Impacts on Minnesota's Aquatic Resources from Climate Change

Section 20, Subd. 7 $250,000

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Overall Project Outcome and Results

This project examined historic climate records and developed a database on key climatic measures and their variability. We also analyzed hydrologic (e.g., streamflow, lake levels, water quantity and quality) and ecological response data (e.g., fish species distributions, walleye spawning phenology). We found that the following trends are evident:

- Temperatures are increasing throughout the state but changes are greater in the northern third. Changes have accelerated since the 1980s, with greater increases in night time temperatures and in the winter.
- Precipitation in the form of both rain and snow has been increasing since the 1930s, although there is variation across the state.
- Lake evaporation is increasing in some regions but not others. Trends in lake levels are not consistent across the state: some regions show large and significant increases in lake levels, while other regions show no significant trend.
- Stream flows are generally increasing, especially in the south to central part of the state.
- Review of historic ice out data show a trend towards earlier ice out dates across the state. Walleye spawning dates are correlated with ice out date. There is some evidence that fish communities are also changing.
- A sizeable fraction of lakes with many years of data indicated a warming of surface waters. Other trends, found in a smaller fraction of lakes, suggest that the summer thermocline of lakes is becoming somewhat more stable consistent with the warming trend.
- A substantial fraction of lakes in the data set also showed increases in various measures of salinity that are consistent with increased warming and increased watershed loading from stormwater and de-icing salts.
- An interesting trend, likely unrelated to climate, is an increase in water clarity of lakes, and a decline in associated nutrients and chlorophyll-a.

Several tools for downloading and visualizing results have been developed. Additional analyses are ongoing.

Project Results Use and Dissemination

Results of these analyses have been presented in various venues, including:

1. Johnson, L.B. Climate change and Minnesota's aquatic ecosystems. Science Museum of Minnesota, Thursday Evening Lecture Series. Exploring Water. 9 April 2009.
2. Johnson, L.B. Climate change and Minnesota's Aquatic Resources. Symposium. Minnesota Waters, Rochester, MN. May 2009.
3. 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. 1 September 2009.
4. Schneider, K.N., D.L. Pereira, V. Card, R.M. Newman, and S. Weisberg. Timing of walleye spawning runs as an indicator of climate change. 138th Annual Meeting of the American Fisheries Society, Ottawa, ON, Canada. 20 August 2008.

5. Schneider, K.N. Timing of walleye spawning runs as an indicator of climate change. Conservation Biology Seminar Series, University of Minnesota, Saint Paul, MN. 16 September 2008.

Project results have been eagerly awaited by numerous agencies and committees working on statewide strategies for assessing adaptation to climate change. Dr. David Thornton invited Lucinda Johnson to present this project's findings to a newly convened committee to address adaptation strategies across state agencies. Results will also be used to inform a newly funded project to quantify impacts of climate change and land use change on cisco habitat (i.e., coldwater lake) in the glacial lakes region of the Midwestern US. In addition, several scientific publications are planned based on results of these analyses.

Project completed: 6/30/2009

LCMR 2005 Work Program Final Report

Date of Report: August 30, 2009
LCCMR 2005 Work Program Final Report
Date of Next Status Report:
Date of Work program Approval:
Project Completion Date: June 30, 2009

I. PROJECT TITLE: Impacts on Minnesota's aquatic resources from climate change Phase I - W-12

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Location: Entire state of Minnesota

Total Biennial LCMR Project Budget:	**LCMR Appropriation:**	**$ 250,000**
	Minus Amount Spent:	**$ 250,000**
	Equal Balance:	**$ 0**

Legal Citation: ML 2006, Chap. 243, Sec. 20, Subd. 7.

Appropriation Language: Impacts on Minnesota's aquatic resources from climate change. $125,000 the fiscal year 2006 and $125,000 the fiscal year 2007 are appropriated to the Board of Regents of the University of Minnesota for the Natural Resources Research Institute to quantify climate, hydrologic, and ecological variability and trends, and identify indicators of future climate. This appropriation is available until June 30, 2009, 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

Historic data trends in climate, lake levels, water chemistry, ice out patterns, and fish communities were examined. Temperature has been rising in Minnesota, a trend that is especially evident in the period since the early 1980s. Before that period, the average annual temperature did not change from the 1890s through the 1980s. Since the early 1980s, the temperature has risen slightly over 1°F in the south to a little over 2°F in much of the north. In addition to increases in annual temperature growing season length is increasing (see data from State Climatology Office cooperator http://climate.umn.edu/climatechange). In general the following climate trends are evident:

