Problem and Research Objectives:

Climate changes predicted for North America over the next century include warming temperatures, long periods of drought, and increased levels of precipitation, all of which pose serious risks to freshwater ecosystems (Poff et al., 2002). Global Climate Models have been used to predict the type and magnitude of physical climate changes. Several scenarios have been suggested and more than one may be accurate, causing great uncertainty in the future of lakes and streams (New England Regional Assessment, 2001).

As climate change is likely to be a complex set of shifts in rainfall and temperature that may have annual, seasonal, and cumulative components, we propose that lakes may provide a sensitive integrator of hydrologic effects of climate change. Prolonged climate shifts such as drought alter the transport of water and solutes to a lake, affecting its water budget and generating strong chemical responses. For example, drier and warmer periods disconnect lakes from their catchments and from local groundwater flowpaths, altering transport of substances such as dissolved organic carbon from adjacent wetlands (Magnuson et al. 1997; Schindler 1997). In addition, during drought lakes often have higher concentrations of more conservative solutes, reflecting increases in evaporation over precipitation and lower lake water levels (Webster et al. 1996; 2000). This response can be complicated in extreme cases where drought is sufficient to reverse groundwater inputs and cause decreased in-lake ion concentrations (Webster et al. 1990).

Landscape position (the position of a lake along a local hydrologic flowpath) can influence the nature of chemical responses to climatic forcing. Lakes located high in the landscape, near groundwater and surface water divides, are subject to more transience in local flowpaths of groundwater and greater variability in lake water levels as climate shifts (Anderson and Cheng 1993; Cheng and Anderson 1994; Winter 1999). Because surface water inlets and outlets are lacking, the hydrologic budgets of high-order, precipitation-dominated, seepage lakes are dominated by precipitation, some groundwater input, evaporation, and inflow from adjacent wetlands. Thus, during climate change, the magnitude of shifts in ionic strength for these water bodies becomes a function of the relative importance of wetland connections, evaporative losses, and groundwater inputs. This close integration between climate and hydrology, make seepage lakes sensitive indicators of climate change (Winter and Rosenberry 1998; Fritz 1996).

In this study we are evaluating chemical indicators that potentially reflect climate-induced shifts in hydrologic connections between lakes and (1) wetlands and (2) groundwater inputs. We expect to find that these precipitation-dominated seepage lakes located higher in the landscape, with weaker connections to groundwater flow systems are responsive to climate and thus provide more sensitive indicators of climate change. In addition, we have access to long-term data on the chemistry of seepage lakes in Wisconsin for comparison with lakes in Maine.

We have three general objectives for this research project:

- Determine if changes in the chemistry of sensitive seepage lakes in Maine reflect climatic shifts over the past two decades.
    - ~ Determine if there is a strong signal of chemical response to climate-induced shifts in a lake's hydrologic connections to wetlands and local groundwater systems.
    - ~ Compare chemical responses of Maine lakes with drought-induced changes in water chemistry observed for similar seepage lakes in Wisconsin.
    - ~ Interpret responses to climate in the context of decreased acid deposition over the past 20 years
- Evaluate the potential for using seepage lakes in Maine as sensitive sentinels of climate change.
- Recommend a research program to monitor lakes for climate change in the future and to identify impacts of concern to the health of lakes and availability of water resources in the future.

In addition to the main objective in this proposal to evaluate the use of Maine lakes as sentinels of climate change, we cannot ignore the value of basic data for increasing our understanding of the ecological responses of lakes to climate. Climate change has the potential to alter physical and chemical features of lakes in ways that could dramatically change community structure of aquatic organisms and ecosystem processes. In addition, we need better information on how climate influences lake ecosystems in order to understand multiple effects of regional disturbances such as acid rain, UV radiation, and land use alteration. Placing results of both short and long-term studies in a context of climate variability greatly improves our ability to make informed decisions on policy and management actions that affect lake ecosystems.

Methodology:

Water chemistry data on ~120 seepage lakes in Maine were collected in the mid-1980's and the late-1990's as part of earlier surveys. We selected a subset of 66 seepage lakes for re-sampling for this study. These lakes all have an ANC less than 100 µeq/L, our operational definition of lakes with low groundwater influence. Lakes were then allocated to classes defined by strength of connection to surrounding wetlands (low, mid, high) using National Wetland Inventory (or Wisconsin Wetland Inventory) and USGS 7.5 Minute Topographical maps, and watershed boundaries (Figure 1 and Table 1). As these lakes have low values of ANC, they all are considered to have transient connections to local groundwater systems.

