2007 Project Abstract
For the Period Ending June 30, 2010

PROJECT TITLE: Minnesota's Water Resources: Impacts of Climate Change - Phase II
PROJECT MANAGER: Lucinda B. Johnson
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2007, Chp. 30, Sec. 2, Subd. 5k

APPROPRIATION AMOUNT: $300,000

<u>Overall Project Outcome and Results</u>

Minnesota's climate has become increasingly warmer, wetter, and variable, resulting in unquantified economic and ecological impacts. Our team assessed future climate scenarios, quantified hydrologic responses to past climate, conducted an economic analysis to assess implications of changing climate to water resources, and identified water quality and fish indicators of response that could be used for future monitoring. Specific products included:

- Data tools to extract and summarize historic climate data from the State Climatology Office database,
- A water quality reporting tool,
- Climate predictions to the end of the century,
- Assessment of economic impacts of climat change on fisheries and water resources,
- Recommendations of indicators for inclusion in future monitoring programs.

Our findings include the following:

- Temperature increases are projected to be greatest in the latter half of this century, with temperatures generally above 2°C above the average from 1950-1999.
- Precipitation is projected to increase on an annual basis, but will decrease or be unchanged during the growing season, resulting in drier growing conditions.
- Overall, water temperatures in streams are projected to increase between 3 and 5°C.
- Ice out dates were found to be occuring about 1.44 days earlier per decade since the 1950's, and trends for increasing air temperatures in the future imply further declines in ice-free days.
- Historic data were utilized to identify climate periods in the record that were extreme (either due to temperature or precipitation). These extreme periods were then used to assess possible water quality and fish responses during those periods. Indicators of water quality responses were identified (e.g., water clarity, surface water temperature, conductivity); no specific fish responses were detected.
- Walleye spawning dates are changing with ice out dates, and there is evidence that some fish species are expanding their distributions (especially largemouth bass, bluegill and black bullhead). Cisco (tullibee) abundance is declining in northern lakes.
- Water quality and biological indicators were recommended for future monitoring.

Individual project components show detailed analyses and results.

Project Results Use and Dissemination

Project team members and their collaborators have made numerous presentations to general audiences, to agencies, and at professional conferences. Additional outreach and communications products include:

- Data from Kristal Schneider's Master's thesis regarding the relationship between walleye spawning and ice out has been published in the Transactions of the American Fisheries Society 139(4):1198-1210.. http://afsjournals.org/doi/abs/10.1577/T09-129.1. Further publications are planned.
- A mapping tools was created to display trends for lakes having between 5 to >18 years of data. Because of the large number of options for analyzing this broad data set, a comprehensive subproject website was constructed to make the trend results available to other project scientists and ultimately others: (http://mnbeaches.org/gmap/trendswebsite). The website includes "processed raw" data, complete metadata, summary tables, links to Google Maps that identify sites with descriptive statistics, and graphs (box and whisker and regressions). The data are also incorporated into the larger project database that is now being used for more detailed examinations of climatic associations, geographic patterns, size and depth patterns, and associations with fish, and ice cover data.
- The climate data retrieval tool, developed by the State Climatology Office, was essential to all climatic research undertaken in this project. The climate data retrieval tool enabled project participants to extract climate variables important to their own specific questions, at time and space scales they deem relevant. While the climate data retrieval tool is available to project investigators only at the present time, the Office of the State Climatologist plans to make it available widely to Minnesota resource managers and researchers at the conclusion of this project.
- A third product is an annotated bibliography for the economics of climate change and environmental quality.

Trust Fund 2007 Work Program Final Report

Date of Report: January 4, 2011
Trust Fund 2007 Work Program Final Report

I. PROJECT TITLE: Minnesota's water resources: impacts of climate change - Phase II – SN 13

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Location: Entire state of Minnesota

Total Trust Fund Project Budget:	**Trust Fund Appropriation:**	**$ 300,000**
	Minus Amount Spent:	**$ 300,000**
	Equal Balance:	**$ 0**

Legal Citation: ML 2007, [Chap. 30], Sec.[1], Subd. 5(k)

Appropriation Language: $300,000 is from the trust fund for the second biennium to the University of Minnesota's Natural Resources Research Institute, to quantify climate, hydrologic, and ecological variability and trends, along with economic impacts of environmental fluctuation on water resources, and to identify indicators of future climate change effects on aquatic systems. This appropriation is available until June 30, 2010, at which time the project must be completed and final products delivered, unless an earlier date is specified in the work program.

II. AND III. FINAL PROJECT SUMMARY

Minnesota's climate has become increasingly warmer, wetter, and variable, resulting in unquantified economic and ecological impacts. Our team assessed future climate scenarios, quantified hydrologic responses to past climate, conducted an economic analysis to assess implications of changing climate to water resources, and identified water quality and fish indicators of response that could be used for future monitoring. Specific products included:

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Result 1: Economic and Engineering Assessment of Potential Impacts on Water Resource Infrastructure.

Description: Recent changes in precipitation patterns, combined with urbanization, wetland loss, and increased tile drainage have resulted in higher riverine base flows in Minnesota, compared to historic averages. These changes are associated with increased flood frequency and intensity. The economic impact of such floods has been substantial. We will use data from our Phase I LCCMR funded Climate Change project, along with the outcome of Result 2 (i.e., future MN climate predictions) to estimate the economic cost of flooding and degraded water quality and assess infrastructure changes needed to meet future climate projections. Outcome: An economic analysis of floods and the cost of water quality protection and infrastructure needs under changing climatic conditions. The analysis will include estimates of flood damages to physical and natural assets, including costs due to increased sedimentation and nutrient enrichment of surface waters using market valuation techniques. Damages to water quality will also be estimated using benefits transfer based on evidence from the literature on the public values of water quality. Costs to mitigate damages from flooding and reduced water quality will also be determined using current and projected engineering costs and market values.

Summary Budget Information for Result 1:	**Trust Fund Budget:**	**$ 85,458**
	Amount Spent:	$ **85,458**
	Balance:	**$** 0

Deliverable	Completion Date	Budget	Status
1. Engineering analysis	September 2008	$25,458	Complete
2. Categorization of economic impacts by market and non-market values	June 2009	$16,000	Complete
3. Finalize economic estimates for infrastructure and water quality impacts	June 2010	$44,000	Complete

Completion Date: *June 30, 2010*

Final Report Summary:

Potential Impacts of Climate Change on Minnesota's Water Resources: An Economic Analysis (see Appendix A).

Patrick G. Welle, Rabi Vandergon
Bemidji State University

Conceptual Framework for Inferring Economic Impacts

Potential economic impacts of climate change must be understood within the conceptual framework about what people value. Environmental economics identifies two major conceptual components of value: use values and passive-use value. The theory and practice has developed toward the conventional wisdom that only recognizing use values in evaluating environmental effects would lead to substantial underestimation of value to the public.

It is also worthwhile to relate conceptual components of value to the benefits estimation techniques available to measure them. Benefits estimation must be grounded in measurement of market and non-market values. Market values ideally measure willingness-to-pay (WTP) based on derivation of the market demand curve. Actual expenditures are a lower-bound estimate of WTP in that consumer surplus would be missed. Non-market values are not directly revealed in market transactions. Purchases of items, such as bird-watching equipment, can indicate people's values for these activities. Existence values are most often measured through direct statements rather than being revealed through market choices.

The focus of the overall project leads to emphasis on the three categories of environmental impacts below. The major mechanisms for economic impacts to occur are included.

1. Lake and stream levels: flood damages, especially to infrastructure
2. Water temperatures: shorter ice duration, changes in fish populations, habitat, winter and summer kills
3. Water quality: multiple values of clean water

Potential Economic Effects of Changes in Minnesota's Water Resources

Empirical economic analyses were performed on two impacts to MN water resources: 1) magnitudes and types of infrastructure damages due to weather-related events, particularly floods, and 2) the trend toward shorter ice duration on MN lakes. This is likely to affect recreational fishing which is extremely important to MN.

Infrastructure Damage: The longest yearly record for weather-related damages in MN comes from figures reported in a NOAA study (2002). From 1955-2000 occasional weather events caused damages (in constant 1995 dollars) in the tens of millions of dollars. Damages in the hundreds of millions of dollars also occurred over this time period. By far the two years with the highest damages were 1997 and 1993. The floods of 1993 caused damages in excess of $1 billion in constant 1995 dollars. During the 1990s there were 14 presidential declarations of major disasters. Most of the damages were the result of flooding, ice storms, snow removal, straight-line winds, tornadoes, and heavy rain (MN Department of Public Safety's Division of Homeland Security and Emergency Management). From the disasters of the 1990s, Minnesota taxpayers spent $827 million and the cost to insurance companies was more than $2 billion.

Water Quality: There is a great deal of evidence that water quality is extremely important to Minnesota. The value of water quality is manifested in recreational and tourism activities, property values for lakeshore, investments in policies to protect water, and other ways in which citizens demonstrate WTP and the role of water in the MN quality of life. The evidence of historical trends on water quality in MN lakes yields mixed results, with general trends toward improving water quality measures (see Appendix F, LCCMR 2005 report). It is difficult to isolate potentially negative impacts of climate change on lake water quality from the backdrop of other complex processes that are having a net positive effect.

If climate change has a negative impact on thousands of lakes within the state, the loss of economic value would be substantial. These assets (natural capital) would be much less valuable to MN than they otherwise could be under static climatic conditions. For a thousand lakes that might be degraded from climate change, the loss could be in the tens of billions of dollars. (Krysel, et al. 2003). It is difficult to predict the exact trajectory of water quality changes across all lakes due to complex, often non-linear responses to multiple and interacting stressors; however, the evidence in the literature indicates climate change is likely to have a negative net effect (See Appendix C).

Ice Duration: Ice duration is getting shorter in the state (Appendix F, this report). The trend analysis indicated that ice-duration has on average been getting shorter by a third of a day in a typical year, or 3.3 days over the course of a decade for the past 35 years, and 1.44 days per decade over the past 60 years. A direct socio-economic impact of shorter ice duration will be the switch of recreational days for ice-related activities to open-water activities. Certainly activities such as ice fishing and skiing which are dependent on ice and snow are likely to suffer based on climate evidence. Changes in fish species distribution and abundance will enhance the fishing experience for some anglers and detract for others. In addition, there is an important linkage between ice-on/ice-off periods, limnological conditions/water quality, fish habitat and species distribution/abundance (Appendices K, L, M).

Creel survey data includes variables on the time respondents spent fishing, catch rates and other aspects of the fishing experience. Shorter ice duration can reasonably be expected to diminish the benefits the public enjoys from ice fishing. Since some MN lakes, most notably Upper Red Lake, see higher use in winter months, the onset of climate change through decreasing lake ice will likely have a net negative impact on recreational benefits from use of these lakes.

Seasonal patterns of use were examined for other large walleye lakes in the state. These generate a very large portion of the overall fishing activity in the state. In contrast to Upper Red Lake, other large walleye lakes (and statewide data for smaller lakes) show that summer effort significantly exceeds effort in the winter. A higher amount of angler effort in the open-water season is likely to lead to a net positive impact from the onset of climate change, unless water quality is degraded to the extent that fish communities are negatively impacted.

An additional empirical question investigates whether changes already occurring in species distribution and abundance are leading to changing patterns of fishing effort. The results from the multiple regressions (see Appendix B) did not show significant results for a change in yield per unit of effort in response to change in species abundance over certain regions of the state over time (Appendix B; this report). Nor did they indicate increasing effort thus far in areas where yields might be expected to increase in the future as certain species become more abundant. As mentioned in the literature (Johnston, et al 2006) certain species, such as trout, have a higher WTP than walleye and panfish. Therefore, a change in these species abundances could have a significant impact on the WTP by anglers. For example, fewer trout (which are predicted to decline from climate change) would be detrimental to recreational benefits. The net impact from these changes in species abundance and the economic consequences cannot be estimated given current limitations of available data.

Further Conclusions

The relative emphases of the economic analyses and the empirical estimation are dependent upon the findings of the other environmental components of this research effort. To a certain extent, the findings on environmental impacts at this juncture are predicated on available data that are constrained in both temporal and spatial scale. So while evidence is mounting that Minnesota's water resources are vulnerable to the effects described in this report (higher surface water levels/streamflow, increased sedimentation, degraded water quality, infrastructure implications) some of the more extreme impacts anticipated at the global or regional scale are difficult to detect statistically at the smaller statewide scale. This is due in part to lack of small spatial scale data over the length of time needed to detect statistically meaningful trends.

MN should adopt a two-pronged approach to risk management to the degree that MN can inventory watersheds for the combination of two groups of characteristics. A convergence of two characteristics that cause greatest vulnerability to damages from flash floods should be inventoried. Watersheds most vulnerable to transportation infrastructure damages have:1) geomorphology conducive to flash floods and 2) human and natural environments that put highly valued assets and human life in harm's way.

See Appendix A for a the complete report on the economic impacts of climate change due to changes in water levels and flows and shorter duration of ice cover in Minnesota's lakes.

Johnston, R. J., M. Ranson, E. Besedin, and E. Helm. 2006. What determines willingness to pay per fish? A meta-analysis of recreational fishing values. Marine Resource Economics 21(1): 1-32.

Categorization of economic impacts by market and non-market values (see Appendix B).

Rabi J. Vandergon
Bemidji State University

Global climate change has recently come into popular light and is becoming widely accepted as a problem that must be addressed for a wide variety of reasons. This study provides an in-depth analysis into the impacts that global climate change may pose to Minnesota fisheries and recreational anglers. The literature review covers a range of topics from biological impacts on recreational fisheries to economic impacts. **The main goal of this study is to determine what impact climate change may pose to recreational benefits provided by the activity of angling.** Creel surveys from the Minnesota Department of Natural Resources Creel Database were utilized to determine statewide angler effort and preferences for certain species. Lake ice duration observations were gathered to determine current trends and future projections. These data were utilized and combined with fishing valuation literature to determine an economic impact from climate change. Lake ice duration is significantly decreasing statewide (Appendix F), extending the open water fishing season. Since more anglers fish during the summer months, this could lead to a net economic gain. On the other hand, bodies of water such as East Upper Red Lake seeing more anglers during the ice-fishing season could potentially see an economic loss. The project also utilized creel surveys to test the hypothesis indicating a statewide decline of trout species and northeastern shift of largemouth bass and sunfish from the onset of climate change (Appendix I). A multiple regression was performed on historical creel data to determine if there was a change in effort over time across different climate regions by species group. These variables were tested to determine their influence on the amount of fish caught. The regression indicated a positive relationship between the amount of effort and the amount of yield, but effort does not yet appear to be shifting regionally in response to climate change predictions. See Appendix B for a full description of this set of analyses.

