A Summary of Paleolimnological Studies Conducted in Alberta

Alberta Environment

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Executive Summary

Paleolimnology is the study of lake development through analysis of physical, chemical and biological information stored in aquatic sediments. Paleolimnology has multiple applications, lake management being one of them. The main objective of this report was to produce a summary of paleolimnological studies completed in Alberta.

Several sources were searched for published and non-published literature. Search results were reviewed and summarized to develop an annotated bibliography. This information was further summarized to present a picture of lake development in Alberta over the distant (~10,000 years) and recent (~200 years) past.

Recommendations were made with respect to the application of future paleolimnological studies for water management issues in Alberta. Paleolimnological techniques can be used to investigate the sensitivity of aquatic ecosystems to drought, to establish cause-effect relationships between land use and water quality changes, to monitor pollution, and to define realistic restoration goals. Paleolimnological studies may be particularly useful for developing lake management plans to address the following management concerns: water shortage, lake eutrophication, algal blooms and lake restoration goals. Paleolimnological techniques can be applied to other industries such as oil and gas, mining and hydroelectric dams as part of monitoring requirements, assessment of remediation targets, assessment of pollutant loads and changes in water quality.

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1 Introduction

There is an ever-increasing need for efficient and effective strategies for water quality assessment and management as water resources become increasingly important in Canada. This is true in particular for the province of Alberta, where multiple stressors (climate change, land use, water use) exert a lot of pressure on aquatic ecosystems that serve as important natural resources for economic, recreational, and conservation purposes. The paleolimnological approach is well recognized and used as a tool for lake management by researchers, and it has recently been included in Alberta's watershed management efforts. Within the framework of the "Water for Life" strategy, three out of over 60 watershed stewardship groups (WSG) are using paleolimnological studies to support the development of watershed management plans. This report provides a summary of paleolimnological studies that have been completed on Alberta lakes and demonstrates the potential of paleolimnological studies for future lake and watershed management in Alberta.

Paleolimnology is a scientific discipline that uses the analysis of physical, chemical and biological information stored in aquatic sediments to infer past changes in environmental conditions and water quality. It can be used to address key management questions, such as:

- What are the background conditions and natural variability of an aquatic system?
- What are realistic, system-specific restoration targets?
- When and how much has water quality changed in the past?
- What are the likely causes of change?

Many of these questions can only be answered with a long-term record of water quality or ecological conditions in a lake. Unfortunately, such records are usually rare and, where they exist, insufficient sampling intensity, changes in detection limits over time, or the natural variance in water quality often reduce their utility. By adding a historical perspective to the understanding of aquatic ecosystems, paleolimnology provides previously unavailable long-term data for lake managers. This has specific applications such as the management of recreational water quality, environmental assessment of industrial projects (mining), routine monitoring of water quality and interpreting the effects of changes in climate or hydrology.

The purpose of this report was to produce a summary and synthesis of paleolimnological studies completed in Alberta. The different sections of this report are therefore intended to:

- Introduce the paleolimnlogical approach including a brief overview of methods;
- Summarize completed paleolimnological studies on Alberta lakes by reviewing published (scientific journals and books) and unpublished (theses, technical reports and communicated information) sources;
- Synthesize the knowledge collected on the history of Alberta lakes using paleolimnology; and
- Make recommendations for future paleolimnological studies to address areas of concern in Alberta lake management.

2 Paleolimnological Approach

In this section, a general overview of paleolimnological methods including sampling techniques, major indicators and potential limitations is presented to provide context for the synthesis and recommendations sections of this report. Documentation of specific paleolimnological methods is beyond the scope of this report, but such documentation is published extensively in the scientific literature. Notably, the ***Developments in Paleoenvironmental Research (DPER)*** book series edited by J.P. Smol and W.M. Last (see References under Last and Smol 2001 to 2006), provides a comprehensive and authoritative reference of paleolimnological techniques and indicator analysis.

The paleolimnological method is conceptually simple. As sediments accumulate at the bottom of a lake basin, so do indicators of environmental conditions that exist at the time of deposition. These indicators can include cyanobacterial and algal remains, insect head capsules, cyanobacterial and algal pigments, chemicals or contaminants. Assuming that the sediments containing these indicators are deposited in an orderly fashion and that the indicators are preserved over time, they can be isolated from the sediment matrix at increasing depths to provide a record of environmental conditions going back in time, from years to millennia.

The basic paleolimnological approach consists of:

A. **Sample Collection** – A sediment core is retrieved from the study lake. The length of the core is sectioned into fine intervals (usually 0.25 to 1-cm thick).

B. **Dating of the Sediments** – The sediments are dated using radioisotopes (^{210}Pb, ^{137}Cs, ^{14}C), or other dating tools.

C. **Indicator Analysis** – Sediment sections are processed to isolate the indicators of interest. Indicators, or environmental ‘proxies’ are assessed using a variety of analytical techniques.

D. **Environmental/Limnological Inferences** – Past environmental/limnological conditions, such as fish presence/absence, lake level changes, stratification patterns, light conditions, aquatic plant community structure, salinity, and nutrient status are inferred from changes in paleolimnological indicators. For biological proxy data, statistical models can be developed from modern relationships with the same environmental variables (i.e., the calibration set approach) and applied to downcore indicator data to infer past conditions.

E. **Environmental Assessment** – The timing, rate and magnitude of changes in lake conditions identified from the paleolimnological data can then be used to help ascertain factors causing those changes.

2.1 Sediment Sampling

There is a large selection of different makes and types of corers that are available to retrieve sediments from aquatic basins; the choice of coring apparatus largely depends on the length of the core required and physical characteristics of the lake and sediments. The project scope and required outcomes of a particular study ultimately determine the length of sediment core that needs to be analyzed. For short cores (usually < 50 cm long), simple gravity corers are used to obtain sediment sequences with an intact sediment-water interface. For longer cores, sediment sequences are typically collected in overlapping sections (usually 1-m sections) from adjacent "boreholes" using any one of a variety of corers. Examples of long corers include piston-type corers (Livingston); freeze corers that use a cooling agent (e.g. liquid nitrogen) to make the sediments attach to the frozen equipment, and percussion corers. Sediment cores are usually taken in the deepest part of the lake or basin of interest, as sediments tend to migrate or "focus" to the deepest areas over time. Equipment for short cores can be used from a small craft (e.g., small motor boat, canoe), while larger equipment requires a stable surface, like a coring platform or ice cover. Extrusion and sectioning of short cores is most often carried out in the field to allow for re-use of equipment and proper preservation of the sediment-water interface. Long core sections are wrapped and packed in solid supports for transportation and can thus be transported and stored in the cold for longer periods of time before sectioning. For detailed information on sediment coring techniques, see Volume 1 of the DPER series (Last and Smol 2001). Although coring techniques are relatively simple, the collection of cores needed for meaningful paleolimnological analyses requires significant expertise and equipment capable of collecting perfect, undisturbed samples.

To determine long-term lake changes in periods prior to modern anthropogenic influence, sediment profiles are extracted and analyzed on a millennial-to-century time scale. Long cores are usually sampled for indicator analysis at a coarse resolution (every 5-10 cm). For higher resolution studies, long cores can be subsampled at finer intervals.

To determine lake response to recent changes, sediments are often analyzed on decade to century time scales, although fine sectioning can often result in annual or even seasonal resolution power. In most cases, short cores of approximately 50 cm include at least 200 years of sediment and thus are sufficient in North America to cover the entire European post-settlement period and some time before. This allows for the interpretation of recent water quality conditions prior to and during human impacts following European settlement. There are two common approaches to study and analyze short cores:

A. The core can be sampled at high resolution (every 0.25 - 2 cm) to provide details on lake responses to watershed disturbances and recovery. This type of sampling requires a high level of sampling and sectioning accuracy and provides a temporal resolution of 1 to 20 years, depending on sedimentation rates. With a high number of samples to be analyzed, this method can be time consuming.

B. "Top-Bottom" analysis (e.g., Dixit et al. 1999), where only the top (modern) and the bottom sediments (approximately 200 years old) are analyzed. This provides a quick assessment of pre- versus post-settlement conditions, and thus can provide potential restoration targets, or an index of coarse changes, for a larger number of lakes.

Finally, to measure response to weather and biological factors, sediments can be analyzed on annual to seasonal scales. This requires the use of sediment traps that can be sampled on a monthly, weekly or even daily basis or frozen core extraction methods that allow fine-resolution sampling that may not otherwise be possible in regular sediment cores.

2.2 Dating and chronology

Radiocarbon dating is the standard method for establishing a chronology for long cores, while the more short-lived radioisotopes of lead and cesium are common methods used for short cores. The method of ^{210}Pb provides dates for sediments up to 150 years old. Different models are used to convert raw ^{210}Pb activity counts into sediment ages (e.g., Oldfield and Appleby 1984). Measuring other components of the polonium decay series (such as ^{214}Bi) can be used to determine if background activities have been reached (i.e., > 150 years), for example for the top and bottom method. The method of ^{137}Cs is based on maximum fallout rates from atmospheric nuclear weapons testing that occurred in the 1960s in North America and thus provides chronological control for one point in time. In areas where the time of initial forest clearing is well documented, the first occurrence of high abundances of pollen indicators for land clearing can be a very useful stratigraphic marker (Francis and Foster 2001). Other stratigraphic markers include tephra layers from known volcanic eruptions, fly-ash particles from different heating sources (coal versus oil) or forest fires, or any other known depositional event for the study site.

2.3 Indicator Analysis

The sediment record contains a myriad of environmental indicators from a variety of sources, which can broadly be divided into allochthonous (from sources outside of the lake, such as from the catchment or atmosphere) and autochthonous (produced within the lake itself) sources. Indicators, commonly referred to as ‘environmental proxies’, can include:

- physical proxies (e.g., general physical properties of the sediment such as water, organic and mineral contents, magnetism, and grain size; fly ash particles and charcoal);
- chemical proxies (e.g., pollutants such as metals and persistent organic contaminants);
- isotopic proxies (e.g., radioisotopes of lead, cesium, carbon, stable isotopes of carbon, nitrogen, oxygen and hydrogen); and/or
- biological proxies (e.g., pollen, plant macrofossils, cyanobacterial, algal and invertebrate remains, plant pigments).

The choice of indicators used in paleolimnological studies is ultimately dependent upon the question being asked because different indicators provide different information of past environmental conditions. Most paleolimnologists agree that using multiple indicators is advantageous, not only to corroborate environmental inferences, but to provide a more holistic reconstruction. Below, very general descriptions and uses of some commonly used paleolimnological indicators are provided for reference and are summarized in Tables 1 through 3.

2.3.1 Physical sediment characteristics

Physical characteristics of the sediment are used to provide interpretations about lake and landscape changes (Table 1). Magnetic susceptibility of the sediments provides information about changes in sediment sources to the lake that can provide interpretations about changes or development in the catchment (Karst-Riddoch et al. 2005). Geomagnetic secular variation (GSV) from lake sediments ranges from sub-century to the multi-millennial scale and has been observed in historical lake-sediment records. Grain size analysis can provide insight to sources of the sediments and transport processes prior to deposition. Changing sedimentation rates can also reflect sediment sources and transport dynamics triggered by changes in land cover in the watershed, or internal productivity changes.

Table 1. List of Some Common Physical Paleolimnological Indicators

Detailed information pertaining to these and other indicators is contained in Last and Smol (2001-2006).

Physical Indicators	Properties indicated	Limitations
Sediment influx rate	Sediment erosion; turbidity/light limitation in lakes	Requires precise chronology
Sediment grain size	Climatic change, sediment source, depositional processes	
Varved Sediments	Annual chronological control; sometimes allows seasonal resolution; climate sensitive	Not consistent within a lake; does not occur in all deep lakes; may be intermittent
Tephra layers	Chronological markers	
Carbonaceous particles (Fly ash)	Atmospheric pollution, type of heating (charcoal versus oil: chronological marker)	
Charcoal	Fire frequency; drought frequency	Small particles can be transported between watersheds; difficult to interpret the spatial aspect of the charcoal signal
Magnetic susceptibility, petrography, mineralogy,	Sediment source; erosion	

2.3.2 Chemical and stable isotope characteristics

The measurement of sedimentary organic matter and carbonate content using Loss-on-Ignition (LOI) is a very simple, inexpensive analysis. It allows inferences about past lake productivity and sediment sources, and is often used as a means to match different cores from the same lake. Carbon and nitrogen elemental analyses usually provide similar information as LOI. Carbon and nitrogen stable isotopes are used to reconstruct primary productivity (Hodell and Schelske 1998), while ^{15}N is also used as an indicator for past anadromous fish abundances in spawning lakes (Finney et al. 2000). Oxygen ($\delta^{18}O$) and deuterium ($\delta^{2}H$) stable isotopes have applications for paleohydrology (Wolfe et al. 2007). The elemental phosphorus content of sediments can reflect nutrient loading and thus eutrophication, but mobility in the sediments and recycling processes can limit its use as a sole trophic indicator. Heavy metals and other contaminants that enter the lake directly via atmospheric deposition or from the watershed can be measured in the sediments and thus allow reconstruction of a pollution history (Nriago and Rao 1987). In this regard, the rise and decline of leaded gasoline is a well-documented indicator. Some of the common chemical paleolimnological indicators along with their limitations are provided (Table 2).

Table 2. List of Some Common Chemical Indicators

Detailed information pertaining to these and other indicators is contained in Last and Smol (2001-2006).