Graduate research assistant Emily Seger sampled the subset of 66 Maine lakes in fall 2001 and fall 2002. Chemical variables measured from the lakes include base cations, acid anions, DOC, true color, silica, conductance, pH, and alkalinity. All chemical analyses were performed at the Environmental Chemistry Lab at the University of Maine. The lake chemistry in both Maine and Wisconsin were collected as part of the same EPA program (Long Term Monitoring), so the data are comparable in field and analytical methods. Precipitation data for both Maine and Wisconsin were compiled from National Climate Data Center monitoring stations near locations of seepage lakes (Augusta Airport, Portland Jetport, and Grand Lake Stream for Maine; Minocqua Dam for Wisconsin). Statistical analysis was performed using ANOVA tests with Systat 10.2 software package.

Principal Findings and Significance:

The field sampling data for the Maine lakes corresponded to periods of (1) normal precipitation in 1986-87; (2) above average in 1998; (3) the lowest precipitation year on record in 2001; and (4) recovery from severe drought in 2002 (Figure 2). In spring to summer 2002 above normal precipitation reversed much of this drought although groundwater levels remain somewhat below normal. In Wisconsin, the most notable climatic event was a severe drought between 1987-1990, followed by a recovery period (Figure 3).

Analyses have focused on the four chemical constituents we proposed as indicators of flowpath shifts due to climate change. We assume that (1) dissolved organic carbon (DOC) and true color levels reflect changes in wetland-lake connections (higher the DOC and true color, the more connected lakes are to wetlands) and (2) changes in silica and calcium concentration reflect shifts in groundwater-lake interactions (higher the silica and calcium, the more connected lakes are to groundwater flowpaths). We found that during dry periods, DOC and silica levels decreased in many Maine and Wisconsin seepage lakes, suggesting that even short-term climate shifts impact flowpath connections to these lakes and thus, their chemical environments.

Lakes in Maine with stronger connections to wetlands had the largest chemical response to precipitation shifts for all constituents analyzed (using ANOVA and a p-value of 0.1). We had expected lakes in the low and mid wetland classes to be more responsive. For both Wisconsin and Maine lakes, true color appeared more responsive to precipitation changes than DOC, and both analytes decreased during dry periods (see Figure 4 for example of Maine results).

Calcium concentrations appeared more susceptible to evapoconcentration and dilution effects than silica. Figure 5 shows this response for Maine. Decreases in silica concentrations occurred during a short period of severe drought in Maine, while in Wisconsin decreases in both silica and calcium were seen during long-term drought.

We conclude that water chemistry does reflect drought-induced shifts in wetland and groundwater hydrologic connections. Thus, water chemistry of precipitation-dominated seepage lakes has potential as an indicator of climate change, and its corresponding effects upon the landscape. Due to their isolated landscape position and precipitation-dominated water budget, the chemistry of higher order seepage lakes is more sensitive to changes in climate-induced groundwater input, evaporative losses, and connection to shoreline wetlands than drainage lakes, in which significant chemical variations occur from noise of large catchment inputs and faster flushing rates. Climate-induced alteration of lake hydrologic connections to the landscape will affect lake DOC, true color, and solute concentrations such as calcium and silica. Climate may also confound recovery of acid-sensitive waters like these seepage lakes through drought-induced re-oxidation of sulfate and decline of base cation inputs. Consequently, precipitation-dominated seepage lakes are a sensitive indicator of climate change and its translation onto the landscape and freshwater systems.

Climate warming is a major issue for humankind globally, but the response and adaptation to climate change will occur locally. Our research addresses needs for information on the effects of climate change on aquatic ecosystems in Maine by evaluating an integrator of climate that does not rely entirely on statistical interpretations of weather variables. Use of the chemistry and hydrology of seepage lakes as early warning indicators, if successful, will provide a method for understanding the direction(s) of change in Maine's climate, and provide expectations of future impacts on water resources. Our research also addresses the need to conduct research that recognizes the impacts of multiple stressors such as acid deposition and climate change on aquatic ecosystems.