- Temperatures are increasing throughout the state but changes are greater in the northern third. Changes have accelerated since the 1980s, with greater increases in night time temperatures and in the winter.
- Precipitation in the form of both rain and snow has been increasing since the 1930s, although there is variation across the state.
- Lake evaporation is increasing in some regions but not others. Trends in lake levels are not consistent across the state: some regions show large and significant increases in lake levels, while other regions show no significant trend.
- Stream flows are generally increasing, especially in the south to central part of the state.
- Review of historic ice out data show a trend towards earlier ice out dates across the state. Walleye spawning dates are correlated with ice out date. There is some evidence that fish communities are also changing.
- A sizeable fraction of lakes with many years of data indicated a warming of surface waters. Other trends, found in a smaller fraction of lakes, suggest that the summer thermocline of lakes is becoming somewhat more stable consistent with the warming trend.
- A substantial fraction of lakes in the data set also showed increases in various measures of salinity that are consistent with increased warming and increased watershed loading from stormwater and de-icing salts.
- An interesting trend, likely unrelated to climate, is an increase in water clarity of lakes, and a decline in associated nutrients and chlorophyll-a.

Several tools for downloading and visualizing results have been developed. Additional analyses are ongoing.

IV. OUTLINE OF PROJECT RESULTS*:*

Result 1: Quantify historic trends in lake fish and macrophyte communities and stream hydrologic and lake water quality responses to climate from historic data.

Description: Quantify historic trends in lake fish and macrophyte communities and stream hydrologic and water quality responses to climate from historic data, quantify the key and/or threshold values relevant to water quality measures, fish and macrophyte indicator species, and identify potential indicators of climate change for use in monitoring programs. First, we will quantify historic trends in hydrologic and aquatic ecosystem responses. Changing precipitation and land use patterns have impacted water quantity and quality; hydrologic and water quality responses in streams and lakes will be summarized from historic data. Biotic communities are responding to changing climate by expanding their geographic distributions northward, breeding or flowering earlier in the season. We will examine existing data about key aquatic communities to determine if such patterns can be documented for Minnesota, and compile a database of these patterns.

Planning for a monitoring program requires identifying scientifically defensible, cost-efficient indicators. However, reliable indicators of climate change and climate change impacts have not been identified and tested. We will use the above data to establish relationships between physical parameters and biological responses expected under changing climate. Based on those results, and a previous LCMR project on

Environmental Indicators, we will evaluate sampling protocols and for their implementation. An inventory of established monitoring programs will ensure existing programs are utilized where possible.

Time Line:

September, 2006 - Begin developing criteria for historic data that will be included in analyses and identify potential data sources.

December, 2006 - Identify key databases that fit selection criteria.

June, 2007 - Complete summaries of historic climate scenarios. Finalize historic database compilations and begin data analysis to examine temporal trends.

January, 2008 - Begin data analysis of physical and biotic data to assess relationships between temporal patterns and historic climate trends.

June, 2008 - Complete data analysis of physical and biotic data to assess relationships between temporal patterns and historic climate trends.

January, 2009 - Complete data analysis of physical and biotic data projecting conditions under future climate scenarios. Identify indicators of climate change.

June 30, 2009 - Submit final report to LCMR.

Summary Budget Information for Result 1:	**LCMR Budget**	**$** 188,485
	Balance	**$** 0

Completion Date: June 30, 2009

Final Report Summary:

BIOLOGICAL INDICATOR AND FISH COMMUNITY RESPONSES TO CLIMATE CHANGE

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

There is growing evidence that climate change is affecting aquatic ecosystems around the world. Thus, as interest in climate change increases, there is an increasing concern for its effects on the distribution and reproduction of species as well as an increasing need for biological indicators. We analyzed walleye (*Sander vitreus*) spawning data to determine whether the timing of walleye spawning was occurring earlier over time. We chose walleye as a biological indicator because it is important to both commercial and recreational fisheries. In addition, Minnesota lake survey data were analyzed to assess fish community responses to local climate change. We used lake survey analyses to answer three questions: 1) Are fish abundances and species distributions changing over time? 2) Are these changes related to local climate? 3) Do lake physical and chemical characteristics influence fish abundance and range changes?