Chemical Indicators	Properties indicated	Limitations
Phosphorus	Eutrophication	Migration under anoxic conditions
Heavy metals	Pollution from aquatic and atmospheric sources	Diagenesis; Migration of some under anoxic conditions
Trace organics	Pollution from anthropogenic sources	Measurement techniques can be difficult.
Iron and manganese	Redox status in lakes and landscapes.	Not always easy to interpret
Sediment Chemistry (e.g., K, Mg)	Land use changes; anthropogenic influence	Different land use history, local topography and surface hydrology could produce varied results/interpretations by lake and within lake
Ratio of sulfur to carbon	Redox status, trophic status	
Organic matter content (LOI), carbon and nitrogen content (%C, %N)	Productivity, sediment source	
Calcium carbonate	Nature of surrounding soils; degree of soil leaching, climate	
Biogenic silica	Siliceous algae productivity	
Stable Isotopes	Human activity, watershed processes ($\delta^{13}C$; $\delta^{15}N$); productivity ($\delta^{13}C$); trophic dynamics ($\delta^{15}N$) temperature, evaporation / precipitation ($\delta^{18}O$, $\delta^{2}H$)	
Radioactive isotopes	Dating sediment horizons (^{14}C, ^{137}Cs, ^{210}Pb);	Cost; suitable material for isotopic analysis; ^{137}Cs can be mobile in highly organic sediments

2.3.3 Biological indicators

Biological indicators are described by group and are summarized in Table 3.

Table 3. List of Some Common Biological Indicators

Detailed information pertaining to these and other indicators are contained in Last and Smol (2001-2006).

Biological Indicators	Properties indicated	Limitations
Algal and cyanobacterial Pigments	Algal abundance; productivity; extent of diagenesis; zooplankton herbivory; UV radiation	Identification to major algal group only (not species specific)
Diatoms	Lake water transparency (DOC, colour), acidity, salinity, depth, biodiversity, productivity, zooplankton grazing.	Labour-intensive taxonomy
Ostracods	Salinity, temperature, depth, specific ionic composition	Identification usually requires dissection (impossible in fossilized remains)
Chrysophyte scales and cysts	Lake acidity, Lake productivity, salinity, taste & odour problems	For some species counting scales is involved (error in converting scales to cells); sediment assemblages may not reflect actual populations;
Chironomids	Productivity, oxygen status in hypolimnion, temperature, fish presence/absence	Identification mostly to genus level; fewer taxa
Zooplankton/Cladocerans	Food-web structure; eutrophication; lake acidity	Overestimate rare species; abundance of microfossils; not all species preserved equally; ratio planktonic/littoral species
Pollen and spores	Vegetation patterns, climate, chronological markers	Long-distance transport
Plant macrofossils	Local vegetation, ratio littoral to pelagic zone, peat development, wetland ecology	Can be scarce; requires large sample; differential preservation

2.3.3.1 Diatoms

Diatoms (Class Bacillariophyceae) are a group of unicellular algae that is widely used for paleolimnological studies. The cell walls (frustules) are composed of silica and are therefore mostly well preserved in sediments and identifiable to the species level or lower. Diatoms are very diverse and sensitive to different environmental parameters, they react quickly to changing environmental factors, and there is abundant information on ecological optima and tolerances of various species. For these reasons, the diatoms are sensitive and versatile indicators of environmental change. For example, they have been used successfully to reconstruct:

- past climate change near the alpine tree line (Lotter et al. 1999; Karst-Riddoch et al. 2005).
- conditions directly related to climate such as:
  - surface water temp (Pientiz et al. 1995; Wunsam et al. 1995); and
  - ambient air temperature (Lotter et al. 1997; Bigler and Hall 2002; Bigler et al. 2003).
- chemical lake variables such as:
  - pH (e.g., Davis et al. 1994; Charles et al. 1990; Wolfe 2002);
  - alkalinity (Laing et al. 1999);
  - salinity (e.g. Wilson et al. 1997);
  - nutrient concentrations (e.g., Hall and Smol 1996; Lotter et al 1998); and
  - DOC and related UV penetration (Pienitz and Vincent 2000).
- lithology and marine incursions or spray influence (Laing and Smol 2000).

2.3.3.2 Algal Pigments

Algal pigments have been used to reconstruct primary productivity related to different algae groups and ultraviolet (UV) light intensity (Gorham et al. 2001; Leavitt et al. 1997). Newer methods permit the measurement of concentrations of pigments produced by specific algal taxa. A pigment by-product can also give indications of diagenesis, an indication of the extent of preservation. Pigment analysis is very useful in studies of lake eutrophication.

2.3.3.3 Zoological Indicators

Remains of benthic and planktonic invertebrates are commonly used as paleolimnological indicators. Benthic animals, notably chironomids, are excellent indicators of oxygen concentration or frequency of anoxia. Chironomids are influenced by primary production, as they are sensitive to oxygen, water chemistry and substrate condition (Quinlan et al. 2002). Other major application of chironomids in paleolimnology are the reconstruction of past temperature trends (Walker et al. 2003) and fish communities. Fossil zooplankton remains, mostly from cladocerans, have been used to quantitatively reconstruct the historical development in planktivorous fish abundance (Jeppesen et al. 1996, 2002), trophic interactions (Leavitt et al. 1994), acidity (Paterson 1994), as well as trophic state and water clarity (Hann et al. 1994, Bos and Cumming 2003). Studies designed to investigate lake salinization can use ostracod remains because they are sensitive to salinity and ionic composition of water. Ostracods have also been used to infer past climate conditions (Hu et al. 1998). Fish remains, such as scales and otoliths can occasionally be found in sufficient numbers and allow the analysis of fish community structure.

2.3.3.4 Pollen, Spores and Plant Macrofossils

Palynology, the study of pollen and spores from terrestrial vegetation, can be a useful complementary tool for paleolimnological studies. It is mainly used to infer changes in the regional vegetation that can exert a large influence on lake water quality, for example, during major climatic shifts or cultural deforestation (Francis and Foster 2001). Plant macrofossil remains are used to reconstruct changes in local and aquatic vegetation that are important for reconstructing past climate trends (Birks 2003), lake level changes (Dieffenbacher-Krall and Halteman 2000), peatland development (Zimmermann and Lavoie 2001), and floodplain ecology (Wolfe et al. 2005).

2.3.3.5 Quantitative Water Quality Reconstructions

An important development that revolutionized the field of paleolimnology over the past ~20 years is the development and application of the calibration set approach, which allows for quantitative reconstructions of water quality variables (e.g., Agbeti and Dickman 1989; Hall and Smol 1992). The calibration set approach involves sampling surficial sediments and water quality in a set of lakes spanning limnological, vegetation, or climate gradients (e.g., Hall and Smol 1992; Pienitz et al. 1995; Rippey et al. 1997; Wilson et al. 1997). Modern-day relationships between the communities of an indicator organism (e.g. diatoms, chironomids, chrysophytes) and specific limnological variables are determined and a statistical equation (transfer function or inference model) is developed. This transfer function is then applied to the fossil assemblages obtained from sediment cores in order to reconstruct past values of the specific variable (e.g., Hall et al. 1997; Reavie et al. 1995). Canadian examples for transfer functions include diatom models for salinity (Wilson et al. 1997), acidity (e.g., Dixit et al. 2002), total phosphorus (Hall and Smol 1992), and DOC (Fallu and Pienitz 1999) and chironomid-based models for hypolimnetic anoxia (Quinlan et al. 1998).

2.4 Limitations and Solutions

The power of paleolimnological analysis must be backed by an appreciation of its limitations and an understanding of how these limitations can be managed.

2.4.1 Preservation

The varying preservation of the sedimentary record can limit paleolimnological interpretations. For example, in some deep or highly alkaline lakes, only a small portion of the diatom frustules reach the sediment surface because erosional or dissolution processes during settling removes silica from the cell walls and weakens the frustule (Moss 1988). In shallow and well-oxygenated water, disturbance from waves or movement by benthic animals can disrupt the sedimentary column. This could result in mixing of sediments from different age strata and thus a decrease in temporal resolution. However, preservation problems and sediment mixing can be readily identified by an experienced paleolimnologist.

2.4.2 Spatial variability

There may be spatial variability in the sediment record across a lake, particularly in large lakes with complex morphometry (e.g., multiple basins). Also, higher rates of deposition may be recorded adjacent to inflowing streams or in the centre of cone shaped basins (Moss 1988). In this case and depending on the study questions, cores from several places may be required in order to draw a complete picture of lake development, or to examine the response of different basins to external influences.

2.4.3 Modern Analogs and Goodness of Fit

One major assumption of the paleolimnological approach is that the mechanisms controlling indicator response to environmental change have not changed over time and thus indicator values established in the present can be used to infer past conditions. This assumption can be violated when a proxy, for example diatoms, is used to reconstruct one variable, for example temperature, while variations in pH also modulate past community changes (Bigler and Hall 2003). Numerical methods can help identify this problem (Goodness-of-fit analysis, see Birks 1995) and the best solution is the analysis of multiple complementary indicators.

Modern aquatic communities that are used to identify ecological indicator values and fossil assemblages extracted from sediment cores are called “analogs”. Poor, or missing modern analogs can pose a problem in paleolimnological studies, because species with unknown ecology introduce uncertainties to the environmental reconstructions. By calculating similarity coefficients between modern and fossil assemblages, the extent of analog problems can be identified and the reliability of the environmental reconstructions assessed (Birks 1995).

2.4.4 Chronology

An adequate sediment chronology is required to properly link lake events to watershed events or climate records. For the past ~150 years, this is usually well achieved by combined ^{210}Pb and ^{137}Cs analyses, thus, the settlement period in Alberta watersheds is well covered. Exceptions are lakes with extremely high sedimentation rates of inorganic material that dilute radioisotopes to a point where analyses are impaired (e.g., Hall et al. 2004), or lakes with extremely low sedimentation rates where the time resolution is too low to provide precise correlation to watershed events (i.e., arctic and subarctic lakes).

2.4.5 Historical Records

Unless specific watershed disturbance markers can be used, it may be difficult to relate proxy-inferred changes to specific events and time periods. Often, excellent paleolimnological records do not find adequate interpretation because of the lack of detailed historical land-use data for the respective watersheds. However, paleolimnological studies using aerial photographs (Field et al. 1996), census data (Hall et al. 1999) and Traditional Knowledge (Wolfe et al 2006) have demonstrated the great potential of such combined efforts. High-resolution satellite imagery has been used extensively in land-cover classifications (e.g., Komex 2005) and is another potential source of historical land-use information.

3 Paleolimnological Studies In Alberta

Several sources were searched for reports and publications of paleolimnological studies that have been completed in Alberta as summarized in Table 4. While this project attempted to be as thorough and inclusive as possible, it is recognized that there may be additional studies not found during the literature search. In a few cases, paleolimnological studies were found in the literature, but were not available for review in the following synthesis (Section 3.1) and annotated bibliography (Appendix A). Also, it is noted that there are ongoing paleolimnological research activities in Alberta. Reference is made to many of these projects, however, the focus of this report is to compile and review completed paleolimnological studies.

Table 4. Summary of Literature Sources

Source	Details
Blackwell-Synergy Publisher	Publish 835 different journals including Freshwater Biology; Journal of Phycology; Ecological Research; Lake and Reservoir Management
SpringerLink	Publish numerous journals including: Journal of Paleolimnology; Hydrobiologia; Aquatic Ecology; Limnology; Landscape Ecology
NRCC	Publish numerous journals including: Canadian Journal of: Fisheries and Aquatic Sciences; Botany; Environmental Review; Earth Science
Elsevier – Science Direct	Publish numerous journals including: Paleogeography Paleoclimatology Paleoecology; Quaternary Research; Journal of Environmental Management;
American Society of Limnology and Oceanography	Publish journal: Limnology and Oceanography
ISI Web of Science	Keyword Search
Research Labs[1]	Pienitz (ULaval); Smol (QueensU); Leavitt (URegina); Quinlan (YorkU); Schindler (UAlberta); Wolfe (UAlberta); Hall (UWaterloo); Gregory-Eaves (UMcGill), Wolfe (Wilfrid-LaurierU)

[1]*includes academic research labs from Canadian universities that have completed or are presently conducting paleolimnological studies in Alberta*

3.1 Synthesis

The following synthesis of paleolimnological studies in Alberta is based on all available literature compiled from a comprehensive search of the sources listed in Table 4. All reviewed studies are summarized in an annotated bibliography (Appendix A). In addition, Table 5 provides a list of Alberta lakes with paleolimnological records including bibliographic references, length of record, proxy indicators used, and purpose/topic of study.

Table 5. Lakes in Alberta with Completed Paleolimnological Studies

Reference numbers (Ref. No.) refer to corresponding references summarized in the Annotated Bibliography (Appendix A).