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Wetland Classification

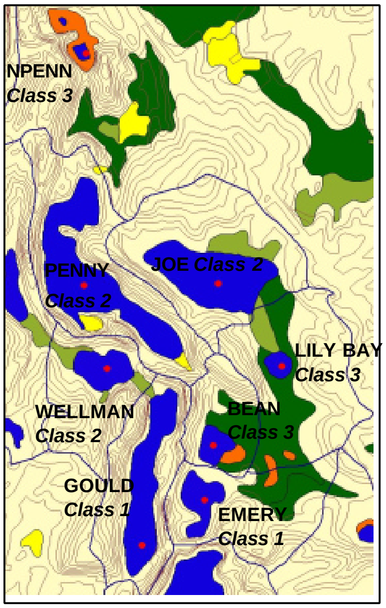

Table 1. Classes based on degree of connection to adjacent wetlands

Class	Description
1 *n = 26*	• No connections to wetlands, or • 1 narrow connection to small wetland (relative to lake size)
2 *n = 23*	• 1 - 4 connections to small/medium size wetland (relative to lake size), or • One half to three quarters of the pond's perimeter is adjacent to small/medium size wetland (relative to lake size)
3 *n = 14*	• Over half of shore perimeter shares interface with large wetland, or • Whole pond is surrounded by medium/large size wetland (relative to lake size)

Numbers of lakes (n) in each class refer to those in the Maine wetland classes.

Figure 1. Lakes were classified qualitatively by using digital National Wetland Inventory maps, topographic contours, and watershed boundaries to determine strength of connection to adjacent wetlands. This map shows several seepage lakes and their surrounding wetlands near Augusta, Maine.

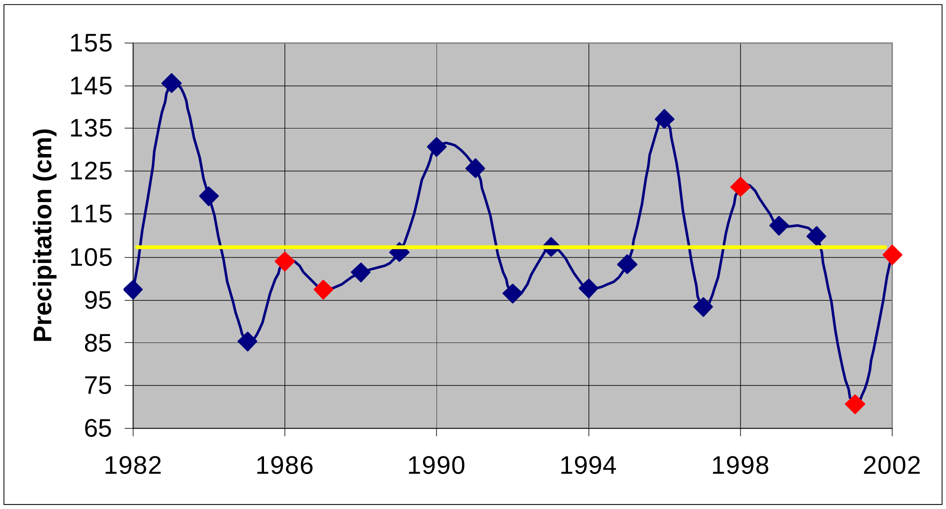

Figure 2. Maine total annual precipitation averaged over three Maine NCDC Stations. NCDC thirty year normal precipitation mean = 105.84 cm (indicated by yellow line). A pattern of normal, to above average, to severely low precipitation, to recovery from drought occurred during years with data.