Methods: We analyzed the trends in the date of first ripe walleye female sighting relative to ice-out date for 12 spawning locations in Minnesota (see Appendix A for manuscript detailing these results). To determine changes in fish abundance and distribution from lake surveys, we analyzed relationships between catch-per-unit-effort (CPUE) and year for 21 lakes with gillnet data and for 21 lakes with trapnet data; 35 unique lakes were analyzed. Results were summarized for 7 fish species (3 families) with the strongest trends: Centrarchids [largemouth bass (*Micropterus salmoides*), smallmouth bass (*Micropterus dooumieui*), bluegill (*Lepomis macrochirus*)]; Ictalurids [black bullhead (*Ameiurus melas*) and yellow bullhead (*Ameiurus natalis*)]; Whitefish [tullibee (*Coregonus artedi*), and lake whitefish (*Coregonus clupaeformis*)]. Linear regressions were also used to analyze the relationship between fish species' catch per unit effort (CPUE) (over time) by lake and 5 temperature variables including: maximum 7-day max temperature, average annual temperature, average summer temperature, average winter temperature, and degree-days about 5°C. We selected lakes having a minimum of 18 years of data for gill nets and 15 years of data for trapnets. We used stepwise regressions (both directions) to determine the relationship between CPUE over time and 5 lake characteristics: lake surface area, maximum depth, latitude, longitude, and Schupp's lake class.

Results: Linear regressions of the date of first walleye egg-take versus ice-out date showed that for each day ice-out is earlier; walleye spawning begins 0.5 to 1 day earlier. All but 2 regressions had slopes significantly less than 1 (indicating that spawning was lagging the iceout), and slopes at the 2 exceptions were equal to 1(indicating perfect correspondence between ice out and spawning). Regressions of first egg-take and ice-out date versus year showed trends toward earlier spawning and earlier ice-out. For regressions of first egg-take versus year, significant negative slopes ($P<0.1$) were observed in 5 out of 14 regressions with negative slopes, and there were 2 positive slopes that were not significant. For regressions of ice-out date versus year, 25 of 26 regressions were negative; there were 9 significant negative slopes ($P<0.1$) and no significant positive slopes. The timing of walleye spawning is linked to ice out and appears to be a good indicator of climate change; walleye spawning and ice-out are occurring earlier in some lakes but not all. (See Appendix A for further details.)

In addition to the timing of walleye spawning and ice-out, climate change is also affecting fish abundances and distributions in Minnesota. Centrarchid (sunfish) abundance is increasing in lakes, black bullhead abundance is decreasing, and all other species are increasing in some lakes and decreasing in other lakes. All species' ranges tested are significantly advancing northward except smallmouth bass and whitefish. Regressions of CPUE versus air temperature showed that overall bass and sunfish are increasing in lakes as summer temperatures increase, and whitefish are decreasing as temperatures increase. Relationships between sunfish CPUE and air temperature reveal mostly significant positive slopes with all temperature variables except annual winter temperature. For ictalurids (bullheads), most significant positive slopes were observed with maximum 7-day max, and most significant negative slopes were observed with average annual temperature, average summer temperature, and degree-days above 5°C. For whitefish, most significant negative slopes were seen in regressions of CPUE versus temperature using every temperature variable except average annual temperature, which produced an equal number of positive and negative slopes. Lake characteristics explained some of the variability in regressions of CPUE versus year. In general, slopes (CPUE vs. year) increased as longitude, lake size, and lake maximum depth decreased. In other words, CPUE increased more quickly over time in smaller, shallow lakes and more quickly moving east across the state than in larger, deeper lakes and lakes in the west.

We have provided evidence that climate change is affecting fish reproduction, abundance, and distributions in Minnesota. We believe that the timing of walleye spawning is a good indicator of climate change, and should continue to be monitored. Some warm-water species have been expanding in Minnesota, and some native cool-water species are decreasing. These changes were related to local changes in air temperature. Lake characteristics such as depth, size and location in the state influence changes in fish species abundance and distribution, and should thus be considered in conjunction with climate change for future management plans of Minnesota's aquatic resources. (See Appendix B for further details.)

LAKE WATER QUALITY TRENDS

Richard Axler, Norm Will, Elaine Ruzycki, Jerry Henneck, Jennifer Olker, Joseph Swintek
Center for Water and the Environment, 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 a MPCA and MDNR to consider for improving public access and understanding of lake water chemistry.