Ref. No.	Lake Name	North	West	Ecoregion	Record Length (years)	Indicators	Topic of Study
28,52,40	Baptiste	54° 45'	113° 33'	Boreal	~4600	pollen, diatoms, pigments, geochemistry, LOI, pyrite spherules	stratification patterns, climate change, eutrophication, anoxia, human disturbance
49	Bighorn	51° 36'	115° 50'	Alpine	*na*	pigments	algal production, fish stocking
9	Birch Island Pond	53° 36'	112° 57'	Boreal forest/Apen Parkland Ecotone	1499	pollen, charcoal, geochemistry, LOI	land use and management on vegetation and fire regime; natural vegetation and fire regime; carbon storage
50,52,21	Buffalo	52° 28'	112° 54'	Aspen Parkland	7500	pollen, pigments, geochemistry	hydrology, climate change, lake development, vegetation patterns
13	Buffalo Head Hills B3	57° 03'	115° 59'	Boreal	50	charcoal, pigments	wild fire on phytoplankton
13	Buffalo Head Hills B3	57° 03'	115° 59'	Boreal	50	charcoal	wild fire on phytoplankton
13	Buffalo Head Hills B3	57° 03'	115° 59'	Boreal	50	charcoal	wild fire on phytoplankton
54,56	Chappice	50° 10'	110° 22'	Prairie	7300	diatoms, mineralogy (x-ray diffraction and x-ray fluorescence), pollen, plant macrofossils	climate change, water levels, salinity, hydrogeology
41	Chatwin	54° 15'	110° 51'	Boreal Mixedwood	70	invertebrates	impacts of toxaphene treatment on invertebrates
32,48	Chauvin	52° 41'	110° 06'	Prairie	2000	diatoms, pigments, stable isotopes (□$^{13}C_{organic}$, □$^{13}C_{inorganic}$, □^{15}N)	lake production, diatom species richness, carbon and nitrogen cycling, climate (drought events)

Ref. No.	Lake Name	North	West	Ecoregion	Record Length (years)	Indicators	Topic of Study
45,33	Christina	54° 40'	110° 00'	Boreal Forest	~200	charcoal, diatoms	fire regimes and lake response
19,52	Cooking	53° 26'	113° 02'	Boreal Forest-Parkland	5500	diatoms, pigments, sediment chemistry	climate change, phytoplankton productivity, lake levels
22	Crowfoot	51° 61'	116° 31'	Subalpine	11,000	diatoms, pollen	Holocene vegetation and climate change
52	Eaglenest	57° 46'	112° 06'	BF	12,000	pollen	Holocene vegetation and climate change
52,55	El Pond	53° 38'	112° 51'	BF-Parkland	4000	pollen	vegetation and climate change
44	Elk Island Wetland	52° 04'	113° 27'	Boreal Mixedwood	5600	macrofossils	peat development, climate change
24,52	Fairfax	52° 58'	116° 34'	Foothills	13,000	diatoms, chrysophytes, pollen, pigments	Holocene climate change and lake productivity
25,50,52	Goldeye	52° 27'	116° 12'	Foothills	14,000	diatoms, pollen	Holocene climate change and lake response, paleosalinity
34,49	Harrison	51° 36'	115° 50'	Alpine	*na*	pigments	algal production, fish stocking
17,52,55	Hastings	53° 30'	113° 00'	BF-Parkland	5500	diatoms, pigments, sediment chemistry, pollen	primary productivity, climate change, vegetation patterns
50,52,6	Isle	53° 38'	114° 44'	Boreal Mixedwood	12000	geochemistry, pigments, diatoms	eutrophication, human disturbance
30,51	Kehiwin	54° 14'	110° 55'	Boreal Mixedwood	~300	diatoms, chironomids, pigments, LOI	climate change, mixing regimes, phosphorus concentrations
52,6,15	Lac Ste. Anne	53° 41'	114° 21'	Boreal Forest-Parkland	6,000	diatoms, pigments, sediment chemistry; PAH, metals	eutrophication, human disturbance
35,52,53	Lofty	54° 44'	112° 29'	Boreal Mixedwood	11,000	pollen	climate change and vegetation patterns
37,52	LoneFox	56° 43'	119° 43'	subalpine	10,700	pollen	climate change and vegetation patterns
31	Marguerite	54° 38'	110° 43'	Boreal Mixedwood	2,400	peat macrofossils	peatland development

Ref. No.	Lake Name	North	West	Ecoregion	Record Length (years)	Indicators	Topic of Study
46	Mariana	55° 57'	112° 01'	Boreal Forest	10,000	diatoms, pigments	climate change, acidification
43,16	Mariana Peatland	55° 57'	112° 01'	Boreal Forest	8200	macrofossils	peatland development, fire history
30,51	Marie	54° 38'	110° 18'	Boreal Mixedwood	~300	diatoms, chironomids, pigments, LOI	climate change, mixing regimes, phosphorus concentrations
26,25,50, 32	Moore	54° 31'	110° 31'	Boreal Forest	11,000	diatoms, pollen, pigments, chrysophyte cysts	climate change, vegetation shifts, lake productivity
30,51	Moose	54° 14'	110° 55'	Boreal Mixedwood	~300	diatoms, chironomids, pigments, LOI	climate change, mixing regimes, phosphorus concentrations
14	Muriel	54° 81'	110° 41'	Boreal Mixedwood	>100	diatoms	lake level changes, salinity, water supply, climate change, land use
31	Muskiki	52° 52'	116° 51'	Foothills	9,000	peat macrofossils	peatland development
47	Otasan	57° 42'	112° 23'	Boreal Forest	8,200	diatoms, chrysophytes	climate change, acidification
18	PAD 12	58° 57'	111° 19'	Boreal Forest	110	Diatoms, pigments, isotopes, macrofossils	river regulation and climate change on hydrology and ecology
18,58	PAD 15	58° 56'	111° 29'	Boreal Forest	75	Diatoms, pigments, isotopes, macrofossils, magnetic susceptibility	river regulation and climate change on flood frequency
18	PAD 18	58° 53'	111° 21'	Boreal Forest	140	Diatoms, pigments, isotopes, macrofossils	river regulation and climate change on hydrology and ecology
18	PAD 23	58° 23'	111° 26'	Boreal Forest	180	Diatoms, pigments, isotopes, macrofossils	river regulation and climate change on hydrology and ecology

Ref. No.	Lake Name	North	West	Ecoregion	Record Length (years)	Indicators	Topic of Study
18	PAD 31	58° 29'	111° 31'	Boreal Forest	200	Diatoms, pigments, isotopes, macrofossils	river regulation, geomorphic processes and climate change on hydrology and ecology
18	PAD 37	58° 40'	111° 26'	Boreal Forest	350	Diatoms, pigments, isotopes, macrofossils, pollen	river regulation and climate change on hydrology and ecology
18	PAD 39	58° 28'	111° 10'	Boreal Forest	240	Diatoms, pigments, isotopes, macrofossils	river regulation, geomorphic processes and climate change on hydrology and ecology
18,58	PAD 54	58° 51'	111° 34'	Boreal Forest	50	Diatoms, pigments, isotopes, macrofossils, magnetic susceptibility	river regulation and climate change on flood frequency
18	PAD 8	58° 48'	111° 21'	Boreal Forest	175	Diatoms, pigments, isotopes, macrofossils, magnetic susceptibility	river regulation and climate change on hydrology and ecology
18	PAD 9	58° 46'	111° 19'	Boreal Forest	160	Diatoms, pigments, isotopes, macrofossils	river regulation and climate change on hydrology and ecology
18,59	Peace-Athabasca Delta (PAD) 5	58° 50'	111° 28'	Boreal Forest	300	Diatoms, pigments, isotopes, macrofossils	river regulation and climate change on hydrology and ecology
41	Peanut	54° 01'	114° 21'	Boreal Mixedwood	70	invertebrates	impacts of toxaphene treatment on invertebrates
9	Pen 5 Pond	53° 36'	112° 57'	Boreal forest/Apen Parkland Ecotone	1567	pollen, charcoal, geochemistry, LOI	land use and management on vegetation and fire regime; natural vegetation and fire regime; carbon storage
15	Pigeon	53° 01'	114° 02'	Boreal Forest-Parkland	110	PAH, metals	impacts of coal-fired power plants

Ref. No.	Lake Name	North	West	Ecoregion	Record Length (years)	Indicators	Topic of Study
8,12,10	Pine	52° 04'	113° 27'	Aspen Parkland	4000	Sediment grain size, mineralogy, geochemistry, charcoal	Holocene climate change, paleohydrology, fire regime
7,11	Pine	52° 04'	113° 27'	Aspen Parkland	pre-1900	diatoms, pigments	anthropogenic eutrophication
34	Pipit	51° 36'	115° 50'	Alpine		pigments	algal production, fish stocking
42,39	Rainbow Lake A	59° 48'	112° 10'	Boreal Forest	200	diatoms, biogenic silica, macroscopic and microscopic charcoal, pollen, LOI, geochemistry, sedimentology	trophic status, stratification patterns, climate change, fire history, vegetation patterns
52,55,16	Small Boy	53° 35'	114° 08'	Boreal Forest-Parkland	7300	pollen	fire regimes, vegetation patterns
34,49	Snowflake	51° 36'	115° 50'	Alpine	*na*	pigments	algal production, fish stocking
9	South Pond	53° 36'	112° 57'	Boreal forest/Apen Parkland Ecotone	1665	pollen, charcoal, geochemistry, LOI	land use and management on vegetation and fire regime; natural vegetation and fire regime; carbon storage
29,52	Spring	55° 31'	119° 35'	Boreal Forest	11,700	diatoms, pigments, sediment chemistry, pollen	climate change, vegetation patterns and lake response (productivity)
38,53,16	Toboggan	50° 46'	114° 36'	Subalpine	10,500	pollen	climate change, vegetation patterns
23,27,50,52,15, 16	Wabamun	50° 30'	114° 26'	Boreal Mixedwood	9000?	Pigments, diatoms, PAH, metals, pollen, geochemistry	impacts of coal-fired power plants, climate change, vegetation patterns, primary production
3,16	Wilcox Pass	52° 14'	117° 13'	Subalpine	9600	pollen	climate change, vegetation patterns
36,52	Wild Spear	59° 15'	114° 09'	Boreal Forest	10,200	pollen	climate change, vegetation patterns
30,51	Wolf	54° 41'	110° 57'	Boreal Mixedwood	~300	diatoms, chironomids, pigments, LOI	climate change, mixing regimes, phosphorus concentrations

Ref. No.	Lake Name	North	West	Ecoregion	Record Length (years)	Indicators	Topic of Study
5	Wood Bog	55° 11'	118° 53'	Aspen Parkland	~9,630	aquatic macrofossils (plants and mollusks)	archeological site evidence
37	Yesterday	56° 46'	119° 29'	Subalpine	10,000	pollen	climate change, vegetation patterns

3.1.1 Long-term Climate and Landscape Development

Long-term climate and landscape development since the time of deglaciation has been described for Alberta and western Canada (e.g., Ritchie et al. 1983; Ritchie and MacDonald 1986; Dyke and Prest 1987). General climate since deglaciation (*ca.* 10,000 – 14,000 years BP) has changed from dry and cold, increasing moisture, increasing temperature to the thermal maximum (*ca.* 6000 years BP), after which climate began to cool with increased precipitation and approached modern conditions. Near modern conditions are interpreted for most lakes since approximately ~3000 years ago. These are the general climate trends that influence lake development. However, regional differences are expected due to different climate and vegetation zones as well as relief and soil characteristics.

Records extending to pre-Holocene (i.e.,before the start of the Holocene approximately 9600 BC) were obtained from lakes in the mountains (Crowfoot Lake: Hickman and Reasoner 1997), the foothills (Fairfax, Goldeye Lakes: Hickman and Schweger 1991, 1993), Central Alberta (Eaglenest Lake: Vance 1986), the southern Boreal Forest (Moore Lake: Hickman and Schweger 1993), and the northern Boreal Forest (Spring Lake: Hickman and White 1989). Lakes in the southern region often do not have entire Holocene sedimentary records. As climate in the mid-Holocene became very dry and warm (hypsithermal; *ca.* 8000-6000 years BP), many lakes dried up (e.g., lakes such as Cooking, Hastings, Lac Ste. Anne which are presently shallow lakes in central Alberta), unless they had ground water sources, such as Chauvin and Chappice lakes in the southern part of the province. Lakes, such as Chappice Lake became shallow and saline (Vance et al. 1993). A strong line of evidence for salinity is the concentration of *Ruppia* pollen (a saline indicator plant species). Buffalo Lake, Wabamun Lake, Lake Isle, Moore Lake and Goldeye Lake (Schweger and Hickman 1989) all had *Ruppia* pollen at some time during the Holocene period. Many of the currently deep lakes in central Alberta became shallow and very productive during the thermal maximum period (e.g., Moore and Wabamun lakes).

3.1.1.1 Lakes in Northern Alberta and the Foothills

Lakes in northern Alberta (e.g., Otasan, Eaglenest) and the foothills (e.g., Fairfax, Spring, and Goldeye lakes) did not show such drastic evidence of water level decreases. Instead, evidence of increased acidity and humic substance content suggest that expanding peatlands influenced some of them. Peatlands were rapidly expanding in central Alberta after 6000 years BP (Nicholson and Vitt 1990). Most peatlands in northern Alberta have basal dates older than 6000 years and their development is related to climate (precipitation and temperature, Zoltai and Vitt 1990). Development of permanent wetlands around Spring

Lake *ca.* 5000 years BP appear to have stabilized water levels and altered the phytoplankton community structure (Hickman and White 1989). Otasan Lake in northeastern Alberta became acidic after *ca.* 5000 years BP in response to peatland expansion (Prather and Hickman 2000).

3.1.1.2 Alpine Lakes

Alpine lakes in the Rocky Mountains of British Columbia and Alberta have very similar post-glacial records (Hickman and Reasoner 1994, 1997). Sites on transition zones were found to respond quickly to climate changes (e.g., MacDonald 1987, 1989; MacDonald et al. 1993). There is a strong response to vegetation development and movement of treeline for lakewater chemistry and phytoplankton development.

3.1.1.3 General Water Quality Trends

Where the sedimentary record extends back to lake initiation following deglaciation, evidence suggests that lakes began in a turbid state. This was likely related to high erosion rates from the open landscape during and after the retreat of the ice sheets. Diatom remains, if found during this phase, were scarce and/or badly preserved. Lakes in the foothills may have begun as saline and shallow due to severe dry weather and wind patterns associated with the retreating ice sheet (e.g., Goldeye Lake, 14,000 to 10,000 years BP). The general trend in lake development for the Holocene period is low to moderate productivity (measured as pigment concentration or diatom concentration) in the pre-hypsithermal period, high productivity or saline during the hypsithermal period, and low to moderate productivity in the post-hypsithermal period. The records indicate that many lakes were even more productive during the hypsithermal period than at present.

