2005 Project Abstract
For the Period Ending June 30, 2009

PROJECT TITLE: .... Enhancing Civic Understanding of Ground Water
PROJECT MANAGER: .... Patrick Hamilton
AFFILIATION:.. Science Museum of Minnesota
MAILING ADDRESS:..120 W. Kellogg Blvd.
CITY/STATE/ZIP:..St. Paul, MN 55102
PHONE:.. 651-221-4761
FAX: 651-221-4514
E-MAIL:.. hamilton@smm.org
WEBSITE:..www.smm.org
FUNDING SOURCE:..Environment and Natural Resources Trust Fund
LEGAL CITATION: ....ML 2006, Chap. 243, Sec. 20, Subd. 2.

APPROPRIATION AMOUNT: $..$150,000

Overall Project Outcome and Results

Ground water is a resource in great and growing demand in Minnesota. Yet many citizens are unaware of the links between land use and ground water and the interconnections between ground water and surface water. The Science Museum of Minnesota, with the help of many partners, created outdoor ground water exhibits for visitors to the Museum and a ground water classroom program for delivery to schools throughout Minnesota.

The creation of the Ground Water Plaza in the Science Museum of Minnesota's outdoor science park, the Big Back Yard, significantly leveraged resources provided by LCMR. The Minnesota Ground Water Association provided $20,463 to drill the artesian well that provides the water for the ground water exhibits. A gift of $10,000 from the Toro Giving Program and in-kind donations from numerous entities also helped make the Ground Water Plaza possible.

Since its opening in August 2007, the Ground Water Plaza has become one of the key educational attractions in the Big Back Yard. About 40,000 people visit the park each summer season. The Big Back Yard and the Ground Water Plaza have become so popular as a destination for field trips that the Museum now sets aside two full weeks each September for exclusive use of the park by schools.

The Ground Water Classroom Program began visiting schools throughout Minnesota in spring 2008. The program reached a total of 50 schools and 7,324 students through spring 2009. Although the LCMR project, Enhancing Civic Understanding of Ground Water has concluded, the ground water classroom program will continue to be offered to schools. It is now included under the Water Residency heading on Science Museum of Minnesota's residency program website - http://www.smm.org/schools/atyourschool/residencies/.

Project Results Use and Dissemination

The Science Museum and the American Museum of Natural History in partnership produced an internationally traveling exhibit about water that opened in New York City in November 2007. Two Ground Water Plaza outdoor exhibit components were modified for indoor use and replicated for inclusion in the 7,000 square-foot water exhibition. The National Ground Water Association provided $54,000 to cover the cost of building these two ground water components. Two copies of the Water exhibition with its ground water components were produced – one to tour North American venues and the second for overseas venues. To date, 712,000 people have seen the Water exhibition with its ground water components and several million more will as the show continues to tour for several more years.

LCCMR 2005 Work Program Final Report
ENHANCING CIVIC UNDERSTANDING OF GROUND WATER

Date of Report: .... August 3, 2009
LCCMR 2005 Work Program Final Report
Date of Work Program Approval: .... May 19, 2006
Project Completion Date: .... June 30, 2009

I. PROJECT TITLE: ENHANCING CIVIC UNDERSTANDING OF GROUND WATER

Project Manager: .... Patrick Hamilton
Affiliation: .... Science Museum of Minnesota
Mailing Address: .... Department of Environmental Sciences and Earth-system Science
Science Museum of Minnesota
120 W. Kellogg Blvd.
St. Paul, MN 55102
Telephone Number: 651-221-4761
Email: .... Hamilton@smm.org
Fax: 651-221-4514
Web Address: .... www.smm.org

Location: .... St. Paul, Ramsey County

Total Biennial Project Budget: .... LCMR Appropriation: $150,000
Minus Amount Spent: $150,000
Equal Balance: $0

Legal Citation: ML 2006, Chap. 243, Sec. 20, Subd. 2.

Appropriation Language:

$75,000 in fiscal year 2006 and $75,000 in fiscal year 2007 are appropriated to the Science Museum of Minnesota to create groundwater exhibits and a statewide traveling groundwater classroom program. 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:

Ground water is a resource in great and growing demand in Minnesota. Yet many citizens are unaware of the links between land use and ground water and the interconnections between ground water and surface water. The Science Museum of Minnesota, with the help of many partners, created outdoor ground water exhibits for visitors to the Museum and a ground water classroom program for delivery to schools throughout Minnesota.

The creation of the Ground Water Plaza in the Science Museum of Minnesota's outdoor science park, the Big Back Yard, significantly leveraged resources provided by LCMR. The Minnesota Ground Water Association provided $20,463 to drill the artesian well that provides the water for the ground water exhibits. A gift of $10,000 from the Toro Giving Program and in-kind donations from numerous entities also helped make the Ground Water Plaza possible.

Since its opening in August 2007, the Ground Water Plaza has become one of the key educational attractions in the Big Back Yard. About 40,000 people visit the park each summer season. The Big Back Yard and the Ground Water Plaza have become so popular as a destination for field trips that the Museum now sets aside two full weeks each September for exclusive use of the park by schools.

The Ground Water Classroom Program began visiting schools throughout Minnesota in spring 2008. The program reached a total of 50 schools and 7,324 students through spring 2009. Although the LCMR project, Enhancing Civic Understanding of Ground Water has concluded, the ground water classroom program will continue to be offered to schools. It is now included under the Water Residency heading on Science Museum of Minnesota's residency program website - http://www.smm.org/schools/atyourschool/residencies/.

IV. OUTLINE OF PROJECT RESULTS:

Result 1: SMM Development of Outdoor Ground Water Education Exhibits

Description: The Science Museum of Minnesota will develop, design, fabricate, and install outdoor exhibits centered around a functioning artesian well. This work will include all outdoor signage and graphic display panels and includes all costs associated with the materials, supplies, and services needed to produce these exhibits and their interpretation.

Summary Budget Information for Result 1:	**LCMR Budget**	$65,000
	Minus Amount Spent	$65,000
	Balance	$0

Completion Date:..August 31, 2007

Result Status as of June 30, 2009
The development of the ground water classroom program did not end up requiring all of the resources originally budgeted for this work. The classroom program, furthermore, was delivered to 71 schools rather than the 72 initially forecasted. The resulting balance of $3,527 was applied toward replicating one of the ground water exhibits in the Water traveling exhibition for year-around display in the Mississippi River Gallery inside the museum. This exhibit – porous stones – is based on the porous stone exhibits originally created for the outdoor Ground Water Plaza in the Big Back Yard. The total cost of the porous stones exhibit replica is about $12,000, with $8,500 of the total project cost being covered by funding from the National Center for Earth-surface Dynamics at the University of Minnesota.

Final Report Summary:
Since its opening in August 2007, the Ground Water Plaza has become one of the key educational attractions in the Museum's outdoor science park, the Big Back Yard. Exhibits were developed, designed, fabricated and installed for the purpose of helping museum audiences better understand 1) the interconnections between surface waters and water-table aquifers; 2) the hydrogeologic conditions that produce artesian well conditions; and 3) how water is able to flow through bedrock via primary and secondary porosity.

The creation of the Ground Water Plaza significantly leveraged the resources provided by LCMR. The Minnesota Ground Water Association provided $20,463 to drill the artesian well that provides the water for the ground water exhibits and that serves as the focal point for the whole plaza. A gift of $10,000 from the Toro Giving Program and in-kind donations from numerous entities also helped make the Ground Water Plaza possible.

In September 2006, SMM and the American Museum of Natural History (AMNH) in New York City both learned that the other was developing a traveling exhibition about water. Both museums agreed in January 2007 to merge their separate exhibition projects into one collaborative traveling exhibition about water. In spring 2007, two exhibit components – porous stones and competing wells – being developed for the Ground Water Plaza were selected to be replicated for inclusion in the 7,000 square-foot traveling water exhibition. The National Ground Water Association agreed in September 2007 to provide $54,000 to cover the cost of building these two ground water components for the Water exhibition (http://www.amnh.org/exhibitions/water/). Below is information on the international tour of the **Water** exhibit:

North America Tour

American Museum of Natural History	350,000 visitors
San Diego Natural History Museum	108,000 visitors
Science Museum of Minnesota, St. Paul	128,000 visitors
The Field Museum, Chicago	show in progress
Great Lakes Science Center, Cleveland	future venue
Natural History Museum, Dallas	future venue
Fernbank Science Center, Atlanta	future venue
Royal Ontario Museum, Toronto	future venue

Overseas Tour:

Singapore Science Center	126,000 visitors
5th Annual World Water Forum, Istanbul, Turkey	show in progress
National Museum of Australia, Canberra	future venue
Instituto Sangari, São Paulo, Brazil	future venue

Total Water exhibition visitation to date............. 712,000 visitors

Result 2: SMM Development of Classroom Ground Water Education Programs

Description: The Science Museum of Minnesota will develop, design and fabricate classroom activities about how water actually moves underground. The focal point will be the development of a 3D visualization of ground water flow. This work will include all interpretive materials and consumable supplies needed to perform the classroom activities.

Summary Budget Information for Result 2:

LCMR Budget	$20,200
Minus Amount Spent	$20,200
Balance	$0

Completion Date: .... August 31, 2007

Result Status as of June 30, 2009
The incorporation of a 3D GeoWall display system into the ground water classroom program did not prove to be as useful as originally anticipated. While students enjoyed the additional element of 3D display, classroom spaces and configurations often were not conducive to the use of the portable GeoWall.

Final Report Summary:
Although the LCMR project, Enhancing Civic Understanding of Ground Water has concluded, the ground water classroom program will continue to be offered to schools. It is now included on SMM's residency program website - http://www.smm.org/schools/atyourschool/residencies/.

Result 3: Delivery Costs for Presenting Ground Water Education Programs to Schools Statewide.

Description: $900 reimbursement to the Museum for each school to which it delivers the ground water education classroom program for a maximum of 72 schools statewide.

Summary Budget Information for Result 3: **LCMR Budget** $64,800
Minus Amount Spent $64,800
Balance $0

Completion Date: .... June 30, 2009

Result Status as of June 30, 2009
SMM originally estimated that the Ground Water Classroom Program would reach 8,600 6th through 12th grade students. The program instead reached 7,324. SMM decided to target this program to 8th grade earth science students because this grade provided the strongest alignment to state science standards and the greatest opportunity to build partnership between classroom teachers and local Soil and Water Conservation Districts. Focusing the program on just one grade resulted in fewer potential students as program recipients. Further reducing the numbers of students reached is that smaller rural schools often have less than 120 students in eighth grade or in middle school science classes.

Final Report Summary:

Region	School	City	# of Days	Sessions Taught	# of Students
1	Lafayette High School	Red Lake Falls	1	3	53
2	Little Falls Community Middle	Little Falls	1	5	350
2	Little Falls Community Middle	Little Falls	1	4	350
2	Little Falls Community Middle	Little Falls	1	5	350
2	Swanville Elementary	Swanville	1	4	100
2	Cyrus Elementary School	Cyrus	1	1	17
2	Minnewaska Intermediate School	Glenwood	1	3	75
2	Glacial Hills Elementary	Starbuck	1	1	14

2	Morris Area High School	Morris	1	5	150
2	Staples-Motley Middle School	Motley	1	4	120
2	Long Prairie-Grey Eagle Middle	Long Prairie	1	6	200
2	New York Mills High School	New York Mills	1	2	60
2	Osakis High School	Osakis	1	3	62
2	Discovery Middle School	Alexandria	1	5	130
2	Discovery Middle School	Alexandria	1	3	78
2	Discovery Middle School	Alexandria	1	3	78
2	Evansville High School	Evansville	1	1	18
2	Prairie Wind Middle School	Perham	1	3	125
2	Rothsay Public School	Rothsay	1	1	9
2	Breckenridge Elementary	Breckenridge	0.5	3	54
2	St. Mary's School	Breckenridge	0.5	1	17
2	Campbell-Tintah Public School	Campbell	1	1	9
3	Chisago Lakes Middle School	Lindstom	1	5	145
3	Chisago Lakes Middle School	Lindstom	1	5	145
3	William Kelley High School	Silver Bay	1	2	31
3	Two Harbors High School	Two Harbors	1	4	88
3	Mora High School	Mora	1	5	141
3	Rush City High School	Rush City	1	3	63
3	North Branch Middle School	North Branch	1	5	151
3	North Branch Middle School	North Branch	1	5	155
4	Belgrade-Brooten-Elrosa Elementary	Brooten	1	4	100
4	Buffalo Community Middle School	Buffalo	1	5	145
4	Buffalo Community Middle School	Buffalo	1	5	145
4	Buffalo Community Middle School	Buffalo	1	5	145
4	Albany High School	Albany	1	3	90
4	South Junior High School	St. Cloud	1	5	160
4	South Junior High School	St. Cloud	1	5	160
4	Chaska Middle School West	Chaska	1	2	60
4	Chaska Middle School West	Chaska	1	5	125
4	Chaska Middle School West	Chaska	1	5	125
4	Anwatin Middle School	Minneapolis	1	5	151
5	Cedar Mountain High School	Morgan	1	1	35
5	Redwood Valley Middle School	Redwood Falls	1	5	146
5	ECHO Charter School	Echo	0	1	25

5	St. John's Lutheran School	Redwood Falls	0	1	21
5	Wabasso School	Wabasso	1	4	96
5	Milroy Public School	Milroy	0	1	19
5	Red Rock Central School	Lamberton	0	1	40
5	Lac Qui Parle Valley High School	Madison	1	3	90
5	Dawson-Boyd High School	Dawson	1	2	34
5	Montevideo Middle School	Montevideo	1	4	128
5	MACCRAY Junior High School	Clara City	1	2	64
5	RTR Middle School	Russell	1	2	40
5	Canby High School	Canby	1	2	51
5	Marshall Middle School	Marshall	1	3	75
5	Marshall Middle School	Marshall	1	3	75
5	Yellow Medicine East High School	Granite Falls	1	3	74
5	JCC Middle School	Lakefield	1	3	77
5	Luverne Middle School	Luverne	1	4	100
6	Butterfield-Odin School	Butterfield	1	2	60
6	Madelia Public School	Madelia	1	4	90
6	St. Peter High School	St. Peter	1	3	60
6	St. Peter High School	St. Peter	1	3	60
7	Hollandale Christian School	Hollandale	1	1	18
7	Southwest Middle School	Albert Lea	1	5	129
7	Lanesboro Public Schools	Lanesboro	0.5	2	48
7	Rushford-Peterson Schools	Peterson	0.5	2	50
7	Mabel-Canton Schools	Mabel	1	1	17
7	Houston High School	Houston	1	2	32
7	Mabel-Canton Schools	Mabel	1	1	20
8	Laporte School	Laporte	1	4	100
8	Nevis School	Nevis	1	5	125
8	Park Rapids Century School	Park Rapids	1	5	125
8	Lake of the Woods Middle School	Baudette	1	2	43
8	Robert J. Elkington Middle School	Grand Rapids	1	5	160
8	Robert J. Elkington Middle School	Grand Rapids	1	4	128
8	Park Rapids Century School	Park Rapids	1	5	125

	# of Days	Sessions Taught	# of Students
Grand Total	71	251	7,324

V. TOTAL LCMR PROJECT BUDGET:

All Results: Personnel:.. **$53,037**
All Results: Development: **$32,163**
All Results: Other (72 schools @ $900 for each school outreach program)**:** **$64,800**

TOTAL LCMR PROJECT BUDGET:..**$150,000**

Explanation of Capital Expenditures Greater than $3,500

No capital expenditures greater than $3,500 are anticipated.

VI. OTHER FUNDS & PARTNERS:

A. Project Partners: All project partners are donating their services to the project.
GeoWall Consortium, Department of Geology and Geophysics, University of Minnesota – Donation of GeoWall programming assistance
GJG Environmental Consultants – Donation of advisory assistance
Metropolitan Council Environmental Services – Donation of advisory assistance
Minnesota Association of Soil & Water Conservation Districts – Donation of school outreach assistance
Minnesota Department of Agriculture – Donation of ground water testing and advisory assistance
Minnesota Department of Transportation – Donation of bedrock core samples
Minnesota Ground Water Association – Donation of fundraising assistance
Minnesota Pollution Control Agency – Donation of advisory assistance
Pace Analytical Services, Inc. – Donation of ground water testing

B. Other Funds Being Spent During the Project Period: $54,000 from the National Ground Water Association to replicate two of the Ground Water Plaza exhibit components for the touring Water exhibition.

C. Past Spending: The Minnesota Ground Water Association has raised $24,255 as of 6/5/06 for *Result 1: Hands-On Outdoor Ground Water Education.* These funds were used to drill and finish off an artesian well in the Big Back Yard and to make other improvements to the Ground Water Plaza.

D. Time: July 1, 2006 through June 30, 2009. 36 of the proposed 72 school outreach programs are scheduled to take place during the 2008-2009 school year at a cost of $32,400.

VII. DISSEMINATION:

Final Report Summary:
The Science Museum and the American Museum of Natural History in partnership produced an internationally traveling exhibit about water that opened in New York City in November 2007. Two Ground Water Plaza outdoor exhibit components were modified for indoor use and replicated for inclusion in the 7,000 square-foot water exhibition. The National Ground Water Association provided $54,000 to cover the cost of building these two ground water components. Two copies of the Water exhibition with its ground water components were produced – one to tour North American venues and the second for overseas venues. To date, 712,000 people have seen the Water

exhibition with its ground water components and several million more will as the show continues to tour for several more years.

SMM originally estimated that the Ground Water Classroom Program would reach 8,600 6^{th} through 12th grade students. The program instead reached 7,324. SMM decided to target this program to 8^{th} grade earth science students because this grade provided the strongest alignment to state science standards and the greatest opportunity to build partnership between classroom teachers and local Soil and Water Conservation Districts. Focusing the program on just one grade resulted in fewer potential students as program recipients. Further reducing the numbers of students reached is that smaller rural schools often have less than 120 students in eighth grade or in middle school science classes.

VIII. REPORTING REQUIREMENTS

Periodic work program progress reports will be submitted no later than January 31, 2007; October 31, 2007; June 30, 2008; February 28, 2009. A final work program report and associated products will be submitted by June 30, 2009.

Attachment A: Budget Detail for ML 2006, Chp. 243, Sec. 20, Subd. 2
Project Title: ENHANCING CIVIC UNDERSTANDING OF GROUND WATER
Project Manager Name: Patrick Hamilton
Trust Fund Appropriation: $75,000 in fiscal year 2006 and $75,000 in fiscal year 2007 are appropriated to the Science Museum of Minnesota to create groundwater exhibits and a statewide traveling groundwater classroom program. 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.

2005 LCMR Proposal Budget	Result 1 Budget:	Amount Spent *(6/30/09)*	Balance *(6/30/09)*	Result 2 Budget:	Amount Spent *(6/30/09)*	Balance *(6/30/09)*	Result 3 Budget:	Amount Spent *(6/30/09)*	Balance *(6/30/09)*	
BUDGET ITEM	Hands-On Outdoor Ground Water Education			Ground Water Classroom Program Development			Ground Water Classroom Program On The Road			TOTAL FOR BUDGET ITEM
PERSONNEL: Staff Expenses, wages, salaries –	36,852	36,852	0	16,185	16,185	0		0	0	53,037
Patrick Hamilton, project manager - responsible for all aspects of this project										0
Bette Schmit, exhibit developer - will develop the outdoor ground water exhibit										0
Peder Thompson, prototyper - will create the hands-on interactive experiences										0
Cary Forss, exhibit designer - will prepare a design for the outdoor ground water exhibit										0
Christine Johnson, graphic designer - will prepare the outdoor graphic panels										0
Tim Motzko, graphic labor - will print and mount the outdoor graphic panels										0
Dan Dahm, project production manager - will oversee exhibit construction										0
TBD, fabricators - will construct and install the outdoor ground water exhibits										0
Larry Thomas, director of school outreach - will develop the ground water program										0
TBD, education program developer - will assist Thomas in the program development.										0
Other direct operating costs - exhibit materials, supplies, and services and school outreach program materials, supplies, and services	11,148	11,148	0	4,015	4,015	0		0	0	15,163
Construction of outdoor ground water exhibit patio	17,000	17,000	0					0	0	17,000
Other - $900 reimbursement to the museum for each school to which it delivers the ground water classroom program for a maximum of 72 schools statewide: • $100 for six contact hours in each school (rate incorporates travel time to and from the school) = $600 • Per diem for meals, lodging, and mileage - per commissioners' plan • Trip preparation work and coordination work with the MN Assoc. of Soil & Water Cons. Dist. of 4 hours per school venue @ $24/hr. plus benefits = $120							64,800	64,800	0	64,800
COLUMN TOTAL	65,000	65,000	0	20,200	20,200	0	64,800	64,800	0	150,000

SMM ground water classroom program @ William Kelley High School, Silver Bay (11-20-08)

SMM ground water classroom program @ Lafayette High School, Red Lake Falls (10-24-08)

SMM ground water classroom program @ Lafayette High School, Red Lake Falls (10-24-08)

SMM ground water classroom program @ Lafayette High School, Red Lake Falls (10-24-08)

SMM ground water classroom program @ Lafayette High School, Red Lake Falls (10-24-08)

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SMM ground water classroom program @ Lafayette High School, Red Lake Falls (10-24-08)

SMM ground water classroom program @ Lafayette High School, Red Lake Falls (10-24-08)

LCMR 2006 Project Abstract
For the Period Ending June 30, 2008

PROJECT TITLE: Laurentian Energy Authority Biomass Project
PROJECT MANAGER: Terry Leoni
AFFILIATION: General Manager, Virginia Public Utility
MAILING ADDRESS: PO Box 1048, 618 Second Street South
CITY / STATE / ZIP: Virginia, Minnesota 55792
PHONE: 218-748-7564
E-MAIL: leonit@vpuc.com
FAX: 218-748-7544
WEB PAGE ADDRESS: www.vpuc.com
LEGAL CITATION: ML 2006, Chap.243, Sec.20, and Subd.4.

Total Biennial LCMR Project Budget: LCMR Appropriation: $400,000

Appropriation Language: Subdivision 10, I (energy) Laurentian Energy Authority Biomass Project $200,000 in fiscal year 2006 and $200,000 in fiscal year 2007 are appropriated to the commissioner of commerce for an agreement with Virginia Public Utility to lease land and plant approximately 1,000 acres of trees to support a proposed conversion to a biomass power plant.

OVERALL PROJECT OUTCOME AND RESULTS:
The project resulted in 1,368 acres of hybrid poplar plantations being planted as a closed loop renewable biomass fuel source for the Laurentian Energy Authority's (LEA) Biomass Project. 35 MWh of electricity will be produced and sold to Xcel Energy to meet a state mandate for renewable energy. The Trust Fund appropriation was used to purchase trees (slips/whips developed by the University of MN, Duluth NRRI – hybrid poplar NM-6), tree planting, and for plantation land leasing on this 1,368 acres. LEA funded all technical assistance, crop care maintenance, and farming. Two separate plantations in Aitkin and Koochiching Counties totaling 1,368 acres were partially funded by the Trust Fund grant and partially funded and LEA.

The Trust Fund grant was also being used as a 50% non-federal match to the latest federal earmark/appropriation request. All of the Trust Fund funding was used directly to establish the initial and important plantings of the closed loop biomass crop. The success of the project depends upon growing a large portion of the fuel supply over the long term and successfully applying the work of the U of M's Natural Resource Research Institute (NRRI) and others on short rotation woody crops to real world production of fuel to large scale commercial projects.

The project assists the State of Minnesota's goal of 25% renewable fuels by 2025. Further it builds on the Federal Government's push to create one billion tons annually of renewable biomass fuels. The research and implementation is being accomplished under the U of M NRRI's direction with assistance from the USDA, Forest Service and is being done under the U.S. Department of Energy guidance and review.

PROJECT RESULTS USE AND DISSEMINATION:
LEA will assemble all data, costs, slips, care, and maintenance records for the 1,368 acres of plantation and this data will be available on paper from the Laurentian Energy Authority. All data, which has been under the auspices of the U of M NRRI with assistance from the USDA Forest Service, will be shared and turned over to them for determining ongoing and the long-term results. The U.S. Department of Energy is providing guidance and review.

LCMR 2006 Final Work Program Report

Project Completion Date: June 30, 2008

I. PROJECT TITLE: Laurentian Energy Authority (LEA) Biomass Project

Project Manager: Terry Leoni
Affiliation: General Manager, Virginia Public Utility
Mailing Address: PO Box 1048, 618 Second Street South
City / State / Zip: Virginia, Minnesota 55792
Telephone Number: 218-748-7564
E-mail Address: leonit@VPUC.com
FAX Number: 218-748-7544
Web Page address: www.vpuc.com

Total Biennial LCMR Project Budget:	**LCMR Appropriation:**	**$ 400,000**
	Minus Amount Spent:	**$ 400,000**
	Balance:	**$ 0**

Legal Citation: ML 2006, Chap.243, Sec.20, Subd.4.

Appropriation Language: Subdivision 10, I (energy) Laurentian Energy Authority Biomass Project $200,000 in fiscal year 2006 and $200,000 in fiscal year 2007 are appropriated to the commissioner of commerce for an agreement with Virginia Public Utility to lease land and plant approximately 1,000 acres of trees to support a proposed conversion to a biomass power plant.

II. & III. FINAL PROJECT SUMMARY: The project will result in 1,368 acres of hybrid poplar plantations being used as a closed loop renewable biomass fuel source for the Laurentian Energy Authority's Biomass Project. 35 MWh of electricity will be produced and sold to Xcel Energy to meet a state mandate for renewable energy. Even though the legislation requires 1,000 acres of plantation, the LEA committed to plant and fund 1,368 acres between July 1, 2006 and June 30, 2008. The LCMR appropriation has been used to purchase trees (slips/whips developed by the University of MN, Duluth NRRI – hybrid poplar NM-6), tree planting, and for plantation land leasing on this 1,368 acres, while LEA will fund all technical assistance, crop care maintenance, and farming. Thus, two separate plantations in Aitkin and Koochiching Counties totaling 1,368 acres will be partially funded by the LCMR grant and LEA.

The Laurentian Energy Authority (LEA) is a joint venture of the municipal, public utilities of Virginia and Hibbing, Minnesota. LEA received Minnesota Pollution Control Agency permits, project financing, and Minnesota Public Utility Commission approval to construct and operate 35 MWh of combined renewable heat and power biomass facilities.

$87 million was invested repowering the Virginia and Hibbing coal plants with new renewable biomass boilers and new wood fuel handling equipment. 71 jobs were retained in aggregate between the two sites and 65 new jobs will be created farming, logging and transporting this renewable biomass fuel. This renewable biomass totaling nearly $11 million annually will come from a 75 mile radius of the two plant sites thereby displacing a major portion of over $7 million in coal acquired and burned from the State of Wyoming. The output from the two renewable energy plants will serve 3,600 commercial and residential customers, along with sales of renewable electricity to Xcel Energy, pursuant to a 1994 legislative mandate to Xcel Energy.

A portion of the renewable biomass fuel must come (by legislation) from closed loop biomass plantations. To that end, LEA has invested in and planted a nursery and almost 1,400 acres of hybrid plantations. A Phase I federal appropriation of $1,237,500 to fund research and development for hybrid poplar plantations and new biomass fuel gathering techniques has been acquired. In addition to the Phase I appropriation a federal earmark of $1,000,000 has been identified to further this plantation activity.

The LCMR grant is also being used as a 50% non-federal match to the latest federal earmark/appropriation request. All of the LCMR funding was used directly to establish the initial and important plantings of the closed loop biomass crop. The success of the project depends upon growing a large portion of the fuel supply over the long term and successfully applying the work of the U of M's Natural Resource Research Institute (NRRI) and others on short rotation woody crops to real world production of fuel to large scale commercial projects. It is pioneering work that will advance renewable biomass projects as the State of Minnesota increases its legislative goal to achieve 25% renewable fuels by 2025. Additionally, the LCMR grant will implement the previous research from the Phase I federal appropriation.

The LCMR grant meets perfectly the State of Minnesota's goal of 25% renewable fuels by 2025. Further it builds on the Federal Government's push to create one billion tons annually of renewable biomass fuels. The research and implementation is being accomplished under the U of M NRRI's direction with assistance from the USDA Forest Service and is being done under the U.S. Department of Energy guidance and review.

IV. OUTLINE OF PROJECT RESULTS:

Result 1: Lease and Plant 640 acres of hybrid poplar on plantation land.

Description: Lease 640 acres of plantation land in Aitkin County (Twp 49N, R24W and Twp 48N, R25W) for FY 2007 at $43.00 per acre. Purchase slips/whips: 1,361 slips/whips/acre @ $0.10 of NM-6. Plant 640 acres at an average price of $119.1515 per acre.

Summary Budget Information for Result 1:	**LCMR Budget**	**$ 190,881**
	Minus Amount Spent:	**$ 190,881**
	Balance:	**$ 0**

Result Status: *July 1, 2006 to June 30, 2008 LEA has a twenty (20) year lease agreement with landowner Gene McClelland, for 640 acres in Aitkin County. One hundred percent (100%) of the acreage has been planted. There does not appear to be an excessive amount of winterkill due to frost or a late snowfall that exceeded 20 inches in early April. Planting in the ground pre-June 2007 are reaching heights of approximately 20 feet with a base diameter of 2.5 to 2.75 inches. A canopy has formed over these plantings thereby eliminating the need for weed control due to sunlight being blocked at ground level. Harvesting of the pre-2007 plantings should take place in 2011. Those plantings post-June 2007 are approximately 6 to 8 feet in height with a base diameter of 1.0 to 1.5 inches. Cultivating and weed control was required. If all goes well during the summer a canopy is expected thereby reducing the need for weed control until harvest in 2013.*

Result 2: Lease and Plant 728 acres of hybrid poplar on plantation land.

Description: Lease 728 acres of plantation land in Koochiching County (Twp 151N, R27W) for FY 2007 at $32 per acre. Purchase slips/whips: 1,361 slips/whips/acre @ $0.10 of NM-6. Plant 728 acres at an average price of $119.1515 per acre.

Summary Budget Information for Result 2:	**LCMR Budget:**	**$ 209,119**
	Minus Amount Spent:	**$ 209,119**
	Balance:	**$ 0**

Result Status: *July 1, 2006 to June 30, 2008 LEA has a twenty (20) year lease agreement with landowner Frenzel, Miller, et.al., 728 acres in Koochiching. One hundred percent (100%) of the acreage has been planted. There does not appear to be an excessive amount of winterkill due to frost or a late snowfall that exceeded 20 inches in early April. Planting in the ground pre-June 2007 are reaching heights of approximately 18 feet with a base diameter of 2.5 inches. A canopy has formed over these plantings thereby eliminating the need for weed control due to sunlight being blocked at ground level. Harvesting of the pre-2007 plantings should take place in 2012. Those plantings post-June 2007 are approximately 6 to 8 feet in height with a base diameter of 1.0 to 1.5 inches. Cultivating and weed control was required. If all goes well during the summer a canopy is expected thereby reducing the need for weed control until harvest in 2013.*

V. TOTAL LCMR PROJECT BUDGET:

All Results: Personnel: $ 0
All Results: Equipment: $ 0
All Results: Development: $ 349,184
All Results: Acquisition: $ 50,816
All Results: Other: $

TOTAL LCMR PROJECT BUDGET: $ 400,000

Explanation of Capital Expenditures Greater Than $3,500: NA

VI. PAST, PRESENT AND FUTURE SPENDING

A. Project Partners: Laurentian Energy Authority. $400,000.

B. Other Funds being Spent during the Project Period: $671,000 in total from the Laurentian Energy Authority. $252/acre for plantation care maintenance, $91/acre for second year plantation care maintenance, and $156,500 over two years for technical assistance.

C. Required Match (if applicable): 0

D. Past Spending: $323,129 for slips, $83,760 for land lease fees, $237,134 for technical assistance, and $5,000 for legal work.

E. Time: The plantation is designed for a twenty year life with four harvests. All additional costs after July 1, 2008 will be assumed by the LEA, and thus there will be no further LCMR commitments on these plantations.

VII. PROJECT PARTNERS: Laurentian Energy Authority, University of Minnesota - Natural Resource Research Institute, USDA Forest Service, and U.S. Department of Energy

VIII. DISSEMINATION: LEA and NRRI will assemble all data, costs, slips, care, and maintenance records for the 1,368 acres of plantation and this data will be available on paper from the Laurentian Energy Authority. There will be no web site. All data, which has been under the auspices of the U of M NRRI with assistance from the USDA Forest Service, will be shared and turned over to them for determining ongoing and the long-term results. The U.S. Department of Energy is providing guidance and review.

IX. LOCATION: Field Plantations: **in Aitkin County, 640 acres in Twp 49N, R 24W and Twp 48N, R 25W and in Koochiching County, 728 acres in Twp 151N, R27W.** LEA plant sites are located at Hibbing Public Utility, 1902 Sixth Avenue East, Hibbing, MN and Virginia Public Utility, 618 Second Street South, Virginia, MN. The Plantation sites have been identified above and the LEA business office is located at c/o Virginia Public Utility, 618 Second Street South, Virginia, MN 55792.

X. REPORTING REQUIREMENTS: Periodic work program progress reports will be submitted no later than December 31, 2006, July 1, 2007, December 31, 2007, and a final work program report and associated products will be submitted by June 30, 2008.

XI. RESEARCH PROJECTS: University of Minnesota Natural Resource Research Institute, USDA Forest Service, and U.S. Department of Energy

Attachment A: Budget Detail for 2006 Projects - Summary and a Budget page for each partner (if applicable)

Proposal Title: Laurentian Energy Authority Biomass Project

Project Manager Name: Terry Leoni

LCMR Requested Dollars: $ *400,000*

1) See list of non-eligible expenses, do not include any of these items in your budget sheet
2) Remove any budget item lines not applicable

2005 LCMR Proposal Budget	**Result 1 Budget:**	**Amount Spent** *(date)*	**Amount Spent** *(date)*	**Amount Spent** *(date)*	**Amount Spent** *(date)*	**Result 2 Budget:**	**Amount Spent** *(date)*	**Amount Spent** *(date)*	**Amount Spent** *(date)*	**Amount Spent** *(date)*	
	Lease 640 acres of plantation land	*31-Dec-06*	*30-Jun-07*	*31-Dec-07*	*30-Jun-08*	*Lease 728 acres of plantation land*	*31-Dec-06*	*30-Jun-07*	*31-Dec-07*	*30-Jun-08*	
BUDGET ITEM											**BALANCE REMAINING FOR**
PERSONNEL: Staff Expenses, wages, salaries – *Be specific on who is paid $, to do what? Make each person paid a separate line item*											
PERSONNEL: Staff benefits – *Be specific; list benefits for each person on a separate line item*											
Contracts											
Professional/technical *(with whom?, for what?)*											
Other contracts *(with whom?, for what?) list out: personnel, equipment, etc.*											
Other direct operating costs *(for what? – be specific)*											
Equipment / Tools *(what equipment? Give a general description and cost)*											
Office equipment & computers - NOT ALLOWED unless unique to the project											
Other Capital equipment *(list specific items)*											
Land acquisition *(how many acres)*											
Land rights acquisition	**Lease 640 acres of plantation land in Aitkin County FY 2006 @ $43.00/acre. Total: $27,520**	**8,256**	**8,256**	**0**	**11,008**	**Lease 728 acres of plantation land in Koochiching County FY 2007 @ $32.00/acre. Total: $23,296**	**6,989**	**6,989**	**0**	**9,318**	**$ 0**
Printing											
Other Supplies *(list specific categories)*											
Travel expenses in Minnesota											
Travel outside Minnesota *(where?)*											
Construction *(for what?)*											
Other land improvement *(for what?)*											
Other *(Describe the activity and cost) be specific*	**Purchase 1,361 NM6 trees/acre @ $0.10 and Plant 640 acres @ $119.1515 for FY 2006 on 640 acres located in Aitkin County. Total: $163,361**	**49,009**	**24,505**	**0**	**89,847**	**Purchase 1,361 NM6 trees/acre @ $0.10 and Plant 728 acres @$119.1515 for FY 2007 on 728 acres located in Koochiching County. Total: $185,823**	**55,746**	**27,873**	**0**	**102,204**	**$ 0**
COLUMN TOTAL	**$190,881**	**$57,265**	**$32,761**	**$0**	**$100,855**	**$209,119**	**$62,735**	**$34,862**	**$0**	**$111,522**	**$ 0**

2006 Project Abstract
For the Period Ending June 30, 2008

PROJECT TITLE: Land Cover Mapping for Natural Resource Protection (H-29)
PROJECT MANAGER: Roel Ronken
AFFILIATION: Hennepin County – Dept. of Environmental Services
MAILING ADDRESS: 417 North 5th Street – suite 200
CITY/STATE/ZIP: Minneapolis / MN / 55401-1397
PHONE: 612 596-1172
FAX: 612 348-8532
E-MAIL: roel.ronken@co.hennepin.mn.us
WEBSITE: (If applicable) www.hennepin.us
FUNDING SOURCE: Minnesota Environment and Natural Resource Trust Fund
LEGAL CITATION:
ML 2006, [Chap.243], Sec.[20], Subd. 5

APPROPRIATION AMOUNT: $250,000

Overall Project Outcome and Results

Much of the land cover within the five Twin Cities metropolitan county partners on this project (Carver, Dakota, Hennepin, Scott, and Washington) has been converted from historic native plant communities to human-disturbed systems. However, remnant natural plant communities persist and their protection remains critical, while significant opportunities also exist for the restoration of other cover types in these landscapes. Restoration within these areas will increase the extent and connectivity of remnant natural areas, provide ecological benefits such as improved wildlife habitat and reduced soil erosion, and present many opportunities for landowners and other citizens to engage in improving the natural resource base in their own communities. Large-scale restoration will be more possible with landscape-scale planning that provides methods for identifying and prioritizing opportunities based on the best available information.

Over a period of years, significant public funding has been invested in land cover mapping as part of a natural resource inventory to help determine regional priorities for wildlife habitat protection and restoration using the Minnesota Land Cover Classification System (MLCSS). The purpose of this project was to create a GIS-based model following MLCSS that the five participating counties could use as a tool for identifying opportunities for ecological restoration at a landscape-scale in their urbanized landscapes.

This project completed identified land cover mapping for the five partner counties and used it along with other data – e.g. soils, slope, and aspect – to develop prioritization criteria to identify and rank potential restoration sites. The Restoration Prioritization and Prediction Model (RePP) was the resulting computer model developed to identify these sites. After the initial categorization of approximately 1.5 million acres, the model was run on approximately 837,000 acres defined as having restoration potential.

Land cover data and an electronic version of the RePP including appendices are available by reviewing the "Restoration Prioritization and Prediction Model" located at the following Minnesota Department of Natural Resources .ftp site:
ftp://ftp.dnr.state.mn.us/pub/gisftp/barichar/restoration_model/Workshop%20Materials/

Additional background data is available at the Minnesota Department of Natural Resources Data Deli:
http://deli.dnr.state.mn.us/

Project Results Use and Dissemination

Increasingly, land cover data is referenced and used as a tool for planners and government officials. Cities and other local forms of government can benefit from the model and understanding how it can be used in planning efforts. A training session with the staff of county partners was conducted. A presentation of the model was made to a partnership of local nonprofit organizations and other entities that promotes protection of open space in the Twin Cities region. Further dissemination will occur through the Data Deli, through project partners familiar with the model, and through planners that find the publicly available model.

LCMR 2006 Work Program Final Report

Date of Report: August 15, 2008
Date of Next Status Report: NA
Date of Work program Approval: June 27, 2006
Project Completion Date: June 30, 2008

I. PROJECT TITLE: Land Cover Mapping for Natural Resource Protection (H-29)

Project Manager: Roel Ronken
Affiliation: Hennepin County – Dept. of Environmental Services
Mailing Address: 417 North 5th Street – suite 200
City / State / Zip : Minneapolis / MN / 55401-1397
Telephone Number: 612 596-1172
E-mail Address: roel.ronken@co.hennepin.mn.us
FAX Number: 612 348-8532
Web Page address: www.hennepin.us

Location: Five County Minneapolis - St. Paul Metropolitan Region. See attached mapping.

Total Biennial LCMR Project Budget:	**LCMR Appropriation:**	**$ 250,000.00**
	Amount Spent	**$ 247,385.43**
	Balance:	**$ 2,614.57**

Legal Citation: ML 2006, [Chap.243], Sec.[20], Subd. 5

Appropriation Language: *$125,000 the first year and $125,000 the second year are from the trust fund to the commissioner of natural resources for an agreement with Hennepin County to develop GIS tools for prioritizing natural areas for protection and restoration and to update and complete land cover classification mapping.*

II. and III. FINAL PROJECT SUMMARY

The term Land Cover can be defined as both native vegetation and areas disturbed by human activity. Over a period of years, significant public funding has been invested in land cover mapping as part of a natural resource inventory to help determine regional priorities for wildlife habitat protection and restoration. The present project, "Land Cover Mapping for Natural Resource Protection (H-29)", completes the identified land cover mapping for the five county project partners which includes: Carver, Dakota, Hennepin, Scott, and Washington counties. Land cover mapping was produced using a combination of aerial photograph interpretation and field surveys that include modifiers that more specifically define attributes of the landscape (e.g. moderate quality maple-basswood forest).

Other goals of this project were to use the result of the land cover mapping along with soils, slope, and aspect to develop prioritization criteria to identify & rank potential restoration sites.

The Restoration Prioritization and Prediction Model (RePP) was the resulting computer model developed to identify these sites. After the initial categorization of approximately 1.5 million acres, the model was run on approximately 837,000 acres defined as having restoration potential. Restoration within the identified project area will increase the extent and connectivity of the remaining natural areas, and provide ecological benefits such as improved wildlife habitat and reduced soil erosion.

Land cover data and an electronic version of the RePP including appendices are available by reviewing the "Restoration Prioritization and Prediction Model" located at the following Minnesota Department of Natural Resources .ftp site:

ftp://ftp.dnr.state.mn.us/pub/gisftp/barichar/restoration_model/Workshop%20Materials/

Additional background data is available at the Minnesota Department of Natural Resources Data Deli:

http://deli.dnr.state.mn.us/

IV. OUTLINE OF PROJECT RESULTS*:* Significant state and local funds have been invested in mapping and classifying land cover in the seven county metropolitan region to help determine regional priorities for wildlife habitat protection and restoration. However, the existing information is incomplete and methodology is not designed for local scale or parcel analysis. New GIS-based tools created through this project will combine current scientific information with statistical analysis of land cover data in order to identify and rank the suitability of sites for protection and/or restoration. Having these new GIS application tools and updated information in priority areas will assist local units of government in protecting wildlife habitat and water quality as they review large scale development projects and develop and adopt new comprehensive plans in 2008.

Result 1: Development, Application, and Training of GIS-based Analysis Tools for Prioritizing Natural Area Protection and Restoration

Description:

A. Design and apply GIS-based Tools

1. Design and apply a protocol and tool to identify and rank existing ecologically-significant terrestrial and wetland areas at a scale sufficiently detailed and accurate for use on individual parcels.
2. A second tool will be designed and applied on at least 550,000 acres to identify sites for potential native plant community restoration which are degraded or where native plant communities no longer exist. This tool will provide the ability to suggest which plant community is best suited to the site based upon existing environmental conditions.

3. A third tool will be designed and applied to rank and refine these potential restoration sites. The system will be designed so that it can be easily modified in response to a variety of financial, ecological, ownership, recreational, and community considerations.

B. Outreach and Training

One presentation and one training session will be conducted. The presentation will be for the Regional Greenways Collaborative, which includes staff of local and state government agencies, nonprofits, and environmental consultants. The training session will be for staff of the partner counties, including natural resource managers and GIS technicians. In addition, web site access through the DNR will be provided.

Summary Budget Information for Result 1:	**LCMR Budget**	**$80,000.00**
	Balance	**$ 1,883.26**

Completion Date Completion Date: Entire result will be completed June 30, 2008.

Result Status as of: (June 30, 2008).

We ended up running the model on 837,000 acres which was significantly more than the 550,000 acre goal that we had at the start of the grant.

This project was straight forward and there were no significant changes from what we initially envisioned. The project management was shared by the individual County representatives and I (Roel Ronken) concentrated on insuring that the modeling consultant and the DNR received data within the outlined timeline along with the overall financial coordination.

The familiarity of the Project Partners gave us confidence that we could complete the project in the allotted time. There was some concern that the consultants conducting the field work may not be able to live up to their agreements/contracts. This was not due to effort but rather the size of the work load they were responsible for completing. Everyone made extraordinary effort in seeing the project through to completion. I can't think of anything I'd change, it went very smoothly although it was perhaps a little too large for us to expect to complete in the two year timeframe of an LCCMR grant. I believe the success of the project was due to the individual County coordinators, the DNR and the relationships with and quality of the consultants.

The completed Restoration Prioritization and Prediction model (RePP), supporting data, and metadata is publicly available at:

ftp://ftp.dnr.state.mn.us/pub/gisftp/barichar/restoration_model/

Staff of the partner Counties attended a training session on June 2nd. A public presentation of the model was made at an Embrace Open Space meeting on June 24th, 2008.

Result 2: **New and Revised Priority Land Cover Mapping in Carver, Hennepin, Scott, and Washington Counties**

Result Status as of: June 30, 2008**:**
All MLCCS data from the individual partner Counties has been given to the DNR and is publicly available at: ftp://ftp.dnr.state.mn.us/pub/gisftp/barichar/restoration_model/ GIS%20Files .

Washington SWCD shifted $3,600 originally budgeted in their workload to their consultant, Critical Connections (Jason Hustvedth). This work consisted of completing the "ground-truthing". Jay Riggs (Washington SWCD Manager) concluded that this was a more efficient means of completing the project. I (Roel Ronken) wasn't aware of this budget change until completing the Final Report. I should have caught this when the invoice was given to me in February, '08 and asked for permission for that budget change from the LCCMR at that time.

In addition, Carver County overspent their GIS costs with their SWCD by $100.00

In regard to both Carver and Washington County, the final result was the same and the amount spent did not exceed the total budget amount per County.

Final Report Summary: Final payment for the Restoration Prioritization and Prediction model was completed by August 15th, 2008. All payments have been completed to partner Counties and Ecological Strategies (model consultant). All the defined project results were completed by June 30th, 2008.

TOTAL LCMR PROJECT BUDGET:

All Results: Personnel: $247,300
All Results: Equipment: $0.00
All Results: Development: $0.00
All Results: Acquisition: $0.00
All Results: Other: $ 2,700 (mileage, printing, and materials)

TOTAL LCMR PROJECT BUDGET: $250,000

Explanation of Capital Expenditures Greater Than $3,500: NA

V. OTHER FUNDS & PARTNERS:

A. Project Partners: Carver County - $51,730; Dakota County SWCD - $1,040; Hennepin County – $128,960, Scott County - $12,000; Washington Conservation District - $56,270; and the Minnesota DNR.

B. Other Funds being Spent during the Project Period: Cash: $20,000 from Hennepin County and $18,000 from Washington Conservation District and $10,000 from Carver County. In-Kind: $15,000 from the DNR, $7,769 from Carver County, $10,000 from Hennepin County, $6,000 from Washington Conservation District, and $3,000 from Scott County.

C. Required Match (if applicable): NA

D. Past Spending: This project is a continuation of work coordinated through Metro Greenways and the Big Rivers Partnership and funded by a variety of local, regional, state, and federal sources over the past six years. Approximately $150,000 will have been expended for similar efforts described in this project proposal in the two years prior to July 1, 2005.

E. Time: The project will be completed by June 30, 2008

VI. DISSEMINATION: *(see Result 1B.)*

The MN Dept. of Natural Resources maintains and manages all MLCCS data, and will add these data and make them available to the public. The DNR will review and assess the quality of the data and will not accept any data that does not comply with the MLCCS standards. Dissemination of the results of the project will be made through the public presentation to interested individuals and organizations as previously described. In addition, the technical training session with staff of partner organizations will ensure the results can be utilized fully by the partner organizations as the end of the project. Written materials and PowerPoint presentations used in Result 1 will also be available on the web.

VII. REPORTING REQUIREMENTS:

Periodic work program progress reports will be submitted not later than: January, 2007; July, 2007; and January 2008. A final work program report and associated products will be submitted by June 30, 2008.

VIII. RESEARCH PROJECTS: NA

Attachment A: Budget Detail for 2006 Project - **Summary and Budget**

Proposal Title: *Land Cover Mapping for Natural Resource Protection (H-29)*

Project Manager Name: Roel Ronken

LCMR Requested Dollars: $250,000

2006 LCMR Proposal Budget	Result 1 Budget:	Amount Spent (6/30/2008)	Balance (6/30/2008)	Result 2 Budget:	Revised Result 2 budget (5/15/2007)	Amount Spent (6/30/2008)	Balance (6/30/2008)	TOTAL(s)
	GIS-based Analysis Tools			*Design protocol & New Priority Land Cover Mapping*				
BUDGET ITEM								**TOTAL(s)**
CARVER COUNTY:								
Staff Expenses, mileage in the State of MN				625.00	625.00	625.00	0.00	625.00
Contract 1 - Carver Soil & Water Conservation District - Fee for Service $29,590 (photo interpretation, field verification)				29,590.00	29,590.00	29,590.00	0.00	29,590.00
Contract 2 - Professional Consultant - $11,615 (support to SWCD & County Planning for field work & MLCCS coding in high quality areas)				11,615.00	11,615.00	11,132.29	482.71	11,615.00
Contract 3 - Carver County GIS - Fee for Service $9,900 (digitizing of land cover data and GIS assistance)				9,900.00	9,900.00	10,000.00	(100.00)	9,900.00
DAKOTA SWCD:								
SWCD wages & benefits (design protocol)				1,040.00	1,040.00	1,040.00	0.00	1,040.00
HENNEPIN COUNTY:								
Contract 1 - consultant contract for land cover mapping and field verification				48,960.00	48,960.00	48,960.00	0.00	48,960.00
Contract 2 - Ecological Strategies, LLC	80,000.00	78,116.74	1,883.26					80,000.00
SCOTT COUNTY:								
Contract 1: Consultant contract for land cover mapping and field verification.				12,000.00	12,000.00	12,000.00	0.00	12,000.00
WASHINGTON SWCD:								
Contract 1 - consultant contract for land cover mapping and field verification				0.00	27,400.00	31,000.00	(3,600.00)	27,400.00
Washington Conservation District GIS, land cover mapping, field evaluation, quality control wages & benefits				0.00	28,870.00	24,921.40	3,948.60	28,870.00
GIS tech wages & benefits - 1172hrs. @ $25.00				29,300.00	0.00	0.00	0.00	0.00
Botanist wages & benefits - remote sensing, ground truthing (Sr tech) 700 hrs. @ $30.00				21,000.00	0.00	0.00	0.00	0.00
Quality Control Project Manager wages and benefits - 150 hrs @ $39.80				5,970.00	0.00	0.00	0.00	0.00
Column Total(s)	80,000.00	78,116.74	1,883.26	170,000.00	170,000.00	169,268.69	731.31	$250,000.00

2006-1008 Project Abstract
For the Period Ending June 30, 2010

PROJECT TITLE:	Lake Superior Research
PROJECT MANAGER:	Steven M. Colman
AFFILIATION:	Large Lakes Observatory, UMD
MAILING ADDRESS:	2205 E. 5th St.
CITY/STATE/ZIP:	Duluth, MN 55812
PHONE:	218-726-6979
FAX:	218-726-6979
E-MAIL:	scolman@d.umn.edu
WEBSITE	www.d.umn.edu/llo

FUNDING SOURCE:	Environment and Natural Resources Trust Fund and Great Lakes Protection Fund
LEGAL CITATION:	M.L. 2006, Chap. 243, Sec. 20, Subd. 6 M.L. 2008, Chap. 367, Sec. 2, Subd. 4(i)
APPROPRIATION AMOUNT:	2006: $295,000 2008: $68,000

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

There is a surprising lack of study and understanding of the ecosystems of the Great Lakes and their properties, especially in the deepwater basins. We know more about many marine systems than we know about the Great Lakes. With current concerns about the environmental health of the Great Lakes, studies supported through this project aimed to contribute to alleviating some of the unknowns. A series of studies were conducted that research the condition, functioning, and processes of Lake Superior, its sediments, and its ecosystem including:

- Studies related to the entire living ecosystem, from top predator fish down to picoplankton.
- Studies of the circulation of the lake using numerical models and oceanographic instrumentation.
- Studies of the water column including the balance between CO_2 production and oxygen consumption, the processes related to the fate of organic matter and nutrients, and the effect of these and other water column processes on primary producers.
- Studies of the transport and delivery of organic and inorganic materials to the lake floor as sediments that accumulate in deep waters of the lake and the erosion, transport, and storage of coarse-grained sediment in coastal waters.

In all of these studies, we took a holistic, “physics to fish” approach, examining the interactions between physical and biological processes.

We conducted a total of 24 field projects, with project funds going primarily to the cost of using of our research ship for an aggregate of 53 days at sea. Project funds leveraged other funding as most of these studies were small pilot projects, extensions to projects funded from other sources, and projects to collect preliminary data often required for proposals to the national science agencies. The projects have a common theme of understanding the dynamics of Lake Superior, its sediments, and its ecosystem. Through these studies, we hope to provide Minnesotans, from lay citizens to environmental managers, a better understanding of how Lake Superior works and how it might change in response to climate change and human activity.

<u>**Project Results Use and Dissemination**</u>

We have now collected a wealth of environmental data for Lake Superior. A significant part of those data have already been used for larger research proposals to the National Science Foundation and other agencies, some of which have already been successful in bringing new federal funding into the state. Plans are for the results of studies supported through this project to be published in peer-reviewed journals where they will be available to Minnesota managers and regulators. With other funding, we are in the process of developing a system called the Global Great Lakes Data and Modeling Center, which will allow incorporation and assimilation of existing data, new data like those collected in this project, and ongoing real-time observational data. The Data and Modeling Center will allow numerical models to be run and compared in real time using the different data sets and make all data readily available though an internet interface.

Trust Fund 2006 and 2008 Final Report

Date of Report: April 16, 2010
Trust Fund 2006 and 2008 Final Report
Date of Work program Approval: June 13, 2006
Project Completion Date: Oct. 31, 2009

I. PROJECT TITLE: Lake Superior Research

Project Manager: Steven M. Colman
Affiliation: Large Lakes Observatory, UMD
Mailing Address: 2205 E. 5th St.
City / State / Zip : Duluth, MN 55812
Telephone Number: 218-726-8522
E-mail Address: scolman@d.umn.edu
FAX Number: 218-726-6979
Web Page address: www.d.umn.edu/llo

Location: Western Lake Superior, map attached to original work plan.

Total ENRT Project Budget:

ENRT 2006 Appropriation:	**$**	295,000
ENRT 2008 Appropriation:	**$**	86,000
Minus Amount Spent:	$	381,000
Equal Balance:	**$**	0

Budget detail: Included in text of Results and Budget Spreadsheet.

Legal Citation: **M.L. 2006, Chap. 243, Sec. 20, Subd. 6**
M.L. 2008, Chap. 367, Sec. 2, Subd. 4(i)

2006 Appropriation Language:
$133,000 in fiscal year 2006 and $134,000 in fiscal year 2007 are appropriated to the Board of Regents of the University of Minnesota for the Large Lakes Observatory for research on Lake Superior waters. $28,000 in fiscal year 2007 from the Great Lakes protection account under Minnesota Statutes, section 116Q.02, is appropriated to the Board of Regents for the same purpose. 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.

2008 Appropriation Language:
$86,000 is from the Great Lakes protection account to the Board of Regents of the University of Minnesota for the Large Lakes Observatory for research on Lake Superior waters. This appropriation is added to Laws 2006, chapter 243, section 20, subdivision 6, Lake Superior research. This appropriation is available until June 30, 2011, 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 AND RESULTS:

<u>Overall Project Outcome and Results</u>
There is a surprising lack of study and understanding of the ecosystems of the Great Lakes and their properties, especially in the deepwater basins. We know more about many marine

systems than we know about the Great Lakes. With current concerns about the environmental health of the Great Lakes, studies supported through this project aimed to contribute to alleviating some of the unknowns. A series of studies were conducted that research the condition, functioning, and processes of Lake Superior, its sediments, and its ecosystem including:

- Studies related to the entire living ecosystem, from top predator fish down to picoplankton.
- Studies of the circulation of the lake using numerical models and oceanographic instrumentation.
- Studies of the water column including the balance between CO_2 production and oxygen consumption, the processes related to the fate of organic matter and nutrients, and the effect of these and other water column processes on primary producers.
- Studies of the transport and delivery of organic and inorganic materials to the lake floor as sediments that accumulate in deep waters of the lake and the erosion, transport, and storage of coarse-grained sediment in coastal waters.

In all of these studies, we took a holistic, "physics to fish" approach, examining the interactions between physical and biological processes.

We conducted a total of 24 field projects, with project funds going primarily to the cost of using of our research ship for an aggregate of 53 days at sea. Project funds leveraged other funding as most of these studies were small pilot projects, extensions to projects funded from other sources, and projects to collect preliminary data often required for proposals to the national science agencies. The projects have a common theme of understanding the dynamics of Lake Superior, its sediments, and its ecosystem. Through these studies, we hope to provide Minnesotans, from lay citizens to environmental managers, a better understanding of how Lake Superior works and how it might change in response to climate change and human activity.

Project Results Use and Dissemination

We have now collected a wealth of environmental data for Lake Superior. A significant part of those data have already been used for larger research proposals to the National Science Foundation and other agencies, some of which have already been successful in bringing new federal funding into the state. Plans are for the results of studies supported through this project to be published in peer-reviewed journals where they will be available to Minnesota managers and regulators. With other funding, we are in the process of developing a system called the Global Great Lakes Data and Modeling Center, which will allow incorporation and assimilation of existing data, new data like those collected in this project, and ongoing real-time observational data. The Data and Modeling Center will allow numerical models to be run and compared in real time using the different data sets and make all data readily available though an internet interface.

IV. OUTLINE OF PROJECT RESULTS*:*

As noted above, project results to date include data collection activities aimed at a better understanding of the condition, functioning, and processes of Lake Superior, its sediments, and its ecosystem. The original three Results were part of funding in FY 2006, and they have been completed for more than a year. In early 2008, a new project, listed below as Result 4, was proposed and planned as described in that Result section. This Result has also been completed, as described below.

Result 1: Field research 2006

Description: A portfolio of research activity was conducted on Lake Superior in the summer of 2006. As mentioned in the Project Summary, these studies are small pilot studies, extensions to projects funded from other sources (see section VI-B), and activities to collect preliminary data often required for proposals to the National Science Foundation. The studies have a common theme of understanding the dynamics of Lake Superior, its sediments, and its ecosystem. All studies have been peer reviewed either by a funding agency or by a committee of scientists that use the RV Blue Heron, commonly both.

Costs paid for with Environment and Natural Resources Trust (ENRT) funds were entirely for field activities, observations, and data collection on board the RV Blue Heron, accounted for at the ship's day rate of $4654. The day rate includes crew, technician and ship manager salaries; insurance; and operational costs (fuel, food, garbage, dock fees, etc.). Total of cost of activities listed above was $65,156. Other sources of project funding (in some case, the main funding for the project) are listed with the individual projects.

Summary Budget Information for Result 1:	**ENRT Budget**	**$ 65,156**
	Expended	**$ 65,156**
	Balance	**$ 0**

Completion Date: Oct. 31, 2006

Final Report Summary: Research activities included:

1. (Wattrus, PI) June 4th-6th, in conjunction with an NSF-funded cruise. An acoustic survey of the western arm of Lake Superior to image the paleo-shorelines associated with earlier (Minong/Houghton) lowstands of the lake. Two days of ship time ($9,308) were paid with ENRT funds, and the National Science Foundation (NSF paid for an additional day, along with support for equipment usage and data analyses. Results: The paleo-shoreline features were located and imaged. The data are also being used to map the size and dimensions of the sediment fan associated with the Nemadji River.
2. (Hrabik, PI) July 26th – August 1st, in conjunction with a MN DNR-funded cruise for fish stock assessments. Four days of ship time ($18,616) were paid with ENRT funds. Two additional days were paid for by MN DNR. Results: These fish stock assessments, in cooperation with the MN DNR, are part of a long term monitoring program; this operation provided the monitoring data for 2006. In addition, with the additional ship time, Dr. Hrabik used both traditional trawling gear as well as hydroacoustic equipment to test the ability of hydroacoustic survey tools to accurately assess fisheries stock when compared to more traditional survey methods (trawls). Results of the comparison are being analyzed.
3. (Wattrus, PI) August 17th-18th. An acoustic survey of the distal sediment fan associated with the Silver Bay mine-tailings delta. Two days of ship time ($9,308) were paid with ENRT funds. Results: This was a pilot study to prepare for a future Sea Grant proposal. Data were collected to determine where the finer sediments derived from the delta turbidity currents have been deposited. These sediments have been mapped and will provide the necessary preliminary data for the Sea Grant proposal.
4. (Hrabik, PI) August 23rd-24th. Mysis nocturnal migration study. Two days of ship time ($9,308) were paid for with ENRT. This study was designed to collect preliminary data for a future NSF grant proposal. Results: The project used trawling to collect fish during the day, at night, and at dusk (for acoustic target id and diet information). The project also collected mysis using plankton tows at a variety of depths to

establish their density at depth during the day and at night. These data are now being analyzed to clarify some of the mysteries related to mysis migrations and the extent to which cisco feed on them during the day, dawn and dusk, as well as night periods.

5. (Brown, PI) October 5th. Supplemental operations for Brown's Sea Grant project. His project uses data from moored instruments to develop a more detailed understanding of biological gas cycling on daily as well as seasonal timescales. One day of ship time ($4,654) paid with ENRT funds. Results: This project supplemented a full two year Sea Grant project and allowed additional limnological data to be collected. These data have been analyzed and are being compiled for an MS thesis and eventual publication in a scientific journal.
6. (Colman, PI) Research activities and training for a variety of graduate, undergraduate, and minority students, using real world problems on Lake Superior. Cruises occurred on July 7th, September 14th and 16th, and October 2nd, 3rd, and 4th. Faculty in charge of the cruise included Drs. Branstrator, Johnson, and Shannon, and Ms. Hardwig and Sharp. Three days of ship time, $13,962. Results: Successful training a research experiences for a variety of students, some of whom are training as future researchers on Lake Superior.

Result 2: Field research 2007

Description: A portfolio of research activity was conducted on Lake Superior in the summer of 2007. As mentioned in the Project Summary, these studies are small pilot studies, extensions to projects funded from other sources (see section VI-B), and activities to collect preliminary data often required for proposals to the National Science Foundation. The studies have a common theme of understanding the dynamics of Lake Superior, its sediments, and its ecosystem. All studies have been peer reviewed either by a funding agency or by a committee of scientists that use the RV Blue Heron, commonly both.

Costs were entirely for field activities, observations, and data collection on board the RV Blue Heron, accounted for at the ship's day rate of $5385. The day rate includes crew, technician and ship manager salaries; insurance; and operational costs (fuel, food, garbage, dock fees, etc.). Total of cost of activities listed above was $110,390.

Summary Budget Information for Result 2:	**ENRT Budget**	**$ 110,390**
	Expended	**$ 110,390**
	Balance	**$ 0**

Completion Date: Oct. 31, 2007

Final Report Summary: Research activities for 2007 included:

1. Austin, PI, June 5th-7th and September 17th-19th – Deployment of a large meteorological buoy off of the North Shore. Six days of ship time, $32,310. Results: four months of data were collected including standard meteorological parameters as well as CO_2 content of the atmosphere and the water column. The fact that the LLO meteorological buoy has been successfully deployed and recovered was noted in a recently submitted National Science Foundation proposal and the buoy's data will be used in the funded project. Additionally, LLO's meteorological buoy was highlighted in a recently submitted GLOS (Great Lakes Observing System) proposal to NOAA (National Oceanic & Atmospheric Administration).
2. Hrabik, PI, May 15th-17th, July 24th – 26th and October 21st-23rd – ENRT funds paid for supplemental operations for Hrabik's SeaGrant project: a study of diurnal vertical

migration of Mysis, prey fish and predatory fish. Four and one-half days of ship time, $24,232, paid by ENRT funds with the remaining time paid by the Minnesota SeaGrant program. Results: Data were collected by trawling, plankton tows, hydroacoustic surveys and surveys using the Triaxus underwater towed vehicle. Hrabik obtained funding through SeaGrant using data collected during his 2006 ENRT funded cruise. This study will help clarify some of the mysteries related to mysis migrations and their interactions with prey and predatory fish during the day, dawn and dusk as well as night periods.

3. Hrabik, PI, August 4th-10th– Fish stock assessment in cooperation with the MN & WI DNR: additional operations in a cooperative project using funds from ENRT, the MN DNR and the WI DNR. Using traditional trawling gear as well as hydroacoustic equipment, Dr. Hrabik tests the ability of hydroacoustic survey tools to accurately assess fisheries stock when compared to more traditional survey methods (trawls). Three days of ship time, $16,155, paid by ENRT funds with the remaining time paid by the MN and WI DNR. Results: These fish stock assessments, in cooperation with the MN and WI DNR, are part of a long term monitoring program. This operation provided the monitoring data for 2007.
4. Minor, PI, August 26th – Preliminary sampling of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and particulate organic carbon (POC) from the Lake Superior water column. One day of ship time, $5,385. Results: Dr. Minor collected a water column profile of DOC, DIC and POC and is undertaking radiocarbon analyses to investigate Lake Superior's carbon cycle. The data support a currently funded Grant-in-Aid award and will be used in a February, 2008, National Science Foundation proposal.
5. Sterner, PI , July 30th-August 1st, October 5th-7th, November 7th-9th – ENRT paid for supplemental operations for Sterner's Sea Grant project: a study of primary production and grazing dynamics in Lake Superior. Two days of ship time, $10,770, paid by ENRT with the remaining time paid by the Minnesota SeaGrant program and the University of Minnesota's Office of the Vice President for Research. Results: Data were collected using our CTD/water sampling system and by using a free-floating buoy system. Ultimately, this study will improve estimates of lake wide primary productivity and make the first estimates of grazing on phytoplankton and bacterioplankton. The resulting data will be used in subsequent proposals to the National Science Foundation and SeaGrant.
6. Wattrus, PI, October 12th – Geophysical survey of underwater (drowned) beach ridges formed during the Houghton Lowstand. One half-day of ship time, $2,693. Results: This work was a continuation of the 2006 Wattrus ENRT/NSF funded survey of the paleo-shorelines associated with a previous lowstand of Lake Superior. The survey was used to identify likely sediment coring sites to collect sediment to help date the lowstands. The resulting data will be used as preliminary results for an NSF proposal that will seek funding to further delineate paleo-shorelines for Lake Superior.
7. Colman, PI - Research activities and training for a variety of graduate and undergraduate students using real world problems on Lake Superior. Cruises occurred on May 1st and 19th, July 6th, September 11th, and October 8th, 9th and 10th. Faculty in charge of the cruises included Drs. Branstrator, Danz, Gallup, Little, Morton and Ricketts and Ms. Sharp. Three and a half days of ship time, $18,848. Results: Successful training and research experiences for a variety of students, some of whom are training as future researchers on Lake Superior.