The water quality variables comprise a primary Core Suite that includes the field sensor parameters that typically determine a meter-by-meter depth profile of temperature, dissolved oxygen, specific electrical conductivity (EC25, that estimates total salt/ion concentrations), and pH; and water clarity estimated by Secchi disk depth. A second group of Advanced Suite parameters includes most of the other "routine" water quality variables such as chlorophyll (in lakes), nutrients (nitrogen and phosphorus in their limnologically relevant forms), dissolved and total organic carbon and/or color, SiO2, Hardness, major anions (ANC/alkalinity, SO4, Cl) and major cations (Ca, Mg, Na, K). Criteria were established for censoring data based on detec*tion limits, fo*r averaging across various time intervals within a year and for limnologically relevant depth strata. A secondary set of calculated variables were added to the data set: the Carlson trophic state index (TSI) that is based on midsummer secchi depth and surface TP and chlorophyl$_{l}$-a concentrations; thermocline depth; and thermocline depth-gradient as a measure of the stability of thermal stratification which directly structures thermal habitat, and indirectly regulates oxygen habitat for aquatic organisms.

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 search 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 2 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 5 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 % 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.

See Appendix C for a full report of this set of analyses. See also, report for LCCMR2007 project (Minnesota's Water Resources: Impacts of Climate Change - Phase II – SN 13)

for continued work relevant to this objective.

STREAM FLOW, LAKE EVAPORATION, AND LAKE LEVEL RESPONSES TO CLIMATE IN MINNESOTA

Filiz Dadaser-Celik, Heinz G. Stefan
St. Anthony Falls Hydrologic Laboratory, University of Minnesota.

Historical water levels in 25 Minnesota lakes with long term data records were examined. Eight were landlocked lakes and seventeen were flow-through lakes. The longest record reached back to 1906 (Lake Minnetonka and Upper Prior Lake in Scott County). We determined statistical parameters such as mean annual lake levels and seasonal variations of the historical lake water levels. Linear regression and Mann-Kendall test were used to evaluate the presence of trends in daily, mean annual, spring (May) and fall (October) water levels.

Results: The majority of the 25 lakes showed rising water levels in the last century (1906 to 2007). The strongest upward trend was observed in a landlocked lake (Lake Belle Taine in Hubbard County) where the rate was 0.030 m/yr. The second largest increase was observed in a flow-through lake (Marion Lake in Dakota County) with a rate of 0.024 m/yr. Swan Lake (in Nicollet County) and Swan Lake (in Itasca County) were the only lakes that showed a falling trend with a rate of -0.011 and -0.002 m/yr, respectively.

The analysis also showed that lake levels have been increasing in most of the 25 lakes in the last 20-years (1987-2006). One landlocked lake and eight flow-through lakes showed their strongest upward trends in the last 20 years. Five of the eight landlocked lakes and eleven of the seventeen flow-through lakes reached their highest recorded levels after 1990. Upward trends in recorded lake water levels were found in both spring and fall in the majority of the 25 lakes analyzed.

We also attempted to understand how Minnesota lake levels have responded to climate changes in the past. Correlation coefficients were calculated between annual lake water levels and mean annual climate variables. The correlation of water levels with precipitation was moderate, and the correlation with dew point and air temperatures was very weak. 48- and 36-month antecedent precipitation was the strongest indicator of average water levels. Multivariate regression analysis of lake levels did not improved the predictive lake level predictions. Numerical indicators for ground water and surface water in- and out-flows appear necessary for further improvement.

The correlation between mean annual water levels was strongest among lakes in the same climate regions and weakest among lakes in distant climate regions. Lake levels in the same Minnesota climate region (with identical precipitation and temperatures) had correlation coefficients as high as 0.78, while those in distant regions were not correlated. The average correlation coefficients among annual water levels in all lakes were 0.43 for the eight landlocked lakes and 0.41 for the seventeen flow-through lakes. Overall, the analyses showed that changes have been observed in lake levels in Minnesota in the last century and in the last 20 years. The majority of the lakes have rising lake levels. The correlation between climate parameters and lake levels was weak. The consistency of water level variations in lakes of the same region is perhaps the strongest indicator of a climate effect. If the trends continue, lakes included in this study may experience significant water level increase by 2050.

A report on lake level responses to climate in Minnesota was completed in December 2007 (see Appendix B).

LAKE EVAPORATION

In this report we analyze the variability of water losses by evaporation from lake surfaces in Minnesota, and trends in lake evaporation for the period 1964 – 2005. Daily evaporation rates were estimated using a mass-transfer equation with recorded daily weather data as input. The weather data came from six Class A weather stations (International Falls, Duluth, and Minneapolis/St. Paul MN, LaCrosse, WI, Sioux Falls, SD, and Fargo, ND). Annual (Jan-Dec) lake evaporation ignoring lake ice-covers and annual evaporation for the actual open-water season were computed from the daily values. Trends in annual evaporation over the periods 1964 – 2005 and 1986 – 2005 were determined using a linear regression method. The trend analysis was repeated for annual water availability (precipitation minus evaporation). Finally correlation coefficients between annual average water levels of 25 Minnesota lakes, and annual evaporation or annual water availability were calculated.