3.1.1.4 Summary

Interpretations of lake development from these records imply that:

- Alberta lakes respond differently to climate change depending on the region where they are located and their basin morphometry;
- many Alberta lakes are naturally eutrophic; and,
- many lakes have been more productive than today during earlier warm climates and therefore could potentially become more productive in the future with climate warming trends.

3.1.2 Assessment of Recent Water Quality Changes Related to Anthropogenic Influence

For some lakes, there are short core studies that focused on the sedimentary record representing the last ~200 years. Interestingly, these were mainly recreationally important lakes such as Lac Ste. Anne and Lake Isle (Blais et al. 2000), Pine Lake (Blakney 1998), Muriel (Donahue 2006), Baptiste Lake (Manning et al. 1999), and Moose Lake (Köster et al. 2007). Various proxies have been used to describe lake response to anthropogenic impacts, but the most common proxies have been diatom assemblages and pigment concentrations that allowed qualitative reconstructions of primary productivity and nutrient availability (e.g., Blais et al. 2000; Blakney 1998; Charette and Prepas 2003; Köster et al. 2007). There was limited information available on the use of other proxies in short-term Alberta paleolimnological studies. One example is the use of invertebrate fossils to investigate long-term effects of pesticides on lake ecology (Miskimmon and Schindler 1994).

3.1.2.1 General Productivity Trends

Studies indicated that overall lake productivity increased in the 1950's to 1970's in most lakes as compared to earlier in the century or compared to pre-settlement times. Changes in productivity are inferred from the paleolimnological record and are not an examination of trends in surface water quality measurements. To date there has been no comparison of recent fossil records from lakes in settled areas versus non-settled areas. Converted land cover, agriculture, increased number of cottages (associated with increased septic system discharges) and modified/altered surface water flow paths were suggested as possible causes for increased productivity. Results from these short core assessments suggest that lake productivity post-1960's is the highest on record. However, in comparison to productivity estimates during the hypsithermal period, it is obvious that current productivity rates are below the maximum and that they are within the range of natural variability. The important difference between climate-driven eutrophication during the Hypsithermal and recent cultural eutrophication, however, is the pace at which changes occurred. While the former developed over a long time frame, e.g., several centuries, the latter transformation happened within a few decades.

3.1.2.2 Recovery Potential

From the long-term studies, we know that these lakes have recovered from eutrophic states in the past due to reversed climate trends. Similarly, there is the potential for recovery of Alberta lakes that were recently eutrophied due to landscape changes, nutrient saturation of soils following fertilizer application and for potential climate-land-use interactions, etc. The timing of such recovery is largely unknown, and dependent on whether or not the nutrient stressors can be reduced. This merits further study.

3.1.2.3 Land Use - Water Quality Linkages

There were very few studies that examined linkages between recent land use alterations and limnology. A recent study completed on Muriel Lake used a water budget model and diatom-based salinity reconstructions to determine causes of declines in lake level (Donahue 2006). Some other studies related diatom-inferred water quality changes to known disturbances in the watershed (Blakney 1998; Blais et al. 2000; Köster et al. 2007). Ongoing studies using subfossil chironomids in lakes across the Boreal and Great Plains are assessing the relationship between watershed disturbance, bottom anoxia, and phosphorus concentrations, contrasting dimictic and polymictic lakes (Taranu et al. 2007).

3.1.2.4 Summary

This review illustrates that there are relatively few paleolimnological studies that have investigated water quality changes in Alberta lakes related to anthropogenic disturbances over the pre- and post-European settlement period. None of them (except the unpublished work of Köster et al.) has attempted to quantitatively reconstruct phosphorus concentrations, probably mainly because of the lack of a published regional phosphorus inference model. There seems to be a general trend of increased productivity since the 1950s, but there is a lot of unused potential in relating changes in various paleolimnological proxies to detailed documented land-use changes from aerial photographs, census records, or satellite imagery.

4 Recommendations

The review of available paleolimnological literature has illustrated that there have been quite a few long-term studies completed providing a detailed history of Holocene climate and vegetation patterns in most ecoregions of Alberta. They provide a good general understanding of basic lake evolution since the last deglaciation in response to climate change and landscape development. There is, however, only scarce information on short-term lake response to recent land-use and climate change for the various lake types and ecoregions found in Alberta. As outlined above, the paleolimnological approach offers a variety of useful methods to fill this information gap. In addition, paleolimnology can be used to define natural baseline conditions that are needed to develop restoration targets, or assist in environmental assessment studies.

The type of paleolimnological study to choose depends largely on the project scope and questions to be addressed. The following recommendations can be made with respect to the application of future paleolimnological studies for specific lake and watershed management issues in Alberta.

4.1 Watershed Management

The goal of watershed management is to plan and work toward an environmentally and economically healthy watershed to benefit all that have a stake in it. The first stage of developing a sound watershed management plan includes uncovering concerns, gathering data and analyzing information defining challenges/opportunities and developing management objectives. This stage is often complicated by the absence of reliable long-term water quality and/or watershed monitoring data. This information is required to identify changes in water quality, determine the causes of those changes, set realistic remedial targets informed by baseline conditions, predict future changes in water quality, and to develop and implement effective management strategies. When traditional monitoring data are lacking, paleolimnology can provide quality, high-resolution, cost-effective historical records of water quality to address a variety of key lake management issues, such as:

- nutrient enrichment ;
- acidification ;
- climate change ;
- algal blooms ;
- fish habitat ;
- flood and drought cycles;
- species invasion;
- oxygen status; and
- pollution.

Paleolimnology is a recognized science that is commonly used by scientists in universities, government institutions and private industry. As such, paleolimnological analyses have become more readily available for use by lake managers.

For Alberta lakes, paleolimnological studies may be particularly useful for developing lake management plans to address the following management concerns.

4.1.1 Water Supply

Water shortage on the prairies is a major concern and drought-sensitive aquatic ecosystems may need different watershed management than less sensitive sites. Short core studies in a lake of concern can inform about water level changes in the recent past to assess changes under current climate conditions, as was demonstrated at Muriel Lake (Donahue 2006). There is also extensive information on the response of Alberta lakes to a warm and dry period in the past (Hypsithermal, *ca.* 6000 years BP, see literature review). This may provide a good database for assessing how lakes of a certain type in a certain region will respond to climate change. If no study for the region and type of lake is available, a study of the lake's response to the Hypsithermal period may be useful.

4.1.2 Lake Eutrophication and Algal and Cyanobacterial Blooms

The recent record (i.e., last ~200 years) should be analyzed to determine recent water quality trends and responses to land development within the watershed and the timing of the onset of nutrient-related problems. The most useful proxies to reconstruct eutrophication trends are diatoms (potentially involving transfer functions for total phosphorus concentrations). Algal pigments will inform past productivity trends and frequency of blooms of nuisance and noxious algae, such as cyanaobacteria. Assessment of historical land-use development via aerial photographs, satellite imagery, and/or census records should be included where possible in order to link disturbances in the watershed to the inferred lake water quality changes, and thus establish cause-effect relationships. Once important drivers of eutrophication are identified and 'natural' predisturbance conditions are established, management efforts can be targeted most effectively.

4.1.3 Lake Restoration Goals

The objectives of restoration vary considerably depending on the dominating concerns and lake uses (recreation, conservation, drinking water supply), but are often related to water quality (trophic state). However, the natural states of lakes range from oligotrophic to eutrophic and thus reasonable restoration targets need to be established for each individual lake. Intrinsic characteristics of a lake (e.g., lake area, lake depth, watershed area, substrate, slope, vegetation cover, amount of seasonal runoff, land use, etc.) determine natural variability and background nutrient levels. Paleolimnological methods are one of the strongest techniques for determining restoration targets (Battarbee et al. 2005) as they may provide a relatively clear assessment of historical condition of the lake, and thus the potential for restoration.

4.2 Other potential applications

4.2.1 Oil and Gas Operations

Oil and gas operations require a lot of water and thus are often located close to rivers or lakes (e.g., oil sands developments along the Athabasca River, near Fort McMurray). Impacts of water withdrawal and contamination on downstream lakes can be assessed using short-core paleolimnological studies involving paleohydrological indicators and measurements of pollutant concentrations such as polycyclic aromatic hydrocarbons (PAH) or other contaminants in the sediments.

4.2.2 Mining Sites

Together with other tools, paleolimnology can assist environmental assessment and monitoring studies at currently active, closed, or future mining sites. Short sediment cores from lakes where a mining site is proposed or active can provide information on baseline conditions, such as natural metal concentrations, pH levels, nutrient status and biota more quickly than conventional monitoring programs, which may take several years to document a statistically valid baseline. The success of remediation of closed mining sites in terms of lake contaminant levels (e.g., mercury) can be assessed by analyzing metals in short cores at a high resolution. They thus provide details on trends in sediment contamination, which has important implications for assessing health risks related to contaminant levels in lake fish.

4.2.3 River Regulation

Reservoirs constructed for hydroelectric power generation create a variety of concerns, such as water quality (eutrophication, mercury) and modified river flow regime. Paleolimnological studies can assess water quality changes in reservoirs over time. Paleohydrological studies in flow-through lakes or lakes adjacent to regulated rivers can provide background information on natural hydrological variability and thus assess the impact of river regulation (Hall et al. 2004). This can be valuable in assessing the relative roles of climate and impoundment in hydrological responses.

5 Conclusions

Watershed management involves the evaluation of past water quality and quantity and related driving factors. At present, this information can only be inferred in detail from paleolimnological records. Paleolimnological techniques can be used to investigate the sensitivity of aquatic ecosystems to drought, to establish cause-effect relationships between land use and water quality changes, to monitor pollution, and to define realistic restoration goals.

Most of the paleolimnological work completed in Alberta has focused on post-glacial lake development (i.e., after lake formation in the plains). If categorized by lake type and region, these studies can be used to assess potential responses of lakes to climate change. In contrast, few studies have examined changes in lake water quality and quantity since European settlement and there is limited information available on the links between watershed land use and lake water quality. However, studies completed so far have demonstrated the usefulness of paleolimnology to assess pre-disturbance lake water quality and quantity.

This report provides recommendations on how paleolimnological studies can help to fulfill the needs of watershed and lake management in Alberta. There is a starting point of information available on Alberta lakes, but future paleolimnological studies will be helpful in solving a variety of water management issues.

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Appendix A

Annotated Bibliography of Paleolimnological Studies Conducted in Alberta

No. Reference

1 **Beaudoin, A.B. 1993. A compendium and evaluation of postglacial pollen records in Alberta. Can. J. Archae. 17:92-112.** This paper provides a summary of Holocene paleoenvironmental conditions in Alberta based on previously published pollen records. General summaries of the types of paleolimnological information collected, and a list of study locations are provided, but actual data was not included. Even though there is a large list of sites from the documented studies, there was little data and information available for many areas of the province.

2 **Beaudoin, A.B. 1998. Recent environmental change in the southwestern Canadian Plains Can. Geographer 42:337-353.** This paper provides an extensive review of climate and landscape changes in the subhumid southwestern Canadian Plains for the past millenium as reconstructed from previous paleolimnological studies and treering records. Comparison of recent 20th-century changes to the climate of the past millennium suggested that anthropogenic landscape change from grasslands to ranchland and cropland has heightened vulnerability to climatic fluctuations, especially drought. Based on the findings of this review, it was concluded that the sustainability of Prairie agriculture depends on adaptation to the amplitudes of climatic change and variability evident in Alberta proxy records.

3 **Beaudoin, A.B. and R.H. King. 1990. Late Quaternary vegetation history of Wilcox Pass, Jasper National Park, Alberta. Palaeogeogr. Palaeoclimat. Palaeoecol. 80:129-144.** A core was extracted from a bog site within the alpine ecoregion in Wilcox Pass, JNP, Alberta. The core was analyzed for pollen and radiocarbon-dated. The core dates to before 9,600 years BP (additional, low organic content material was present below this and made it impossible to provide radiocarbon dates). Pollen assemblages prior to 9,600 years BP were typical of most early post-glacial records and dominated by *Artemesia*. Forests developed around the site still prior to *ca.* 9,600 years BP. There was evidence that temperatures warmer than present developed. After the deposition of Mazama tephra (*ca.* 6,800 years BP) forests expanded to higher elevations. After *ca.* 2,800 years BP, climate began to cool and treeline receded to lower elevations. This record showed similar environmental trends to records from other sites in the Canadian Rocky Mountains.

4 **Beaudoin, A.B. and G.A. Oetelaar. 2003. The changing ecophysical landscape of southern Alberta during the late Pleistocene and early Holocene. Plains Anthropologist 48:187-207.** This paper reviews competing models of Late Wisconsinan glacial advance, coalescence and retreat as they pertain to early human occupation of the interior of western Canada. Previously published paleolimnological evidence on the developing ecophysical landscape of southern Alberta is described for the late Pleistocene and early Holocene, which supports a model of rapid deglaciation sometime around 12,000 years ago with an equally rapid colonization of the recently deglaciated landscapes by plants, animals, and people.