Result 3: Field research 2008

Description: A portfolio of research activity was conducted on Lake Superior in the summer of 2008. As mentioned in the Project Summary, these studies are small pilot studies, extensions to projects funded from other sources (see section VI-B), and activities to collect preliminary data often required for proposals to the National Science Foundation. The studies have a common theme of understanding the dynamics of Lake Superior, its sediments, and its ecosystem. All studies have been peer reviewed either by a funding agency or by a committee of scientists that use the RV Blue Heron, commonly both.

Costs are entirely for field activities, observations, and data collection on board the RV Blue Heron, accounted for at the ship's day rate of $5,556. The day rate includes crew, technician and ship manager salaries; insurance; and operational costs (fuel, food, garbage, dock fees, etc.). Total of cost of activities listed above is $119,454, which was charged during the field season.

Summary Budget Information for Result 3:	**ENRT Budget**	**$ 119,454**
	Expended	**$ 119,454**
	Balance	**$ 0**

Completion Date: Oct. 31, 2008

Final Report Summary: Research activities for 2008 included:

1. Austin, PI, June 13th-16th – Deployment of a meteorological buoy off of the North Shore and three subsurface buoys throughout the rest of Lake Superior. One day of ship time, $5,556. Results: five months of data were collected including standard meteorological data as well as fluctuations in water column temperature. On the basis of data from 2008 and previously years (also ENRT supported), Austin was recently funded by the National Science Foundation (NSF) for three more years of data collection using the meteorological buoy and the subsurface buoys. Data from the North Shore meteorological buoy was available to the public online while the buoy was deployed.
2. Brown, PI, August 28th-29th – Preliminary sampling of waters in the western arm of Lake Superior to determine dissolved oxygen content for calculations of deep water respiration. Two days of ship time, $11,112. Results: Brown was able to determine that coastal deep water oxygen content is higher than off-shore deep water oxygen content in late summer. This indicates that near shore deep water respiration is higher than off-shore deep water respiration, which brings into question previous calculations of Lake Superior primary productivity. These data will be used in future proposals submitted to NSF and the Sea Grant program.
3. Hrabik, PI, May 28th-30th, July 23rd-25th, and October 23rd-25th – ENRT paid for supplemental operations for Hrabik's Sea Grant study of diurnal vertical migration of Mysis, prey fish, and predatory fish.. The project required nine days on board the Blue Heron during 2008, of which ENRT paid for 3.5 days. The remaining ship time necessary for the project were paid by the Minnesota Sea Grant program. Three and one-half days of ship time, $19,446. Results: data were collected by trawling, plankton tows, hydroacoustic surveys and surveys using the Triaxus underwater towed vehicle. Hrabik obtained funding through Sea Grant on the basis of data collected during his 2006 ENRT-funded cruise. This study will help clarify some of the mysteries related to mysis migrations and their interactions with prey and predatory fish during the day, dawn and dusk, as well as night periods.

4. Hrabik, PI, August 6th-12th – Fish stock assessment in cooperation with the DNR: additional operations in a cooperative project using funds from ENRT, the MN DNR and the WI DNR. Using traditional trawling gear as well as hydroacoustic equipment, Dr. Hrabik is testing the ability of hydroacoustic survey tools to accurately assess fisheries stock when compared to more traditional survey methods (trawls). Three days of ship time, $16,668. Four additional days of ship time were paid by MN and WI DNR. Results: These fish stock assessments, in cooperation with the MN and WI DNR, are part of a long term monitoring program. This operation provided the monitoring data for 2008.
5. McNeill, PI, August 26th - Supplemental operations for McNeill's NSF project: 'Singlet oxygen's role in the photochemical-biochemical degradation of dissolved organic carbon.' The study intends to determine the impact of oxygen on microbial use of organic matter in Lake Superior. One half-day of ship time, $2,778. Results: McNeill was able to extend the data set he has collected over the last six years. His current NSF grant has ended so this cruise was extremely valuable for maintaining continuity in his data set, strengthening any future proposals.
6. Minor, PI, May 20th-23rd and September 23rd-26th- Undertook preliminary sampling of the Lake Superior water column to determine dissolved organic carbon (DOC), dissolved inorganic carbon (DIC) and particulate organic carbon (POC) content. Minor is undertaking radiocarbon analyses of these various forms of carbon to investigate Lake Superior's carbon cycle. Two days of ship time, $11,112. Results: Dr. Minor used data from this and previously ENRT-funded cruises in a successful NSF proposal to continue these measurements throughout the lake through 2010.
7. Sterner, PI, April 29th-May 1st, July 30th-August 1st and September 16-18th - ENRT paid for supplemental operations for Sterner's Sea Grant project: a study of primary production and grazing dynamics in Lake Superior. Two and one half days of ship time, $13,890, paid by ENRT, with the remaining time paid by the Minnesota Sea Grant program and the University of Minnesota's Office of the Vice President for Research. Results: Data were collected using our CTD/water sampling system and by using a free-floating buoy system. Ultimately, this study will improve estimates of lake wide primary productivity and make the first estimates of grazing on phytoplankton and bacterioplankton. The resulting data will be used in subsequent proposals to the National Science Foundation and Sea Grant.
8. Werne, PI, May 20th-23rd and September 23rd-26th – Supplemental operations for Werne's NSF project: 'Linking archaeal membrane lipids and ecology in great lakes: Understanding the TEX86 paleotemperature proxy'. Werne's project proposes to better understand crenarchaeota, an aquatic organism that is poorly understood, but whose membrane structures might be useful in reconstructing past lake temperature. Four and one half days of ship time, $25,002. Results: ENRT funding allowed for an extension of this NSF funded project. By allowing Werne to extend his project by deploying and recovering moorings during 2008, additional data were collected which may be useful in getting additional funding from NSF.
9. Colman, PI - Research activities and training for a variety of graduate and undergraduate students using real world problems on Lake Superior. Cruises occurred on May 6th, September 11th, 13th, 20th, and October 1st. Faculty in charge of the cruises were Drs. Gallup, Johnson and Werne and Ms. Sharp. Two and half days of ship time, $13,890. Results: Successful training and research experiences for a variety of students, some of whom are training as future researchers on Lake Superior.

Result 4: Buoy observations on Lake Superior in 2008-09

Description: This result was added to the Project in January, 2008, as a result of a supplemental application for funds from the Great Lakes Protection Account (see supplemental appropriation language). Jay Austin, the PI, deployed a large meteorological buoy off of the North Shore as well as three subsurface moorings in Eastern, Central and Western Lake Superior. The meteorological buoy measures standard meteorological parameters (humidity, wind speed, air temperature, cloudiness), as well as water temperature at multiple depths in the water column. The subsurface moorings measure water temperature at multiple depths. Using this information, in conjunction with satellite data (indicating, for example, the extent of ice cover) Austin will, among other things, gain a better understanding of the relationship between ice cover and water temperature in Lake Superior. This, in turn, will give us a better understanding of the effect of regional climate on lake temperature and lake level. Data collected from this buoy and moorings will be used to augment a NSF-funded project Austin currently is conducting and a GLOS (Great Lakes Observing System) project in which Austin is participating. Both of these related proposals are currently active, and the work described here is an extension of research that has been peer reviewed in two published scientific journal articles.

Costs are for 12 days of ship time for field activities, observations, and data collection on board the RV Blue Heron, accounted for at the ship's day rate of $5,556, totaling $66,672. The day rate includes crew, technician and ship manager salaries; insurance; and operational costs (fuel, food, garbage, dock fees, etc.). An additional cost is approximately 16 weeks of technician salary and benefits ($19,328), before and after the field operations, for mobilizing and demobilizing the buoys. Total of cost of activities listed above is $86,000.

Summary Budget Information for Result 4:	**ENRT Budget**	**$ 86,000**
	Expended	**$ 86,000**
	Balance	**$ 0**

Result Status as of March 1, 2010: Completed.

Final Report Summary:

During 2008 the supplemental funds paid for ship time on June 13-16th (three days), September 3rd-6th (four days) and October 30th (one half day). Seven and one half ship days: $41,670. Five months of data were collected including standard meteorological data as well as fluctuations in water column temperature. Data from the North Shore meteorological buoy was available for five months to the public online while the Meteorological buoy was deployed. The subsurface buoys were redeployed in September and will be collecting data under the ice during the winter. In addition, technician salary and benefits ($19,328) were accrued for mobilization and demobilization of the buoys.

During 2009, we used four and one half additional ship days ($25,002) on this project to deploy and recover the meteorological buoys and a total of seven subsurface buoys. As a result of these two seasons of data collection on Lake Superior, we now have an unparalleled set of observations of physical properties of the water column through the changing seasons. This is especially true of the temperature field of the water column, which drives the overall circulation of the lake. We also have some of the first continuous measurements of in-situ ice extent and thickness anywhere in the world. These data are currently being analyzed and promise to lead to a new understanding of seasonal changes in Lake Superior.

V. TOTAL ENRT PROJECT BUDGET:

All Results: Personnel: $19,328
All Results: Equipment: $ 0
All Results: Development: $ 0
All Results: Acquisition: $ 0
All Results: Other: Field observations and data collection costs $ 361,672

TOTAL ENRT PROJECT BUDGET: $381,000

Explanation of Capital Expenditures Greater Than $3,500: none

VI. OTHER FUNDS & PARTNERS:

A. Project Partners:

1. Several partners from the Large Lakes observatory at the University of Minnesota Duluth, including Steven Colman, Nigel Wattrus, Jay Austin, Elizabeth Minor, Thomas Johnson, Erik Brown, and Josef Werne.
2. Several partners from science Departments at the University of Minnesota Duluth, including Donn Branstrator, Thomas Hrabik, Timothy Demko, James Miller, Angela Sharp Nick Nanz, Christina Gallup, and Amanda Little.
3. Several partners from science departments at the University of Minnesota Twin Cities, including Robert Sterner, James Cotner, Christopher McNeill

The partners are involved with different projects at different times. The distribution of funds to the project Principle Investigator is listed with each project above.

B. Other Funds being Spent during the Project Period:

Summary of other funds related to the projects listed for Results 1-4, with sources and approximate amounts. These projects either (1) were funded as a result of pilot projects funded by the ENRT grant, (2) were enhanced and expanded by ENRT funding of field operations, or (3) are related to and ran concurrently with the ENTR project. They include:

1. National Science Foundation, $ 3,100,000
2. Minnesota Sea Grant, $380,000
3. Minnesota Dept. of Natural Resources, $210,000
4. Great Lakes Observing System (GLOS), $52,000

C. Required Match (if applicable): Not applicable

D. Past Spending: None

E. Time: Appropriation language extends project until June 30, 2011.

VII. DISSEMINATION:

Plans are for the results of all of these projects to be published in peer-reviewed journals and presented at national meetings. The results will also be presented to state environmental managers where appropriate. The results will also be available on the web site of the Large Lakes Observatory (www.d.umn.edu/llo).

VIII. REPORTING REQUIREMENTS:

Periodic work program progress reports will be submitted not later than:
Dec. 31, 2006 (submitted)

May 31, 2007 (submitted)
Dec. 31, 2007 (submitted)
May 31, 2008 (submitted)
Jan. 15, 2009 (submitted)
April 16, 2010 (this report, final)

IX. RESEARCH PROJECTS:

Research projects are listed along with a brief description in the Outline of Project Results (Section IV).

Attachment A: Budget Detail for 2005 Projects - Summary and a Budget page for each partner (if applicable)

Proposal Title: *Fill in your proposal title and Proposal # (A-01)*

Project Manager Name: *Fill in your name.*

LCMR Requested Dollars: $ *Fill in the dollar amount you are requesting.*

1) **See list of non-eligible expenses, do not include any of these items in your budget sheet**
2) **Remove any budget item lines not applicable**

2005 LCMR Proposal Budget	**Result 1 Budget:**	**Result 1 Budget, revised:**	**Amount Spent** *(12/31/06)*	**Balance** *(4/21/08)*	**Result 2 Budget:**	**Result 2 Budget, revised:**	**Amount Spent** *(12/31/07)*	**Balance** *(4/21/08)*	**Result 3 Budget:**	**Result 3 Budget, revised:**	**Amount Spent** *(10/31/08)*	**Balance** *(10/31/08)*	**Result 4 Budget:**	**Amount Spent** *(11/01/09)*	**Balance** *(6/25/09)*	
	Field research 2006				*Field research 2007*				*Field research 2008*				*Field research 2008-9*			TOTAL FOR BUDGET ITEM
BUDGET ITEM																
PERSONNEL: Staff Expenses, wages, salaries													14,496	14,496	0	14,496
PERSONNEL: Staff benefits –													4,832	4,832	0	4,832
Contracts																
Professional/technical *(with whom?, for what?)*																
Other contracts *(with whom?, for what?) list out: personnel, equipment,*																
Other direct operating costs *(for what? – be specific)*																
Equipment / Tools *(what equipment? Give a general description and cost)*																
Office equipment & computers - NOT ALLOWED unless unique to the project																
Other Capital equipment *(list specific items)*																
Land acquisition *(how many acres)*																
Land rights acquisition *(less than fee)*																
Printing																
Other Supplies *(list specific categories)*																
Travel expenses in Minnesota																
Travel outside Minnesota *(where?)*																
Construction *(for what?)*																
Other land improvement *(for what?)*																
Other: Field observations and data collection on board the RV Blue Heron at the ship's day rate of $4654 (increasing after 1st yr). Includes crew, technician and ship manager salaries; insurance; and operational costs (fuel, food, garbage, dock fees, etc.)	67,483	65,156	65,156	0	113,759	110,390	110,390	0	113,758	119,454	119,454	0	66,672	66,672	0	361,672
COLUMN TOTAL	67,483	65,156	65,156	0	113,759	110,390	110,390	0	113,758	119,454	119,454	0	86,000	86,000	0	381,000

Impacts on Minnesota's Aquatic Resources from Climate Change

Section 20, Subd. 7 $250,000

Lucinda Johnson
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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

Project Manager: Lucinda B. Johnson
Affiliation: University of Minnesota Duluth, Natural Resources Research Institute
Mailing Address: 5013 Miller Trunk Highway
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E-mail Address: ljohnson@d.umn.edu
FAX Number: (218) 720-4328
Web Page address: http://www.nrri.umn.edu/staff/ljohnson.asp

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

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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

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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**

Timing of Walleye Spawning as an Indicator of Climate Change

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Keywords: walleye, spawning, temperature, climate change, ice-out, *Sander vitreus*

Abstract

We obtained historical walleye (*Sander vitreus*) egg-take records for 12 spawning locations from the Minnesota Department of Natural Resources to determine if the timing of walleye spawning could be used as an indicator of climate change. We used ice-out data instead of temperature for our analyses because walleye often spawn soon after ice-out, and ice-out has been previously related to climate change. We used linear regressions to determine the relationship between the start of spawning and ice-out date and to determine if there were long-term trends in ice-out and spawning over time. Linear regressions of the date of first walleye egg-take versus ice-out date showed that for each day ice-out gets earlier, walleye spawning begins 0.5 to 1 day earlier. All but 2 regressions had slopes significantly less than 1, and slopes at the 2 exceptions were equal to 1. 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. Overall, ice-out and walleye spawning are getting earlier in Minnesota, and the timing of walleye spawning may be a good biological indicator of climate change.

Introduction

As interest in climate change increases, there is a growing concern for its effects on the distribution and reproduction of species as well as an increasing need for biological indicators of climate change. Defining multiple parameters as indicators of climate change allows us to compare trends that can be used to predict future changes or reconstruct past changes in climate and allows us to choose cost-effective methods to monitor effects of climate change. Past research has documented climate trends by analyzing hydrologic parameters such as freeze and ice-out dates (Robertson et al. 1992; Magnusson et al. 1997; Jensen et al. 2007), climatic variables such as temperature and precipitation (Karl et al. 1996; IPCC 2001), and biological parameters such as changes in algal assemblages (Smol and Cumming 2000), diatom community structure (Kilham et al. 1996), and species distributions (Larocque et al. 2001; Chu et al 2005; Balanya et al. 2006). Indicators such as these help to answer questions from researchers, policy-makers, and the public about future climate projections, the effects of climate change on species and ecosystems, and anthropogenic forces that may be driving climate change.

The purpose of our study was to identify a biological indicator of climate change from an aquatic species that is an important commercial and recreational resource. Biological indicators are important because they provide us with a response that is a function of some stimulus over time instead of just a snapshot that may record a single extreme event (such as one random day with record high temperatures). By choosing walleye (*Sander vitreus*), a species important both commercially and recreationally, we were able to obtain long-term records to determine if the timing of walleye spawning was related to ice-out, and to identify any long-term trends in walleye spawning and ice-out data.

Walleye have been a popular sport and commercial fish in Minnesota for more than 100 years (Minnesota Department of Natural Resources 1997). Walleye egg-take for hatcheries started in the late 1800s, and by 1923 seven walleye hatcheries and collection sites were established (Minnesota Department of Natural Resources 1996). Fish trapping sites are used to capture walleye for egg collection. Walleye spawning typically occurs soon after ice-out when ambient water temperatures are between 4-11°C (Scott and Crossman 1973; Wolfert et al. 1975; Becker 1983), and is partly dependent on these conditions and photoperiod to induce gonadal and hormonal changes that prepare the fish for spawning (Hokanson 1977; Malison and Held 1996; Malison et al. 2004). Thus some climate variable(s) likely influence the timing of the spawning run.

Air temperature (e.g., mean monthly or maximum daily) has been used frequently in previous studies to examine the effects of climate change on various organisms. Air temperature has a strong relationship with life history traits of several species of birds (Winkel and Hudde 1997; Dunn and Winkler 1999; Both et al. 2005) and some amphibians (Reading 1998; Blaustein et al. 2001). For example, Dunn and Winkler (1999) discovered a strong negative relationship between the egg-laying date of tree swallows and spring temperatures, and Reading (1998) showed that the arrival of the common toad (*Bufo bufo*) to their breeding pond was strongly correlated with mean daily temperatures preceding the toads' arrival. Earlier studies of fishes have shown that climate change has significant relationships with species range shifts (Chu et al. 2005), recruitment (Shuter et al. 2002), fecundity (Sundby and Nakken 2008), and abundance (Kallemeyn 1987; Wingate and Secor 2008), but few have documented climate change effects on the timing of spawning in fishes.

For our study we decided to focus on the relationship between the timing of walleye spawning and ice-out instead of air temperature. Ice-out is generally described as the time when a lake is free of all ice. We used ice-out because walleye spawning generally occurs soon after ice-out (Scott and Crossman 1973; Becker 1983) and because previous research has documented changes toward earlier ice-out, which may be evidence of climate change (Magnuson et al. 1997; Magnuson et al. 2000; Jensen et al. 2007). We also chose to use ice-out data because it is broadly available geographically and historically (more than 100 years of data in some cases) whereas air and water temperature data are not. Moreover, Robertson et al. (1992) suggest that the climate signal is amplified by using ice cover as a response. Based on their analyses, a 1°C change in air temperature should result in a 5.1 (±0.4) day change in mean ice-out dates. Other research suggests that the timing of ice-out may be a good indicator of climate change because it is strongly correlated with air temperatures (Palecki and Barry 1986; Johnson and Stefan 2006). Previous studies suggest that the period 1970-onward is a distinct period of warming with increases in temperature occurring at a rate that is nearly double that of the previous period (IPCC, 2001; Walther et al. 2002). In agreement, a shift toward earlier ice-out in North America was documented during that same time period (Robertson et al. 1992; Johnson and Stefan 2006).

In this paper we determine the relationship between the timing of walleye spawning and ice-out, and we determine if there are trends in walleye spawning and ice-out over time in Minnesota lakes. If the timing of walleye spawning is related to ice-out, it may provide a convenient biological indicator to aid in future management plans for aquatic resources and in future climate change studies.

Methods

We obtained walleye (*Sander vitreus*) spawning records from the Minnesota Department of Natural Resources (MN DNR), and acquired Minnesota ice-out records from the Minnesota Ice Cover Database, the Minnesota Historical Society, and the Cook Herald News. For three of our spawning locations, we used ice-out data (measured as the number of days ice-out occurred after January 1st) from the same lake where walleye spawning data were collected (Table 1). Two spawning sites were in streams that flowed directly into the ice-out lakes, one site was in a system indirectly connected to the ice-out lake, and six sites were in water bodies not connected to the ice-out lakes but within 17 to 48 km. For Lake Sallie we evaluated two different ice-out datasets, Lake Sallie and Detroit Lake (connected to Lake Sallie) because the Detroit Lake ice-out record had 8 more sampled years than the Lake Sallie ice-out record. Statistical analyses were performed using R version 2.5.1, except Microsoft Excel was used to calculate some correlations. All statistical results were judged significant at the $P<0.05$ level unless otherwise stated. ArcGIS 9 (ESRI 2004) was used to map walleye spawning and ice-out locations and to measure the distance between spawning and ice-out data collection sites.

Walleye Spawning Records

Walleye spawning records collected by the MN DNR contained information on egg-take (number of eggs stripped from ripe walleye females) and individual fish counts obtained from twelve walleye egg collection operations conducted by various Minnesota hatcheries from 1938 to 2007 (Table 1). The timing of the walleye spawning runs could be described by the beginning of spawning, peak of spawning, or the end of spawning. From 1987 to 2007, the data recorded included number of walleye captured by sex and reproductive state of females (green, ripe, or spent), along with egg-take on each date. Prior to 1987, data on individual walleyes were generally not recorded and only data on egg-take were available. Because egg collection quotas were common among hatcheries and tended to halt egg collections before the actual end of walleye spawning, we decided to focus on the dates for beginning and peak of spawning only. We wanted to know if we could use these dates interchangeably or if one response was a better indicator of the timing of spawning runs. We also needed to determine whether males or ripe females would most accurately describe the timing of these walleye spawning runs and if the selected response was correlated with egg-take records so that data prior to 1987 could be used. We chose to use ripe females rather than green or spent females because these fish were ready to spawn.

We first determined if the arrival of ripe females or males was best associated with the timing of the spawning run, and if the timing was best described by the date of first or peak capture. We computed correlations between capture dates and sampling year for males and for ripe females at each location and between locations to determine if males and ripe females could be used interchangeably, and to see if there may have been variability due to different locations. We found that on average, correlations were higher for ripe females than males for both peak and first capture dates. We then used a one-way ANOVA to determine if capture dates for males and ripe females were different. There were significant differences between dates of male and ripe female capture for the peak of spawning (P<0.001) and for the start of spawning (P<0.05). On average, the first sighting of males was one day earlier than that of ripe females, and peak male capture occurred three days earlier than peak ripe female capture. For ripe females, correlations between capture date and year for the beginning and peak of spawning ranged from -1 to 0.99, so some variability may be explained by differences in location. For males, correlations between capture date and year for dates of first capture ranged from -1 to 0.99 and from -0.40 to 0.92 for dates of peak capture. Because Fitzimons *et al.* (1995) found that the initiation of spawning was associated with ripe females, and because we found that dates of capture for males and ripe females were significantly different (ANOVA), we decided to use ripe females instead of males, or the combination of males and ripe females. Moreover, because egg-take is directly from ripe females, we expected a stronger relationship between dates of ripe female capture and egg-take.

We then needed to determine if peak capture dates or dates of first capture better described the timing of the spawning run. Coefficient of determination (R^2) values from regressions of the peak of spawning versus the start of spawning for ripe females ranged from 0.16 to 0.94, and all but two locations, Otter Tail River and Rice Lake, were significantly different from zero. On average, peak capture of ripe female occurred 2 to 8 days later than first occurrence of ripe females. When correlations were computed separately across locations for the start of spawning and for the peak of spawning, correlations were larger on average for the start of spawning versus year than for the peak of spawning versus year. After considering effects of quotas on peak capture dates of ripe females (and egg-take) and the strong relationship between first capture dates versus year compared to dates of peak capture, we decided to use the date of first capture of ripe females for analyses.

To determine if egg-take (which greatly extended the data set) could be used instead of ripe females, we computed correlations between dates of first egg collection and dates of first ripe female sightings at all locations. They were highly correlated, with correlations (r) ranging from 0.78 to 0.99, and Rice Lake and Otter Tail River were the only locations with correlations less than 0.97. This allowed us to greatly extend our datasets by using egg-take data instead of data on adult walleyes that were typically not available prior to 1987.

Spawning and Ice-out Regressions and Time Series

We regressed the dates for the beginning of walleye spawning against ice-out dates for all 12 locations to determine if there was a relationship between the two variables. For these regressions April 1st was designated as day 1 to make intercepts easier to interpret. The slopes and intercepts were compared across latitudes to determine if there were obvious spatial trends, and were also compared using the "lmList" function in R (Pinhero and Bates, 2000) to create a list of slopes and intercepts as objects with 95% confidence intervals. T-tests were used to test the null hypothesis at each location that the slope was equal to one. To test for serial dependence in the datasets (Oehlert, 2000), the "acf" function in R was used to plot residuals from the regressions of walleye spawning versus ice-out date. We used a Bonferroni correction to control the family-wise error rate.

To determine if there were long-term trends in the timing of walleye spawning, we computed regressions of the beginning of walleye spawning (first egg-take) versus year for each location. Because Pike and Pine Rivers both had about a twenty year gap in data, regressions were also computed for these locations that restricted the analyses to those years after 1970. We used the "pbinom" function in R to test the probability of getting our observed number of negative slopes.

To determine if there were long-term trends in ice-out, we computed the regressions of ice-out dates versus year for all locations. Regressions were computed using full ice-out datasets at each location and using ice-out data that were matched to the sampling years represented in the spawning datasets. More than half of the ice-out locations had records that started around 1970 or later. To determine if significant trends were present for that period, the datasets with longer-term records (prior to 1970) were restricted to the years 1970 onward. We then used the "pbinom" function in R to test the probability of getting our observed number of negative slopes.

The "lowess" function in R, an algorithm based on the Ratfor original by W.S. Cleveland (1981), was used to compute a LOWESS smooth (SPAN=2/3) for each time series (spawning and ice-out). These were then compared to the linear regressions by computing the G-test statistic for lack of fit in R (Weisberg, 2005) to determine if the LOWESS smooth improved the fit. All time series datasets were tested for autocorrelation using the "acf" function in R, and a Bonferroni correction was used to control family-wise error rate.

Results

Relationship Between Spawning and Ice-out

The timing of walleye spawning runs was highly correlated with the timing of ice-out, and there was no evidence of autocorrelation. Slopes from linear regressions of first egg-take versus ice-out date were significant at all locations, and all R^2 values were greater than 0.30 (Figure 1). After a Bonferroni correction, 10 of 13 regressions were significant; only Bucks Mill, Otter Tail River, and Rice Lake were not significant. The relationships described by linear regression suggested that walleye spawning gets half a day to one day earlier for each day that ice-out gets earlier (Figure 1). Comparison of slopes and 95% confidence intervals indicated that all but 2 locations had slopes less than 1 (Figure 2), and t-tests (H_0: Slope=1) revealed that slopes were significantly different from 1 at all locations except Lake Koronis and the St. Louis River. We found no obvious trends across Minnesota latitudes to explain the differences in slope.

Spawning and Ice-out Time Series

The regressions of walleye spawning versus year revealed significant negative slopes at Otter Tail River and at Lake Koronis (Figure 3). Marginally significant (P<0.1) negative slopes were observed at Lake Sallie and for the restricted Pine River and Pike River datasets (Table 2). After a Bonferroni correction, Lake Koronis was the only location where the regression of egg-take versus year was significant (P<0.0063). Positive slopes were observed at Rice Lake and Bucks Mill, but these were not significant even without a Bonferroni correction; the other 14 slopes were negative. The probability of getting 14 negative slopes out of 16 was 0.0018. The LOWESS function improved the fit of the data (P<0.05) compared to linear regression at only Pike River, Pine River, and Rice Lake, which implied that data were well represented by the fit of the linear regressions at most locations.

For ice-out regressions there were 25 negative slopes and 1 positive slope (Table 3). Even if there were no significant relationships between ice-out date and year, the probability of getting 25 negative slopes out of 26 regressions was <0.0001. Significant negative slopes were observed at Lake Koronis, for the Lake Koronis time series restricted to Lake Koronis walleye sampling years, and for McDonald Lake restricted to Otter Tail River walleye sampling years (Figure 4, Table 3). A marginally significant (P<0.1) negative slope was observed at Detroit Lake using the full dataset, at McDonald Lake when the dataset was restricted to walleye sampling years at Dead River, and at Lake Sallie restricted to the Lake Sallie walleye sampling range (Table 3). For long-term time series where datasets could be restricted to years 1970 onward (5 out of 13 locations), a significant negative slope was observed at Rice Lake, and marginally significant (P<0.1) negative slopes were observed at Lake Koronis and Leech Lake (Table 3). No slopes were significant with the Bonferroni correction (P<0.0038). Linear regressions described the ice-out datasets better than LOWESS fits at most locations. Lack of fit G-test statistics to test if the LOWESS improved the fit compared to linear regressions were only significant ($P<0.05$) for Lake Vermilion (full dataset) and for the Lake Vermilion dataset that was restricted to the range of years represented in the Pike River egg-take dataset.

Discussion

There was a significant positive relationship between the start of walleye spawning and ice-out at all locations. Even with the Bonferroni correction, 10 of 13 regressions were significant. Walleye spawning occurred 0.5 to 1 day earlier for every day ice-out occurred earlier. Two locations had a slope equal to one: the Saint Louis River and Lake Koronis. The other 10 locations had slopes of about 0.5. Although it is typically reported that spawning occurs soon after ice-out (see Scott and Crossman 1973; Wolfert et al. 1975; Becker 1983), our results indicate that in many cases spawning may be initiated before ice-out. This may be a result of using the first occurrence of ripe females as an indicator of the start of spawning and because the peak occurrence of ripe females occurred 2 to 8 days after the first sighting of ripe females. Neither spawning habitat (river versus lake spawning), nor location (location of egg-take site or distance to corresponding ice-out location) could explain the two groups of slopes (0.5 and 1), which may mean that other lake characteristics are affecting slopes. Photoperiod and prior thermal history also determine timing of spawning (see Hokanson 1977; Malison and Held 1996; Malison et al. 2004) and likely constrain the dates of spawning.

Previous studies have shown a strong relationship between ice-out and air temperature (Palecki and Barry 1986; Robertson et al. 1992; Johnson and Stefan 2006), and temperature has significant relationships with life history traits of fishes (Bohlin et al. 1993; Shuter et al. 2002;

Sundby and Nakken 2008). In a study of the effects of temperature and climate change on year-class production of fishes in the Great Lakes Basin, Casselman (2002) noted that although the time of spawning in lake trout (*Salvelinus namaycush*) had been relatively consistent over time, an increase in fall temperatures at spawning time had a negative impact on year-class strength. Casselman observed a similar negative relationship between July-August temperatures and year-class strength for northern pike (*Esox lucius*), but observed the opposite for smallmouth bass (*Micropterus dolomieu*). Moreover, Sundby and Nakken (2008) observed that increasing temperatures induced a northward shift of spawning areas and an increase in fecundity for Arcto-Norwegian cod. Studies of walleye have shown that temperature affects the production and yield of walleye (Christie and Regier 1988; Schupp 2002) and that the timing of walleye spawning depends on water temperature and location (Scott and Crossman 1973; Hokanson 1977; Becker 1983), but the exact relationship between the timing of walleye spawning and temperature has not been well documented. Because our results show that there is a strong relationship between the timing of walleye spawning and ice-out, and ice-out has extensive evidence for its use as an indicator of climate change (e.g., Magnuson et al. 2000; Johnson and Stefan 2006), we believe the timing of walleye spawning is a useful biological indicator of climate change.

Regressions of walleye spawning versus year showed 14 negative slopes and 2 positive slopes; there were 5 significant negative slopes ($P<0.1$) and no significant positive slopes, which indicates that walleye spawning is getting significantly earlier at some locations in Minnesota, but not all. If we applied a Bonferroni correction, only 1 (Lake Koronis) of 16 regressions would be significant. However, the probability of getting 14 negative slopes out of 16 regressions was very low (0.0018). Walleye spawning regressions with more than 30 years of data comprised 80% of significant negative slopes. Four of the 5 significant regressions were for lakes where spawning records started in 1970 or later. Otter Tail River was the only significant relationship with records prior to 1970. We were unable to detect any spatial trends that would explain variability in relationships among locations.

For ice-out, our results were consistent with previous studies that documented ice-out occurring earlier over time (Schindler et al. 1990; Robertson et al. 1992; Magnuson et al. 2000; Johnson and Stefan 2006). For example, 25 of 26 regressions were negative; there were 9 significant negative slopes ($P<0.1$) and no significant positive slopes. Although a Bonferroni correction would result in no significant regressions, the probability of getting 25 negative slopes out of 26 regressions was very low (<0.0001). Ice-out regressions with more than 30 years of data comprised 75% of significant negative slopes. Six of the 9 significant regressions were for locations where ice-out records started in 1970 or later; Lake Koronis, McDonald Lake restricted to Dead River walleye sampling years, and McDonald Lake restricted to Otter Tail River walleye sampling years were the only significant relationships with records prior to 1970. Some literature (IPCC, 2001; Walther et al. 2002) suggests that 1970-forward is a period of distinct warming occurring at rates nearly double those of previous years. There was some indication of accelerating ice-out in our datasets.

Our results suggest that the timing of walleye spawning could be used as a biological indicator of climate change because it has a strong relationship with ice-out. Both walleye spawning and ice-out in Minnesota seem to be occurring earlier over time. Although all slopes were not negative and those that are negative were not all significant, both variables (spawning and ice-out) show mostly negative trends over time. Moreover, the very low likelihood of getting so many negative slopes and few positive slopes for both spawning and ice-out suggest the trends are real.

Aside from being used as an indicator of climate change, the relationship between walleye spawning and ice-out may provide information about how climate change is affecting walleye populations. One potential consequence of earlier spawning may be a mismatch in the timing of larval walleye abundance and peak prey availability. Gotceitas et al. (1996) showed that larval Atlantic cod (*Gadus morhua*) tended to exhibit poorer growth and survival when there was a temporal mismatch in peak larvae abundance and peak prey availability compared to match conditions. This type of interaction has also been documented outside of the laboratory. Winder and Schindler (2004) found that there was a temporal mismatch in diatom and zooplankton blooms due to differences in sensitivity to warming in Lake Washington. *Daphnia* densities declined because the peak diatom bloom occurred too early to allow for maximum foraging by *Daphnia* populations. Because zooplankton availability significantly influences the survival and growth of larval walleye (Mayer and Wahl 1997; Hoxmeier et al. 2004), a temporal mismatch between peak larvae abundance and peak zooplankton (or other prey) availability may also significantly affect walleye populations. Additionally, change in the timing of walleye spawning may also affect recruitment if there is a temporal mismatch between the timing of peak larval emergence and optimal discharge events. There is strong evidence that discharge affects larval walleye survival (Becker 1983; Mion et al. 1998; Jones et al. 2006) and that discharge events may be significantly affected by climate change (Middelkoop et al. 2001; Peterson et al. 2002; Graham 2004).

We have presented evidence that the timing of walleye spawning may be a good biological indicator of climate change that could also provide insight into how climate change is affecting walleye populations. The timing of walleye spawning is a convenient indicator because walleye are an important sport and commercial fish that are continually monitored and managed in

Minnesota. Further research investigating lake and river characteristics is needed to identify factors that could be influencing the relationship between the timing of walleye spawning and ice-out. This information would be useful for developing models that may be able to reliably predict the timing of walleye spawning. It would also be useful for creating a universal climate change model instead of several models that vary based on individual locations.

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Table 1. Summary of spawning locations and associated ice-out locations in Minnesota. Distance from spawning location to associated ice-out location was measured, and the number of years (N pairs) were counted where both spawning and ice-out data were available. Sampling range of years for both spawning and ice-out records is shown. The overlap range represents the range of years when spawning and ice-out data were both available, and superscripts identify the type of connectivity, if any, between spawning and ice-out locations.

Spawning location	Range (years)	Ice-out location	Range (years)	Site-to-site distance (km)	N pairs	Overlap range
Big Lake Creek	1971-2006	Big Turtle Lake[4]	1965-2008	21.86	29	1971-2005
Boy River	1970-2006	Long Lake (Cass)[4]	1974-2008	14.25	32	1974-2005
Bucks Mill	1985-1993	Long Lake[3] (Becker)	1980-2003	10.49	9	1985-1993
Dead River	1966-2007	McDonald Lake[4]	1968-2005	18.56	35	1969-2005
Lake Koronis	1996-2007	Lake Koronis[1]	1950-2005	NA	8	1996-2007
Lake Sallie	1971-2007	Lake Sallie[a]	1970-2007	NA	29	1971-2007
Lake Sallie		Detroit Lake[c]	1970-	1.2	37	1971-

			2007			2007
Little Cut Foot Sioux	1942-2007	Leech Lake[d]	1936-2007	48.10	61	1942-2007
Otter Tail River	1954-2002	McDonald Lake[d]	1968-2005	19.91	24	1971-2002
Pike River	1938-1946, 1971-2007	Lake Vermilion[b]	1906-2007	10.23	44	1938-2007
Pine River	1925-1942, 1970-2006	Edna[d]	1980-2005	17.33	26	1980-2005
		Ponto[d]		20.72		
		Gull[d]		26.99		
Rice Lake	1987-2007	Rice Lake[a] (& synthetic)	1962-2005	NA	10	1987-2005
St. Louis River	1992-2006	Fond du Lac[b]	1996-2007	< 1	11	1996-2006

[a]Same location as egg-take

[b]Egg-take location runs into ice-out lake

[c]Connected to egg-take site through a system of lakes and streams

[d]No connection to egg-take location

Table 2. Summary of linear regressions of first egg-take versus year. The y-intercept, slope, *P*-value, and number of years with egg-take data (N) are shown for each spawning location. Years for restricted regressions are given in parentheses.

Spawning location	Y-intercept	Slope	*P*	N
Big Lake Creek	135.35	-0.013	0.891	33
Boy River	240.07	-0.067	0.453	37
Bucks Mill	-692.71	0.400	0.433	9
Little Cut Foot Sioux	195.49	-0.042	0.363	66
Little Cut Foot Sioux (1970-2007)	474.12	-0.182	0.108	38
Dead River	238.50	-0.067	0.388	39
Lake Koronis	3540.21	-1.714	0.005	8
Lake Sallie	419.29	-0.158	0.053	37
Otter Tail River	442.60	-0.168	0.037	32
Otter Tail River (1971-2002)	474.20	-0.184	0.213	23
Pike River	152.69	-0.022	0.640	46
Pike River (1971-2007)	493.09	-0.193	0.070	36
Pine River	122.36	-0.009	0.781	55
Pine River (1970-2006)	527.90	-0.213	0.061	37
Rice Lake	-218.55	0.160	0.484	12
St. Louis River	788.60	-0.339	0.383	15

Table 3. Summary of linear regressions of ice-out date versus year for full and restricted datasets. The y-intercept, slope, *P*-value, and number of years with ice-data (N) are shown for each location. Parentheses indicate datasets restricted to a range of years or restricted to years sampled at the corresponding spawning location. Brackets indicate county names for lakes with identical names.

Ice-out location	Y-intercept	Slope	*P*	N
Big Turtle Lake	383.00	-0.137	0.192	42
Big Turtle Lake (Big Lake Creek)	401.52	-0.146	0.387	30
Big Turtle Lake (1970-2007)	388.19	-0.139	0.276	37
Detroit Lake	558.91	-0.227	0.064	38
Detroit Lake (Lake Sallie)	509.32	-0.202	0.121	37
Edna, Ponto, and Gull	-124.09	0.116	0.500	26
Fond du Lac	1255.88	-0.573	0.283	12
Fond du Lac (St. Louis River)	1690.70	-0.791	0.211	11
Lake Koronis	437.74	-0.169	0.027	56
Lake Koronis (Lake Koronis)	2964.18	-1.429	0.041	8
Lake Koronis (1970-2005)	680.02	-0.291	0.084	36
Lake Sallie	512.55	-0.204	0.101	30
Lake Sallie (Lake Sallie)	551.48	-0.223	0.095	29
Lake Vermilion	130.30	-0.006	0.846	88
Leech Lake	256.29	-0.071	0.137	72
Leech Lake (1970-2007)	533.39	-0.210	0.069	38

Long Lake [Cass]	239.97	-0.066	0.640	34
Long Lake [Becker]	120.84	-0.007	0.974	24
McDonald Lake	486.45	-0.191	0.125	38
McDonald Lake (Dead River)	580.99	-0.238	0.082	35
McDonald Lake (Otter Tail River)	912.34	-0.405	0.007	27
Rice Lake (and synthetic)	372.96	-0.137	0.225	43
Rice Lake (1970-2005)	563.48	-0.233	0.042	36
Lake Vermilion	130.30	-0.0064	0.846	89
Lake Vermilion (1970-2007)	467.03	-0.176	0.106	38
Vermilion Lake (Pike River)	468.72	-0.177	0.243	32

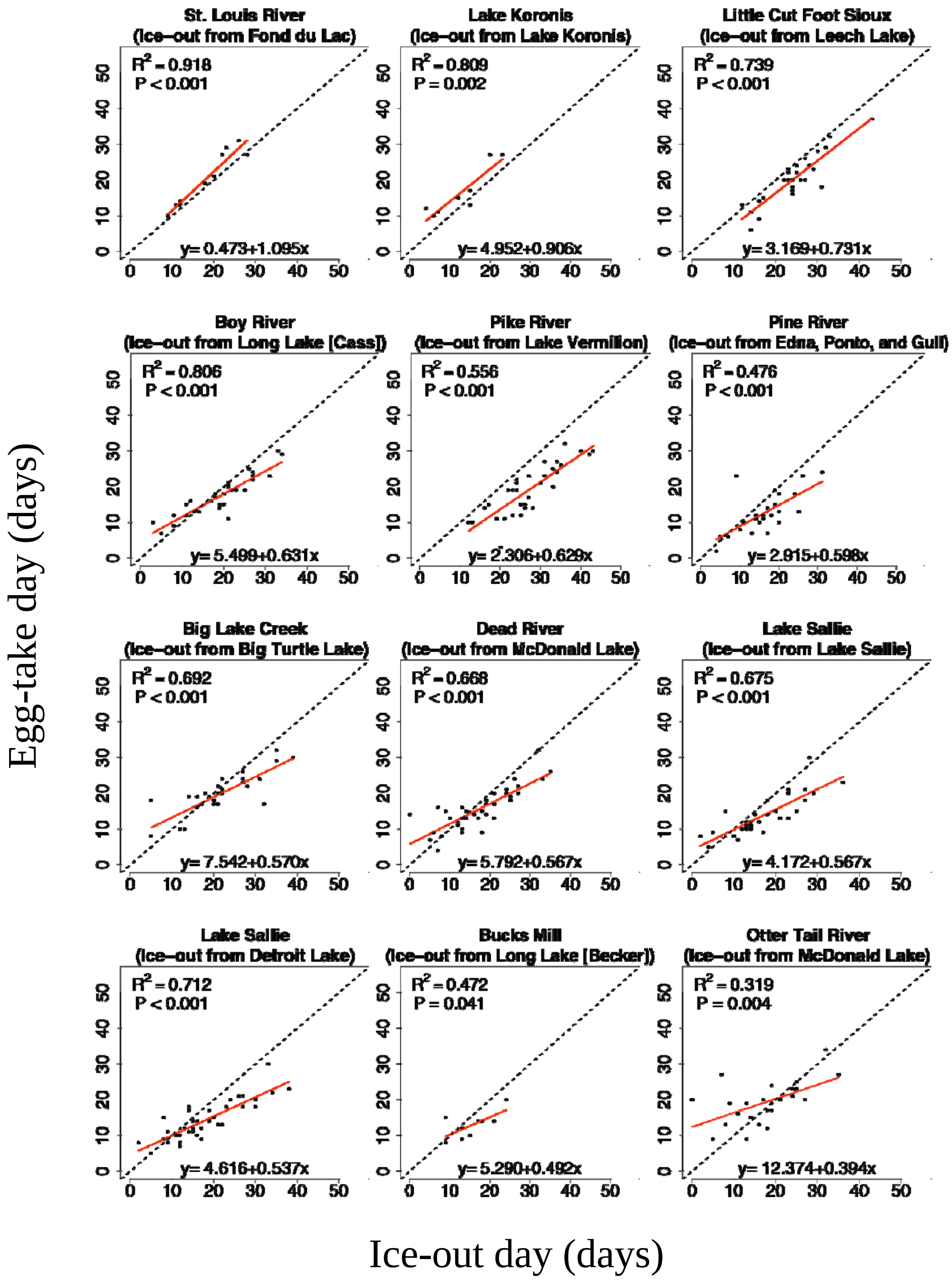
Figure 1. Regressions of first day of egg-take versus ice-out day in order of decreasing slope. All slopes were significant at the 0.05 level. The solid line is the linear regression. The dashed line is y=x. Each point represents one year, and the origin is April 1st.

Figure 2: List of linear model objects from regressions of egg-take day versus ice-out day with 95% confidence intervals in order of decreasing slope. All slopes were significantly less than 1 except for Lake Koronis and the St. Louis River.

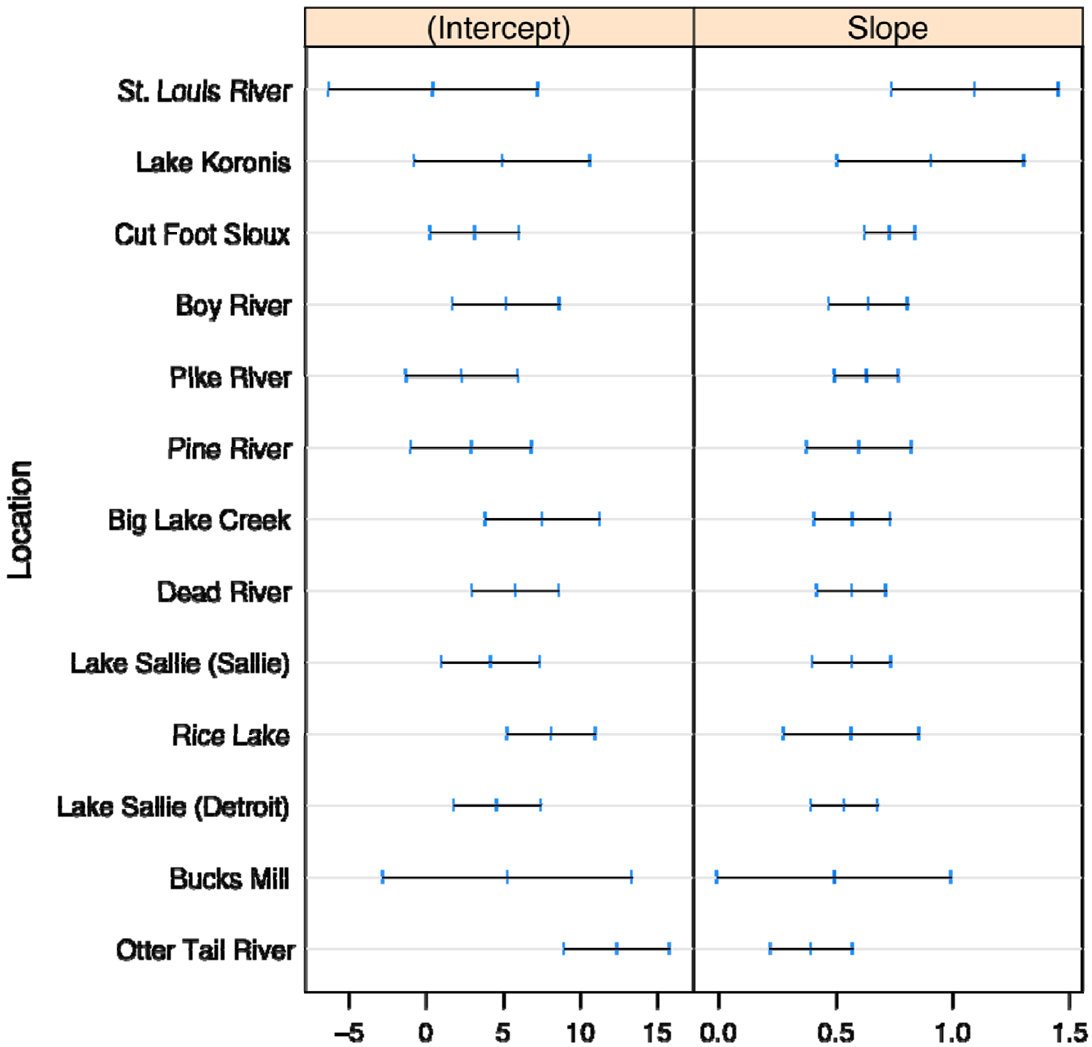
Figure 3. Example relationships of walleye first egg-take versus year. First egg take is recorded as the number of days from 1 January. The solid line is the linear regression, and the dashed line is the LOWESS fit. The linear regression was a better fit than the LOWESS smooth at all locations shown except Lake Koronis. All slopes shown except Little Cut Foot Sioux were significant at the 0.1 level. Little Cut Foot Sioux is shown as an example of a long-term time series that didn’t have a significant slope.

Figure 4. Example regressions of ice-out date over time. Ice-out is recorded as the number of days from 1 January. The solid line is the linear regression, and the dashed line is the LOWESS fit. All slopes shown except Leech Lake (full dataset) were significant at the 0.1 level. The Leech Lake time series is shown as an example of a long-term dataset that didn’t have a significant slope. The LOWESS smooth did not improve the fit of the data compared to linear regression for all time series shown.

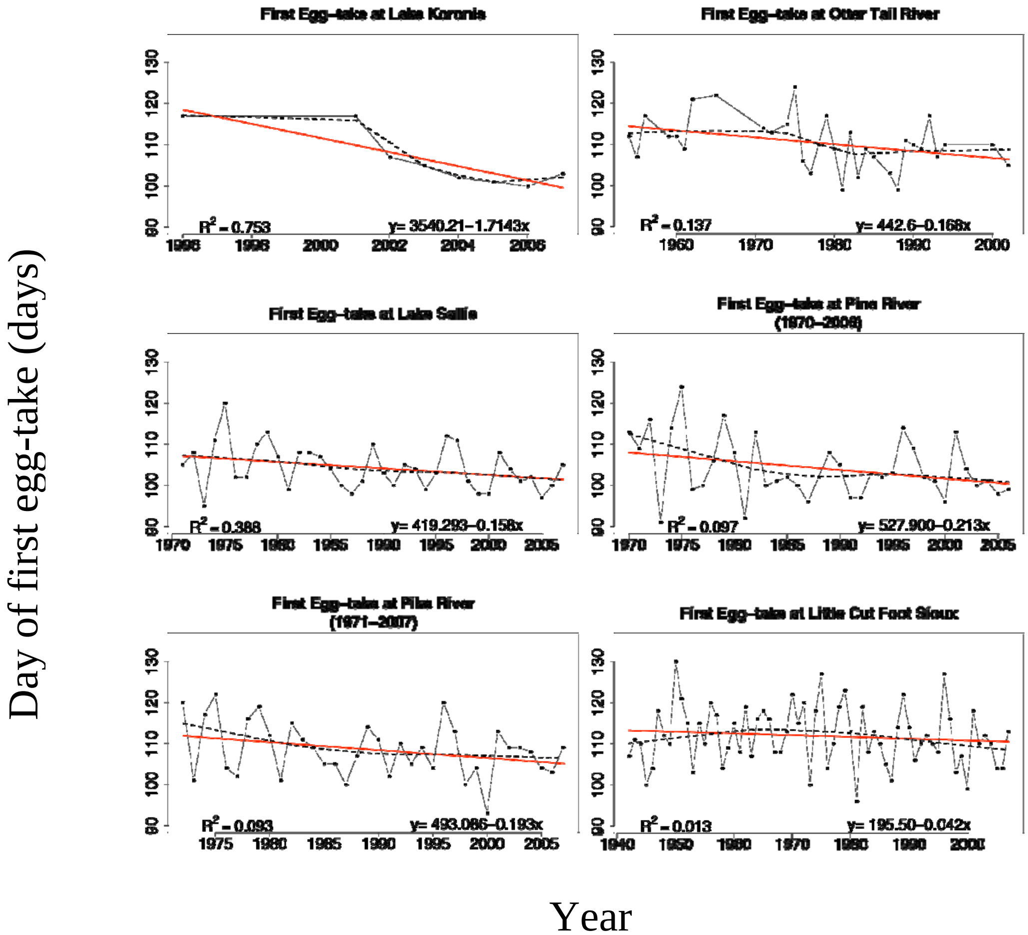
Schneider Figure 1



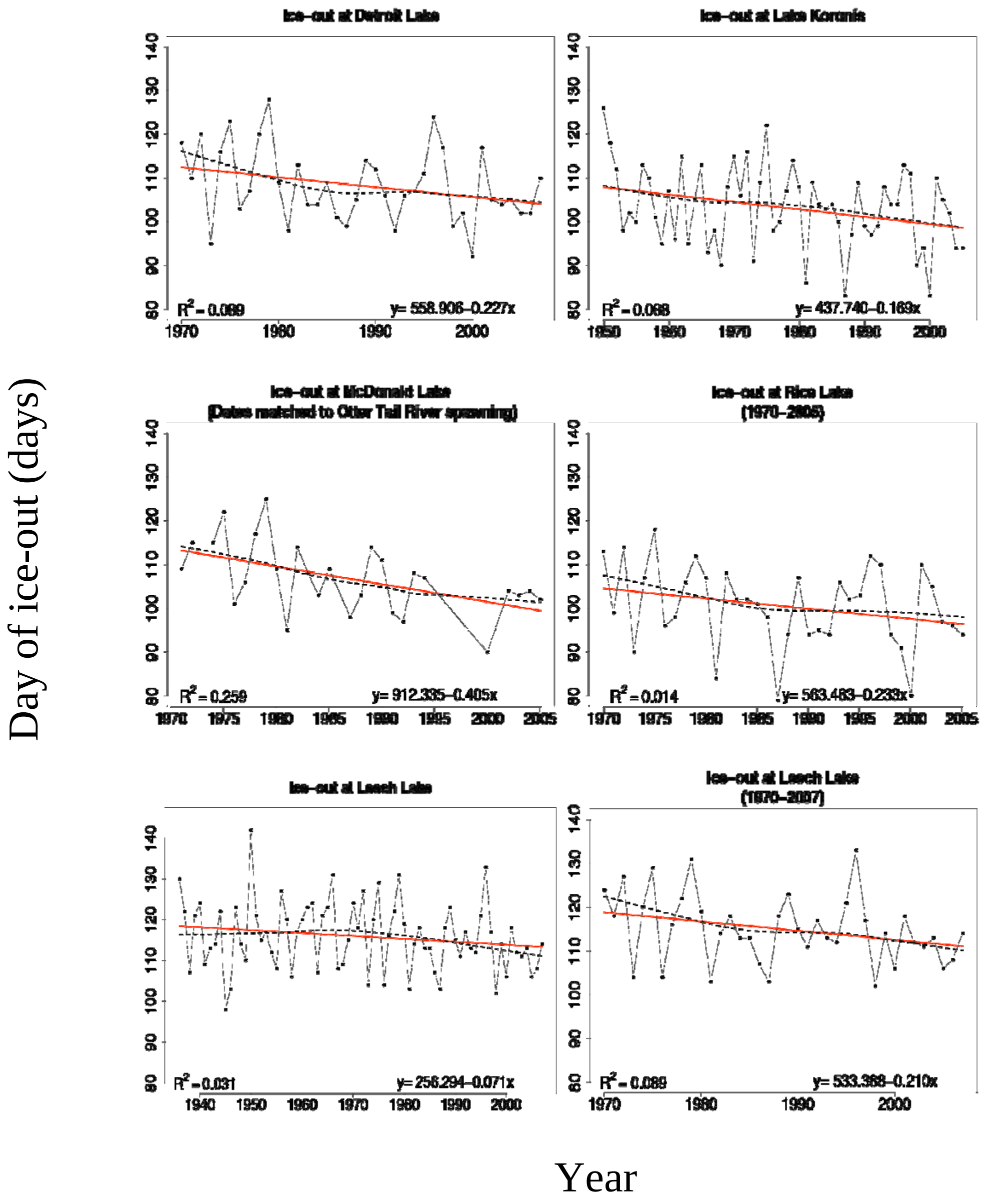
Schneider Figure 2



Schneider Figure 3



Schneider Figure 4



Minnesota lake water quality on-line database and visualization tools for exploratory trend analyses

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I. Minnesota lake water quality on-line database and visualization tools for exploratory trend analyses

A. Background

Warming temperatures have been shown to have negative environmental impacts in both lakes and streams. In lakes, warmer temperatures may increase temperatures in the upper mixed layer (epilimnion) enough to affect algal, aquatic plant, invertebrate and fish communities. The IPCC analysis for the Upper Midwest suggested the following potential consequences of increased water temperatures due to increased air temperatures:

> *Earlier and longer period of density/thermal stratification in summer in deeper lakes, leading to longer periods of hypolimnetic "stagnation" and isolation from atmospheric oxygen mixing into the epilimnion. This can lead to the increased duration and magnitude of oxygen depletion in the hypolimnion, increasing the risk of developing a 'dead zone' and associated fish kills.*

These consequences were in part based upon more detailed models developed to predict potential climate change effects on Minnesota lakes (Stefan et al. 1993; Stefan et al. 2001; Fang and Stefan 1999).

In such cases, this increased duration of stratification can reduce oxygen inputs to bottom layers, increasing the risk of oxygen-poor or oxygen-free "dead zones" that will stress or kill fish and other organisms. In culturally nutrient-enriched lakes in particular, enhanced oxygen depletion would also be expected to increase phosphorus diffusion from bottom sediments leading to larger injections of bio-available phosphorus during periods of intermittent mixing in spring and summer, and during fall turnover. Such sudden inputs of P typically lead to large blooms of algae, in some cases producing noxious scums and increased likelihood of cyanobacterial (i.e. "bluegreen algae") toxins (e.g. MPCA 2007). Oxygen depleted bottom waters also are characterized by increased concentrations of chemically reduced nitrogen (ammonium-N) and sulfur (hydrogen sulfide); both can be toxic to fish and other aquatic animals at concentrations that often are found in such lakes, and the injection of ammonium along with phosphate into the epilimnion during mixing usually leads to more algal growth than would P alone. In lakes with contaminated sediments, warmer water and low-oxygen conditions may act to mobilize mercury and other persistent pollutants, potentially increasing health hazards for animals that eat fish from the lakes, including humans (e.g. Dodds 2002, Stefan et al. 2001, MPCA 2004). Poff et al. (2002) and Kling et al. (2003) list specific impacts to lakes that include an increase in nuisance algae, the reduction of fish habitat with the warming of lakes, and changes in runoff (both increases and decreases), that will in turn affect lake levels, and finally, expansion and contraction of aquatic species ranges.

The Water Quality component of the project was included in the following main objective:

<u>Summarize the follow variables in lakes and streams</u>:

(1) lake transparency (secchi depth);
(2) lake chlorophyll (a measure of algal abundance);

(3) lake total phosphorus (and nitrogenous nutrients when available);
(4) lake levels (see Appendix B);
(5) Stream flows, specifically annual mean flow, annual maximum flow, annual minimum daily low, and mean monthly flow (see Appendix D);
(6) Timing of stream flows, such as date of annual maximum daily flow, date of spring maximum daily flow, date of spring freshet (initiation of the spring/snowmelt runoff), date of annual minimum daily flow (see Appendix D); and
(7) Other ancillary water quality parameters, including temperature and total dissolved solids / specific conductance, dissolved oxygen, DOC/color, pH/alkalinity, TSS/turbidity

These parameters were selected for two reasons: a) their direct linkage to climate; and b) their potential direct impact on water quality and ecology (see Proposal Appendix A). Influences of land use changes, e.g. urbanization or agricultural use, have to be acknowledged, and to the extent possible based on funding limitations, will be taken into account in the interpretation of the results.

B. Lake Water Quality Trends Specific Objectives

The amount of lake water quality data that has been collected for Minnesota lakes is enormous and therefore, a series of meetings were held with project partners to distill down the scope of this task based on available funding 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 trend analyses on all available parameters.

As the project proceeded, using a third component became possible as a result of tools developed from other non-LCCMR funded projects:

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 water quality data.

C. Methods

1). Data compilation: Data from MPCA STORET files was re-organized and summarized in various ways (see below) in preparation for determining statistical associations with ice-out and ice-on data that was being compiled as a separate component of the overall project. With help from MPCA, we began by compiling data for an initial set of 26 lakes with long-term ice-out records compiled by co-PI V. Card. This set of lakes was then augmented to include an additional set of ~255 lakes for which ice-out records had been compiled. However, since the *ice-out record lakes set* had no *a priori* relationship to the amount of water quality data available for these lakes, we examined a larger set of lakes that contained at least 15 years of data for at least one parameter. This generated a set of 560 Minnesota lakes which ultimately grew to total

638 lakes totaling 1.9 million data records as other data bases were discovered that included quality assured data. Several water quality data sets were investigated, including those from MPCA (EDA), EPA (STORET), DNR Fisheries, Metropolitan Council, and our own (NRRI-UMD) cooperative work with Itasca County and Three Rivers Park District.

2). Water quality variables: Measured parameters comprise a primary *Core Suite* that includes the field sensor parameters that typically determine a meter-by-meter depth profile of temperature, dissolved oxygen (and a calculated percentage oxygen saturation), specific electrical conductivity (EC25, that estimates total salt/ion concentrations), and pH; and water clarity estimated by Secchi disk depth. Lake level is also considered to be a *Core* parameter, but trends in lake level were analyzed as a separate TASK by co-PI H. Stefan's group for the overall project (see Appendix B for details). 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 its limnologically relevant forms), dissolved and total organic carbon and/or color, SiO_2, Hardness, the major anions (ANC/alkalinity, SO_4, Cl) and the major cations (Ca, Mg, Na, K). These classifications derive from the *Vital Signs* program used by the National Park which was used by NRRI-UMD to structure analyses of historical water quality in the Great Lakes Network of National Parks (Axler et al. 2005, 2006; Pennoyer 2003). It is useful since there will be many more *Core* than *Advanced Suite* data available for Minnesota lakes and streams.

3). Data quality assurance was assumed to have been properly completed prior to being stored in the MPCA EDA (Electronic Data Access) data base and EPA's STORET databases. However, numerous erroneous and anomalous values were uncovered during initial data screening that involved visually inspecting the data for outliers due to either entry error or changes in method detection limits. Outliers were identified based on best professional limnological judgment by NRRI staff and PI. In most cases, the problem was clearly due to a typographic error and was corrected. Ultimately, these outliers were either deleted from the data set used for statistical analyses, or allowed to remain in the database for lack of evidence to reject them. For some data we made assumptions about sampling depths based on maximum depths (Z_{max}) taken from MN DNR morphometry data available on the agency's Lake Finder website (http://www.dnr.state.mn.us/lakefind/index.html). Water quality parameter terminology follows standard limnological procedures (e.g. APHA 2003).

4). Depth strata: After data were manually reorganized and sorted into spreadsheets, a computer program was developed to automate the computation of depth stratum mean values, tabulation of data summaries, graphical presentation, and export to trend analysis software.

Each parameter from each site was averaged for all sampling dates and sampling periods for the following depth strata; 0m (surface values), 0-2m, 3-5m, 6-8m, 9-11m, 12-14m, 15-19m, 20-24m, 25-29m, 30-34m, etc. Strata were chosen for limnological reasons as well as data availability for the deeper strata in order to facilitate analyses of epi- meta- and hypolimnetic waters as manageable, but limnologically relevant "habitats" within a lake. These strata were selected to accommodate comparisons of lake trends across climatic regions and across groups of lakes classified by maximum depth. For example, our visual inspection of temperature and dissolved oxygen (DO) profiles from many shallow and deep, and productive and unproductive lakes has indicated that the strata 0-2, 3-5, 6-8 and 9-11m should capture the key seasonal and depth changes in temperature and DO for most lakes and eliminate the need for meter by meter comparisons of profiles. This also would eliminate about one third of the statistical analyses needed:

- [0-2m] - near-surface water in the mixed layer (epilimnion) where surface scums of algae can lead to supersaturated DO; averaging data from 0, 1 and 2m should also facilitate comparisons with chlorophyll and water chemistry measurements which have mostly been collected using 2m integrating tube samplers over the past 20 years.

- [3-5m] and [6-8m] – near-bottom water in polymictic shallow lakes (~4-8m bottom depth) and the thermocline region in stratified lakes whether the stratification persists throughout the ice-free growing season or not.

- [9-11m] - sub thermocline (uppermost hypolimnion) for most stratified lakes; may also be near-bottom for many lakes.

- [?-?] – undetermined for deeper hypolimnion strata. These analyses will likely focus on specific lakes within the set of ~ 255 lakes for which ice records exist.

- depth of the mixed layer (epilimnion depth for thermally stratified lakes); mean and maximum

- thermocline depth for stratified lakes - defined by the maximum temperature gradient with depth where the value exceeds 1 ^{o}C/meter (and 0.7 ^{o}C/meter); mean and maximum

- depth of anoxia – defined by DO $\leq$ 1 mgO_2/L; mean and maximum depth of acute warm, cool and cold water fish stress defined by values of 3 mgO_2/L, 5 mgO_2/L, and 7 mgO_2/L, respectively; these values are used as water quality criteria by the MPCA in various sections of Chapter 7050 (e.g. http://www.revisor.leg.state.mn.us/arule/7050/0222.html 7050.0222 SPECIFIC STANDARDS OF QUALITY AND PURITY FOR CLASS 2 WATERS OF THE STATE; AQUATIC LIFE AND RECREATION and http://www.epa.gov/waterscience/standards/wqslibrary/mn/mn_5_0150.htm 7050.0216 REQUIREMENTS FOR AQUACULTURE FACILITIES. As with temperature data, analyses will likely focus on specific lakes within the set of ~ 255 lakes for which ice records exist.

The statistics for each layer were calculated using the average of the daily averages within each time period. Note that stratum averages were not volumetrically weighted and only represent water column means for a site in the deepest portion of the lake.

5). Detection limit issues: We also needed to develop a set of "rules" for incorporating data listed as below detection into the database. This was particularly important for low nutrient lakes. There were two possibilities in the "raw" dataset extracted from the MPCA database -- "*Non-detect*" and "**Present <QL*", where QL is the *Quantitation Limit* for which the follow rules were adopted:

- If the record contains a value for "*MinDetectLimit*": use MinDetectLimit/2
- If the record contains a value for "*MinQuantLimit*": use MinQuantLimit/6
- Otherwise skip the record "*for now*"; we intend to examine this dataset more closely to see how important these deletions are to the results of the nutrient trends analyses.

6). *Secondary* parameters: In addition to the primary set of *Core* and *Advanced* suite water quality variables, several secondary, calculated parameters were generated for trend analysis:

- The Carlson Trophic State Index (TSI) was included because of its regulatory and management importance to lakes in Minnesota and its wide use in general. The index is actually three calculations based on midsummer secchi depth, surface TP and surface chlorophyll-*a* concentrations (details below in the Metadata).

- Algorithms were developed to calculate thermocline depth and the rate of change, or gradient, of temperature at the thermocline for over 500 lakes in the database since these are potentially important indicators of thermal trends in lakes. Thermal stratification and its stability (i.e. strength) act to structure habitat for aquatic organisms. This effort is also important because it provides a prototype for new calculated MPCA EDA (Electronic Data Access) thermal parameters since field temperature profiles are now simply entered into the database without further analysis.

- A third set of parameters compiled for each lake includes the various morphometric characteristics (e.g. surface area, maximum depth, mean depth, lake area to watershed area ratio, fetch, shoreline development, relative depth, et al.) as well as spatial classifications such as climate region and ecoregion.