Rabi Vandergon completed his masters of science in Environmental Studies in April 2010 at Bemidji State University with his thesis titled “Economic Impacts of Global Climate Change on Minnesota Fisheries through Decreases in Lake Ice” (see Appendix B).

Literature Review: Economic estimates for infrastructure and water quality impacts (see Appendix C).

Rabi Vandergon, Patrick G. Welle
Bemidji State University

An annotated bibliography for the economics of climate change and environmental quality was completed December 2008 (see Appendix C).

Result 2: Future Climate Projections for Minnesota.

Description: We propose to construct a database of possible climate scenarios (including temperature and precipitation patterns, frequency of extreme events, drought and flood episodes) that Minnesota may experience over the next 50 years. Scenarios will be constructed from observed episodes including cooler and wetter conditions at the end of the last century, warmer and drier conditions from the 1930s, and drier conditions from the 1950s. Trend and frequency analyses of historical data will guide the scenario selection. From climate projections we will develop projections of hydrologic and water quality responses of lakes and streams. Outcome: A database of temperatures, extreme events, flood and drought episodes, and physical responses likely to determine the character of Minnesota's water resources over the next 50 years.

Summary Budget Information for Result 2:		
	Trust Fund Budget:	**$ 47,017**
	Amount Spent:	**$ 47,017**
	Balance:	**$ 0**

Deliverable	**Completion Date**	**Budget**	**Status**
1. Climate data access system	December 2007	$14,672	Complete
2. Definition and analysis of climate regimes	June 2008	$14,672	Complete
3. Projection of climate regime scenarios to 2050	December 2008	$14,673	Complete
4. Model ice-out dates	December 2009	$ 3,000	Complete

Completion Date: *June 30, 2010*

Final Report Summary:

Climate data access system (see Appendix D, part 1).

Richard Skaggs[1], Kenneth Blumenfeld[1], James Zandlo[2]
[1]University of Minnesota, [2]Minnesota Department of Natural Resources, State Climatology Office

The climate data retrieval tool, developed by the State Climatology Office, was essential to all climatic research undertaken in this project, because relating climate data to aquatic ecosystems and hydrology is a complex undertaking: different species have different critical and optimal climate conditions that vary geographically and through time, and the hydrologic implications of climate vary with the local topography. Thus, climate summaries must be tailored to the specific questions and locations of interest. The climate data retrieval tool enabled project participants to extract climate variables important to their own specific questions, at time and space scales they deem relevant. While the climate data retrieval tool is available to project investigators only at the present time, the Office of the State Climatologist plans to make it available widely to Minnesota resource managers and researchers at the conclusion of the second phase of this project.

The climate data retrieval tool has two major components—a climate scenario visualizer and a climate time-series generator. The climate scenario visualizer uses monthly climate data and allows researchers to examine two climate variables of interest simultaneously, over an area or spatial unit of the investigator's choosing, including point locations, lakesheds, major and minor ecoregions, river basins, counties, climate divisions, and the entire state. Data can be viewed in the native monthly form, or aggregated into user-defined "seasons," such as November through March, or the "water year" of October through September.

For the spatial unit and month or season selected, the visualizer ranks the climate variables from lowest to highest and plots them on a graph. This allows to the investigator to determine which years match some important combination of the two climate variables for a particular location or area. For example, the investigator can isolate the years that were in the warmest and driest 10 percent during May through September over the Cottonwood River basin. Further details on using the visualizer, including example queries and the resulting images, are included in Appendix D.

The time-series generator extracts climate time series data for point locations in the state. The location is specified by the user, and the data can be summarized in many different ways. Once again, a user-defined season can be specified, along with the starting and ending years if the entire record is not wanted. For example, the cooling degree days for Roseville can be obtained by asking for the total or average degree days above 65 Fahrenheit for ZIP code 55113 from 1890 to the present. More detailed examples are provided in Appendix D.

Definition and analysis of climate regimes (see Appendix D, part 2)
Kenneth Blumenfeld, Richard Skaggs
University of Minnesota

Identification of historical climatic episodes was obtained by statistical analyses of monthly temperature and precipitation values for climatological divisions of Minnesota. Over the past 100 years, approximately half the years have experienced at least one multiple-month period of extreme temperature and/or precipitation. Here, an "extreme" is defined as a value of temperature and/or precipitation that is at least one standard deviation above or below the average during the season of interest. More specific results include the following:

- simultaneous wet/warm, and also cool/dry regimes are uncommon, especially during the growing season and summer
- warm regimes tend to be dry or have near-normal precipitation
- wet periods tend to be cool or near-normal
- dry periods tend to have warm or near-normal temperatures

Detailed statistics and results for a variety of seasons over Minnesota's nine climatic divisions are given in Appendix E.

Projection of climate regime scenarios to 2050 (see Appendix E).

Richard H. Skaggs
University of Minnesota

Introduction: Projections the climate of Minnesota for the remainder of this century must be rather general and include rather large uncertainties. In light of the resources available this report presents two projections. The first is of temperature, precipitation, and soil moisture on a monthly time scale for four points representing the northwest, northeast, southwest, and southeast climatological division of Minnesota. The data are part of the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset and are bias-corrected and spatially downscaled climate projections, which were obtained from the CMIP3 data The specific GCM used is the GFDL CM2.1 as run under the A2 (business as usual) scenario for CO_2 change over the century.

The second projection uses the GFDL CM2.1 A2 and B1 (rapid control of CO_2) scenarios but for daily data for a grid point that is located close to the Twin Cities metropolitan area. These data are used to estimate projected changes in maximum daily precipitation, annual maximum daily temperature, and annual minimum daily temperature for 10-year and 100-year return periods. The results are based on the generalized extreme value (GEV) distribution. The daily data are not bias-corrected. And it is likely that there is residual bias in the monthly data. Therefore, projected changes and not absolute values are presented for both the monthly and daily data analyses. The monthly temperature and precipitation data are time averaged over three periods: 1950-99, 2000-49, and 2050-99.

Results: It is clear that the temperature change will be greatest in the second half of the 21st century. Monthly temperature increases in the 2000-49 period are generally less than 2 degrees Celsius and generally well above 2 degrees Celsius in the second half of the century. There is an annual cycle of the monthly temperature increases with the largest increases occurring in the late summer and in the winter. The late summer temperature increases are larger than the winter increases in the southern part of the state but in the northern part of the state the two increases are comparable in magnitude. The late summer peak in temperature increase is very important when combined with the projected changes in precipitation.

Changes in precipitation are shown as percent change. Precipitation is projected to increase in most months with peaks of increase occurring in the late fall and early winter and in the spring. However, the months of July, August, and September are projected to have precipitation decreases or little change, which is crucial when combined with the temperature increase peak in the same months. In general, the projected precipitation changes are larger in the second half of the 21st century. Also the projected precipitation changes appear to be more erratic than the projected temperature changes. It is likely that using percent change is partially responsible, but it also the case that GMCs have a much harder time projecting precipitation.

The combination of the projected late summer increases in temperature and decreases in precipitation is crucial for soil moisture. The higher temperatures imply larger amounts of water loss (evapotranspiration) at the same time water supply is reduced. With rare exceptions, soil moisture is projected to decrease throughout the year. And the soil moisture decreases in the late summer are projected to be very large. In general, the soil moisture results demonstrate that the projected increases in precipitation are well short of what are required to offset the projected temperature increases and the associated projected increases in evapotranspiration. The soil moisture changes are shown as constant for four to six months depending on the location, scenario, and time averaging period, as the result of frozen soil.

While these monthly analyses are instructive, they do not provide insight into combinations of months into important seasons. For a look at seasons, we analyzed mean seasonal temperature and total seasonal precipitation for each year, for the two seasons of summer (June, July, and August) and winter (November through March), for the four climatological divisions, and for two carbon dioxide scenarios A2 (business as usual) and B1 (rapid emissions reductions). Twentieth century means and standard deviations were then calculated. Five categories of temperature and precipitation were constructed for each climatological division and season based on standard deviations from the mean as indicated in table 1.

Table 1. Five categories of temperature and precipitation.

Limits	Temperature	Precipitation
-2 sds or greater below the mean	very cold	very dry
-1 to -2 sds below the mean	cold	dry
-1 to +1 sds around the mean	normal	normal
1 to 2 sds above mean	warm	wet
2 sds or more above the mean	very warm	very wet

For each division and season the value of the boundaries of these categories were determined and the output of the A2 and B1 scenarios results were compared with the critical values to produce a frequency count of seasons in each category, season, and division in 50 year increments from 1950 through 2100

Conclusions drawn from analyses include:

- After removing the bias the models reproduce the 20th century temperature and precipitation regimes, as the second half of the century is well known to have been slightly warmer and wetter.
- The summer temperatures in the 21st century, especially in the last half, are projected to be much warmer for all divisions with most of the summer seasons being in the 20th century category of very warm.
- The winter temperature also are projected to be warmer but not to the degree of summer temperatures.
- Precipitation will not change to the degree that temperature changes; the changes are toward slightly wetter conditions but not significantly so.
- The largest changes in both temperature and precipitation occur in the second half of the current century.
- The combination of much high temperatures and little change in precipitation imply that summers will be much drier than was experienced in the 20th

century leading to a reduction in lake volume and stream flow and an increase in moisture stress for plants.

Daily Data Analyses: The GFDL CM2.1 daily data are for the period 1961 through 2099. Daily time series of maximum temperature, minimum temperature, and precipitation were acquired for the A2 and the B1 scenarios. The total time period was divided into segments: 1961-2000, 2000-49, and 2050-99. Within each time segment and each scenario, time series of the maximum temperature each year, the minimum temperature each year, and maximum daily precipitation each year were extracted. The GEV distribution was fit to each of the 18 time series. Results are expressed as changes rather than absolute values because the input data from the models are biased. The 24-hour, 10-year and 100-year return period maximum daily precipitation for the A2 and B1 scenarios are presented. But it is clear that the absolute values for the 1961-2000 base period are underestimates by nearly 50 percent. Thus it is necessary to focus attention on the percent increases, which range from about 1 percent for the B1 10 year return period to about 24 percent for the B1 100 year return period. The full 20th century records for annual maximum temperature, annual minimum temperature, and annual daily precipitation were analyzed by fitting the GEV to the appropriate annual time series. The differences were then applied to the results for the observed 20th century.

Summary

The broad outlines of the likely climate of Minnesota over the remainder the 21st century as projected by a particular GCM (GFDL CM2.1) seem relatively clear. The temperature will be warmer especially in the second half of the century and the late summer and winter. Precipitation will increase marginally except in the late summer. The combined temperature and precipitation changes likely will lead to decreases in available soil moisture and a general drying of the climate. The magnitude of maximum temperature extremes will increase while the coldest days are likely to be warmer. Precipitation in extreme events such as the 100 year storm will be larger.

Details of these analyses are presented in Appendix E.

Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy (2007). Fine-resolution climate projections enhance regional climate change impact studies', *Eos Trans. AGU, 88*(47), 504.

Model ice-out dates
Virginia Card
Metropolitan State University

Modeling of lake ice cover was completed in August 2009, and thus the results for both the LCCMR Climate Change Phase I and LCCMR Climate Change Phase II (LCCMR2007: this project) were reported in the final report for LCCMR2005 project: Impacts on Minnesota's aquatic resources from climate change Phase I - W-12. Below is a description of the ice-out modeling completed and available for use in other results. These data have been used for economic analyses, fish community and spawning responses, more in-depth analysis of statewide trends in ice-out date, and development of indicators.
Observational records of lake ice-cover were collected from across the state from a variety of sources including observers, newspapers, the Minnesota Department of Natural Resources, the Minnesota State Climatology Office, and the Minnesota Pollution Control Agency Citizens Lake Monitoring Programs, assembled into database form, checked for errors, and analyzed. This data set now includes more than ten thousand individual reports of ice-cover break-up, from 65 of Minnesota's 87 counties, from more than 1,400 lakes– approximately 1% of all lakes in Minnesota. Most of the ice-cover records are short, spanning an average of 6 or fewer years per lake, but many of the records are long or very long, including more than 120 lakes with records 21 years long or longer.

A set of 106 lakes was selected for further analysis, each of which had, in addition to ice-cover data, both long-term water quality and gill-net fish data, including at least 15 years of water quality data with at least 1 record in 1970s or before, and at least 8 years of gill-net fish data including at least 1 record in 1970s. This set includes 29 lakes with fisheries data from 1948-50 or earlier, and 23 lakes with water quality data from 1948-50 or earlier. From this set of 106 lakes, 75 lakes had either complete ice-out records for the period 1948-2008, or sufficient observational ice-out data to permit a complete record to be re-constructed for the period 1948-2008.

Ice-out records were checked and reconstructed using an empirical numerical model. Many ice-out records include occasional missing years in an otherwise continuous record. The empirical neighbor-comparison model used for this project is based on the principal that for any pair of neighboring lakes in the state, the ice tends to go out later on one than the other; in general, for any two lakes of similar depth and size, the lake to the north goes out later. This model compares the ice-out records from pairs of lakes are compared, calculates the exact relationship for years in which there are ice-out observations for both lakes, and uses this relationship to predict the ice-out date for each year in which the neighboring lake has an ice-out report. These predictions are made using a selected set of 6-10 lakes, generally with 50 km of the target lake, and the average of those predictions is used as the final modeled date. For the target lakes in this study, the dates produced by the model have average difference of less than 2-3 days, when compared to observational dates.

Error rates in historical records of lake ice-cover, due to observational, typographical and other sources, are within this same range or 2-3 days. Error rates in the ice-out records were assessed in three ways: by comparison of ice-out records from one lake by two or more independent observers; by comparison of multiple redactions of the same record; and by comparison of each year of a very long ice-out record to contemporary reports of ice-out dates from archival record at the Minnesota Historical Society. Overall, error rates in historical ice-out reports were found to be very low: untrained individual observers tend to differ in their report of ice-out date by an average of 1-2 days each year, and errors introduced during transcription tend to occur at a rate of about 1 per 20 dates, with an average error of about 2-3 days. The data set collected by the CLMP program of the MPCA has a very low error rate overall, the result of efforts that include providing a program definition of 'ice-out' and 'ice-in', regular annual collection of observations, and provision of a mechanisms for observers to do their own checking of the data entered into the CLMP data set.

The trend in ice out has been towards earlier dates, with the average loss of ice cover being 3-4 days earlier than 35 years ago. These ice-out records and the results of the modeled and error analysis were provided to other project- members, for use in analysis with regard to climate scenarios, fish populations, water quality, and economic impacts.