5 **Beaudoin A.B., M. Wright and B. Ronaghan. 1996. Late quaternary landscape history and archaeology in the 'ice-free corridor': Some recent results from Alberta. Quatern. Internat. 32:113-126.** This paper provides preliminary results of the ‘First Albertans’ project that was initiated in 1986 by the Archaeological Survey, Provincial Museum of Alberta. The project used paleogeographical evidence from the ‘Ice-Free Corridor' in western Alberta as a tool to search for archaeological evidence of Late Wisconsinan/Early Holocene human occupation. In this paper, the authors provide a detailed history of climate and vegetation patterns in the ‘Ice-Free Corridor’ (~12,000-9,000) based on published paleogeographical studies, with a focus on two archeological sites in the Grande Prairie and James Pass areas. In addition, the developmental history (since *ca.* 9,630 14C years BP) of Wood Bog (near Grande Prairie) was inferred from aquatic macrofossils (plants and mollusks). It was concluded that paleogeographical evidence is useful to formulate

archaeological search strategies. Until publication of this paper, the approach had resulted in the discovery of six significant Paleo-Indian sites in the region, including the two sites detailed in the paper (Saskatoon Mountain, and the James Pass Meadow Complex). No evidence had yet been found to that confirms human occupation of the corridor before about 11,000 years BP.

6 **Blais, J.M., K.E. Duff, D.W. Schindler, J.P. Smol, P.R. Leavitt and M. Agbeti. 2000. Recent eutrophication histories in Lac Ste. Anne and Lake Isle, Alberta, Canada, inferred using paleolimnological methods. Lake and Reserv. Manage. 16(4):292-304.** This study examined the recent sedimentary record from two lakes in central Alberta to determine causes of their eutrophic conditions. Results indicated that these lakes are naturally eutrophic. They have been eutrophic since before major human settlement and alteration of the catchment. However, both lakes have become increasingly eutrophic after the 1960s as more of their watersheds were developed for urban and agricultural purposes. The predominance of Chironomidae head capsules indicated periods of anoxia in the hypolimnion. There have been further high abundances of eutrophic indicator diatom species and in Lac Ste. Anne, there has been an increase in the concentration of pigments from filamentous cyanobacteria. The rarity of reducible phosphorus in the sediments provided further evidence of periodic anoxia in the deep water zone. Lac Ste. Anne showed the greatest change during the 1960s and 1970s. There were increases in the abundance of hyper-eutrophic diatoms, sediment phosphorus and algal pigments. In contrast, changes in Lake Isle were more gradual. Reduction in anthropogenic activities and uses of the catchment would make improvements in water quality however, both lakes would still be eutrophic due to natural conditions.

7 **Blakney, S.D. 1998. Diatoms as indicators of eutrophication in lakes, Pine Lake, Alberta, Canada: A case study. Master of Science Thesis. Department of Biological Sciences, University of Alberta, Edmonton, Alberta.** Short cores were extracted from the north, central and south basins of Pine Lake, Alberta and analyzed for diatom composition and pigment concentration in order to interpret lake development in recent years. Diatom assemblages and concentrations were similar in multiple cores taken within the same sub-basin. In addition, diatom assemblages were similar between the different sub-basins. Diatom assemblages indicate that the lake was eutrophic pre-1900, became mesotrophic between *ca.* 1926 to 1953 and then reversed back to eutrophic. The lake has existed in a eutrophic state since the 1950's. Water quality drastically decreased between 1978 and 1984 and was likely a result of increased phosphorus inputs from agricultural runoff and septic systems. Anthropogenic stresses on the lake catcment have altered lake productivity as evidenced by the diatom and pigment sedimentary records.

8 **Campbell, C. 1998. Late Holocene Lake Sedimentology and Climate Change in Southern Alberta, Canada. Quat. Res. 49:96-101.** Climate changes are reflected in the size distribution of grains in lake sediments. Fine-grained sediments should be removed from lakes by stream outflow. As stream outflow decreases, the relative amount of fine-grained sediments retained and deposited within the lake increases. On the other hand, course sediments are brought into lakes by inflowing streams. The expected results are coarse, clay-deficient sediments during periods of high streamflow and fine, clay-rich sediments during low flow. The analysis of sediment grain size provides a non-biological proxy to infer climate change. Major Holocene climatic events including the Little Ice Age and the Medieval Warm Period were reflected in the grain-size record from Pine Lake. In addition, more recent historic climate fluctuations were reflected in the sediment record.

9 **Campbell I.D. and C. Campbell. 2000. Late Holocene vegetation and fire history at the southern boreal forest margin in Alberta, Canada. Palaeogeogr. Palaeoclimatol. Palaeoecol. 164:263-280.** Pollen and charcoal in sediment cores from three shallow ponds spanning the the Aspen Parkland/Boreal Forest transition in Elk Island National Park, Alberta, Canada, were used to reconstruct vegetation patterns and fire regimes in response to climate change and to human disturbance. Post-disturbance fire activity was shown to have declined likely due to land clearance for agriculture, but also due to the extirpation of bison and related expansion of less fire-prone aspen (Populus tremuloides), and managed fire suppression. Pollen evidence suggests that pre-human impact fluctuations in fire regime may be due to changes in hydrology (e.g., declining groundwater levels during the Medieval Warm Period). During this time, substantial areas of shrub birch (Betula glandulosa) are inferred to have been replaced with the less fire-prone aspen causing a decline in fire frequency and/or severity despite warmer and drier climates. The authors suggest that these results have implications for management practices within the park to maintain 'natural' conditions.

10 **Campbell I.D., C. Campbell, M.J. Apps, N. Rutter and A.J. Bush. 1998. Climatic periodicities of 1440 and 1540 years. Geology 26:471–480.** A 4,000-year paleoclimate proxy record based on sediment grain size from Pine Lake, AB was used to test periodicities that may explain Holocene climatic events including the Little Ice Age (*ca.* A.D. 1400–1850), the Medieval Warm Period (*ca.* A.D. 800–1250), and the Younger Dryas (*ca.* 11,000 B.C.). Results indicated strong climatic periodicities of ~1,500 years and several weaker century- to millenial-scale periodicities that explain, in part, these major climatic events. By projecting the observed periodicities into the future, the authors suggested that even in the absence of anthropogenic climate forcing, a natural warming trend would continue until *ca.* A.D. 2400.

11 **Campbell, C., I.D. Campbell, C.B. Blythe and J.H. McAndrews. 1994. Bison extirpation may have caused aspen expansion in western Canada. Ecography 17:360–362.** Previously published records of vegetation shifts within the present aspen parkland region of the northern North American grassland were used to determine the impacts of Plains bison extirpation on expansion of aspen (*Populus tremuloides*). Bison are thought to have inhibited growth of aspen by browsing, wallowing, trampling and toppling. Historical and palynological records indicated that aspen populations have expanded over the past century and that the expansion occurred mainly after the near extinction of bison but before European homesteading and subsequent fire suppression in the late 1800s. Therefore, the authors hypothesize that the 'natural' cycle of grassland fire, aspen suckering, bison activity, and return to grassland was interrupted by the removal of bison, allowing aspen expansion. It is also suggested that the recent expansion of aspen may continue with current warming trends thereby creating moister, cooler microhabitats that might allow for the southward advance of boreal species into the area.

12 **Campbell, I.D., W.M. Last, C. Campbell, S. Clare and J.H. McAndrews. 2000. The late Holocene paleohydrology of Pine Lake, Alberta: a multiproxy investigation. J. Paleolim. 24:427-441.** Interpretations were made about changes in anoxia, water flow in the surrounding catchment, and changes in the fire regime. Evidence indicated that there has been increasing available moisture in the late Holocene. Anoxia conditions increased and there was a shift in sulphur deposition from gypsum to pyrite. The shallow aquifer around this lake is rich in magnesium. There was a decrease in the flux of magesium rich water into this lake. It was inferred that the development and expansion of the aspen forest reduced water flow through this shallow aquifer thus reducing influx of magnesium into the lake. Charcoal evidence suggested that the fire regime changed from frequent grass fires (low-biomass) to infrequent under-story fires (high-biomass). This also encouraged the development and expansion of the aspen forest. The different proxies used in this study are sensitive to different types of change and can provide similar information. Mineral composition and sediment geochemistry can provide evidence for interpretations of water level and redox potential (anoxia) while grain size analysis can provide evidence for interpretations of hydrological balance.

13 **Charette, T. and E.E. Prepas. 2003. Wildfire impacts on phytoplankton communities of three small lakes on the Boreal Plain, Alberta, Canada: a paleolimnological study. Can. J. Fish. Aquat. Sci. 60:584-593.** The response of the phytoplankton community to wildfire in three lakes on the Boreal Plain was investigated. Short sedimentary records (the last ~50 years) extracted from each lake (shallow lake, deep headwater lake, deep non-headwater lake) were analyzed for pigment concentration using HPLC. Presently the shallow lake is eutrophic while the two deep lakes are mesotrophic. The shallow lake had the strongest response to wildfire with increased concentrations of B-carotene (common pigment), cyanobacterial pigment and chlorophyte pigment. The deep headwater lake did not show immediate post-fire changes but rather a 4-year delayed response. Finally, the deep but non-headwater lake showed little response to fire. Cyanobacterial blooms in shallow Boreal Plain lakes are very likely to occur as a post-fire event.

14 **Donahue, W.F. 2006. Historical interpretation of water supply to Muriel Lake in the 20th Century. Prepared for the Lakeland Industry and Community Association. Freshwater Research Ltd., Edmonton, AB.** This study investigated recent changes in water supply to Muriel Lake, Alberta by using a long-term, model-based reconstruction of water supply and by a paleoecological reconstruction of past salinity changes. The objective was to determine if current lake levels were similar to past lake levels and to determine if water salinity increases could be linked to climate or landuse changes. A model to predict surface water runoff from the main contributing creek was developed and used to predict surface water supplies to Muriel Lake and corresponding lake levels. Current lake levels in Muriel Lake are significantly lower than in the preceding 50-100 years and even compared to the 1930's to 1950's. Lake water salinity was predicted from sedimentary diatom record and salinity transfer functions. Lake water salinity remained low and constant until the 1990's. The increase in salinity within the last two decades increased more than would be expected from declines in water volume and evapoconcentration of salt in the lake. Based on the two models, water level decreases in Muriel Lake are attributed to climate change and landuse changes that have altered the flow of water to the lake.

15 **Donahue, W.F., E.W. Allen and D.W. Schindler. 2006. Impacts of coal-fired power plants on trace metals and polycyclic aromatic hydrocarbons (PAHs) in lake sediments in central Alberta, Canada. J. Paleolimn. 35:111-128.** Short sediment cores were extracted from three lakes in central Alberta and samples were analyzed for trace metals and polycyclic aromatic hydrocarbons (PAH). These analyses were done to determine the contributions of coal-fired plants to contaminant loadings in local lakes. There are four power plants along the shoreline of Wabamun Lake, Lac Ste. Anne and Pigeon Lake (20km north and 70km south, respectively) that were chosen to determine areal extent of metal and PAH deposition in the region. Sediment concentrations of trace metals, mercury and PAH have increased in Wabamun Lake since the 1950s (1.2-4-fold, 6-fold, 730-1100 ug/m2/yr, respectively). In contrast these contaminants have increased at a lower rate in Lac Ste. Anne and at the lowest rate in Pigeon Lake. There is evidence of direct loading into Wabamun Lake, but also aerial transport to lakes within the region. Lakes closer to the contaminant source are impacted more than lakes further away. In conclusion, without use of pollution abatement technology, usage and increase in the coal-burning industry will result in increased contaminant deposition.

16 **Flannigan, M., I. Campbell, M. Wotton, C. Carcaillet, P. Richard and Y. Bergeron. 2001. Future fire in Canada's boreal forest: paleoecology results and general circulation model - regional climate model simulations. Can. J. For. Res. 31:854-864.** Simulations produced by the general circulation model (GCM) suggest that the earth's climate will be 1 to 3.5°C warmer by AD 2100. It is believed that this will increase the frequency, intensity and size of forest fires. The Canadian Forest Fire Weather Index was used to simulate future forest fires. It predicted an increase in fires in most of Canada but with significant regiona variability. The interval around 6000 years BP is generally

accepted as the Holocene thermal maximum. Interpretations of lake ecology, climate and fire intensity from that time period are often used as analogues for a future climate. Fire Weather Indicies from both the 6000 years BP and 2 x CO2 simulations agree with the spatial pattern of charcoal anomalies at 6000 years BP except in Western Canada, especially Alberta. The simulations suggest there will be a decrease in fire frequency while the charcoal data show an increase at 6000 years BP. The discrepancy is likely due to inadequate representation of data in the general climate models. An altered fire regime may be more important than climate on the migration, substitution and extinction of species. For example, increased fire frequency may increase the conversion of boreal forest to aspen parkland and aspen parkland to grassland in Alberta.

17 **Forbes, J.R. and M. Hickman. 1981. Paleolimnology of two shallow lakes in central Alberta, Canada. Int. Revue ges. Hydrobiol. 66:863-888.** This paper describes the paleolimnological records from two lakes in central Alberta. It is a summary of the Masters Thesis of the same title submitted to the University of Alberta in 1980. The cores were analyzed for pigments, organic matter and sediment chemistry (nutrients and ions). Hastings Lake is very sensitive to minor shifts in the balance between precipitation and evaporation. The record in Hastings Lake extends back to *ca.* 5555 years BP. Sediment deposition rates were initially high but have declined over time. After *ca.* 4400 years BP, lake levels rose, the north and central basins were joined and lake productivity increased. Productivity has never been nutrient limited. Lac Ste. Anne is located near the Boreal Forest-Parkland transition zone. Cores from this lake date back to *ca.* 6500 years BP. Productivity in Lac Ste. Anne has changed very little.