In the last 40 years (1964 – 2005), annual average open-water season evaporation ranged from 580 to 747 mm/yr (22.8 to 29.4 in/yr) at the six locations. The trend over the 1964 – 2005 period was upward (rising) at three stations (International Falls, Duluth, and Sioux Falls), and downward (falling) at three stations (Fargo, Minneapolis, and La Crosse). The strongest upward trend in evaporation (0.64 mm/yr) was for Duluth and the strongest downward trend (-1.65 mm/yr) for La Crosse. Annual evaporation for the 12-month (Jan-Dec) period, i.e., disregarding ice covers, was from 79 mm/yr (3.1 in/yr) to 140 mm/yr (5.5in/yr) higher than annual evaporation computed for the open-water season at the six locations.

In the last 20-years (1986–2005) annual open-water season evaporation had a decreasing trend at five of the six locations. The decreasing trends were stronger than for the 1964 – 2005 period and ranged from -0.69 for International Falls and Minneapolis to -1.57mm/yr for La Crosse. The only positive trend was 1.09mm/yr for Sioux Falls.

Annual average measured precipitation for the 1964 – 2005 period at the six locations ranged from 536mm/yr to 812 mm/yr (21.1 in/yr to .30.0 in/yr) and showed a rising trend at four of the six stations (International Falls and Duluth were the exceptions). For the 1986 – 2005 period precipitation showed an increasing trend at all stations except Duluth and La Crosse.

Water availability, calculated as the difference between annual open-water season precipitation and annual open-water evaporation, showed upward trends at all stations from 1964 to 2005. The trends ranged from 0.05mm/yr for Duluth to 4.27mm/yr for Fargo. From 1986 to 2005 five locations showed an upward trend and one a downward trend in water availability. The five upward trends were much stronger than for the 1964 – 2005 period, ranging from 0.58mm/yr for La Crosse to 15.06 mm/yr for Fargo. The only downward trend was -2.67mm/yr for Duluth.

Overall, the analysis showed that positive and negative trends in lake evaporation have occurred in Minnesota in the last 40 years. Trends in measured precipitation during the same time period were stronger and upwards. As a result, water availability in Minnesota also has an upward trend. No strong correlation between lake levels, annual evaporation rates or annual water availability was found, but the increase in water availability can explain the observed water level increases in 25 Minnesota lakes.

A report on lake evaporation response to climate in Minnesota was completed March 2008 (Appendix C).

STREAM FLOW:
The variability of stream flows in Minnesota, and the relationship between stream flows and climate are the focus of this report. We analyze historical flow records of Minnesota streams to determine how much frequency and magnitude of flows have been affected by climate and land use changes. Flow duration analysis, high and low flow ranking, and flood frequency analysis were applied to recorded mean daily stream flows, 7-day average low flows, and annual peak flows. Data from 36 gauging stations located in five river basins of Minnesota (Minnesota River, Rainy River, Red River of the North, Lake Superior, and Upper Mississippi River basins) covering the 1946-2005 period were used.

To detect any changes that have occurred over time, data from the 1986-2005 and the 1946-1965 periods of record were analyzed separately. Flow duration curves were prepared for all gauging stations, and low flows (Q90, Q95), medium flows (Q50), and high flows (Q5, Q10) in the two time periods were examined. Multiple stream gauging stations in the same river basin generally showed consistent changes in stream flows, although deviations from a typical river basin pattern were noted at a few gauging stations.

The Minnesota River basin has experienced the largest stream flow changes compared to the other four basins. High, medium, and low flow have increased significantly from the 1946-1965 to the 1986-2005 period in the Minnesota River basin. The increases in medium to low flows were larger than the increases in high flows. Considerable changes in flows were also observed in the Upper Mississippi River basin and the Red River of the North basin. Streams in the Rainy River basin and tributaries to Lake Superior showed little or no change in stream flow between the 1946-1965 and 1986-2005 periods. The changes observed in these river basins were also variable. In two tributaries to Lake Superior, average flows seem to have increased on the order of 10%, 7-day low flows seem to have decreased, and annual peak flows seem to be unchanged.