Ice-out timing trend analysis for Minnesota lakes 1948-2008 (see Appendix F)

David Staples[1], Lucinda Johnson[2], Dan Breneman[2], Virginia Card[3]
[1]Minnesota Department of Natural Resources, [2] Natural Resources Research Institute, University of Minnesota Duluth, [3] Metropolitan State University

One of the most obvious changes that can be attributed to changing climate is the shift in the seasonal patterns associated with lake ice formation and disappearance. Ices out dates are captured from a range of sources, including citizen monitoring in recent years. Virginia Card has assembled the historic ice out data for Minnesota lakes (see above), and has developed regression models to predict ice out records for neighboring lakes. A detailed examination of the observed and modeled ice out data are presented below, in an attempt to establish patterns in the geographic distribution of ice out patterns across the state, and with respect to lake characteristics (area and depth). Details of analyses are presented in Appendix G.

Methods: Data from 71 lakes in MN were used to show trends in both observed and modeled ice out dates. To account for repeated measures of lakes over time and correlated annual variation in ice out date among lakes, we used a mixed model (Venables and Ripley, 2002) to estimate the temporal trend in ice out date using the *lmer* function from the lme4 package in version 2.8.1 of the R statistical program (R Development Core Team, 2008).

The model was fit with the observed and modeled data separately, both models had practically identical trend estimates and very similar variance estimates as the model fit to the full data set, confirming no differences between the observed and modeled ice out data; all results shown below reflect the full data set with observed and modeled data combined.

Results: There was a significantly negative estimate of the fixed trend in ice out date; ice out dates were 0.144 days earlier per year, which translates to ice out happening about 1.4 days earlier per decade (Figure 1). The average ice out date, excluding random year effects, for the earliest measurements (1948-1950) was approximately the 111th day of the year. There was large variation among lakes (σ_L = 7.29 days) which represent the large variation in climate and lake morphologies across the state; however, when compared to spatial location (UTM coordinates) there did not appear to be a spatial pattern in the random lake effects.

There was a slight difference in the geographic pattern of the predictions in which more southerly points tended to ice out earlier than predicted and northerly points tended to be a little later than predicted. When accounting for north-south variation, the North-South predictor variable was highly significant suggestions that going North 1 km makes ice out tend to be .6 days later per decade. Over the course of the study period this would mean that southern lakes now lose their ice an average of 3.6 days earlier than southern lakes. No significant trends were apparent in the ice out patterns with respect to lake area or depth when geographic trends were also included in the models.

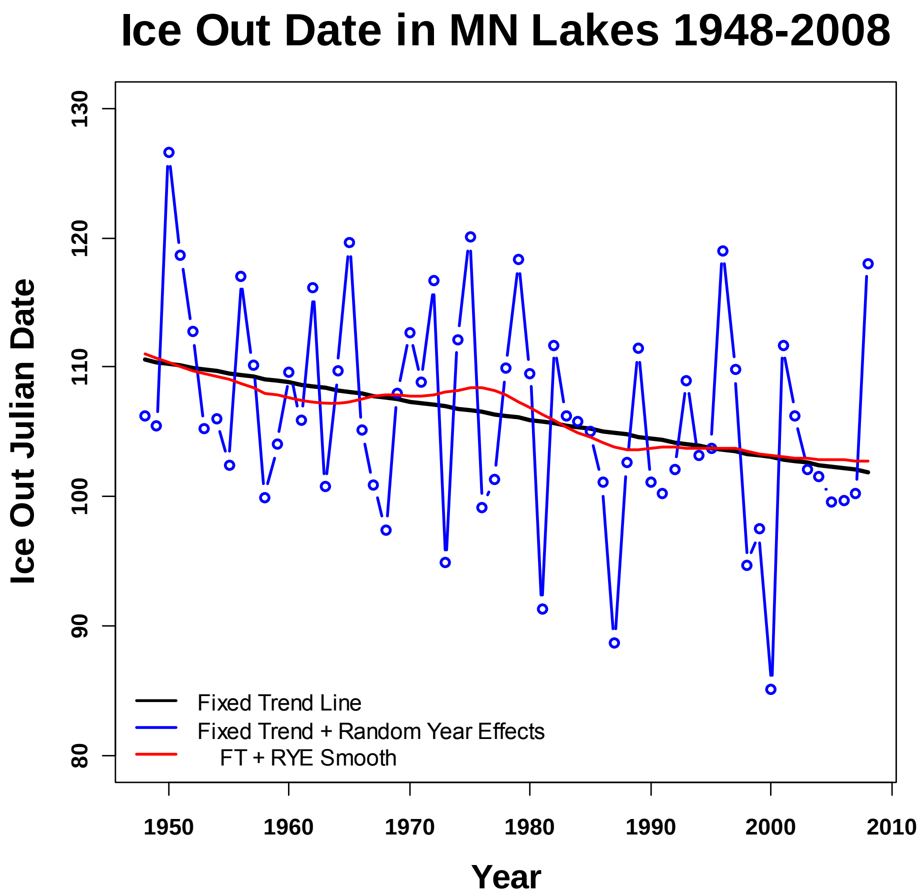

Figure 1. The fixed ice-out trend and year effects (added to show the annual deviations about the trend), in additional to a smooth fit of the trend plus year effects. This trend represents a decline in cie cover of 1.44 days per decade since 1950.

Result 3: Projecting Biological Responses to Changing Climate

Description: Fish populations and other biological communities will be affected by warmer water temperatures, and altered thermal regimes, changes in flow regimes, total flows, water level, and water quality. These changes will affect the health of aquatic ecosystems, with impacts on productivity, species diversity, and species and predict biological responses to climate change. However, data for physical properties such as hydrology and water quality are more abundant, and their responses to future climate scenarios can be modeled**.** We will use the historic trend data for biological communities, stream hydrology, lake level, and lake water quality data from our Phase I LCCMR Climate Change project and Result 2 (future MN climate predictions) of this proposal to predict invertebrate and fish population responses in Minnesota's rivers and lakes and make generalized projections across the state. Outcome: Projections of aquatic invertebrate and fish community responses to climate change scenarios from Result 2 using appropriate physical models.

Summary Budget Information for Result 3:	**Trust Fund Budget:**	**$ 94,931**
	Amount Spent:	**$ 94,931**
	Balance:	**$** 0

Deliverable	Completion Date	Budget	Status
1. Hydrologic and physical models predicting responses to future climate scenarios	June 2009	$19,879	Complete
2. Fish community responses to future climate	December 2009	$25,934	Complete
3. Water quality responses to future climate	June 2009	$24,558	Complete
4. Invertebrate responses to future climate	December 2009	$24,560	Complete

Completion Date: *June 30, 2010*

Final Report Summary:

HYDROLOGIC AND PHYSICAL MODELS

Annual stream runoff and climate in Minnesota's river basins (see Appendix G).
Todd R. Vandegrift, Heinz G. Stefan
St. Anthony Falls Hydrologic Laboratory, University of Minnesota

Stream flows recorded by the USGS from 1946 to 2005 at 42 gauging stations in the five major river basins of Minnesota and tributaries from neighboring states were analyzed and related to associated climate data. Goals of the study were (1) to determine the strength of the relationships between annual and seasonal runoff and climatic variables in these river basins, (2) to make comparisons between the river basins of Minnesota, and (3) to determine trends in stream flows over time. Climatic variables were air temperature, precipitation, the Palmer Drought Severity Index (PDSI), and the Palmer Hydrological Drought Index (PHDI); the latter are common indices of soil moisture.

Results: Water year averages showed stronger correlations than calendar year averages. Precipitation was a good predictor of stream flow, but the PDSI was the best predictor and slightly better than PHDI when linear regressions at the annual timescale were used. With an exponential regression PDSI gave a significantly better fit to runoff data than PHDI. Five-year running averages made precipitation almost as good a predictor of stream flow (runoff) as PDSI.

A seasonal time scale analysis revealed a logical stronger dependence of stream flow on precipitation during summer and fall than during the winter and spring, but all relationships for seasonal averages were weaker than for annual (water year) averages. Dependence of stream runoff on PDSI did not vary significantly by season. On a monthly timescale the strength of correlation between precipitation and runoff dropped off significantly, while PDSI was still a decent predictor in all months but the spring.

Annual stream flow in the Upper Mississippi River basin, including the Minnesota River basin, had the strongest dependence on precipitation and PDSI. The Red River of the North basin showed lower than average dependence on precipitation and average dependence on PDSI. The Rainy River basin and the Lake Superior basin showed the weakest dependence of annual stream flow on precipitation and PDSI.

The relationship between stream flow and precipitation can be expressed most easily by an annual average runoff coefficient, i.e., the ratio of runoff to precipitation in a year. Runoff coefficients vary significantly across the state of Minnesota, from more than 0.4 in the northeast to less than 0.1 in the northwest. Trends in runoff coefficients were estimated from averages for 20-year periods from 1926-1945 to 1986-2005, although data for 1926-1945 were sparse. According to our analysis, runoff coefficients in some of the major river basins of Minnesota have increased significantly during the last 40 years.

The Lake Superior and Rainy River basins have high and invariant characteristic runoff coefficients around 0.35. The Red River basin has the lowest characteristic runoff coefficient at ~0.14 but its value has consistently increased from the beginning of the record. The Mississippi Headwaters basin characteristic runoff coefficient has increased to ~0.24. The Minnesota River basin runoff coefficient (from the Minnesota River at Jordan, MN station) has also increased significantly and consistently to 0.19. The largest increases in runoff coefficients were found in the Red River and the Minnesota River basins, the two basins with the lowest runoff coefficients; runoff coefficients in some tributary or sub-watersheds have doubled. In the Lake Superior and Rainy River basins, and in the St. Croix River watershed, little change in runoff coefficients was found.

Overall runoff coefficients drop significantly from east to west in Minnesota. This distribution does not seem to have changed over time. Increases in runoff coefficients over time have been highest in the west, and lowest in the east of Minnesota. One can hypothesize that changes in stream flow in Minnesota's west are mainly due to land use changes that have lead to faster and easier surface runoff from the land since the beginning of European settlement. An explanation based on climatological factors can, however, also be offered. Precipitation has increased in all of the river basins of Minnesota over the time period of 1926 to 2005, but the largest changes have occurred in the south and west and little change in the northeast of Minnesota.

Changes in total annual runoff (in/yr) between 1946 - 1965 and 1986 – 2005 increased at 38 of 42 stream gaging stations analyzed. Only 4 gaging stations, 3 in the Lake Superior and Rainy River basins showed decreases, with all being less than 3%. The largest increases in average annual runoff were at 19 gaging stations in the Red River and Minnesota River basins; at 17 of these, increases were from 60% to 132%, and at the remaining two stations the increases were 19% and 20%. The southern Minnesota watersheds with the largest increases in runoff also had the largest increases in precipitation.

Overall, stream flow, expresses as annual runoff (in/yr), has increased since the beginning of stream gaging in Minnesota and the Upper Midwest, although periods of substantially lowered stream flows have occurred, e.g., in the drought period of the 1930s. Not only has the runoff (cm/yr) increased, but runoff coefficients, i.e., the ratio of runoff to precipitation, have also increased. When viewed as a percent change of annual runoff, the largest stream flow changes have occurred in the western part and the lowest in the eastern part of Minnesota. Increases in absolute values of annual runoff, percent of runoff, and runoff coefficients have been quantified in this study.

Projecting the impact of climate change on coldwater stream temperatures in Minnesota using equilibrium temperature models (see Appendix H)
William Herb, Heinz G. Stefan
St. Anthony Falls Hydrologic Laboratory, University of Minnesota

Coldwater streams are valued because they provide unique habitat for coldwater fish such as trout, and other animal species. Water temperature is the most important characteristic of coldwater stream habitat. Stream temperature is controlled by the balance of the heat fluxes across the water surface and the heat fluxes across the sediment surface (groundwater inflow and conduction to the sediment). In this study, a modified equilibrium temperature model was developed for coldwater streams, including the effects of both climate and groundwater inflow on stream temperature. It gives an upper bound, and in some cases, good prediction of, daily average temperature based on climate conditions, riparian shading, stream width, and groundwater inputs.

The modified equilibrium temperature models developed in this study are intended to be applicable to stream-average (generic) analyses with minimal in-situ data on stream geometry, rather than for detailed analyses of individual stream reaches. Additional expressions are derived and tested for distances and times required to reach thermal equilibrium, and for diurnal temperature amplitude. For a small tributary stream with relatively uniform riparian shading (South Branch), the modified equilibrium temperature gave good predictions of daily average stream temperature. The modified equilibrium temperature model also gave good estimates of daily average stream temperature for the main stem of the Vermillion when riparian shading was averaged over sufficiently long distances.

The stream temperature models were then used to characterize the response of water temperatures in three Minnesota coldwater stream basins to two projected climate change scenarios. Two of the study streams, Miller Creek and Chester Creek, are located in Duluth, Minnesota and are primarily fed by upland wetlands. The third stream, the South Branch of the Vermillion River, is located south of the Twin Cities, Minnesota, and is primarily fed by shallow groundwater. Two climate change scenarios were run: the Canadian Global Climate Model (CGCM) version 2.0 for a doubling of atmospheric CO_2, and the CGCM version 3.1 A1B scenario.

A sensitivity analysis conducted with the modified equilibrium temperature model confirms that water temperature in coldwater streams varies strongly with riparian shading, stream width, and both groundwater inflow rate and temperature. This sensitivity of stream temperature to groundwater parameters needs to be taken into account in climate change studies, since groundwater temperatures are expected to rise with air temperatures.

Overall, water temperatures in the streams were projected to increase between 4 and 5°C for the CGCM 2.0 CO_2 doubling climate change scenario, and between 3 and 4°C for the CGCM 3.1 A1B scenario. These stream temperature increases are larger than temperature increases projected by previous climate change studies based on air temperature – stream temperature regression analysis (2 to 3°C). Estimated increases in source water temperatures of groundwater due to climate change contributed about 60% of the total stream temperature increase, and the remaining 40% were provided by increases in atmospheric heat transfer. The ratio of the stream temperature increment to air temperature increment was found to vary from 0.8 to 1.08, larger than the slope of the observed stream temperature versus air temperature relationship.

Increases in source water temperatures were therefore found to contribute significantly to the response of stream temperatures to climate change. For the streams in Duluth, wetland temperatures were predicted to increase 2.7 to 3.5°C, based on a separate, calibrated heat transfer model. For the South Branch of the Vermillion River, groundwater temperatures were assumed to match long term increases in air temperature, ranging from 4 to 5°C. These results suggest that source water temperatures need to be considered in predicting the response of stream temperature to climate change. More work is needed to characterize groundwater and other water sources for coldwater streams.

A detailed report on stream temperature responses to climate in Minnesota can be found in Appendix G.