7). Time intervals: Since this initial phase of the Climate Change project was intended to be exploratory, it was decided that trend analyses should be performed for a variety of potentially useful periods that could be used to characterize a particular year. For example, the MPCA has long requested Citizen Lake Monitoring Program (CLMP) volunteers, the group that has collected most of Minnesota's long-term Secchi disk water clarity data, to focus their measurements from June 15 – September 15. Therefore, all data within this time frame can be averaged to generate a single value for a particular year as has been routinely done by the agency for many years. Alternatively, a set of monthly or bimonthly mean values could be calculated and then analyzed singly for the year or considering their within-year variation. A monthly average for August, when algal biomass is usually thought to be at its peak could be useful to examine in comparison to weather patterns either at that time or perhaps over a longer period to include the contribution of spring runoff to the lake's nutrient loading. Similar arguments can be made for other ice-free months, or for any particular month, or two or three month period for that matter.

Limnological researchers have also used several different time periods and methods for generating annual averages, the most common periods perhaps being entire calendar year or the USGS *Water Year* defined as Oct 1 –Sep 30 of the following year, the *summer* (defined by the calendar season, or Jun-Aug, or Jun-Sep), or the *ice-free season* which on average could reasonably be defined as May through Oct (R.Axler, personal observations). Therefore, data was compiled in a manner that would allow analyses to be performed using any or all of these time intervals. Consideration was also made of the potential for biasing averages if sampling was not spread evenly over a given interval and further statistical considerations of this issue are discussed below.

Initial examination of exploratory analyses focused on the following four time intervals:

- All data for the entire calendar year

- May through October 15, corresponding to the vast majority of the "ice-free growing season" for most lakes and most years.

- June 15 – September 15; the summer period as defined by MPCA for its Citizen Lake Monitoring Program (CLMP), CLMP-Plus, and most of its Lake Diagnostic studies. At least 4 monthly surveys will be required for this data set.

- June 1 – September 30; the "summer" as defined in Minnesota Rules, Chapter 7050, 7050.0150 DETERMINATION OF COMPLIANCE WITH WATER QUALITY STANDARDS AND WATER QUALITY CONDITION (http://www.epa.gov/waterscience/standards/wqslibrary/mn/mn_5_0150.htm)

- A midsummer window for some specified July – August period that is selected to maximize our use of data for a lake even if there was only a single survey for a year.

8). Trend analyses: Trends and trend rates over time were determined using the *Seasonal Kendall Trend Analysis* software developed by the U.S. Geological survey (2005; Computer Program for the Kendall Family of Trend Tests, Dennis R. Helsel, David K. Mueller, and James R. Slack SIR 2005-5275, U.S. Geological Survey; available at http://pubs.usgs.gov/sir/2005/5275) that allow for trend analyses both seasonally and regionally. The main advantage of the seasonal Kendall trend test is that it is a non-parametric, rank-based procedure suitable for non-normally distributed data, censored data, data containing outliers, and non-linear trends (Helsel et al. 2005; Helsel and Hirsch 1992; Hirsch and Slack 1984).

Sites were initially identified sites as "Qualifying" if they had records from at least 5 different years and with a level of significance of $p \leq 0.1$ for either a positive or negative trend over time. Additional exploratory trend summaries with accompanying mapping tools were generated for $p < 0.05$ and lakes having more years of data (8, 12 and >18 years).

It should be noted that in order to have been included in the original data set for which trend analyses were performed, a lake had to have "some" data for at least 15 different years and in virtually all cases, this long-term monitoring parameter was secchi depth clarity. Data records for all other parameters were considerably sparser.

9). Data, analyses, and visualization options: Mapping 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 and for the new

DNR/MPCA *SLICE* (i.e. sentinel) lakes. A comprehensive subproject website was constructed to make the trend results available to other project scientists. Our Minnesota Lake Trends website:

Minnesota Lake Trends Analyses website: ***http://mnbeaches.org/gmap/trends***

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). Detailed metadata were also created for the website and are included below.

The data are also incorporated into the larger project database that is now being used for more detailed examinations of geographic patterns, size and depth patterns, and associations with fish, macrophyte, weather, and ice cover data.

D. Results

1). Trend analyses: All statistical information is indexed at http://mnbeaches.org/gmap/trends/results/avg/index.html via a table with hyperlinks to specific statistical analyses (Figure 1). "Seasons" define how the data are averaged. For example, a one (1) season analysis computes the median of all data for a particular interval during the year, such as a single month, two months, or the generalized ice-free growing season (May 1 – Oct15). These analyses weight all data equally, even if there is a bias towards one period within the specified interval. In order to account for this potential bias, several additional "seasons" were defined, in particular the 3-"season" summer field season period that groups data into one month "seasons" from Jun15 - Jul15, Jul16 - Aug15, and Aug16 - Sep15, that collectively encompass the MPCA's historically defined Jun15 - Sep15 field season. Additional analyses were performed based on a standard 4-season year and a 12-month year, but we focused our initial conclusions on the results from the 3 season statistical analyses. In fact, because most data were collected during the period June through September, and distributed relatively uniformly in summer when multiple surveys were performed on a lake, the results from the 3-season analyses did not differ much from the 1-season Jun-Aug, 1-season Jun-Sep, or 1-season May-Oct15 interval results.

Figure 1. **MN Lake Trends - Seasonal Kendall Results**

These results were calculated by first averaging the results for each layer by day, then averaging those results for each time period (season).

Go to Metadata for details.

# of seasons per year	Season definition	≥ 5 yrs data & $p \le 0.1$	≥ 5 yrs data & $p \le 0.05$	≥ 8 yrs data & $p \le 0.05$	≥ 12 yrs data & $p \le 0.05$	≥ 18 yrs data & $p \le 0.05$	≥ 8 yrs data & $p \le 0.01$	≥ 12 yrs data & $p \le 0.01$
12	Monthly	-X-	-X-	-X-	-X-	-X-	-X-	-X-
4	JanFebMar, AprMayJun, JulAugSep, OctNovDec	-X-	-X-	-X-	-X-	-X-	-X-	-X-
3	Jun15 - Jul15, Jul16 - Aug15, Aug16 - Sep15	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	May01 - Oct15	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	Jun15 - Sep15	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	Jun - Jul - Aug	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	Jun - Jul - Aug - Sep	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	May - Jun	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	Jun - Jul	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	Jul - Aug	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	Aug - Sep	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	April	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	May	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	June	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	July	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	August	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	September	-X-	-X-	-X-	-X-	-X-	-X-	-X-

- return to index -

This page was updated: 29-Jul-2009

Exemplary results for temperature are show in Figure 2 for the 3-season summer analysis where the criteria for a statistically significant trend required at least 5 years of data for the particular parameter of interest, and a significance level of 5% (i.e. $p \leq 0.05$). The row highlighted in the

Figure 2.

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MN Lake Trends

Seasonal Kendall Trend Analysis
3Periods_Jun15_thru_Sep15 Summary (3 seasons/year)

The statistics for each layer were calculated using the average of the daily averages of the result values within each time period.

Temperature, water

Qualifying sites: Sites with records from at least 5 different years and with p ≤ 0.05

[Download the complete results (csv)]

Summary type (averaged values)	Characteristic	Layer	[A] # of Sites with data	[B] # of sites with data from at least 5 different years	Sites with significant trends (p ≤ 0.05) & data from at least 5 different years			Trend direction				Map	List
								Count		% of C			
					[C] Count	% of A	% of B	Negative trend count	Positive trend count	Negative trend percent	Positive trend percent		
3Periods_Jun15_thru_Sep15	Temp_H2O	00-00m	543	218	30	5.5%	13.8%	1	29	3%	97%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	00-02m	551	247	65	11.8%	26.3%	5	60	8%	92%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	03-05m	524	187	35	6.7%	18.7%	10	25	29%	71%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	06-08m	444	155	34	7.7%	21.9%	25	9	74%	26%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	09-11m	374	119	25	6.7%	21.0%	19	6	76%	24%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	12-14m	283	81	20	7.1%	24.7%	15	5	75%	25%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	15-19m	203	52	9	4.4%	17.3%	7	2	78%	22%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	20-24m	127	27	8	6.3%	29.6%	7	1	88%	13%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	25-29m	67	8	1	1.5%	12.5%	1	0	100%	0%	map	list

red box shows summary trends data for these criteria for near surface temperature (the 0-2 m depth stratum). There were 551 lakes that had data for this stratum, of which 247 had at least 5 different years with data. Sixty-five (65) had a significant trend (26% of the 247 *qualifying* sites) and 92% of these showed a positive, i.e. warming trend. Clicking on the hyperlink **list** at the end of the row opens up a table listing all of the lakes by MDNR DOW #, shown in red if the trend was positive and blue if negative (see Figure 3) and grouped based on how many years of data each had (through 2007). The **map** hyperlink provides the *Googlemap*™ based geographic distribution of the lakes with significant trends, and if desired, of the entire set of lakes with data (Figure 4). Overlays of counties, MPCA Ecoregions and MDNR Ecoprovinces are also available. Markers denoting individual lakes are coded to indicate the sign, magnitude (%-ile), and level of statistical significance of the trend. Individual lake trends are shown as box and whiskers plots that show the data color coded and shown for each "season" according to the specific seasonal Kendall analysis, along with trend slope and its significance (Figure 5). Further description of the analysis outputs are found in the website METADATA below.

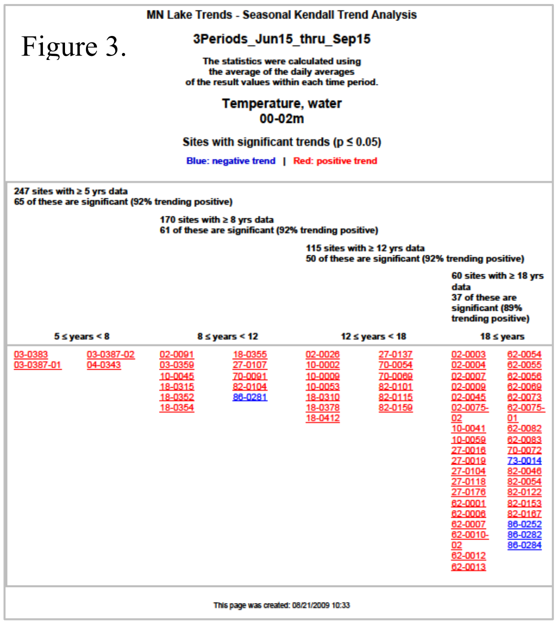

Figure 3.

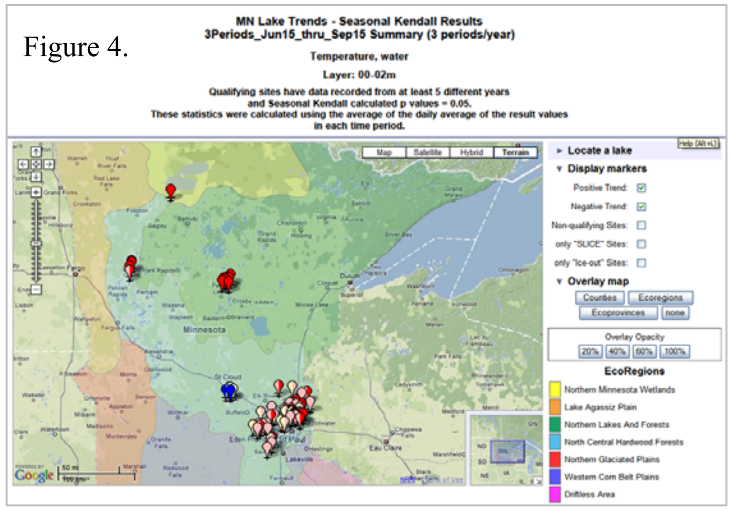

Figure 4.

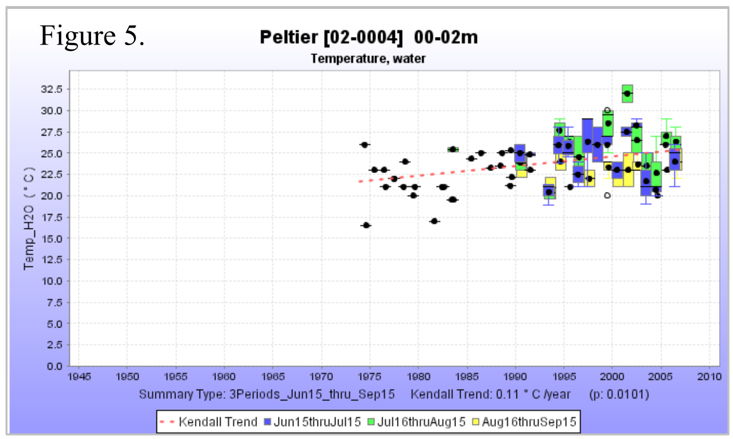

Figure 5.

2). <u>Comparison with MPCA Citizen's Lake Monitoring Program (CLMP) trends analyses</u>: This comparison was of immediate interest because the MPCA has been performing trend analyses for lakes with more than about 8-10 years of volunteer secchi data. The statistical basis for these analyses are apparently now being reviewed but it appears that MPCA has been using a similar type of Kendall analysis (details are currently unavailable). MPCA staff provided a spreadsheet summarizing the results of their trend calculations based on the average of the secchi readings taken each year between June 1 and September 30. Therefore, we compared our results with these for the identical time period as a "single season" in the sense of the Seasonal Kendall test software (see METHODS).

We initially examined sites that had the largest discrepancy between our calculated trends and theirs. We discovered that 7 of these sites had Secchi data that was improperly entered in STORET. Some of the readings were recorded in feet, but the units were entered as meters. MPCA had apparently caught these errors, and corrected them for their calculations and on their website where these data are posted (http://www.pca.state.mn.us/water/clmp/clmpSearch.cfm), but the corrections had not filtered back to STORET. These entries were corrected in our dataset and the trends were recalculated. This resulted in 274 sites showing significant trend results ($p \leq 0.1$) with 268 reported to show statistically trends by MPCA (% agreement, Figure 6).

Figure 7 displays the magnitude of the trend rate difference between the two analyses across all sites. All but 5 of the MPCA results were within 0.05 m/yr of the NRRI results and >90% were within 0.02 m/yr. These differences did not seem to be due to differences in the way annual means were computed since there was close agreement between NRRI annual means and those posted on the MPCA website- usually within 0.1 m for each year's average result which is approximately the method detection limit for volunteer secchi data. There were however, some differences in the methodology NRRI used to calculate the annual averages compared to MPCA. NRRI averaged all of the results for a site that were taken on the same day (i.e. from different stations) and then averaged all of these averages for the entire season. Most sites only have one reading for a given day, but there are some that have more than one. For example, site #29-0146 (the right-most data point in Figure 7) has 4-5 records in STORET for that StationID on some days, with different ActivityIDs and although NRRI averaged them all together for that day, MPCA seems to have only considered records with certain ActivityIDs, presumably using local information as a basis for their data editing. Three of the five sites with the largest discrepancy had identical data posted to what we used in our calculations. The differences seem to be explainable by the fact that MPCA did not use data from all of the years posted on their website when doing their trend calculations. For example, site #31-0424 has data posted from 13 years, but MPCA's summary spreadsheet indicates that only 8 were used in the calculation and unfortunately there are no notes explaining why this was done.

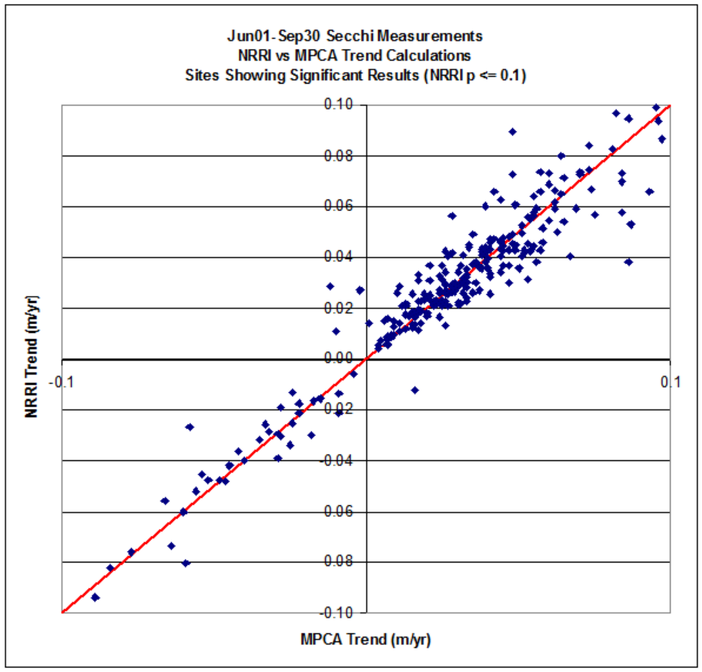

Figure 6. Comparison of Kendall analysis trend rates between NRRI (this study) and MPCA (CLMP, unpublished) for 274 lake sites selected on the basis of having at least 15 years of "some" data (see METHODS). Red line denotes 1:1 correspondence.

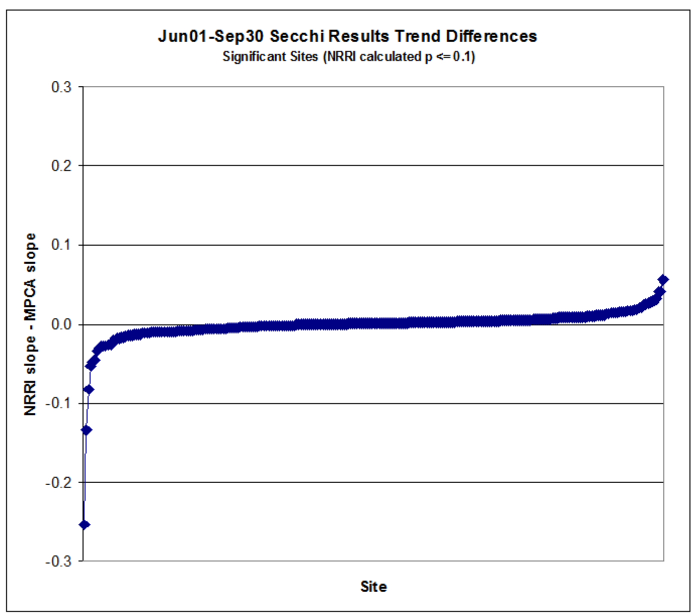

Figure 7. Magnitude of difference between NRRI and MPCA calculated trend rate for sites with ≥ 15 years of data.

Site #21-0106-01 shows the largest difference (-0.25 m/yr), even though the data used as input to the NRRI Kendall trend calculation is the same as what is shown on the MPCA website and so some of the data from the MPCA's EDA website suffers from the same unit-conversion errors mentioned above. MPCA seems to have corrected the data for their trend calculations, but not in the EDA database, so the discrepancy wasn't caught when we did our site by site comparisons. Figure 8 shows a plot of NRRI results, showing the effect of the erroneous values.

Although there are likely other uncaught errors, the close agreement between the two independent analyses is taken to be supportive of our approach to identifying the overall trends in Minnesota lakes.

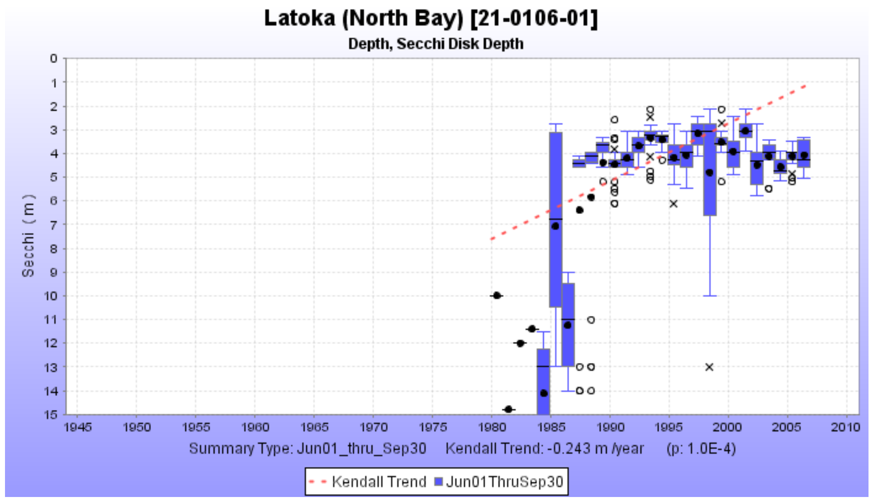

Figure 8. Secchi depth trend for site 21-0106-01 illustrating the effect of feet-to-meter conversion error the early years of the data record.

Discovering significant errors in the EDA and STORET databases almost exclusively due to *feet-to-meter* mis-conversions led us to conduct an extensive computerized and manual (visual) re-screening to identify and correct other secchi errors as well as for temperature, where we found additional unit errors from the *Fahrenheit-to-Celsius* conversion. All errors discovered as part of this project will be reported to MPCA for complete correction in the EDA and STORET databases.

3). A second confirmation of the web-reported trends was performed using the Mann-Kendall (MK) function in R from the Kendall software package written and maintained by McLeod (2005). The analysis was recreated from the NRRI website data summaries for near-surface temperature (0-2m), secchi depth, thermocline depth, TSI-Secchi, near-surface chlorophyll-*a* concentration (0-2m), and near-surface total phosphorus concentration (0-2m). Values for each parameter were averaged for the Jun15-Sep15 season (i.e. comparable to the 1-season analysis in Figure 1) and then the means for each lake and year were entered into the MK function as a vector. Table 1 compares the percent of lakes that showed a trend at a 5% level of significance for the different software analyses and indicates excellent agreement.

Table 1. Comparison of Helsel (2006; USGS) and McLeod (2005) trend analyses. Values indicate the percentage of lakes with at least 5 years of "some" data that showed a statistically significant trend at $p \leq 0.05$. RPD = relative percent difference.

	Helsel (2006)	McLeod (2005)	RPD
Secchi depth	32.3	32.1	0.6 %
Total Phosphorus	20.2	19.9	1.5 %
Chlorophyll-*a*	10.4	11.0	5.6 %
TSI-Secchi	31.3	31.2	0.3 %
Thermocline depth	10.3	9.6	7.0 %
Surface temperature	7.3	7.2	1.4 %

4). <u>Summary of exploratory trend analyses</u> (provisional observations, August 2009)

In the context of the climate change issue that spawned the present study, the most important result derived from the exploratory trend analyses has been that for lakes with significant time trends during the period June – September, more than 90% showed surface water warming as compared to cooling (Figure 9). 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 lakes with 18 years or more data. For the 37 lakes that showed statistically significant warming over their period of record, the mean trend was 0.080 $\pm$ ^{o}C/yr. This would project to an average increase of 0.8 ^{o}C (1.4 ^{o}F) in 10 years, and 3.3 ^{o}C (5.9 ^{o}F) by 2050.

Another important effect predicted from models of the thermal characteristics of lakes in response to climate change relates to the depth of the summer thermocline in deeper lakes and its thermal stability (i.e. resistance to wind mixing and destratification). Warmer growing season air temperatures have generally been predicted to decrease the depth of the thermocline (i.e. creating a shallower epilimnion) in most lakes as a consequence of increased warming of the epilimnion and increased thermal stability. The period of stable stratification is also predicted to begin earlier due to earlier ice-out and persist longer into the fall (e.g. Kling et al. 2003; Fang and Stefan 1999; Schindler et al. 1996). Both empirical and theoretical (i.e., modeling) studies have qualified these predictions because of the variability introduced by the uncertainty of wind velocities, site specific morphometry, and the potential effects of water color changes and light penetration due to changes in dissolved organic matter (DOM) loading and the effect of DOM on light absorption (i.e. heat storage) with depth (Parker et al. 2007; Fang and Stefan 1999).

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 (Figure 9). 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 (Figure 9). Together, these thermal effects over time suggest a shallower, but more stable depth of stratification, which is consistent with surface warming. The data also suggest that in those lakes, the hypolimnion could be more isolated from mixing of epilimnetic water although the population of lakes with such trends is relatively small. Trends in hypolimnetic water for depth strata below a depth of 6 meters, showed the opposite effect with about 20% of the lakes having at least 5 years of temperature profile data having statistically significant trends and more than 75% of those being negative (cooling)(data not shown but see http://mnbeaches.org/gmap/trends/results/avg/3Periods_Jun15_thru_Sep15Summary_5yrs-005p.html). 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. Both patterns, warming epilimnia and cooling hypolimnia when trends were found, were consistent across the many exploratory analyses that were performed for the period June through September, whether data were pooled for two or three months or examined for individual months (see http://mnbeaches.org/gmap/trends/results/avg/index.html)

The duration of thermal stratification was not investigated for this study and it is presumed that most of the lake data sets lack enough surveys during the ice-free season to assess potential trends in this important parameter. However, there may be some lakes with frequent enough summer sampling for enough years to warrant closer examination.

Trend results were less clear for dissolved oxygen (DO). The number of positive versus negative trends in surface waters was approximately similar although 60-75% showed increasing DO in the lakes with 12 to more than 18 yrs of data – an anomalous finding since one might have expected slightly decreasing DO due to warmer water (Figure 9). However, hypolimnetic strata for >20% of the lakes with available data showed significant trends with a clear (>75%) preponderance of increased DO.

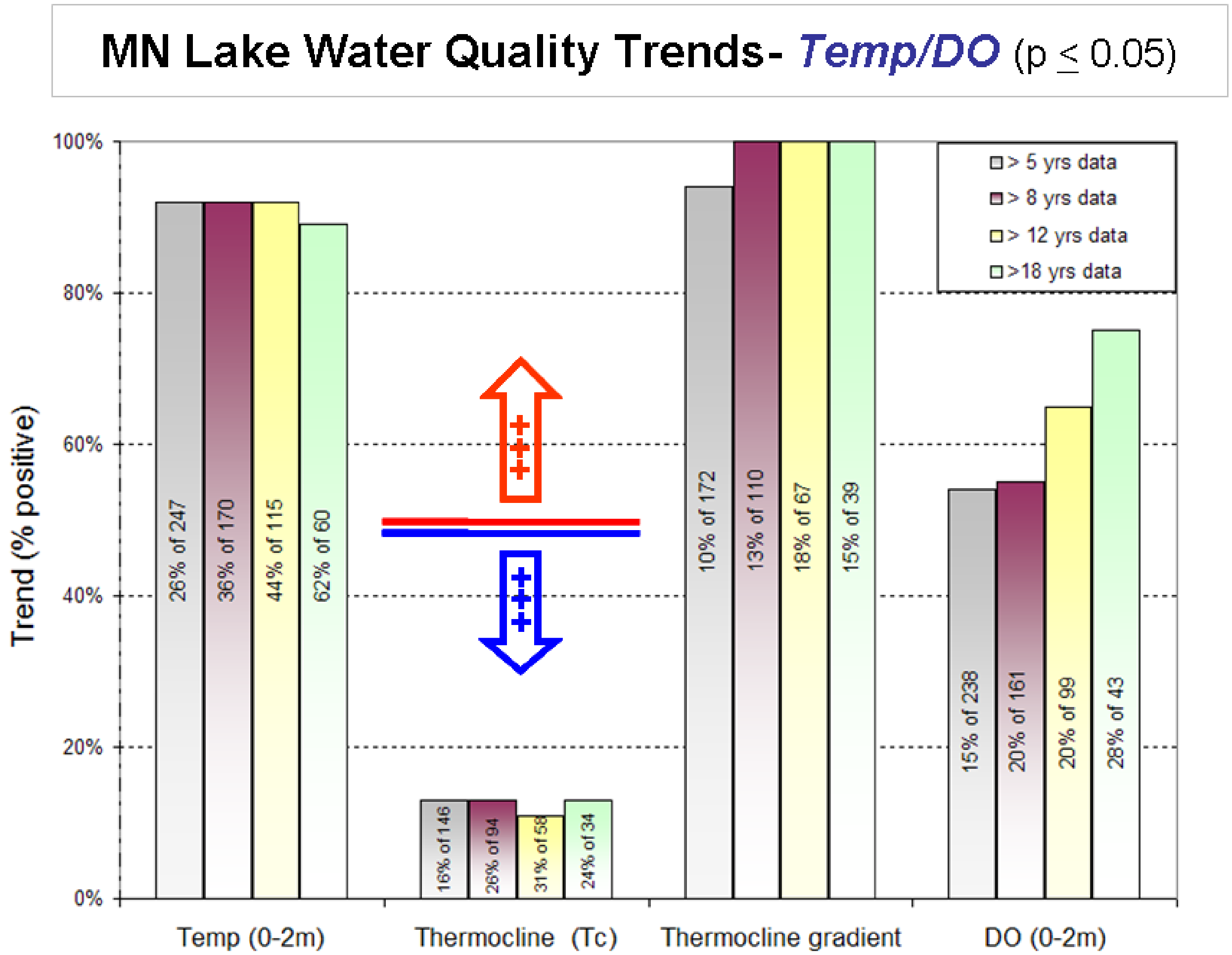

Figure 9. Summary of temperature and dissolved oxygen related trends for Minnesota lakes having at least 15 years of at least one water quality parameter. Bars indicate the percentage of statistically significant trends at $p \leq 0.05$ that were positive for sites with a given number of years of data. Bar colors denote the length of the parameter records; numbers inside the bars indicate the percentage of those sites that were statistically significant. A Trend value of 50% indicates equal likelihood of the significant trend being + or – This is show by the red (positive) and blue (negative) arrows.

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 (Figure 10). 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.

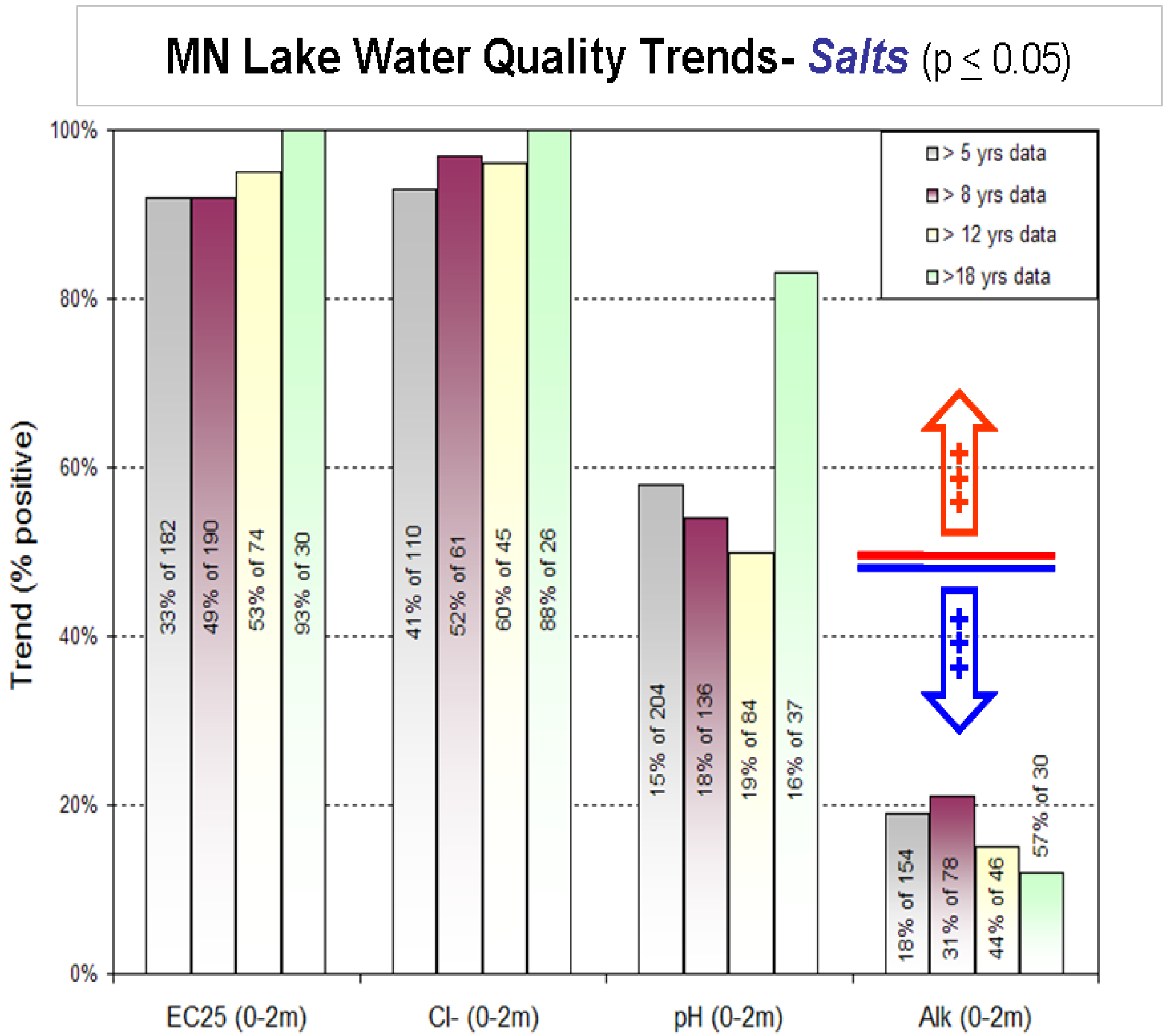

Figure 10. Summary of specific electrical conductivity (EC25), chloride concentration, pH and alkalinity trends for Minnesota lakes having at least 15 years of at least one water quality parameter. Bars indicate the percentage of statistically significant trends at $p \leq 0.05$ that were positive for sites with a given number of years of data. Bar colors denote the length of the parameter records; numbers inside the bars indicate the percentage of those sites that were statistically significant. A trend value of 50% indicates equal likelihood of the significant trend being + or – This is show by the red (positive) and blue (negative) arrows.

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.

The Minnesota Lake Trends website also summarizes exploratory trend analyses for the major ions calcium, magnesium, potassium, sodium, and sulfate, hardness, color and dissolved organic carbon (see http://mnbeaches.org/gmap/trends/results/avg/3Periods_Jun15_thru_Sep15Summary_5yrs-005p.html for the 3-season period Jun15-Sep15). Most of these analyses either lack enough years of data to test for trends, or the number of statistically significant trends that were found were few enough that we are not confident in drawing even provisional conclusions at present.

Perhaps the most surprising result found in this study was that there was internal consistency within the group of trophic status indicators (secchi depth clarity, chlorophyll-a, total phosphorus and total Kjeldahl nitrogen) that suggests a strong overall improvement in water quality (Figure 11). 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 (Table 1) and also by cross-comparing our secchi trend rates with MPCA's estimates for CLMP lakes with more than 15 years of data (Figures 6 and 7). In both cases, the differences in results were negligible.

Additional analyses were performed on other nutrient fractions, including ammonium-, nitrate+nitrite-N, nitrate-N, nitrite-N, total Kjeldahl-N (TKN), and ortho-phosphorus. Ammonium-N, TKN and ortho-phosphorus also exhibited a predominance of negative relative to positive trends although there were fewer overall data. The other nutrient fraction data sets were inconclusive because of even fewer data (see http://mnbeaches.org/gmap/trends/results/avg/3Periods_Jun15_thru_Sep15Summary_5yrs-005p.html). Analyses of Carlson TSI's similarly indicated that about 80% of the lakes with > 5 years of data that had significant trends had shown improvement (data not show but available at http://mnbeaches.org/gmap/trends/results/avg/3Periods_Jun15_thru_Sep15Summary_5yrs-005p.html).

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.

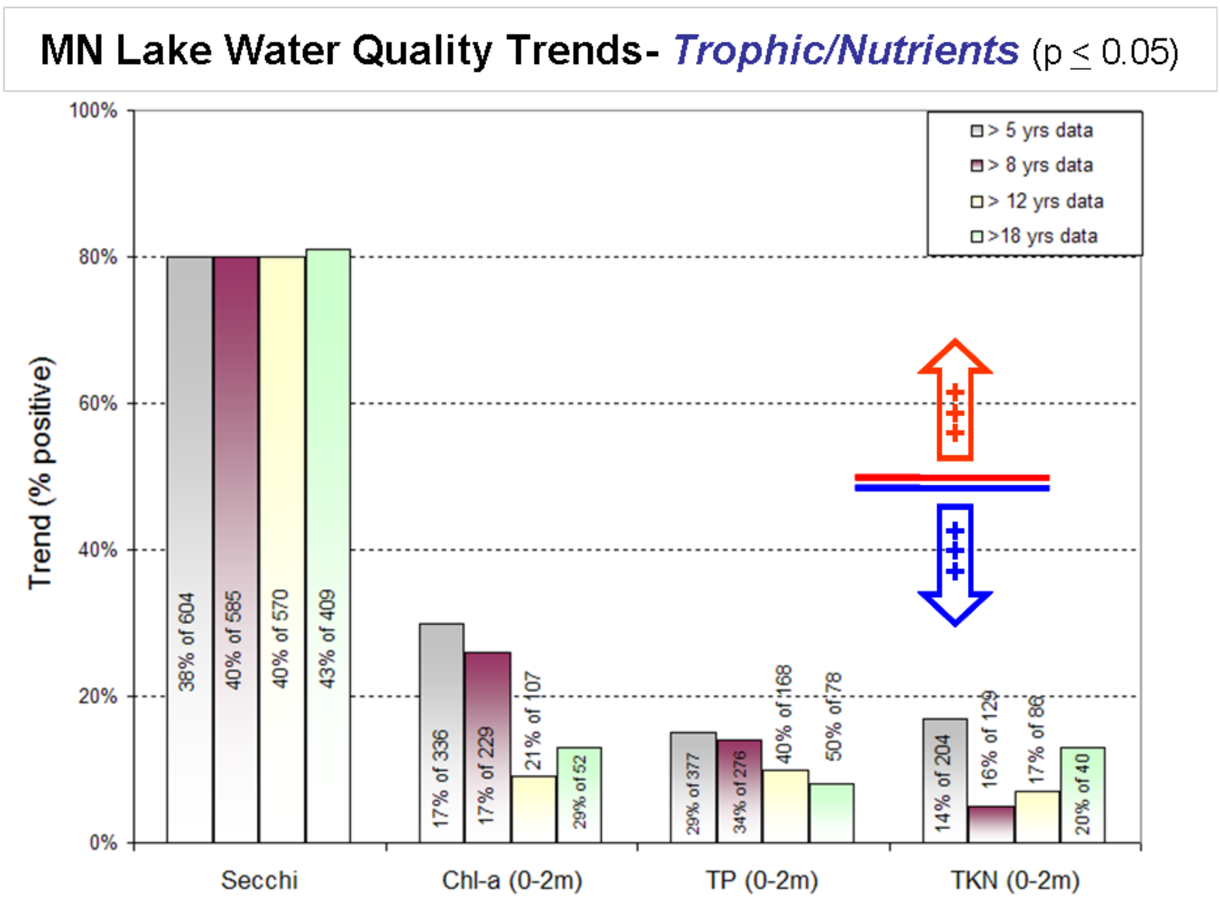

Figure 11. Summary of temperature and dissolved oxygen related trends for Minnesota lakes having at least 15 years of at least one water quality parameter. Bars indicate the percentage of statistically significant trends at $p \leq 0.05$ that were positive for sites with a given number of years of data. Bar colors denote the length of the parameter records; numbers inside the bars indicate the percentage of those sites that were statistically significant. A trend value of 50% indicates equal likelihood of the significant trend being + or – This is show by the red (positive) and blue (negative) arrows

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Attachment: Minnesota Lake Trends website home page and metadata:

: ***http://mnbeaches.org/gmap/trends***

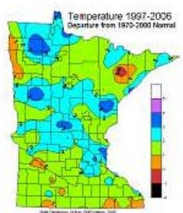
Minnesota Lake Trends Analyses

Page ▾ Safety ▾ Tools ▾

Minnesota Lake Trends Analyses

The data analysis in this websection is one element of a collaborative University-State Agency project funded in 2006 to compile and analyze data that would help Minnesota address natural resource issues associated with potential changes in climate. Phase I (2006-2009) objectives are to:

1. Quantify historic trends in lake fish and higher plant (macrophyte) communities and stream hydrologic and water quality responses to climate
   - Responses of hydrologic and water quality parameters to climate in streams and lakes will be extracted from historical data and summarized.
   - Existing data will be examined to determine if patterns exist for Minnesota, if these patterns are related to climate, and if possible to land use.
2. Develop a database of historic and future climate data for Minnesota
   - Examine existing data sets of climate and records of lake ice-out to determine if patterns can be documented for Minnesota over the past 50 years.

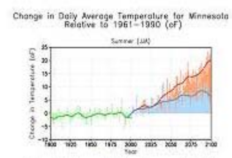


Minnesota Climatology Working Group

Data Summaries

MetaData

Project Team



Wuebbles & Hayhoe (2004)

NRRI Natural Resources Research Institute

UMD Duluth

Minnesota Pollution Control Agency

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Funding:
Legislative-Citizen Commission on Minnesota Resources

Updated: August 13, 2009

Minnesota Lake Trends - Metadata

Page updated: Aug 13, 2009

I. Data sources

- STORET via MPCA retrieval
- Water quality data from lakes with >15 years of at least one water quality parameter to perform exploratory trend analyses on all available parameters
- Status (8/31/09): 638 Minnesota lakes having more than 15 years of at least "some" water quality data totaling 1.9 million data records.
- MPCA data is "current" through 2007
- Met Council data is "current" through 2006
-

II. Data screening

- Already screened for basic QA/QC via STORET data entry rules
- Further "visual, but non-systematic" scanning for errors, outliers, and anomalies
- After comparing NRRI trend analyses of secchi records with Minnesota Pollution Control Agency (MPCA) trends calculated for their Citizen Lake Monitoring Program (CLMP) on a lake-by-lake basis, a number of STORET errors were discovered. These had been previously corrected for the CLMP analysis, but <u>not</u> corrected in STORET. Errors were largely associated with the feet-to-meters conversion. Therefore, the entire MN Lake Trends data set was screened and corrected as needed. A similarly small but significant set of lakes also had Fahrenheit to Celsius conversion errors.

III. Data censoring rules

- For incorporating data listed as <u>below detection</u> into the database and this is particularly important for low nutrient lakes.
- There were two possibilities in the raw dataset -- "*Non-detect" and "*Present <QL", where QL is the Quantitation Limit:
    1. If the record contains a value for "MinDetectLimit": use MinDetectLimit/2 (one-half the specified detection limit). This technique has been widely used for decades and there is still no "accepted" guidelines for censoring below-detection data (e.g. EPA. 2004. Revised Assessment of Detection and Quantitation Approaches. EPA-821-B-04-005. October 2004. Office of Science and Technology, Office of Water (4303T), U.S. Environmental Protection Agency, Washington, DC 20460 (www.epa.gov/waterscience/methods/det/rad.pdf; Helsel, D. 2005. More

Than Obvious: Better methods for interpreting non-detect data. Environ. Sci. Technol., 2005, 39 (20), pp 419A–423A.).

2. If the record contains a value for "MinQuantLimit": use MinQuantLimit/6.6 based on the approximation that MDL ~ 3*SD and QL ~ 10*SD where SD is the Standard Deviation for a set of replicate water samples in the lower concentration range of interest (cf. EPA. 2004 above)
3. Otherwise skip the record "for now (7/14/09)"; we intend to examine this dataset more closely to see how important these deletions are to the results of the nutrient trends analyses if continued funding becomes available.

IV. Parameter groups

- ***Core Suite*** - field sensor parameters that typically determine a meter-by-meter depth profile of temperature, dissolved oxygen (and a calculated percentage oxygen saturation), specific electrical conductivity (EC25, that estimates total salt/ion concentrations), and pH; and water clarity estimated by Secchi disk depth.
- ***Advanced Suite*** - most of the other "routine" water quality variables such as chlorophyll-a, nutrients (TN [measured and calculated], TKN, [nitrate+nitrite]-N, ammonium-N, TP, ortho-P), dissolved and/or total organic carbon and/or color, SiO2, Hardness, major anions (ANC/alkalinity, SO4, Cl) and major cations (Ca, Mg, Na, K).
- We think this is a useful classification since there will be many more *Core* than Advanced Suite data available for Minnesota lakes and streams. This nomenclature was borrowed from the *Vital Signs* long-term monitoring program of the U.S. National Park Service.
- ***Calculated Indicators*** —

1. Carlson Trophic State Index (TSI) as individual TSI-secchi, TSI-TP, TSI-Chlorophyll-a; Mean-TSI (= [TSI-P + TSI-C + TSI-S]/3).
   - TSIs calculated for data collected only during the period May 1 - Oct 15;
   - if there is a 0-2m value, use it, otherwise use the value from the shallowest reading if it's < 5m, otherwise do not calculate the TSI;
   - any records for Secchi, Chlor, or TP that had result values of “0” were ignored because they would cause the TSI formulas to *explode* due to the log function. These records were probably data entry errors, obviously for Secchi depth.
   - The TSI values are calculated as show below (from MPCA;
   - *www.pca.state.mn.us/water/basins/305blake.html ; Carlson 1977*)

Secchi disk (SD): TSI (TSIS) = 60 - [14.41(natural log)(Secchi average)]

Total phosphorus (TP): TSI (TSIP) = [14.42 (natural log)(TP average)] + 4.15

Chlorophyll-a (chl-a): TSI (TSIC) = [9.81(natural log)(chl-a average)] + 30.6

(TP and chl-a in micrograms per liter (ug/L) and SD transparency in meters).

The index ranges from 0 to 100 with higher values indicating more eutrophic conditions. The TSI values were calculated for each variable, then averaged for each lake (Figure 1). Although *Mean TSI* values were calculated, they must be used with caution since this analysis assumes that water clarity is controlled by algal biomass, which is in turn controlled by available phosphorus as estimated by TP. TSIS, TSIP, and TSIC might be expected to diverge in lakes that are turbid due to high loads of suspended or re-suspended sediment, or when algal biomass is regulated by another factor such as nitrogen availability or grazing by invertebrates.

Figure 1. Carlson's Trophic State Index (TSI)

TSI <30	Classic Oligotrophy: Clear water, oxygen through the year in the hypolimnion, salmonid fisheries in deep lakes.
TSI 30-40	Deeper lakes still exhibit classical oligotraphy, but some shallower lakes will become anoxic in the hypolimnion during the summer.
TS 40-50	Water moderately clear, but increasing probability of anoxia in hypolimnion during summer.
TS 50-60	Lower boundary of classical eutrophy: Decreased transparency, anoxic hypolimnion during the summer, macrophyte problems evident, warm-water fisheries only.
TSI 60-70	Dominance of blue-green algae, algal scums probable, extensive macrophyte problems.
TSI 70-80	Heavy algal blooms possible throughout the summer, dense macrophyte beds, but extent limited by light penetration. Often would be classified as hypereutrophic.
TSI > 80	Algal scums, summer fish kills, few macrophytes, dominance of rough fish.

2. <u>Actual thermocline depth</u> – calculated directly from temperature profiles as the depth of the maximum temperature gradient provided it is > 1°C /meter for each site with a H2O Temp dataset.

For each profile in the dataset:

- combine any adjacent readings that are within 0.25 m into a single reading consisting of the averaged depths and temperatures

- calculate dtdz between adjacent readings in the profile,
- determine which is the maximum dtdz,
- ignore and move on to the next profile if dtdz_max is < 0.7 °C /m,
- otherwise:
    - create a record in the Thermocline_Rate dataset for the site,
    - set the upperDepth & lowerDepth variables to the depths of the 2 adjacent readings that gave dtdz_max,
    - if the dtdz for the previous (shallower) reading pair is within 0.05 of dtdz_max use its upper depth for upperDepth,
    - if the dtdz for the next (deeper) reading pair is within 0.05 of dtdz_max use its lower depth for lowerDepth,
    - calculate the thermocline depth = (lowerDepth + upperDepth) /2,
    - create a record in the ThermoclineDepth(rate $\geq$ 0.7 °C /m) dataset for the site,
    - if dtdz_max is >= 1.0 °C /m create a record in the ThermoclineDepth (rate $\geq$ 1.0 ^{o}C/m) dataset for the site

3. Predicted thermocline depth (to be done)– estimated based on lake morphometry from the equation developed in: Gorham, E. and F.M. Boyce, 1989. Influence of lake surface area and depth upon thermal stratification and the depth of the summer thermocline. Journal of Great Lakes Research, 15(2): 233-245.

V. Depth strata

- After data were manually reorganized and sorted into spreadsheets, a computer program was developed to automate the computation of depth stratum mean values, tabulation of data summaries, graphical presentation, and export to trend analysis software. Each parameter from each site was averaged for all sampling dates and sampling periods for the following depth strata; 0m (surface values), 0-2m, 3-5m, 6-8m, 9-11m, 12-14m, 15-19m, 20-24m, 25-29m, 30-34m, 35-39m, 40-49m, 50-59m, 60-69m, 70-79m, 80plus. Strata were chosen for limnological reasons as well as based on data availability for the deeper strata. The statistics for each layer were calculated using the average of the daily averages of the result values within each time period.

VI.Time intervals

- Since there are many periods of interest for these data, we performed trend analyses for a variety of periods that could be used to characterize a particular year. For example, the MPCA has long requested Citizen Lake Monitoring Program (CLMP) volunteers who have collected most of Minnesota's long-term Secchi disk water clarity data to take their measurements from June 15 – September 15. Therefore, all data within this time frame can be averaged to generate a single value for a particular year.

- Alternatively, a set of monthly or bimonthly mean values can be calculated and then analyzed singly for the year, or considering their within-year variation. A monthly average for August, when algal biomass is usually thought to be at its peak, would be useful to examine in comparison to weather patterns either at that time or perhaps over a longer period to include the contribution of spring runoff to the lake's nutrient loading.

- The statistical analysis software described below also permits the user to select a single period to characterize a year (e.g. the mean of data from the period Jun 15 – Sep 15 for each year), and also incorporate the variability from sub-periods within that period that are defined as "seasons". For example, each year can be characterized by its mean (or median) parameter value for the MPCA field season defined as all data from June 15 - September 15. Or, the variation from three separate month-long seasons from June15-July 15, July16 - August 15, and August 16 - September 15) can be identified and incorporated into the statistical analysis.

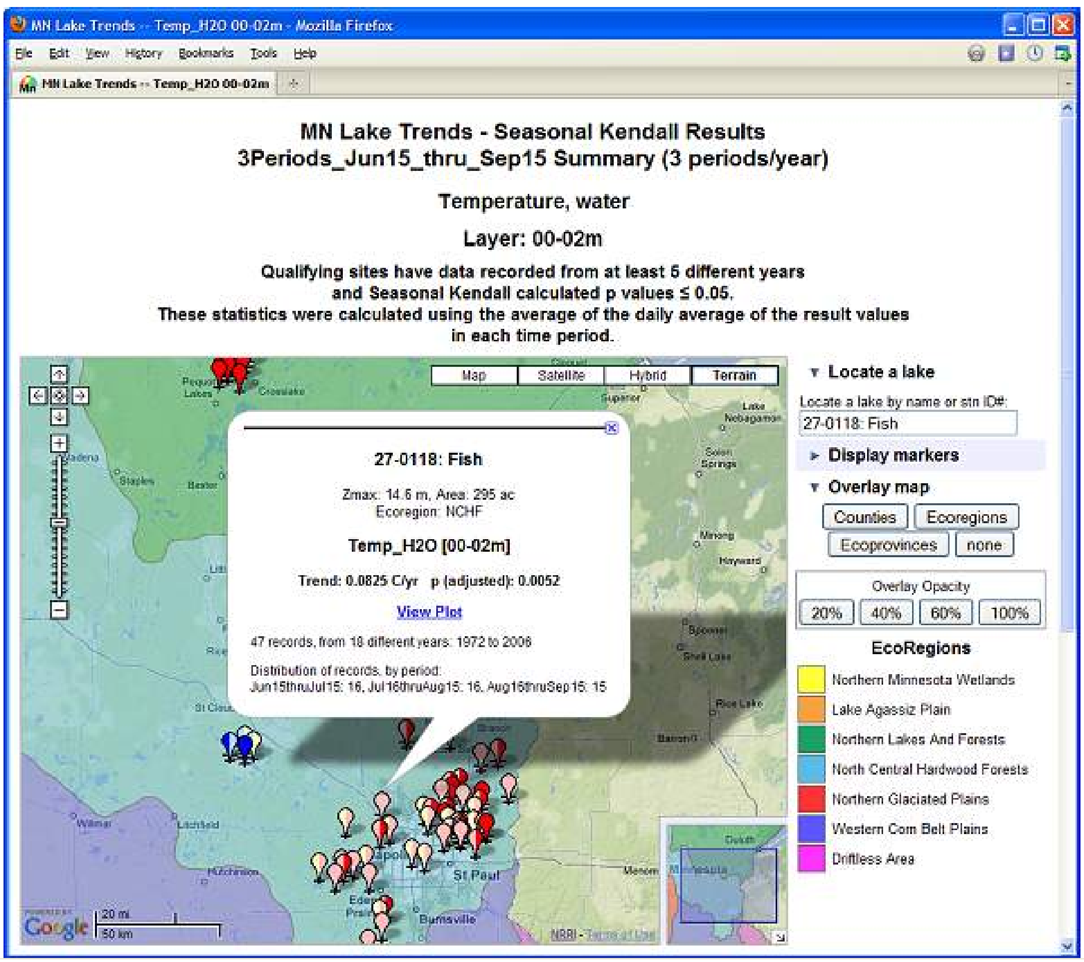
VII. Trend analyses

Trends and trend rates were determined using the Seasonal Kendall Trend Analysis software developed by the U.S. Geological survey (2005; Computer Program for the Kendall Family of Trend Tests, Dennis R. Helsel, David K. Mueller, and James R. Slack SIR 2005-5275, U.S. Geological Survey) that allow for trend analyses both seasonally and regionally. Sites were initially identified sites as "Qualifying" if they had records from at least 5 different years and with a level of significance of $p \leq 0.1$ for either a positive or negative trend over time. Additional exploratory trend summaries with accompanying mapping tools were generated for $p \leq 0.05$ and lakes having more years of data (8, 12 and $\geq$18 years).

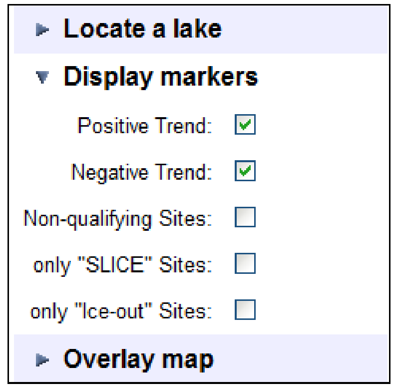
- Minnesota Lake Trends Analyses website*: http://mnbeaches.org/gmap/trends/*
- The USGS report "Computer Program for the Kendall Family of Trend Tests" and the computer program is available at *http://pubs.usgs.gov/sir/2005/5275/*

VIII. Graphical and tabular displays

- Data tabulated in *csv* format for easy import to spreadsheet and database software
- Data have been incorporated into "*Master*" NRRI-UMD Climate Change Database for association with other Project variables and use by other scientists
- Statewide distribution of lakes with statistically significant trends (e.g. p < 0.1 with >5 years of data) are denoted as tear drop shaped markers on a zoomable and scrollable map of Minnesota. Red denotes an increasing trend and blue a decreasing trend with half-tones to show the magnitude of the gradient for each plot based on quartiles for that plot. Levels of significance are shown as "hash" marks across the bottom of the tear drop.

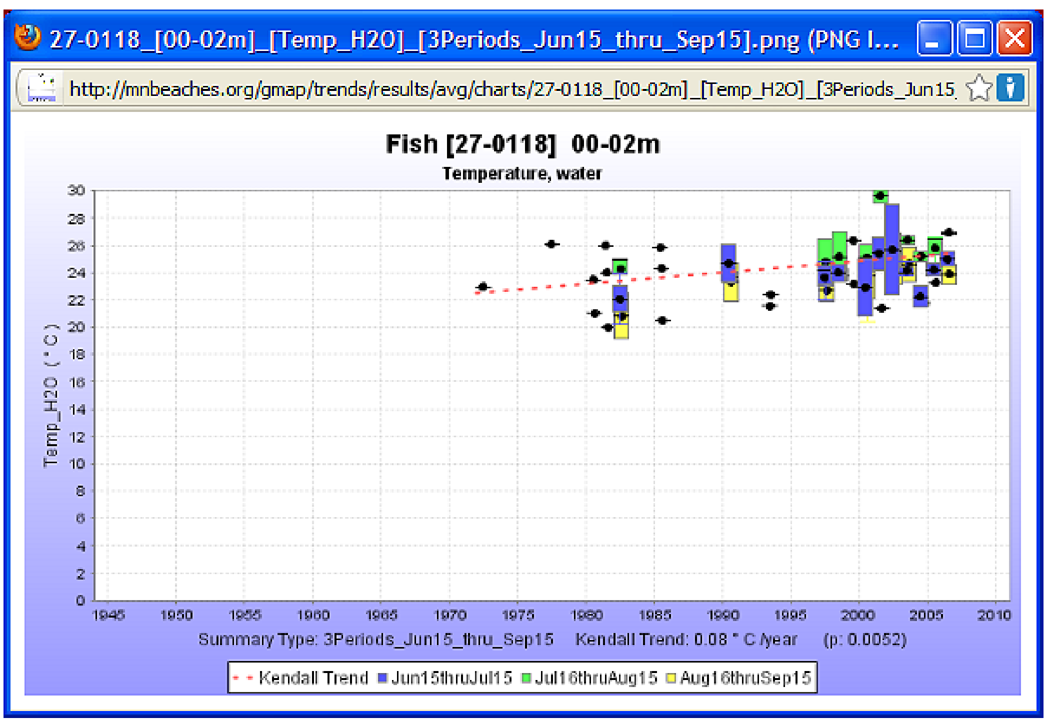


1. **Locate a Lake** is a search tool available for finding individual lakes by Lake Name or MDNR DOW #

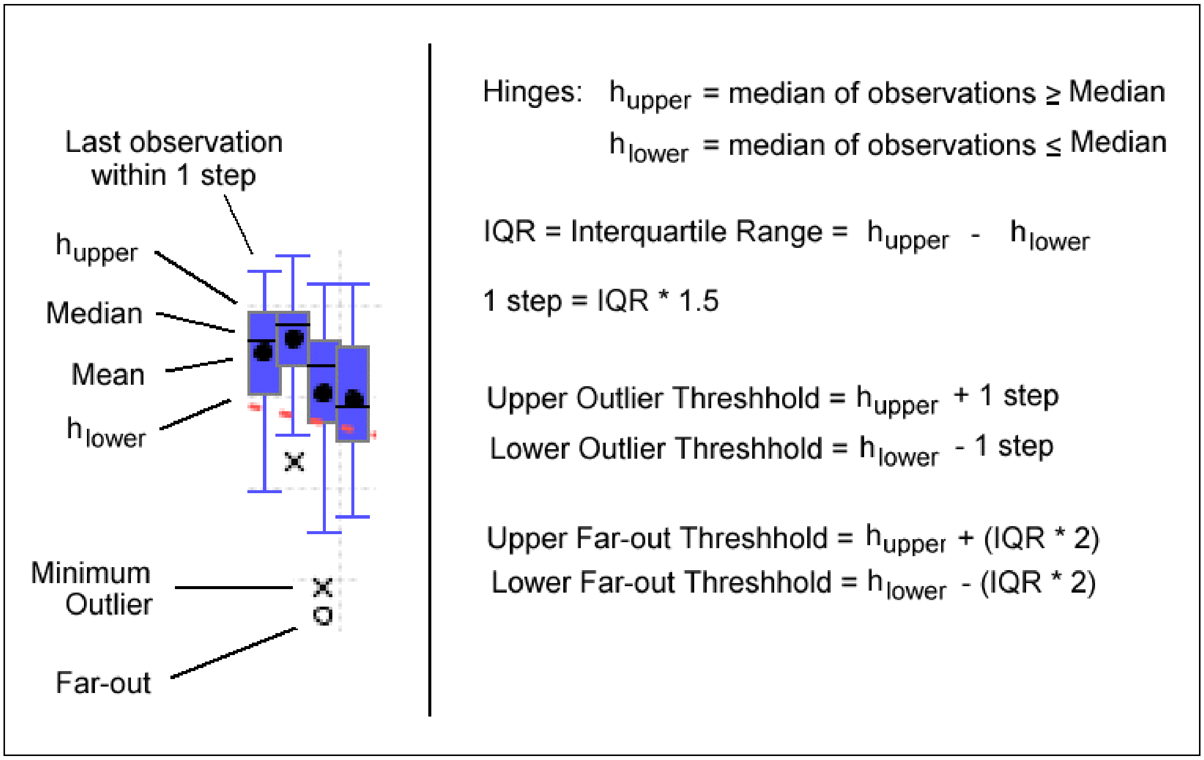


2. **Display Markers** offers choices for displaying markers on the map. Positive and negative trend sites were statistically significant; non-qualifying sites were not statistically significant or did not have data from enough years; "SLICE" sites refers to the 24 lakes from the MN DNR Sustaining Lakes in a Changing Environment (SLICE) project that includes a focus on monitoring basic watershed, water quality, habitat, and fish indicators in 24 sentinel lakes across a gradient of ecoregions, depths, and nutrient levels. "Ice-out" lakes refers to the set of lakes with long-term winter ice records that was compiled for the overarching U of MN Climate Change project.
3. **Overlay map** offers templates for county, ecoprovince and ecoregion boundaries. The data itself is classified in the main project database for these divisions but is not directly retrievable as such from the current MN Lake Water Quality Trends website.

- **Trend lines over time** are available by mouse clicking a particular lake on the map for a particular parameter x depth stratum x time period. This opens an information window with the lake name and MDNR DOW #, the trend slope and its significance, depth, area, ecoregion, and a link to open a box & whisker plot of the data and the calculated trend line:



- o the data are color-coded and shown for each "season" according to the specific seasonal Kendall analysis.
- o the box and whiskers depict the distributional characteristics of the independent measurements for that period are depicted as for that year



- return to the MN Lake Trends homepage -

Minnesota's Water Resources: Climate Change Impacts

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UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 502

Lake Level Response to Climate in Minnesota

by

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Prepared for
Legislative Citizens Committee on Minnesota Resources
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Abstract

We are interested in the variability of lake levels in Minnesota, and the relationship between lake levels and climate. We analyzed historical water levels in 25 Minnesota lakes. Eight were landlocked lakes and seventeen were flow-through lakes. The data were daily values, but substantial gaps existed. 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.

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 improve 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.

Table of contents

1. INTRODUCTION

In the 1930, during a sequence of warm and dry years, Lake Minnetonka water levels fell to their lowest recorded elevations. Currently Lake Superior is approaching a record low level. At other times lake levels have been above normal levels. We wish to analyze the variability of lake levels in Minnesota, and to examine if there is a relationship with specific climate parameters.

Lake levels show seasonal and long-term fluctuations in response to lake water inputs and outputs. Water inputs to a typical Minnesota lake are by surface runoff (I), precipitation (P), and ground-water inflow (GI); water losses are by surface outflow (O), evaporation (E), and ground-water outflow (GO). The difference between water input and loss rates over a specific time period (Δt) determines the change in lake water volume and hence water level. If all flows are expressed per unit surface area of a lake in units of mm/year, the water level change is given by a water balance equation (Eq. 1) as:

$$\Delta L/\Delta t = P - E + I - O + GI - GO \qquad \text{(Eq. 1)}$$

The complexity of hydrologic processes that control each of the terms in Eq. 1 provides a challenge when the relationship between lake water levels and climate is to be explored. Changes in climatic variables, such as air temperature, relative humidity, and precipitation, can affect all water budget components directly or indirectly, and cause fluctuations in water levels (IPCC, 2001). Although a change in lake water levels can be an indicator of climate change - because of its dependence on precipitation and evaporation - it can also have other causes such as anthropogenic changes in land and water uses. Changes in surface and ground-water flows due to changes in land use or land cover, water diversions and ground-water pumping can affect lake water levels strongly. Outlet control structures can be the most important determinant of level in a regulated lake or impoundment (reservoir).

Although individual water budget components of a lake can provide a picture of the changes in climatic and hydrologic factors over time, it is not always easy to quantify them. For example the identification and measurement of multiple tributaries to a lake can require an extensive amount of time and effort: Sub-watersheds have to be delineated, and runoff from them has to be gauged or modeled. Overland flow may have to be specified. There is usually only one natural outflow from a lake, but multiple man-made withdrawal points may exist. A stage/discharge relationship is required to quantify the outflow rate at any time. Ground-water inflow and/or outflow depends on the hydrogeology of a lake setting, and field or model studies are required to develop at least estimates of the ground-water components in a lake water budget (Winter 1997). Fellows and Brezonik (1980) used a direct measurement technique to estimate seepage from Florida lakes with consolidated sediments and found that shoreline length relative to surface area was related to the relative importance of seepage. In many lake water budget studies, it has been common practice to estimate ground-water flow as the residual of the surface water components (e.g., Watson et al. 2001), or to omit the ground-water components altogether. In a regional assessment of multiple lakes, calculating water balances becomes even more challenging.

The magnitude of errors and uncertainties in lake water budgets is often underestimated. According to a very thorough study by Winter (1981) in New England, South Dakota, and California lakes, errors in measurement and regionalization create significant uncertainties in lake water balances. For example, the error in precipitation inflows can be up to 30% in annual water budgets and 42% in monthly water budgets (Table 1). Ground-water components can include errors over 100%, when estimated as the residual of the water budget (Winter 1981).

Table 1. Errors (percent) in estimation of water budget components with commonly used methodology (reproduced from Winter 1981).

Water Balance Component	Source of Error	Annual Water Balance	Monthly Water Balance
Precipitation	Gage	2	2
	Placement	5	5
	Areal averaging	10	15
	Gage density	13	20
Evaporation	NWS Class A Pan	10	10
	Pan to lake coefficient	15	50
	Areal averaging	15	15
Stream Flow In/Out	Current meter measurement	5/5	5/5
	Stage discharge relationship	20/10	30/10
	Channel bias	5/5	5/5

Mann and McBride (1972) investigated the hydrologic balance of Lake Sallie, in Minnesota. The lake is connected to Detroit Lake and has a significant amount of surface water outflow. Ground-water inflow was determined from flow nets based on weekly measurements in

32 observation wells in the watershed and compared to the residual of the surface-water budget. Based on the precision and adequacy of the data used, 5% error was found in precipitation, surface-water inflow, surface-water outflow, and change in storage components, 10% error was found in evaporation and 30% error was present in ground-water inflow.

The objective of our study is to analyze historical data of lake levels in Minnesota and to explore if and how lake level changes are related to climate. Because lake levels are affected by many factors, the relationship is expected to be strongest when precipitation and evaporation are the most prominent components of the water balance (Eq.1). Levels of "landlocked" (endorheic or closed-basin) lakes with no surface water outflow and stable ground-water levels, can be good indicators of weather (short-term) or climate (long-term). On the other hand, water levels of regulated water bodies with large surface water inflows and outflows such as the Mississippi River impoundments behind Dams 1 to 26 are not expected to be indicators of climate change. Many Minnesota lakes are of glacial origin and hence "natural", but have been fitted with small dams and gates as water level control structures. Such "flow-through" or exorheic lakes, may handle a large range of surface water inflows without an apparent response in water levels. Only exceptionally large floods may cause a water level rise because most control structures operate under a specific stage-discharge relationship. In extended or exceptionally dry weather periods, the water level response of exorheic lakes will be more apparent.