18 **Hall, R.I., B.B. Wolfe, T.W.D. Edwards, T.L. Karst-Riddoch, S.R. Vardy, S. McGowan, C. Sjunneskog, A. Paterson, W. Last, M. English, F. Sylvestre, P.R. Leavitt, B.G. Warner, B. Boots, R. Palmini, K. Clogg-Wright, M. Falcone, P. van Driel, and T. Asada. 2004. A multi-century flood, climatic and ecological history of the Peace-Athabasca Delta, Northern Alberta, Canada. Final Report. BC Hydro, Burnaby, Canada. 163 pp.** The ecosystem of the Peace-Athabasca Delta (PAD) is believed to be strongly dependent upon periodic flooding of the two main rivers (Peace and Athabasca rivers). Paleolimnology was used to determine the relative influence of Peace River flow regulation and natural processes (climate variability and geomorphic changes) on the hydrology and ecology of the PAD. Sedimentary records were extracted from lakes outside the most extreme flood event (n=1), oxbow lakes within the Peace River flood zone (n=2), closed and restricted-drainage basin lakes in the Peace (n=5) and Athabasca (n=3) sectors of the delta. Sediments were analyzed for physical (mineralogy, grain size and magnetic susceptibility), chemical, isotopic (^{15}N, ^{13}C, ^{18}O, ^{2}H), and biological indicators (diatoms, pigments, macrofossils) as a way to identify flood events and hydro-ecological conditions. Hydro-ecological conditions were inferred from the proxy records based on relationships between sedimentary proxies and modern hydrology and water quality developed from more than 60 floodplain lakes in the PAD. Data suggest that flood frequency began declining in the early 1900's. There was no evidence to suggest significant decreases in intensity or frequency of floods post-1968 with the construction of the W.A.C. Bennett Dam at the head of the Peace River for hydroelectric power production. Research on the hydro-ecology of the PAD is ongoing (R.I. Hall, University of Waterloo, B.B. Wolfe, Wilfrid Laurier University, T.W.D. Edwards, University of Waterloo) and forms the basis of several post-graduate research projects. Results contained in this study have been published or are in preparation for publication in peer-review scientific journals.

19 **Hickman, M. 1987. Paleolimnology of a large shallow lake; Cooking Lake, Alberta, Canada. Arch. Hydrobiol. 111:121-136.** The paleolimnological record of Cooking Lake (113^{o} 02' W; 53^{o} 26' N), in the Boreal Forest-Parkland transition region, extends to about 5,200 years ago. A long core sampled on a course scale was used for this study (sub-samples taken every 10-cm). Samples were processed for diatoms, sedimentary pigments (chlorophyll *a* and carotenoids), and sediment chemistry (phosphorus and ions). The lines of evidence were complementary. Cooking Lake began as an unproductive lake with high erosional input. Lake levels were inferred to be deeper in the early years but phytoplankton productivity was hampered by high turbidity. By around 2,900, present day vegetation had established around the lake and the lake entered a productive phase. The next major change was evident at about 50 cm (after 1,600). Planktonic taxa dominance dropped off drastically suggesting a major change in water levels. There were only two radiocarbon dates available for this sediment core so interpretations on precise timelines are not possible. Short cores that are sampled on a more regular frequency coupled with more dates would be required to extrapolate recent changes in this lake.

20 **Hickman, M. and D.M. Klarer. 1981. Paleolimnology of Lake Isle, Alberta, Canada - (including sediment chemistry, pigments and diatom stratigraphy). Arch. Hydrobiol. 91:490-508.** Cooking Lake is a shallow eutrophic lake of central Alberta. The paleolimnolgy was examined through chemistry, pigments and diatom analyses. Fluctuations in calcium, iron and carbonate indicated that the lake was shallower than at present during the hypsithermal period. The lake was most productive during this period. Benthic species initially dominated the record but they were quickly replaced by planktonic species. After deposition of ash from Mount Mazama, benthic (epipelic) species dominated. Little change in the paleolimnological record was noted during the post-hypsithermal period.

21 **Hickman, M., E. Bombin and M. Bombin. 1983. A paleoenvironmental history derived from a core taken from Buffalo Lake, Alberta. Report Prepared for Alberta Environment.** A long sediment core was retrieved from Buffalo Lake, Alberta and analyzed for pollen, pigments and sediment chemistry in order to describe lake development in relation to landscape development. The sedimentary record extends to 7400 years. Vegetation that presently surrounds the lakeis predominantly pine. From about 6700 to 3175 years BP vegetation was non-arboreal and comprised mainly sedges, grasses, and Ruppia (a saline water indicator species). This corresponds to the Hypsithermal interval. During this time the lake was most productive, shallow and saline with high evapotranspiration. Post *ca.* 3175 years BP, climate became gradually wetter and erosion around the lake increased (more sodium, magnesium and potassium in the sediments) and lake production decreased. Primary production increased again from *ca.* 1500-2000 years BP to present. The long paleolimnological record of this lake is similar to the other lakes in central Alberta.

22 **Hickman, M. and M.A. Reasoner. 1997. Late Quaternary diatom response to vegetation and climate change in a subalpine lake in Banff National Park, Alberta. J. Paleolim. 20:253-265.** Sedimentary diatom composition and abundance were analyzed in subalpine Crowfoot Lake (116^{o} 31' W; 51^{o} 61' N),Banff National Park to assess changes in diatom production with climate change and vegetation shifts since ~11,000^{14}C years BP. Diatoms first appeared in the sedimentary record at ~10,000 ^{14}C years BP likely due to delayed limnological development between deglaciation and the advance of Crowfoot glacier during the Younger Dryas. Diatom production increased rapidly with expansion of Pinus-dominated forestsaround the lake and as the climate became warmer reaching maximum productivity before the Mazama tephra (*ca.* 6600 years BP). Diatom productivity decreased coincident with the transition to cooler and wetter climates of the Neoglacial beginning ~4,100 to 3,500 ^{14}C years BP.

23 **Hickman, M. and C.E. Schweger. 1991. Oxcillaxanthin and myxoxanthophyll in two cores from Lake Wabamun, Alberta, Canada. J. Paleolim. 5:127-137.** The paleolimnological record of Lake Wabamun (114^{o} 26' W; 50^{o} 30' N) was determined through the analysis of two post glacial sediment cores. One core was retrieved from deep water (west end of the lake) and was identified as "Seba" and the other core was retrieved from shallow water (east end of the lake) and identified as "Moonlight Bay". These cores provide complimentary information to describe the post-glacial development of the lake. Sediments were analyzed for blue-green algal pigments and diatom composition. The core from the deepwater station was a longer record (more sediment, early basal date) than the shallow water core. Planktonic diatoms were predominant at the deepwater station, but their relative abundance fluctuated over the last ~2,500 years. At the shallow water station, planktonic diatoms were an important part of the community initially but dropped out after ~6,800 years ago. Other lines of evidence suggest that there was a shift in dominance to blue-green algae. Benthic diatoms appear as the dominant algal group after 5000 years ago. Maximum primary productivity is suggested in the mid Holocene period.

24 **Hickman, M. and C.E. Schweger. 1991 A palaeoenvironmental study of Fairfax Lake, a small lake situated in the Rocky Mountain Foothills of west-central Alberta. J. Paleolim. 6:1-15.** The sedimentary record of Fairfax Lake, west-central Alberta, was analyzed for diatoms, chrysophytes, pollen and pigments to determine the paleoenvironmental history. The record spans *ca.* 13,200 years. The landscape was initially open and tree-less but was replaced by pioneering parkland vegetation *ca.* 11,600 years BP and then by spruce forest *ca.* 10,100 years BP. Pine trees appeared *ca.* 7,800 years BP. Maximum chlorophyll concentrations occurred between *ca.* 11,255 to 7000 years BP corresponding to the warm Holocene period. The lake was inferred to be eutrophic during this time period but then shifted to the present status as oligotrophic to mesotrophic status. Lake water levels have fluctuated over this record. Catchment vegetation responded directly to Holocene climate changes while the lake and its biota have responded directly and indirectly to climate changes.

25 **Hickman, M. and C.E. Schweger. 1993. Late glacial - early Holocene palaeosalinity in Alberta, Canada - climate implications. J. Paleolim. 8:149-161.** This paper compared paleolimnological records from two lakes that are currently in different ecoregions. Diatoms and pollen were analyzed from both lakes to infer lake response to post-glacial climate changes and paleosalinity. Goldeye Lake is located in the Rocky Mountain Foothills. This lake was saline from its inception (prior to *ca.* 14,500 years BP) until *ca.* 10,400 years BP. Moore Lake is located in east-central Alberta at the southern end of Boreal Forest zone. The lake record dates to at least 11,300 years BP. The lake began as a freshwater lake but became saline between *ca.* 9,000 to *ca.* 6,000 years BP. Factors influencing the salinity of these lakes differed. Goldeye Lake was saline because it was surrounded by glacial ice and cut off from moisture sources until significant ice had receded. Moore Lake was under the influence of high summer insolation induced by orbital fluctuations. Goldeye Lake was influenced by climate, wind and precipitation patterns during deglaciation while Moore Lake was influence by early to mid Holocene drought conditions that increased in severity in an easterly direction.

26 **Hickman, M. and C.E. Schweger. 1996. The Late Quaternary palaeoenvironmental history of a presently deep freshwater lake in east-central Alberta, Canada and palaeoclimate implications. Palaeogeogr., Palaeoclimat., Palaeoecol. 123:161-178.** This paper reviews the complete postglacial record from Moore Lake in east-central Alberta. Moore Lake is a small, head-water lake with limited residential shoreline development. The paleoenvironmental record was interpreted through analysis of pollen, diatoms, chrysophytes and sedimentary pigments. Earliest lake records (pre 11,500 years BP) indicate that the lake was initially shallow and the surrounding catchment was predominantly treeless. Boreal forest characteristic tree species quickly developed around the lake resulting in a shift to eutrophic indicator species. The lake has shown transitions between fresh water periods and saline periods while overall paleoproduction was inferred to be similar throughout the record. Diatoms accounted for high productivity during the fresh water periods while blue-green algae accounted for high productivity during the saline water periods.

27 **Hickman, M., C.E. Schweger and T. Habgood. 1984. Lake Wabamun, Alberta: a paleoenvironment study. Can. J. Bot. 62:1438-1465.** Two long sediment cores were extracted from Lake Wabamun. One core was taken from a deep water station (Seba) and the other core was taken from a shallow water station (Moonlight Bay). The Seba core was long (1554 cm) and

represents the entire Holocene period while the Moonlight Bay core was slightly shorter (1067 cm) and covered a slightly shorter time period. Sediments were analyzed for diatoms, pollen, pigments and chemistry. Mazama tephra was evident in both cores (*ca.* 6600 years BP). The evidence suggests that Moonlight Bay may have been dry in the early lake stages. Three zones of production were inferred for the post-glacial history of Lake Wabamun. Moderate production occurred shortly after initiation until *ca.* 6600 years BP. Forests had developed in the catchment area. Minimum production occurred in the middle zone (*ca.* 6600 to 5000 years BP). Lake Wabamun responded to the dry Hypsithermal period and experienced decreased water levels and saline conditions as indicated by abundant *Ruppia* pollen. Increased fire activity and instability in the catchment were inferred for this time period corresponding to higher erosional intensity. Maximum primary production occurred in the last 5000 years with an increase in production during the last 1,000 years. This lake has been productive for many thousands of years.

28 **Hickman, M., C.E. Schweger and D.M. Klarer. 1990. Baptiste Lake, Alberta - A late Holocene history of changes in a lake and its catchment in the southern Boreal forest. J. Paleolim. 4:253-267.** Cores were extracted from the southern, deeper basin of this lake. The sedimentary record spans ~4,600 years. Interpretations were based on analysis of diatoms, pollen and organic matter. High but irregular sedimentation rates were inferred. Changes in the presence of pyrite spherules suggested that deoxygenation of the water column occurred irregularly and intensity of anaerobic conditions varied. There is evidence that the lake changed from incomplete water column mixing (meromixis) to complete mixing The lake has become more eutrophic over time but most noticeably after complete lake mixing began.

29 **Hickman, M and J.M. White. 1989. Late Quaternary palaeoenvironment of Spring Lake, Alberta, Canada. J. Paleolim. 2:305-317.** The post-glacial record of Spring Lake (55^{o} 31' N; 119^{o} 35' W) was determined through analysis of one sedimentary core. Diatoms, pollen, sedimentary pigments and sediment mineralogy were examined. The complete record, dating to 11,700 years BP, was retrieved from this lake. This lake is in north-west Alberta in the Boreal Forest ecoregion, but close to the northern most extent of Aspen Parkland. Changes in diatoms and sediment chemistry coincide with regional climatic change. Benthic diatoms dominate most of this record. The pigment record indicates that highest production occurred after deglaciation and only within the last few hundred years has production increased again. Paleoproduction of this lake is different from lakes in central Alberta. Many of those lakes had peak production during the warm mid-Holocene.

30 **Köster, D. and R. I. Hall, 2007. Historical water quality dynamics in naturally eutrophic Albertan boreal plain lakes: Does land-use matter? Department of Biology, University of Waterloo, Ontario. Presented at the Society of Canadian Limnologists (SCL), Montreal.** This study identifies the timing and extent of past changes in the water quality and quantity of several lakes in the Beaver River Basin, and relates them to possible causes such as climate variability, land-use, and water use. Additionally, baseline conditions are identified to inform goal setting for water management decisions. Fossil remains of diatoms (Bacillariophyceae), organic matter and carbonate content were analyzed in ~40-cm long sediment cores from three lakes with differing degree of land use in the respective watersheds. Diatom assemblages were remarkably similar between lakes and indicated that the lakes had been eutrophic since pre-settlement times. Implications of these results for watershed management and restoration are discussed for lakes in the Cold Lake region.