FISH COMMUNITY RESPONSES

Changes in Minnesota fish species abundance and distribution associated with local climate and lake characteristics (see Appendix I, Chapter 2).

Kristal Schneider[1], Raymond Newman[1], Donald Pereira[2]
[1]University of Minnesota, [2]Minnesota Department of Natural Resources

We analyzed historical Minnesota fisheries lake survey data (gillnet and trapnet) for 34 lakes, each with 15 to 43 years of data, to determine if fish distributions and abundances were changing over time. We then analyzed trends to determine effects of local climate on fish abundance and to determine if lake characteristics influenced trends in catch-per-unit-effort (CPUE) over time. Seven fish species from three families showed the strongest trends: centrarchids (*Micropterus salmoides*, *Micropterus dolomieu*, and *Lepomis macrochirus*); ictalurids (*Ameiurus melas* and *Ameiurus natalis*); whitefish (*Coregonus artedi* and *Coregonus clupaeformis*). We used simple linear regression to analyze CPUE over time, and we regressed mean latitudes of species occurrence against year to determine if ranges were advancing northward or contracting. Linear regressions were used to analyze the relationship between fish species' CPUE by lake and the following 5 temperature variables: maximum 7-day max temperature, average annual temperature, average summer temperature, average winter temperature, and degree-days above 5°C. We used stepwise regressions to determine if variability in slopes of CPUE vs. year could be explained by lake surface area, maximum depth, latitude, or longitude, and ANOVA to determine if variability in slopes could be explained by Schupp's lake classes. Linear regressions of CPUE vs. year indicated that centrarchid abundance was increasing, black bullhead (*Ameirus melas*) abundance was decreasing, and other species were increasing in some lakes and decreasing in others. The ranges of all species were significantly advancing northward except smallmouth bass and whitefish. Regressions of CPUE versus air temperature showed that bass and sunfish were increasing in lakes as summer air temperatures increased, and whitefish were decreasing in lakes as air temperatures increased. Location, lake surface area, and lake class may explain some variability in slopes of CPUE versus year. In summary, temporal trends in the abundance and distribution of some centrarchids, ictalurids, and whitefish may be responding to climate change, and trends may be affected by lake characteristics. Detailed results can be found in Appendix K.

Kristal Schneider completed her masters of science in June 2010 at the University of Minnesota with her thesis titled 'Biological Indicators of Climate Change: Trends in Fish Communities and the Timing of Walleye Spawning Runs in Minnesota". Chapter 3 of her thesis addressed fish community trends and is summarized above. Chapter 2 of her thesis was included in the final report for LCCMR2005 project: Impacts on Minnesota's aquatic resources from climate change Phase I - W-12 and has been accepted for publication.

Trend analyses for species of concern: Analysis of CPUE data for walleye, cisco, and smallmouth bass 1970-2008 (see Appendix J.)

David Staples[1], Lucinda Johnson[2], Jennifer Olker[2], Dan Brenneman[2]
[1]Minnesota Department of Natural Resources, [2]Natural Resources Research Institute, University of Minnesota Duluth

In addition to expected changes in the ranges of fish species, abundance also is expected to change. Prior models have projected changes in the availability of cold water fish habitat (REF) in Minnesota lakes. We hypothesized that cold water fish species such as cisco (also known as tulibee) and other salmonids would decline in abundance, while cool and warm water species (walleye, smallmouth bass) would increase in abundance.

Methods: Abundance measured as gill net catch per unit effort (CPUE) on walleye (2203 lakes), smallmouth bass (465), and cisco (701) from Minnesota lakes were examined for trends during the period 1970-2008. To account for repeated measures of lakes over time and correlated annual variation in catch per unit effort

(CPUE) among lakes, we used a linear mixed model (Venables and Ripley, 2002) to estimate the temporal trend in CPUE using the *lmer* function from the lme4 package in version 2.8.1 of the R statistical program (R Development Core Team, 2008).

A mixed model has two components, a fixed effects portion and a random effects portion. In this case, the fixed effect portion was an ordinary linear regression of $\log_e$ CPUE+1 versus time:

$$CPUE_j = \beta_0 + \beta_1 * j + \varepsilon_j,$$

for $j = (-19,\dots, 19)$ representing the years 1970-2008, and for residual error $\varepsilon_j \sim N(0, \sigma)$. The β_1 parameter represents the intrinsic growth rate of the population (assuming CPUE is proportional to abundance); if the β_1 parameter is greater than zero, abundance is exponentially increasing, and conversely, if the β_1 parameter is less than zero, the abundance is declining over time.

The above regression would be a satisfactory model for a time series from a single population; however, our interest is not just in CPUE trends for a single lake, we also wanted to estimate the large scale, statewide trend in CPUE for each species. To analyze the data at that level, we use time series from many lakes (e.g., over 2200 lakes for walleye); however, the joint analysis of multiple time series introduces correlations among the observations that could potentially bias the trend estimate. We accounted for these correlations with random effects for year and lake-specific trends, giving the mixed effects model for the CPUE value in year *j* at lake *i*:

$$CPUE_{ij} = (\beta_0 + b_{0i}) + (\beta_1 + b_{1i}) * j + \psi_j + \varepsilon_{ij},$$

where b_{oi} and b_{1i} are random adjustments to the intercept and slope terms for lake *i*, and were assumed to be distributed as $N(0, \sigma_{L0})$ and $N(0, \sigma_{L1})$ respectively. The ψ_j term accounts for correlations in CPUE measurements within year *j*. Note that using the random effects adds 3 variance parameters to the model; an equivalent fixed effects-only model would use thousands of parameters for to account for individual lake and year effects. Though b_{0i}, b_{1i}, and ψ_j are not estimated parameters in the model, we can derive unique predictors of the individual lake regression coefficients and year effects. These predictors are denoted as BLUPs for 'best unbiased linear predictors,' and can be used to determine annual deviations from the linear trend and to estimate CPUE trends in the individual lakes. For example, the terms (β_0 + b_{0i}) give the mean CPUE value for lake *i* in 1989 (excluding the random year effect), and the (β_1 + b_{1i}) terms give the trend in CPUE for lake *i*. We also used the lake BLUPs to evaluate differences in mean CPUE or trend over latitudinal, longitudinal, maximum lake depth, and lake geomorphic (lake area, depth) gradients.

Walleye (*Sander vitreus)***:** The overall trend estimate for walleye was slightly positive (0.0007), but was not statistically different from zero ($t = 0.52$; $p = 0.61$ on 37 df). The variation in mean $\log_e$(CPUE+1) among lakes had a standard deviation σ_{L0} = 0.65, and the standard deviation of individual lake trends was σ_{L0} = 0.019; BLUPs of individual lake trends varied from a 5% per year decline to a 5% per year increase. Of the 2203 lakes with walleye gillnet captures 10.1% (223 lakes) had per year declines greater than 1%, while only 12.9% (283 lakes) had per year increased greater than 1%; the remainder of the lakes (77%) had changes less than 1%, which could not be distinguished from no or flat trend. The annual variation about the fixed trend (i.e., random year effects) had a standard deviation $\sigma_Y = 0.074$ (see figure below for plot of fixed trend along with random year effects).

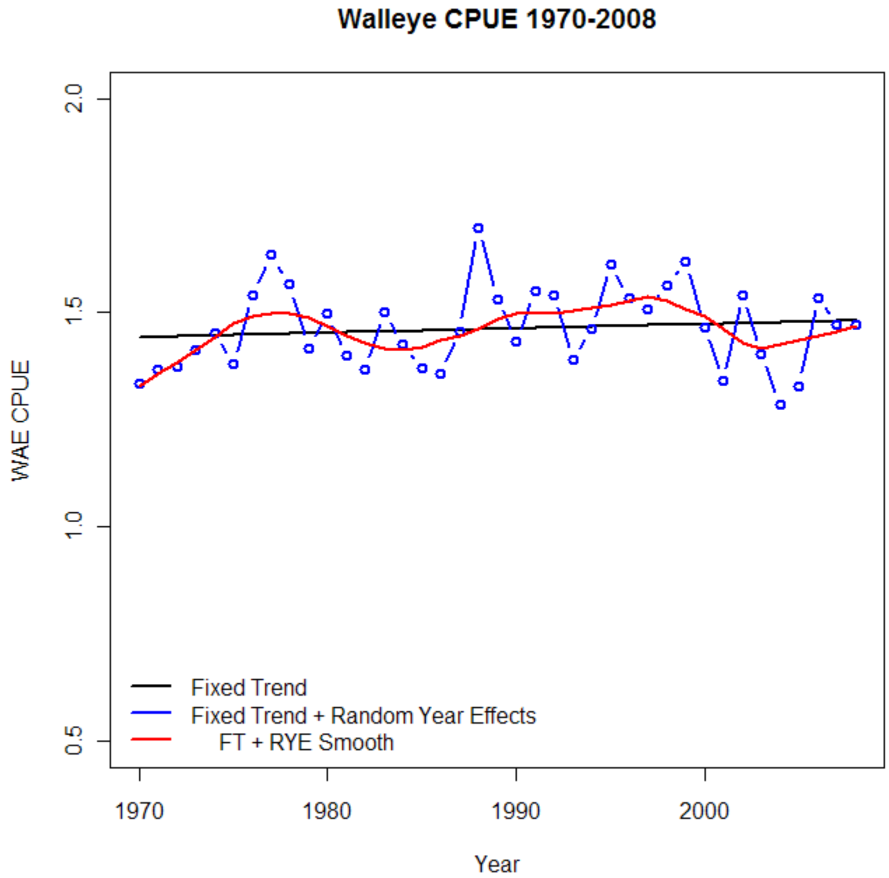

Figure 1. Average CPUE trend and annual deviations for walleye CPUE in 2203 MN lakes.

Cisco (*Corregonus species*): The overall trend estimate for cisco was significantly negative (-0.014, t = -5.28, p < .0001 on 37 df), indicating about a 1.5% per year decline since 1970. The variation in mean $\log_e$(CPUE+1) among lakes had a standard deviation σ_{L0} = 0.73, and the standard deviation of individual lake trends was σ_{L0} = 0.025; BLUPs of individual lake trends varied from a 5% per year decline to a 5% per year increase. Of the 701 lakes with cisco gillnet captures 63.9% (448 lakes) had per year declines greater than 1%, while only 4.4% (31 lakes) had per year increased greater than 1%. The annual variation about the fixed trend (i.e., random year effects) had a standard deviation σ_Y = 0.13 (see Figure 2 for plot of fixed trend along with random year effects).

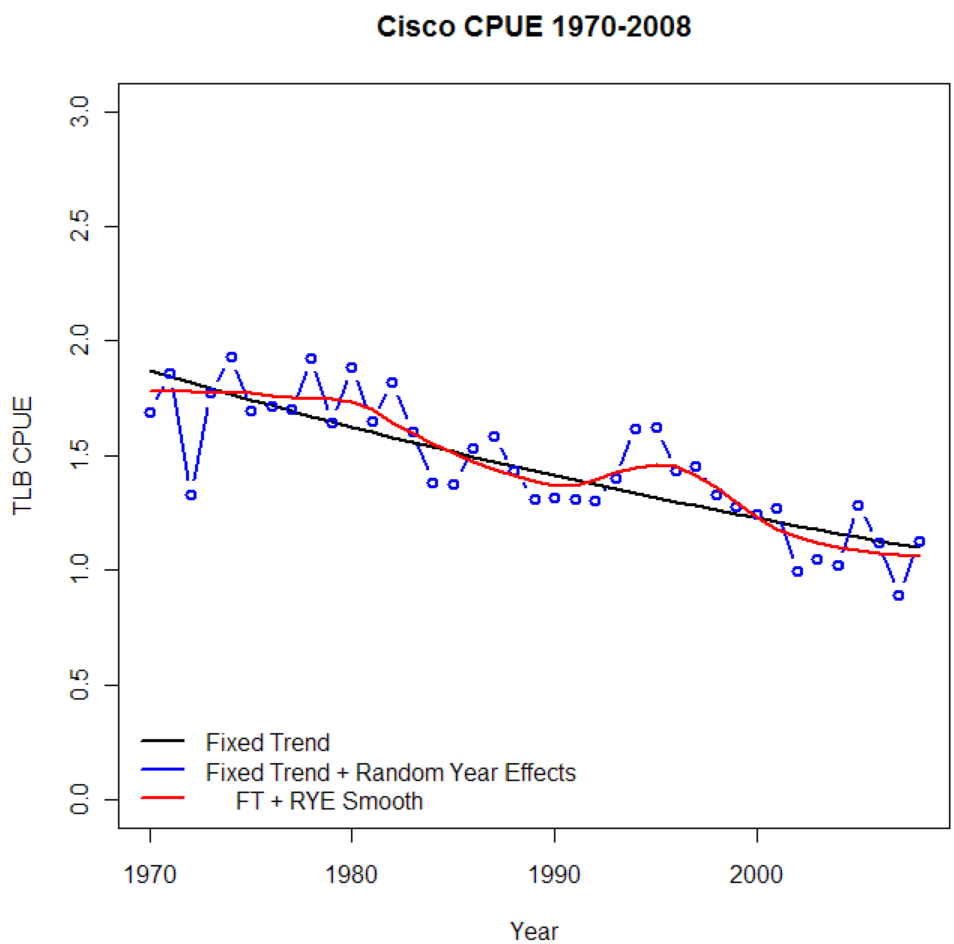

Figure 2. Average CPUE trend and annual deviations for cisco CPUE in 701 MN lakes.