In this study, we analyzed water levels recorded in 8 landlocked lakes and 17 flow-through lakes in Minnesota to identify changes and climate connections in the last century. We examined the full records and 20-year periods of the records to identify long-term and short-term trends in water levels. We also examined the relationships between water levels and climatic variables such as precipitation, air temperature, and dew point temperature.

2. PREVIOUS STUDIES OF LAKE LEVELS IN THE U.S./ MINNESOTA

Lake level trends in 11 northern Wisconsin headwater lakes of the LTER (Long-Term Ecological Research Program) (Trout Bog, Crystal Bog, Crystal Lake, Big Muskellunge Lake, Sparkling Lake, Allequash Lake, Trout Lake) and in five southern Wisconsin lakes (Fish Lake, Lake Mendota, Lake Wingra and Lake Monona) were investigated by Magnuson et al. (2006). Both increasing and decreasing trends were found in the water levels recorded. For example, water levels in Lake Mendota increased by 2.2 cm/decade from 1916 to 2001. Fish Lake showed a rising trend of 73.3 cm/decade from 1966 to 2001. Water levels in Buffalo Lake increased about 3.7 cm/decade from 1943 to 1988. The increase in Fish Lake was found to be related to long-term increases in precipitation and ground-water recharge. The increase in water levels of Lake Mendota was due to a combination of climatic and land use changes (i.e., increases in intense rainfall events and impervious surfaces in the watershed) and water regulation practices. For the 1984-2001 period, water levels in Allequash Lake decreased by 16.5 cm/decade due to water level regulation practices.

Changnon (2004) evaluated the water level fluctuations observed and recorded in Lakes Superior, Michigan-Huron and Erie from 1861 to 2001. The analysis showed that during the 1923-1938 and 1973-2001 periods, climatic changes caused exceptional water level fluctuations in lake levels. After the 1923-1938 period, all lakes except Lake Superior experienced increasing water levels. The cause of this trend was explained to be the wetter and cooler weather conditions in the basins of Lakes Michigan-Huron and Erie since 1935-1940. During the same time period, air temperature increased and precipitation remained stable in the Lake Superior Basin.

Devils Lake, a natural closed-basin lake in northeastern North Dakota, showed a 24.5 ft (7.35 m) water level increase from 1993 to 1999 and was only 13 ft (3.9 m) below its natural spill elevation to the Sheyenne River in 2000 (Wiche and Vecchia 2000). The water level increase was consistent with increases in precipitation since 1990s and a slight decrease in annual average air temperatures since 1980s. Since 2000, the water level in Devils Lake has continued to remain high and reached 24.6 ft (7.38m) above its 1993 level in 2005 (Anonymous 2005).

Brown (1985) investigated the factors that caused an 11 ft (3.3m) rise in water levels in another closed basin lake, Big Marine Lake, Washington County, MN from 1938 to 1983. The analysis showed that increased precipitation and groundwater recharge were responsible for the increase in water levels.

Christensen and Bergman (2005) investigated water level fluctuations in Long Lost Lake, Clearwater County, MN between 1939 and 2001 and reported that they were caused by changes in precipitation, which showed similar fluctuations during the same time period.

Vining (2003) calculated the evaporative losses from three regulated lakes, Lake Ashtabula in North Dakota, Orwell Lake in Minnesota, and Lake Traverse in Minnesota and South Dakota for the 1931-2001 period, and found a downward trend in evaporation rates. The author argued that the trend could be due to drought conditions in the mid 1930s and wet conditions in the late 1990s.

In summary, most of these studies confirm the expectation that lake water level rise is correlated with a precipitation increase; a decrease in evaporation rate which depends on climate parameters such as dew point and wind speed may be a significant contributing factor. In regulated lakes the relationship between lake level and climate parameters is less evident.

3. CLIMATE OF MINNESOTA

3.1. Seasonal and geographic climate parameter distributions

Climatic and hydrologic parameters have been recorded in Minnesota over approximately a century. Precipitation, air temperature, dew point temperature and pan evaporation are climatic parameters of particular interest for a lake level study. An example of the seasonal distribution of these parameters is given in Figure 1. The precipitation, air temperature, and dew point were recorded at the Minneapolis/St. Paul Airport (downtown Minneapolis prior to 1938) and pan evaporation data were collected at the St. Paul Climatological Observatory. Monthly precipitation is highest in June and about two-thirds of the total annual precipitation occurs between May and September. Average annual precipitation for the 1891-2006 period was 700 mm (27.5 in). Pan evaporation is highest during July and about twice as large as precipitation from May to September. Average pan evaporation for May-September was 857 mm (33.7 in) for the period 1972-2006. Average daily air temperature between 1891 and 2006 was 7.3°C (45.2°F). Average daily temperature from June to September was 20.2°C (68.4°F), highest in July 22.9°C (73.2°F). Dew point temperature followed the same seasonal pattern as air temperature.

Precipitation and mean daily temperature data collected at International Falls, Detroit Lakes, and Fairmont (Figure 2) were assembled to illustrate geographic differences in these parameters throughout Minnesota. Data was available for the 1948-2006, 1896-2006, and 1931-2006 periods, respectively. International Falls is located on the northern Minnesota border with Canada at 49^o latitude, Detroit Lakes is located in the western portion of central Minnesota, and Fairmont is in south-eastern Minnesota between 44^o and 45^o latitude. Air temperature and precipitation increase going towards southern Minnesota (Figure 2). Average annual air temperature was 2.8°C (37.1°F), 4.2°C (39.5 °F), 7.3°C (45.2 °F), and 7.6°C (45.8 °F) at International Falls, Detroit Lakes, Minneapolis and Fairmont, respectively. Average annual precipitation was 617 mm (24.3 in), 630 mm (24.8 in), 700 mm (27.6 in), and 761 mm (30.0 in) at those same locations, respectively.

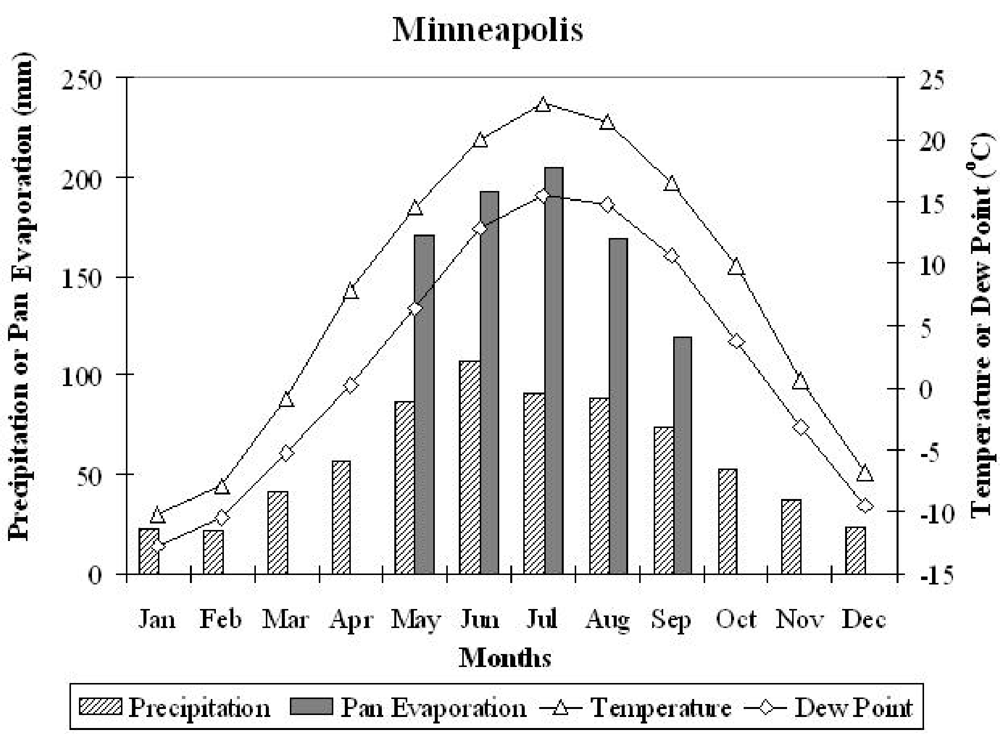

Figure 1. Average monthly precipitation, pan evaporation, air temperature and dew point temperature for Minneapolis/St. Paul, MN (1 in = 25.4 mm and ^{o}F = 1.8 x ^{o}C + 32) (data from: http://www.climate.umn.edu/ and http://www.ncdc.noaa.gov/oa/ncdc.html).

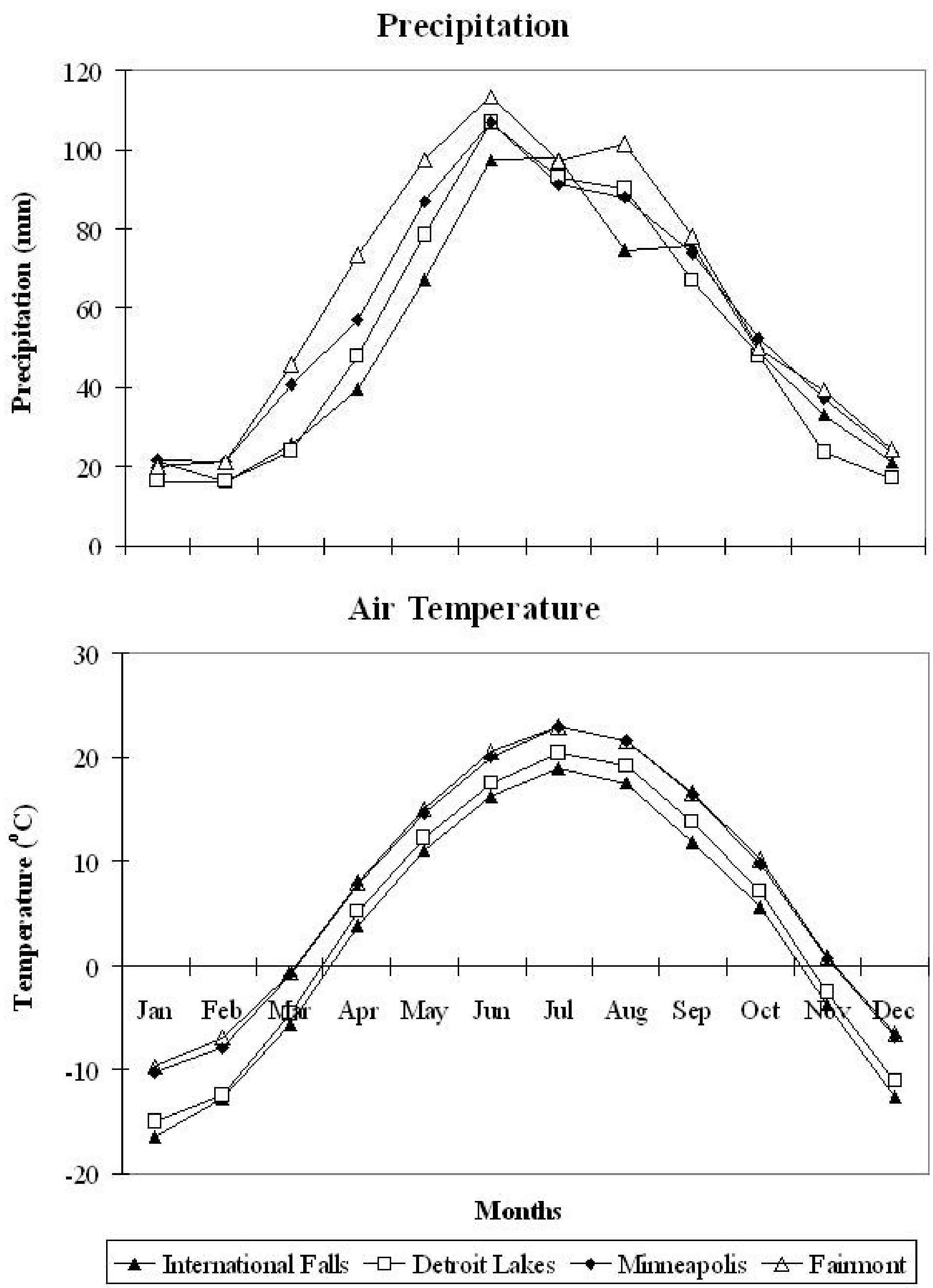

Figure 2. Average monthly precipitation and air temperature at International Falls, Detroit Lakes, Minneapolis, and Fairmont, MN (1 in = 25.4 mm and $^oF = 1.8 \times {}^oC + 32$) (data from: http://www.ncdc.noaa.gov/oa/ncdc.html).

3.2. Observed climatic and hydrologic changes in Minnesota

Seeley (2003) found that Minnesota is now having warmer winters, higher minimum temperature, higher frequency of tropical dew points, and greater annual precipitation.

Air temperature and precipitation showed raising trends of 2-3 °C/100 years and 5-10%/100 years , respectively, in Minnesota, from 1900 to 1994 (Gleick 2000). The average precipitation and daily temperature in Detroit Lakes, MN and Minneapolis, MN for the1903-1922 and 1987-2006 periods are given in Figure 3. Annual average precipitation increased about 24 mm (0.94 in from 25.47 to 26.41 in) and 25 mm (0.97 in from 29.04 to 30.01 in) in Detroit Lakes and Minneapolis, respectively. Precipitation increased particularly during spring and fall in Detroit Lakes and during summer in Minneapolis. Average annual temperature also increased 2.34 °C (4.21 °F from 38.04 to 42.25 °F) in Detroit Lakes and 1.03 °C (1.9 °F from 44.5 to 46.4 °F) in Minneapolis. Average daily temperatures in all months in Detroit Lakes and all months except October in Minneapolis became higher.

Pan evaporation data were available for only two locations in Minnesota: Minneapolis (1972-2006) and Waseca (1964-2002). Despite the increases in air temperatures, pan evaporation rates in both locations showed decreasing trends for the given periods. The trend was -6.21 mm/yr (0.25 in/yr) for Minneapolis and -0.99 mm/yr (0.04 in/yr) for Waseca.

The effects of a changing climate have been observed in Minnesota's water resources. Changnon and Kunkel (1995) found upward trends in flood flows that occur in the warm-season (May-November) and in the cold-season (December-April). Heavy-precipitation events in Minnesota (e.g., 7-day precipitation events qualifying at the 1-yr recurrence level) from 1921 to 1985 according to Changnon and Kunkel (1995). Johnson and Stefan (2006) found earlier ice-out dates and later ice-in dates in Minnesota lakes. They also showed that first stream runoff due to snowmelt is occurring earlier and stream temperatures are rising. They concluded that all these changes are well correlated with air temperatures. Novotny and Stefan (2007) found significant trends in seven stream-flow statistics including mean annual flow, peak and low flows, high and extreme flow days, and strong correlations between mean annual stream flows and total annual precipitation.

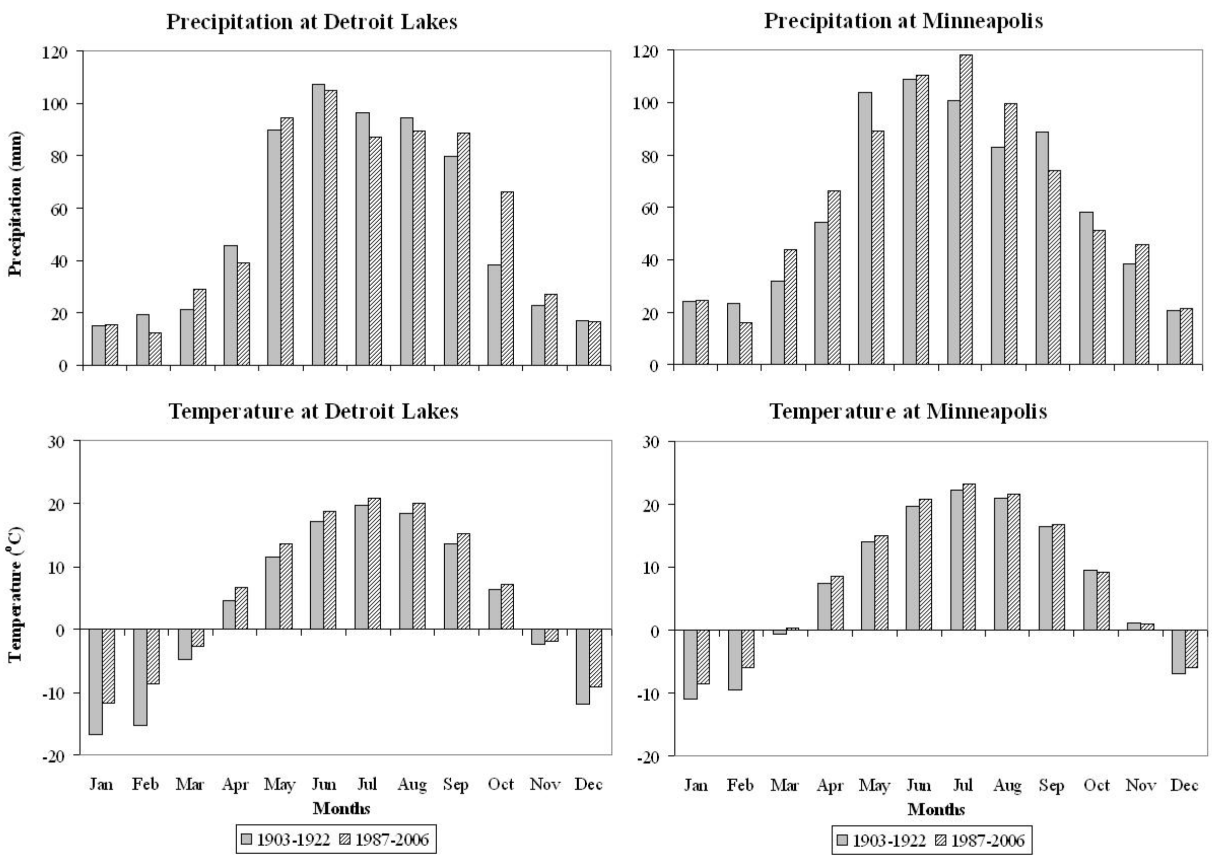

Figure 3. Average precipitation and temperature for Detroit Lakes and Minneapolis, MN for 1903-1922 and 1987-2006 (data from: http://www.ncdc.noaa.gov/oa/ncdc.html).

4. LAKE SELECTION FROM MINNESOTA LAKE LEVEL DATA BASE

In this study we evaluated lake levels in Minnesota. There are 11,842 lakes in Minnesota greater than 10 acres in surface area. Unfortunately long-term measurements of water levels are not available for most of these lakes. We obtained the data on lake levels from the Department of Natural Resources (DNR) website. These DNR lake level data are daily visual readings on a lake gauge collected mostly by volunteers who participate in the Lake Level Minnesota program. Currently, the DNR's Division of Waters has a record of water levels (10 or more readings) for about 4000 lakes (DNR-Waters 2005).

We first focused on closed or landlocked lakes because they have no surface water outflows and are therefore better indicators of climatic changes due to a strong dependence of water levels on water inflows and evaporation (IPCC, 2001). A list of landlocked lakes in Minnesota was obtained from DNR. However, after examination of water-level data, we decided to include all lakes in the analysis because most landlocked lakes did not have long-term records. Although records were available for a significant number of flow-through lakes, their water levels are often controlled by DNR by outlet dams. This means that water levels observed in flow-through lakes are not as reliable as those observed in landlocked lakes.

We followed three steps (criteria) to select lakes for our analysis. We first developed a list of lakes where data collection had started prior to 1957 and extended up to at least 2005. We looked for daily lake level records. All lake-level records had gaps, i.e., the data were non-continuous. In the second step, we therefore identified 40 lakes (20 landlocked lakes and 20 lakes with surface outlets), which provided the longest and most continuous records. In the third step, we selected the lakes which provide at least one data from at least 40 years. Final set of lakes selected for study contained 8 landlocked lakes (Table 2) and 17 flow-through lakes (Table

3). Landlocked lakes had water elevations in the range of 270 – 460 m (900 – 1,500 ft) and flow-though lakes had water elevations in the range of 270 – 550 m (900 – 1,800 ft). Other characteristics of the lakes included in this study are provided in Tables 2 and 3, and their locations are shown in Figure 4.

Period of data record and number of daily lake level data were also provided in Tables 2 and 3, which can provide an idea about the magnitude of the gaps in data. Flow-through lakes had longer and more continuous records than the landlocked lakes. Data from Lake Minnetonka was available for the period 1906-2006 and were mostly continuous (data were available about 50% of the days included in the analysis). Lake Swan (Itaska) and Lake Vermilion had comparatively shorter records but more continuous data (available for about 58% and 68% of the days, respectively) than Lake Minnetonka. Other flow-though lakes had records available in the range of 9-27%. The average data availability for flow-through lakes was 22%. The most continuous record available for landlocked lakes was from Lake Belle Taine (11%) and most sparse data was available for Swan Lake (Nicollet) (1%). The average data availability for landlocked lakes was about 7%. Most records were collected from April to October in both landlocked and flow-though lakes. Landlocked lakes Island and Otter Tail and flow-though lakes Birch, Minnetonka, Mud, Peltier, Swan and Vermilion also had significant amounts of data from the November-March period. Multi-year gaps were present in records of lakes other than Lakes Birch, Height of Land, Minnetonka, Peltier, Pelican, Swan and Vermilion.

Table 2. Landlocked lakes selected for study.

No	Lake ID	Lake name	Location (County)	Period of record	Number of daily lake level data	Surface area (ha)	Littoral area (ha)	Max. depth (m)
1	29014600	Belle Taine	Hubbard	07/20/1935 to 05/18/2007	2,936	480	312	17
2	40012400	Emily	Le Sueur	12/28/1940 to 04/17/2007	1,442	95	67	11
3	62007500	Island	Ramsey	01/01/1924 to 06/30/2006	2,041	24	24	3
4	29015000	Little Sand	Hubbard	05/11/1956 to 05/18/2007	1,828	156	60	24
5	31057100	Loon	Itasca	02/01/1955 to 05/22/2007	1,278	94	19	21
6	56024200	Otter Tail	Otter Tail	07/18/1919 to 04/27/2007	3,004	5,559	2,620	37
7	58006700	Sturgeon	Pine	06/22/1945 to 05/02/2007	575	691	201	12
8	11030400	Swan	Nicollet	11/22/1946 to 04/17/2007	299	3,785	N/A	3

Table 3. Flow-through lakes selected for study.

No	Lake ID	Lake name	Location (County)	Period of record	Number of daily lake level data	Surface area (ha)	Littoral area (ha)	Max. depth (m)
1	41004300	Benton	Lincoln	07/31/1947 to 04/17/2007	2,325	1,157	1,157	3
2	62002400	Birch	Ramsey	06/04/1930 to 04/13/2007	2,537	N/A	N/A	N/A
3	3038100	Detroit	Becker	08/25/1943 to 05/17/2007	3,625	1,249	767	27
4	18029800	East Fox	Crow Wing	04/22/1937 to 05/15/2007	2,401	97	41	20
5	30013600	Green	Isanti	06/22/1937 to 04/20/2007	2,407	325	145	9
6	3019500	Height of Land	Becker	03/24/1938 to 05/16/2007	3,004	1,426	1,292	6
7	19002600	Marion	Dakota	05/03/1946 to 04/16/2007	2,963	227	184	6
8	27013300	Minnetonka	Hennepin	05/30/1906 to 04/18/2007	18,616	5,672	2,369	34
9	61013000	Minnewaska	Pope	05/29/1935 to 04/25/2007	2,860	2,880	867	10
10	34015800	Mud	Kandiyohi	12/02/1945 to 04/26/2007	3,735	939	939	4
11	18030800	Pelican	Crow Wing	11/29/1933 to 05/04/2007	3,125	3,342	1,584	32

12	2000400	Peltier	Anoka	04/02/1951 to 04/10/2007	5,584	188	167	5
13	56014100	Rush	Otter Tail	06/26/1934 to 04/27/2007	3,195	2,162	1,347	21
14	51004600	Shetek	Murray	11/05/1926 to 04/13/2007	3,245	1,456	1,456	3
15	31006700	Swan	Itasca	09/21/1937 to 05/31/2007	14,881	1,001	205	20
16	70007200	Upper Prior	Scott	04/04/1906 to 04/05/2007	4,188	143	133	15
17	69037800	Vermilion	St Louis	10/03/1950 to 05/31/2007	14,097	16,426	6,077	23

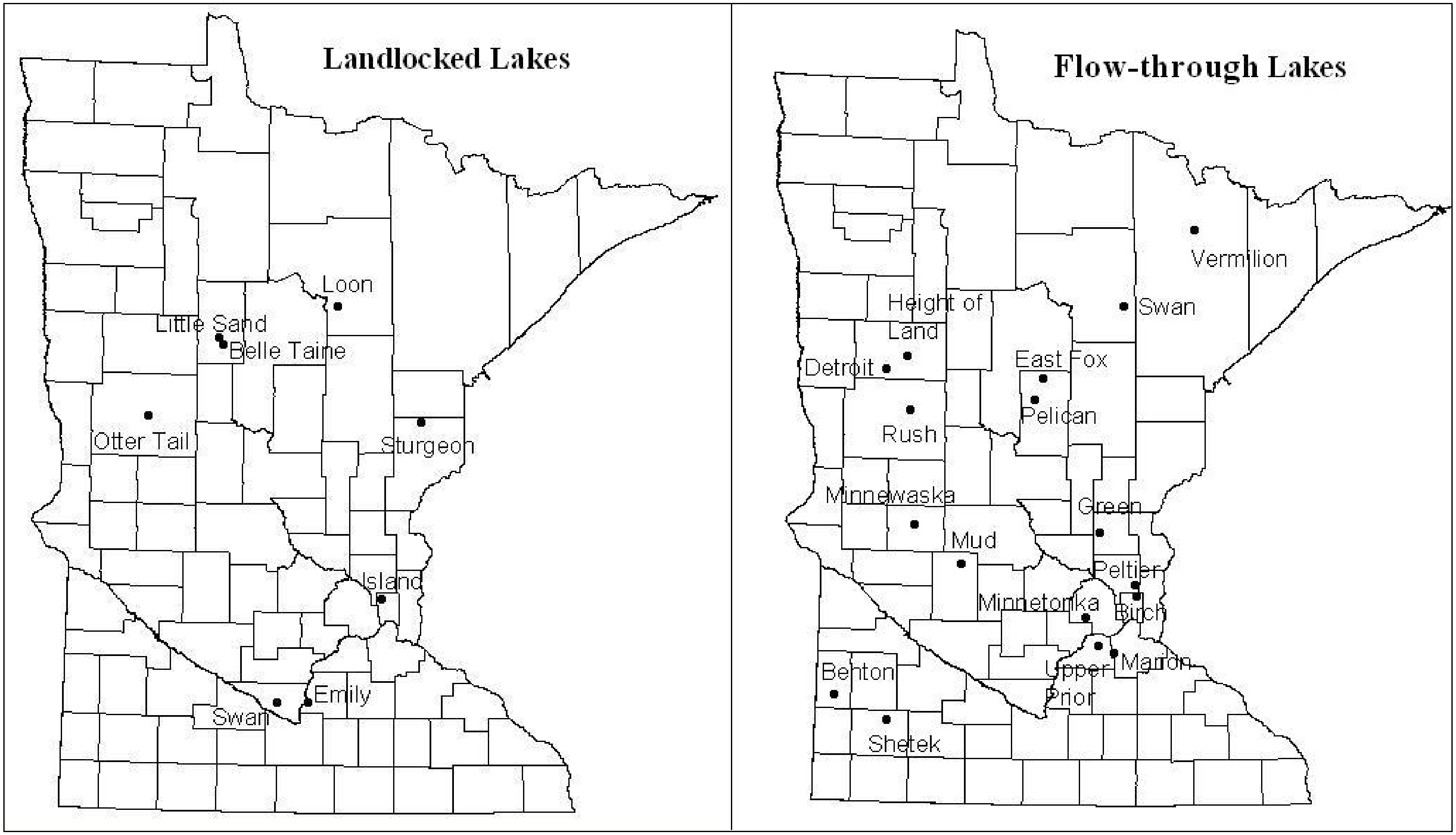

Figure 4. Location of lakes selected for study.

5. METHODS OF ANALYSIS

In this study we analyze records of lake levels and climate parameters to determine a) statistical characteristics of Minnesota lake levels, b) trends in Minnesota lake levels, and c) relationship between lake levels and climate parameters.

5.1. Statistical characteristics

The standard parameters (means, standard deviations, maxima and minima, ranges, etc.) were determined for lake levels at daily and annual timescales for the full records, 20-year periods and selected months.

5.2. Trend Estimation

We used linear regression to test the trends in daily water levels. Although daily time series had significant amounts of missing data, linear regression provided meaningful estimates of trends in lake water levels. Linear regression was used because it provides a good visual presentation (Svensson et al. 2005). We accepted that the linear trends are significant when $p<0.01$.

The Mann-Kendall test (Mann 1945, Kendall 1975) was used to test trends in annual average lake levels, spring lake levels (May), and fall lake levels (October).

The Mann-Kendall test is a non-parametric test which has been used widely for detection of trends in hydrologic data (e.g., Lins and Slack 1999, Abdul Aziz and Burn 2006, Cengiz and Kahya 2006, Novotny and Stefan 2007). The first step in this test is the estimation of the test statistic, S:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i) \qquad \text{(Eq 2)}$$

In Eq. 2, x denotes the data values, n denotes the length of the record and the sgn function is defined as:

$$\text{sgn}(\theta) = \begin{cases} 1 \ if \ \theta > 0 \\ 0 \ if \ \theta = 0 \\ -1 if \ \theta < 0 \end{cases} \qquad \text{(Eq 3)}$$

The S statistic is normally distributed when n>0. Mean (μ) and variance (σ) of S are given in Eqs. 4 and 5.

$$\mu = 0 \qquad \text{(Eq 4)}$$

$$\sigma = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i i(i-1)(2i+5)}{18} \qquad \text{(Eq 5)}$$

where t_i is the number of ties of extent i.

A test statistic Z is estimated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\sigma}} if \ S > 0 \\ 0 \quad if \ S = 0 \\ \frac{S+1}{\sqrt{\sigma}} if \ S < 0 \end{cases} \qquad \text{(Eq 6)}$$

We accepted that Z is significant when p<0.01.

We also estimated Sen's slope (Sen 1968) for these parameters. Sen's slope provides a measure of the slope if a trend is present in data. It is also a non-parametric method and works well with time series with missing data. Sen's slope can be found as the median of the slopes calculated from all pairs of values in the data series using Eq. 7.

$$Q_i = \frac{x_j - x_k}{j-k} \text{ for } i=1 \text{ to } N \qquad \text{(Eg 7)}$$

In Eq. 7, N is the number of data pairs, x_j and x_k are the data values at times j and k, respectively, where j is greater than k.

5.3. Correlations of lake levels with climate parameters

Correlation coefficients were calculated to explore the relationships between water levels and climate variables. Climatic variables that are directly related to water levels include precipitation, air temperature, dew point temperature, wind speed, solar radiation, and pan evaporation. Precipitation is not only a direct input to a lake, but also affects surface and ground-water flows. Several other variables determine jointly the amount of evaporation from a lake, which is often the most significant water loss component in the lake water balance. In this study we included only precipitation, air temperature and dew point temperature in the correlation analysis considering that solar radiation is directly related to air temperature and changes in average wind speed are small compared to the changes in other variables. We could not use pan evaporation data (which is a direct measure of evaporation from the lakes) in the correlation analysis because pan evaporation data were available only for two locations (Minneapolis and Waseca) for a short time period (1972-2006 and 1964-2002) and on a monthly time scale.

Because several climate parameters influence a lake's water balance, single variable regression is not the best approach for the analysis of lake levels in relation to climate. We pursued a multiple variable regression analysis by first examining the basic deterministic relationships between climate parameters and the water budget components. We then formulated appropriate regression equations, and finally estimated parameter values by analysis of the data. If Eq. 1 is rewritten, we obtain the following equation. The components labeled 1,2,3,4, and 5 on the right-hand side of Eq. 8, denote precipitation, evaporation, surface runoff, surface outflow, and net ground-water flow, respectively.

$$(\Delta L / \Delta t)\, A = [p\, A] - [N\, (R_w T_a - T_d) W] + [p\, C\, A_b] - [K\, w\, (L - L_b)^{3/2}] + T\, W_a\, (L - L_a)/d \qquad \text{(Eq 8)}$$

1 **2** **3** **4** **5**

where

A = lake surface area, m^2

p = rainfall intensity, m/d

W = wind speed above water surface (m/s)

T_a = air temperature

T_d = dewpoint temperature

R_w = the ratio of water temperature to air temperature (assumed to be 0.82 from stream water/air temperature relationships)

C =runoff coefficient, (dimensionless)

A_b = basin area = m^2

K = weir coefficient

w = outflow channel width, m

L = lake water level, m

L_b = water level at which outflow starts, m

T = transmissivity

W_a= aquifer width, m

L= water level at the lake, m

L_a = ground-water level at distance d

d = horizontal distance, m

Because no information on the parameters in terms 3, 4, and 5 was readily available for most lakes, we formulated the final equation as below and estimated coefficients X and Y.

$$(\Delta L / \Delta t) = X\, [p] - Y[(R_w T_a - T_d) W] \qquad \text{(Eq 9)}$$

6. RESULTS

6.1. Statistics of daily water level records of 25 Minnesota lakes

The recorded daily water levels for the lakes investigated have been plotted in Figure 5 for landlocked lakes and in Figure 6 for the flow-through lakes. The period of record is given in Table 1 and reached back to at least 1957 for all lakes, and as far as 1919 (Otter Tail) for landlocked lakes and 1906 (Minnetonka) for flow-through lakes.

One can see in Figures 5 and 6 that there were significant reversals in lake water levels within the period of record. All landlocked lakes whose records went back to the period 1930-1940 had their lowest water levels between 1930 and 1940 (Table 4). Six of the 10 flow-though lakes whose records start earlier than 1940 had their lowest water levels also between 1930 and 1940 (Table 5). The highest water levels in five of the landlocked lakes and 11 of the flow-through lakes were recorded after 1990 (Tables 4 and 5).

All but three lakes showed at least 1 m fluctuation over their entire record (Tables 4 and 5). The largest fluctuation over the entire record in landlocked lakes was observed in Lake Belle Taine (4.38 m) and the largest fluctuation in flow-through lakes was in Marion Lake (4.03 m). Although histogram of daily lake levels could provide us information about the distribution of water levels, we could not prepare histograms, since significant amounts of data were missing and majority of the data were collected during certain periods (April-October).

Table 4. Highest and lowest recorded lake levels and their dates for landlocked lakes

Lake Name	Highest Recorded	Highest Recorded	Lowest Recorded	Lowest Recorded	Range of fluctuations

	Value	Date	Value	Date	for entire record (m)
Belle Taine	435.79	6/14/2001	431.42	11/4/1936	4.37
Emily	296.83	7/1/1993	294.59	12/28/1940	2.24
Island	288.87	8/11/1993	286.02	8/1/1931	2.85
Little Sand	435.82	6/14/2001	434.76	10/8/1976	1.06
Loon	389.52	5/12/1980	388.42	7/29/1975	1.10
Otter Tail	403.04	5/16/1999	401.63	12/18/1934	1.41
Sturgeon	326.17	10/10/1986	324.94	9/15/1977	1.23
Swan (Nic)	299.41	5/5/1969	296.48	8/17/1989	2.93

Table 5. Highest and lowest recorded lake levels and their dates for flow-through lakes

Lake Name	Highest Recorded Value	Highest Recorded Date	Lowest Recorded Value	Lowest Recorded Date	Range of fluctuations for entire record (m)
Benton	533.40	4/16/1993	531.58	4/18/1977	1.82
Birch	280.81	4/17/1952	278.63	6/4/1930	2.18
Detroit	407.15	6/28/1998	406.40	9/13/1970	0.75
East Fox	384.33	6/9/2005	383.51	8/10/1976	0.82
Green	281.79	5/1/2001	280.29	7/25/1958	1.50
Height of Land	443.88	8/6/1993	442.52	2/20/1940	1.36
Marion	300.08	7/6/1993	296.06	5/25/1964	4.02

Minnetonka	283.62	9/7/2002	280.96	12/13/1937	2.66
Minnewaska	347.37	6/2/1972	344.32	5/29/1935	3.05
Mud	367.41	9/20/1991	365.18	12/2/1945	2.23
Pelican	368.13	6/26/2001	366.74	3/13/1935	1.39
Peltier	270.24	7/3/1975	267.30	2/2/1960	2.94
Rush	403.58	8/31/1993	402.40	1/26/1944	1.18
Shetek	453.20	4/10/1969	450.86	11/21/1952	2.34
Swan (Itasca)	407.94	5/15/1950	406.52	9/19/1944	1.42
Upper Prior	276.05	7/20/1983	272.33	10/25/1940	3.72
Vermilion	414.30	5/28/2001	413.33	11/16/1976	0.97

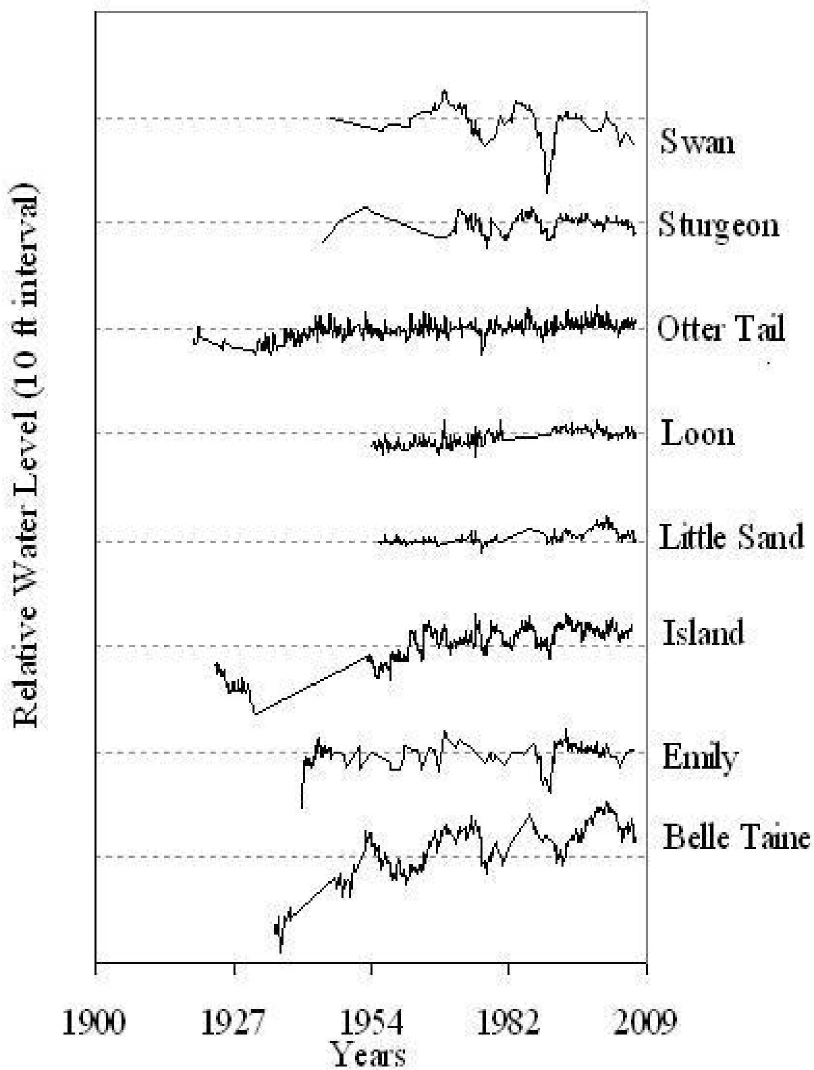

Figure 5. Daily water level data in landlocked lakes.

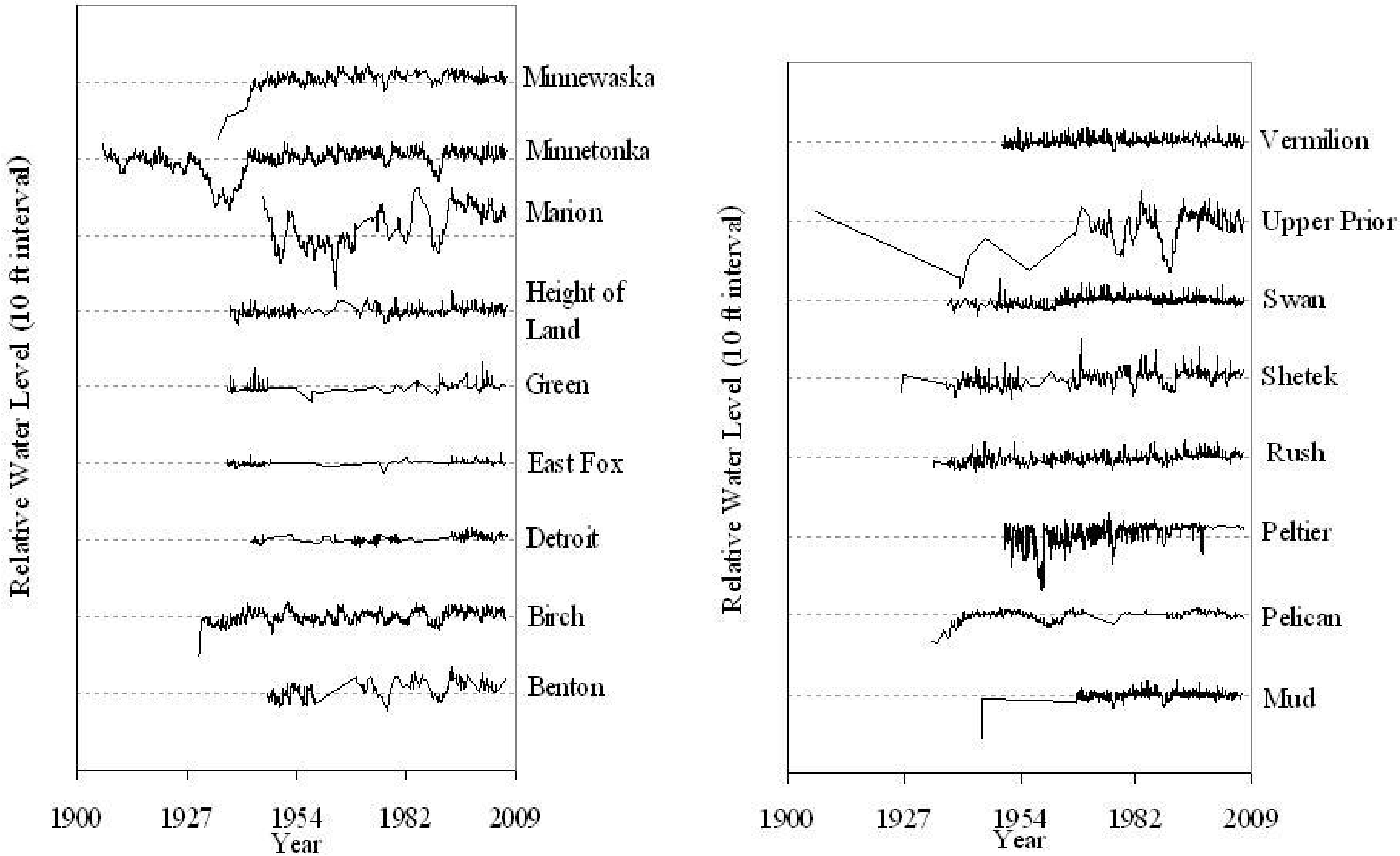

Figure 6. Daily water level data in flow-through lakes.

6.2. Seasonal water level fluctuations in 25 Minnesota lakes

Water levels in Minnesota's lakes typically rise during spring and early summer, then fall during mid-summer and early fall, and remain low and stable during winter (Rosenberry et al. 1997). The rise in early spring is due to snowmelt and spring rainfall as well as lack of evaporation due to low lake and temperatures. During mid summer and early fall, precipitation has usually been low and evaporation has been high due to dry air and high water temperatures. During winter, ice covers and low air temperatures inhibit evaporation and precipitation is in the form of snow.

The eight landlocked lakes included in this study showed the seasonal pattern described by Rosenberry (Figure 7). In the 8 landlocked lakes peak water levels occurred between May and July (five in May). Water levels decreased during fall, and minimum water levels in landlocked lakes occurred between November and February. The seasonal patterns in all lakes were similar.

Water levels in 17 flow-through lakes seem to peak about one month earlier in the season (Figure 8) than in landlocked lakes. Flow-through lakes reach their highest water levels between April and July (seven in April, only one in July). The minimum water levels in flow-through lakes are observed between October and March (13 between Dec and Feb).

The values plotted in Figures 7 and 8 are monthly averages over the period of record. Average standard deviations of average monthly lake levels from the record mean were in the range of 0.18-0.81 m (0.60-2.66 ft with an average of 1.31 ft) for landlocked lakes and 0.06-0.79 m (0.21-2.60 ft with an average of 0.87 ft) for flow-through lakes. The medians of average standard deviations were in the range of 0.19-0.83 m (0.61-2.73 ft) and 0.06-0.79 m (0.21-2.58 ft), respectively. These results indicate that landlocked lakes had larger fluctuations in monthly lake levels from year to year than flow-through lakes. This is not unexpected. Largest standard deviations were observed in Lake Belle Taine (landlocked) and Lake Marion (flow-through).

Average annual (water year) fluctuations in most landlocked and flow-through lakes were calculated by DNR (DNR-Waters 2005) and given in Table 6. Average of average annual fluctuations was 0.35 m for landlocked lakes and 0.45 m for flow-through lakes. This shows that flow-through lakes show larger fluctuations in levels than landlocked lakes in a water year. Largest annual fluctuation in landlocked lakes was observed in Lake Island (0.46 m) and largest annual fluctuation in flow-through lakes was in Upper Prior Lake (0.70 m).

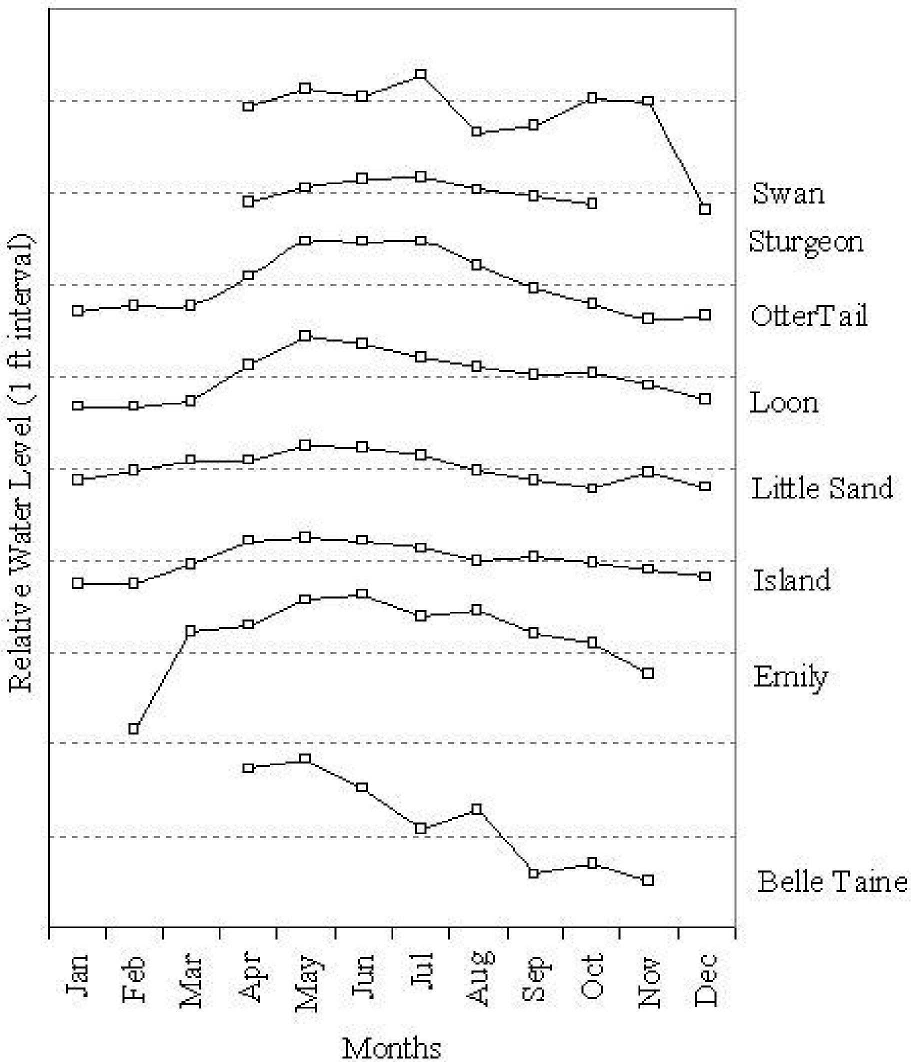

Figure 7. Seasonal water level fluctuations in eight landlocked Minnesota lakes (1 ft = 0.305 m)

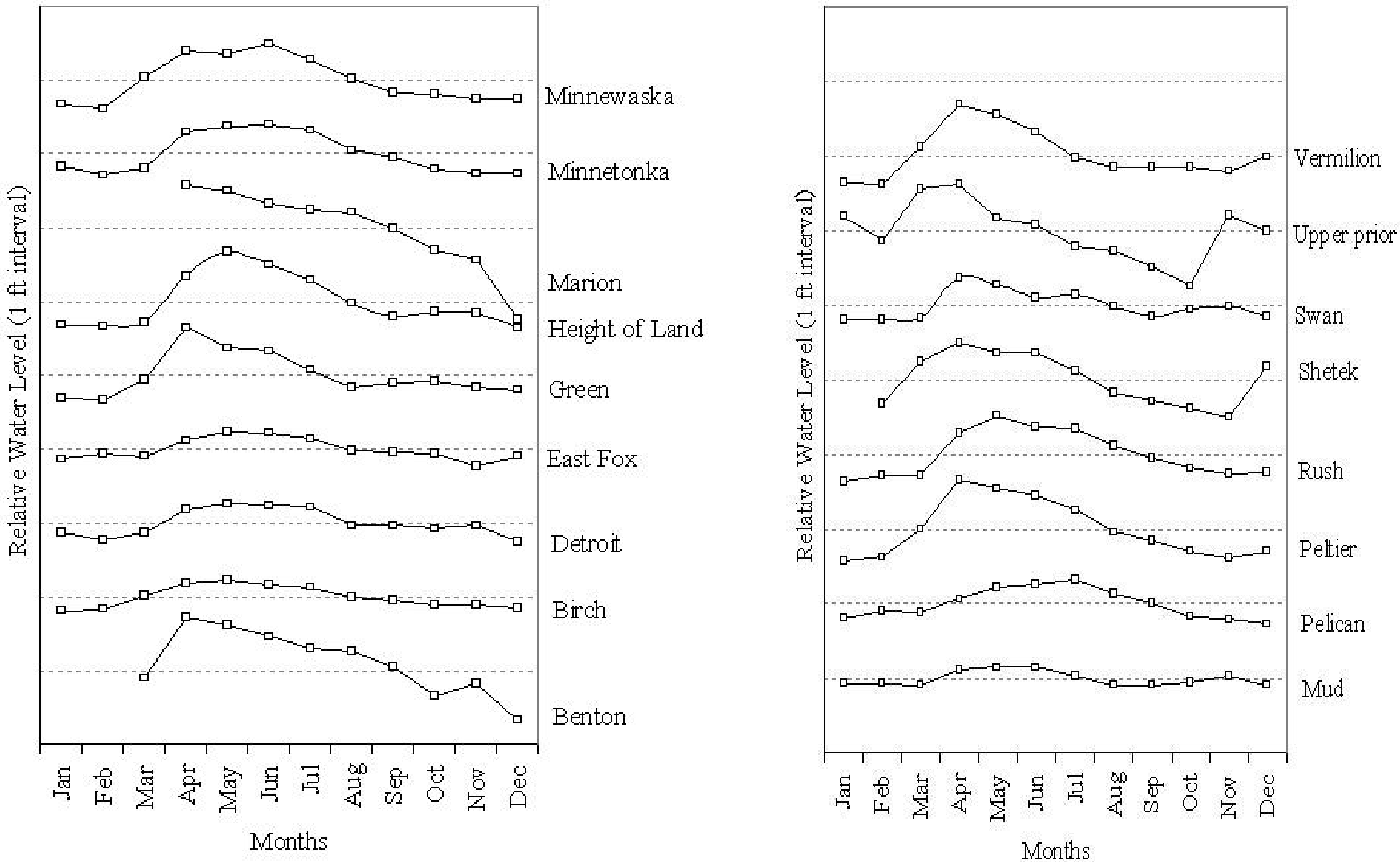

Figure 8. Seasonal water level fluctuations in 17 flow-through lakes in Minnesota. (1 ft = 0.305m)

Table.6. Range and average of annual fluctuations in landlocked and flow-through lakes (from DNR-Waters, 2005)

Landlocked Lakes				Flow-through Lakes			
Lake name	**Average annual fluctuations (m)**	**Range of annual fluctuations (m)**	**Number of water years**	**Lake name**	**Average annual fluctuations (m)**	**Range of annual fluctuations (m)**	**Number of water years**
Belle Taine	0.41	4.38	51	Benton	0.46	1.82	30
Emily	-			Birch	0.41	2.17	75
Island	0.43	2.84	59	Detroit	0.29	0.74	26
Little Sand	0.22	1.06	31	East Fox	0.17	0.71	24
Loon	0.31	1.10	40	Green	0.46	1.50	22
Otter Tail	0.43	1.41	75	Height of La	0.46	1.36	47
Sturgeon	0.27	1.23	28	Marion	0.63	4.03	46
Swan (Nic)	-			Minnetonka	0.45	2.66	99
				Minnewaska	-		
				Mud	0.40	2.23	37

				Pelican	0.26	1.39	48
				Peltier	-		
				Rush	0.46	1.18	65
				Shetek	0.62	2.34	55
				Swan (Itasca)	0.46	1.42	56
				Upper Prior	0.70	3.72	33
				Vermilion	0.48	0.97	54
Average	**0.35**	**2.00**		**Average**	**0.45**	**1.88**	

6.3. Trends of daily water levels in 25 Minnesota lakes

There are thousands of lakes in Minnesota. We only had long enough records for 25 of these lakes, a very small sample indeed. Trends in these 25 lakes were estimated by applying a linear regression method to the entire water level records, and to the last 20-year segment (i.e.,1987-2007) of the record. The complete period of record for each lake is given in Table 1 and reached back to at least 1957 for all lakes, and as far as 1919 (Otter Tail) for landlocked lakes and 1906 (Minnetonka) for flow-through lakes. The trends in the last twenty years of record (1987-2007) are of particular interest for the study of climate change effects on lake levels.

All of the 8 landlocked lakes, except Swan Lake in Nicollet County had a rising water level trend in the long-term, i.e., over the period of record. In the last 20 years (1987-2006) all landlocked lakes, except Emily and Loon, showed rising lake level trends also (Table 7). The calculated trends for all landlocked lakes, except Sturgeon Lake, were significant at the 0.01 level. Swan Lake and Lake Emily, located in close proximity show water level patterns in the last 20 years that are somewhat different from the long-term pattern (Figure 5 and Table 6).

All of the 17 flow-through lakes investigated, except Swan Lake (Itasca), showed rising water levels (increasing trends) throughout their period of record (Table 8). With the exception of Detroit Lake, Height of Land Lake and Lake Minnewaska all flow-through lakes also showed increasing lake level trends in the last 20 years.

Of the 8 landlocked lakes Belle Taine in Hubbard County had by far the strongest upward water level trend (0.033 m/yr) and an even faster rise (0.054 m/yr) in the last 20 years. Marion Lake was the flow-through lake which stood out with the strongest increasing lake level trends trend (0.023 m/yr for the period of record, and 0.040 m/yr for the last 20 years). By comparison, the medians of the trends over the period of record were 0.007 m/yr and 0.004 m/yr for the landlocked and flow-through lakes, respectively; medians for the last twenty years (1987-2007) were 0.005m/yr and 0.002 m/yr landlocked and flow-through lakes, respectively. It would therefore appear that the data indicate a rising lake level trend both over the long-term (period of record) and over the last 20 years (1987-2007) and that the median rise in lake water level for both the long-term and the most recent 20-year period is on the order of 5 mm/yr.

Table 7. Trends of daily water levels (m/year) in landlocked lakes

Lake name	Trend for period of record	Trend for 1987-2007
Belle Taine	0.033*	0.054*
Emily	0.004*	-0.004
Island	0.022*	0.017*
Little Sand	0.007*	0.007*
Loon	0.008*	-0.012*
Otter Tail	0.006*	0.003*
Sturgeon	0.002	0.000
Swan (Nicollet)	-0.019*	0.030*

* significant at the 0.01 level

Table 8. Trends of daily water levels (m/year) in flow-through lakes

Lake name	Trend for period of record	Trend for 1987-2007
Benton	0.008*	0.031*
Birch	0.003*	0.023*
Detroit	0.004*	-0.005*
East Fox	0.001*	0.000
Green	0.003*	0.020* (I)
Height of Land	0.002*	-0.004
Marion	0.023*	0.040*
Minnetonka	0.010*	0.029*
Minnewaska	0.010*	-0.005*
Mud	0.001*	0.000
Pelican	0.002*	0.002 (I)
Peltier	0.016*	0.001
Rush	0.005*	0.009*
Shetek	0.005*	0.015*
Swan (Itasca)	-0.002*	0.000
Upper Prior	0.018*	0.049*
Vermilion	0.003*	0.000

* significant at the 0.01 level

(I) data not available from the start and/or end of the time period

6.4. Trends of average annual water levels in 25 Minnesota lakes

Annual average lake levels were calculated by averaging the daily data available for each year. The data were therefore considerably reduced in size. The annual values were calculated because averaging could reduce the effect of missing data on the results. It could, however, also introduce a bias if seasonal patterns and data gaps existed.

The trends in annual average lake water levels were tested with the Mann-Kendall test (Test Z) and Sen's slope was also calculated. The trends derived from the daily lake level data and from the mean annual lake levels would be expected to be similar.

Five of the 8 landlocked lakes (Emily, Sturgeon and Swan (Nicollet) are the exceptions) showed an increasing trend significant at the 0.01 level (Table 9). No significant trend was found for the three lakes. The direction of the trends and the magnitude of the trends (Sen's slope) were found to be similar to the trends obtained from linear regression of the daily water level data (Table 9)

Table 9. Trends of annual average water levels in landlocked lakes

Lake name	Years of record	Test Z	Sen's Slope (m/yr)
Belle Taine	58	6.63*	0.030
Emily	54	1.16	0.002
Island	61	6.73*	0.020
Little Sand	42	5.03*	0.007
Loon	44	6.06*	0.009
Otter Tail	82	7.71*	0.007
Sturgeon	42	0.82	0.003

Swan (Nic)	44	-2.43	-0.012

*significant at the 0.01 level.

Table 10. Trends of annual average water levels in flow-through lakes

Lake name	Years of record	Test Z	Sen's Slope (m/yr)
Benton	49	3.09*	0.008
Birch	78	3.56*	0.004
Detroit	41	3.88*	0.004
East Fox	47	3.83*	0.001
Green	49	3.34*	0.004
Height of Land	66	3.01*	0.002
Marion	59	4.24*	0.024
Minnewaska	69	4.31*	0.004
Minnetonka	102	5.63*	0.005
Mud	41	1.74	0.001
Pelican	64	3.44*	0.003
Peltier	56	5.68*	0.008
Rush	72	5.21*	0.005
Shetek	70	5.16*	0.007
Swan (Itaska)	71	3.61*	0.003
Upper Prior	44	2.56	0.015
Vermilion	58	3.96*	0.003

* significant at 0.01 level.

All flow-through lakes showed a rising trend for lake water levels (Table 10). For 15 of the 17 lakes investigated the trend was significant at the 0.01 level. Except for Swan Lake (Itasca), the annual (Table 10) and the daily lake level data (Table 8) gave the same directions and similar magnitudes for the trends in lake levels. The medians of the trends are 0.002 m/yr and 0.001 mm/yr for the landlocked and the flow-through lakes, respectively.

6.5. Trends of May and October water levels in 25 Minnesota lakes

We have already determined trends of Minnesota lake levels in the previous sections. The data were daily and mean annual lake levels. Knowing the seasonal lake level cycles we can also determine trends in the highest and lowest annual lake levels. Based on the previous section we selected the May and October lake levels for this analysis, and the results were as follows.

A positive trend in May water levels was observed in seven of the eight landlocked lakes studied (five lakes had significant trends), but not in Swan (Nicollet) (Table 11). Positive trends in May water levels were also observed in all of the flow-through lakes, except Lake Vermilion (Table 12). Seven flow-through lakes had significant positive trends.

A positive trend in October lake levels was observed in six of landlocked lakes, but not in Sturgeon and Swan (Table 11). The positive trends were significant for all lakes, except Lake Emily. A positive trend in October water levels was also observed in all flow-through lakes, except Mud Lake (Table 12). Eight of the positive trends were significant.

The magnitude of these trends in May and October water levels concurs with those given in Tables 4 to 9 except for lakes Sturgeon, Mud and Vermilion. All three lakes showed a positive trend in daily/annual average lake water levels when the full record was used, but the trend was negative for data for the months of May and October. This is an odd result, because a similarity in trends would be expected over the long term.

Table 11. Trends of May and October water levels in landlocked lakes

	May		October	
Lake name	**Test Z**	**Sen's slope (m/yr)**	**Test Z**	**Sen's Slope (m/yr)**
Belle Taine	5.24*	0.080	5.35*	0.092
Emily	1.58	0.015	0.42	0.004
Island	3.72*	0.038	6.35*	0.068
Little Sand	4.48*	0.020	3.81*	0.019
Loon	4.16*	0.024	4.05*	0.027
OtterTail	2.94*	0.015	4.61*	0.017
Sturgeon	0.00	0.000	-1.21	-0.021
Swan (Nic)	-0.95	-0.038	-0.67	-0.041

* significant at the 0.01 level

Table 12. Trends of May and October water levels (m/yr) in flow-through lakes

	May		October	
Lake name	**Test-Z**	**Sen's slope (m/yr)**	**Test Z**	**Sen's Slope (m/yr)**
Benton	2.01	0.023	2.31	0.017
Birch	2.89*	0.011	3.89*	0.016
Detroit	3.64*	0.010	2.90*	0.015
East Fox	1.54	0.002	1.78	0.005

Green	0.51	0.003	2.20	0.007
Height of Land	2.23	0.009	1.39	0.004
Marion	3.46*	0.072	2.85*	0.067
Minnetonka	4.72*	0.015	4.35*	0.013
Minnewaska	2.51	0.011	3.40*	0.015
Mud	0.55	0.001	-0.47	-0.001
Pelican	1.93	0.006	1.30	0.005
Peltier	3.85*	0.015	4.26*	0.040
Rush	3.91*	0.015	3.92*	0.014
Shetek	3.42*	0.019	2.99*	0.020
Swan	1.39	0.005	1.72	0.009
Upper Prior	0.54	0.020	1.60	0.043
Vermillion	-0.76	-0.003	1.84	0.007

*significant at the 0.01 level

6.6. Recent trends in water levels in 25 Minnesota lakes

Climate is never stationary (IPCC) and hence lake levels can be expected to be continuously changing. We are concerned especially with lake level changes in the last 20 years (1987-2007). Information presented in the forgoing sections can be summarized as follows:

1) A majority of the 25 lakes studied showed significant positive trends, i.e. increasing lake levels in the past 20 years.

2) There is no indication of a uniform change in trends in the last 20years of record for the 8 landlocked lakes. Compared to the full record length, trends in the past 20 years reversed in 3 of the 8 landlocked lakes studied, accelerated in one lake, and remained about the same in the in the remaining 4 lakes (Table 6).
3) There is also no indication of a uniform change in trends in the last 20years of record for the 17 flow-through lakes. A comparison of water level trends in flow-through lakes in the last 20-year period to trends in the full record (Table 7) shows that 4 lakes reversed trends, 8 accelerated trends, 3 had about the same trends, and 2 lakes had reduced water level trends in recent years compared to the long-term record.
4) Summarizing points 1), 2) and 3) above: there is a weak positive trend in the water levels of the 25 lakes studied, but there is no conclusive evidence for an acceleration of the positive trend.
5) The remaining question is: How long can the positive trend continue, and where will it end?

7. CORRELATIONS OF LAKE LEVELS AND CLIMATE PARAMETERS

7.1. Correlations among lake levels

Climate is a common determinant of lake levels on a regional scale. When several lakes are studied in a region, synchronous fluctuations in lake characteristics or similar long-term patterns can be indicators of climatic change (Magnuson et al. 2006).

If lake water levels are driven predominantly by weather (climate), we would expect lake levels to be strongly correlated with each other, although watershed parameters (topography, land cover and soil characteristics) and hydrogeological parameters would weaken the correlation. The time scale and geographic scale are factors in the correlation because in small lakes with large watersheds water levels will change faster and by more than in large lakes with small watersheds, i.e. ratios such as (lake surface area)/(watershed surface area), (seepage flowrate/precipitation) and (surface runoff/precipitation), for example, will influence the correlation. To avoid the shortest timescales of hydrologic processes we examined correlations among annual average water levels of our 25 lakes in Minnesota.

For landlocked lakes (Table 13), the strongest correlation was observed between water levels of Lake Belle Taine and Little Sand Lake (correlation coefficient = 0.83). Given the diversity of geology, land-use and climate in Minnesota, this is to be expected because the two lakes are located in the same climate region (Division 2 in Table 13). The average correlation coefficient for pairs of landlocked lakes located in the same climate region was 0.50 (0.64 for Division 2, 0.34 for Division 6, 0.52 for Division 8).The average of the correlation coefficients between water levels in any two landlocked lakes, located in any region of Minnesota, was 0.43. Water levels in lakes located in distant climate regions of Minnesota (Appendix 1), e.g., one lake in the central north (Division 2) and the other in the central south (Division 8) had an average correlation coefficient of 0.11, i.e. no correlation. Swan Lake (Nicollet) and Loon Lake in this Division 2/8 set even had a negative correlation coefficient (-0.4). All the others were positive (Table 13).

The strongest relationship among flow-through lakes was observed between Lake Minnetonka and Lake Minnewaska (0.87) (Table 14). All pairs of lakes were positively correlated except for Swan Lake (Itasca) and Detroit Lake which are in very different climate regions. The average of the correlation coefficients of water levels in all pairs of flow-through lakes was 0.41. Water levels in flow-through lakes of the same climate region had an average correlation coefficient of 0.46 (0.33 for Division 1, 0.46 for Division 4, 0.37 for Division 5, 0.47 for Division 6, and 0.67 for Division 7). Water levels in flow-through lakes of very different climate regions (e.g., 1,2, 3 and 7,8, and 9) had an average correlation coefficient of 0.35. The affect of lake location on correlation coefficients can be observed for Division 7. The average correlation coefficient

Table 13. Correlations of water levels for landlocked lakes

Lake Name	Belle Taine	Emily	Island	Little Sand	Loon	Otter Tail	Sturgeon	Swan
Climate Division	2	8	6	2	2	4	6	8
Correlation coefficients								
Belle Taine	1.00							
Emily	0.26	1.00						
Island	0.52	0.44	1.00					
Little Sand	0.83	0.34	0.50	1.00				
Loon	0.50	0.25	0.68	0.60	1.00			
Otter Tail	0.76	0.58	0.80	0.70	0.64	1.00		
Sturgeon	0.39	0.43	0.34	0.51	0.33	0.44	1.00	
Swan (Nicollet)	0.10	0.52	0.22	0.10	-0.40	0.16	0.40	1.00

between water levels of Divisions 1 and 7 was 0.31, 0.44 for Divisions 2-7 and 0.40 for Divisions 3-7 although the correlation coefficient between water levels of lakes located in Division 7 (Lakes Benton and Shetek) was 0.67.