31 **Kubiw, H., M. Hickman and D.H. Vitt. 1989. The developmental history of peatlands at Muskiki and Marguerite lakes, Alberta. Can J. Bot. 67:3534-3544.** Two lake and peatland complexes from different ecoregions in central Alberta were cored to make inferences about peat development and climate over the Holocene period. Muskiki Lake is in the Rocky Mountain foothills ecoregion. Peat accumulation began *ca.* 9000 years BP. Peat accumulation at Marguerite Lake, in the dry Mixedwood section of the Boreal Forest ecoregion of eastern Alberta, began *ca.* 2400 years BP.

Macrofossils were identified to determine peatland succession. The mid-Holocene warm period likely delayed peatland development in eastern Alberta relative to western Alberta. Peatland development and succession within a complex can be influenced by local factors and site specific factors such as fire, damming, topography and drainage. Peat accumulation within one site can be by both terrestrialization and paludification.

32 **Laird, K.R., B.F. Cumming, S. Wunsam, J.A.Rusak, J.R. Oglesby, S.C. Fritz and P.R. Leavitt. 2003. Lake sediments record large-scale shirts in moisture regims across the northern prairies of North America during the past two millennia. PNAS. 100(5): 2483-2488.** Short, high-resolution, cores were taken from six lakes from the northern prairies of North Ameri*ca.* Chauvin Lake in southern Alberta was used in this study. Diatom based transfer functions for salinity were used to make inferences in lake sensitivity and response to drought. All lakes exhibited shifts from wet to dry or vice versa. Lakes in the northern United States underwent pronounced changes between 700 to 1000 years ago while lakes in the southern Canadian prairies underwent changes between 1200 to 1500 years ago. It was suggested that changes in these lakes are due to alterations in the shape and location of the jet stream and associated storm tracks.

33 **Laird, L.D. and I.D. Campbell. 2000. High resolution palaeofire signals from Christina Lake, Alberta: a comparison of the charcoal signals extracted by two different methods. Palaeogeogr. Palaeoclimatol. Palaeoecol. 164:111-123.** Short sediment cores were extracted from Christina Lake in the Boreal Forest region of Alberta and analyzed for charcoal fragments. A charcoal curve (charcoal concentration) was extracted and compared to the known fire history near the lake since 1900. The analysis of charcoal to interpret paleofire frequencies is a useful complement to climate and paleoclimate studies as a way to interpret local effects of climate on aridity. This paper describes two different methods to extract charcoal from lake sediments and make inferences about fire intensity and fire frequency within the watershed.

34 **Leavitt P.R., D.E. Schindler, A.J. Paul, A.K. Hardie and D.W. Schindler. 1994. Fossil pigment records of phytoplankton in trout-stocked alpine lakes. Can. J. Fish. Aquat. Sci. 51:2411–23.** Paleolimnology bioenergetics modeling, and mesocosm experiments were used to quantify changes in phytoplankton following introduction of trout into fishless alpine lakes (Snowflake and Pipit lakes) in the Canadian Rocky Mountains. Algal abundance inferred from sedimentary pigments increased 4- to 10-fold shortly after fish stocking in the 1960s. In contrast, phytoplankton composition and biomass were constant in nearby, unstocked Harrison Lake, as inferred from fossils. Results suggested that nutrient recycling by stocked trout was one of several mechanisms that contributed to increased algal biomass in alpine lakes.

35 **Lichti-Federovich, S. 1970. The pollen stratigraphy of a dated section of Late Pleistocene lake sediment from central Alberta. Can J. Earth Sci. 7:938-945.** This was the first complete Late Pleistocene pollen stratigraphy retrieved from the province of Alberta. Basal sediments dated at 11,400 +/- 190 ^{14}C years BP and Mazama ash (*ca.* 6800 years BP) provided chronology. The pollen record began with a typical pioneering forest-shrub assemblage. Forests continued to develop around the area (spruce followed by birch dominance) until *ca.* 6000 years BP when birch-alder assemblages reached their maximum. Spruce began to expand after this time and continued to the present. Deterioration in climate was inferred *ca.* 3500years BP. The lack of initial grassland vegetation supports the hypothesis that there was never a connection between the Peace River area and main southern grasslands during the Late Pleistocene.

36 **MacDonald, G.M. 1987. Postglacial vegetation history of the Mackenzie River Basin. Quat. Res. 28:245-262.** Post-glacial sediment cores from three lakes in the Mackenzie River Basin were analyzed to determine vegetation development since deglaciation in northern Alberta and the Northwest Territories. Results from this study are combined with results from other studies to reconstruct vegetation development from the Arctic Ocean to central Alberta. A continuous corridor

of herb and shrub dominated vegetation existed between Beringia (Siberia-Alaska connection) and the Great Plains of North America until *ca.* 10,000 years BP. Vegetation change continued until *ca.* 5000 years BP when the present subarctic vegetation was established. Forest development in the basin was a combination of complex climatic and other factors (e.g., physical features enhancing wind induced seed dispersal).

37 **MacDonald, G.M. 1987 Postglacial development of the Subalpine-Boreal transition forest of Western Canada. J. Ecol. 75:303-320.** Little was known about the paleoecology of the current subalpine-boreal forest vegetation zone. This study attempted to determine if this vegetation region has a long post-glacial history or if it is a recent configuration of vegetation typical of continuous climate change. Between *ca.* 11,000 to 5,000 years BP there was continuous vegetation change. There are no modern, regional analogues for the early post-glacial communities. Since *ca.* 5,000 years BP vegetation patterns remained relatively constant, and the extent of peatlands and frequency of fires has been similar to modern conditions. Vegetation development in the subalpine-boreal transition forest is different from post-glacial development of the subalpine forest, but similar to the early Holocene development of the southern Boreal Forest. The subalpine-boreal forest transition is characterized by pine forests with shade-intolerant shrubs and herbs.

38 **MacDonald, G.M. 1989. Postglacial palaeoecology of the subalpine forest - grassland ecotone of southwestern Alberta: new insights on vegetation and climate change in the Canadian Rocky Mountains and adjacent foothills. Palaeogeogr. Palaeoclimat. Palaeoecol. 73:155-173.** A small lake, Tobaggan Lake (unofficial name), located in the foothills of southwest Alberta was cored and analyzed for pollen, plant macrofossils and charcoal in order to reconstruct climate and vegetation changes over the Holocene. Changes of temperature and aridity over the Holocene period are interpreted by comparing records of vegetation change (interpreted through pollen records) from the current upper and lower elevational limit of the subalpine forest. Shrub and herbs dominated the vegetation at *ca.* 10,000 years BP. The post-glacial climate continued to warm, fire activity in the region reached a maximum between *ca.* 9400 to 8000 years BP and the general climate was likely arid but not severely cold. Between *ca.* 8000 to 5000 years BP spruce and pine forests were replaced by grassland and pine. Treeline migrated to elevations above modern positions. Little vegetation change is recorded at sites in the northern foothills and at mide-elevations at this time. Vegetation change in the southern foothills and at high-elevation suggests both elevational and latitudinal displacement of vegetation zones in the mid-Holocene.

39 **MacDonald, G.M., C.P.S. Larsen, J.M. Szeicz and K.A. Moser. 1991. The reconstruction of boreal forest fire history from lake sediments: a comparison of charcoal, pollen, sedimentological, and geochemical indices. Quat. Sci. Rev. 10:53–71.** This study evaluates commonly used paleolimnological proxies (micro- and macroscopic charcoal, elemental carbon, pollen, and sedimentological and geochemical indicators) to reconstruct fire history and resulting vegetation changes in the northern Boreal forest of Alberta. Paleolimnological records from Rainbow Lake A were compared to local and regional fire history in Wood Buffalo National Park, Alberta. Results indicated that the ability of different paleolimnological proxies to provide detailed histories of past fire is dependent upon the spatial extent, proximity, intensity and impact of individual fires. Microscopic charcoal provided an indication of regional fire activity, while local fires that occurred in the drainage basin primarily influenced macroscopic charcoal. Pollen composition and accumulation rates closely tracked burns that were sufficiently widespread and intense to destroy above-ground vegetation in an area at least as great as the drainage basin.

40 **Manning, P.G., E.E. Prepas and M.S. Serediak. 1999. Pyrite and vivianite intervals in the bottom sediments of eutrophic Baptiste Lake, Alberta, Canada. The Canadian Mineralogist. 37:593-601.** A short core was extracted from the south basin of Baptiste Lake to investigate eutrophication since settlement. Baptiste Lake is a naturally eutrophic, but has become more eutrophic since colonial settlement. The eutrophic status may be related to altered groundwater flow

from land clearing activities. Short sediment cores were analyzed for iron, phosphorus, sulfur and carbon to define redox regimes. Groundwater may be an important mechanism for enhancing P recycling from bottom sediments to the euphotic zone. Vivianite forms when orthophosphate is available and sediments are oxygenated. Pyrite forms under anoxic conditions. Vivianite was more abundant is the bottom sediments while pyrite was more abundant in the top 25cm of sediments. This is further evidence of recent eutrophication in Baptiste Lake and anoxic conditions at the sediment surface.

41 Miskimmin, B.M. and D.W. Schindler. 1994. Long-term invertebrate community response to toxaphene treatment in two lakes: 50-yr records reconstructed from lake sediments. Can. J. Fish. Aquat. Sci. 51:923-932. In the 1950's and 1960's, lakes may have been treated with chemicals as a less expensive and more lethal alternative to removing undesirable fish species from lakes. Toxaphene was applied to lakes to remove the undesirable species, but it was later determined that this caused both direct and indirect ecological damage. Invertebrates were equally affected by chemical treatments and varied in recovery time from months to years. Chatwin Lake received high toxaphene applications as compared to Peanut Lake and short-term toxic effects were detected. In both lakes, large invertebrates became dominant with the absence of native fish species (trout was stocked after toxaphene treatment). Stocked fish had poor survival (toxicity effect) while Chaoborus (invertebrate predator) increased. Toxaphene also accumulates in the plants and animals and can cause effects for up to a decade. This type of paleolimnological study could easily be applied to other lakes to reconstruct the effects of perturbations (e.g., logging, stream diversion, culvert installations/upgrades, urban development).

42 Moser, K.A., J.P. Smol, G.M. MacDonald and C.P.S. Larson. 2002. 19th Century eutrophication of a remote boreal lake: a consequence of climate warming? J. Paleolim. 28:269-281. The recent sedimentary record (~200 years) from a lake in northern Alberta was investigated to determine its responsto recent climate warming fromdiatom assemblages and biogenic silica concentrations. Total phosphorus concentrations were inferred using a diatom-based transfer function developed from area lakes. It was concluded that TP concentrations have increased since the early to mid-1800s due to increased internal cycling of phosphorus with enhanced thermal stratification (in response to warmer summer temperatures) and/or decreased meromictic stability. Results from this lake and other lakes from northern latitudes suggest widespread response of aquatic communities to increasing temperatures beginning in the 19^{th} century.

43 Nicholson, B.J. and D.H. Vitt. 1990. The paleoecology of a peatland complex in continental western Canada. Can. J. Bot. 68:121-138. Development of a peatland complex was determined through analysis of peat cores. Deposition of organic matter began at *ca.* 8,200 years BP around the currently close lake basin. There was evidence of fires in area before *ca.* 7,000 years BP. This also corresponds to the timing of the climactic optimum in Alberta (between *ca.* 9,300 to 5,600 years BP). Climate changed to cooler and wetter conditions (decreased evapotranspiration) and peatland expansion by paludification occurred at *ca.* 6,000 years BP and occurred extensively by *ca.* 5,000 years BP. These results suggest that much of the extensive shallow forested peatlands formed by paludification after *ca.* 5,000 years BP and ombrotrophic peatlands (bogs) are rare and are currently being developed.

44 Nicholson, B.J. and D.H. Vitt. 1994. Wetland development at Elk Island National Park, Alberta, Canada. J. Paleolim. 12:19-34. Long-cores were extracted from peatlands in central Alberta to determine development sequence in relation to climate. Climate is the main factor controlling timing of peat accumulation. Peat will not accumulate under dry conditions. Timing of peatland development and lake infilling provides additional clues about climate warming or cooling. Early Holocene thermal maximum delayed wetland development until after *ca.* 5,620 years BP. Peatland succession (e.g., aquatic to fen or bog; aquatic to marsh) is not related to peatland age but to local edaphic features such as site elevation and catchment hydrology. Peatlands have not developed via paludification and climate still exerts a strong influence on these peatlands.

45 **Philibert, A., Y.T. Prairie, I. Campbell and L. Laird. 2003. Effects of late Holocene wildfires on diatom assemblages in Christina Lake, Alberta, Canada. Can. J. Fors. Res. 33:2405-2415.** The impact of forest fires on a boreal lake was investigated through interpretation of the diatom assemblage from a sediment core. Diatom concentration, and diatom assemblages were examined before, within and after charcoal rich horizons in the sediment core. Three main, local fire events were identified. The fire events occurred between 1040-1045, 1844-1885 and 1903-1943. Peaks of charcoal concentration occurred during those time periods. Peaks of charcoal concentration around 1929 and 1948 represent different fire events but they were combined to represent one fire because there likely would have been continuous charcoal influx to the lake and continuous impact on lake chemistry during that period. Diatom concentration increases after fire events, the relative abundance of benthic taxa increased significantly during fire events as compared to pre and post fire and there was no change in diatom species assemblage in response to fire.