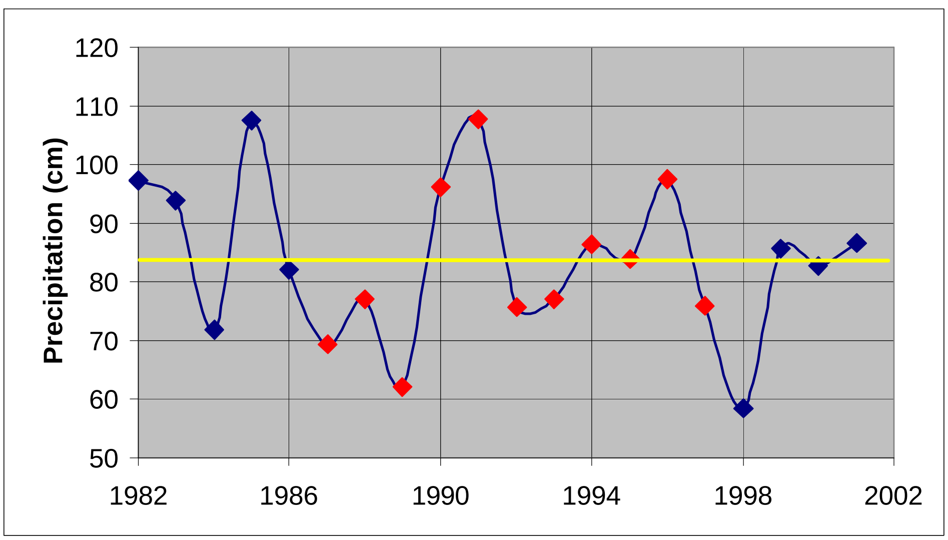

Figure 3. Wisconsin total annual precipitation at Minocqua Dam NCDC station in northern Wisconsin. Shaded areas indicate years with lake data. NCDC thirty year normal precipitation mean = 83.24 cm (indicated by yellow line). A severe drought from 1987 to 1990 occurred, followed by a transition to above/normal precipitation.

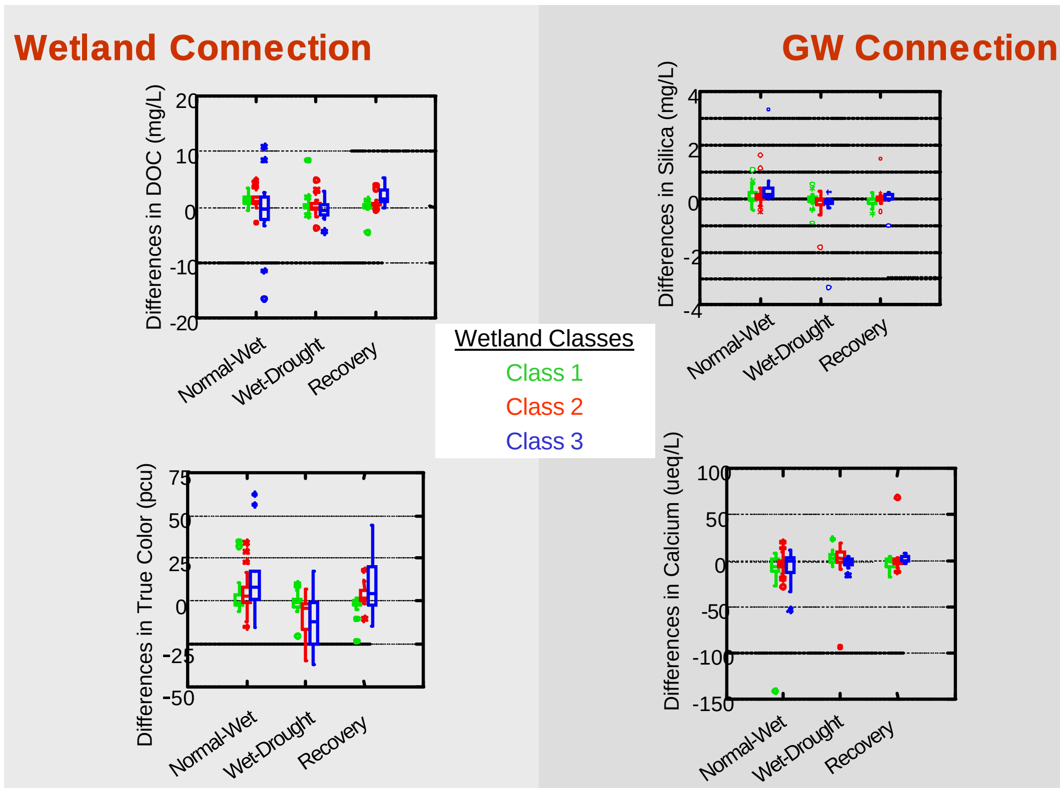

Figure 4. **Maine Results:** Boxplot graphs show *differences* in concentrations from each year with available data, grouped by lake class (the strength of connection with wetlands increases from class 1 to 2 to 3). The Normal-Wet period represents changes in chemistry from 1986/87 to those samples gathered in 1998. The Wet-Drought period represents changes in data from 1998 to 2001, and Recovery represents 2001 to 2002. The starting points for comparison are data from 1986/87 (the first years of the dataset and normal precipitation conditions) and represents zero on the y-axis of these graphs.

Class 3 lakes, with the strongest connection to wetlands, had the largest response to changes in DOC and true color. DOC and true color decreased during drought, and increased with increased precipitation. Silica concentrations slightly decreased during drought, and increased during wet or recovery years. Calcium had an opposite pattern, with some increases during drought, possibly due to evaporation and dilution effects.