The occurrence (temporal distribution) of extreme flows (annual peak flows and annual 7-day [average] low flows) over the period of record (1946-2005) was examined using a sorting/ranking method. The occurrence of extreme flows was not distributed uniformly over the period from 1946 to 2005. Most of the lowest 7-day (average) low flows did not occur in the recent 1986-2005 period, except in the Lake Superior basin. Based on event occurrence, both annual peak flows and 7-day average low flows were higher in 1986-2005 than in 1946-1965 in the Minnesota River basin, Red River of the North basin, and Upper Mississippi River basin.

Separate flood frequency analyses were conducted on the stream flow data from the 36 stream gauging stations for the 1946-1965 and the 1986-2005 periods to identify changes in the 1-, 2-, 5-, 10- and 25-year floods. The results were most consistent for the Red River of the North basin. In this basin, magnitudes of the 2- to 25-year floods increased at all six stream gauging stations (average increases were from about 30 to 60%) and the magnitude of the 1-year flood decreased (average of 20%). Results obtained for the Minnesota River, Rainy River, Lake Superior, and Upper Mississippi River basins were not conclusive because the changes observed at individual stations in each river basin were not consistent; both increases and decreases were observed. Average changes in the 1- to 25-year floods were between 21 and 320% in the Minnesota River basin, -7% and -20% in the Rainy River basin, -11% and 26% in the Lake Superior basin, and -8 and 23% in the Upper Mississippi River basin.

A low flow frequency analysis was conducted on the stream flow data for 1946-1965 and 1986-2005 to identify changes in the 2-, 5-, 10- and 20-year seven-day annual (average) low flows. The largest changes in low flows were identified for stream gauging stations in the Minnesota River basin. In this river basin flows with 2-, 5-, 10- and 20-year return periods increased from the 1946-1965 to the 1986-2005 period. Similar changes were also evident in the Red River of the North and Upper Mississippi River basins. Frequent low flows, e.g., 7-day average low flows with a 2-year return period (7Q2) increased more than low flows of rarer occurrence, e.g., 7Q10 or 7Q20.

There are many potential causes for changes in stream flows. Precipitation is one. The river basins which showed the largest increases of stream flows (Minnesota River basin and Red River of the North basins) drain regions (climate divisions) where significant increases in precipitation have been observed. River basins which showed little or no change in stream flow (Rainy River and Lake Superior basin) drain climate divisions where changes in precipitation were not significant. Agricultural drainage, changes in crop patterns, and urbanization are other potential causes for stream flow changes that need to be considered in separate studies.

A report on stream flow response to climate in Minnesota was completed April 2009 (Appendix D).

ADDITIONAL DATA

Additional data was acquired in this project and continues to be used in the LCCMR2007 project (Minnesota's Water Resources: Impacts of Climate Change - Phase II – SN 13).

Macrophyte Communities

Our lists of 2037 lakes with MN DNR macrophyte community surveys have been compared to a list of lakes with MN DNR fish surveys. We found that 1600 lakes had both fish and aquatic macrophyte surveys completed. Timing of the aquatic macrophyte surveys has been compiled in a table that shows years in which vegetation data were collected for each of the 1600 lakes also surveyed for fish communities. Of these 1600 lakes, 139 (9 %) had only one survey conducted, 264 lakes (16.5 %) had surveys in two or three different years, 299 lakes (19 %) had surveys in 4 or 5 different years, 554 lakes (34%) had surveys in 6 to 9 different years, 329 lakes (20.5%) had surveys in 10 to 24 different years, and 15 lakes (1%) had surveys done in 25 to 41 different years. The earliest surveys were conducted in 1926, and the most recent in the available dataset were conducted in 2004. Most of the surveys were conducted in the years from 1940 to 2002.

Land Use
Land use data sets that will provide a historic context for assessing impacts of climate change have been assembled and summarized for the 3928 lakes that have defined lakesheds. Lakesheds are a smaller hydrologic unit than watersheds which may contain a number of lakesheds. They are being used for lake management by MN DNR. The data were obtained from the MN DNR Department of Water, and accumulated to incorporate all drainage that flowed into the immediate lakesheds based on the next-down identifier. We calculated proportion of 6 land use classes (agriculture, urban, barren, forest and wetland, grass, open water) for data from 1969 (Land Management Information Center), 1991 (GAP, USGS) and 2001 (National Land Cover, USGS) for immediate and accumulated lakesheds. These classes were further lumped to compare natural versus disturbed land use types. Percent change and trend of each land use type are now available to use as covariates in future analyses for other components of this project.