Table 14. Correlations of water levels for flow-through lakes

Lake Name	Benton	Birch	Detroit	East Fox	Green	Height of Land	Marion	Minnetonka	Minnewaska	Mud	Pelican	Peltier	Rush	Shetek	Swan	Upper Prior	Vermillion
Climate Divisions	7	6	1	6	6	1	9	6	4	5	6	6	4	7	2	5	3
Benton	1.00																
Birch	0.54	1.00															
Detroit	0.10	0.34	1.00														
East Fox	0.40	0.19	0.44	1.00													
Green	0.47	0.60	0.48	0.38	1.00												
Height of Land	0.54	0.36	0.33	0.59	0.30	1.00											
Marion	0.64	0.65	0.38	0.25	0.58	0.25	1.00										

Minnetonka	0.69	0.57	0.35	0.21	0.35	0.30	0.53	1.00									
Minnewaska	0.75	0.44	0.24	0.19	0.32	0.36	0.43	0.87	1.00								
Mud	0.45	0.03	0.32	0.31	0.21	0.21	0.35	0.25	0.51	1.00							
Pelican	0.51	0.57	0.19	0.38	0.51	0.34	0.43	0.79	0.81	0.12	1.00						
Peltier	0.40	0.31	0.20	0.32	0.61	0.13	0.49	0.39	0.38	0.43	0.40	1.00					
Rush	0.50	0.58	0.61	0.49	0.57	0.54	0.59	0.60	0.46	0.32	0.56	0.44	1.00				
Shetek	0.67	0.45	0.30	0.42	0.46	0.30	0.54	0.53	0.43	0.37	0.22	0.41	0.52	1.00			
Swan (Itasca)	0.40	0.23	-0.09	0.30	0.18	0.29	0.35	0.44	0.47	0.40	0.41	0.50	0.42	0.48	1.00		
Upper Prior	0.61	0.59	0.37	0.28	0.46	0.40	0.78	0.76	0.47	0.37	0.51	0.27	0.58	0.66	0.39	1.00	
Vermilion	0.35	0.11	0.04	0.51	0.36	0.44	0.30	0.19	0.36	0.14	0.26	0.48	0.46	0.46	0.47	0.17	1.00

The correlation coefficients of annual average water levels of 17 flow-through lakes and annual precipitation was in the range of 0.06-0.49 with an average of 0.34 (Table 16). Water levels in landlocked lakes had the highest average correlation with 48-month antecedent precipitation (0.61), while water levels of flow-through lakes were correlated best with 36-month antecedent precipitation (0.54). Although high correlation with antecedent precipitation was observed for some lakes, in general correlation of water levels with antecedent precipitation was moderate for both landlocked and flow-through lakes. Long-term rather than short-term (i.e.,annual or 12-month) precipitation was more effective in determination of water levels in lakes.

7.2. Correlations of mean annual lake levels with mean annual climate parameters

To address the possible causes of lake level changes more explicitly we examined correlations between lake level changes and climate parameters, especially precipitation, air temperature and dew point temperature. A correlation between long-term lake water levels and long-term precipitation averages is expected and has been found in several studies discussed and referenced earlier. Precipitation not only provides direct water input through the lake water surface, but it is also the source of water input to lakes by surface runoff and/or groundwater flow. Air temperature, dew point temperature, and wind speed are directly related to evaporative water losses, and therefore also reasonable climate parameters to include in the analysis.

We first examined the correlation of average water levels with annual and antecedent precipitation data. Annual precipitation refers to the total precipitation from January to December (12 months) in the same year with water level measurement. We used fairly long time periods for antecedent precipitation because lake level responses are cumulative in time. The correlations coefficients of annual average water levels in the 8 landlocked lakes and the annual precipitation were in the range of 0.12-0.53, and the average was 0.27 (Table 15).

Table 15. Correlation of annual average water levels with precipitation in landlocked lakes

Lake name	Annual precipitation	24-month antecedent precipitation	36-month antecedent precipitation	48-month antecedent precipitation	60-month antecedent precipitation
Belle Taine	0.22	0.46	0.64	0.72	0.78
Emily	0.16	0.54	0.56	0.51	0.49
Island	0.39	0.62	0.67	0.67	0.67

Little Sand	0.35	0.55	0.65	0.67	0.69
Loon	0.23	0.41	0.35	0.40	0.37
Otter Tail	0.53	0.72	0.78	0.79	0.79
Sturgeon	0.15	0.47	0.55	0.64	0.55
Swan	0.12	0.37	0.46	0.49	0.41
Average	**0.27**	**0.52**	**0.58**	**0.61**	**0.59**

Table 16. Correlation of annual average water levels with precipitation in flow-through lakes

Lake name	**Annual precipitation**	**24-month antecedent precipitation**	**36-month antecedent precipitation**	**48-month antecedent precipitation**	**60-month antecedent precipitation**
Benton	0.32	0.67	0.74	0.71	0.67
Birch	0.48	0.72	0.72	0.68	0.61
Detroit	0.38	0.47	0.51	0.47	0.46
East Fox	0.49	0.37	0.43	0.46	0.41
Green	0.39	0.56	0.68	0.58	0.59
Height of Land	0.41	0.46	0.50	0.45	0.44
Marion	0.26	0.57	0.72	0.75	0.76
Minnetonka	0.34	0.55	0.62	0.64	0.65

Minnewaska	0.22	0.48	0.56	0.65	0.69
Mud	0.31	0.33	0.31	0.24	0.17
Pelican	0.38	0.62	0.69	0.75	0.79
Peltier	0.44	0.47	0.47	0.48	0.46
Rush	0.36	0.49	0.59	0.56	0.58
Shetek	0.42	0.60	0.57	0.55	0.48
Swan	0.25	0.36	0.33	0.20	0.38
Upper Prior	0.06	0.36	0.47	0.52	0.52
Vermilion	0.33	0.35	0.24	0.26	0.17
Average	**0.34**	**0.50**	**0.54**	**0.53**	**0.52**

The correlation coefficients of annual average water levels of 17 flow-through lakes and annual precipitation was in the range of 0.06-0.49 with an average of 0.34 (Table 16). Water levels in landlocked lakes had the highest average correlation with 48-month antecedent precipitation (0.61), while water levels of flow-through lakes were correlated best with 36-month antecedent precipitation (0.54). Although high correlation with antecedent precipitation was observed for some lakes, in general the correlation of water levels with antecedent precipitation was moderate for both landlocked and flow-through lakes. Long-term rather than short-term (i.e.,annual or 12-month) precipitation was more effective in determination of water levels in lakes.

We identified 10 years with highest and lowest water levels for all lakes and conducted a correlation analysis to understand if extremely high and low water levels in lakes are related to annual and antecedent precipitation. Although the analyses provided higher correlations with precipitation for some lakes (e.g., Lake Emily and Lake Minnetonka), the results were not consistent for all lakes. Some lakes (e.g., Lake Otter Tail and Lake Height of Land) showed very low (even negative) correlations with precipitation. Overall average correlation values were very low (on the order of 0.10s-0.30s for landlocked lakes and 0.10s-0.20s for flow-through lakes). These results may suggest that extreme water levels are probably due to a combination of climatic factors rather than changes in precipitation patterns.

We also examined the correlations between annual average water levels of lakes and annual, May-October and June-August average air temperature and annual average dew point, May-October and June August dew point data. The air temperature data used in the analysis are average air temperature for appropriate climate divisions. Dew point data was obtained from the weather stations (if available) closest to the each lake. We did not include average antecedent air temperature and dew point temperature in the analyses, because the change from one year to another was low for these parameters. Correlation coefficients between annual average water levels of landlocked lakes and annual average air temperature were in the range of -0.33-0.50 with an average of 0.14 (Table 17). The correlations of water levels with May-October and June-August average air temperatures provided average correlation coefficients of -0.07 and -0.02 (Table 17). Correlation coefficients between annual average water levels of flow-through lakes and annual average air temperature were in the range of -0.16-0.52 with an average of 0.09 (Table 18). The correlations of water levels with May-October and June-August average air temperatures provided average correlation coefficients of -0.07 and -0.08 (Table 18). Correlation coefficients of extremely high and low water levels with air temperature were also very low. The correlation coefficients calculated for both landlocked lakes and flow-through lakes are much lower than expected and show that there is almost no correlation between average annual water levels and air temperatures.

Correlation coefficients between annual average water levels of landlocked lakes and annual average dew point temperatures were in the range of 0.09-0.62 with an average of 0.34. The correlations of annual average water levels of flow-through lakes with annual average dew point temperatures provided average correlation coefficients of in the range of -0.08 and 0.50 with an average of 0.21. Correlation coefficients of extremely high and low water levels with dew point temperatures were also very low (average correlation coefficients were lower that 0.25 for both landlocked and flow-through lakes). Although correlations of water levels with dew point temperatures seem to be stronger than correlations with air temperatures, they are still weak to come to a conclusion that changes in dew point temperatures are responsible for lake level changes.

Table 17. Correlation of annual average water levels with air and dew point temperatures in landlocked lakes.

Lake name	Corr. with annual average air temp.	Corr. with May-October average air temp.	Corr. with June-August average air temp.	Corr. with annual average dew point	Corr. with May-October average dew point	Corr. with June-August average dew point
Belle Taine	0.40	-0.08	-0.05	0.41	0.14	0.23

Emily	-0.10	-0.27	-0.14			
Island	0.15	0.20	0.14	0.07	0.06	0.00
Little Sand	0.50	0.06	0.16	0.62	0.36	0.35
Loon	0.35	0.00	-0.02	0.45	0.23	0.23
Otter Tail	-0.03	-0.21	-0.25	0.36	0.32	0.22
Sturgeon	0.14	0.09	0.13	0.22	0.06	0.15
Swan	-0.33	-0.33	-0.13			
Average	**0.14**	**-0.07**	**-0.02**	**0.36**	**0.20**	**0.20**

Table 18. Correlation of annual average water levels with air and dew point temperatures in flow-through lakes.

Lake name	**Corr. with annual average air temp.**	**Corr. with May-October average air temp.**	**Corr. with June-August average air temp.**	**Corr. with annual average dew point**	**Corr. with May-October average dew point**	**Corr. with June-August average dew point**
Benton	-0.09	-0.34	-0.15	0.39	0.34	0.38
Birch	0.06	-0.21	-0.23	0.18	0.07	0.11
Detroit	0.52	0.38	0.20	0.50	0.34	0.30
East Fox	0.21	0.18	0.07	0.39	0.34	0.37

Green	0.28	0.14	0.23	0.36	0.23	0.44
Height of Land	-0.07	-0.16	-0.11	0.17	0.27	0.29
Marion	0.31	-0.02	0.03			
Minnetonka	0.09	-0.14	-0.20	0.12	0.05	0.03
Minnewaska	0.10	-0.14	-0.25	-0.03	0.06	-0.04
Mud	0.23	0.26	0.10	0.18	0.13	0.19
Pelican	0.18	-0.14	-0.23	0.15	-0.06	0.21
Peltier	0.09	-0.12	-0.12	0.11	0.05	-0.01
Rush	-0.08	-0.28	-0.24	0.23	0.26	0.09
Shetek	-0.16	-0.19	-0.16	0.44	0.49	0.37
Swan	-0.09	-0.10	-0.09	-0.08	-0.02	0.03
Upper Prior	0.13	-0.03	-0.01	0.28	0.13	0.08
Vermilion	-0.14	-0.33	-0.25	-0.01	0.30	-0.03
Average	**0.09**	**-0.07**	**-0.08**	**0.21**	**0.19**	**0.17**

7.3. Correlations of May lake levels with antecedent precipitation

To moved closer to a process-oriented analysis we correlated the high lake water levels after snowmelt (May) with the antecedent 6-month to 60-month total precipitation. The results are shown in Tables 19 and 20.

The correlations coefficients of May water levels in the 8 landlocked lakes and the 12-month antecedent precipitation were in the range of 0.12-0.68, and the average was 0.47 (Table 19). These are disappointingly low values indicating only a weak correlation with antecedent annual precipitation. The correlation coefficients with 6-month antecedent precipitation were even lower, with a range of -0.12 to 0.46 and an average of 0.22 (Table 19). The best correlation was obtained with 36-month antecedent precipitation. The correlation coefficient range was 0.38 to 0.70 with an average of 0.63 (Table 19).

The correlation coefficients between May lake levels in the 17 flow-through lakes and the 12-month antecedent precipitation were in the range of 0.19-0.71, with an average of 0.48 (Table 20). The correlation coefficients with 6-month antecedent precipitation were again significantly lower, with a range of 0.01-0.64 and an average of only 0.32. The best correlation of May lake levels was obtained with12-month and 24-month precipitation. The correlation coefficient range for 12-month and 24-month antecedent precipitation was 0.19 to 0.71 and 0.10 to 0.74, respectively, with an average of 0.48 (Table 20).

Table 19. Correlation coefficient of May water levels in landlocked lakes with antecedent precipitation.

Lake name	**Corr. with 6-month antec. precip.**	**Corr. with 12-month antec. precip.**	**Corr. with 24-month antec. precip.**	**Corr. with 36-month antec. precip.**	**Corr. with 48-month antec. precip**	**Corr. with 60-month antec. precip**
Belle Taine	0.10	0.36	0.56	0.78	0.75	0.78
Emily	0.37	0.56	0.63	0.52	0.52	0.36
Island	0.46	0.60	0.68	0.66	0.69	0.67
Little Sand	0.32	0.44	0.61	0.69	0.65	0.68
Loon	-0.07	0.12	0.36	0.38	0.33	0.29
OtterTail	0.38	0.60	0.67	0.67	0.72	0.72

Sturgeon	-0.12	0.38	0.64	0.74	0.71	0.55
Swan (Nic)	0.32	0.68	0.65	0.60	0.58	0.55
Average	**0.22**	**0.47**	**0.60**	**0.63**	**0.62**	**0.57**

Table 20. Correlation coefficient of May water levels in flow-through lakes with antecedent precipitation.

Lake name	Corr. with 6-month antec. precip.	Corr. with 12-month antec. precip.	Corr. with 24-month antec. precip.	Corr. with 36-month antec. precip.	Corr. with 48-month antec. precip	Corr. with 60-month antec. precip
Benton	0.36	0.71	0.74	0.69	0.64	0.52
Birch	0.35	0.67	0.66	0.62	0.56	0.47
Detroit	0.42	0.54	0.63	0.63	0.28	0.30
East Fox	0.48	0.19	0.10	0.07	0.19	0.22
Green	0.60	0.55	0.27	0.42	0.30	0.10
Height of Land	0.45	0.57	0.49	0.39	0.17	0.20
Marion	0.19	0.52	0.66	0.73	0.75	0.76
Minnetonka	0.08	0.44	0.55	0.59	0.59	0.60
Minnewasha	0.01	0.27	0.49	0.49	0.51	0.52
Mud	0.41	0.36	0.33	0.19	0.22	0.17
Pelican	0.03	0.37	0.52	0.57	0.60	0.62
Peltier	0.35	0.30	0.31	0.34	0.32	0.36
Rush	0.36	0.48	0.41	0.39	0.47	0.49

Shetek	0.38	0.61	0.62	0.54	0.16	0.14
Swan	0.30	0.46	0.36	0.21	0.45	0.42
Upper prior	0.01	0.50	0.54	0.62	0.54	0.42
Vermillion	0.64	0.59	0.50	0.35	0.27	0.23
Average	**0.32**	**0.48**	**0.48**	**0.46**	**0.41**	**0.38**

7.4. Correlations of October lake levels with antecedent air and dew point temperatures

The correlations coefficients of October water levels in landlocked lakes with antecedent May-October air temperatures were in the range from -0.38 to 0.25 with an average of -0.11 (Table 21). The negative correlation is plausible since warmer air temperatures are likely to lead to more evaporation, but the correlation coefficient is very weak. The correlation coefficients of October lake levels with June-August air temperatures, i.e., for a shorter period, were even poorer with a range from -0.43 to 0.33, and an average of -0.06.

Dew point temperature is a better measure of evaporation potential than air temperature. For landlocked lakes the correlation coefficients of October water levels with June-August dew point temperatures ranged from 0.07 to 0.42 with an average of 0.26. The June-August period covers the 3 months with the largest evaporative water losses. The positive correlation is meaningful because a higher dew point is associated with less evaporation, hence higher lake levels. The correlation was in the range of 0.11-0.47 with an average of 0.36 when May-October dew point temperatures were chosen (Table 21).

For flow-thorough lakes, the correlations coefficients of October water levels with May-October air temperatures ranged from -0.28 to 0.43 with an average of -0.10 (Table 22). The correlation coefficients of October water levels with June-August air temperatures was in the range from -0.40 to 0.30 with an average of -0.11. The correlation coefficients of October water levels with June-August dew point temperature ranged between -0.24 and 0.50 with an average of 0.15. It improved to a range from -0.27 to 0.67 with an average of 0.19 when May-October dew point temperatures were chosen.

Table 21. Correlation coefficients of October water levels in landlocked lakes with air and dew point temperatures.

Lake name	**Corr. with May-October average air temp.**	**Corr. with June-August average air temp.**	**Corr. with May-October average dew point**	**Corr. with June-August average dew point**
Belle Taine	-0.13	-0.08	0.47	0.18
Emily	-0.24	-0.29		
Island	0.25	0.13	0.17	0.16
Little Sand	0.06	0.33	0.63	0.40
Loon	0.16	0.04	0.42	0.31
OtterTail	-0.38	-0.43	0.38	0.42
Sturgeon	-0.21	0.05	0.11	0.07
Swan	-0.35	-0.26		
Average	**-0.11**	**-0.06**	**0.36**	**0.26**

Table 22. Correlation coefficients of October water levels in flow-through lakes with air and dew point temperatures.

Lake name	Corr. with May-October average air temp.	Corr. with June-August average air temp.	Corr. with May-October average dew point	Corr. with June-August average dew point
Benton	-0.15	0.20	0.37	0.50
Birch	-0.24	-0.25	0.16	0.16
Detroit	0.43	0.24	0.38	0.29
East Fox	-0.04	-0.10	0.08	-0.24
Green	0.03	0.30	-0.16	0.49
Height of Land	-0.21	-0.29	0.46	0.27
Marion	-0.10	-0.04		
Minnetonka	-0.22	-0.25	0.11	0.05
Minnewasha	-0.03	-0.13	0.20	0.11
Mud	-0.28	-0.40	-0.12	0.12
Pelican	-0.16	-0.05	-0.07	0.22
Peltier	-0.14	-0.27	0.14	-0.02
Rush	-0.28	-0.24	0.36	0.21

Shetek	-0.03	-0.16	0.67	0.35
Swan	0.00	-0.08	0.08	0.04
Upper Prior	-0.20	-0.10	0.00	0.17
Vermillion	0.16	0.77	-0.27	0.27
Average	-0.10	-0.11	0.15	0.19

7.5. Multivariate regression of lake levels with climate variables

We estimated parameter values X and Y given in Eq 3 for selected lakes (lakes which have most continuous records) and selected time periods (where continuous data are available). We used both daily and monthly average values to estimate parameters. Our multi-variate regression did not provide a significant improvement of the results obtained by single variable regression (correlation). The value obtained for variable X (which denotes the correlation with precipitation) was almost the same as the correlation coefficient obtained from single variable regression. We found a weak positive correlation with the evaporation term (low and positive Y value) although we expected a strong negative correlation. One reason that explains these unexpected results could be omission of surface water and ground water inflow, surface water outflow components. Lake water budgets are the result of complex interactions of multiple variables and cannot be well explained with selective variables in most cases.

8. PROJECTIONS FOR MINNESOTA CLIMATE AND LAKE LEVELS

8.1. Projections of climatic and hydrologic changes in Minnesota

It is projected that air temperature and precipitation in Minnesota will continue to increase in the next century (Kling et al. 2003). Based on the results from the United Kingdom

Hadley Centre's climate model (HadCM2) and projections of the Intergovernmental Panel on Climate Change (IPCC), the increase in air temperature is expected in all seasons around 2.2 °C (4°F with a range of 2 to 7°F) (Anonymous 1997). Precipitation is projected to increase by about 15% in summer, fall and winter and to remain mostly stable for spring (Anonymous 1997). Along with these changes, evaporation is projected to increase, which will affect the amount of runoff to the lakes and streams and infiltration to ground water (Kling et al. 2003). Lake evaporation could increase by 20% (102 to 178 mm or 4 to 7 inches) for a 4°F warmer climate (Anonymous 1997). Increased water losses by evaporation could decrease lake levels but increased precipitation could compensate for the additional losses. The difference between increases in precipitation and increases in evaporation is projected to remain the same or become positive in fall, winter and spring and negative in summer in the next century (Kling et al. 2003). In previous simulations of lake temperatures in Minnesota, Stefan et al. (1998) used the a 2xCO2 climate scenario relative to past climate (1955-1979) shown in Table 23. The values came from GCM simulations of the Canadian Climate Center.

Table 23. Weather parameter increments and ratios for Minnesota. Values were obtained from the Canadian Climate Center General Circulation Model (CCC GCM) for a 2xCO2 climate scenario (Stefan et al. 1998).

Month	Air temperature (°C)[a]	Solar radiation ratio[b]	Wind speed ratio[b]	Specific humidity ratio[b]	Precipitation ratio[b]

Jan	8.17	0.94	1.08	1.85	1.23
Feb	8.5	0.92	1.1	1.94	1.26
Mar	4.37	0.95	0.88	1.53	1.22
Apr	5.76	0.95	1.01	1.78	1.5
May	5.39	0.97	0.97	1.46	1.05
Jun	4.27	0.96	0.85	1.32	0.99
Jul	3.54	0.96	0.8	1.23	0.87
Aug	5.24	0.99	0.83	1.35	0.87
Sep	4.51	0.99	0.9	1.29	0.79
Oct	2.71	0.98	1.01	1.19	0.96
Nov	2.9	1.01	1.02	1.29	0.96
Dec	4.38	1	0.91	1.25	0.97
Average	4.98	0.97	0.95	1.46	1.06

a Increment = 2xCO2 CCC GCM output – 1xCO2 CCC GCM output

b Ratio = 2xCO2 CCC GCM output divided by 1xCO2 CCC GCM output

8.2. Projections of lake level changes in Minnesota

Despite the increase in average global temperature and projections that show evaporation rates will increase in the future, Peterson et al. (1995) found a downward trend in pan evaporation rates over most of the United States and former Soviet Union over the last century. According to Roderick (2002), these decreases are caused by a decrease in solar radiation due to increasing cloud cover and aerosol concentrations. If pan evaporation rates continue to decrease or stay stable, lake levels can be expected to become higher due to increased precipitation.

Our analysis of the water level records from 25 lakes leads to the conclusion that there is a weak positive trend in the water levels of the 25 lakes studied, but there is no conclusive evidence for an acceleration of the positive trend. Increasing trends can be due to climatic factors (i.e., increasing precipitation and decreasing evaporation rates) or non-climatic factors (i.e., land-use changes).

If the current trends in lake levels continue, we may expect 0.08-0.75 m increase in water levels in landlocked lakes and 0.03-0.60 m increase in flow-through lakes included in this study in the next 23 years. Water levels of Lake Swan (Nicollet), which is the only lake with a negative trend, can decrease by 0.30 m by 2030. The change in water levels in some lakes (e.g., Lake Belle Taine with 0.75 m and Lake Marion with 0.60 m increase) can be very significant.

9. SUMMARY AND CONCLUSIONS

We analyzed historical water levels in 25 Minnesota lakes. Eight were landlocked lakes and seventeen were flow-through lakes. The data were daily values, but substantial gaps existed. The longest record reached back to 1906 (Lake Minnetonka and Upper Prior Lake in Scott County). We determined statistical parameters such as annual mean values 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.

The majority of the 25 lakes showed increasing trends (rising water levels) in the last century (1906 to 2007) (Tables 1 and 2). 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) was the only landlocked lake that showed a falling trend with a rate of 0.011 m/yr. Swan Lake (in Itasca County) was the only landlocked lake that had a negative trend (0.002 m/yr) in daily water levels, but it showed a positive trend when annual average water levels were used.

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 (May) and fall (October) in the majority of the 25 lakes analyzed.

We also attempted to understand how Minnesota lake levels have responded to climate changes. Correlation coefficients were calculated between annual lake water levels and mean annual climate variables such as precipitation, dew point and air temperature.

The correlation of water levels with precipitation was moderate while correlations of water levels with dew point and air temperatures were weak. The correlation coefficients of average water levels were largest with 48- and 36-month antecedent precipitation for landlocked lakes and flow-through lakes, respectively. A multivariate regression of lake levels did not provide a significant improvement of the correlations probably due to the omission of significant components in the water budget equation such as groundwater and surface water flows.

The correlation between mean annual lake levels was strongest among lakes in the same climate regions and weakest among lakes in distant climate regions. Some lakes in the same Minnesota climate region (with similar precipitation and temperature characteristics) had correlation coefficients of 0.78, while those in distant regions had low and even negative correlation coefficients. The average of the correlation coefficients among water levels in all lakes was 0.43 for the eight landlocked lakes and 0.41 for the seventeen flow-through lakes investigated.

Overall, analyses of the lake levels 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 showed an upward trend (rising lake levels). However, the correlation between climate parameters and lake levels was weak. The regional consistency in lake level responses is perhaps the strongest indicator of a climate effect. If the trends continue, lakes included in this study may experience water level increase up to 0.75 m by 2030.

ACKNOWLEDGEMENTS

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The lake level data used in this study came from a database of the Minnesota Department of Natural Resources in St. Paul. Weather data were extracted from the database of the State Climatologist Office. We thank these institutions and individuals for their help and co-operation.

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Appendix 1. Minnesota climate divisions and counties.

http://www.cpc.noaa.gov/products/analysis_monitoring/regional_monitoring/CLIMDIVS/minnesota.gif


Minnesota
Kittson
Roseau
Lake of the Woods
Marshall
Koochiching
Pennington
Red Lake
Beltrami
Cook
Polk
1
Clearwater
2
St. Louis
Lake
Itasca
3
Norman
Mahnomen
Hubbard
Clay
Becker
Cass
Wadena
Crow Wing
Aitkin
Carlton
Wilkin
Otter Tail
Pine
Mille Lacs
Todd
Morrison
Grant
Douglas
Kanabec
6
Benton
Traverse
Stevens
4
Pope
Stearns
Big Stone
Sherburne
Isanti
Chisago
Swift
Kandiyohi
5
Anoka
Wright
Lac Qui Parle
Chippewa
Meeker
Washington
Ramsey
Hennepin
Renville
McLeod
Carver
Yellow Medicine
Scott
Dakota
Sibley
Lincoln
Lyon
Redwood
Goodhue
Nicollet
Le Sueur
Rice
Wabasha
Brown
Pipestone
7
Murray
Cottonwood
Watonwan
Blue Earth
8
Waseca
Steele
Dodge
Olmsted
9
Winona
Rock
Nobles
Jackson
Martin
Faribault
Freeborn
Mower
Fillmore
Houston

UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 506

Lake Evaporation Response to Climate in Minnesota

by

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Prepared for
Legislative Citizens Committee on Minnesota Resources
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Minneapolis, Minnesota

The University of Minnesota is committed to the policy that all persons shall have equal access to its programs, facilities, and employment without regard to race, religion, color, sex, national origin, handicap, age or veteran status.

Abstract

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, Minneaplis/St. Paul, 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 32.0 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.

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1. INTRODUCTION

About a foot of water is lost annually by evaporation from Minnesota lakes, more in the south and less in the north. In this report we examine lake evaporation in Minnesota in the last four decades and relate this information to climate and observed lake water levels. Trends are of particular interest.

Precipitation and evaporation are the amounts of water received and emitted at a lake's surface. They are component of a lake's water budget which also includes surface inflow from the watershed, surface outflow from a lake to a stream, seepage and ground-water recharge from a lake, and storage resulting in lake level change. The water budget of a lake can be stated as:

$$\Delta L/\Delta t = P - E + I - O + GI - GO \tag{1}$$

In Equation (1), P refers to precipitation on the lake surface, E is evaporation from the lake surface, I is surface runoff from a watershed into a lake, GI is ground-water inflow, and GO is ground-water outflow. All water budget components can be expressed as flow per unit surface area of a lake, e.g., in units of mm/yr. L is the water level in mm and Δt is a time interval, typically one year.

Changes in Minnesota's climate (recorded weather) in recent years have increased the concern for changes in annual evaporation rates and the consequences for lake levels and water availability from lakes. Seeley (2003) reported that Minnesota is now having warmer winters, higher minimum air temperatures, higher frequency of tropical dew points, and greater annual precipitation. Air temperature and precipitation showed rising trends of 2 – 3°C/100 years and 5-10%/100 years , respectively, from 1900 to 1994 (Gleick, 2000). Effects of a changing climate have already been identified in some of Minnesota's water resources (Changnon and Kunkel, 1995; Johnson and Stefan, 2006; Novotny and Stefan, 2007). Although evaporation is one of the most important parameters affecting water resources in Minnesota, no studies of changes in this parameter have yet been conducted.

Mean annual lake evaporation and mean summer evaporation in the United States including Minnesota are given in Figures 1 and 2. The maps were developed by a Minnesota hydrologist (Adolph Meyer) and published in 1942. Meyer (1942) conducted extensive studies on lake evaporation in Minnesota, and developed an evaporation equation that we will use. In Meyer's studies (Meyer 1942), mean annual lake evaporation in Minnesota was in the range 559 - 914 mm (22 - 40 in), while mean summer evaporation was in the range 508 - 889 mm (20 - 35 in). Evaporation rates vary with geographic location and increase from north to south. According to an unpublished report prepared by the National Climatic Data Center (NCDC), annual lake evaporation in Minnesota ranges from 508 mm (20 in) at the northeast corner to 889 mm (35 in) at the southwest corner (NCDC, unpublished report). Pan evaporation varies from 762 mm (30 in) to 1270 mm (50 in)(NCDC, unpublished report) .

Another noteworthy study on lake evaporation in Minnesota was conducted by Sturrock, Rosenberry, and Winter (1992) on Williams Lake in central Minnesota. In this study evaporation from May to September for the 1982 – 1986 period was estimated using both energy budget and mass-transfer methods. Evaporation for the May – September period was found to be 419 mm (16.5 in) with the energy balance method and 427 mm (16.8 in) with the mass transfer method (Sturrock et al., 1992).

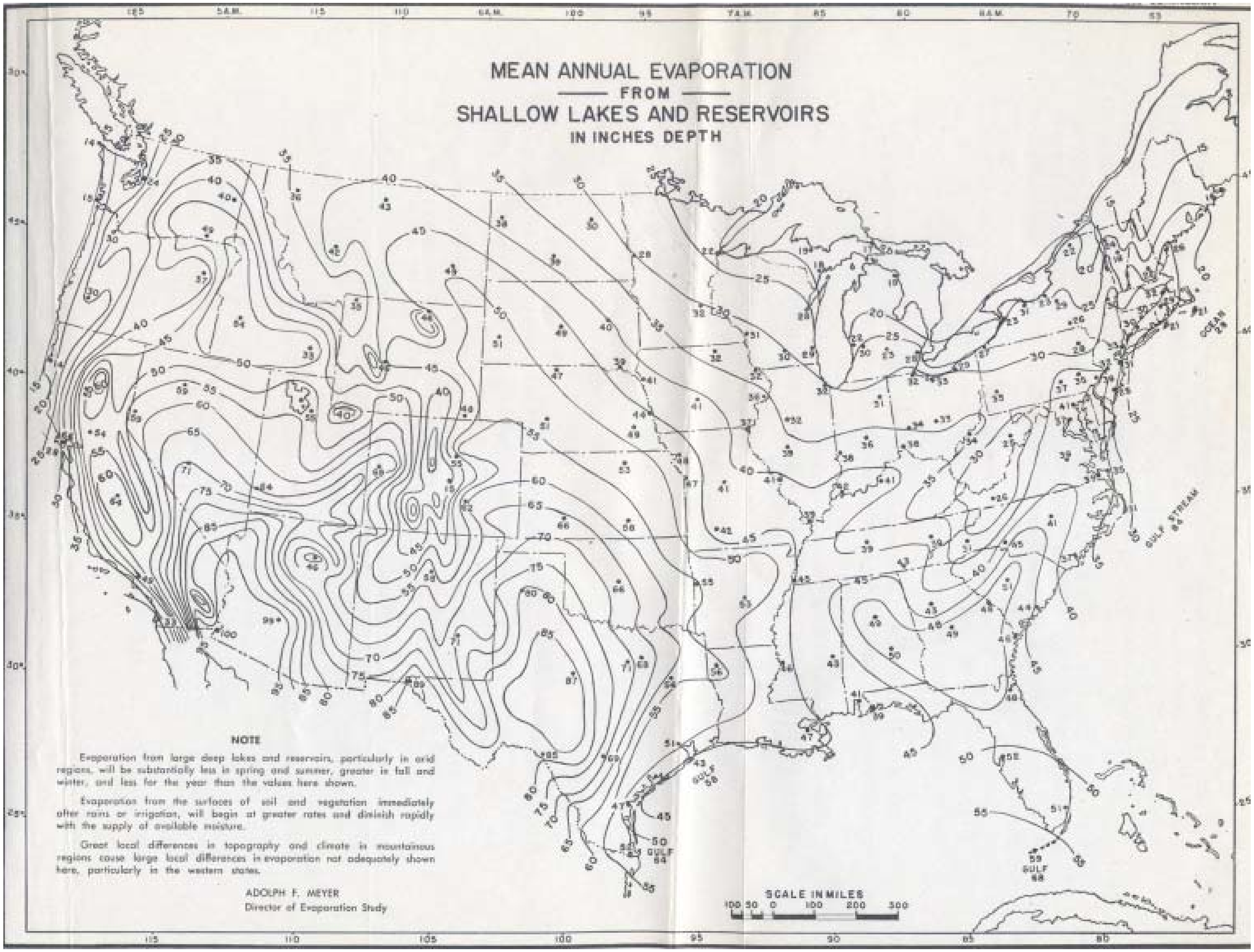

Figure 1.Mean annual lake evaporation in the U.S. (Meyer, 1942).

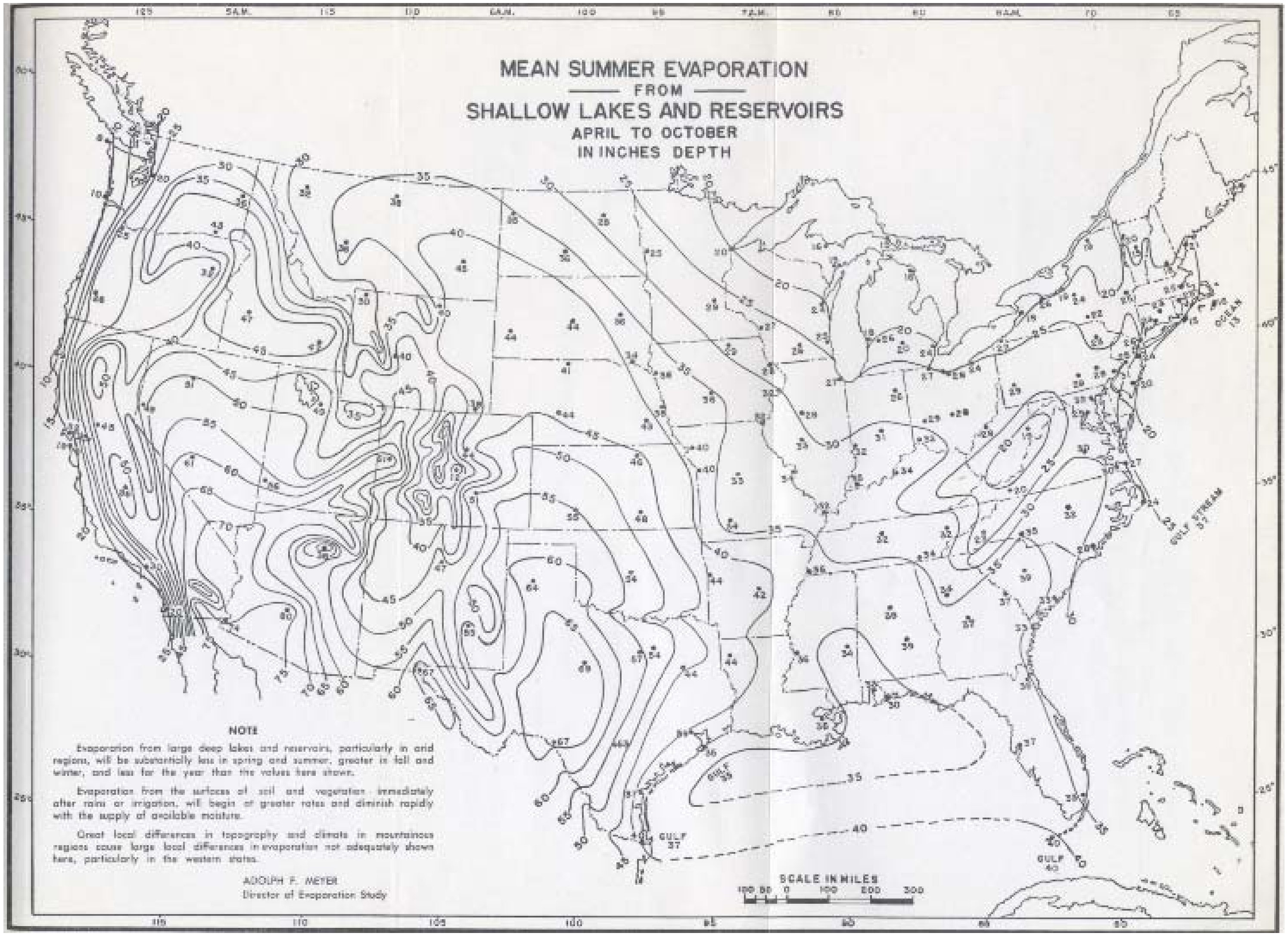

Figure 2.Mean summer lake evaporation in the U.S. (Meyer, 1942).

Direct measurements of evaporation (pan evaporation) are available for recent years only at two locations in Minnesota, and only for the summer months (May to September) (http://www.climate.umn.edu). Based on these data, average annual summer pan evaporation in Minneapolis was 857 mm (33.7 in) with a standard deviation of 112 mm (4.4 in) for the period 1972 – 2006. In Waseca, it was 917 mm (36.1 in) with a standard deviation of 9.7 mm (3.8 in) for the period of 1964 – 2002. Pan evaporation is generally higher than lake evaporation for a number of reasons, and a pan coefficient on the order 0.6 to 0.9 has to be applied to pan evaporation to obtain lake evaporation (Winter, 1981). If a pan coefficient of 0.7 is used, annual summer lake evaporation in Minneapolis and Waseca correspond to 560 mm (23.6 in) and 642 mm (25.3 in), respectively.

By comparison mean annual precipitation was 752 mm (29.61 in) in Minneapolis (1972 – 2006) and 875 mm (34.43 in) in Waseca (1964 – 2002). Pan evaporation measured in Minneapolis (May-September, 1972 – 2006) and Waseca (May-September, 1964 – 2002) has decreased at a rate (trend) of -5.08 mm/yr (-0.20 in/yr; significant at the 0.01 level) and -1.27 mm/yr (0.05 in/yr; significant at the 0.5 level), respectively. These results are at best representative of southern Minnesota because of the high climate variability throughout the state. Measurements of pan evaporation in northern Minnesota are not available.

The downward trend in measured pan evaporation at two Minnesota locations contradicts projections for evaporation rates due to climatic change (warming). Rising air temperatures are thought to stimulate evaporation in the future (Kling et al., 2003). Annual lake evaporation was estimated to increase by 20% (112 to 183 mm/yr or 4.5 to 7.2 in/yr) for a 4°F warmer climate in Minnesota (Anonymous, 1997). Simulations of lake temperature changes based on heat budgets under a 2xCO2 climate scenario in Minnesota (Table 1) showed an increase in evaporative heat fluxes corresponding to approximately 200mm/yr (7.9 in/yr) of water (Figure 3) (Fang and Stefan, 1999).

Table 1. Weather parameter increments and ratios for Minnesota. Values were obtained from the Canadian Climate Center General Circulation Model (CCC GCM) for a 2xCO2 climate scenario (Stefan et al., 1998).

Month	Air Temperature (^oC)[a]	Solar radiation ratio[b]	Wind speed ratio[b]	Specific humidity ratio[b]	Precipitation ratio[b]
Jan	8.17	0.94	1.08	1.85	1.23
Feb	8.5	0.92	1.1	1.94	1.26
Mar	4.37	0.95	0.88	1.53	1.22
Apr	5.76	0.95	1.01	1.78	1.5
May	5.39	0.97	0.97	1.46	1.05
Jun	4.27	0.96	0.85	1.32	0.99
Jul	3.54	0.96	0.8	1.23	0.87
Aug	5.24	0.99	0.83	1.35	0.87
Sep	4.51	0.99	0.9	1.29	0.79
Oct	2.71	0.98	1.01	1.19	0.96
Nov	2.9	1.01	1.02	1.29	0.96
Dec	4.38	1	0.91	1.25	0.97
Average	4.98	0.97	0.95	1.46	1.06

a Increment = 2xCO2 CCC GCM output – 1xCO2 CCC GCM output

b Ratio = 2xCO2 CCC GCM output divided by 1xCO2 CCC GCM output

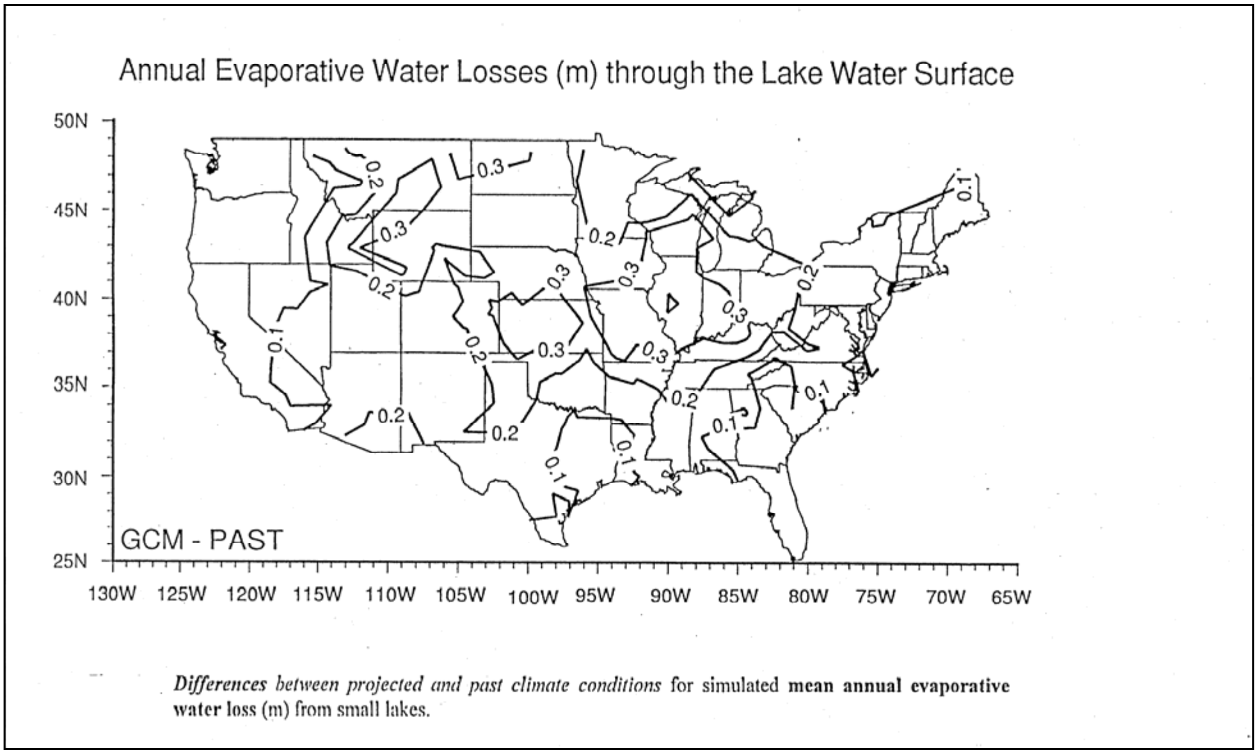

Figure 3. Projected changes in mean annual evaporative water loss (m) from small lakes under 2xCO2 scenario (reproduced from (Fang and Stefan, 1999) (1 in = 0.0254 m).

The impact of changed evaporative water losses from a lake can be mitigated by the other water budget components in equation (1). For example, precipitation is projected to increase in Minnesota. The increase can be about 15% in summer, fall and winter with no change in spring (Anonymous, 1997). Lower lake levels due to increased evaporative water losses can be prevented by increased precipitation. The difference between increases in precipitation and increases in evaporation in Minnesota, therefore, will be an important factor to control the future state of the lakes in Minnesota.

In this study, we will calculate annual evaporation rates from water surfaces during 40 years of changing Minnesota climate conditions. We will use weather data recorded at six locations in and around Minnesota for the 1964 – 2005 and 1986 – 2005 periods, and four different evaporation equations. We will then determine the linear trends in the calculated annual evaporation rates.

For comparison we will also examine the trends in precipitation at the same locations, and trends in the difference between precipitation and evaporation, i.e. net water input through the surface of lakes (water availability). To be able to understand the relationships between evaporation rates and lake levels, we will correlate the calculated annual net water input through the surface of lakes with observed lake levels.

2. METHODS

2.1. Estimation of Daily Evaporation

Evaporation from a water surface can be determined by several methods based on different principles (Chow, 1964; Winter, 1981). Methods used include (1) measurement in evaporation pans, (2) the water budget method, (3) the energy budget method, and (4) aerodynamic methods (e.g., eddy correlation, gradient or mass transfer method). Most of these methods require extensive data collection. For example, to use the energy budget method, all energy fluxes to and from a lake, e.g., incoming and reflected solar radiation, and the change in heat energy stored within the lake have to be estimated. The water budget method requires estimation of water inputs and outputs for a lake. Overland flow and ground-water inflow and outflow can be difficult to determine because of uncertainties in watershed characteristics, ground-water/surface-water relationships, etc. The pan evaporation method is a straightforward method, but the accurate estimation of pan coefficient is very difficult (Winter, 1981). In this study, we chose to use an aerodynamic mass transfer method because most of the data required by this equation are climatic data that are available from weather stations. We also had no water temperature time series data that were long enough to use the more accurate energy balance equation. Mass transfer methods have been shown to be useful in estimating lake evaporation with sufficient accuracy (Singh and Xu, 1997a).

The mass transfer method for estimating evaporation is based on the principles developed by Dalton (1802). According to Dalton, the evaporation rate from a water surface depends on the difference between the water-vapor pressure at the evaporating surface (e_o) and the water vapor pressure in the air above that surface (e_a) and on wind speed (u) above the water surface. A general equation based on Dalton's principles is provided as equation (2) and a general equation for estimating wind function, f(u), is given as equation (3).

$$E = f(u)(e_o - e_a) \qquad (2)$$

$$f(u) = a + Nu^n \qquad (3)$$

Parameters in equations (2) and (3), i.e., a, N, n, were estimated by calibrating equation (2) with climatic data at specific locations. The equations obtained in this way by numerous investigators can be found in the hydrological literature (e.g., Chow 1964). An evaluation and generalization of most commonly used empirical equations is provided in Singh and Yu (1997). Singh and Yu concluded that empirical equations can provide satisfactory estimation of evaporation if parameter values were estimated by calibration with local climatic data. However, transfer of parameter values from other regions (even within a small region with similar climatic characteristics) can significantly affect the reliability of the evaporation estimates.

In this study, sufficient historical data were not available to estimate parameter values for different regions of Minnesota. Therefore, we had to transfer parameter values from other studies. To show the degree of uncertainty in evaporation values estimated by different parameter values, we calculated evaporation with four different empirical equations. These equations were the Meyer equation, Lake Hefner equation, Rohwer equation, and Ryan & Harleman equation. The first three of these equations have been commonly used to estimate evaporation from lakes in the United States (Chow, 1964). The fourth equation provides a different perspective, because it was originally developed for estimating water losses from heated water bodies, e.g., cooling ponds, rather than natural water bodies. Below we provide a brief discussion and explanation of these equations.

The Meyer equation (equation (4)) (Meyer, 1942) was developed to estimate evaporative water losses from lakes. Meyer was a hydrologist based in Minnesota and the equation was originally developed for Minnesota conditions. In equation (4), E refers to evaporation rate (in/day), e_o is the saturation vapor pressure (in Hg) at mean water temperature, e_a is the vapor pressure (in Hg) of the air measured at 7.6 m (25 ft) above the water surface, u is the wind speed (mph) measured at 7.6 m (25 ft) above the water surface, and C is an empirical constant. C was determined to be 0.33 for daily evaporation from Lake Minnetonka when climate data from the Minneapolis/St. Paul Airport were used as input.

$$E = C(e_o - e_a)(1 + \frac{u}{10}) \quad (4)$$

The Lake Hefner equation (Marciano and Harbeck, 1954) was developed for a water-supply reservoir (Lake Hefner) located near Oklahoma City, OK. In equation (5), E is again the evaporation rate (in/day), e_o is saturation vapor pressure (mb) at the water temperature and e_a is vapor pressure (mb) of the air, and u is the mean daily wind speed (mph). To develop this equation Marciano and Harbeck used wind speed and relative humidity data from the nearest airport (13 miles away), and water-surface temperatures were measured.

$$E = 0.00177u(e_o - e_a) \quad (5)$$

The Rohwer equation (Rohwer, 1931) is provided in equation (6). In equation (6) E is evaporation (in/day), e_o and e_a are saturation vapor pressure (mb) at the mean water temperature and vapor pressure (mb) of the air, respectively, and u is the wind speed (mph) measured at the water surface. P is air pressure in Pa.

$$E = 0.771(1.465 - 0.0186P)(0.44 + 0.118u)(e_s - e_a) \quad (6)$$

The Ryan & Harleman equation (equation (7)) was developed to estimate evaporation from heated water bodies. In that case, both forced (wind driven) convection and free (buoyancy driven) convection effectively control evaporation rates, while for natural water bodies forced convection is the dominant factor. In equation (7), Q_e is evaporative heat flux (W/m^2), ΔQ_v is virtual temperature difference (^0C), u is the wind speed measured at 2 m (m/s) and, e_o and e_a are saturation vapor pressure at the water surface and vapor pressure of the air (mb), respectively.

$$Q_e = (2.7\Delta Q_v^{1/3} + 3.1u)(e_s - e_z) \quad (7)$$

ΔQ_v can be calculated with equation (8), where T_w is water temperature (^oC), T_a is air temperature (^oC), and P is air pressure (mb).

$$\Delta Q_v = T_w(1+0.378\frac{e_s}{P}) - T_a(1+0.378\frac{e_a}{P}) \quad (8)$$

Evaporation can be found by dividing Q_e by latent heat of vaporization (L_v) (equation (9)). L_v is nearly constant. A relationship with water temperature used by (Stefan et al., 1980) is given in equation (10).

$$E = \frac{Q_e}{L_v} \quad (9)$$

$$L_v = 597.5 - 0.592T_w \quad (10)$$

Saturation vapor pressure and vapor pressure of the air were estimated using equations (11) and (12), respectively. In these equations, e_o and e_a are in millibars, T is in ^oC and T_d is dew point temperature in ^oC.

$$e_o = 6.11\times 10^{\frac{7.5\times Tw}{237.7+Tw}} \quad (11)$$

$$e_a = 6.11\times 10^{\frac{7.5\times T_d}{237.7+T_d}} \quad (12)$$

Because daily water temperature measurements were not available, we used equilibrium temperature, T_e, as a substitute for surface water temperature (T_w). T_e was calculated using the equation (13) developed by Edinger et al. (1968).

$$T_e = T_d + \frac{H_s}{K} \quad (13)$$

In equation (13), H_s is the shortwave solar radiation in (W/m^2) and K is the bulk surface heat exchange coefficient ($W/m^2/^oC^1$). K can be calculated from equation (14), where β is an approximation of the slope of the saturation pressure vs. water temperature curve (mm $Hg/^oC$) and f(u) is a function ($W/m^2/mmHg^{-1}$) of wind speed u (m/s)

$$K = 4.5 + 0.05T + \beta f(u) + 0.47 f(u) \qquad (14)$$

β and f(u) can be calculate with equations (15) and (16).

$$f(u) = 9.2 + 0.46u^2 \qquad (15)$$

$$\beta = 0.35 + 0.15T_m + 0.0012T_m^2 \qquad (16)$$

In equation (17), the mean temperature T_m is calculated as:

$$T_m = \frac{T + T_d}{2} \qquad (17)$$

As explained by Singh and Xu (1997b), the mass-transfer based evaporation equations are most sensitive to the vapor pressure difference, which is affected by water temperature and air temperature measurements. Because we did not have long time series of actual measured water temperature data, we used equilibrium temperatures in our calculations. The equilibrium temperature is by definition the water temperature that a water body with no thermal inertia, i.e., zero depth, assumes instantaneously under a given set of weather (climate) conditions. The equations to evaluate equilibrium temperature are based on the heat flux balance at a water surface. Water temperatures of water bodies of finite depth generally lag in temperature behind the equilibrium temperature. That means that the water temperatures we used are good estimates for very shallow water, but are too low in spring and too high in fall for water bodies of greater depth. We evaluated the sensitivity of the calculated evaporation values to changes in equilibrium temperature. The approach and the results of the sensitivity analysis are presented in Appendix 1. The sensitivity analysis shows how much water temperatures deviate from equilibrium temperatures as the lake water depth increases.

2.2. Climate Data Input

The climate data (air temperature, dew point temperature, and wind speed) required for the evaporation computations came from six weather stations (Figure 4). The stations chosen are on the boundaries of Minnesota. Geographic variability is therefore well-covered. Although we wanted to include some stations inside Minnesota (i.e., Bemidji, Brainerd, Detroit Lakes and St. Cloud), climate data for those stations were not available for long enough period of time (they were available after mid-1990s). The climate data included in this analysis were obtained from the State Climatology Office. Shortwave solar radiation data required for estimating daily equilibrium temperatures were obtained from the National Solar Radiation Database (http://rredc.nrel.gov/solar/old_data/nsrdb/). Daily climate data from 1964 to 2005 were used in the analysis. Prior to 1964, daily climate data for some parameters (e.g., wind speed) were unavailable. The 40-year period was deemed long enough to detect trends due to global climate change. Daily precipitation data were available for a longer period (prior to 1950 to 2005)

Figure 4. Location of weather stations used in this study

2.3. Estimation of Annual Evaporation/Ice Cover Effects

Annual evaporation from lakes will first be calculated by accumulating the daily evaporation values from January 1 to December 31.

During the winter months most Minnesota lakes are covered by ice. We therefore calculated separately the annual evaporation for the natural open-water period to estimate the actual amount of water lost from lakes. For the ice-cover period we assumed that no water was evaporated, even though a small amount of water transfers from lake ice and snow covers to the atmosphere, i.e. the water loss by ablation of snow and ice covers during the ice cover period was neglected. The most important water loss from a lake to the atmosphere in winter is not in the form of water vapor but most likely as snow drift blown from lake ice covers on to the land. This would be particularly important for lakes with a large surface area, i.e. wind fetch. Although snow removal from lake surfaces by wind can be easily observed, not much data seems to have been collected on this phenomenon. Snow accumulation in a suburb was reported to be substantially larger than on a lake in the Twin Cities area (Stefanovic, 2000)

To calculate annual evaporation for the open-water season, we ignored evaporation calculated for the ice-cover period. The ice-cover periods on northern and southern Minnesota lakes are significantly different (average ice-in and ice-out dates for Minnesota lakes are given in Appendix 2) According to Johnson and Stefan (2004) the average lake ice-out date in Minnesota varies from April 1 at 44.3^{o} latitude to May 1 at 48.6^{o} latitude. In the same study, ice-in dates were found to vary from November 12 at 47.0^{o} latitude to December 8 at 47.2^{o} latitude. The effect of latitude is not as apparent in recorded ice-in dates as in ice-out dates, because in addition to latitude lake depth has a strong effect on ice-in (Williams et al., 2004). Based on recorded ice-in and ice-out dates, the ice-cover period was assumed to be from November to May at northern locations (Fargo, International Falls, and Duluth) and December to April for southern stations (Sioux Falls, Minneapolis, and La Crosse). The bulk of the annual evaporation occurs in summer and only a small fraction in winter (Meyer, 1942). A precise estimation of the ice cover period is therefore not necessary.

2.4. Estimation of Trends in Evaporation

Trends in evaporation, precipitation and water availability (annual precipitation minus open-water evaporation) were estimated using a linear regression. Water availability was calculated in two ways:

1) as the difference between measured total annual precipitation and open-water evaporation, which is based on the assumptions that (a) water loss from snow and ice covers of lakes will not

be significant during ice-cover periods and (b) snowfall on an ice or snow covered lake will accumulate and be entirely captured by the lake as snowmelt. It should be noted that during warm weather periods in winter a lake's snow cover can be melted from below by heat conducted from the lake water through the ice cover or by radiative and conductive heat input from the atmosphere. The resulting snowmelt water accumulates between the snow cover and the lake ice cover, and freezes to "white ice" on the top of the existing lake ice cover when cold weather sets in.

2) as the difference between precipitation during the natural open-water period and open-water evaporation. This procedure is based on the assumption (a) that snowfall will not accumulate on a lake ice cover, but will be blown away by wind, and (b) water loss from the ice/snow surface of a lake is negligible.

It is likely that case (1) is more appropriate for wind sheltered, i.e. small lake surrounded by significant vegetation (trees) or buildings, while case (2) is representative of a lake with large surface areas and lack of wind sheltering.

2.5. Correlation of lake levels with evaporation

Correlation coefficients between water levels recorded in 25 Minnesota Lakes (8 landlocked and 17 flow-through lakes) and calculated annual evaporation or water availability (precipitation minus evaporation) were calculated. The names, locations and characteristics of the lakes included in this study are provided in Appendix 3.

3. RESULTS

3.1. Statistics of Daily Lake Evaporation in Minnesota

Daily evaporation rates at the six weather stations were calculated by the Meyer, Lake Hefner, Rohwer, and Ryan & Harleman equations with daily weather data for the 1964 – 2005 period as input. Examples of daily evaporation values for the month of July are given in Figures 5a and 5b. These figures were obtained by averaging daily evaporation values calculated by four equations for every July day from 1964 to 2005. Average daily evaporation values for July were in the range 3.5 - 6 mm/day (0.14 - 0.24 in/day). The Meyer equation gave the highest estimates for all stations and the Lake Hefner equation the lowest. Variations in daily evaporation in July were in the range 0.15 - 0.30 mm/day (0.006 - 0.012 in/day). Mean daily evaporation rates for

July calculated with the Meyer equation varied between 4.4 and 6.7 mm/day (0.17 and 0.26 in/day) for the six weather stations. The Lake Hefner equation gave mean annual evaporation rates from 3.1 to 4.9 mm/day (0.12 to 0.19 in/day); the Rohwer equation predicted values in the range from 3.9 to 5.5 mm/day (0.15 to 0.22 in/day), and the Ryan & Harleman equation gave values in the range from 3.6 to 6.6 mm/day (0.14 to 0.26 in/day).

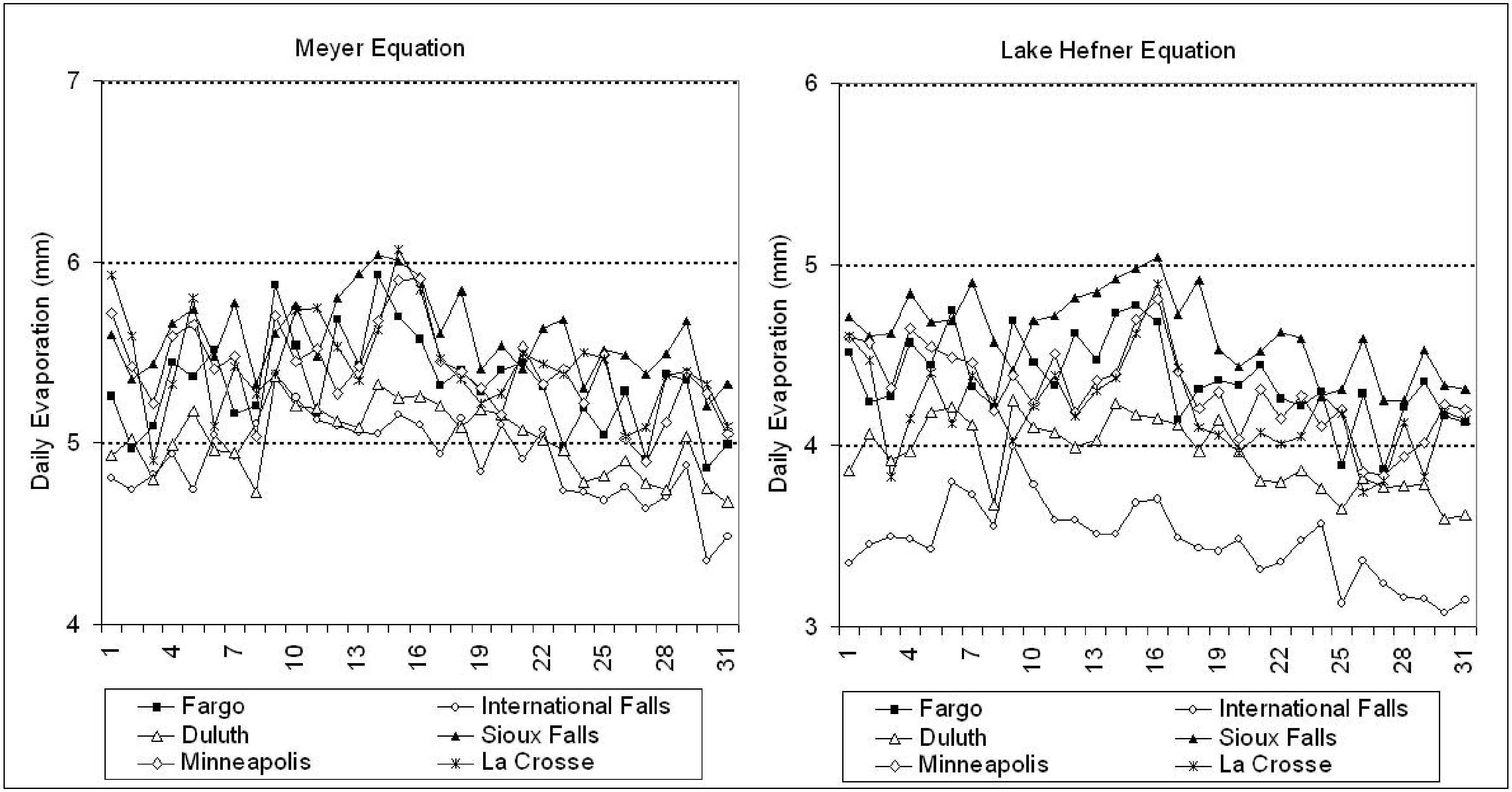

Figure 5a. Average daily evaporation for July calculated using the Meyer and Lake Hefner equations (1 in = 25.4 mm).

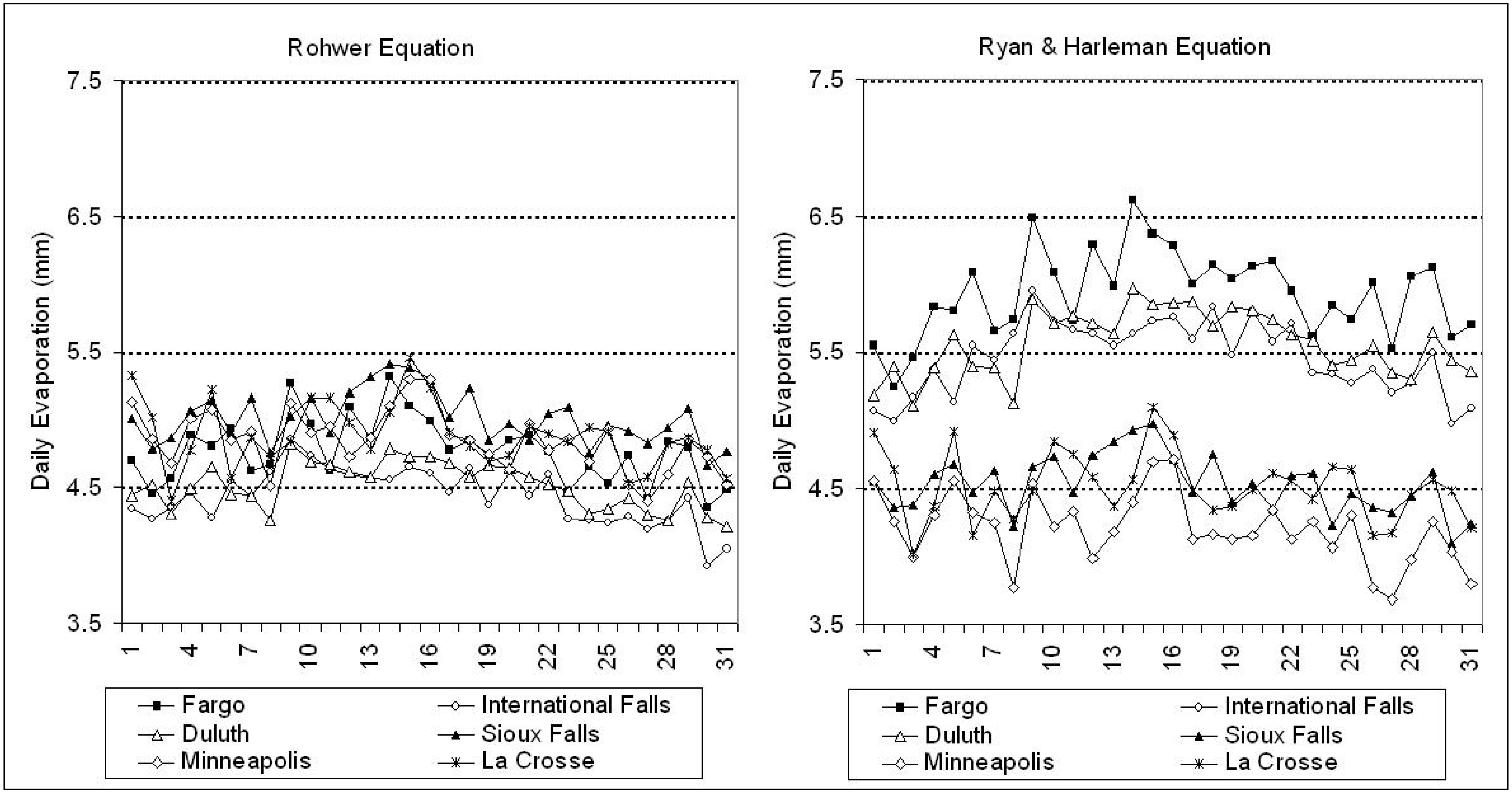

Figure 5b. Average daily evaporation for July calculated using the Rohwer and Ryan & Harleman equations (1 in = 25.4 mm).