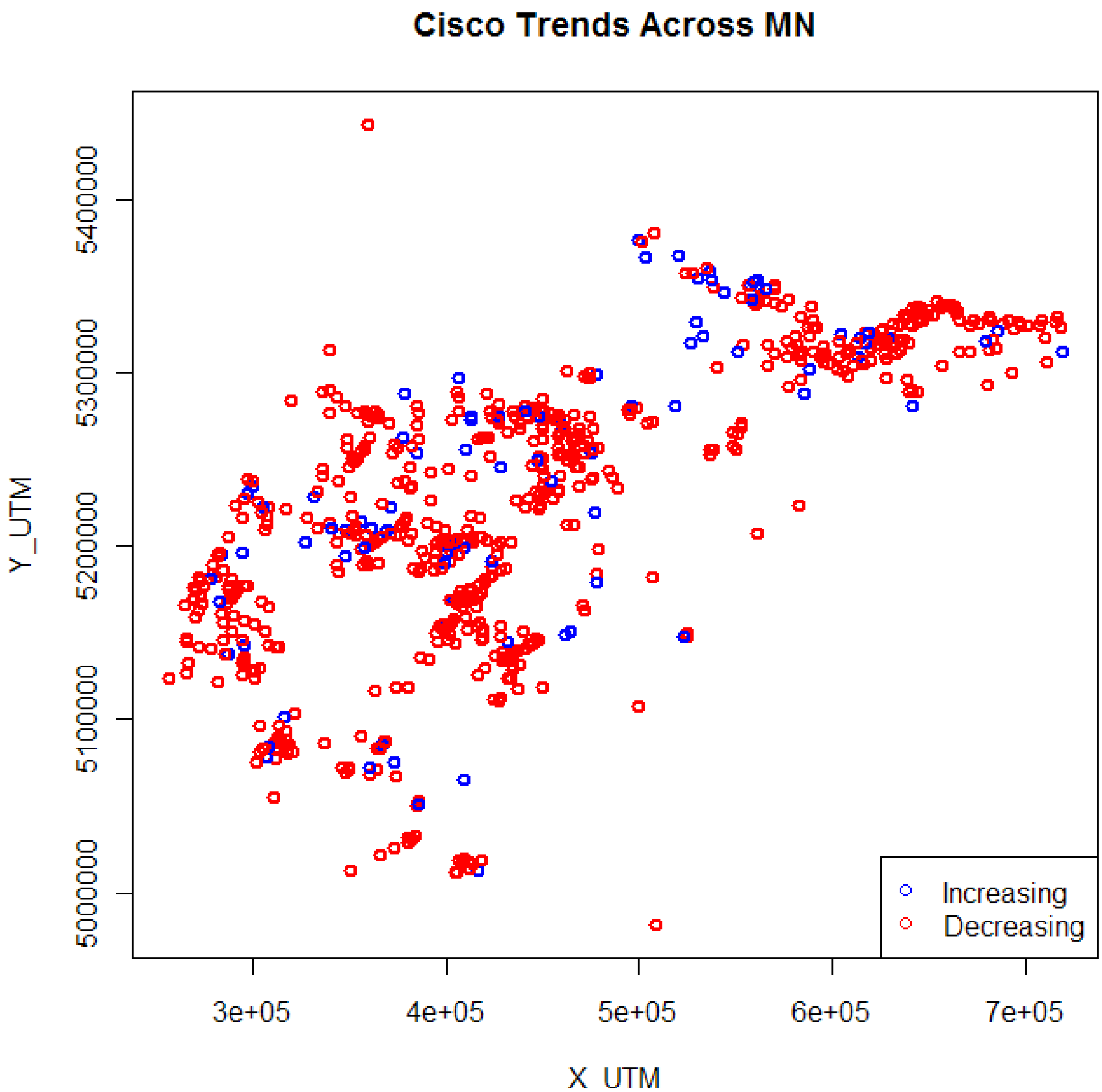

Figure 3. Spatial distribution of increasing and decreasing cisco lakes.

We did not detect a strong spatial pattern for increasing versus decreasing lakes (Figure 3). Nor did we detect any geomorphic relationship to increasing versus decreasing lakes or strength of decreasing trends. This is likely because the natural distribution of cisco includes deeper, coldwater lakes which mainly occur in the northern part of the state.

Smallmouth Bass (*Micropterus dolomieu*): The overall trend estimate for smallmouth bass was slightly positive (0.0006), but was not statistically different from zero (t = 0.35; p = 0.73 on 37 df). The variation in mean $\log_e$(CPUE+1) among lakes had a standard deviation σ_{L0} = 0.40, and the standard deviation of individual lake trends was σ_{L0} = 0.016; BLUPs of individual lake trends varied from a 4% per year decline to a 3.5% per year increase. Of the 465 lakes with smallmouth bass gillnet captures 6.7% (31 lakes) had per year declines greater than 1%, while 9.3% (43 lakes) had per year increased greater than 1%; the remainder of the lakes (84%) had changes less than 1%, which could not be distinguished from no or flat trend. The annual variation about the fixed trend (i.e., random year effects) had a standard deviation σ_Y = 0.067 (see Figure 4 for plot of fixed trend along with random year effects).

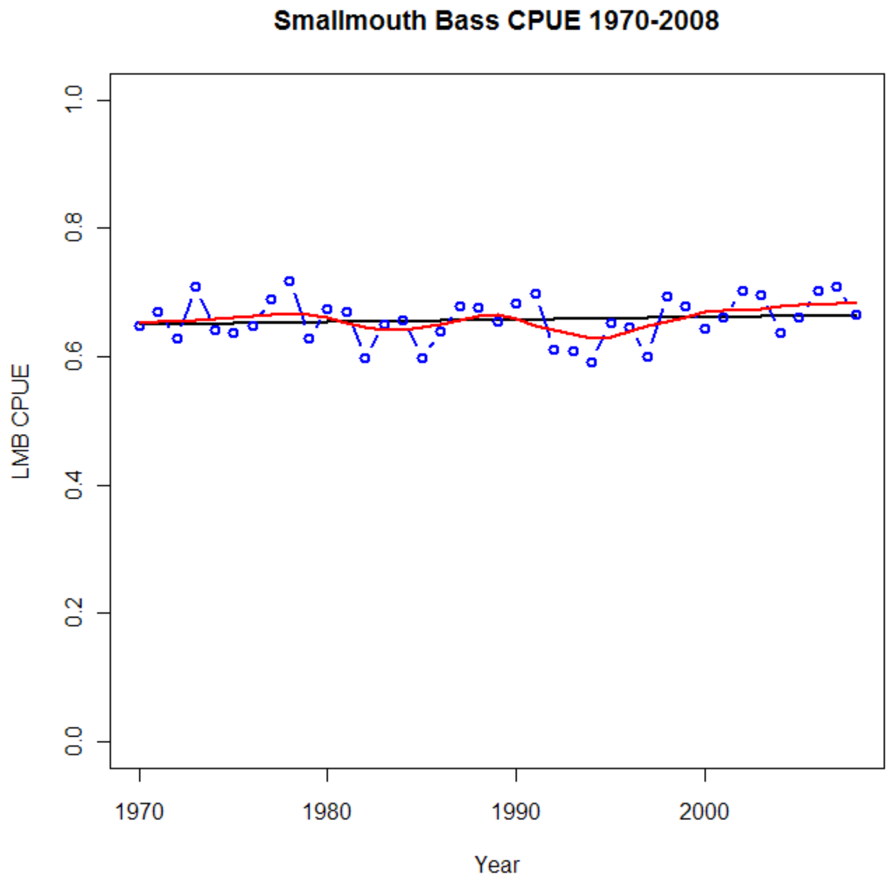

Figure 4. Average CPUE trend and annual deviations for smallmouth CPUE in 465 MN lakes.

We then plotted the average decadal abundance of four groups of fish adapted to different thermal regimes including cisco (coregonids), and trout (salmonids)), bullhead (ictalurids) and bluegill (centrarchids) for lakes which were shown to have surface water temperatures that were increasing at a greater than average rate (positive BLUPs; see below). These plots show a trend for large increases in centrarchid abundance, and a decline in coregonid abundance (Figure 5).

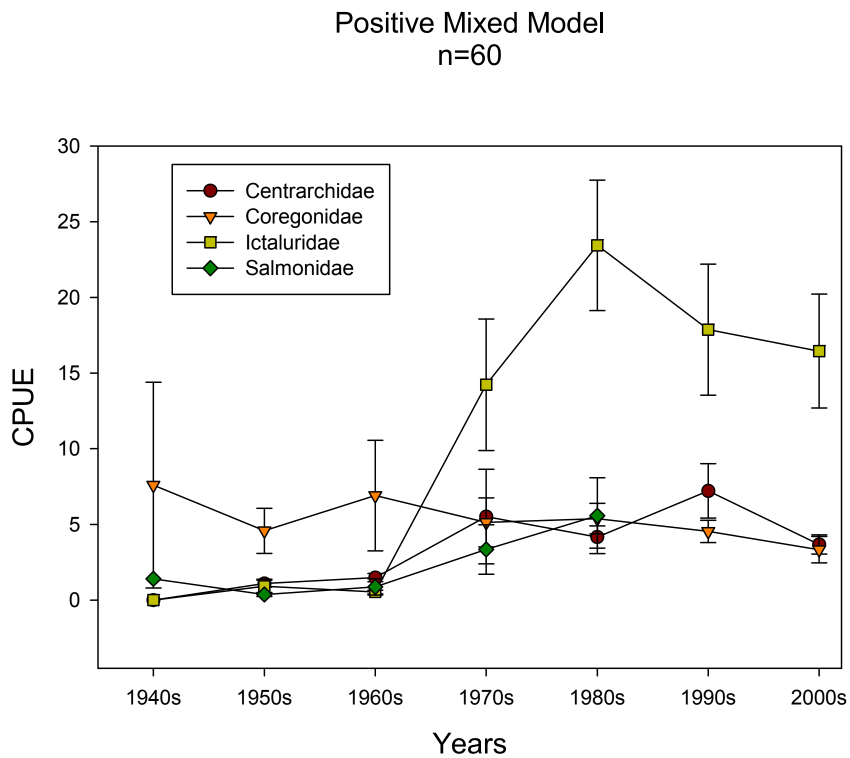

Figure 5. Fish assemblage changes in lakes showing a positive temperature trend based on results of the mixed model regression (60 lakes with long-term temperature records and fish abundance records).

Similar, but more exaggerated trends were observed for the 24 lakes with long term fish abundance data whose surface water temperatures showed significant positive trends based on the Mann Kendall analysis (see below).

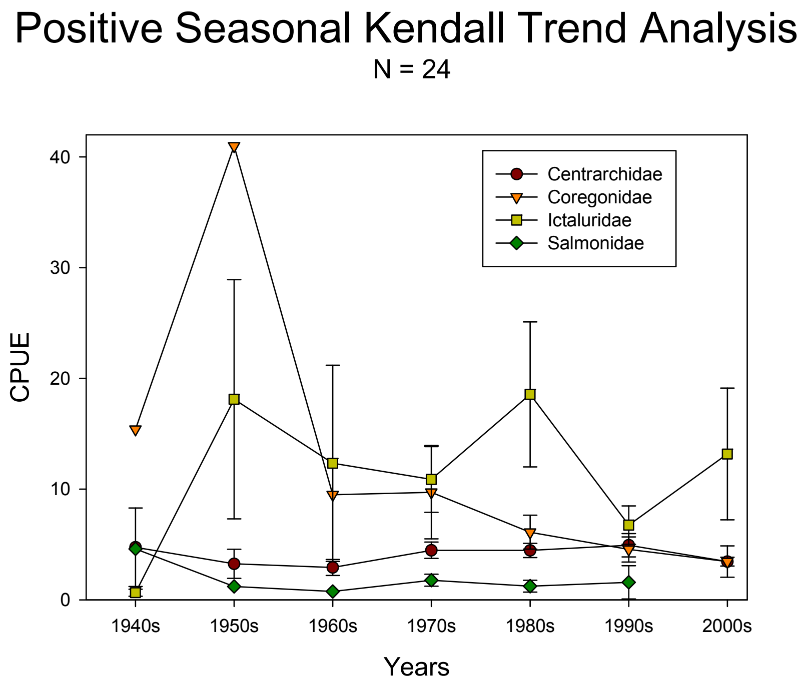

Figure 6. Fish assemblage changes in lakes showing a positive surface water temperature trend based on the Seasonal Kendall Trend analysis (24 lakes). See Appendix M for a discussion of these trend analysis data.

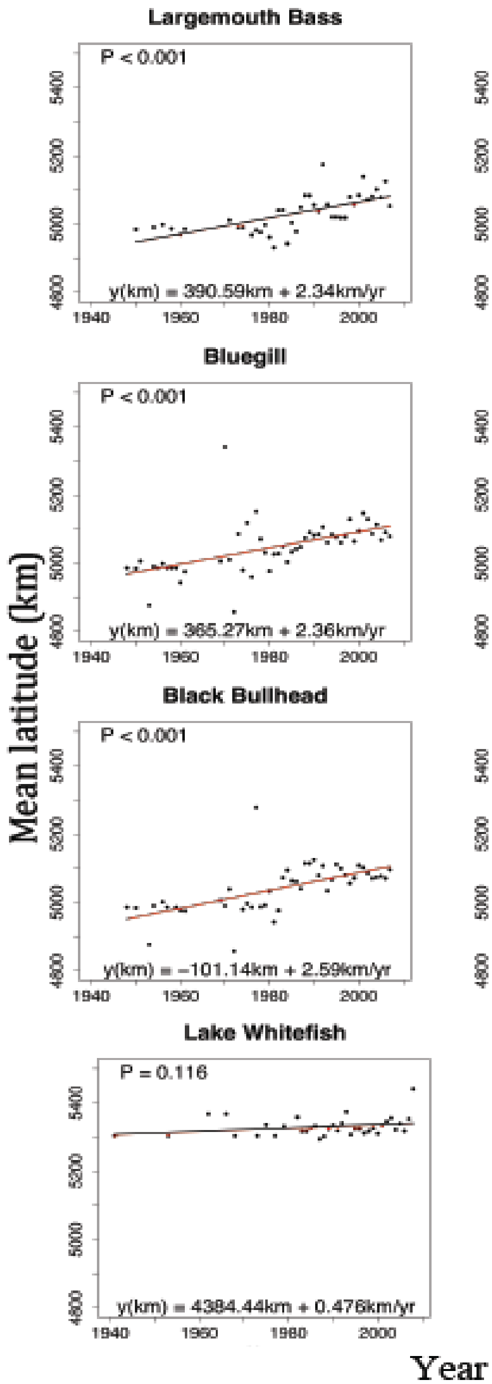

Figure 7. Changes in fish assemblages with latitude (from Schneider 2010). See Chapter 2 within Appendix I for a detailed discussion of these data.

WATER QUALITY RESPONSES

Water quality data was compiled, summarized and made available to project personnel as part of the LCCMR2005 project: Impacts on Minnesota's aquatic resources from climate change Phase I - W-12. The main accomplishments are summarized below but the full report is included in Appendix F of the 2005 project. Trends in water quality have been further analyzed with several methods, which are summarized below and detailed in Appendix K.

Lake water quality data

Richard Axler, Norm Will, Elaine Ruzycki, Jerry Henneck, Jennifer Olker, Joseph Swintek

[1]Natural Resources Research Institute, University of Minnesota Duluth

The focus of this effort was to:

1. Compile existing water quality data from lakes with long ice-out records to test for statistical associations;
2. Compile water quality data from lakes with >15 years of at least one water quality parameter and perform exploratory time trend analyses on all available parameters;
3. Develop an on-line Google-map based website for summarizing and presenting the results of the exploratory statistical analyses to allow other investigators to better visualize the data. The Water Quality Trend Tool would be a prototype for the Minnesota Pollution Control Agency and Minnesota Department of Natural Resources to consider for improving public access and understanding of lake water chemistry.