Additional Lake Levels
Lake levels were acquired from the MN DNR for lakes with long data records for other variables. Of the 640 lakes that had fifteen plus years of water quality data, 490 lakes had lake level data. Of these lakes, 388 have lake level records consisting for fifteen or more years, with 100+ year records. This data is available for use as predictor or covariates in future analyses for other components of this project.

Result 2: Develop a database of historic climate data
Description: Develop a database of historic climate data for Minnesota by examining existing climate data sets and records of timing and duration of lake ice cover to determine if patterns can be documented for Minnesota over the past 50 years, and construct a database of possible climate scenarios that Minnesota may experience over the next 50 years. We will document historic trends in Minnesota's climate, including temperature and precipitation patterns, frequency of extreme events, drought and flood epidodes. Many of the scenarios will be constructed from observed episodes that differed significantly from current climate conditions 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. Scenarios based on predictions of global and regional climate models also will be constructed.

Time Line:
September, 2006 Begin developing criteria for historic data that will be included in analyses and identify potential data sources.
December, 2006 Identify key databases that fit selection criteria.
June, 2007 Complete future climate scenarios for the next fifty years. Begin data analysis of physical and biotic data to assess relationships between temporal patterns and historic climate trends.
January, 2008 Complete data analysis of physical and biotic data to assess

relationships between temporal patterns and historic climate trends. Assist with data analysis of physical and biotic data projecting conditions under future climate scenarios.

June, 2008-	Identify indicators for monitoring climate change.
June 30, 2009	Submit final report to LCMR.

Summary

Budget Information for Result 2:	LCMR Budget	$ 61,515
	Balance	$ 0

Completion Date: June 30, 2009.

Final Report Summary:

HISTORIC CLIMATE DATA

Temperature has been rising in Minnesota, a trend that is especially evident in the period since the early 1980. Before that period, the average annual temperature did not change- the trend was essentially zero. Since the early 1980s, the temperature has risen slightly over 1°F in the south to a little over 2°F in much of the north. In addition to increases in annual temperature, the temperatures are rising in the months around the annual dates of the first and last frosts (April and November), and growing season length is increasing. In general the following trends have been observed: temperatures are increasing throughout the state but changes are greater in the northern third. Changes have accelerated since the 1980s, with greater increases in nighttime temperatures and in the winter. In addition, data from 1981-2006 show that surface water temperatures are increasing in Lake Superior. Finally, precipitation in the form of both rain and snow has been increasing since the 1930s (although there is variation across the state). The number of heavy rain events has been increasing over the past several decades (State Climatology Office, 2008; http://climate.umn.edu/climatechange)

Result 2, Climate Episodes and Scenarios: Develop**ment of a comprehensive climate data** retrieval tool and the identification of historical patterns or episodes of climatic extremes.

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% 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 E. 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 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 65ºF for ZIP code 55113 from 1890 to the present. More detailed examples are provided in Appendix E.

Identification of historical climatic episodes were 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.

LAKE ICE COVER

Observational records of lake ice-cover were collected from across the state from a variety of sources including observers, newspapers, the Minnesota State Department of Natural Resources, the Minnesota State Climatologists 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.

Result 3: Assemble an advisory committee to help define the initial questions to be answered and review products as produced.

Description: An advisory committee consisting of State and Federal agency and Private sector representatives from tourism, infrastructure, and natural resource management sectors will help define initial questions to be answered and review products as produced.

Time Line:
August 1, 2006 – Begin assembling names of advisory committee members.
December, 2006 –First meeting of Advisory Committee.
December, 2007 – Advisory Committee meets to review progress.
December, 2008 – Advisory Committee meets to review progress.

Summary Budget Information for Result 3:	**LCMR Budget**	**$ 0**
	Balance	**$ 0**

Completion Date: June 30, 2009.

Final Report Summary:
An advisory committee was assembled consisting of agency partners and appropriate agency personnel including: Jim Zandlo, state climatologist (DNR); Peter Ciborowski (PCA); Kurt Rusterholz (DNR); Edward Swain (PCA); David Wright (DNR); and Don Pereira (DNR). We have consulted advisors on a regular basis as required for each objective. Cooperators and advisors are invited to participate in monthly conference calls. Additionally, project personnel and advisors participated in a mini-symposium in February 2009 to share and discuss results from project and Phase II (LCCMR2007: Minnesota's Water Resources: Impacts of Climate Change - Phase II – SN 13); see Appendix G for symposium agenda and participant list.