3.2. Statistics of Monthly Lake Evaporation in Minnesota

Monthly evaporation values were obtained from computed daily values. A plot of monthly evaporation values is given in Figures 6a and 6b. Figure 6 was obtained by averaging daily evaporation values calculated by the four equations for every month from 1964 to 2005. Monthly evaporation values calculated with the Meyer, Lake Hefner, and Rohwer equations showed similar seasonal fluctuations for all six climate stations. Monthly evaporation values were consistently lowest at International Falls and highest at La Crosse. This geographic difference is expected and matches the gradients shown in Figures 1 and 2. Results were not quite as consistent when the Ryan & Harleman equation was used.

All equations predicted the occurrence of peak monthly evaporation in July. Variations in the monthly evaporation by latitude can be seen in Figures 6a and 6b, one panel for each equation used. The geographic range of computed July evaporation values was 134 - 160 mm (5.3 - 6.3 in) when the Meyer equation was used, 103 - 130 mm (4.1 - 5.2 in) for the Lake Hefner equation, 132 - 144 mm (5.2 - 5.7).for the Rohwer equation, and 123 - 179 mm (4.8 - 7.1 in) when the Ryan & Harleman equation was used.

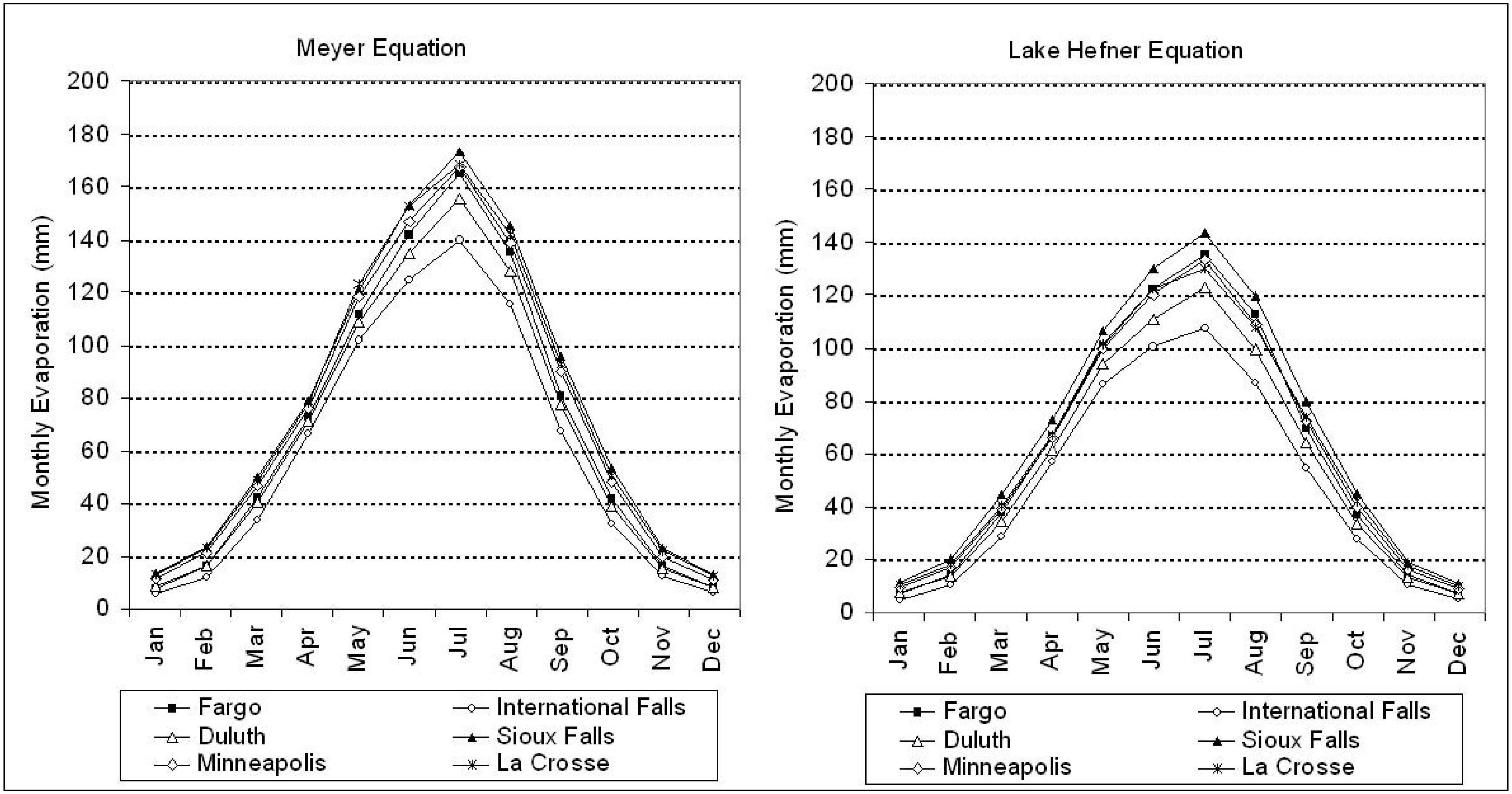

Figure 6a. Average monthly evaporation calculated using the Meyer and Lake Hefner equations (1 in = 25.4 mm).

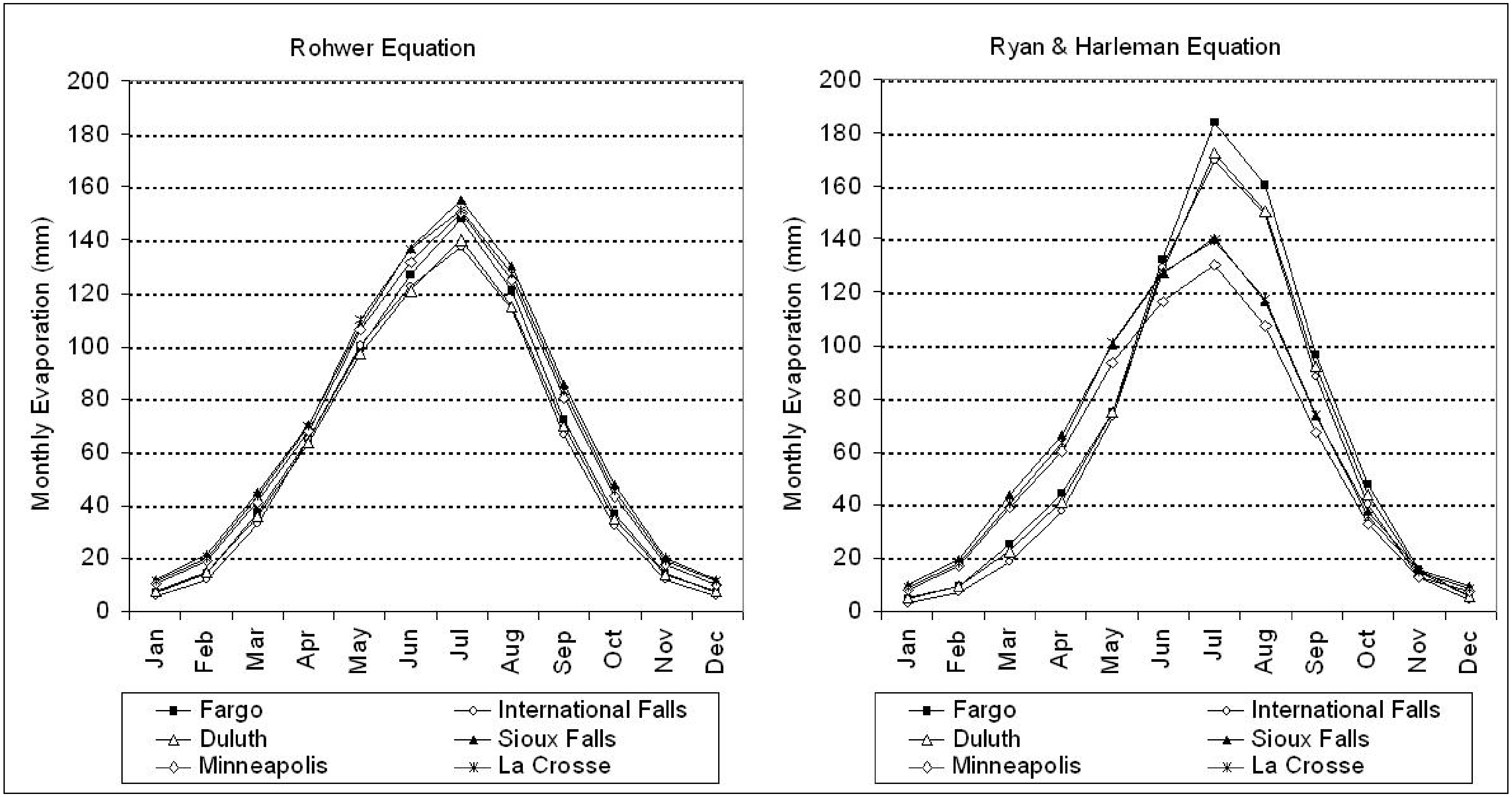

Figure 6b. Average monthly evaporation calculated using the Rohwer and Ryan & Harleman equations (1 in = 25.4 mm).

3.3. Statistics of Annual (Jan-Dec) Evaporation in Minnesota

Annual (Jan to Dec) evaporation was obtained as the sum of the daily values. Annual evaporation varied, as to be expected, by location and from year to year (Figures 7a and 7b). The four equations gave somewhat different results. Annual (Jan-Dec) evaporation values estimated by the Meyer Equation were consistently higher than values obtained from the other three equations. The Lake Hefner, the Rohwer, and the Ryan & Harleman equations provided similar results. Mean annual evaporation rates for the period 1994 – 2005 calculated with the Meyer equation varied between 781 and 942 mm/yr (30.8 and 37.1 in/yr) for the six locations investigated. The Lake Hefner equation gave mean annual evaporation rates from 579 to 802 mm/yr (22.8 to 31.6 in/yr); the Rohwer equation predicted values in the range from 704 to 843 mm/yr (27.7 to 33.2 in/yr), and the Ryan & Harleman equation gave values in the range from 692 to 800 mm/yr (27.2 to 31.5 in/yr).

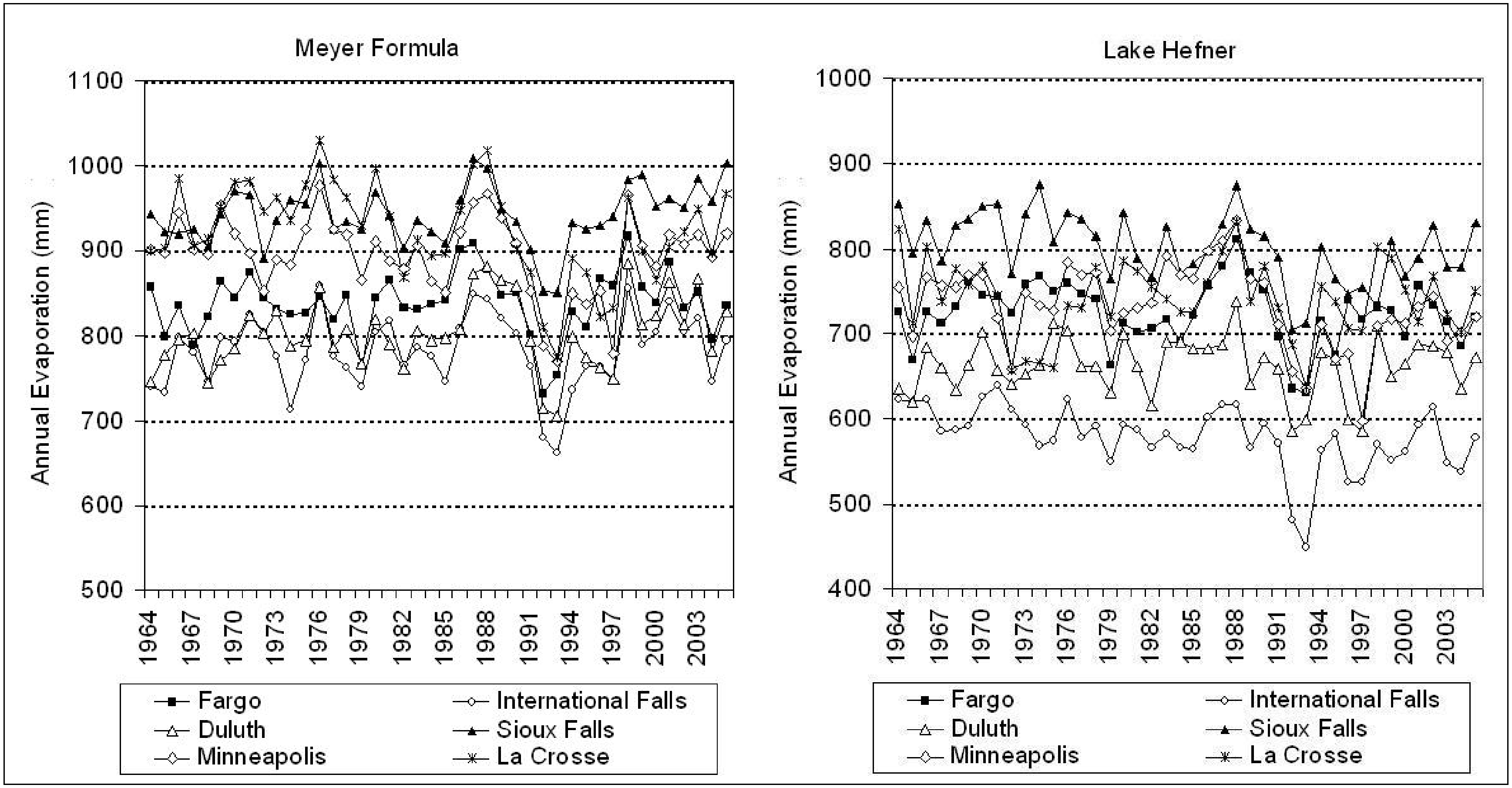

Figure 7a. Annual evaporation (Jan – Dec) from 1964 to 2005 calculated using the Meyer and Lake Hefner equations (1 in = 25.4 mm).

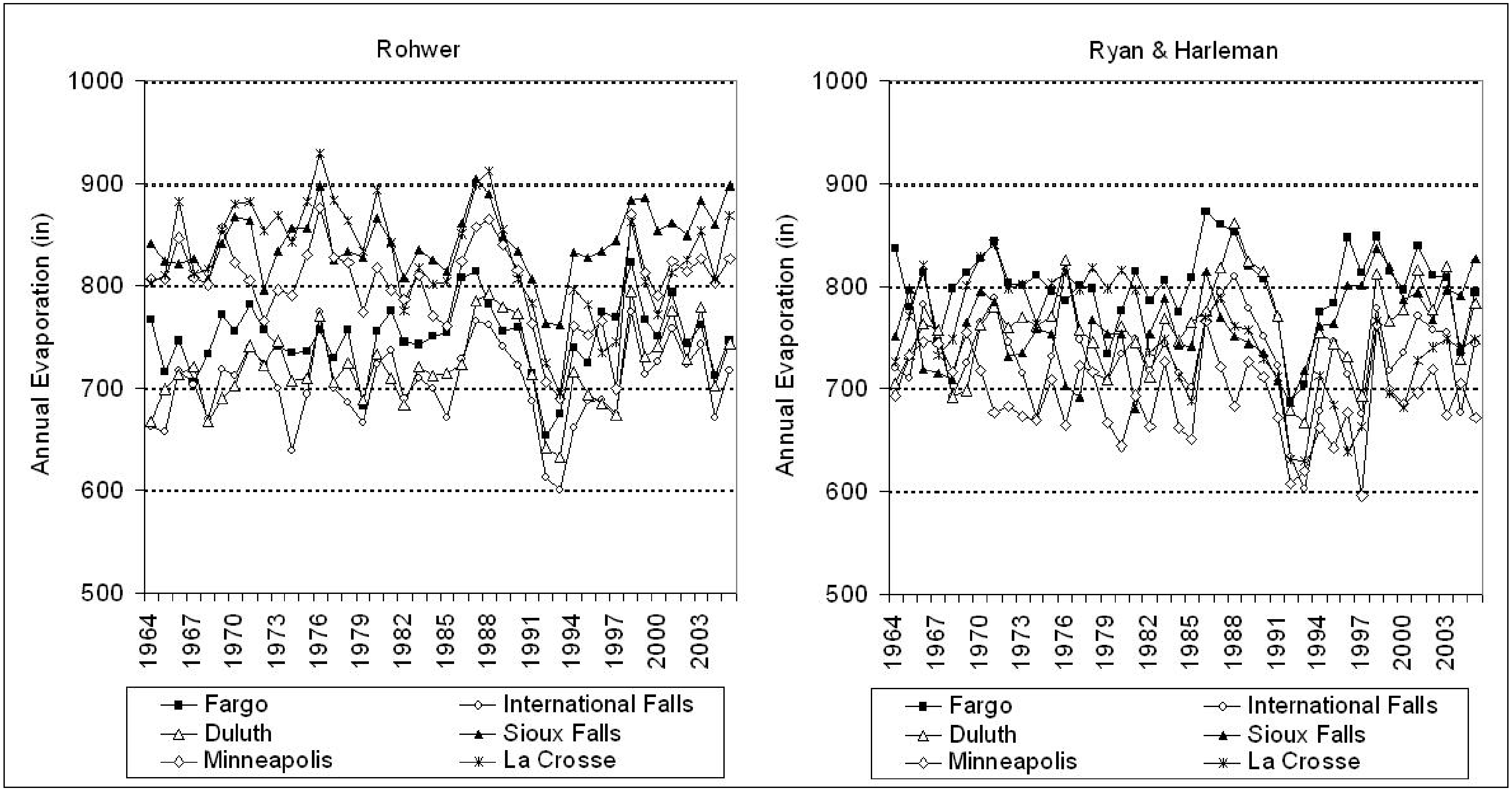

Figure 7b. Annual evaporation (Jan – Dec) from 1964 to 2005 calculated using the Rohwer and Ryan & Harleman equations (1 in = 25.4 mm).

When the values obtained with the four equations were averaged for every year and plotted against time, Figure 8 was obtained. Statistics of the time-series for the period 1964 – 2005 in Figure 8 are given in Table 2. According to Table 2 mean annual evaporation rates varied going from north to south. This is in agreement with Figures 1 and 2. The absolute values in Figures 1 are about the same as those in Table 2 for central Minnesota, but the gradient from north to south in Figure 1 is stronger than in Table2.

Standard deviation of mean annual evaporation does not seem related to latitude (Table 2), but the extreme values (minimum and maximum annual evaporation in the 1964 – 2005 period show a weak dependence on latitude.

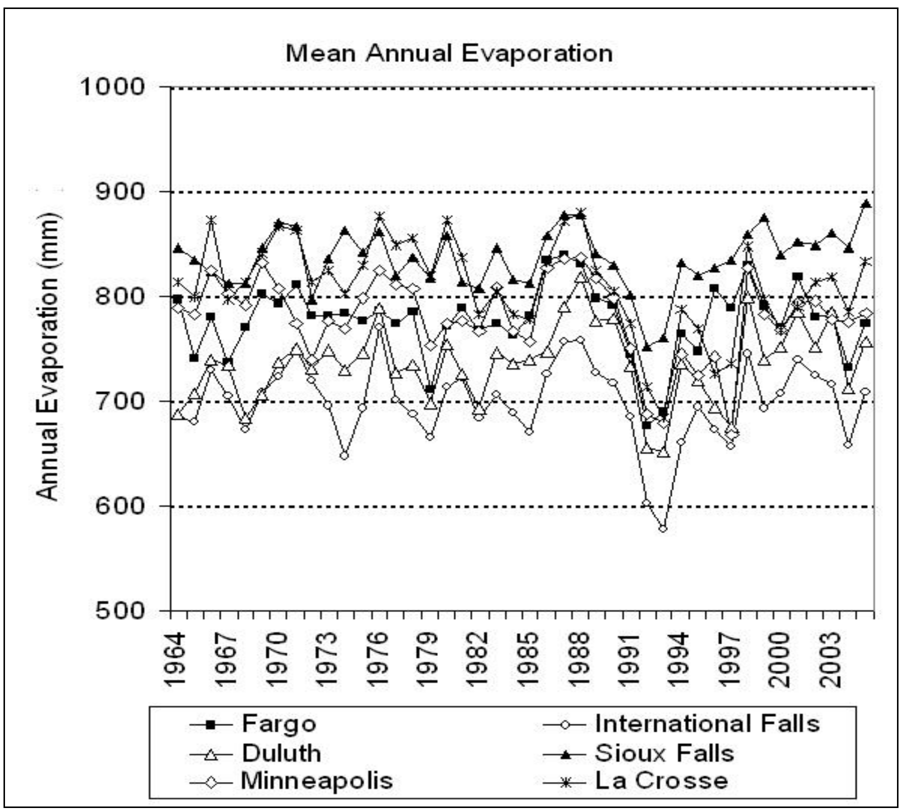

Figure 8. Mean annual evaporation calculated for six locations. Average values obtained by four equations are used.

Table 2. Statistics of annual (Jan-Dec) evaporation in mm/yr (in/yr) for 1964 – 2005. Values obtained by the four equations are averaged (1 in = 25.4 mm).

Location	Mean	Stand. Dev.	Minimum	Maximum
International Falls	699 (27.5)	38 (1.5)	579 (22.8)	770 (30.3)
Duluth	736 (29.0)	37 (1.4)	652 (25.7)	819 (32.2)
Fargo, ND	778 (30.6)	34 (1.3)	678 (26.7)	841 (33.1)
Minneapolis	780 (30.7)	40 (1.6)	668 (26.3)	838 (33.0)
La Crosse, WI	811 (31.9)	45 (1.8)	685 (27.0)	881 (34.7)
Sioux Falls, SD	837 (33.0)	29 (1.1)	752 (29.6)	889 (35.0)

According to Figure 8, the maximum of annual evaporation occurred in the years 1987 – 1988 for all stations except for International Falls and Sioux Falls. The minimum of annual evaporation for all stations occurred in the 1992 – 1993 period. 1987 – 1988 is recalled as an extremely dry period with very low river flows and lake stages. 1992 – 1993 was a wet period.

The periods of extreme evaporation also appear aligned with the periods of extreme annual air temperatures in Minnesota (Figure 9). Maximum annual average air temperature in Minnesota was observed in 1987 and minimum annual average air temperature in 1996. Overall the correlation between annual evaporation and annual average air temperature is not strong. Correlation coefficients varied from 0.12 to 0.38. The highest correlation was found for Duluth and the lowest for La Crosse.

The statistics (mean and standard deviation) of annual (Jan – Dec) evaporation rates obtained by individual equations are given in Table 3.

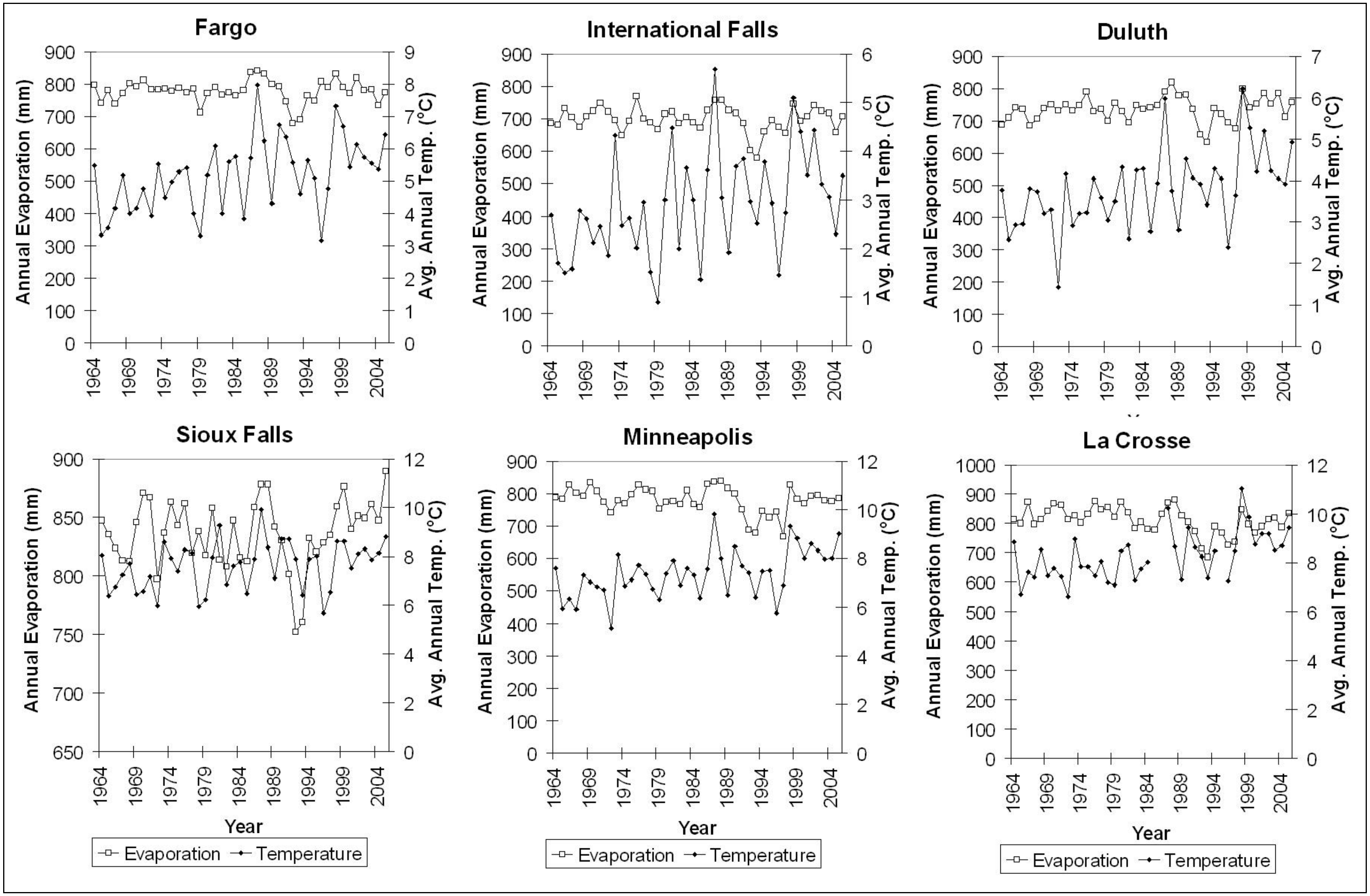

Figure 9. Annual evaporation vs. annual average air temperature at six locations.

Table 3. Statistics of annual (Jan – Dec) evaporation in mm/yr (in/yr) calculated with four evaporation equations for 1964 – 2005.

Equation	Statistic	Meyer	Lake Hefner	Rohwer	Ryan & Harleman
International Falls	Mean	781 (30.7)	579 (22.8)	704 (27.7)	733 (28.9)
	Std. Dev.	44 (1.7)	38 (1.5)	40 (1.6)	44 (1.7)
Duluth	Mean	803 (31.6)	662 (26.1)	721 (28.4)	760 (29.9)
	Std. Dev.	42 (1.7)	35 (1.6)	39 (1.5)	43 (1.7)
Fargo, ND	Mean	838 (33.0)	725 (28.5)	750 (29.5)	800 (31.5)
	Std. Dev.	38 (1.5)	37 (1.5)	34 (1.3)	38 (1.5)
Minneapolis	Mean	895 (35.2)	732 (28.8)	802 (31.6)	692 (27.2)
	Std. Dev.	47 (1.9)	48 (1.6)	42 (1.3)	39 (1.5)
La Crosse, WI	Mean	925 (36.4)	741 (29.2)	829 (32.6)	750 (29.5)
	Std. Dev.	56 (2.2)	45 (1.8)	52 (2.0)	55 (2.2)
Sioux Falls, SD	Mean	942 (37.1)	802 (31.6)	843 (33.2)	759 (29.9)
	Std. Dev.	36 (1.4)	41 (1.6))	32 (1.3)	39 (1.5)

All equations, except the Ryan & Harleman equation showed that the highest mean annual evaporation rate was at Sioux Falls and the lowest was at International Falls. The three northern locations (Fargo, International Falls, and Duluth) had lower mean annual evaporation rates than the three southern locations (Sioux Falls, Minneapolis, and La Crosse). Evaporation rates calculated with the Ryan & Harleman equation deviated from those obtained by the other three equations, possibly because the Ryan & Harleman equation was developed with data from heated water bodies such as cooling water ponds of power plants and warm springs, not natural lakes.

3.4. Statistics of Annual Natural Open-Water Evaporation in Minnesota: Effects of Ice Cover

Mean annual evaporation rates for the period 1964 – 2005, calculated for the **natural open-water period,** i.e. excluding the ice-cover period, were from 71 to 163 mm/yr (2.8 to 6.4

in/yr) lower than the calculated total annual evaporation from Jan to Dec. Mean annual evaporation rates for a natural open-water season, i.e. averages obtained from the four equations are plotted in Figure 10. The statistics of these values are given in Table 4. Averages of annual open-water evaporation rates obtained by individual equations are provided in Table 5.

Comparing the values in Tables 2 for the Jan-Dec period and in Table 4 for the open-water period leads to very similar conclusions. The same holds true for a comparison of Table 3 and Table 5. The geographic distribution of the mean annual evaporation rates for the open-water period resembles that for the full year (Jan to Dec). The highest and lowest annual open-water evaporation values were calculated for the southernmost and the northernmost locations, i.e. Sioux Falls and International Falls, respectively, when the Meyer, Lake Hefner, and Rohwer equations were used. The Ryan & Harleman equation deviated from that result.

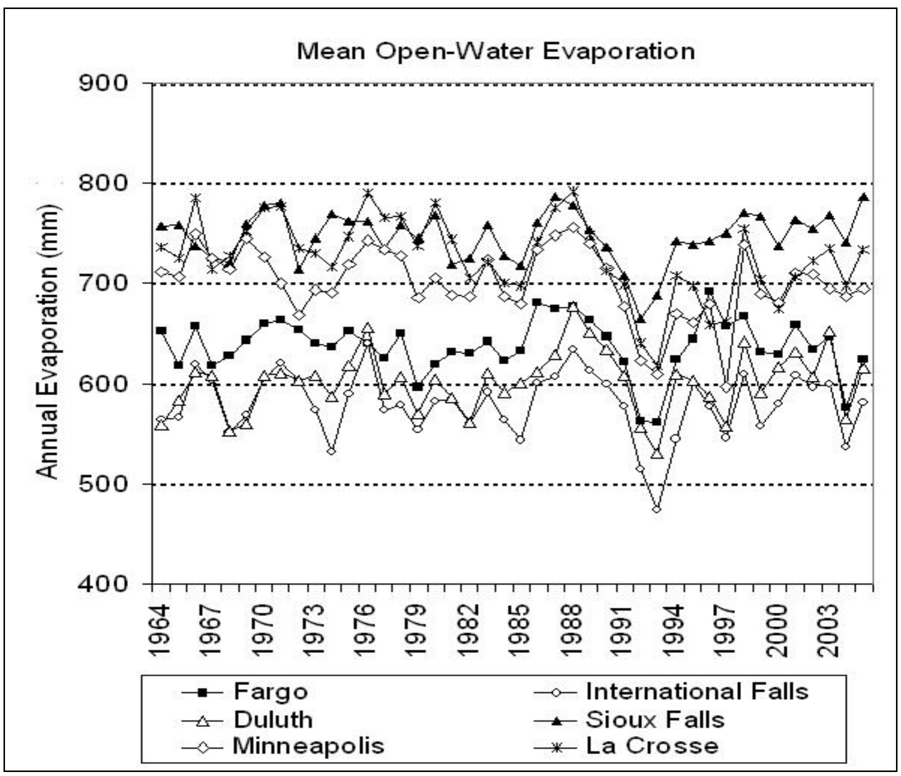

Figure 10. Annual natural open-water evaporation at 6 locations for 1964 – 2005. Values obtained by the four equations are averaged.

Table 4. Statistics of annual open-water evaporation in mm/yr (in/yr) for 1964 – 2005. Values obtained by the four equations for the natural open-water season are averaged.

Location	Mean	Stand. Dev.	Minimum	Maximum
International Falls	580 (22.8)	33 (1.3)	474 (18.7)	642 (25.3)
Duluth	602 (23.7)	31 (1.2)	531 (29.9)	678 (26.7)
Fargo. ND	638 (25.1)	28 (1.1)	561 (22.1)	693 (27.3)
Minneapolis	701 (27.6)	36 (1.4)	597 (23.5)	756 (29.8)
La Crosse, WI	727 (28.6)	40 (1.6)	619 (24.4)	793 (31.2)
Sioux Falls, SD	747 (29.4)	26 (1.0)	666 (26.2)	788 (31.0)

Table 5. Statistics of annual open-water evaporation in mm/yr (in/yr) calculated with four evaporation equations for 1964 – 2005.

Equation	Statistic	Meyer	Lake Hefner	Rohwer	Ryan and Harleman
International Falls	Mean	634 (25.0)	463 (18.2)	572 (22.5)	650 (25.6)
	Std. Dev.	36 (1.4)	31 (1.2)	33 (1.3)	41 (1.6)
Duluth	Mean	643 (25.3)	524 (20.6)	578 (22.8)	662 (26.1)
	Std. Dev.	35 (1.4)	28 (1.1)	32 (1.2)	39 (1.5)
Fargo, ND	Mean	676 (26.6)	578 (22.7)	605 (23.8)	696 (27.4)
	Std. Dev.	29 (1.1)	31 (1.2)	26 (1.0)	34 (1.4)
Minneapolis	Mean	805 (31.7)	657 (25.9)	722 (28.4)	621 (24.4)
	Std. Dev.	43 (1.7)	43 (1.7)	38 (1.5)	35 (1.4)
La Crosse, WI	Mean	829 (32.6)	662 (26.1)	744 (26.5)	674 (26.5)
	Std. Dev.	50 (2.0)	40 (1.6)	47 (1.9)	49 (1.9)
Sioux Falls, SD	Mean	843 (33.2)	716 (28.2)	754 (29.7)	677 (26.7)
	Std. Dev.	31 (1.2)	37 (1.5)	29 (1.1)	36 (1.4)

3.5. Trends in Annual (Jan-Dec), Open-Water and Peak Monthly (July) Evaporation in Minnesota

We examined the trends in evaporation for the 1964 – 2005 and 1986 – 2005 periods by using linear regression. In this trend estimation we used the evaporation values calculated by the Meyer equation. Although the Meyer equation provided somewhat higher results than the other three equations, we chose to use it for the trend analysis because (1) parameters of the Meyer equation were developed and tested with data from a Minnesota lake (Lake Minnetonka) -mass-transfer equations are expected to provide better estimates if parameters are obtained by calibration with local data-, and (2) the results obtained by the Meyer equation agree well with lake evaporation estimates for the Minnesota region (NCDC).

The a**nnual (Jan-Dec) evaporation** for the 1964 – 2005 period showed an increasing trend at four of the six locations investigated (Table 6). La Crosse and Minneapolis showed a decreasing trend. Only the trend for La Crosse was significant at the 0.05 level; trends for Duluth, Minneapolis and Sioux Falls were significant at the 0.5 level. The long-term trends were obviously weak, and are not readily apparent in Figure 7. The annual (Jan-Dec) evaporation for the more recent 1986 – 2005 period showed a decreasing trend (Table 6). These trends were negative, except for Sioux Falls. All trends were significant near the 0.5 level. It therefore appears that the trends over the 40-year and 20-year periods are reversed, but not significant. Even the strongest trends in the calculated annual evaporation were not hugely different. The extreme values were found for La Crosse (-1.7mm/yr; -0.065 in/yr) for the 1964 – 2005 period and for Sioux Falls (1.2mm/yr; 0.046 in/yr) for the 1986 – 2005 period.

The statistics of annual evaporation rates calculated by the Meyer equation for the two periods (1964 – 2005 and 1986 – 2005) are summarized in Table 7. Average annual evaporation rates were higher during the 1986 – 2005 period than the 1964 – 2005 period for four stations, except Minneapolis and LaCrosse. Standard deviations of mean annual evaporation rates were higher for the 1986 – 2005 period than the 1964 – 2005 period for all stations.

Overall the results suggest that evaporation became more variable in the last 20-year period, but that no significant trend can be established.

Annual open-water evaporation from 1964 to 2005 showed no conclusive trends. (Table 6). From 1986 to 2005 all stations, except Sioux Falls, showed a negative trend. The trends for Fargo, Sioux Falls, and La Crosse were significant at the 0.5 level. The strongest trends in both time periods were observed at La Crosse (-0.065 and -0.062 in/yr, respectively). Means and standard deviations of annual open-water evaporation values for the two periods showed similar geographic distributions as the annual (Jan-Dec) evaporation (Table 7).

Table 6. Trends in annual evaporation, open-water evaporation, and peak monthly evaporation calculated by linear regression on values from the Meyer equation (1 in=25.4 mm).

		1964 – 2005			1986 – 2005		
Location	Trend And Sig.	Annual Evap. (mm/yr)	Open Water Evap. (mm/yr)	Peak Monthly Evap. (mm/mo)	Annual Evap. (mm/yr)	Open Water Evap. (mm/yr)	Peak Monthly Evap. (mm/mo)
International Falls	Trend	0.30	0.13	0.08	-0.05	-0.69	0.53
	Sig.	0.58	0.79	0.56	0.98	0.69	0.35
Duluth	Trend	0.84	0.64	0.13	-0.25	-1.07	0.25
	Sig.	0.13	0.16	0.46	0.90	0.52	0.67
Fargo, ND	Trend	0.23	-0.03	-0.03	-0.89	-1.32	0.33
	Sig.	0.63	0.93	0.90	0.64	0.39	0.54
Minneapolis	Trend	-0.81	-0.99	-0.25	-0.20	-0.69	0.30
	Sig.	0.18	0.07	0.15	0.93	0.75	0.63
La Crosse, WI	Trend	-1.65	-1.65	-0.30	-1.17	-1.57	-0.13
	Sig.	0.02	0.01	0.04	0.65	0.48	0.84
Sioux Falls, SD	Trend	0.56	0.23	0.03	1.63	1.09	0.36
	Sig.	0.22	0.56	0.79	0.35	0.47	0.50

Maximum (peak) monthly evaporation occurred in July. From 1964 to 2005 it had a decreasing trend for Fargo, Minneapolis, and La Crosse and an increasing trend for International Falls, Duluth, and Sioux Falls (Table 6). Only the trend for La Crosse was significant at the 0.05 level, while all others were near the 0.5 level. From 1986 to 2005, peak monthly evaporation showed an upward trend at all stations except La Crosse (Table 7). The trends were significant near the 0.5 level. The strongest trend in July evaporation was obtained for La Crosse for the

1964 – 2005 period (-0.012 in/month) and in Sioux Falls for the 1986 – 2005 period (0.021 in/month).

Table 7. Mean and standard deviation of annual (Jan – Dec) and open-water evaporation in mm/yr (in/yr) for the periods 1964 – 2005 and 1986 – 2005 from the Meyer equation

		Annual Evaporation		Annual Open-Water Evaporation	
Location	Statistic	1964 – 2005	1986 – 2005	1964 – 2005	1986 – 2005
International Falls	Mean	781 (30.7)	785 (30.1)	634 (25.0)	637 (25.1)
	Std. Dev.	44 (1.7)	53 (2.1)	36 (1.4)	41 (1.6)
Duluth	Mean	803 (31.6)	813 (32.0)	643 (25.3)	653 (25.7)
	Std. Dev.	42 (1.7)	54 (2.1)	35 (1.4)	41 (1.6)
Fargo, ND	Mean	838 (33.0)	843 (33.2)	676 (26.6)	678 (26.7)
	Std. Dev.	38 (1.5)	48 (1.9)	29 (1.1)	38 (1.5)
Minneapolis	Mean	895 (35.2)	887 (34.9)	805 (31.7)	796 (31.3)
	Std. Dev.	47 (1.9)	60 (2.3)	43 (1.7)	53 (2.1)
La Crosse, WI	Mean	925 (36.4)	904 (35.6)	829 (32.6)	809 (31.8)
	Std. Dev.	56 (2.2)	64 (2.5)	50 (2.0)	56 (2.2)
Sioux Falls, SD	Mean	942 (37.1)	948 (37.3)	843 (33.2)	845 (33.3)
	Std. Dev.	36 (1.4)	43 (1.7)	31 (1.2)	38 (1.5)

To summarize, all three parameters (i.e., annual (Jan-Dec), open-water, and peak monthly evaporation) had an upward trend at International Falls, Duluth, and Sioux Falls and a downward trend at Minneapolis and La Crosse for the period 1964 – 2005. In recent years (1986 – 2005), there has been a change in direction of annual and open-water evaporation trends for International Falls and Duluth and peak monthly evaporation trend for Minneapolis. The trends at all other locations have remained the same, although their magnitudes have changed. For example, the magnitude of annual and open-water evaporation trends has decreased for Minneapolis and La Crosse in recent years, but increased for Sioux Falls.

3.6. Statistics and Trends of Annual Precipitation in Minnesota

Precipitation is considered in this study because the difference between annual evaporation and annual precipitation gives the net water loss through a lake's surface. To maintain a stable lake level the net loss of water through a lake's surface has to be made up by surface runoff from the watershed into a lake or by a net groundwater input.

Annual precipitation time series at the six locations Figure 4 have been plotted in Figure 11. The lowest annual precipitation for the 1964 – 2005 period was observed at Fargo with an average rate of 536 mm/yr (21.1 in/yr). The highest annual precipitation was observed at La Crosse with an average rate of 812 mm/yr (32.0 in/yr). The highest variation in annual precipitation was at Minneapolis (standard deviation was 154 mm/yr or 6.1 in/yr) and the lowest variation was at International Falls (standard deviation was 91 mm/yr or 3.6). Both annual (Jan-Dec) and annual open-water season precipitation were higher during the 1986 – 2005 period than the 1964 – 2005 period for all stations except International Falls (Table 8).

Table 8. Mean and standard deviation of annual (Jan – Dec) and open-water season precipitation in mm/yr (in/yr) for the periods 1964 – 2005 and 1986 – 2005 .

		Annual (Jan-Dec) Precipitation		Annual Open-Water Precipitation	
Location	Statistic	1964 – 2005	1986 – 2005	1964 – 2005	1986 – 2005
International Falls	Mean	616 (24.3)	599 (23.6)	466 (18.3)	461 (18.1)
	Std. Dev.	91 (3.6)	93 (3.7)	77 (3.0)	81 (3.2)
Duluth	Mean	786 (31.0)	792 (31.2)	551 (21.7)	567 (22.3)
	Std. Dev.	133 (5.2)	139 (5.5)	110 (4.3)	117 (4.6)
Fargo, ND	Mean	535 (21.1)	572 (22.5)	395 (15.6)	431 (17.0)
	Std. Dev.	131 (5.1)	136 (5.3)	115 (4.5)	118 (4.6)
Minneapolis	Mean	751 (29.6)	774 (30.5)	633 (24.9)	669 (26.3)
	Std. Dev.	154 (6.1)	130 (5.1)	148 (5.8)	129 (5.1)
La Crosse, WI	Mean	812 (32.0)	837 (32.9)	678 (26.7)	696 (27.4)
	Std. Dev.	151 (5.9)	145 (5.7)	143 (5.6)	125 (4.9)
Sioux Falls, SD	Mean	632 (24.9)	656 (25.8)	547 (21.6)	575 (22.6)
	Std. Dev.	148 (5.8)	149 (5.9)	132 (5.2)	136 (5.4)

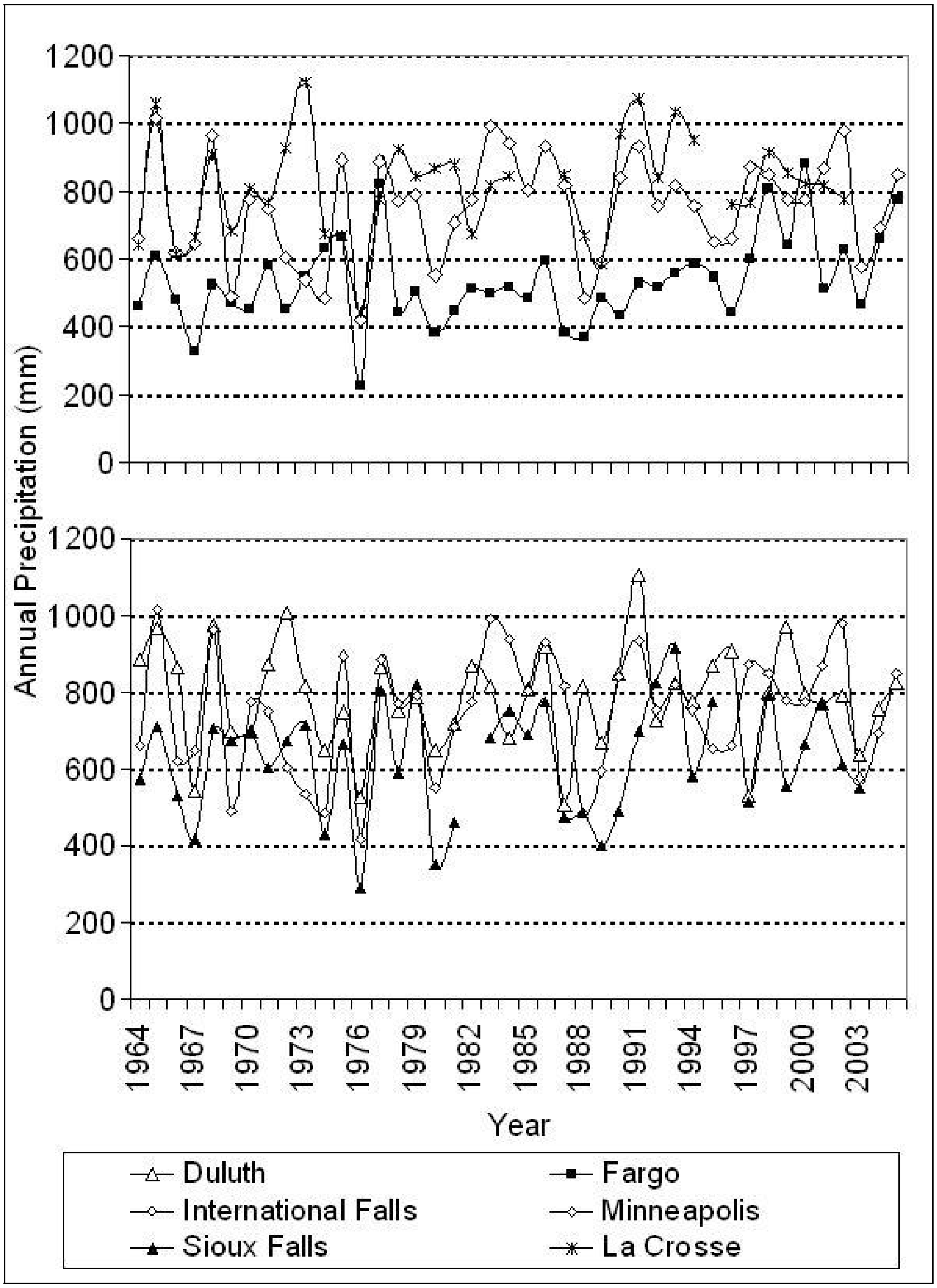

Figure 11. Annual precipitation at six weather stations.

Trends in precipitation were analyzed for the 1964 – 2005 and 1986 – 2005 periods (Table 9). For the 1964 – 2005 period, precipitation at the three southern locations, i.e. Sioux Falls, La Crosse, Minneapolis, as well as Fargo had an upward trend. Only the trend for Fargo was significant at the 0.05 level. Trends at all other locations, except International Falls, were significant at the 0.5 level (Table 9).

For the more recent 1986 – 2005 period, precipitation at all stations, except La Crosse and Duluth, showed an upward trend. The trend for Fargo was significant at the 0.05 level and the trends at the other stations, except Duluth, were significant at the 0.5 level (Table 9).

Table 9. Trends in precipitation (mm/yr) for 1964 – 2005 and 1986 – 2005.

Location	Period	1964 – 2005	1986 – 2005
International Falls	Trend	-0.84	5.10
	Sig.	0.47	0.16
Duluth	Trend	-0.44	-1.10
	Sig.	0.80	0.84
Fargo, ND	Trend	3.89	13.18
	Sig.	0.02	0.01
Minneapolis	Trend	2.47	1.78
	Sig.	0.21	0.73
La Crosse, WI	Trend	1.70	-1.53
	Sig.	0.39	0.78
Sioux Falls, SD	Trend	2.61	7.20
	Sig.	0.17	0.22

3.7. Statistics and Trends of Annual Water Availability (Precipitation minus Evaporation)

Annual water availability is defined as precipitation minus evaporation through a lake surface. Water availability is calculated as a) annual precipitation minus annual open-water evaporation, and b) annual open-water season precipitation minus open-water evaporation. This dual approach is used because in the winter months when lakes are ice-covered and precipitation is in the form of snow, the water gains and losses are more difficult to quantify then for the summer months. Under the scenario (a) the water availability is maximum, i.e. winter precipitation is retained in its entirety as an input to the lake. There is no water loss by snow blown away from the lake surface onto land, or by ablation of snow and ice from the frozen lake surface. Under scenario (b) the water availability is a minimum because winter precipitation is ignored entirely, i.e. snow fall on a lake surface is blown away by the wind or evaporated. It is likely that scenario (a) matches conditions on small, wind-sheltered lakes better, while scenario (b) may be more appropriate for lakes with large wind-exposed fetches.

Table 10 provides the statistics of water availability for the six stations. The values in Table 10 are the differences between measured precipitation (Table 8) and calculated annual evaporation (Table 7). All are annual values averaged over the indicated period. According to Table 10, water availability (for scenarios (a) and (b)) in all stations except International Falls and Duluth was higher in the last 20 years (1986 – 2005). Water availability at International Falls showed a slight decrease in the 1986 – 2005 period. Water availability at Duluth calculated with scenario (a) showed a slight decrease and water availability calculated with scenario (b) showed an increase in the last 20 years.

Annual water availability has a negative value for most years at all six locations because evaporation tends to exceed precipitation. This water deficit has to be made up by surface runoff from the watershed into a lake or by a net groundwater input if a stable lake level is to be maintained.

Table 10. Mean and standard deviation of annual water availability in mm/yr (in/yr) for the periods 1964 – 2005 and 1986 – 2005 . Water availability is calculated as a) annual precipitation minus annual open-water season evaporation, and b) annual open-water season precipitation minus annual open-water season evaporation.

		Precipitation - Open-Water Evaporation		Open-Water Precipitation - Open-Water Evaporation	
Location	Statistic	1964 – 2005	1986 – 2005	1964 – 2005	1986 – 2005
International Falls	Mean	-18 (-0.7)	-39 (-1.5)	-168(-6.6)	-177 (-7.0)
	Std. Dev.	106 (4.2)	106 (4.2)	92 (3.6)	93 (3.6)
Duluth	Mean	256 (10.1)	253 (10.0)	21 (0.8)	28 (1.1)
	Std. Dev.	141 (5.6)	147 (5.8)	118 (4.7)	128 (5.1)
Fargo, ND	Mean	-140 (-5.5)	-107 (-4.2)	-281 (-11.0)	-248 (-9.7)
	Std. Dev.	138 (5.4)	147 (5.8)	121 (4.8)	131 (5.2)
Minneapolis	Mean	-54 (-2.1)	-22 (-0.9)	-173 (-6.8)	-127 (-5.0)
	Std. Dev.	171 (6.7)	151 (5.9)	166 (6.5)	153 (6.0)
La Crosse, WI	Mean	-16 (-0.6)	30 (1.3)	-150 (-5.9)	-110 (-4.3)
	Std. Dev.	167 (6.6)	153 (6.0)	167 (6.6)	153 (6.0)
Sioux Falls, SD	Mean	-212 (-8.3)	-190 (-7.5)	-308 (-12.1)	-294 (-11.6)
	Std. Dev.	164 (6.4)	170 (6.7)	171 (6.7)	204 (8.0)

Trends in annual water availability are given in Table 11. For the period 1964 – 2005, annual water availability – calculated as annual precipitation minus annual open-water evaporation – showed an upward trend, i.e. a smaller annual water deficit at the lake surface, for Fargo, Minneapolis, Sioux Falls, and La Crosse. The trend calculated for Fargo was significant at the 0.05 level, all others were significant at the 0.5 level. Annual water availability for International Falls and Duluth showed a decreasing trend. For International Falls this trend was significant at the 0.5 level; for Duluth the trend was not significant.

For the period 1986 – 2005, water availability trends were upward for International Falls, Fargo, Minneapolis, and Sioux Falls (Table 11). Trends for Fargo were significant at the 0.05 level; trends for International Falls, Minneapolis, and Sioux Falls were significant at the 0.5

level. Annual water availability had an upward trend for Duluth, but a downward trend for La Crosse.

For the period 1964 – 2005, annual water availability – calculated as the difference between open-water precipitation minus open-water evaporation – showed increasing trends at all stations (Table 11). The trends for Fargo and Minneapolis were significant at the 0.05 level, and the trends for La Crosse and Sioux Falls at the 0.5 level. The trends for International Falls and Duluth were near zero, but the other four ranged from 1.6 to 4.3 mm/yr.

For the period 1986 – 2005, annual water availability for the open-water season (Table 11) showed an upward trend at all locations, except Duluth. The trends for Fargo and Sioux Falls were significant at the 0.05 level, the trend for International Falls at the 0.5 level. The strongest trend was at Fargo (15.1mm/yr).

Table 11. Trends (mm/yr) in annual water availability. Water availability is calculated as a) annual precipitation minus annual open-water evaporation, and b) annual open-water season precipitation minus annual open-water evaporation.

		Precipitation - Open-Water Evaporation		Open-Water Precipitation - Open-Water Evaporation	
Location	Trend Sig.	1964 – 2005	1986 – 2005	1964 – 2005	1986 – 2005
International Falls	Trend	-0.96	5.77	0.18	6.76
	Sig.	0.48	0.17	0.88	0.06
Duluth	Trend	-0.98	-0.22	0.05	-2.67
	Sig.	0.59	0.97	0.97	0.61
Fargo, ND	Trend	3.93	14.50	4.27	15.06
	Sig.	0.02	0.01	0.00	0.00
Minneapolis	Trend	3.45	2.47	4.17	2.29
	Sig.	0.11	0.68	0.05	0.71
La Crosse, WI	Trend	3.68	1.89	3.23	0.58
	Sig.	0.09	0.78	0.13	0.93
Sioux Falls, SD	Trend	2.37	6.09	1.63	5.04
	Sig.	0.27	0.37	0.47	0.54

3.8. Correlations of lake levels with evaporation or water availability

In a previous study (Dadaser-Celik and Stefan 2007) historical lake levels recorded in 25 Minnesota lakes were analyzed and correlated with climate parameters. That study can be extended by examining the lake level correlations with evaporation or water availability at the water surface. It is a logical step forward although it still does not include inflows from the watershed or groundwater interaction of a lake.

The correlation coefficients between observed annual average water levels of 8 landlocked and 17 flow-through lakes and computed annual evaporation, annual open-water evaporation, and annual water availability were calculated (Tables 12 and 13). Evaporation and water availability values were taken from one of the six weather stations (Figure 4) nearest the lake. The correlation between lake levels and evaporation would be expected to be negative (higher evaporation = lower lake levels); while the correlation with water availability would be expected to be positive (more net water input = higher lake levels).

The correlation coefficients in Tables 12 and 13 are very low indicating that evaporation alone is not a predictor of lake levels. Water levels correlated slightly better with annual water availability, but it also cannot be used as a sole predictor variable. As to be expected lake levels of 22 out of 25 lakes (88%) had a negative correlation with evaporation, but even the best correlation coefficients was only -0.47. The correlation between lake levels and water availability at the lake surface was positive for 24 of 25 lakes (96%), but the highest correlation coefficient was only 0.66. For **landlocked lakes** the average correlation coefficients were poorer than for **flow-through lakes**, especially for evaporation. The reason for this is unknown, but it can be speculated that the interaction of landlocked lakes with groundwater is so dominant that evaporation becomes fairly negligible.

Table 12. Correlations coefficients of observed water levels in 8 landlocked lakes with calculated evaporation or water availability.

Lake Name	Jan – Dec Evaporation	Open-Water Evaporation	Maximum Water Availability[1]	Minimum Water Availability[2]
Belle Taine	0.42	0.35	0.23	0.28
Emily	-0.36	-0.36	0.03	0.02
Island	-0.37	-0.37	0.34	0.34
Little Sand	0.30	0.16	0.41	0.45
Loon	-0.07	-0.12	0.30	0.37
Otter Tail	-0.06	-0.03	0.37	0.42
Sturgeon	-0.34	-0.37	0.28	0.31
Swan	-0.21	-0.19	0.15	0.10
Average	**-0.08**	**-0.12**	**0.26**	**0.29**

[1] annual precipitation – annual open-water evaporation

[2] annual open-water precipitation – annual open-water evaporation

Table 13. Correlations coefficients of observed water levels in 17 flow-through lakes with calculated evaporation and water availability.

Lake Name	Jan – Dec Evaporation	Open-Water Evaporation	Maximum Water Availability[1]	Minimum Water Availability[2]
Benton	-0.18	-0.12	0.24	-0.04
Birch	-0.39	-0.41	0.38	0.38
Detroit	0.16	0.12	0.46	0.50
East Fox	-0.29	-0.34	0.53	0.53
Green	-0.44	-0.44	0.40	0.41
Height of Land	-0.14	-0.06	0.27	0.30
Marion	-0.32	-0.36	0.26	0.28
Minnetonka	-0.37	-0.39	0.35	0.33
Minnewaska	-0.19	-0.05	-0.09	-0.06

Mud	-0.41	-0.47	0.66	0.64
Pelican	-0.31	-0.32	0.23	0.20
Peltier	-0.41	-0.45	0.48	0.52
Rush	-0.12	-0.09	0.40	0.40
Shetek	-0.19	-0.12	0.56	0.09
Swan	-0.37	-0.40	0.11	0.09
Upper Prior	-0.27	-0.32	0.23	0.20
Vermillion	-0.29	-0.33	0.38	0.42
Average	**-0.27**	**-0.27**	**0.34**	**0.31**

[1] annual precipitation – annual open-water evaporation [2] annual open-water precipitation – annual open-water evaporation

We also calculated the correlation coefficients between lake levels in October and evaporation during the summer (June-August and May-October) (Tables 14 and 15). May-October evaporation had a higher average correlation coefficient than June-August evaporation. Correlation coefficients of October water levels with May-October evaporation were negative, as to be expected for 22 out of 25 lakes (88 %), but the best value was only -0.64, and the average only -0.22 and -0.27 for **landlocked and flow-through lakes**, respectively.

Table 14. Correlation coefficients of observed October water levels in 8 landlocked lakes with calculated summer evaporation.

Lake Name	June-August Evaporation	May-October Evaporation
Belle Taine	0.45	0.32
Emily	-0.56	-0.64
Island	-0.44	-0.48
Little Sand	0.10	0.00
Loon	-0.21	-0.14
Otter Tail	-0.13	-0.19
Sturgeon	-0.06	-0.27
Swan	-0.30	-0.38
Average	**-0.14**	**-0.22**

Table 15. Correlation coefficients of observed October water levels in 17 flow-through lakes with calculated summer evaporation.

Lake Name	June-August Evaporation	May-October Evaporation
Benton	0.29	-0.01
Birch	-0.40	-0.49
Detroit	0.03	0.15
East Fox	0.02	-0.13
Green	-0.02	-0.24
Height of Land	-0.12	-0.10
Marion	-0.55	-0.53
Minnetonka	-0.42	-0.52
Minnewasha	-0.14	-0.11
Mud	-0.51	-0.50
Pelican	-0.04	-0.12
Peltier	-0.41	-0.47
Rush	-0.21	-0.18
Shetek	-0.23	-0.21
Swan	-0.34	-0.35
Upper prior	-0.49	-0.57
Vermillion	-0.34	-0.26
Average	**-0.23**	**-0.27**

In summary, these results show that the correlation between lake water levels and evaporation and water availability is low. This is attributed to the fact that surface water inflow from the watershed of a lake and groundwater interactions (Eq.1) affect lake water levels at least as much or more than evaporation and precipitation on the lake surface. The obvious conclusion is that for most lake water budgets surface water runoff from the watershed must be considered.

4. SUMMARY & CONCLUSIONS

Lake evaporation can be measured as pan evaporation or computed from relationships with climate parameters. We reviewed measured pan evaporation data and computed evaporation rates from Minnesota lakes by using daily weather data recorded at six Class A weather stations (Figure 4) from 1964 to 2005. Daily evaporation at these stations was estimated using mass-transfer equations named after Meyer, Lake Hefner, Rohwer, and Ryan and Harleman. Results were analyzed individually or as averages.

Trends in evaporation and water availability (precipitation minus evaporation) were calculated using linear regression. We also compared results for the full period of record (1964 – 2005) with results for the recent 20 years (1986 – 2005). For the trend analysis we selected the Meyer equation as most appropriate for Minnesota conditions.

We examined the correlation coefficients between annual average water levels of 25 previously analyzed Minnesota lakes (Dadaser-Celik and Stefan (2007) and annual evaporation or water availability. Eight lakes were landlocked and 17 flow-through lakes.

The results can be summarized as follows:

1) July is the month with the highest evaporation from lake surfaces in Minnesota. Daily evaporation from Minnesota lakes in July is on average 4.4 – 6.7 mm/day (0.17 – 0.26 in/day). Monthly evaporation in July varied in the range 134 – 160 mm (5.3 – 6.3 in).
2) Annual evaporation from Minnesota lakes ranged from 781 to 942 mm/yr (30.8 to 37.1 in/yr). To obtain these results, daily values calculated by the Meyer equation for six locations were averaged for the 1964 – 2005 period. The lowest evaporation occurs when Minnesota lakes are ice-covered.
3) The open-water season evaporation showed no consistent trend in the 1964 – 2005 period (Table 6). Three locations (International Falls, Duluth and Sioux Falls) had a weakly rising trend (0.13 to 0.64 mm/yr), and the other three locations (Fargo, Minneapolis and La Crosse) had a weakly falling trend (-0.03 to -1.65 mm/yr).
4) Over the last 20 years (1986 – 2005), the open-water season evaporation trends became slightly more negative. Five of the six locations had negative trends from -0.69 to -1.57mm/yr. The exception was Sioux Falls with a positive trend of 1.09mm/yr (Table 6).

5) Annual average precipitation at the six locations ranged from 536mm/yr to 812 mm/yr (21.1 in/yr to 32.0 in/yr) in the 1964 – 2005 period. Annual precipitation showed a rising trend at four of the six locations (International Falls and Duluth were the exceptions) from 1964 to 2005. Increasing trends were in the range of 1.70 to 3.85 mm/yr, while the strongest decreasing trend was -0.84 mm/yr (Table 8).

6) Over the last 20 years (1986 – 2005), the annual precipitation also showed a rising trend at four of the six locations (Duluth and La Crosse were the exceptions). Increasing trends were in the range of 1.78 to 13.18 mm/yr, while the strongest decreasing trend was –1.53 mm/yr (Table 8).

7) Water availability had trends similar to precipitation for the period 1964 – 2005. The strongest upward trend was found for Fargo with a rate of 3.93 mm/yr and the strongest negative trend for Duluth with a rate of -0.98 mm/yr. For the last 20 years (1986 – 2005) water availability had a stronger upward trend (e.g., 14.5 mm/yr in Fargo) than for the 40-year period (1964 – 2005).

8) Water availability during the open-water period – calculated as annual open-water season precipitation minus annual open-water evaporation – increased at all six locations from 1964 to 2005 (Table 9). The strongest rise was at Fargo with a rate of 4.27 mm/yr.

9) From 1986 to 2006, water availability during open-water periods showed even stronger rising trends for all locations, except Duluth. The strongest upward trend was again at Fargo (15.06mm/yr). Duluth had a downward trend of -2.67mm/yr.

We have also attempted to understand how Minnesota lake levels have responded to climate in the past 40 year, and evaporation is an important component of this investigation. Correlation coefficients between annual lake water levels and annual evaporation or annual water availability were, however, very weak. Similarly weak were correlation coefficients between lake levels in October and evaporation from May to October.

Overall, the analysis shows that lake evaporation in Minnesota in the last 40 and the last 20 years has had trends that were not strong enough to form a conclusion about evaporation changes. Evaporation seems to have become more variable from year to year in the last 20 years. By comparison trends in precipitation during the same time periods were positive and much stronger than trends in evaporation. As a result, upward trends in annual water availability exist in the state of Minnesota. That is mostly good news.

Although we did not find strong correlations between lake levels and evaporation and water availability, increases in water availability can perhaps explain the increased observed water levels of 25 lakes, which we analyzed before (Dadaser-Celik and Stefan 2007).

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APPENDIX 1. Sensitivity of evaporation to water temperature assumption

In the sensitivity analysis, we estimated average daily lake water water temperatures by solving equation A1.1

$$\frac{dT}{dt} = \frac{K(T_e - T_w)}{\rho Ch} \qquad \text{(A1.1)}$$

In Equation A1.1, T_w is water surface temperature (^oC), t is time (day), K is the bulk surface heat exchange coefficient ($W/m^2/C$), T_e is the equilibrium temperature (^oC), ρ is density of water (1,000 kg/m^3), C is the heat capacity of water (4,186 $J/kg/^oC$), and h is the surface mixed layer depth (m) of a lake. Daily T_e and K values were obtained by using the climatic data and equations provided by Edinger (1974) as explained in the Methods section. Equation A1.1 was solved numerically for T_w for mixed layer depths of 0, 1.0, 5.0, and 20.0 m.

Average daily and average monthly water temperatures corresponding to different mixed layer depths are shown on Figures A1.1 and A1.2, respectively, for the year 1964. As can be seen, daily water temperatures become more dynamic when mixed depth is decreased (Figure A1.1). Day to day temperature fluctuations are highest when mixed layer depths are 0 and 1 m and small when mixed water depths are 5 and 20 m. The peak water temperatures decrease and the timing of peaks is delayed as mixed layer depths increase (Figures A.1 and A.2). Average annual surface water temperatures for mixed layer depths of 0, 1, 5 and 20 m were 8.4 ^oC (47.2 ^oF), 8.0 ^oC (46.4 ^oF), 8.6 ^oC (47.2 ^oF), and 9.1 ^oC (48.4 ^oF), respectively, under 1964 climate conditions. This is a fairly narrow range. In our evaporation estimates/calculations we used the water temperatures for 0 m mixed layer depth, which is within 0.7^oC of the other values.

