process:

To improve an existing service:

To develop a new product:

To develop a new process:

To develop a new service:

To contribute to a policy, regulation or standard:

Other (specify):

Knowledge and Technology Transfer

Briefly describe these outcomes

The main application of this research is to provide background information for water resources managers and those charged with policy development regarding mitigation of future environmental problems relative to fluctuations in water levels in closed basins in the northern Great Plains.

Knowledge and Technology Transfer

Describe any environmental or social benefit that resulted or could result in the future from this research

Water is one of the most critical resources affecting the prosperity of the southern Canadian Prairies. In much of the vast region of the northern Great Plains there are well documented water supply/demand imbalances, which have been strongly influenced by historic climate variability. Thus, any future climate change for this region, such as the trends predicted by various Global Circulation Model simulations, will have a significant and probably adverse impact on water availability. In short, water in the Great Plains region of western Canada is an essential resource that is vitally important to economic development, environmental health and social stability.

Any strategy for water resources management in this region must recognize and accommodate large variances imposed by natural fluctuations and trends over the longer term, and episodic drought and flooding caused by anthropogenic stresses over the short term. Effective management at the local and regional levels requires not only collaboration among agriculturalists, developers, industrialists, outdoor enthusiasts, and environmentalists, but most importantly a scientific knowledge base and a sound understanding of the impact of climate change on lacustrine and wetland hydrology of the prairies.

Impact on Researcher

Impact the project had on your teaching

- [ ] Creation of new courses
- [ ] New content for existing courses
- [ ] Use of real world examples in courses
- [ ] Guest lectures from partners
- [ ] New equipment/material
- [x] Project has had no impact on my teaching
- [ ] Other (specify)

Impact the project had on your research

- [ ] Influenced the direction to more industrially relevant topics
- [x] Opened up new opportunities for research beyond the original objectives
- [ ] The project has had no impact on my research
- [x] Other (specify)

The cores and samples collected as part of this study are an important archive for future research

Contributions from Other Sources

Partners	Total Cash		Total In-Kind	
Company Name	**Committed**	**Received**	**Committed**	**Received**
Natural Resources Canada	0	0	0	35,000
	Have you had previous research collaborations with this partner? Yes - In the same research area			
Saskatchewan Watershed Authority	0	0	0	35,000
	Have you had previous research collaborations with this partner? No			
	0	0	0	0
	Have you had previous research collaborations with this partner?			
	0	0	0	0
	Have you had previous research collaborations with this partner?			
	0	0	0	0
	Have you had previous research collaborations with this partner?			
	0	0	0	0
	Have you had previous research collaborations with this partner?			
	0	0	0	0
	Have you had previous research collaborations with this partner?			

Contributions from Other Sources

Other Sources	Total Cash		Total In-Kind	
		Received		Received
		0		0
		0		0
		0		0
		0		0
		0		0
		0		0
		0		0
Total (partners and other sources)	**$0**	**$0**	**$0**	**$70,000**

Contributions from Other Sources

Variation described between commitment and actual cash and in-kind contributions

Natural Resources Canada provided core samples and various unpublished data and information that was collected as part of their Palliser Triangle Global Change Project.
Saskatchewan Watershed Authority provided unpublished data and logistical support.

Financial Information

Consolidated balance remaining at the end of the project:

Budget Items	**Total Budget**	**Total Actual Expenditure**	**Percent Variation**
1) Salaries and benefits			
PhD students	0	19,000	999
Master's students	30,000	0	-999
Undergraduate students	4,800	0	-999
Postdoctoral fellows	52,000	0	-999
Technical/professional assistants	0	0	0
	0	0	0
2) Equipment or facility			
Purchase or rental	7,000	51,931	642
Operation and maintenance costs	3,500	3,951	13
User fees	64,900	72,074	11
	0	0	0
3) Materials and supplies			
Lab supplies	1,000	4,797	380
Office/computer supplies	0	1,802	999
	0	0	0
4) Travel			
Conferences	0	10,074	999
Field work	9,700	5,253	-46
Project related travel	1,510	0	-999
	0	0	0
5) Dissemination			
Publication costs	0	2,519	999
	0	0	0
6) Technology transfer activities			
Field trials	0	0	0
Prototypes	0	0	0
	0	0	0
7) Others (specify)			
chronology	9,050	12,059	33
	0	0	0
Total	183,460	183,460	0

Financial Information

Explanation for the variation of each budget item

1. Salaries and benefits: Recruitment of a suitable post-doc fellow to work on this project as originally anticipated was not successful despite repeated advertising and searches during the life of this two year project. In addition, the M.Sc. student did not begin until the final stages of this project and although he is working on aspects of this project for his thesis research, his stipend is being covered by other sources of funds. An undergraduate student was not available during the first year of this project as originally planned. Because of these graduate student and post-doc recruitment problems, funds originally intended for salary and stipend were used to support a Ph.D. student who worked on this project. It was not originally planned to have a Ph.D. student involved in the project.

2a. Equipment purchase: In the final year of the project, it was necessary to acquire a new epifluoresence microscope for the Ph.D. student use. This was, in part, required because of the unanticipated importance of the laminated organogenic structures discovered in one of the basins. Existing microscope equipment in the Department was not suitable for this effort and the project would not have been able to generate the results it has without this necessary microscopic equipment. A computer also had to be purchased for the graduate student to use.

3a. Laboratory Supplies: Miscellaneous laboratory supplies relative to this project were underestimated in the original budget; it was originally anticipated that the M.Sc. student and post-doc would be able to prepare their own petrographic samples for examination, however, because of the late arrival of this student and the inability to recruit a suitable post-doc, it was necessary to pay for these items.

3b. Office Supplies/Consumables: There were also several unexpected items that had to be acquired for the completion of this project including the purchase of Geochemists Workbench and several plotting/graphics programs because existing departmental site licenses expired; the department now charges for all telecommunications and photocopying.

4a. Conference Travel: It was originally estimated that all conference travel would be supported by other sources of funding from University of Manitoba and society sources. However, these other sources of funds did not materialize and it was necessary to support the two graduate students involved with this project as well as myself with regard to presentation of the results of the project at conferences.

4b.Field Work: Warm winter conditions during the first year of the project prohibited formation of a stable ice platform on the lakes, so field work for that season was cancelled.

5. Publication costs: It was not anticipated that publication costs would be incurred, however, both Sedimentary Geology and Sedimentology are now applying publication costs.

7. Chronology: The cost of radiocarbon dating increased because the only Canadian source for commercial dating was not accepting any samples which necessitated using laboratories in United States.