46 **Prather, C.M. 1999. Recent and fossil diatom assemblages from lakes in central and northern Alberta: Ecological and palaeoecological inferences. Ph.D. Thesis. University of Alberta.** The thesis describes the paleolimnology of two lakes from northern Alberta (Otasan Lake and Mariana Lake), a surface diatom-water quality calibration set and inference model for lakes in central to northern Alberta and application of the model to the sedimentary diatom assemblages from seven lakes. The paleolimnological record of Otasan lake is described in Prather and Hickman (2000). Mariana Lake is located in northeast Alberta in the Boreal Forest ecoregion. Sedimentary record dates to before 11,300 years BP. Lake productivity was initially very low. Climate gradually warmed over the early to mid Holocene. Catchment vegetation changed from tree-less to treed, peatlands began to form by *ca.* 7,000 years BP and lake productivity increased. Wetlands and peatlands have continued to develop in this catchment. There was no evidence of acidification in this lake as compared to Otasan Lake or decreased water levels and nutrient enrichment as compared to central Alberta lakes.

47 **Prather, C.M. and M. Hickman. 2000. History of a presently slightly acidic lake in northeastern Alberta, Canada as determined through analysis of the diatom record. J. Paleolim. 24:183-198.** Otasan Lake is in the Boreal Forest ecoregion in northeastern Alberta. The sedimentary diatom and chyrsophyte records were analyzed to determine lake development over the Holocene. The sedimentary record dates to *ca.* 8200 years BP indicating that the entire record was not retrieved however, there were distinct changes in this lake. The lake began with very low productivity and alkaline indicator species. Diatom productivity gradually changed along with diatom community composition. Lake acidity increased overtime and peaked between *ca.* 5000 to 3100 years BP. No significant pH changes or algal productivity changes occurred after this time. Changes in catchment vegetation and climate influenced this lake. Cooler temperatures in northern Alberta limited lake development longer than in central Alberta and development of evergreen forests and peatlands influenced pH levels of this lake.

48 **Rusak, J.A., P.R. Leavitt, S. McGowan, G. Chen, O. Olson and S. Wunsam. 2004. Millenial-scale relationships of diatom species richness and production in two prairie lakes. Limnol. Oceanogr. 49:1290-1299.** This paper investigated causes and consequences of changes in aquatic biodiversity in relation to ecosystem function using a paleolimnological approach. High-resolution cores, spanning 2000 years, were collected from two prairie lakes (Chavin (AB) and Humboldt (SK) lakes) and analyzed for diatoms, algal pigments and stable isotopes ($^{13}C_{organic}$, $^{13}C_{inorganic}$, ^{15}N). Prairie lakes naturally fluctuate between freshwater and saline phases in response to climate change. During the freshwater phases there was a significant negative correlation between diatom species richness and diatom production (inferred from pigments). This relationship was eliminated through abiotic disturbances such as droughts. C and N biogeochemistry was also strongly correlated with algal species richness. The authors concluded that given ongoing human-induced changes in climate and biogeochemical systems, it may no longer be possible to identify future relationships between biodiversity and ecosystem function.

49 **Schindler D.E., K.A. Knapp and P.R. Leavitt. 2001. Alteration of nutrient cycles and algal production resulting from fish introductions into mountain lakes. Ecosystems 4:308–21.** Sedimentary pigments were analyzed in alpine lakes (Snowflake, Bighorn and Harrison lakes) to assess fish-induced changes in phosphorus cycling on primary production. Algal production increased following introductions of trout and was maintained at high levels for the duration of fish presence. These findings and the results of bioenergetic modeling of phosphorus cycles in lakes from Sierra Nevada, California (from the same study) indicate that introduced trout fundamentally alter nutrient cycles and stimulate primary production.

50 **Schweger, C.E. and M. Hickman. 1989. Holocene paleohydrology of central Alberta: testing the general-circulation-model climate simulations. Can. J. Earth Sci. 26:1826-1833.** This paper presents a summary of Holocene hydrological interpretations from 28 lakes and bogs across central Alberta. Most shallow lake basins that were empty in the early Holocene filled between *ca.* 6,500 to 4,500 yearsyears BP. Some filled before *ca.* 8,000 years BP and none filled later than *ca.* 3,000 years BPyears BP. *Ruppia* pollen (saline indicator) was found in sediment cores of lakes where it does not currently grow. This indicated that between *ca.* 8,000-3,000 years BPyears BP there was increased salinity, lower lake levels and evaporation stress in some Alberta lakes. Some presently shallow lakes largely dried up between *ca.* 8,000 to 6,000 years BP, while some presently deeper lakes experienced significant lake elevation declines during the same period. Lakes that were shallow during this mid-Holocene period were also highly productive (indicated by sedimentary pigments). Modern climatic and vegetation conditions were established by *ca.* 3,000 years BP. Many lakes also exhibited modern conditions after *ca.* 3,000 years BP.

51 **Taranu, Z. and I. Gregory-Eaves. 2007. Tracking the effects of land-use changes on water quality of Albertan Lakes: A Spatio-temporal analysis. Conference presentation for the 30th Congress of the International Association of Theoretical and Applied Limnology (SIL), Montreal.** In this study, the importance of non-point sources of nutrient loading is quantified for lakes spanning the province of Alberta, a region where nutrient concentrations are among the highest in Canada. A combination of modern spatial analyses and paleolimnology is used to define the proportion of variance in water-quality that can be explained by land-use changes and other factors (e.g. climate). Percent catchment disturbance and mean lake depth explained 44.3% of the variation in [TP] among lakes. Paleolimnological analyses of sub-fossil chironomid assemblages through time also revealed an interaction between land-use and lake morphometry. Overall, results suggest that the response of lakes to environmental and anthropogenic drivers differs between dimictic and polymictic mixing regimes. Given that droughts are forecasted to be more intense in this region in the near future, and thus could alter lake mixis, defining the response of lake types to land-use changes is important for effective management.

52 **Vance, R.E. 1986. Aspects of the postglacial climate of Alberta; calibration of the pollen record. Géographie Physique et Quaternaire. 40:153-160.** Calibration modelswere developed to infer growing season temperature and precipitation from pollen assemblages. Palynological studies from across Alberta indicate that late-glacial vegetation (open vegetation) was replaced by spruce dominated assemblages between *ca.* 12,000 and 10,000 years BP. Current vegetation boundaries developed north of modern positions over the early- to mid-Holocene. These vegetational boundaries eventually moved south to their current limit by *ca.* 3,500 years BP. Little, significant large scale vegetational change has occurred since that time. Application of the pollen based inference model to the pollen record from a central Alberta lake (Lake Isle, Baptiste)? suggested that in the mid-Holocene period growing season temperature was warmer (1.5^{o}C) and precipitation was lower (50 mm) than at present.

53 **Vance, R.E., A.B. Beaudoin and B.H. Luckman. 1995. The paleoecological record of 6 Ka BP climate in the Canadian prairie provinces. Géographie physique et Quaternaire 49:81-98.** A synthesis of paleoecological studies from the Canadian prairies suggests that in the mid-Holocene period (*ca.* 6,000 years BP) climate was warmer and drier than present. In comparison to modern conditions, treeline elevations were higher, alpine glaciers were smaller, lake levels were lower, grassland and boreal forest ecozones were further north, and forest fires occurred more frequently. It has been suggested that atmospheric circulation at *ca.* 6,000 was characterized by frequent incursions of Pacific air masses. The zonal air circulation patterns of the 1930s may be the best comparable analogue. However, the precipitation deficiencies of the 1930s, even if they would have continued for decades and with warmer temperatures, would have been insufficient to initiate the widespread desiccation of shallow wetlands and northward migration of vegetation zones experienced *ca.* 6,000 years BP. The authors suggest that ecotonal areas are most sensitive to climate changes and should therefore be used for future studies.

54 **Vance, R.E., J.J. Clague and R.W. Mathewes. 1993. Holocene paleohydrology of a hypersaline lake in southeastern Alberta. J. Paleolim. 8:103-120.** Chappice Lake is located on the northern margin of the Great Plains. This lake was chosen for study to investigate and interpret paleohydrological changes over the Holocene. Chappice Lake is a small, hypersaline lake. The sediment core extracted spans the last 7,300 years. The lake has undergone major changes in lake water level and chemistry. Water level fluctuated greatly between 7,300 and 6,000 years BP. Between 6,000 to 4,400 years BP the open water of the lake was smaller than at present and highly saline. Between 4,400 to 2,600 years BP, water levels fluctuated less than in previous time periods and displayed a general increasing trend. A large freshwater lake existed between 2,600 to 1,000 years BP. There were a series of shallow and saline periods between 1,000 to 600 years BP although not as shallow and saline as in earlier time periods. The second to last interval, 600 years BP to the late 1800s, was characterized by relatively high water levels. Finally, lake water levels declined significantly during the last one hundred years, especially during the documented droughts of the late 1800s, 1920s, 1930s and 1980s. Lake level fluctuations and saline events correspond closely with documented Holocene climatic intervals and in addition to historically recorded climate events. Since this lake responded with these important climate intervals, the sedimentary record from Chappice Lake provides a high-resolution, analagous record of Holocene climate and its effect on lake chemistry and biota from the northern Great Plains.

55 **Vance, R.E., D. Emerson and T. Habgood. 1983. A mid-Holocene record of vegetative change in central Alberta. Can. J. Earth Sci. 20:364-376.** Three lakes in the central region were cored and pollen records analyzed. Mixed-wood parkland vegetation developed in central Alberta (Edmonton area) by 7,400 years BP. By 5,000 years BP the vegetation was more open due to increased fire frequency as a response to the warm, dry Hypsithermal climate at this time. The development of a cooler, moister climate enhanced development of denser forests. The local vegetation around each lake responded to altered climate in a unique manner but in general little vegetational change was evident after *ca.* 3,000 years BP.

56 **Vance, R.E., R.W. Mathewes and J.J. Clague. 1992. 7000 year record of lake-level change on the Northern Great Plains: A high-resolution proxy of past climate. Geology 20:879-882.** Sediment mineralogy and pollen and plant macrofossil remains were used to reconstruct hydrological changes for the past ~7,000 years in Chappice Lake, a saline prairie lake in southern Alberta. Drought conditions were inferred during sediment intervals characterized by carbonate-rich laminae and abundant halophytic plant remains, while massive, silicate-rich sediments with few halophytic plant remains were indicative of fresh water stages. Results indicated alternating intervals of droughts and freshwater periods with the most intense drought events occurring during the Hypsithermal and Medieval Warm Period. More recent drought events of the late1800s, 1930s and 1980s were comparatively less severe.

57 **Wolfe A.P., R.D. Vinebrooke, N. Michelutti, B. Rivard and B. Das. 2006. Experimental calibration of lake-sediment spectral reflectance to chlorophyll *a* concentrations: methodology and paleolimnological validation. J. Paleolimn. 36:91-100.** This study assesses the spectral properties of sedimentary chlorophyll a using visible-near infrared reflectance (VNIR) spectroscopy to establish a new, non-destructive paleolimnological proxy. The VNIR inferences are validated by comparison with high performance liquid chromatography (HPLC) measurements in sediments from Lac La Biche. Results indicated that HPLC-measured and VNIR-inferred concentrations of total chlorophyll a and derivatives were comparable and were both able to chronicle progressive enrichment of the lake after *ca.* 1985. The authors suggest that for applications in lake management that require baseline historical lake trophic status, the VNIR technique provides a rapid and cost-effective method to reconstruct chlorophyll a concentrations.

58 **Wolfe, B.B, R.I. Hall, W.M. Last, T.W.D. Edwards, M.C. English, T.L. Karst-Riddoch, A. Paterson and R. Palmini. 2006. Reconstruction of multi-century flood histories from oxbow lake sediments, Peace-Athabasca Delta, Canada. Hydrol. Process. 20:4131-4153.** Flood frequency over the past ~300 years is inferred from two oxbow lakes (PAD 15 and 54) from sedimentary records of magnetic susceptibility and physical and geochemical parameters to assess the relative influence of natural and anthropogenic factors in regulating hydrological conditions in the Peace-Athabasca Delta. Results suggest that flood frequency was greatest in the late 1800s and early 1900s and has declined to present times beginning as early as the late 1800s (PAD 15). Variability in reconstructed flood events is most likely related to climate-related mechanisms and there was no evidence to suggest a directional change in flood frequency resulting from regulation of the Peace River for hydroelectric power production since the construction of the W.A.C. Bennett Dam in 1968. As such, management strategies for the PAD need to account for natural variations in flood regimes.

59 **Wolfe, B.B., T.L. Karst-Riddoch, S.R. Vardy, M.D. Falcone, R.I. Hall and T.W.D. Edwards. 2005. Impacts of climate and river flooding on the hydro-ecology of a floodplain basin, Peace-Athabasca Delta, Canada since AD1700. Quatern. Res. 64:147-162.** Hydro-ecological conditions over the past ~300 years were reconstructed from a small delta lake that is presently disconnected from the main channel network in the northern sector of Peace-Athabasca Delta. Paleolimnological analysis of sedimentary physical, geochemical and biological indicators revealed a pronounced dry period in the 1700s coincident with the relatively colder and drier conditions that characterized the Little Ice Age. With climate amelioration, wetter conditions and pronounced floodwater inputs to the lake were inferred during the early 1800s to the early 1900s. Recent drying trends were observed beginning as early as 40 years prior to regulation of the Peace River in 1968 and continue until present. Comparison of inferred hydro-ecological changes and independent climate records suggest a strong influence of climate variability in regulating conditions in the PAD.