Mann-Kendall trend analysis

Trends and trend rates over time were determined using the Seasonal Kendall Trend Analysis software developed by the U.S. Geological survey that allow for trend analyses both seasonally and regionally. Sites were initially identified sites "Qualifying" if they had records from at least 5 different years and with a level of significance of $p < 0.1$ for either a positive or negative trend over time. Additional exploratory trend summaries with accompanying mapping tools were generated for $p < 0.05$ and < 0.01 and lakes having more years of data (5, 8, 12 and >18 years). Because of the large number of options for analyzing this broad data set, a comprehensive subproject website was constructed to make the trend results available to other project scientists and ultimately other interested individuals and groups (Minnesota Lake Trends Analyses website: (http://mnbeaches.org/gmap/trendswebsite). Google Maps TM-based tools were added for retrieving and displaying trend data including: a seaarch tool for lakes; ecoprovince, ecoregion and county boundary overlays; selection options for the long-term "Ice Out" lakes from this project and for the new DNR/MPCA SLICE (i.e., Sentinel) lakes. The website includes "processed raw" data, complete metadata, summary tables, links to Google Maps TM that identify sites with descriptive statistics, and graphs (box and whisker and regressions). The data are also incorporated into the larger project database that is now being used for more detailed examinations of climatic associations, geographic patterns, size and depth patterns, and associations with fish, and ice cover data.

Results: Thus far, the exploratory analyses have shown that for lakes with significant time trends during the period June–September, more than 90% showed surface water warming as compared to cooling. This result was found for over 26% of those lakes with at least 5 years of data (247 of the 551 lakes examined) and almost 2/3 of the 60 with 18 years or more data. Significant temperature trends were found in 37 of 60 lakes with 18 or more years of data. Of these, four flow-through lakes showed a negative trend in temperature, and 33 lakes showed positive trends. These lakes exhibited an increase of about 3°F over the period of record. Unfortunately, all of these lakes are clustered around the Twin Cities region, thus no trend is available for outstate lakes. Although only 16% of lakes with >5 years of data had significant trends in thermocline depth, 85% of those that did exhibited decreasing (i.e., shallower) thermocline depths. Thermocline gradient (stability) only showed statistically significant trends in 10-18% of lakes depending on the length of data record, but almost all trends were positive. Together these thermal effects over time suggest shallower, but more stable depth of stratification which is consistent with surface warming. The data also suggest that in those lakes, the hypolimnion (bottom most waters) could be more isolated from mixing of epilimnetic (surface waters) water although the population of lakes with such trends is relatively small. Trends in hypolimnetic water for two meter depth strata below a depth of 6 meters, showed the opposite effect with a preponderance of cooling trends. About 20% of the lakes having at least 5 years of temperature profile data had statistically significant trends and more than 75% of these exhibited cooling over time. This result is consistent with the surface warming and thermocline trends described above and the findings were similar whether there were 5, 8, 12 or 18 years of data.

Trend results were less clear for dissolved oxygen (DO). The number of positive versus negative trends in surface waters was similar although 60-75% showed increasing DO in the lakes with 12 to more than 18 years of data – an anomalous finding since one might have expected slightly decreasing DO due to warmer water. However, hypolimnetic strata for >20% of the lakes with available data showed significant trends with a clear (>75%) preponderance of increased DO.

The salt content of surface waters, as estimated by specific electrical conductivity (EC25), and chloride concentration has increased over time in more than a third of the lakes with >5 years of data, 50% of those with >8 years, and 90% with >18 years of data. This is consistent with increased summer surface warming but also with potential increased exposure to winter de-icing salts and/or increased stormwater runoff from either urban or agricultural areas. Increased loading to the whole lake such as would occur from runoff inputs are suggested by the fact that the trends with depth examined for the entire summer and for just the warmest month (July) all exhibited large (82-100%) predominance in increased relative to decreased salinity. Only ~15-19% of the lakes with >5 years of surface water pH data exhibited trends and there were roughly similar numbers of positives and negatives; only for the 37 lake data set having >18 years of data was there an excess in one direction - this being towards higher pH. This could potentially be a consequence of the Minnesota sulfate emission standards program but would need to be assessed on a lake by lake basis. Anomalously, alkalinity trends were overwhelming negative by > 80%: 20% for a substantial number of lakes and for all lengths of data records. We currently do not have an explanation for this rather striking result.

Perhaps the most surprising result found in this study was that there was internal consistency within the group of trophic status indictors (secchi depth clarity, chlorophyll-a, total phosphorus and total Kjeldahl nitrogen) that suggests an overall improvement in water quality. These trends were found for a large number of lakes- ~40% of the lakes in the secchi data set had statistically significant trends, and of these >80% were increasing (i.e., clearer water). This result was similar whether there were 5, 8, 12 or 18 years of data so the trend is nearly two decades old. We corroborated this result using an independent (software) Kendall statistical analysis for surface temperature, thermocline depth, secchi depth, surface chlorophyll-a, surface total phosphorus, and TSI-secchi data and also by cross-comparing our secchi trend rates with MPCA's estimates for CLMP lakes with more than 15 years of data. In both cases, the differences in results were negligible.

Overall, many lakes showed trends for many water quality parameters. However, it is extremely important to note that the current set of lakes is not distributed randomly across the state and is visually heavily biased towards the Minneapolis-St-Paul metropolitan area. More work is needed to examine individual lake records to see if these general trends are consistent for well monitored lakes. The analysis should also be extended to lakes with five or more years of data for parameters highlighted by this exploratory analysis since many of the trends found for longer data records were also significant when lakes were pooled with those with 5-8 years of data. There is also a need to calculate percent dissolved oxygen saturation as a "check" on some of the DO concentration results. Irrespective of temperatures in the upper mixed layer (epilimnion), most lakes would be expected to be saturated with oxygen in surface and near-surface water. This parameter was historically not calculated nor entered into STORET but could be calculated from DO concentration based upon corresponding temperature and EC25 values coupled with approximate lake surface elevation. As for other components of this overall Climate Change project, the exploratory analyses conducted to date point to the value and need for consistently collected environmental data over long periods of time for a large number of geographically distributed lakes in order to manage them most effectively.

Water quality responses during historical climate regimes (see Appendix K).

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To detect the effects of extreme seasonal weather on water quality we used the water quality data and climate regimes (also called scenarios) summarized in Appendix E and reported in Appendix F of the LCCMR2005 project: Impacts on Minnesota's aquatic resources from climate change Phase I - W-12.

Methods: We used the following water quality indicators to test for responses in years with temperatures and precipitation outside of the ‘normal’ range: secchi depth, surface temperature, specific electrical conductivity (EC25), thermocline depth, trophic state index (TSI), surface levels of chlorophyll, and surface levels of phosphorus. Surface measurements included measurements from zero to two meters deep, with averages across these depths if both were recorded.

Each variable was tested independently over 3 different extreme weather cases: warm-wet, cold-wet and warm-dry. A region was considered ‘warm’ for a particular year if the temperature of that region for that year or portion of year was greater than 1.5 standard deviations above the mean temperature for that region over all years. Similarly a year was considered to be ‘cold’ for a region when the temperature for that year or portion of year was 1.5 standard deviations below the mean temperature. ‘Wet’ and ‘dry’ were identified with the same process using precipitation for the year or portion of year and 1.5 standard deviations above or below the mean precipitation levels, respectively. Only years that were extreme in both temperature and precipitation were included in these analyses: warm and dry, warm and wet, or cold and wet. Cold-dry was not used do to the lack of years that would be considered cold and dry. All three combinations of the comparisons for the contrasts of warm-wet, cold-wet and warm-dry are used. A lakes value for a variable for an extreme climate was the average of the lakes values for that variable over all years that were considered that combination of extreme climate for which there was data.

The effect extreme climate on water quality was tested using two methods with two sub-deviations of each way. Lakes that have values for both types of extreme climates were compared using a Mann-Wilcox paired test. This paired comparison analysis was completed for all lakes statewide as well as for lakes considered shallow across the state. Shallow lakes were further examined on a regional basis, using climate divisions, which allowed pooling of lakes by assuming that the sample set included lakes fairly homogeneous in water quality and morphometry. This analysis tested the effect extreme weather has on water quality within a region by performing a Mann-U test on all lakes within that region over all three possible extreme weather contrasts. Non-parametric tests were used because of the non-normality and heavy tailed nature of the data.

Table 1. Summary of significant water quality responses comparing years that were cold-wet, warm-wet, warm-dry (based on at least two standard deviations from the mean temperature and precipitation) across all lakes across Minnesota, and shallow lakes by climate division as well as statewide. Results are in **bold** if response in both all lakes and one of shallow lakes analyses; results in ***bold italics*** if response in both shallow lake analyses. n=sample size; Δ = difference between compared climate regimes

	Type of analysis		
Water quality indicator	**All lakes - statewide[a]** (pairwise comparisons)	**Shallow Lakes - Statewide[b]** (pairwise comparisons)	**Shallow Lakes - by Climate Division[c]**
Secchi depth (m)	Cold-wet<warm wet (n=235; p<0.0001; δ 0.18 m) Warm-wet> warm-dry (n=72; p<0.0001; δ 0.38 m)	***Cold-wet>warm-wet*** (n=42; p<0.05; δ 0.17 m)	South central: ***cold-wet>warm-wet*** (n=19,37; p<0.02; δ 0.17 m)
Mean trophic state index (TSI)	**Cold-wet<warm-dry** (n=90; p<0.05; δ 1.3) **Warm-wet<warm-dry** (n=72; p<0.01; δ 2.2)	**Cold-wet<warm-dry** (n=41; p<0.01; δ 3.6) ***Cold-wet<warm-wet*** (n=43; p<0.001; δ 3.4) Note: warm-dry to warm-wet comparison non-significant with n=252	South central: ***cold-wet<warm-wet*** (n=21,37; p<0.05; δ 3.4) West central: **warm-wet<warm-dry** (n=76,61; p= 0.08; δ 4.0)
Specific electrical conductivity (EC25)	Cold-wet<warm-wet (n=23; p<0.001; δ 140 µs /cm)	Warm-wet<warm-dry (n=42; p<0.001; δ 31 µs/cm)	None significant
Surface water temperature (°C)	**Cold-wet<warm-dry** (n=11; p<0.05; δ 2.6°c) **Cold-wet<warm-wet** (n=44; p<0.001; δ 4.0°c)	**Cold-wet<warm-dry** (n=6; p<0.05; δ 3.4°c) **Cold-wet<warm-wet** (n=7; p<0.05; δ 3.2°c) ***Warm-dry<warm-wet*** (n=80; p<0.01; δ 0.4°c)	South central: **cold-wet<warm-dry** (n=6,10; p<0.05, δ 2.0°c) **cold-wet<warm-wet** (n=6,10; p<0.05, δ 1.3°c) West central: **cold-wet<warm-dry** (n=8,16; p<0.05; δ 2.1°c) **cold-wet<warm-wet** (n=8,17; p<0.01; δ 2.5°c) East central: ***warm-dry<warm-wet*** (n=86,227; p<0.001; δ 0.9°c)
Thermocline depth (m)	None significant	None significant	None significant
Chlorophyll	None significant	None significant	None significant
Total phosphorous	None significant	None significant	None significant

[a] May-Oct Climate data, June-Sept WQ data
[b] May-Oct Climate data, June-Sept WQ data, (same results with water year Climate data)
[c] May-Oct Climate data, May-Oct WQ data

Summary: Across all lakes and analyses, warmer air temperatures resulted in warmer surface water temperatures. This pattern occurred in both warm-wet years and warm-dry years. Additionally, warm years had greater productivity than cold years, with the highest productivity in warm-dry years in shallow lakes as well as when all lakes were analyzed. We did not detect any effect of the potential for extra nutrients from runoff or wind in wet years. Specific electrical conductivity (EC25) was higher in warm and wet years in the statewide analysis with all lakes. This suggests a warm versus cold effect, which could be due to evaporation. Warm wet years also were associated with reduced algal growth and increased clarity, but we have been cautious about making conclusion due to the small sample size (n=23) which may be skewing the data.

In shallow lakes, secchi depth was shallower in warm years compared to cold years. This was an expected response, as cooler summers could have led to reduced algal growth (or vice versa); however the opposite response was detected when all lakes statewide were analyzed. We did not expect to find this response of deeper secchi depth in warm-wet years than in cold-wet years, suggesting that warm and wet periods from May-Oct led to clearer water (presumably from decreased algal growth). Although a warm summer could lead to a more stable stratification, a wet year might be expected to produce more wind leading to higher mixing (of some hypolimnetic nutrients) and certainly increased watershed runoff of nutrients.

Surface water temperature trends

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Water temperature data from 558 Minnesota lakes were examined for trends during the period 1970-2007. The data are temperature readings over time for the lakes, taken at a variety of water depths and at different times during the open-water season. For these analyses, we utilized only water temperature readings from depths of 0-2m taken from June to October. To account for repeated measures of lakes over time and correlated annual variation in temperature among lakes, we used a linear mixed model (Venables and Ripley,2002) to estimate the temporal trend in temperature using the *lmer* function from the lme4 package in version 2.8.1 of the R statistical program (R Development Core Team, 2008). The analysis goals were to describe patterns and trends in temperature data at state-wide, regional, and individual lake levels, in addition to examining for differences in temperature trends over spatial and geomorphology gradients. Specific results are presented in Appendix L.

Methods: A mixed model has two components, a fixed effects portion and a random effects portion. In this case, the fixed effect portion was an ordinary linear regression of water temperature versus time, adjusted for month of sample (Jun-Oct) and water depth category (0m and 0-2m):

$$\text{Temp}_j = \beta_0 + \beta_1 * j + M_k + D_h + \varepsilon_j,$$

for j = (-24,…, 13) representing the years 1970-2007 shifted by subtracting 1994, M_k representing the effect of month k = (Jun, Jul,…,Oct), D_h representing the effect of depth category h = (0 m and 0-2 m), and for residual error $\varepsilon_j \sim N(0, \sigma)$. The β_1 parameter represented the average annual change in temperature for this group of 558 lakes. Because the year data were shifted, the β_0 parameter represents the average temperature (excluding year effects we discuss below) over the group of lakes in 1994 for the reference month and depth category (August and 0 m respectively).