V. TOTAL LCMR PROJECT BUDGET: $ 250,000

All Results: Personnel: $ 243,514
Fringe benefits for graduate students at the University of Minnesota includes both tuition and health insurance; therefore these costs are listed under a single line item for each graduate student.

All Results: Equipment: $ 3,704
All Results: Development: $ 0
All Results: Acquisition: $ 0
All Results: Other: Travel $ 2,782

TOTAL LCMR PROJECT BUDGET: $ 250,000

Explanation of Capital Expenditures Greater Than $3,500:

VI. OTHER FUNDS & PARTNERS:

A. Project Partners: Peter Ciborowski and Edward Swain- Pollution Control Agency will assist with data collection as part of their current job responsibilities; David Wright, James Zandlo- Department of Natural Resources will assist with data compilation and acquisition as part of their current job responsibilities; Clarence Turner- Forest Resources Council ($0) will assist the indicator development effort by providing data previusly assembled through an LCMR project; Lance Yohe- Red River Basin Commission has volunteered to provide data and to serve on the Advisory Committee.

B. Other funds being spent during the Project Period: $0

C. Required Match (if applicable): $ 0

D. Past Spending: $0

E. Time: June 30, 2009

VII. DISSEMINATION:

The key product will be a database of daily maximum temperature, minimum temperature, precipitation values that will have uses far beyond the current research project. Regional average records of long-term records of ice cover duration will be also be archived. Appropriate indicators that can be measured in a monitoring framework will be identified and this information will be transmitted to the appropriate agencies. Databases will be archived individually by each investigator with a full copy of the complete database to be archived at the Natural Resources Research Institute. Data sets will be disseminated to project partners within the MPCA and MDNR for use in decision-making. Investigators and students will attend and present findings at the Minnesota Water Conference in 2008. Scientific publications will be written and disseminated.

VIII. REPORTING REQUIREMENTS:

December 15, 2006
June 30, 2007
December 15, 2007
June 30, 2008
December 15, 2008
June 30, 2009

IX. RESEARCH PROJECTS: See Research Addendum.

Attachment A: Budget Summary for 2005 Projects

Proposal Title: *Climate change impacts on Minnesota's Aquatic Resources W-12*
Project Manager Name: *Lucinda B. Johnson*
LCMR Requested Dollars: $ *250,000*

2005 LCMR Proposal Budget	Result 1 Budget:	Amount Spent	Balance	Result 2 Budget:	Amount Spent	Balance	Result 3 Budget:	Amount Spent	Balance		
	Database of historic trends in physical, biological, and chemical	*8/302009*	*8/302009*	Database of historic & future climate trends	*8/302009*	*8/302009*	Advisory Board	*8/302009*	*8/302009*		
BUDGET ITEM										**TOTAL FOR BUDGET**	**Overall Balance**
PERSONNEL: Staff Expenses, wages, salaries	**121,479**	**131,430**	**-9,951**	**37,822**	**40,290**	**-2,468**	**0**			**159,301**	**-12,419**
Lucinda Johnson, PI (1% effort required); Project Manager NRRI UMN											
Dan Breneman Res. Fellow- Will assist with project management responsibilities, NRRI UMN											
Jennifer Olker Research Fellow (NRRI) UMN-Will assist with data collection and analysis											
Graduate Research Assistant (Civil Engineering)-TBA UMN											
Graduate Research Assistant (College Nat. Resources)- TBA UMN											
Graduate Research Assistant (Geography) TBA UMN											
Virginia Card, PI Metro State University											
PERSONNEL: Staff benefits –	**60,920**	**53,609**	**7,311**	**23,293**	**21,225**	**2,068**	**0**			**84,213**	**9,379**
Lucinda Johnson, PI (1% effort required); Project Manager NRRI UMN											
Dan Breneman Res. Fellow- Will assist with project management responsibilities, NRRI UMN											
Graduate Research Assistant (Civil Engineering)-TBA UMN-includes tuition											
Graduate Research Assistant (College Nat. Resources)- TBA UMN-includes tuition											
Graduate Research Assistant (Geography)-includes tuition											
Virginia Card, PI Metro State University											
Other Supplies	**3,704**	**2,463**	**1,241**	**0**	**0**		**0**			**3,704**	**1,241**
GIS user fees										**0**	
GIS lab supplies											
Travel in Minnesota	**2,382**	**983**	**1,399**	**400**	**0**	**400**	**0**			**2,782**	**1,799**
COLUMN TOTAL	**188,485**	**188,485**	**0**	**61,515**	**61,515**	**0**	**0**			**250,000**	**0**