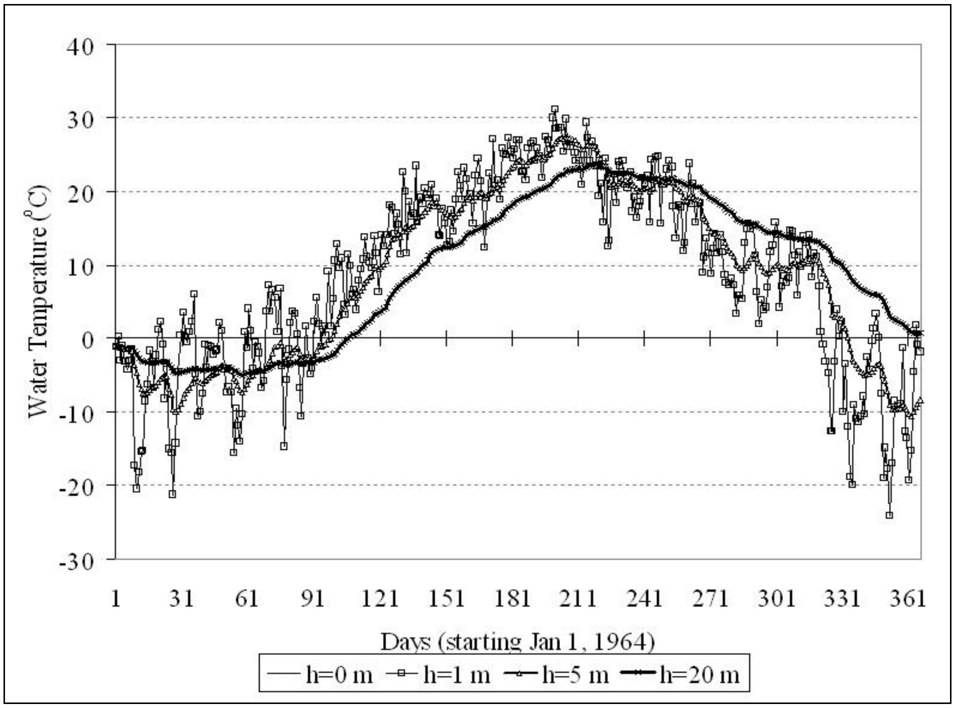

Figure A1.1. Daily water temperatures for the year 1964 corresponding to mixed water depths of 0, 1, 5 and 20 m.

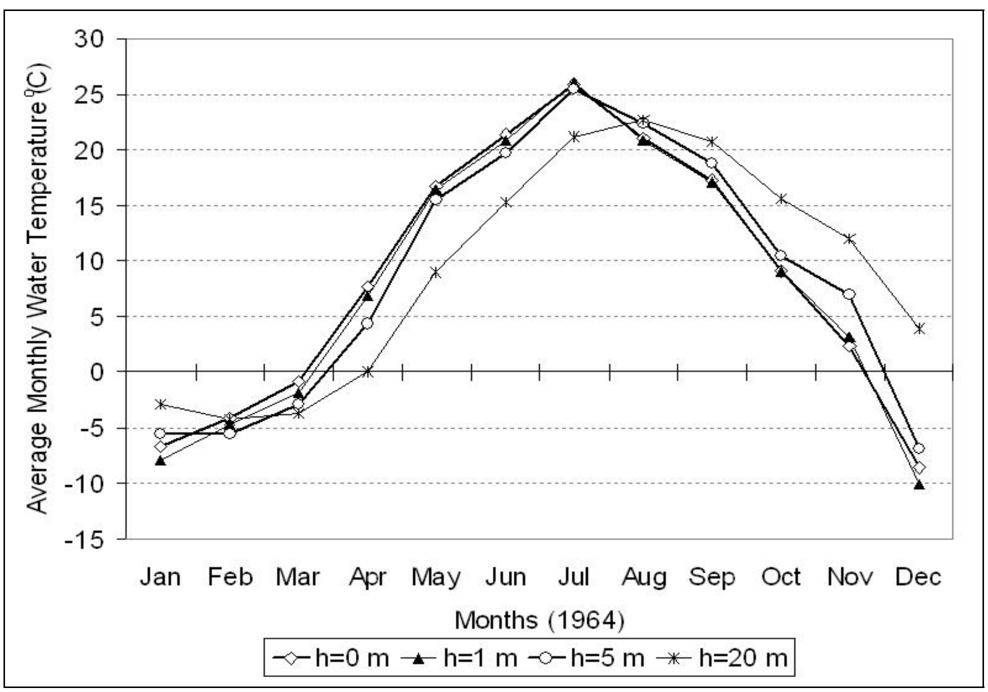

Figure A1.2. Average monthly water temperatures for the year 1964 corresponding to mixed layer depths of 0, 1, 5 and 20 m.

The annual evaporation values calculated with the Meyer equation corresponding to different mixed water depths are provided in Figure A1.3. As expected, annual evaporation decreased as mixed water depth increased because the surface water remained colder. Average annual evaporation values for the 1964 – 2005 period corresponding to mixed water depths of 0, 1, 5 and 20 m were 895 mm (35.2 in), 851 mm (33.5 in), 840 mm (33.1 in), and 767 mm (30.2 in), respectively. Mixed layer depths in Minnesota's dimictic lakes are typically from 2 to 5 m in summer, when evaporation is at a maximum. Evaporation values for those depths given in Figure A1.3 are on the order of 5 to 8% lower than those for 0m mixed layer depth. Absolute evaporation estimates may be too high by this fraction, but trends would not be much affected.

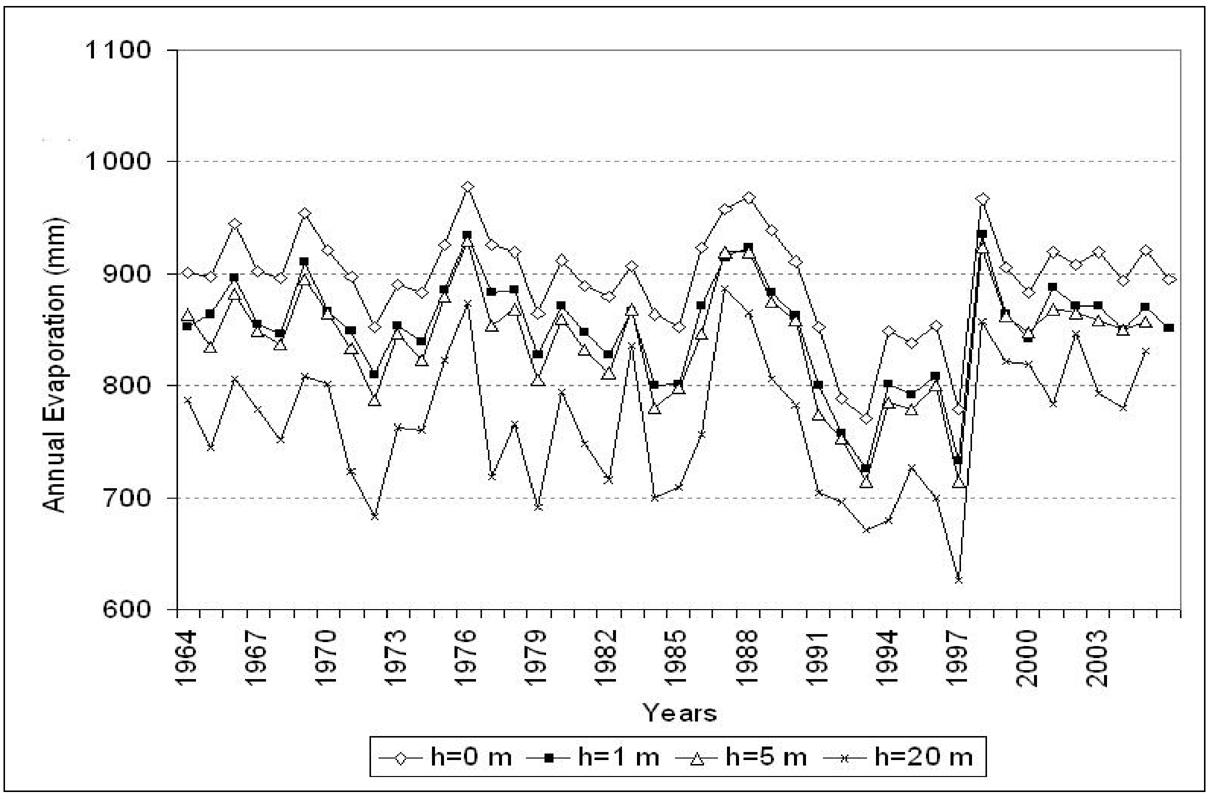

Figure A1.3. Annual evaporation calculated with water temperatures estimated for mixed layer depths of 0, 1, 5, and 20 m.

APPENDIX 2. Average Ice-out and Ice-in dates for Minnesota Lakes

Ice-out and ice-in dates for Minnesota lakes are shown in Figures A2.1 and A2.2. The data cover the latitudes over which the state of Minnesota extends. The data are averages of many years of record (Johnson and Stefan 2006). Ice-out date data show less scatter because ice-out is more directly correlated with climate variables some of which are strongly dependent on latitude. Ice out depends also on climate, but in addition has a strong dependence on average lake depth which is not accounted for in the data plot.

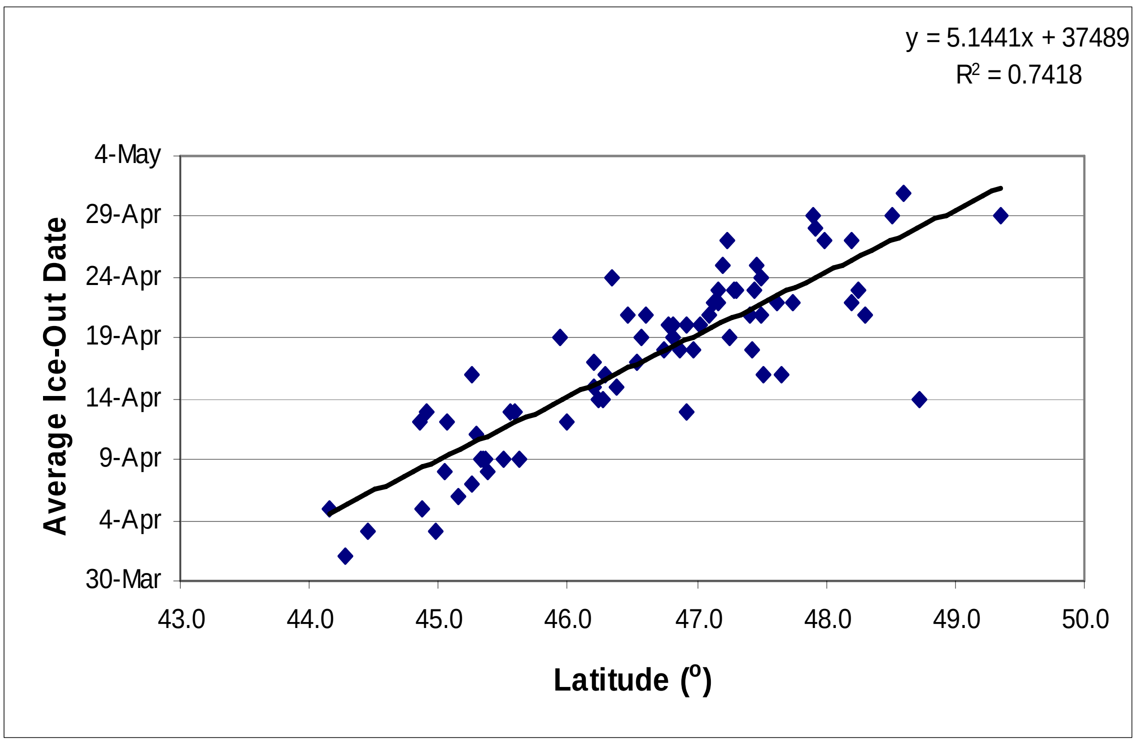

Figure A2.1. Average ice-out dates for Minnesota lakes (Johnson and Stefan, 2006)

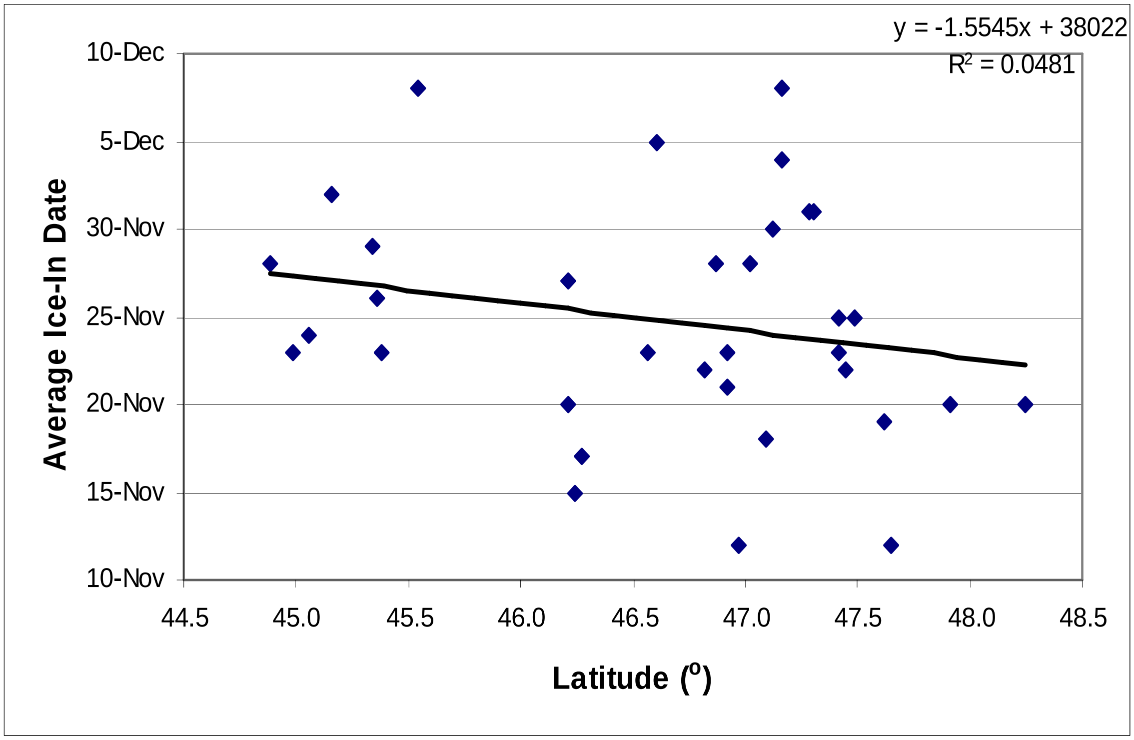

Figure A2.2. Average ice-in dates for Minnesota lakes (Johnson and Stefan, 2006)

APPENDIX 3. Names, locations, and characteristics of Minnesota lakes included in this study

The names and locations of the lakes included in the lake level study (Dadasser-Celik and Stefan 2007) are given in Figure A3.1. The lake characteristics are listed on Table A3.1.

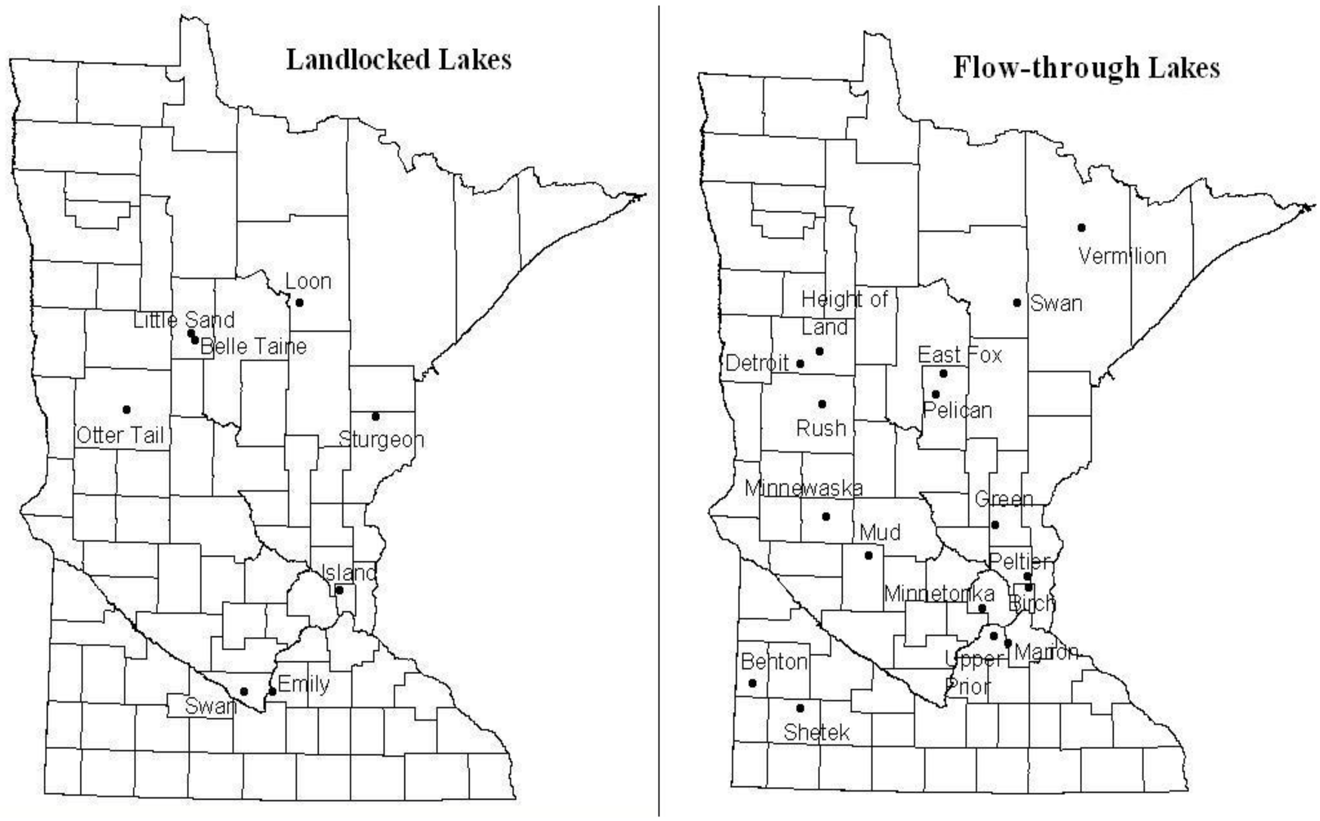

Figure A3.1.Locations and names of Minnesota lakes included in the lake level study (Dadasser-Celik and Stefan 2007)

Table A3.1. Landlocked lakes included in this study.

No	Lake ID	Lake name	Location (County)	Period of record	Number of daily lake level data	Surface area (ha)	Littoral area (ha)	Max. depth (m)
1	29014600	Belle Taine	Hubbard	07/20/1935 to 05/18/2007	2,936	480	312	17
2	40012400	Emily	Le Sueur	12/28/1940 to 04/17/2007	1,442	95	67	11
3	62007500	Island	Ramsey	01/01/1924 to 06/30/2006	2,041	24	24	3
4	29015000	Little Sand	Hubbard	05/11/1956 to 05/18/2007	1,828	156	60	24
5	31057100	Loon	Itasca	02/01/1955 to 05/22/2007	1,278	94	19	21
6	56024200	Otter Tail	Otter Tail	07/18/1919 to 04/27/2007	3,004	5,559	2,620	37
7	58006700	Sturgeon	Pine	06/22/1945 to 05/02/2007	575	691	201	12
8	11030400	Swan	Nicollet	11/22/1946 to 04/17/2007	299	3,785	N/A	3

Table A3.2. Flow-through lakes included in this study.

No	Lake ID	Lake name	Location (County)	Period of record	Number of daily lake level data	Surface area (ha)	Littoral area (ha)	Max. depth (m)
1	41004300	Benton	Lincoln	07/31/1947 to 04/17/2007	2,325	1,157	1,157	3
2	62002400	Birch	Ramsey	06/04/1930 to 04/13/2007	2,537	N/A	N/A	N/A
3	3038100	Detroit	Becker	08/25/1943 to 05/17/2007	3,625	1,249	767	27
4	18029800	East Fox	Crow Wing	04/22/1937 to 05/15/2007	2,401	97	41	20
5	30013600	Green	Isanti	06/22/1937 to 04/20/2007	2,407	325	145	9
6	3019500	Height of Land	Becker	03/24/1938 to 05/16/2007	3,004	1,426	1,292	6
7	19002600	Marion	Dakota	05/03/1946 to 04/16/2007	2,963	227	184	6
8	27013300	Minnetonka	Hennepin	05/30/1906 to 04/18/2007	18,616	5,672	2,369	34
9	61013000	Minnewaska	Pope	05/29/1935 to 04/25/2007	2,860	2,880	867	10
10	34015800	Mud	Kandiyohi	12/02/1945 to 04/26/2007	3,735	939	939	4
11	18030800	Pelican	Crow Wing	11/29/1933 to 05/04/2007	3,125	3,342	1,584	32

12	2000400	Peltier	Anoka	04/02/1951 to 04/10/2007	5,584	188	167	5
13	56014100	Rush	Otter Tail	06/26/1934 to 04/27/2007	3,195	2,162	1,347	21
14	51004600	Shetek	Murray	11/05/1926 to 04/13/2007	3,245	1,456	1,456	3
15	31006700	Swan	Itasca	09/21/1937 to 05/31/2007	14,881	1,001	205	20
16	70007200	Upper Prior	Scott	04/04/1906 to 04/05/2007	4,188	143	133	15
17	69037800	Vermilion	St Louis	10/03/1950 to 05/31/2007	14,097	16,426	6,077	23

UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 510

Stream Flow Response to Climate in Minnesota

by

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Prepared for
Legislative Citizens Committee on Minnesota Resources
St. Paul, Minnesota

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Minneapolis, Minnesota

The University of Minnesota is committed to the policy that all persons shall have equal access to its programs, facilities, and employment without regard to race, religion, color, sex, national origin, handicap, age or veteran status.

Abstract

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 flows 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-yr floods. The results were most consistent for the Red River of the North Basin. In this basin, magnitudes of the 2- to 25-yr floods increased at all six stream gauging stations (average increases were from about 30 to 60%) and the magnitude of the 1-yr 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-yr 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-yr 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-yr 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-yr 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 in 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.

TABLE OF CONTENTS

1. INTRODUCTION

The State of Minnesota is proud of its more than 10,000 lakes. However, the State's streams and rivers are equally important as wildlife habitat, for recreation, as a source of water supply, and as recipients of waste water. On rare occasions the streams and rivers of Minnesota have become devastating torrents. An enlightening description of Minnesota's streams and rivers was given by Waters (1977). Now the threat of climate change raises legitimate questions about the future of Minnesota's streams and rivers

Stream flow changes with climate and is therefore an indicator of climatic change. In this study we will analyze historical flow records of streams in Minnesota to determine how frequency and magnitude of flows have changed, i.e., been affected by climate and climatic changes in the past. It is important to identify the response of stream flows to climate because changes in stream flow, particularly in flood/drought patterns, have important ecological impacts and socio-economic implications. Flood characteristics affect the design of structures such as dams, bridges, culverts, and water intakes. Flood insurance programs depend on flow frequency, and so do the ecological characteristic of streams. Low flows and droughts affect stream and river water quality, as well as municipal or agricultural water uses, and the health of stream biota (Gordon et al., 2004) to mention but a few concerns.

This study is a continuation of a previous study by Novotny and Stefan (2006; 2007) on Minnesota stream flows. Novotny and Stefan (2006; 2007) analyzed the trends in seven stream-flow statistics (e.g., mean annual flows, peak and low flows, and number of days with high and low flows) in the 20th century. In this study, we analyze mean daily stream flow, 7-day low flow, and annual peak flow for the 1946-2005 period to identify changes in frequencies and magnitudes of stream flows in Minnesota. Since climate is progressively changing in Minnesota (Seeley, 2003), our analysis will focus on a comparison of stream flows in the 1986-2005 period and the 1946-1965 period. We will use flow duration analysis, peak flow ranking, low flow ranking, flood frequency analysis, and low flow frequency analysis.

2. BACKGROUND

2.1 Previous Studies of Stream Flows and Climate Change

Previous studies of stream flows in various parts of the world have shown that stream flow patterns have been changing due to climatic changes (IPCC, 2001). Lettenmaier et al.

(1994) examined trends in annual and monthly stream flows across the conterminous United States (U.S.) and found positive trends, i.e., increasing stream flows, particularly in the north-central states. Lins and Slack (1999) calculated the trends in selected quantiles of stream discharge at 395 stream gauging sites distributed over the conterminous U.S. and found mostly positive or upward trends in the annual minimum to median flow range. Trends in annual maximum stream flows were not as apparent. Douglas et al. (2000) examined the trends in floods and low flows and found upward trends in low flows particularly in the Midwest region. A trend in floods was not evident. Milly et al. (2002) found that the frequency of great floods (floods that came from basins larger than 200,000 km^2 and had return periods greater than 100 years) increased worldwide in the 20th century. McCabe and Wolock (2002) examined the trends in minimum, median, and maximum daily stream flow at 400 stream sites in the conterminous U.S. and found a step increase in minimum and median flows around 1970s. The timing of the increase in flow coincided with an increase in precipitation. Kundzewicz et al. (2005) analyzed the trends in annual maximum flows at 195 stream flow stations worldwide with at least 40 years of records. Their analysis showed that only 27 stations had a significant increasing trend and 31 had a significant decreasing trend. Among the 70 U.S. stations included in the study, 14 showed significant increases and 12 showed significant decreases. Svensson et al. (2005) used daily stream flow records of 68-year average length (range of 44-100 years) from 21 stream gauging stations worldwide (including 4 U.S. stations) to analyze the trends in floods and low flows. They found that a majority of the stations had decreasing trends in floods and increasing trends in low flows. The only station from the midwestern U.S. was a station in North Dakota where strong increasing trends in both floods and low flows were observed.

Several other studies focused on the stream flow changes in the midwestern U.S. including Minnesota. Knox (1993) analyzed the relationships between floods and climatic changes in the Upper Mississippi River watersheds using 7,000-year geological records of overbank floods. His analysis concluded that abrupt changes in flood magnitudes and frequencies occurred with moderate changes in mean annual temperature (1 - 2 ^{o}C) and mean annual precipitation (less than 10% to 20%). Knox (1993) concluded that climatic changes projected by global circulation models are much larger than historical changes and can cause significant changes in flood magnitudes and frequencies in many regions. Changnon and Kunkel (1995) found upward trends in flood flows that occur in the warm-season (May-November) or in the cold-season (December-April) in Minnesota. The former are caused by heavy rainfall events, while the latter are snowmelt floods. Heavy-precipitation amounts in Minnesota (e.g., from 7-day precipitation events at the 1-yr recurrence level) increased from 1921 to 1985 according to Changnon and Kunkel (1995). Schiller and Libra (2003) found increased base flow in Iowa over the second half of the 20th century, and Gebert and Krug (1996) analyzed stream flow trends in Wisconsin's driftless area. An analysis of historical stream flow records from 36 USGS stream gauging stations in Minnesota (Novotny and Stefan, 2007) showed significant trends in seven stream-flow statistics including mean annual flows, peak and low flows, and number of days with high and low flows. A strong correlation between mean annual stream flow and total annual precipitation was also documented.

It has been projected that climate change will increase the likelihood of floods and droughts over many regions due to increases in intensity and variability of precipitation (Kundzewicz et al., 2007). For Minnesota, the trends found by Novotny and Stefan (2007) support this general finding for rainfall-induced floods. There seems to be no trend towards a lowering of low flows in Minnesota in either summer or winter, indicating that sufficient ground-water sources exist to overcome any seasonal shortages of rainfall. The annual precipitation in Minnesota has a rising trend. Considering the historical changes and projections of further changes in intensity and variability of precipitation in Minnesota, potential variations in stream flow patterns deserve further analysis.

2.2. Historical Floods and Droughts in Minnesota

Major floods in Minnesota river basins have been caused by either snowmelt, sometimes accompanied by heavy rainfall, or by summer thunderstorms of high intensity (Carlson, 1991). The five most damaging floods prior to 1991 occurred in 1950, 1965, 1969, 1978, and 1979 (Carlson, 1991). A major and damaging flood occurred in Minnesota in the summer of 1993 due to extreme wet conditions (MN-DNR-Division of Waters, 1995). Recently, a devastating flood occurred in southeastern Minnesota due to heavy rainfall on 18-20 August 2007. Flash floods in Minnesota (http://www.climate.umn.edu/doc/flashflood.htm) have been analyzed by the Minnesota Department of Natural Resources (MNDNR) - Division of Waters, the State Climatology Office, and the University of Minnesota's Department of Soil, Water and Climate using rainfalls records (rather than stream flow records).

In this study 114 flash floods between 1970 and 2006 have been identified. A flash flood was defined as “the occurrence of 6 inches or more rainfall within a 24 hour period” at a given range gage. In addition it would be desirable to determine flashfloods from stream flow records. In fact, the National Weather Service (NWS, 2005) defines a flash flood as “the flood which is caused by heavy or excessive rainfall in a short period of time, generally less than 6 hours”. However, identification of historical flash floods in stream flow records requires analysis of historical data collected at least on an hourly timescale. Such records are rarely available.

Major droughts were experienced in Minnesota in the periods 1911-1914, 1921-1942, 1954-1961, and 1976-1977 (Carlson, 1991). The recurrence interval of these droughts was 30 years, 60 to 70 years, 50 years, and 10 to 30 years, respectively (Carlson, 1991). The most recent drought was experienced during the 1987-1988 period. Although dry conditions started in October 1987, the observed drop in stream flow was not strong until April 1988 due to adequate groundwater and lake water supply in the winter. In July 1988, stream flow throughout Minnesota was deficient or within the range of low flows that occur 25% of the time for the month (MN-DNR-Division of Waters, 1989).

2.3. Characteristics of River Basins in Minnesota

Minnesota is divided into eight major river basins (Figure 2.1). These basins were separately analyzed in the previous study by Novotny and Stefan (2007).

The Minnesota River Basin covers about 16,770 square miles, and is located in southern Minnesota (http://mrbdc.mnsu.edu/mnbasin/fact_sheets/fastfacts.html), except for small portions that extend into South Dakota and Iowa (Figure 2.1). 92% of the basin area is used for agriculture. The basin includes an extensive network of agricultural drainage tiles and man made ditches.

The Red River of the North Basin comprises 37,100 square miles of land in Minnesota, South Dakota and North Dakota. 17,730 square miles of it is in Minnesota. The majority of the land in the Minnesota portion of the Red River of the North Basin is used for agriculture (66%), some is covered by forests (12%), and some is urban residential land (8%) (Paakh et al., 2006).

The Rainy River Basin covers a total area of 27,114 square miles, of which 11,244 square miles are located in northern Minnesota. The majority of the Rainy River Basin is covered by forests, lakes, and wetlands (MPCA, 2001).

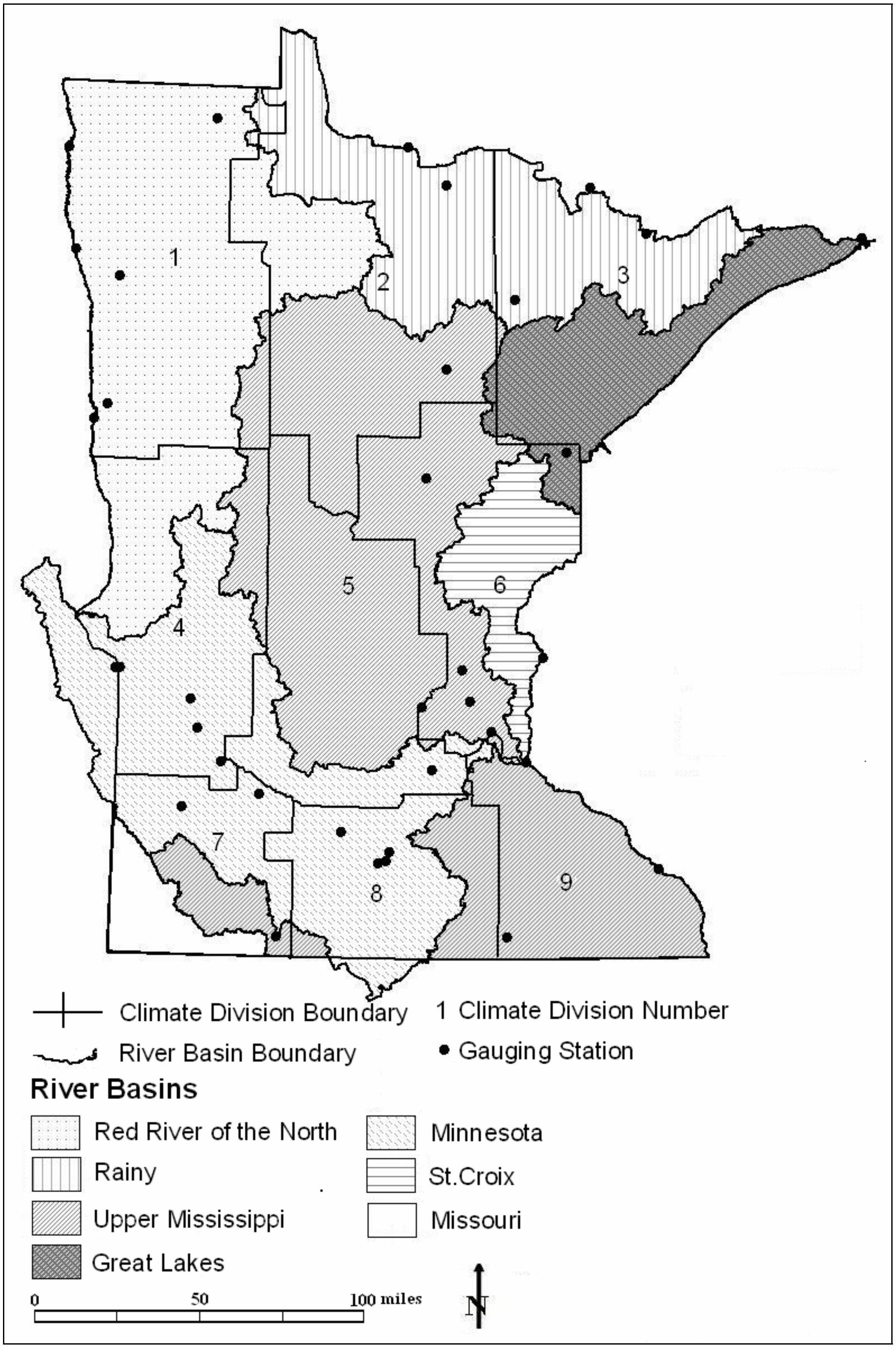

Figure 2.1. River basins (shaded) and climate divisions (numbered) of Minnesota. Stream gauging stations included in this study are shown as black dots.

The Lake Superior Watershed Basin in Minnesota is 6,200 square miles in size, and is covered mainly by forests with little agriculture and several urban areas.

The Upper Mississippi River Basin covers 30,800 square miles entirely within the state of Minnesota. Land cover in this part of the Upper Mississippi River Basin ranges from conifer and hardwood forests to agriculture where corn, soybean, and forage crops are cultivated (MPCA, 2000). In St. Paul the Minnesota River discharges into the Mississippi River and puts its imprint on Mississippi River flows. Downstream from St. Paul the St. Croix River, which drains portions of eastern Minnesota and western Wisconsin, enters the Mississippi River at Prescott, WI. Downstream from Prescott additional portions of western Wisconsin and southeastern Minnesota become part of the Mississippi River drainage (Figure 2.1). The Twin Cities metropolitan area is in the Mississippi River drainage.

A small piece of southwestern Minnesota (Figure 2.1) drains into the Missouri River, and another into the Upper Mississippi River through Iowa; both are not included in the study.

3. METHODS OF ANALYSIS

3.1. Stream Flow Data Used

Thirty-six gauging stations in the five major basins of Minnesota, previously analyzed by Novotny and Stefan (2007), were used in the analysis (Figure 2.1). These stations were selected based on the length and continuity of data and included the stations which were not affected by man-made structures. Twelve of the stations were in the Minnesota River Basin, 5 in the Rainy River Basin, 6 in the Red River of the North Basin, 11 in the Upper Mississippi River Basin, and 2 on tributary streams to Lake Superior. The locations of the stream flow gauging stations are shown in Figure 2.1. The list of gauging stations and where their drainage area is located (climate division) can be found in Table 3.1. Nine climate divisions of Minnesota and 2 climate divisions of North Dakota (no. 3 and 4) and a climate division of Wisconsin (no. 1) are included. The climate divisions of Minnesota are identified in Figure 2.1 by numbers 1 to 9. Stream flow data analyzed in this study include (1) daily average flows, (2) annual 7-day average low flows, and (3) annual peak flows. Records were available for at least 50 years (1946-2005) for most of the 36 stream gauging stations.

Table 3.1. Stream gauging stations included in this study

USGS Gauging Station No.	Stream/River Name	Record Length Used	Climate Division
Minnesota River Basin			
05291000	Whetstone River Big Stone City, SD	1993-2005	SD 3,4
05292000	Minnesota River at Ortonville, MN	1929-2005	4, SD 3
05304500	Chippewa River Near Milan, MN	1938-2005	4,5
05311000	Minnesota River at Montevideo, MN	1939-2005	4, SD 3
05313500	Yellow Medicine River Granite Falls, MN	1940-2005	4,7
05315000	Redwood River Near Marshall, MN	1941-2005	7
05316500	Redwood River Near Redwood Falls, MN	1936-2005	7
05317000	Cottonwood River Near New Ulm, MN	1939-2005	7,8
05320000	Blue Earth River Near Rapidan, MN	1950-2005	8
05320500	Le Sueur River Near Rapidan, MN	1950-2005	8
05325000	Minnesota River at Mankato, MN	1930-2005	4,5,7,8
05330000	Minnesota River Near Jordan, MN	1935-2005	4,5,7,8
Red River of the North Basin			
05054000	Red River of the North at Fargo, ND	1902-2005	1
05062000	Buffalo River Near Dilworth, MN	1932-2005	1
05079000	Red Lake River at Crookston, MN	1902-2005	1
05082500	Red River of the North Grand Forks, ND	1904-2005	1
05092000	Red River of the North at Drayton, ND	1942-2005	1
05104500	Roseau River Near Milung, MN	1947-2005	
Rainy River Basin			
05127500	Basswood River Near Winton, MN	1939-2005	3
05128000	Namakan River at outlet of Lac La Croix	1923-2005	3
05130500	Sturgeon River Near Chisholm, MN	1943-2005	3
05131500	Little Fork River at Littlefork, MN	1929-2005	2
05133500	Rainy River at Manitou Rapids, MN	1929-2005	2

USGS Gauging Station No.	Stream/River Name	Record Length Used	Climate Division
Tributaries to Lake Superior			
04010500	Pigeon River at Middle Falls	1924-2005	3
04024000	St. Louis River at Scanlon, MN	1908-2005	3
Upper Mississippi River Basin			
05211000	Mississippi River at Grand Rapids, MN	1912-2005	2
05227500	Mississippi River at Aitkin, MN	1946-2005	2,6
05280000	Crow River at Rockford, MN	1935-2005	5
05286000	Rum River Near St. Francis, MN	1934-2005	6
05288500	Mississippi River Near Anoka, MN	1932-2005	2,5,6
05331000	Mississippi River at St. Paul, MN	1907-2005	2,4,5,6,7,8
05340500	St. Croix River at St. Croix Falls, WI	1910-2005	6, WI1
05344500	Mississippi River at Prescott, WI	1929-2005	2,4,5,6,7,8
05378500	Mississippi River at Winona, MN	1929-2005	2,4,5,6,7,8,9
05457000	Cedar River Near Austin, MN	1945-2005	9
05476000	Des Moines River at Jackson, MN	1936-2005	7

3.2. Selection of Time Periods for Analysis

The analysis of historical stream flow records described in this report focused on two twenty-year time periods, 1946-1965 and 1986-2005, for each station. These time periods were selected for comparison to determine if stream flow conditions had changed over time. A trend analysis over the total record lengths was previously conducted by Novotny and Stefan (2006; 2007). 1946 was selected as the starting year because continuous data for 33 of the 36 stream gauging stations were available after 1946. By selecting 1946, we did not include the very dry 1920-1940 period in our analysis (Figure 3.1).

Annual average precipitation and annual average temperatures over the 1895-2007 period are shown in Figure 3.1(http://www.wrcc.dri.edu/spi/divplot1map.html). The values plotted are statewide averages. Both climate parameters showed an upward linear trend over this period of record. The rates of increase were 0.028 in/yr (0.71 mm/yr) and 0.014 ^{o}F/yr (0.008 ^{o}C /yr), respectively. The average annual precipitation was 26.1 in (662 mm) for the 1946-2005 period, compared to 28.0 in (710 mm) for the 1986-2005 period. The annual average temperature for the 1946-1965 and 1986-2005 periods were 40.64 ^{o}F (4.82 ^{o}C) and 41.94 ^{o}F (5.52 ^{o}C), respectively. In other words, the 1986-2005 period was slightly warmer and wetter than the 1946-2005 period.

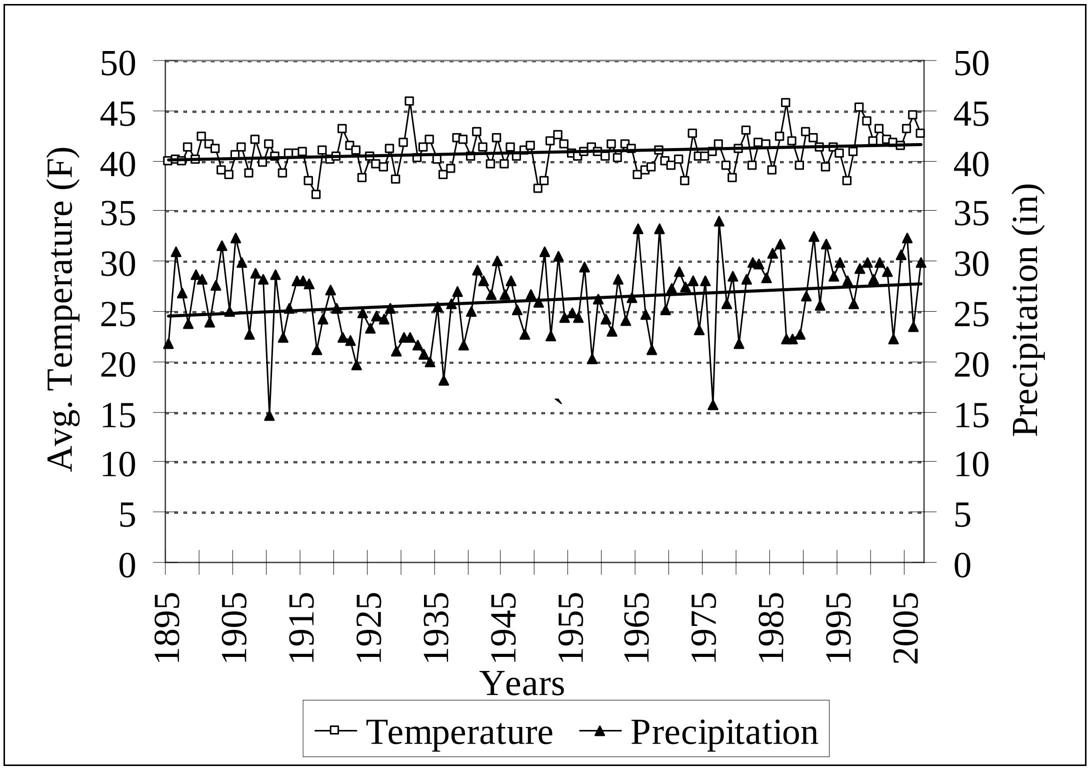

Figure 3.1. Annual average temperature and annual precipitation in Minnesota for the 1895-2007 period.

3.3. Determination of Flow-Duration Curves (FDCs)

In a flow-duration curve (FDC), stream discharge is plotted as a function of exceedence probability (percent of the time a certain magnitude of discharge is exceeded). A FDC provides a graphical representation of cumulative frequency of discharge (Chow, 1964; Mosley and McKerchar, 1992). Flow-duration curves (FDCs) were prepared for the daily average stream flow data.

Stream flow distributions depend strongly on precipitation and basin (watershed) characteristics. An FDC can therefore be used to detect changes in precipitation or land use in a river basin. FDCs have been used in a wide range of applications including stream water quality management, hydropower feasibility studies, and in-stream low flow requirement determination (Smakhtin, 2001; Vogel and Fennessey, 1995). Lane et al. (2005) evaluated the response of FDCs to land-use changes (i.e., deforestation). FDCs have also been used to evaluate the effects of different climate scenarios on stream flow (e.g., Gosain et al., 2006; Wilby et al., 1994).

To prepare FDCs, we first sorted the flow data from the highest to the lowest and determined the order (m) of each flow. Probability of exceedence (P) was found using Equation 1, where N is the total number of data points. FDCs were prepared by plotting the probability of exceedence on the horizontal axis and stream flow on a logarithmic scale on the vertical axis.

$$P = \frac{m}{N+1} \times 100 \tag{1}$$

FDCs provide a visual and quantitative representation of stream flows. Index values can be extracted from FDCs to evaluate the similarities or differences in the shape of the FDC curves for two time periods. For example, the discharge (Q50) at which flows are exceeded 50% of the time denotes the median flow. According to Pyrce (2004), the Q95 and Q90 flows are most often used as low flow indices. Smakhtin (2001) gave the "design" low flow in the Q70 to Q99 range. Another low flow index is the ratio (Q20/Q90). This index is called "flow-duration ratio" and represents the slope of the straight line portion of a FDC (Arihood and Glatfelter, 1991). This slope integrates several factors affecting low flow characteristics such as geology, climate, land use, and soils (Arihood and Glatfelter, 1991). A low (Q20/Q90) value is an indicator of high base flows that cause stream discharge to become stable. A high (Q20/Q90) value indicates a "flashy stream", i.e. where flows are more variable. The base flow contribution to streams can be evaluated by the ratio (Q90/Q50) (Gordon et al., 2004). The opposite ratio is an indicator of variability of low flows (Smakhtin, 2001). Q5 and Q10 can be used as high flow indices (Pyrce, 2004).

In this study we used Q95 and Q90 to evaluate changes in low flow characteristics and Q5 and Q10 for high flow characteristics of streams. We also calculated the ratios Q90/Q50, Q50/Q90, Q20/Q90, and Q10/Q50 to evaluate the changes in contributions from base flow and variability of low flows.

3.4. Analysis of Extreme Flow Occurrences in Time

The temporal distribution of extreme events (annual peak flows and annual 7-day average low flows) over the period of record was examined using a sorting/ranking method explained by Johnson and Stefan (2006). In this approach, peak flows are sorted from the highest to the lowest, and low flows from the lowest to the highest. The years when the highest 3-, 5-, and 10-year events occurred are marked against time. It becomes thus apparent if extreme flow events are distributed uniformly over the period of record, of if they occurred more frequently in an earlier or a later period of the record. This procedure worked well, but did not for the 7-day (average) low flow because in several tributaries theses flows were zero. Therefore low-flows were ranked also from the highest to the lowest – just as peak flows and plotted on a time line without loss of information. The plot still showed if there was a shift in time in the low flow distributions – not the lowest low flows, but the highest.

To determine if a shift had occurred we determined the number of extreme events expected in a period, e.g., 1986-2005. If the events were distributed uniformly over the entire period of record (1946-2005), for example, 1 out of 3 highest or 3 of the 9 highest events that occurred in the 1946-2005 period would be expected in the 1986-2005 period. We compared the expected number with the actual number of events observed. By this method, we were able to examine if the extreme events were distributed uniformly or aggregated within a specific time period.

3.5. Flood Frequency Analysis (FFA)

A flood frequency analysis (FFA) was conducted for the 36 gauging stations by using the data from 1946-1965 and 1986-2005. The purpose was to identify changes in the magnitude of floods. Annual peak flow data were used in the analysis.

In FFA, a flood frequency curve is developed by fitting historical flood data to a statistical distribution function. Flood values corresponding to different return periods can then be estimated by using the fitted distribution function. Floods can be fitted to Log normal distributions, Pearson type 3 distributions, Log- Pearson type 3 distributions, and extreme value distributions (Stedinger et al., 1992). We followed the guidelines in Bulletin 17B by the U.S. Geological Survey (Interagency Advisory Committee On Water Data, 1982) and used the Log-Pearson Type 3 distribution. According to this method, a log-transformation is applied to a minimum of 10 years of annual flood data to determine the appropriate frequency distribution. The Log-Pearson Type 3 distribution is given in its general form by Equation 2.

$$\log Q = \mu_{\log Q} + K\sigma_{\log Q} \tag{2}$$

In Equation 2, Q = peak annual stream discharge (cfs), and μ and σ are mean and standard deviation of log transformed annual flood flow (cfs) data. K is a frequency factor, which is a function of the selected return period skew coefficient of the frequency distribution; K can be found in a table given in Bulletin 17B.

Statistical parameters (i.e., mean, standard deviation, and skew coefficient (C_s)) can be obtained from the stream flow data using Equations 3 to 5. n is the number of years of data included in the analysis.

$$\mu_{\log Q} = \frac{\sum Q}{n} \tag{3}$$

$$\sigma_{\log Q} = \sqrt{\frac{\sum (\log Q - \mu_{\log Q})^2}{n-1}} \tag{4}$$

$$C_s = \frac{n\sum (\log Q - \mu_{\log Q})^3}{(n-1)(n-2)(\sigma \log Q)^3} \tag{5}$$

When a small number of data is used, the error in the estimation of the skew coefficient increases. To solve this problem, Bulletin 17B recommends the use of a weighted skew coefficient (C_w) that is obtained by weighting the skew coefficient obtained from the station record (C_s) with a generalized skew coefficient (C_g) obtained by using information from nearby sites (Equation 6). In this study, we used the generalized skew coefficients estimated by the U.S. Geological Survey for Minnesota (Lorenz, 1997).

$$C_w = WC_s + (1-W)C_g \tag{6}$$

In Equation 6, W is a weighting factor obtained using equation 7, where V_s denotes the variance of C_s and V_g denotes to variance of C_g..

$$W = \frac{V_s}{V_s + V_g} \tag{7}$$

V_s can be calculated by equation 8.

$$V_s = 10^{[A-B[\log(n/10)]]} \tag{8}$$

where $\quad A = -0.33 + 0.08|C_s| \quad if \quad |Cs| \leq 0.90$

$$A = -0.52 + 0.30|C_s| \qquad if \qquad |Cs| > 0.90$$

$$B = 0.94 - 0.26|C_s| \qquad if \qquad |Cs| \leq 1.50$$

$$B = 0.55 \qquad if \qquad |Cs| > 1.50$$

3.6. Low Flow Frequency Analysis

A low flow frequency analysis was conducted using the data from the 1946-1965 and 1986-2005 periods to determine the changes in 7-day low flow values. One of the most widely used low flow indices in the U.S. is 7-day 10-year low flow or 7Q10. It refers to the lowest average flow that occurs for a 7-day period with 10 year recurrence interval. In this study we calculated the changes not only in 7Q10 but also 7-day low flows with 2, 5, and 20 year recurrence intervals.

7Q2, 7Q5, 7Q10, and 7Q20 values were determined using a computer program, DFLOW 3.1b, which was developed and is distributed by the U.S. Environmental Protection Agency (available at http://www.epa.gov/waterscience/models/dflow/) to estimate flows for low flow water quality analysis. This computer program uses the principles explained in the USGS Surface Water Branch Technical Memorandum NO. 79.06, "PROGRAMS AND PLANS - Low-Flow Programs (available at http://water.usgs.gov/admin/memo/SW/sw79.06.html), which recommends fitting low flow data to a Log-Pearson Type III distribution. The data used by the program are mean daily flows. However, these data are converted to annual 7-day average low flow values by the program before fitting.

4. RESULTS - FLOW DURATION CURVES (FDCs)

4.1. FDCs for the Minnesota River Basin

The flow duration curves (FDCs) for daily data from 12 stream gauging stations in the Minnesota River Basin showed a substantial shift to higher stream flows from 1946 -1965 to 1986-2005. (Figure 4.1a and b). All 12 stations consistently had higher flows in the range of Q5 to Q90 in the 1986 -2005 period (Q5 are high flows that are exceeded 5% of the time, Q90 are low flows exceeded 90% of the time). Q95 showed an increase at 11 of the 12 stations between the two periods. Median flow (Q50) during the 1986 -2005 period increased on average by 203% (range from 68% to 300%) relative to the median flow during the 1946 -1965 period (Figure 4.2

and Table 4.1). In other words, the average median flow in the Minnesota River Basin in the 1986 -2005 period was about three times (303%) of the average median flow in the 1946 -1965 period. The largest increases in flows were recorded in the Redwood River and the Chippewa River, both tributaries of the Minnesota River (Figure 4.1a).

To increase the resolution for the extreme high flows, e.g., flows that occur during 10 days in 20 years (probability of occurrence = 0.00137), log-log plots of the FDCs were generated (Appendix A. Figures A.1a and b). To increase the resolution for extreme low flows, exceedence probabilities (p) have to be converted to non-exceedence probabilities (1 – p). The resulting plots are given in Appendix B as Figures B.1a and b.

The slopes of the straight-line portions of the FDCs for the 12 gauging stations did not show any consistent change. The Q20/Q90 ratios changed on average by only -3% from the 1946-1965 period to the 1986-2005 period, but the changes for individual gauging stations ranged from -72% to 48% (Table 4.1). This indicates that the relationship between base flow and high (quick) flow at most stations was not consistent from 1946 to 2005, although the average change for all 12 stations was nearly zero. Similarly, the base flow ratio to mean stream flow as measured by the (Q90/Q50) ratio varied from -48% to 182% between the earlier and the latter time periods, but the average for all 12 stations was 0% (Table 4.1).

Q95 and Q90 are low flow indices. Q95 increased in the more recent 20-year period for all stations with one exception (Minnesota River at Montevideo). On average Q95 increased to 148% (range from -16% to 390%) (Table 4.2). Similarly, Q90 showed an average increase to 187% (range from 34% to 418%) at the 12 gauging stations. Overall, the low flows became higher and more variable (Table 4.1).

Q5 and Q10 are indicators of high flows including floods. Both Q5 and Q10 were higher in the latter period. The average rise in Q5 was 79% (range of 62 to 97%) and the average rise in Q10 was 100% (in the range of 58 to 142%) (Table 4.1). Change in flow (%) in Table 4.1 is the difference in flow between the 1986 -2005 period and the 1946-1965 period divided by the flow in the 1946 -1965 period. These numbers show that the changes in high flows in the Minnesota River Basin were not as large as the changes in low flows.

In summary, the FDC indices for the Minnesota River Basin suggest that in the 60-year period from 1946 - 2005 low flows have, on average, increased about 150%, median flows have increased, on average, about 200%, and high flows have increased on average, about 100%. Deviations from these averages are, however, very large for individual stream gauging sites. Specifically, high flows have increased in the upper reaches of the Minnesota River (Figure 4.1a), but have decreased in the lower reaches (Figure 4.1b).

Table 4.1. Change in FDC index values in the Minnesota River Basin from the 1946 - 1965 period to the 1986 - 2005 period.

Flow Percentile	Average Change (%)	Std. Dev. of Change (%)	Minimum Change(%)	Maximum Change(%)
Q5	79	10	62	97
Q10	100	28	58	142
Q50	203	75	68	300
Q90	187	143	34	418
Q95	148	153	-16	390
Q20/Q90	-3	39	-72	48
Q90/Q50	0	65	-48	182
Q50/Q90	27	52	-65	92

Note: Change in flow (%) is the difference in flow between the 1986-2005 period and the 1946-1965 period divided by the flow in the 1946-1965 period.

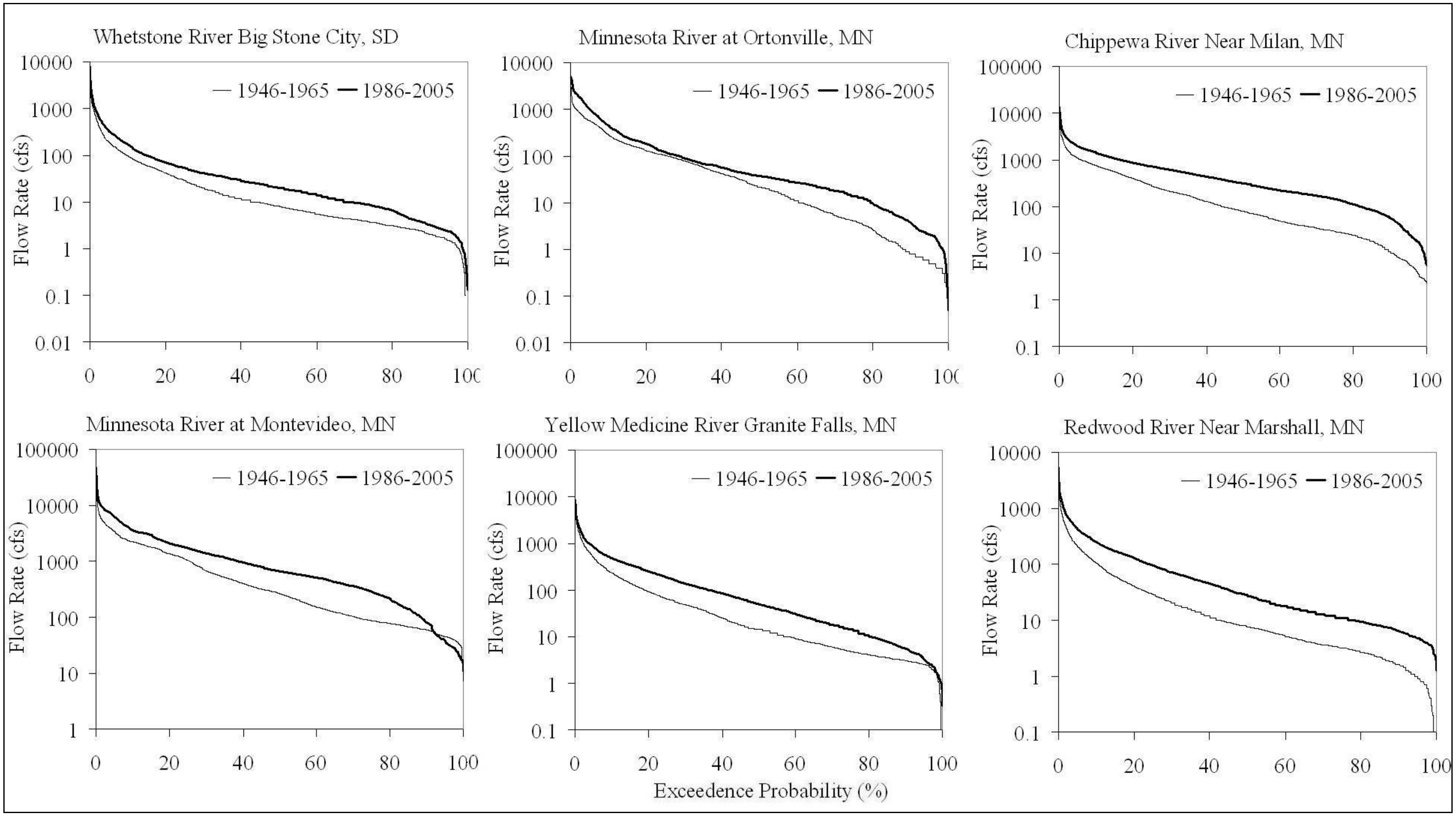

Figure 4.1a. FDCs at stream gauging stations in the Minnesota River Basin for the periods 1946 -1965 and 1986 -2005.

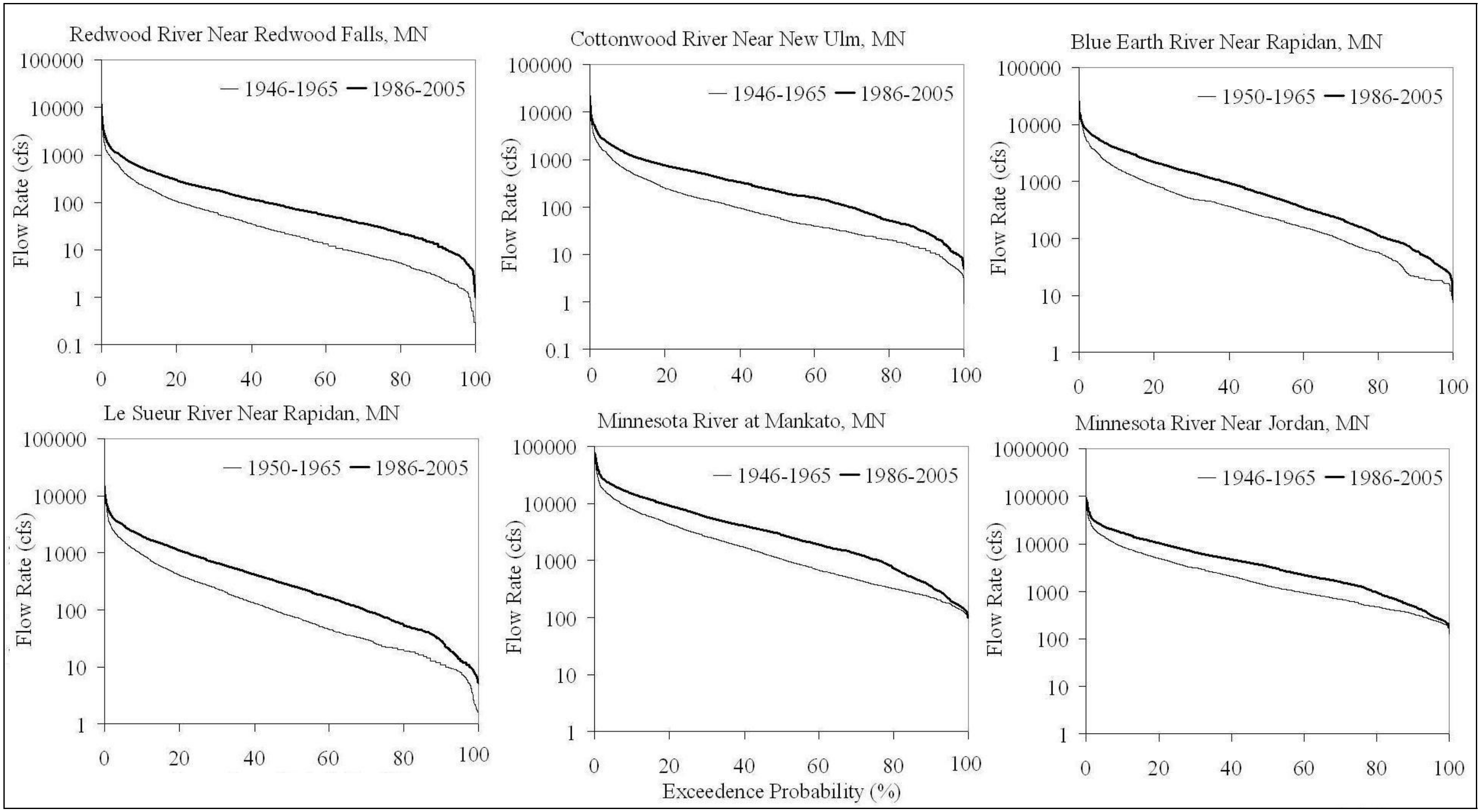

Figure 4.1b. FDCs at stream gauging stations in the Minnesota River Basin for the periods 1946 -1965 and 1986 -2005.

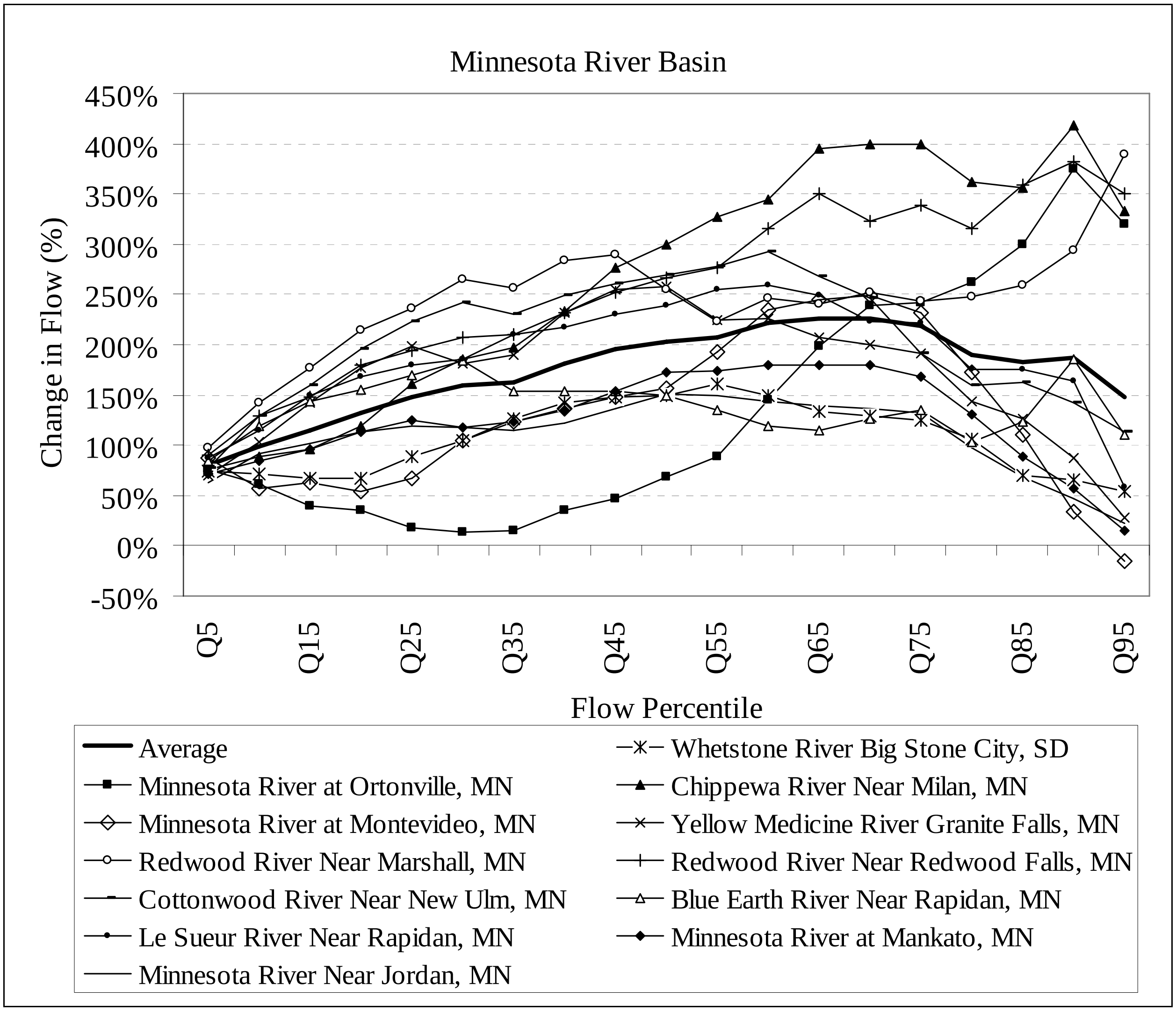

Figure 4.2. Change in flows at stream gauging stations in the Minnesota River Basin from the 1946 -1965 period to the 1986 -2005 period. Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

4.2. FDCs for the Red River of the North Basin

We analyzed stream flow data from 6 gauging stations in the Red River of the North Basin. High and medium flows in the FDCs (Q5-Q75) for all stations (Figures 4.3 and 4.4) were higher in the 1986 - 2005 period compared to the 1946 -1965 period. Low flows in the FDCs showed an increase at two of the stations (Red River of the North in Fargo and Buffalo River near Dilworth) and decrease at the four other stations in the latter period. Median flow in the 1986-2005 period was on average 78% (range from 14% to 141%) higher than the median flow in the 1946-1965 period (Table 4.2). The highest increases in medium to low flows were observed at the Buffalo River near Dilworth, MN and the highest increases in high flows were observed in the Red River of the North at Fargo, ND (Figure 4.4).