The joint analysis of multiple time series introduces correlations among the observations that could potentially bias the trend estimate. We accounted for these correlations with random effects for year and lake-specific trends, giving the mixed effects model for the temperature in year j at lake i:

$$\text{Temp}_{ijkh} = (\beta_0 + b_{0i}) + (\beta_1 + b_{1i}) * j + M_k + D_h + \psi_j + \varepsilon_{ijkh},$$

where b_{oi} and b_{1i} are random adjustments to the intercept and slope terms for lake i, and were assumed to be distributed as $N(0, \sigma_{L0})$ and $N(0, \sigma_{L1})$ respectively. The ψ_j term accounts for correlations in temperature measurements within year j, and was assumed to be distributed as $N(0, \sigma_Y)$. Though b_{0i}, b_{1i}, and ψ_j are not estimated parameters in the model, we can derive unique predictors of the individual lake regression coefficients and year effects. These predictors are denoted as BLUPs for 'best unbiased linear predictors', and can be used to determine annual deviations from the linear trend and to estimate temperature trends in the individual lakes. For example, the terms $(\beta_0 + b_{0i})$ give the mean temperature for lake i in 1994 (excluding the random year effect), and the $(\beta_1 + b_{1i})$ terms give the trend in temperature for lake i. We used the lake BLUPs to evaluate regional differences in mean temperature or trend over latitudinal, longitudinal, maximum lake depth, and lake geomorphic gradients.

The temperature data were not the result of a true random sample of MN lake water temperatures over time; e.g., over 57% of the 29,275 temperature readings in the data set were taken from the East Central region of the state. Thus, there was the potential that the fixed estimate of trend, β_1, would not represent temperature trends in areas of the state with fewer samples. To evaluate the robustness of the full model in describing trends across the state, we fit the above model for 9 regions of the state separately.

Results:

Statewide model

The trend estimate for the statewide model was slightly positive (0.014), but was not statistically significant (t = 1.28; p = 0.21 on 38 df). The variation in mean temperature among lakes had a standard deviation σ_{L0} = 1.18, and the standard deviation of lake trends was σ_{L1} = 0.05. The annual variation about the trend (i.e., the random year effects) had a standard deviation σ_Y = 0.69 degrees C; there was no temporal autocorrelation in the year effects, though they do suggest a slight nonlinearity in water temperatures between 1970 and 2007 (see figure below for temporal plot of fixed trend and random year effects).

Random effects:			
Groups Name	Variance	Std. Dev.	Corr
DOWLKNUM (Intercept)	1.3822266	1.175681	
Year	0.0021308	0.046161	0.151
Year (Intercept)	0.472351	0.687278	
Residual	4.6782457	2.162925	
Number of obs: 29275, groups: DOWLKNUM, 558; Year, 38			

Fixed effects:			
	Estimate	Std. Error	t value
(Intercept)	23.0138	0.14002	164.36
DepthRange00-02m	-0.17413	0.0258	-6.75
PeriodNameJul	1.13891	0.03997	28.49
PeriodNameJun	-1.99697	0.04077	-48.98
PeriodNameMay	-7.81504	0.04342	-179.98
PeriodNameOct	-11.75615	0.05555	-211.62
PeriodNameSep	-4.29226	0.04139	-103.71
Year	0.01403	0.01098	1.28

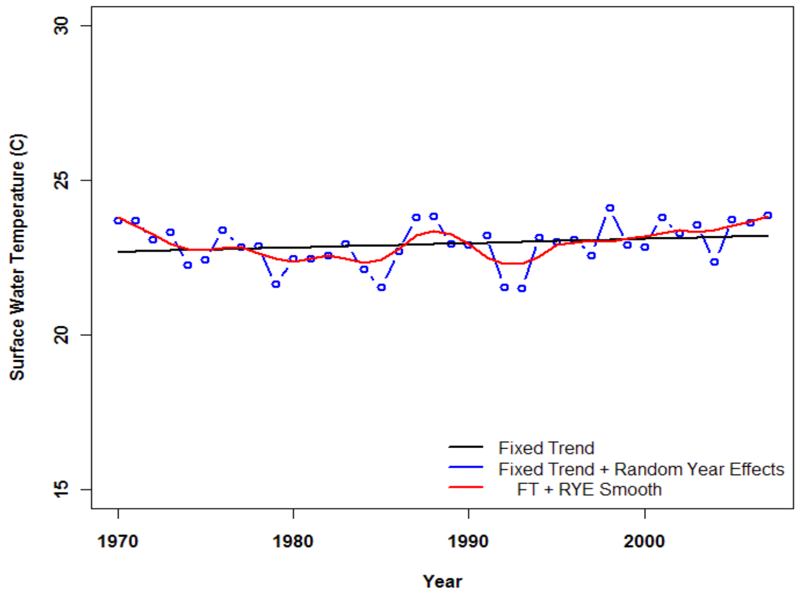

Figure 1. Fixed temperature trend and annual deviations for the statewide water temperature model.

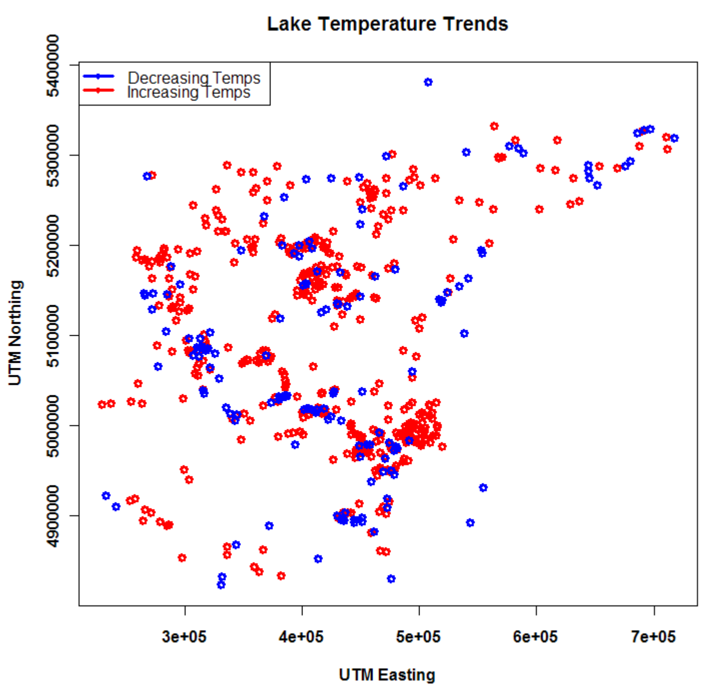

Figure 2. Spatial comparison of lakes with increasing and decreasing temperature trends.

Regional Model Comparisons

The estimated trend in all regions was similar to the statewide estimate in that they were all slightly positive but statistically not different from zero (see table and figure below for regional trends).

Region	Fixed trend
Northwest	0.029
North Central	0.047
Northeast	0.006
West Central	0.009
Central	0.015
East Central	0.018
Southwest	0.011
South Central	0.007
Southeast	0.009
Statewide	*0.014*

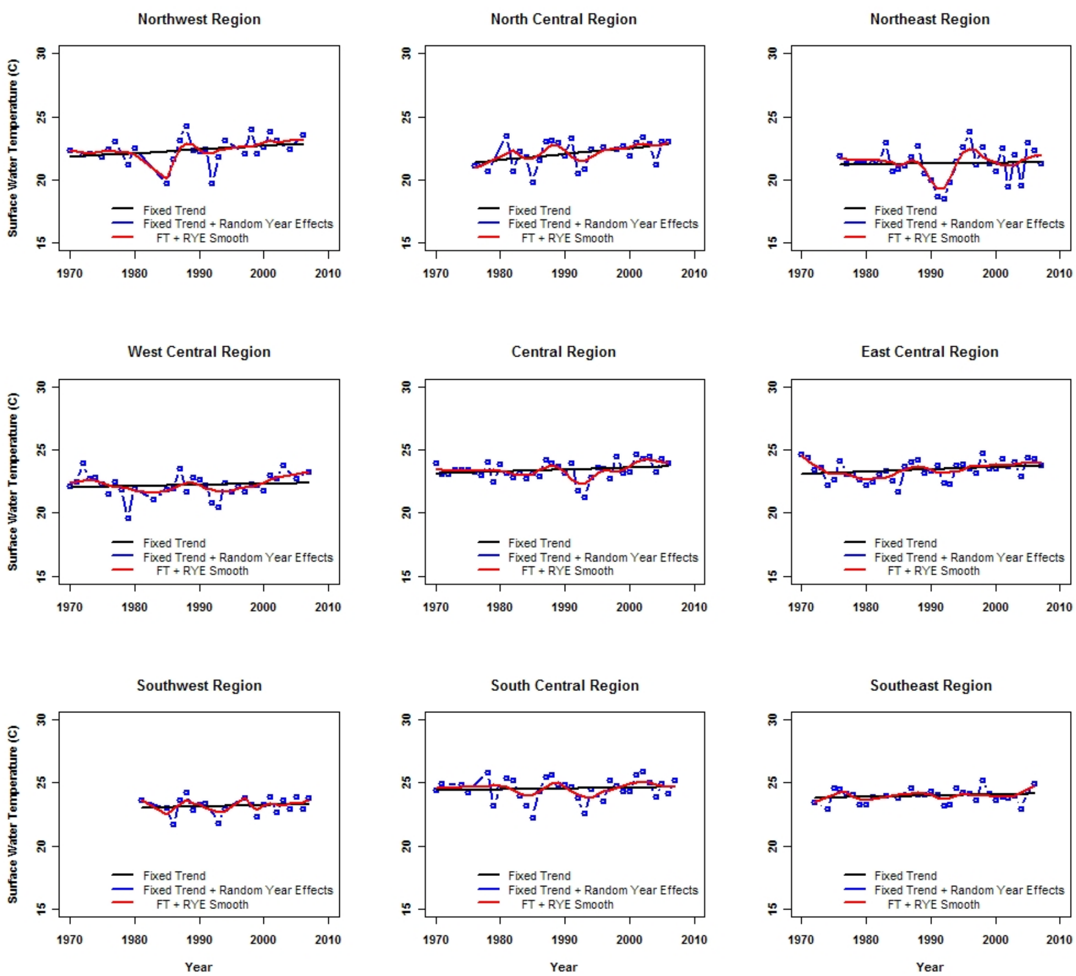

Figure 3. Trends in surface water temperatures for lakes within the 9 climate of Minnesota.

INVERTEBRATE RESPONSES

Aquatic invertebrates are important constituents of the food web in lakes, serving as prey for important fish species, and as biological indicators for environmental assessment. We planned to assess trends in lake and riverine invertebrate responses to changing climate, but found insufficient historic data upon which to base our analyses. Monitoring invertebrates within Minnesota lakes and rivers has been sporadic, with only 21 streams samples between 1976 – 1979, and 45 streams sampled in the Minnesota River Basin in 1990-1992l Thus, both the total number of systems monitored, and the number of lakes or rivers with repeated visits is low. As a result, trends could not be established for this indicator. Similarly, aquatic vegetation data, which was earlier compiled from MN DNR databases (Reschke et al. 2005, NRRI), was poorly distributed with respect to overlap with existing water quality and fishery data.

We used the resources dedicated to this result to enhance the web tools for extracting water quality data (see water quality trends, above), and to conduct additional analyses on fish community and ice out responses.

Result 4: Identify Optimal Indicators of Climate Change on Aquatic Systems.

Description: Planning an effective long-term monitoring and surveillance program requires identifying scientifically defensible, cost-efficient indicators, and testing methods for their deployment. However, reliable indicators of climate change and climate change impacts have not been identified. Based on the results from our Phase I LCCMR Climate Change project and this Phase II project, plus data compiled from a previous LCMR project on Environmental Indicators (led by Clarence Turner) and other related projects conducted by our team of scientists, we will propose indicators and recommend appropriate sampling protocols. An inventory of established monitoring programs will ensure existing programs are utilized where possible. Outcome: Recommendations of indicators and sampling protocols for assessing potential climate change impacts.

Summary Budget Information for Result 4:		
	Trust Fund Budget:	**$ 72,594**
	Amount Spent:	**$ 72,594**
	Balance:	**$ 0**

Deliverable	**Completion Date**	**Budget**	**Status**
1. Identify indicators	December 2009	$54,443	Completed
2. Compile sampling protocols	June, 2010	$18,151	Completed

Completion Date: *June 30, 2010*

Final Report Summary:

A cascade of interacting factors involving climate change-related shifts in temperature extremes and precipitation patterns, interacting with anthropogenic disturbances is certain to alter both water quality and biological assemblages in Minnesota's rivers and lakes. Climate change will affect chemical and biological water quality standards during development of the standard and during compliance monitoring (Barbour et al. 2010). It also can affect the underlying habitat in lakes and streams as a result of both temperature extremes, as well as disruption resulting from extreme weather events. The cumulative effects of changing climate will shift the baseline conditions at reference locations, and will thus require shifts in water quality and biological criteria. Furthermore, interactions with other anthropogenic factors (e.g., changing land use patterns) may cause unanticipated changes as thresholds and nonlinear responses occur within the ecosystem. Managers and policy makers must be prepared to adaptively manage regulations in response to these uncertainties.

Outside of the U.S. a number of countries have begun to implement regulatory frameworks and research agendas in response to the global challenge of a changing climate. The European Union (EU; (http://ec.europa.eu/environment/climat/studies/) and Australia (http://ec.europa.eu/environment/climat/studies/) are two countries with robust research agendas intended to provide support for science-based decision making. The United States Global Change Research Program (http://www.globalchange.gov/) also is intended to provide research support for climate-related studies. In addition, programs within the US government are being established to promote strategies to address effects of climate change at local and regional levels (e.g., Landscape Conservation Cooperatives (LCC's)).

A recent symposium published in the Journal of the North American Benthological Society (2010: volume 29(4), examined the impacts of climate change in relation to aquatic ecosystem management issues. Papers focused on describing impacts of climate change to aquatic ecosystems and communities, shifts in functional responses of the biotic communities, and responses to interacting stressors. Important take-home messages include:

1. Headwater streams may be important refugia and source of colonizers for aquatic assemblages in higher elevation regions (Herbst and Cooper 2010)
2. Changes in biodiversity as a result of differential responses to changing climate may have profound effects on baseline conditions that are used to define ecological status of a system (Durance and Omerod 2010).
3. Many metrics used in environmental assessment protocols respond differentially to temperature stress and other pollutants; new protocols are proposed to correctly identify metrics that are responsive to intended stressors rather than changing climate (Hamilton et al. 2010).
4. Shifts in species equitability (i.e., relative dominance of individuals within a community) may be an early warning indicator of climate change disturbance (Feio et al. 2010).
5. Species traits associated with thermal preferences are able to distinguish climate-related impacts from other stressors (Stamp et al. 2010); but other

traits including dominance of macroinvertebrates with large, long-lived species, and maximum body size of individuals (Lawrence et al. 2010) or flow-sensitive taxa (Poff et al. 2010) may be good indicators as well.

6. Restoration of streams impaired by land use appears to buffer the impacts of changing climate (Verdonschot and van den Hoorn 2010).

Recommended Indicators

Based on the data derived from our analyses, we recommend the following indicators be considered for monitoring potential impacts of climate change on Minnesota's lakes and streams. This list is biased towards data for which there are currently reasonably long-term records; additional indicators are listed below.

1. Ice-out date- Minnesota's historical ice-out dates for lakes is a useful tool for monitoring climatic conditions. Continued cooperation with state agencies and volunteers will provide even more standardized data collection and better indicators of change. Citizen monitoring is an essential component of this data gathering effort. See http://climate.umn.edu/doc/ice_out/ice_out_historical.htm for pertinent information about documenting ice out.

   Data should be sent to: ice.pca@state.mn.us. Reports should include name of the observer, CLMP number, lake name, ice-off date, and ice-on date (if available). If not already reported, historical dates from past years are especially valuable. Questions about ice cover can be submitted by e-mail, or from Ed Swain at 651-757- 2772 (Twin Cities) or 800-657-3864 (Greater MN).

2. Timing of walleye spawning runs- Walleye spawning runs and ice-out are occurring earlier in some lakes but not all (Schneider et al. Appendix K). However, there was a strong relationship between first egg-take and ice-out dates, and walleye egg-take appears to provide a good biological indicator of climate change. Because there is a strong relationship between dates of first egg-take and ice-out, and because ice-out has previously been related to climate change, the timing of walleye spawning runs may be a useful biological indicator of climate change.

3. Abundance of fish species:
   a. Largemouth bass and sunfish
   b. Whitefish and trout
   c. Cisco (Coregonus sp.)

   Sampling protocols are cited in MN DNR (1993).

4. Water Quality Parameters: The water quality parameters that have been found to respond to changing climate are listed below. These parameters are currently embedded in the state's water quality monitoring program (see *Minnesota's Monitoring Strategy 2004–2014; Anderson and Lindon 2006).*

a. Transparency (measured as water clarity observed from surface to Secchi plate disappearing and reappearing in the water column. Indicates light penetration, water staining, and amount of suspended particles in the water column. An average depth to nearest 0.1 m from repeated observations is recommended.)
b. Water Temperature (in degrees C from surface and 5 m increments where possible)
c. Conductivity (the ability of water to carry an electrical current. Measured as specific conductance (µmhos/cm) of water compensated to 25^0C)
d. Dissolved Oxygen (% saturation or mg/L. the oxygen concentration available for respiration by aquatic organisms)
e. Turbidity (light scattering property of water caused by suspended particles. Measured with a turbidimeter and expressed in nephelometric turbidity units (NTUs))
f. pH (negative log of hydrogen ion [H+] concentration)
g. Nutrients: (total phosphorus (P), total suspended solids (TSS), ammonia nitrogen (NH_3+NH_4), and nitrite-nitrate (NO_2+NO_3)).

The indicators identified herein are biased towards long-term data that are currently collected by the state's agencies. Additional indicators that could also provide important information include:

1. Macroinvertebrate assemblage traits related to thermal preferences, body size, life history, and flow preferences.
2. Trends in macroinvertebrate and fish assemblage composition that account for species shifts in dominance patterns.

Finally, we also recommend that: 1) management agencies increase efforts to collaborate on data collection to maximize the number of lakes for which both water quality and biological data are collected. Only 17 lakes have both 20 years of gillnet fish data and water quality data as well. When we tried to incorporate data dating back to the 1970's when climatic conditions began to change perceptibly, far fewer lakes has both data types, thus, long term trends are very difficult to track given this data record. 2) Agencies maximize efforts to use a common data framework to ensure that data can be assembled into a common database with minimal effort. 3) Further resources should be set aside to ensure the long-term viability of the climate data retrieval tool developed by the State Climatology Office. Currently this tool is accessible to a small number of researchers and staff because of limited computing (server) resources required to allow simultaneous access to the system. 4) Further resources also should be made available to allow all of the state's water quality data into the climate change database. Currently, the database contains data records for lakes with a minimum of 15 years of data for a single water quality parameter. We feel this database should be expanded to include data from lakes with a minimum of 5 years of data for a single parameter. This would maximize our ability to detect trends across both water quality and biological monitoring programs. 5) The state should consider establishment of a sentinel river (or watershed) program, in parallel with the sentinel lake program (http://www.dnr.state.mn.us/fisheries/slice/index.html).

References Cited:

Anderson, P, and M. Lindon. 2006. Standard operating procedures (sop): lake water quality sampling. Wq-sl-16. Minnesota Pollution Control Agency, Water Quality Programs and Monitoring Standard Operating Procedures. (http://www.pca.state.mn.us/index.php/view-document.html?gid=6492).

Barbour, M. T., B. G. Bierwagen, A. T. Hamilton, and N. G. Aumen. 2010. Climate change and biological indicators: detection, attribution, and management implications for aquatic ecosystems. Journal of the North American Benthological Society 29:1349-1353.

Durance, I., and S. J. Ormerod. 2010. Evidence for the role of climate in the local extinction of a cool-water triclad. Journal of the North American Benthological Society 29:1367–1378.

Feio, M. J., C. N. Coimbra, M. A. S. Grac¸A, S. J. Nichols, and R. H. Norris. 2010. The influence of extreme climatic events and human disturbance on macroinvertebrate community patterns of a Mediterranean stream over 15 y. Journal of the North American Benthological Society 29:1397–1409.

Hamilton, A. T., J. D. Stamp, and B. G. Bierwagen. 2010. Vulnerability of biological metrics and multimetric indices to effects of climate change. Journal of the North American Benthological Society 29:1379–1396.

Herbst, D. B., and S. D. Cooper. 2010. Before and after the deluge: rain-on-snow flooding effects on aquatic invertebrate communities of small streams in the Sierra Nevada, California. Journal of the North American Benthological Society 29:1354–1366.

Lawrence, J. E., K. B. Lunde, R. D. Mazor, L. A. BeˆChe, E. P. Mcelravy, and V. H. Resh. 2010. Long-term macroinvertebrate responses to climate change: implications for biological assessment in mediterranean-climate streams. Journal of the North American Benthological Society 29: 1424–1440.

Minnesota's Water Quality Monitoring Strategy 2004 to 2014. A report prepared for the U.S. Environmental Protection Agency, August 2004.

Minnesota Department of Natural Resources. 1993. Manual of instructions for lake survey. Special Publication No. 147. Minnesota Department of Natural Resources Section of Fisheries Saint Paul, MN.

Poff, N. L., M. I. Pyne, B. P. Bledsoe, and C. C. Cuhaciyan. 2010. Developing linkages between species traits and multi-scaled environmental variation to explore vulnerability of stream benthic communities to climate change. Journal of the North American Benthological Society 29: 1441–1458.

Verdonschot, P. F. M., and M. Van Den Hoorn. 2010. Using discharge dynamics characteristics to predict the effects of climate change on macroinvertebrates in lowland streams. Journal of the North American Benthological Society 29:1491–1509.

V. TOTAL TRUST FUND PROJECT BUDGET:

Staff or Contract Services:		
Personnel (not included in contracts):		$218,298
Contracts Total:		66,000
Metropolitan State University	$ 6,000	
Bemidji State University	$60,000	
Equipment:		2,500
Supplies:		8,387
Travel within Minnesota:		4,815
TOTAL TRUST FUND PROJECT BUDGET:		**$ 300,000**

VI. OTHER FUNDS and PARTNERS:

A. Project Partners: Dr. Richard Axler, University of Minnesota Duluth; Dr. Virginia Card, Metropolitan State University; Dr. Raymond Newman, University of Minnesota, Dr. Heinz Stefan, University of Minnesota; Dr. Patrick Welle, Bemidgi State University;

Peter Ciborowski, Dr. Edward Swain, Bruce Wilson, Minnesota Pollution Control Agency; Don Pereira, Kurt Rusterholz, David Wright, Jim Zandlo, Minnesota Department of Natural Resources.

VII. DISSEMINATION:

Project team members and their collaborators have made numerous presentations to general audiences, to agencies, and at professional conferences. Examples from the lead investigator are listed below.

Johnson, LB. et al. 2010. Impacts on Minnesota's Water Resources from climate change. Symposium. North American Benthological Society, June, 2010. Santa Fe.

Johnson, L.B. 2009. Are climate conditions changing? How can we tell? Invited presentation, Lake Superior Binational Forum. Duluth, MN, May 2009.

Johnson, L.B. Adapting to climate change in Minnesota. Invited presentation to Minnesota Pollution Control Agency- Committee to evaluate Adaption to climate change in Minnesota. September 1, 2009.

Johnson, L.B. Climate change and Minnesota's Aquatic Resources. Symposium. Minnesota Waters, Rochester, MN May 2009.

Johnson, L.B. Climate change and Minnesota's aquatic ecosystems. Science Museum of Minnesota, Thursday Evening Lecture Series. Exploring Water. April 9, 2009.
Johnson, L.B. Climate change and Minnesota's Natural Resources. Invited Presentation to Minnesota Coastal Zone Management Board. May, 2008.
Johnson, L.B., J. Pastor, G.R. Guntenspergen, J.H. Olker, W. C. Johnson, P. Schoff. Impacts of Climate Change on Northern Ecosystems. Special Symposium. Air Water Waste 2008. Bloomington, MN. February 27, 2008.
Johnson, L.B. Climate change impacts in Minnesota. Minnesota Water Conference Special event on Climate change sponsored by Will Steger. October 2007.
Johnson, L.B. Great Lakes in a Changing Climate. Minnesota DNR Parks and Recreation Annual Meeting, March 9, 2007.
Johnson, L.B. Great Lakes in a Changing Climate. Minnesota DNR Wildlife School. October 9-10, 2006.

Outreach and Communication products:

1. Data from Kristal Schneider's Master's thesis regarding the relationship between walleye spawning and ice out has been published in the Transactions of the American Fisheries Society 139(4):1198-1210.. http://afsjournals.org/doi/abs/10.1577/T09-129.1. Further publications are planned. In addition, the following products have been generated from this project.
2. A mapping tools was created to display trends for lakes having between 5 to >18 years of data. Because of the large number of options for analyzing this broad data set, a comprehensive subproject website was constructed to make the trend results available to other project scientists and ultimately others: (http://mnbeaches.org/gmap/trendswebsite). The website includes "processed raw" data, complete metadata, summary tables, links to Google Maps TM that identify sites with descriptive statistics, and graphs (box and whisker and regressions). The data are also incorporated into the larger project database that is now being used for more detailed examinations of climatic associations, geographic patterns, size and depth patterns, and associations with fish, and ice cover data.
3. The climate data retrieval tool, developed by the State Climatology Office, was essential to all climatic research undertaken in this project. The climate data retrieval tool enabled project participants to extract climate variables important to their own specific questions, at time and space scales they deem relevant. While the climate data retrieval tool is available to project investigators only at the present time, the Office of the State Climatologist plans to make it available widely to Minnesota resource managers and researchers at the conclusion of this project.
4. A third product is an annotated bibliography for the economics of climate change and environmental quality.

VIII. REPORTING REQUIREMENTS:
Periodic work program progress reports will be submitted not later than December 15, 2007; June 30, 2008 December 15, 2008; June 30, 2009; December 15, 2009; June 30, 2010. A final work program report and associated products will be submitted between June 30 and August 1, 2010 as requested by LCCMR.

IX. RESEARCH PROJECTS:

Attachment A: Budget Detail for 2007 Projects -

Proposal Title: ***Minnesota's Water Resources: Impacts of Climate Change- Phase II _Serial Number 13***
Project Manager Name: *Lucinda B. Johnson*
LCMR Requested Dollars: $ *300,000*

2007 LCMR Proposal Budget	Result 1 Budget:	Amount Spent	Balance	Result 2 Budget:	Amount Spent	Balance	Result 3 Budget:	Amount Spent	Balance	Result 4 Budget:	Amount Spent	Balance	TOTAL FOR BUDGET ITEM
University of Minnesota Budget	*Economic Assessment*	*6/30/2010*	*6/30/2010*	*Climate Projections*	*6/30/2010*	*6/30/2010*	*Biological projections*	*6/30/2010*	*6/30/2010*	*Indicator Development*	*6/30/2010*	*6/30/2010*	
BUDGET ITEM													
PERSONNEL: Staff Expenses, wages, salaries	**19,198**	**19,198**	**0**	**26,066**	**29,428**	**-3,362**	**72,503**	**81,901**	**-9,398**	**51,626**	**51,626**	**0**	**169,393**
L. Johnson													
R. Axler													
J. Olker													
T. Hollenhorst													
E. Ruzycki													
GRA TBA - Department of Geography													
GRA TBA - St. Anthony Falls Laboratory													
GRA TBA - St. Anthony Falls Laboratory													
GRA TBA - Dept. Fisheries, Wildlife & Conserv.													
PERSONNEL: Staff benefits – *Be specific; list benefits for each person on a separate line*	**4,510**	**4,510**	**0**	**14,601**	**5,169**	**9,432**	**16,891**	**33,607**	**-16,716**	**12,903**	**12,903**	**0**	**48,905**
L. Johnson													
R. Axler													
J. Olker													
T. Hollenhorst													
E. Ruzycki													
GRA TBA - Department of Geography													
GRA TBA - St. Anthony Falls Laboratory													
GRA TBA - St. Anthony Falls Laboratory													
GRA TBA - Dept. Fisheries, Wildlife & Conserv.													
Contracts	**60,000**	**51,351**	**8,649**	**3,000**	**3,000**	**0**				**3,000**	**3,000**	**0**	**66,000**
Ice-Out Modeling: Metropolitan State University, St. Paul				**3,000**	**3,000**					**3,000**	**3,000**		
Economic Analysis: Bemidji State University	**60,000**	**51,351**											
Equipment / Tools: computer for database manager, devoted to project.				**1,250**	**0**	**1,250**	**1,250**	**0**	**1,250**				**2,500**
Other Supplies (field, computer / printing supplies)	**1,000**	**203**	**797**	**1,000**	**0**	**1,000**	**3,187**	**114**	**3,073**	**3,200**	**1,438**	**3,200**	**8,387**
Travel expenses in Minnesota	**750**	**0**	**750**	**1,100**	**1,076**	**24**	**1,100**	**800**	**300**	**1,865**	**703**	**1,162**	**4,815**
COLUMN TOTAL	**85,458**	**75,262**	**10,196**	**47,017**	**38,673**	**8,344**	**94,931**	**116,422**	**-21,491**	**72,594**	**69,670**	**2,924**	**300,000**