The changes in observed low flow indices, Q95 and Q90, varied over a large range for the 6 stations and the average changes for the basin were low (Table 4.2). Q95 varied in the range of -92% to 50% with an average of 0% and Q90 varied in the range of -77% to 70% with an average of 6%. The change in Q20/Q90 ratio was 98% (range from 5% to 366%) and the change in the Q90/Q50 ratio was -43% (range from -79% to -29%). The low flow results were inconsistent because two of the stations (Red River near Crookston and Roseau River Near Milung) showed a distinctly different behavior from the others (Figure 4.4).

High flows in the Red River of the North Basin shifted upwards at all stations. Q5 varied in the range of 13% to 86% with an average of 55% and Q10 varied in the range of 15% to 110% with an average of 62%.

In summary, the FDC indices for the Red River of the North Basin suggest that in the 60-year period from 1946 to 2005 high flows have, on average, increased about 60%, and median flows have increased about 80%. Low flows at 6 stream gauging stations showed inconsistent behavior. It must be considered that 6 individual stream gauging stations provide a small data base, and standard deviations from averages are large.

Table 4.2. Change in FDC index values in the Red River of the North Basin from the 1946 - 1965 period to the 1986 - 2005 period.

Flow Percentile	Average Change (%)	Std. Dev. of Change (%)	Minimum Chang(%)	Maximum Change(%)
Q5	55	33	13	86
Q10	62	38	17	110
Q50	78	45	14	141
Q90	6	49	-77	71
Q95	0	52	-92	58
Q20/Q90	98	133	5	366
Q90/Q50	-43	18	-79	-29
Q50/Q90	112	134	40	385

Note; Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

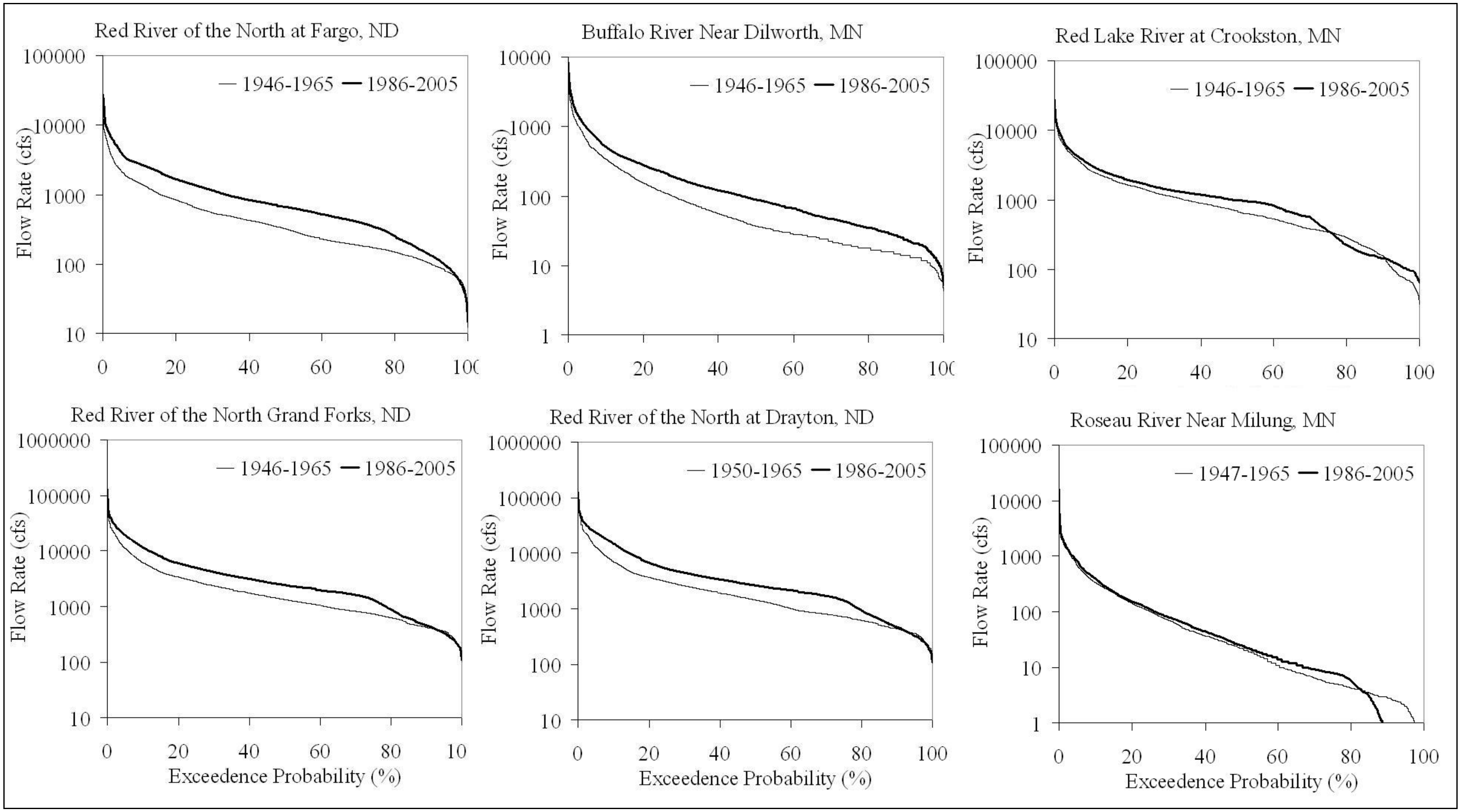

Figure 4.3. FDCs at stream gauging stations in the Red River of the North Basin for the periods 1946 -1965 and 1986 -2005.

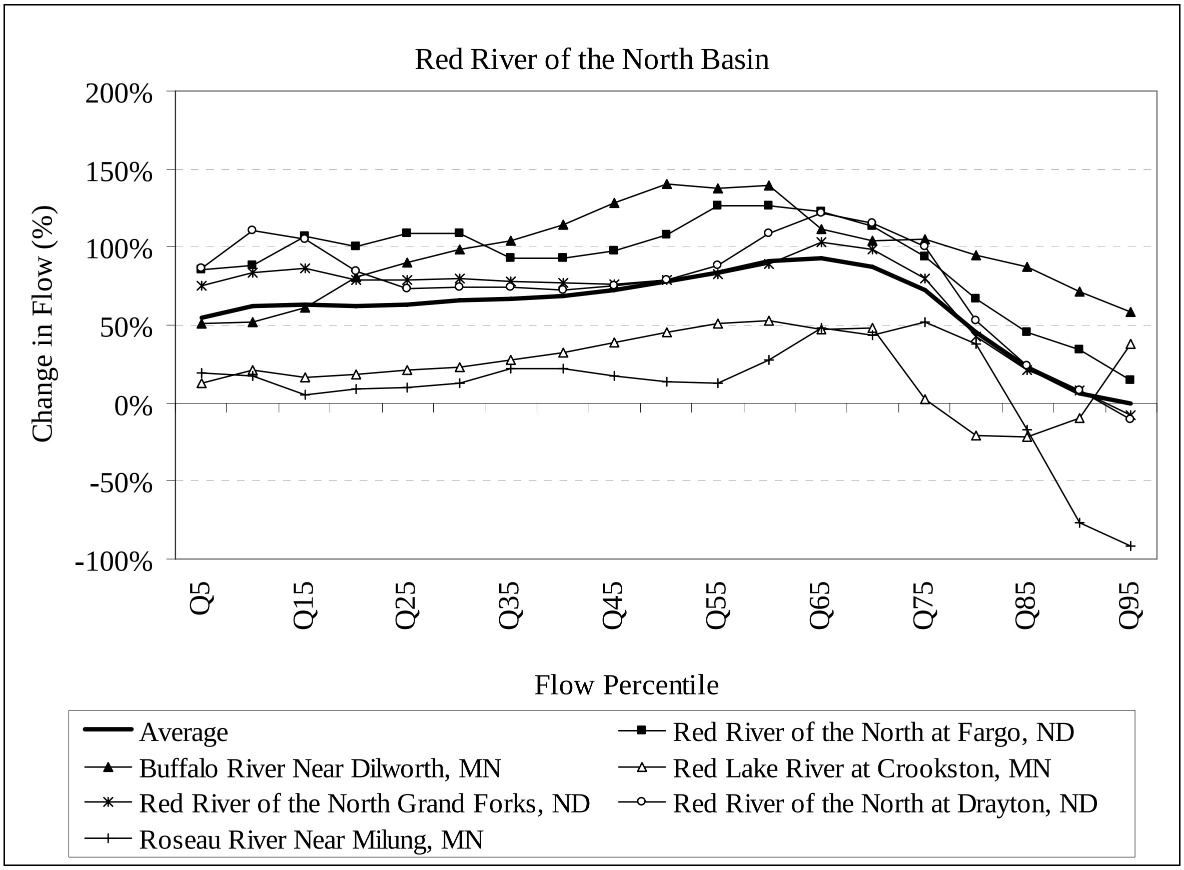

Figure 4.4. Change in flows between Q5 and Q95 at stream gauging stations in the Red River of the North Basin from the 1946 -1965 period to the 1986 -2005 period. Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

4.3. FDCs for the Rainy River Basin

Data from 5 gauging stations were analyzed in the Rainy River Basin. Medium and low flows (corresponding to the Q25-Q75 and Q75-Q95 ranges, respectively) increased, and high flows decreased at most of the stations between the 1946 -1965 and 1986 -2005 periods (Figures 4.5 and 4.6). An exception was the Rainy River near Manitou Rapids, where a downward shift was observed in the Q50-Q95 range, and an upward shift was observed in the Q5-Q50 range. Another exception was the Namakan River at the outlet of Lac La Croix, where decreases were observed in the Q5-Q55 and the Q95 flows, but increases were observed in other flows. The magnitudes of the shifts in the Rainy River Basin were not as large as those observed in the Minnesota River Basin and Red River of the North Basin. Median flow in the 1986 -2005 period was on average 22% (range from -4% to 56%) higher that the median flow in the 1946 -1965 period (Table 4.3). The largest increases in flows were observed in the Sturgeon River near Chisholm, MN and Little Fork River near Littlefork, MN (Figure 4.6).

Low flows, Q95 and Q90, had increased on average by 25% (range of -7% to 75%) and 23% (range of -17% to 73%), respectively, from 1946 - 1965 to 1986 - 2005. Changes in the flow variability index (Q50/Q90) were in the range of -10% to 16% with a basin average of 0%, and changes in the high to low flow ratio (Q20/Q90) were in the range of -35% to 22% with an average of -13% from 1946-1965 to 1986-2005. These numbers indicate that changes in low flow in the Rainy River Basin are far from uniform for the entire basin. Changes in high flows in the Rainy River Basin between 1946 -1965 and 1986 -2005 were low and negative. The average decreases in Q5 and Q10 were 9% (range from -14% to 5%) and 1% (range from -5% to 8%), respectively.

In summary, from 1946 to 2005, the low flows and median flows in the Rainy River Basin increased about 25%, while high flows decreased about 5%. Because the number of stations analyzed in the Rainy River Basin was only five and two of these stations showed patterns different from the others, the results are not conclusive.

Table 4.3. Change in FDC index values in the Rainy River Basin from the 1946 - 1965 period to the 1986 - 2005 period.

Flow Percentile	Average Change (%)	Std. Dev. of Change (%)	Minimum Change (%)	Maximum Change (%)
Q5	-9	8	-14	5
Q10	-1	5	-5	8
Q50	22	30	-4	56
Q90	23	36	-17	73
Q95	25	35	-7	75
Q20/Q90	-13	22	-35	22
Q90/Q50	1	11	-14	11
Q50/Q90	0	11	-10	16

Note: Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

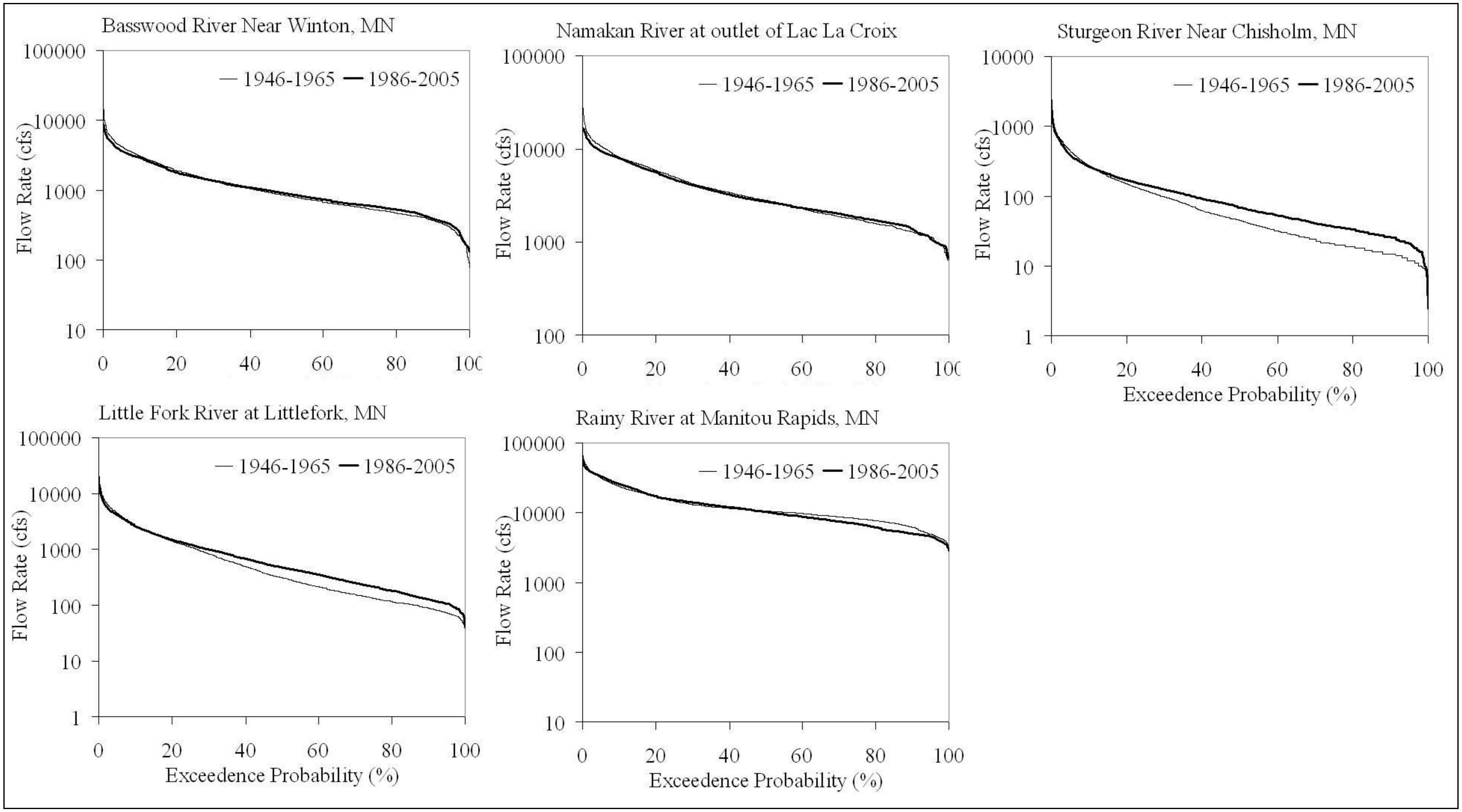

Figure 4.5. FDCs at stream gauging stations in the Rainy River Basin for the periods 1946-1965 and 1986-2005.

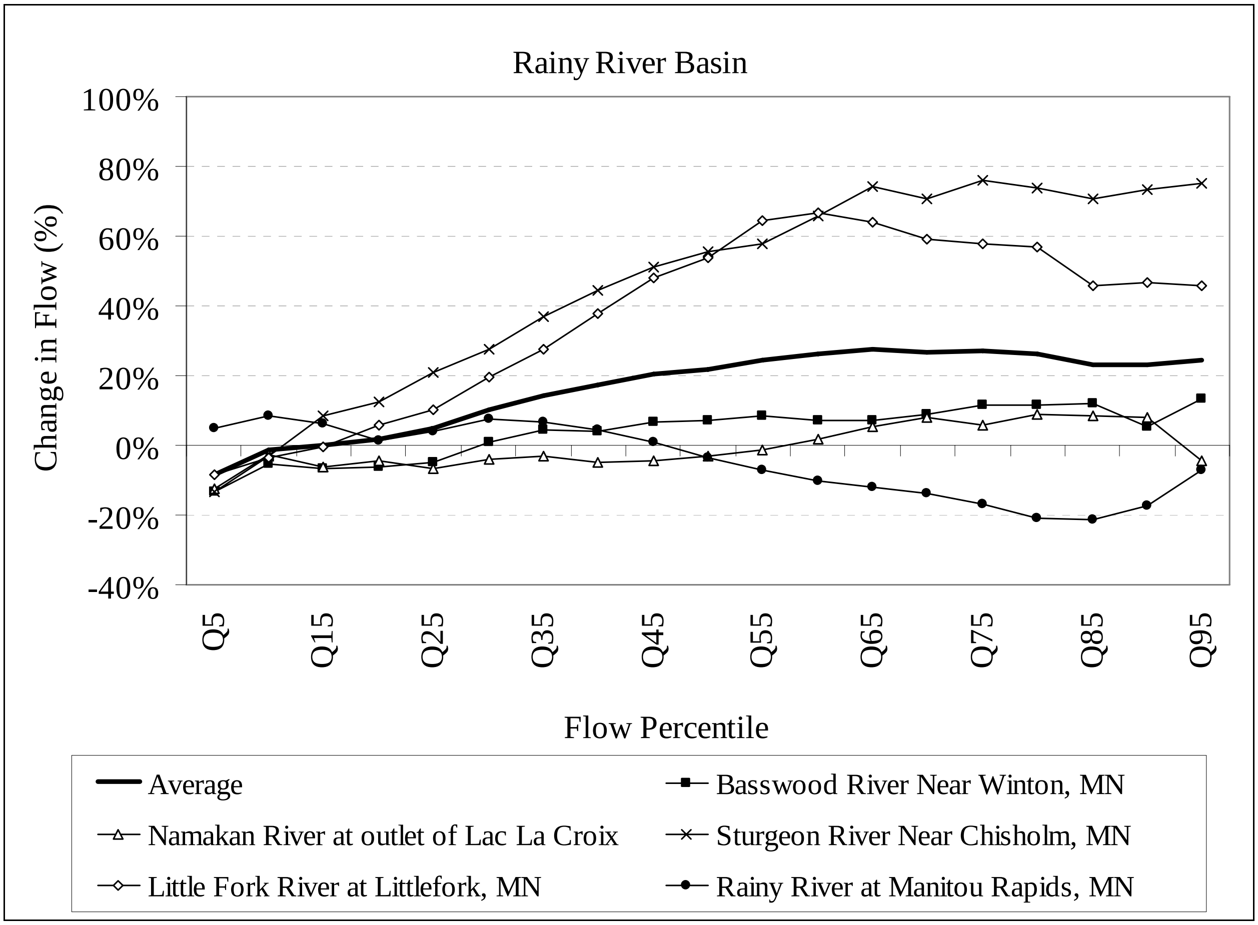

Figure 4.6. Change in flows between Q5 and Q95 at stream gauging stations in the Rainy River Basin from the 1946 -1965 period to the 1986-2005 period. Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

4.4. FDCs for Tributary Streams to Lake Superior

Data from 2 gauging station on tributaries to Lake Superior were analyzed. At both stations, medium flow portions of FDCs (Q25-Q75) showed an upward shift from 1946 -1965 to 1985 -2005, indicating that medium flows increased. The average increase in median flows was 13% (range from 11% to 15%) (Table 4.4).

Very low flows (i.e., Q95) showed a decrease in both streams between the two periods. The average decrease observed at the two stations was 19% (range from -29% to 8%). Q90 decreased by 9% in the Pigeon River at Middle Falls, MN and increased by 6% in the St. Louis River at Scanlon, MN from 1946 -1965 to 1986 -2005. The variability of low flows increased at both stations in the 1986 -2005 period by 15%. The Q20/Q90 index, which is a ratio of high flow to quick flow, increased by 12% and 17% at the two stations. The Q90/Q50 index, which indicates the base flow fraction of mean stream flow decreased by 18% and 8%. The results of the Q20/Q90 and Q90/Q50 indices are opposite to each other. Very high flows (i.e., Q5) decreased in both streams (range of 5% to 6%). Q10 decreased in the Pigeon River at Middle Falls, MN by 3%, but increased in St. Louis River at Scanlon by 5%.

In summary, the changes observed in flows from 1946 to 2005 were not consistent for the two stream gauging sites. The changes were, however, smaller than the changes observed in other river basins (about 10 to 20%).

Table 4.4. Change in FDC index values in tributaries (St. Louis River and Pigeon River) to Lake Superior from the 1946 -1965 period to the 1986 -2005 period.

Flow Percentile	Average Change (%)	Std. Dev. of Change (%)	Minimum Change(%)	Maximum Change(%)
Q5	-5	0	-6	-5
Q10	1	5	-3	5
Q50	13	3	11	15
Q90	-2	10	-9	6
Q95	-19	14	-29	-8
Q20/Q90	15	4	12	17
Q90/Q50	-13	7	-18	-8
Q50/Q90	15	9	9	22

Note: Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

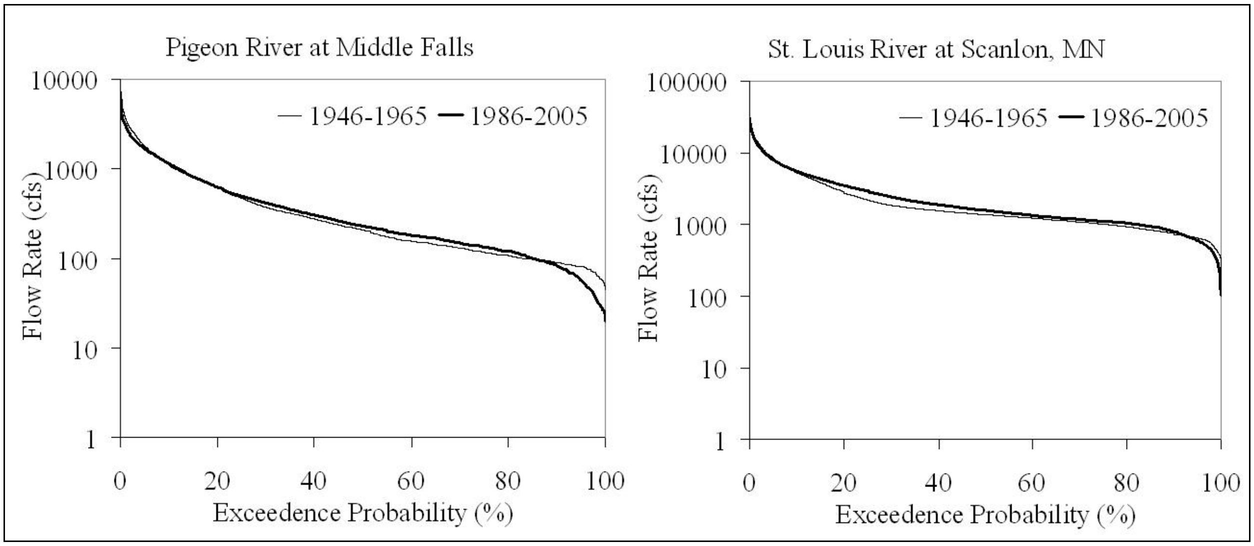

Figure 4.7. FDCs at stream gauging stations in tributaries to Lake Superior for the periods 1946 -1965 and 1986 -2005.

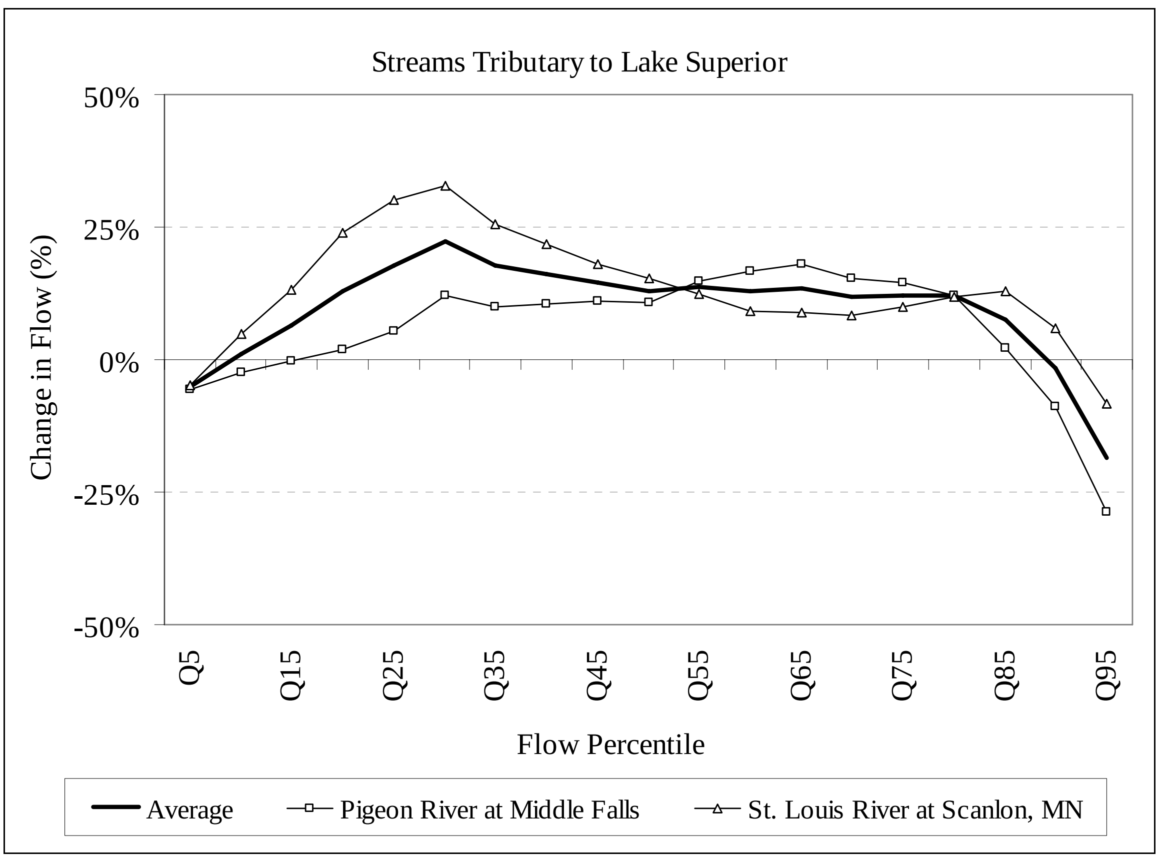

Figure 4.8. Change in flows at stream gauging stations in tributaries to Lake Superior from the 1946 -1965 period to the 1986 -2005 period. Change in flow (%) is the difference in flow

between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 - 1965 period.

4.5. FDCs for the Upper Mississippi River Basin

Data from 11 gauging stations in the Upper Mississippi River Basin were analyzed. The FDCs in the range of Q15 - Q95 made an upward shift for all stations from the 1946-1965 to the 1986-2005 period (Figures 4.9a and b). Median flow in the 1986-2005 period was on average 82% (range from 16% to 259%) higher than the median flow in the 1946-1965 period (Table 4.5). The largest increases in flows were observed in the Des Moines River at Jackson, MN; the Crow River at Rockford MN, and the Cedar River near Austin MN (Figure 4.10).

Low flow indices, Q95 and Q90, increased by 66% (range from 13% to 358%) and 435% (range from 5% to 4500%), respectively, in the latter period. The wide range of changes observed at the stations in the Upper Mississippi River Basin was caused by the changes in three of the stations, which have patterns not similar to the patterns observed in the other 8 stations. These stations were in the Cedar River near Austin, MN; the Crow River at Rockford, MN; and the Des Moines River at Jackson, MN. On average the variability of low flow (Q50/Q90) changed by 14% (range from -22% to 53%) between the 1946-1965 and 1986-2005 periods. Average changes in the Q20/Q90 and Q90/Q50 indices were 2% and -9%.

Q5 and Q10 made upward shifts for all stations except two. The exceptions were the Mississippi River at Aitkin, MN and the St. Croix River at St. Croix Falls, WI. The average increase in Q5 was 29% (range from -13% to 129%) and the average increase in Q10 was 41% (range from
-3% to 154%).

In summary, from 1946 to 2005, high flows in the Upper Mississippi River Basin increased about 35%, medium flows increased about 80%, and low flows increased about 60% (with one exception, the Des Moines River at Jackson, MN).

Table 4.5. Change in FDC index values in the Upper Mississippi River Basin from the 1946 - 1965 period to the 1986 - 2005 period.

Flow Percentile	Average Change (%)	Std. Dev. of Change (%)	Minimum Change(%)	Maximum Change (%)
Q5	29	43	-13	127
Q10	41	52	-3	154
Q50	82	85	16	259
Q90	66	102	13	358
Q95	435	1348	5	4500
Q20/Q90	2	24	-37	58
Q90/Q50	-9	19	-35	28
Q50/Q90	14	22	-22	53

Note; Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

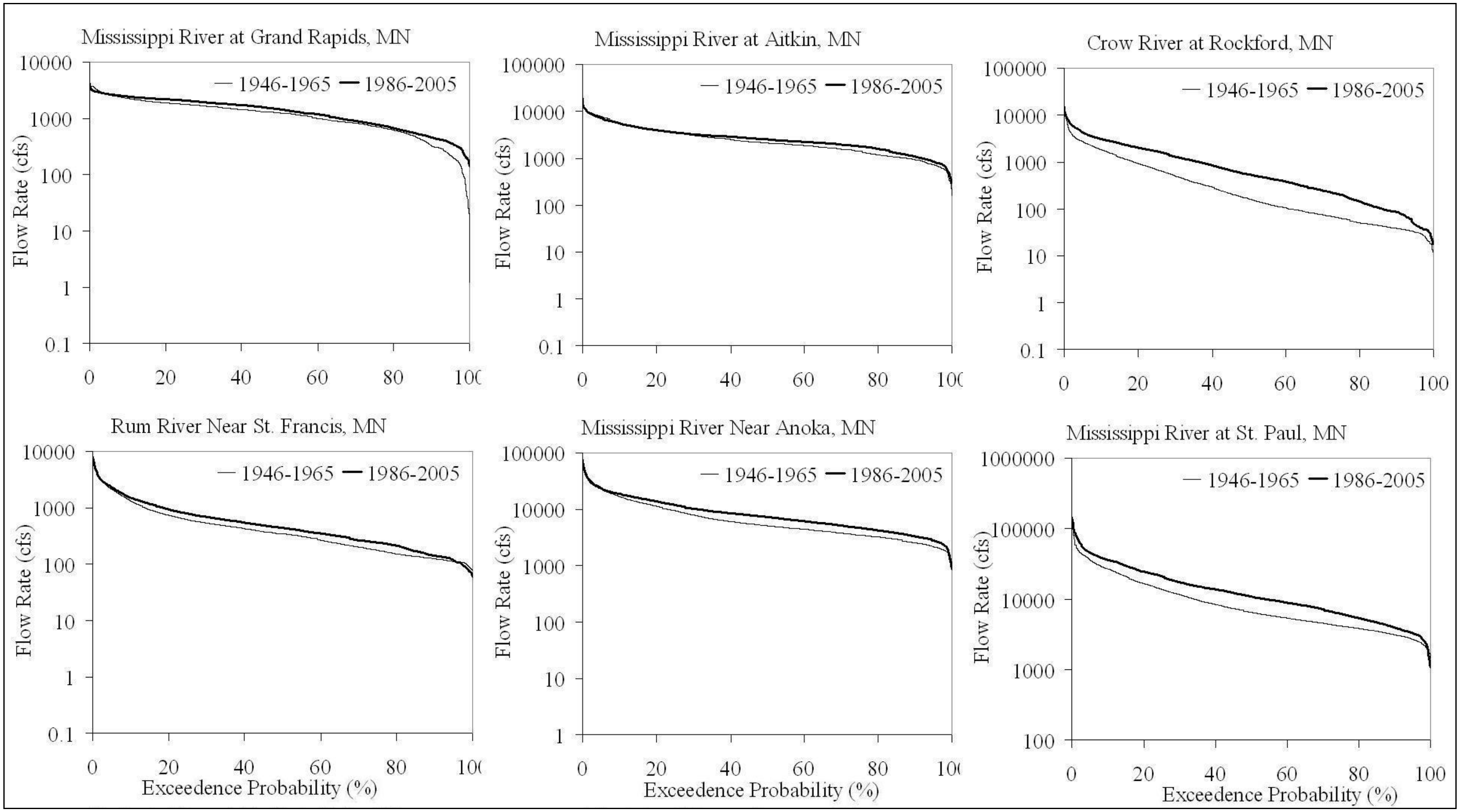

Figure 4.9a. FDCs at stream gauging stations in the Upper Mississippi River Basin for the periods 1946 -1965 and 1986 -2005.

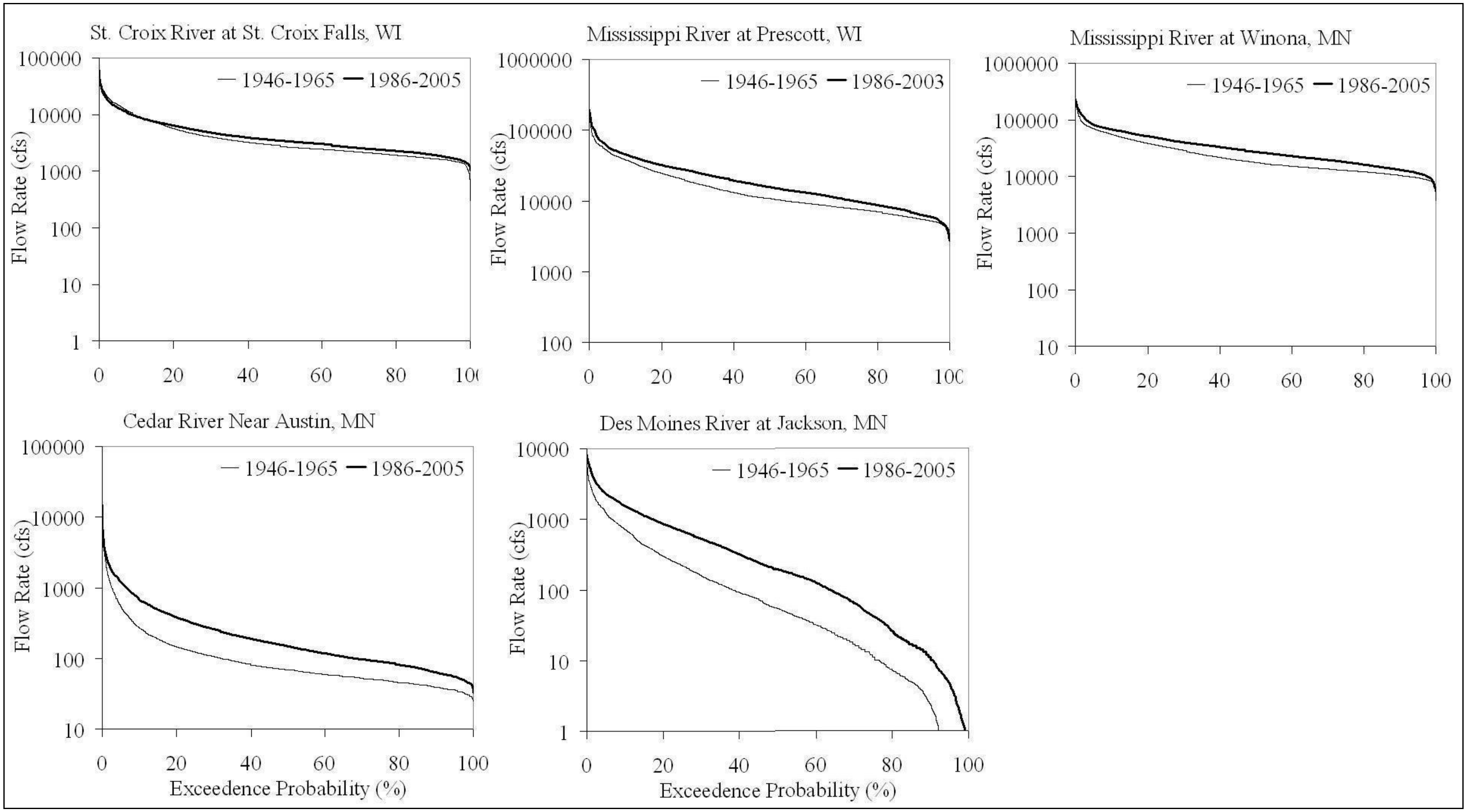

Figure 4.9b. FDCs at stream gauging stations in the Upper Mississippi River Basin for the periods 1946 -1965 and 1986 -2005.

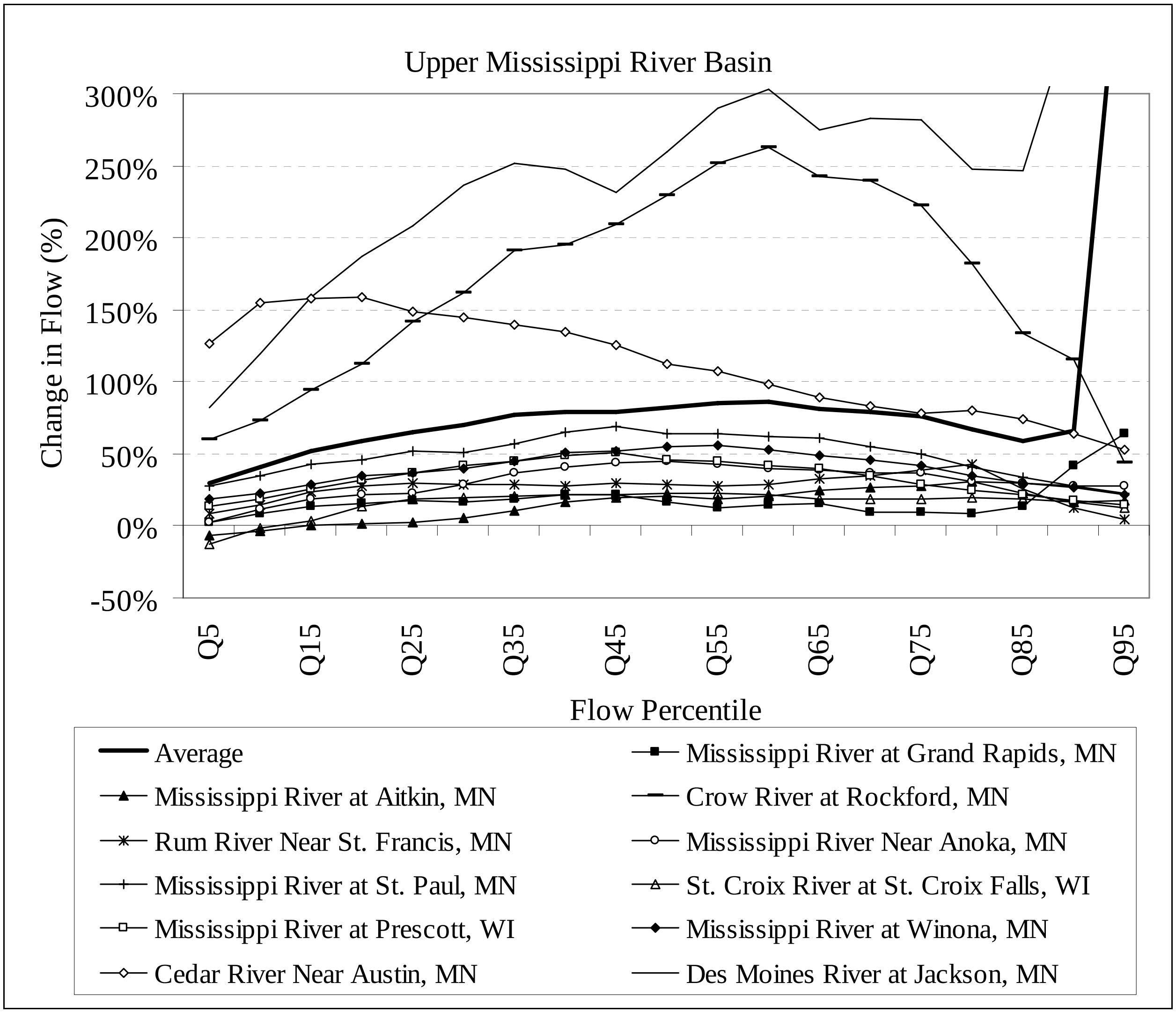

Figure 4.10. Change in flows between Q5 and Q95 at stream gauging stations in the Upper Mississippi River Basin from the 1946 - 1965 period to the 1986 - 2005 period. Change in flow (%) is the difference in flow between the 1986-2005 period and the 1946 - 1965 period divided by the flow in the 1946 - 1965 period.

4.6. Summary of Results from the FDC Analysis

Flow Duration Curves (FDCs) for 36 stream gauging stations in Minnesota showed significant changes from the period (1946-1965) to the period (1986-2005). The changes were mostly consistent for stream gauging stations located in the same river basin, although deviations from a typical river basin pattern were noted at a few gauging stations, e.g., for the Roseau River near Milung, in the Red River of the North Basin, or the Des Moines River at Jackson, and the

Crow River at Rockford in the Upper Mississippi River Basin. Consistency of changes observed in a river basin can be an indicator of climatic effects. However, the deviations from general patterns at some stations may have other causes, e.g., land-use/land cover changes.

The Minnesota River Basin has experienced the largest stream flow changes in the last 20 years compared to the other four basins. In that basin high, medium, and low flows have increased significantly. 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 Red River of the North Basin. The changes, although smaller in magnitude, showed the same pattern as the Minnesota River Basin. Streams in the Rainy River Basin and tributaries to Lake Superior showed little change in stream flow distribution (10-20%). 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%, low flows seem to have decreased, and high flows seem to be unchanged.

5. RESULTS – OCCURRENCE OF RANKED ANNUAL PEAK FLOWS

When peak flows occur in streams or rivers, it is typical that flooding causes damage to infrastructure and buildings. In addition, water quality and habitat conditions for many aquatic organisms become stressed. Peak flow events are therefore economically and ecologically very significant. Annual peak flow events in a stream flow record can be ranked from highest to lowest, and the occurrence of the highest peak flows can be studied. The time series plots in Figures 5.1 to 5.5 identify the actual years in which the top 1, 3, 5, and 10 peak flow events have occurred at stream gauging stations of major Minnesota streams. Plots are provided for all stream gauging stations in the five major river basins of Minnesota. Have peak flows been more common in the recent 1986-2005 period compared to the longer 1946-2005 period? The number of stations where the observed number of annual peak flows during the 1986-2005 period was higher than the average number expected from the analysis of the full record (1946-2005) is therefore given in Table 5.1.

Figures 5.1 to 5.5 and Table 5.1 provide evidence that the occurrence of peak stream flow events may have shifted somewhat during the 1946 to 2005 period, at least in the Minnesota River Basin and the Red River of the North Basin. For example, up to 6 of the 12 stations in the Minnesota River Basin had more than the expected number of annual peak flow events in the

1986-2005 period (Table 5.1). The stream gauging station which experienced the changes are all in the upper reaches of the Minnesota River. The increase is readily apparent in the records for the Whetstone River near Big Stone City, SD, the Minnesota River at Ortonville and at Montevideo, and the Chippewa River near Milan (Figure 5.1). In the Red River of the North Basin, up to 5 of 6 stations had more than the expected number of annual peak flow events in the recent period (1986 to 2005). The temporal distribution of the top 1, 3, 5, and 10 peak flow events in the last 20 years is shown in Figure 4.13 for 4 of the 6 stations in the Rainy River Basin (Red Lake River at Crookston, MN and Red River of the North at Drayton, ND are excluded because peak flow data were not available for these stations). In the Rainy River Basin and in tributary streams to Lake Superior the temporal distribution of annual peak flow events does not seem to have changed. In the Upper Mississippi River Basin the evidence of change is mixed: only 2 of 11 stream gauging stations show a shift in the occurrence of the top 1, 3, and 5 peak flow events (Table 5.1), but peak flows that are in the top 10 have occurred more often at 6 of the 11 stream gauging stations on the Upper Mississippi River in the recent period (1986-2005).

Table 5.1. Number and percentage of stations which had more than the expected number of peak flow events in the 1986-2005 period.

	Number of peak flow events in (1946-2005) record	**1**	**3**	**5**	**10**
	Number of events expected in the (1986-2005) period	**0**	**1**	**2**	**3**
Minnesota River Basin (12 sta)	Number of sta above expected	5	5	6	6
	Percent of sta above expected	42	42	50	50
Red River of the North Basin (6 sta)	Number of sta above expected	4	3	3	5
	Percent of sta above expected	67	50	50	83
Rainy River Basin (4 sta)	Number of sta above expected	0	0	0	0
	Percent of sta above expected	0	0	0	0
Lake Superior Tributaries (2 sta)	Number of sta above expected	0	0	0	0
	Percent of sta above expected	0	0	0	0
Upper Mississippi River Basin (11)	Number of sta above expected	2	1	1	6
	Percent of sta above expected	18	9	9	55

Note: "Number above expected" is the number of stream gauging stations at which more than the expected number of peak flow events occurred. "Percent above expected" is the number of stream gauging stations at which more than the expected number of high flow events occurred, divided by the total number of stream gauging stations in the river basin.

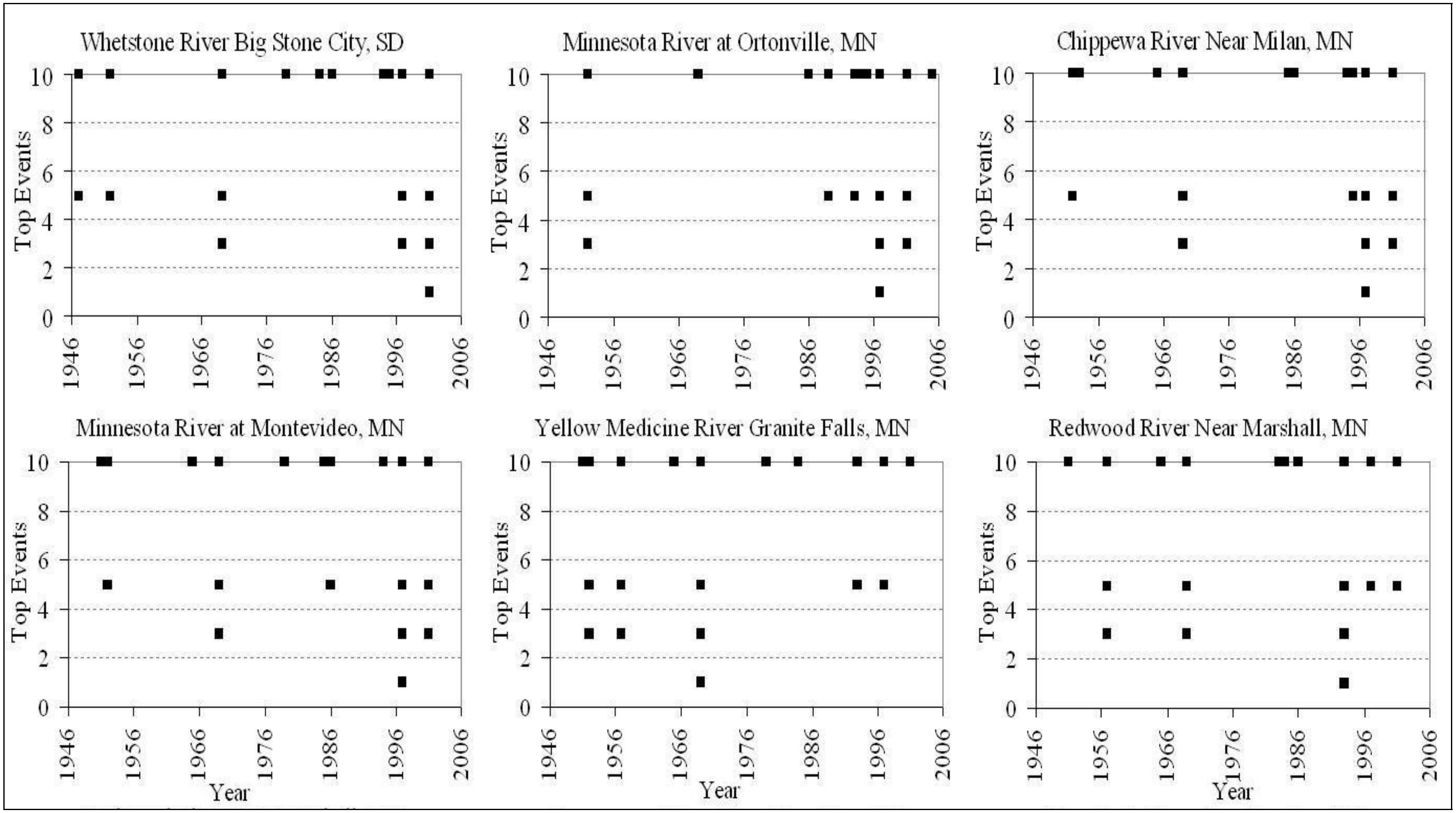

Figure 5.1a. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in the Minnesota River Basin

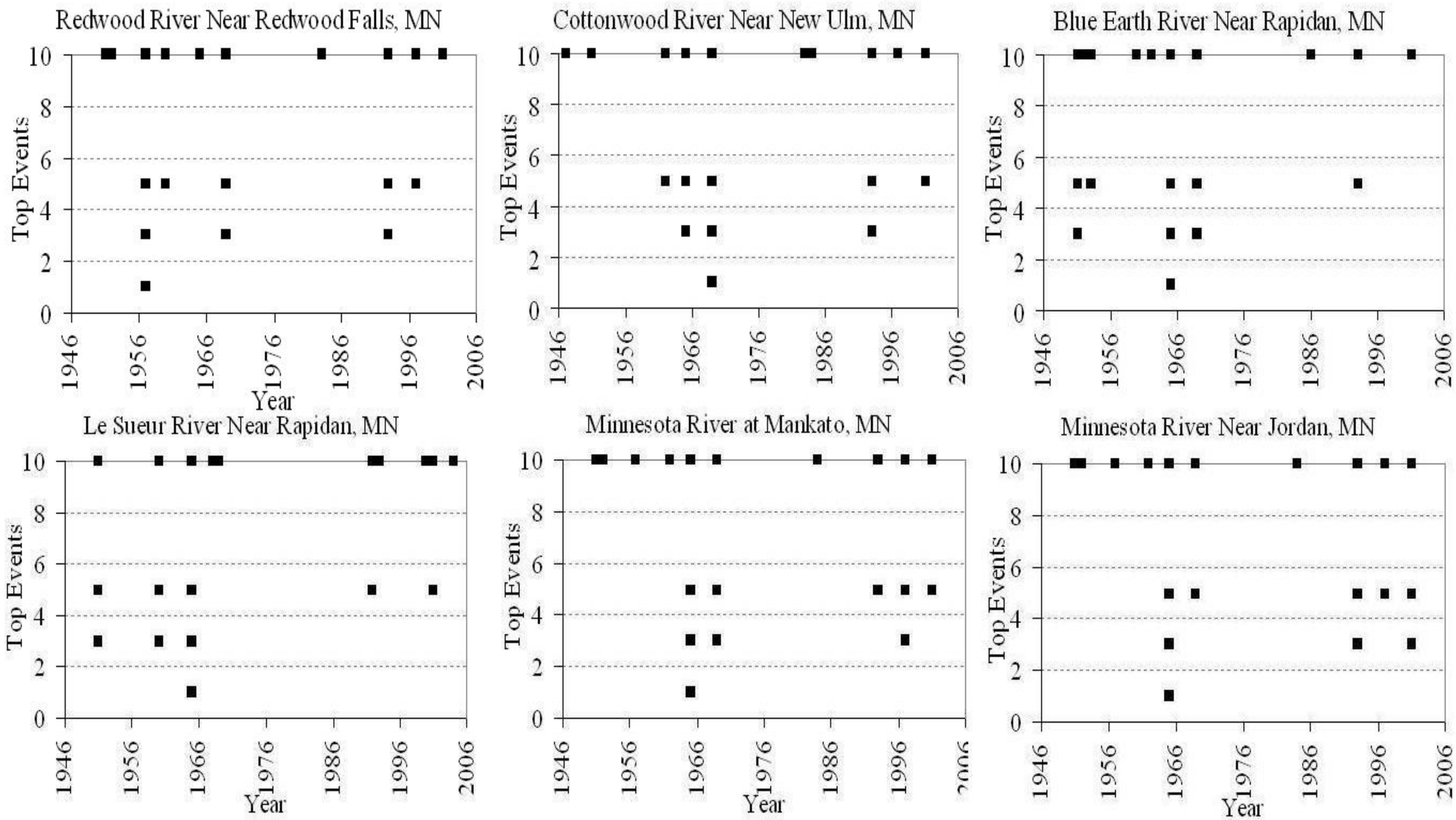

Figure 5.1b. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in the Minnesota River Basin

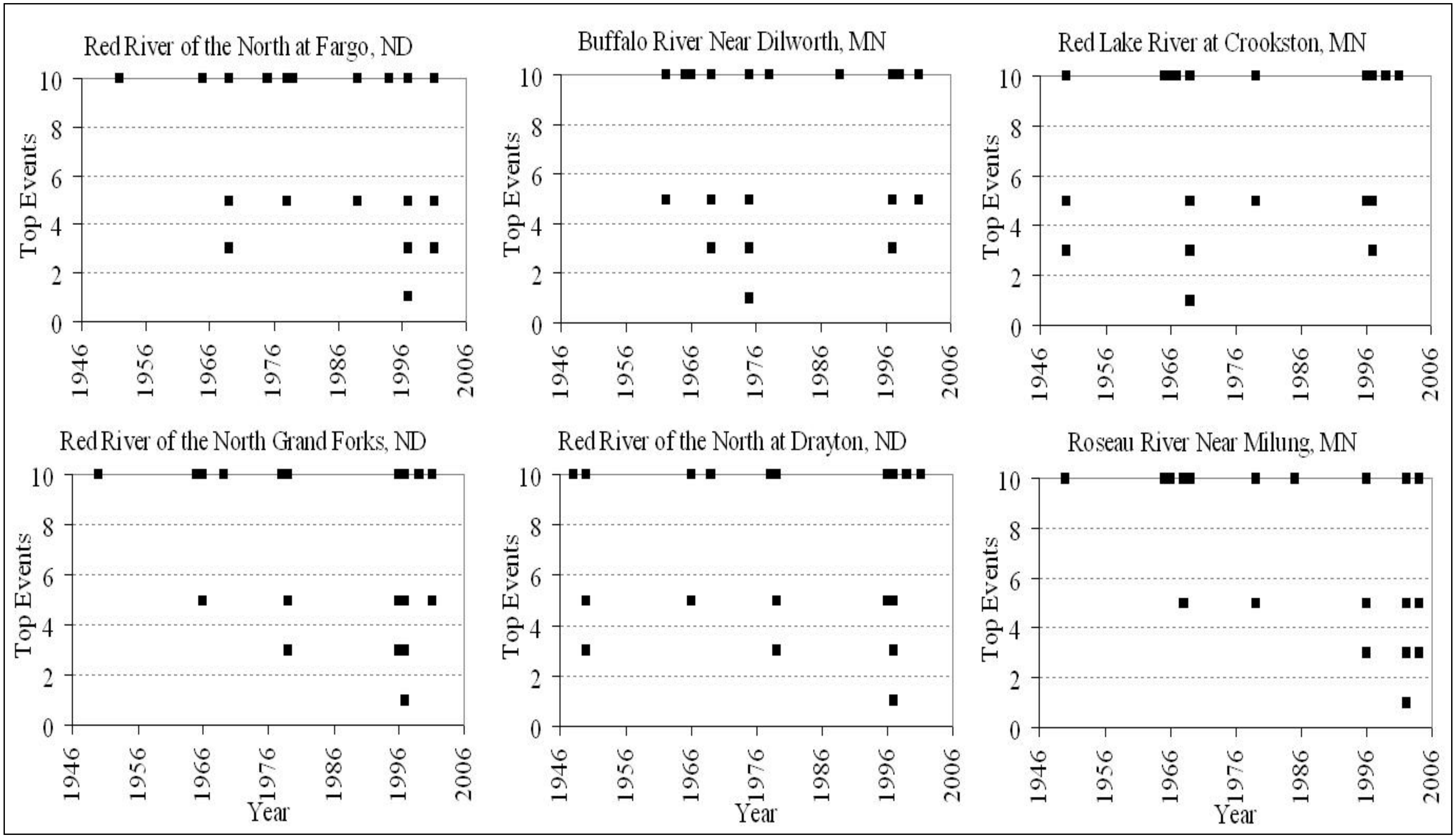

Figure 5.2. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in the Red River of the North Basin

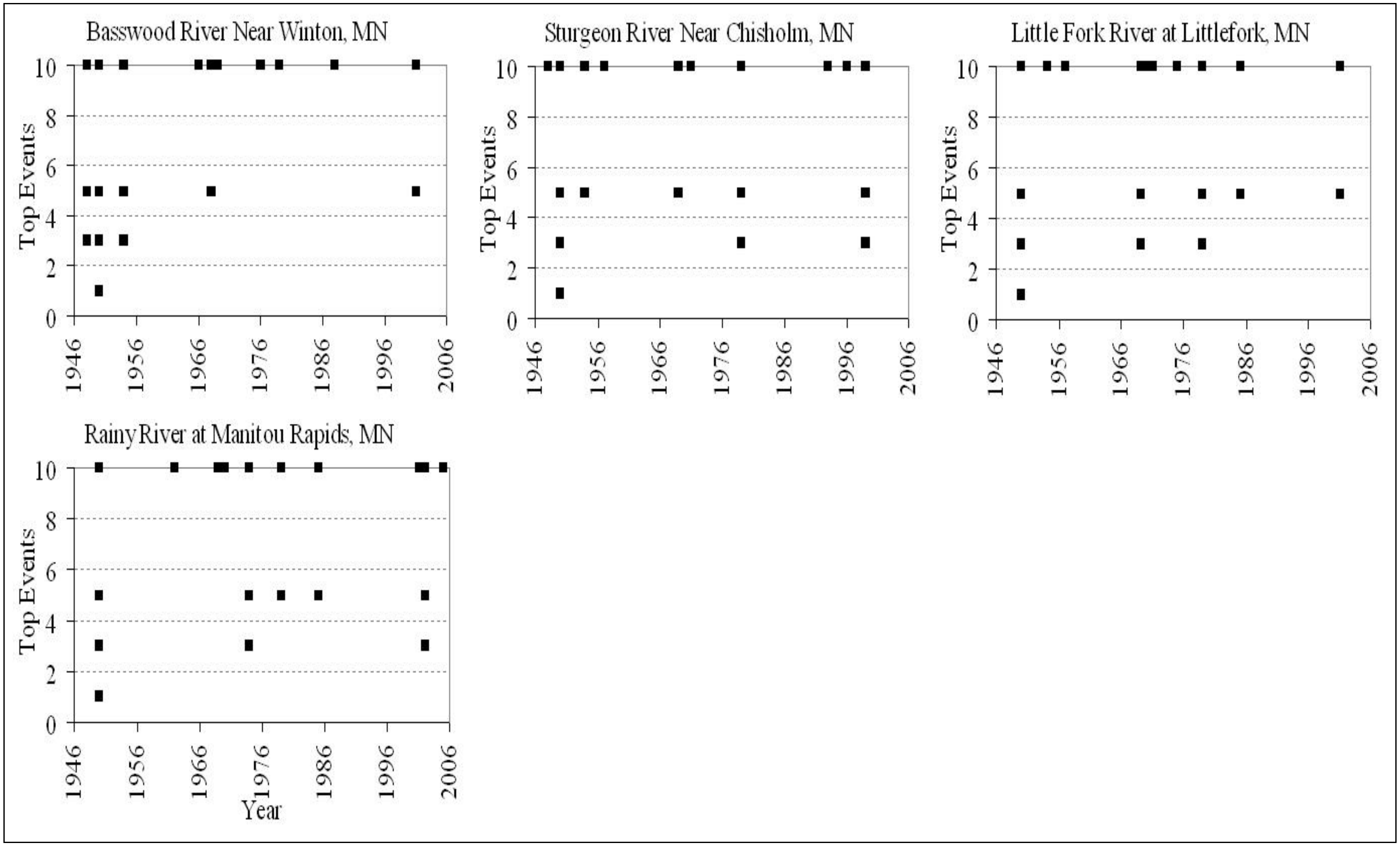

Figure 5.3. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in the Rainy River Basin

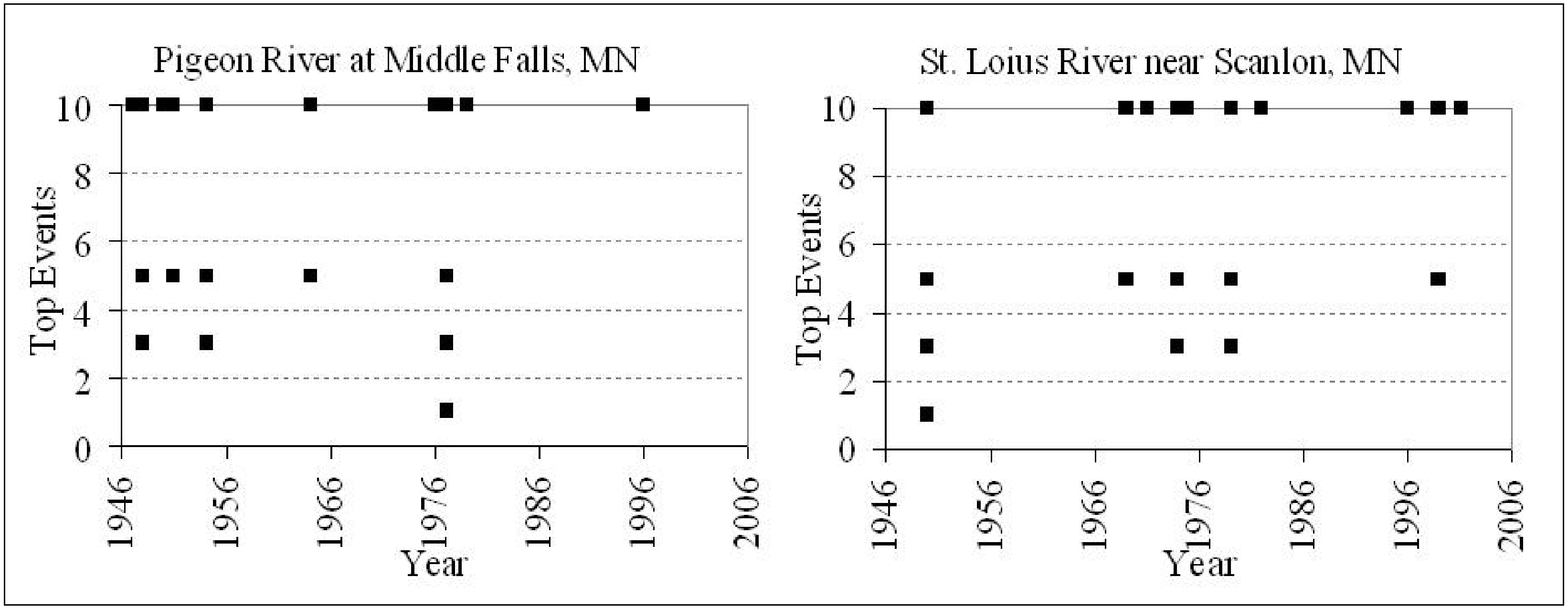

Figure 5.4. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in tributaries to Lake Superior.

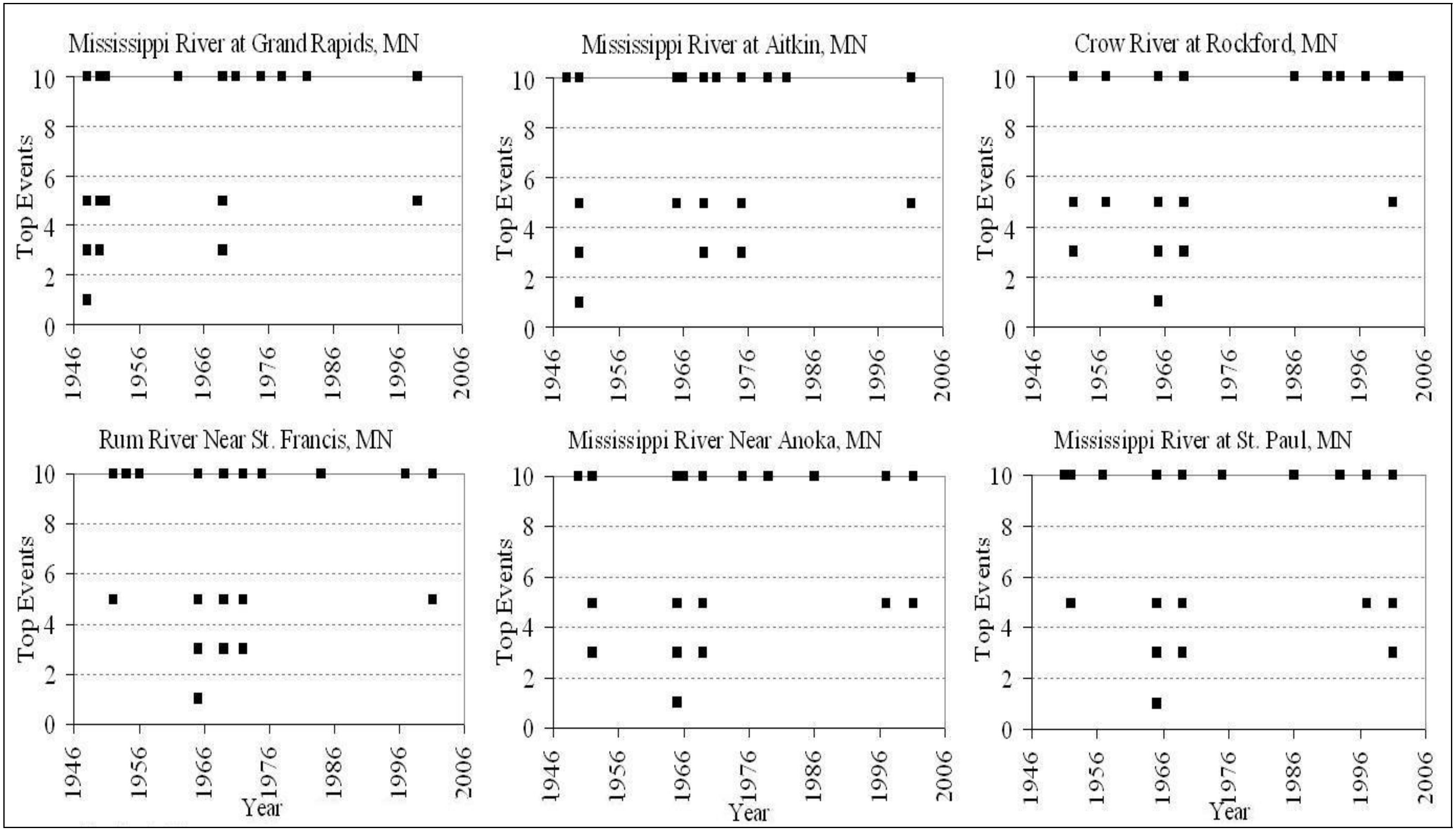

Figure 5.5a. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in the Upper Mississippi River Basin

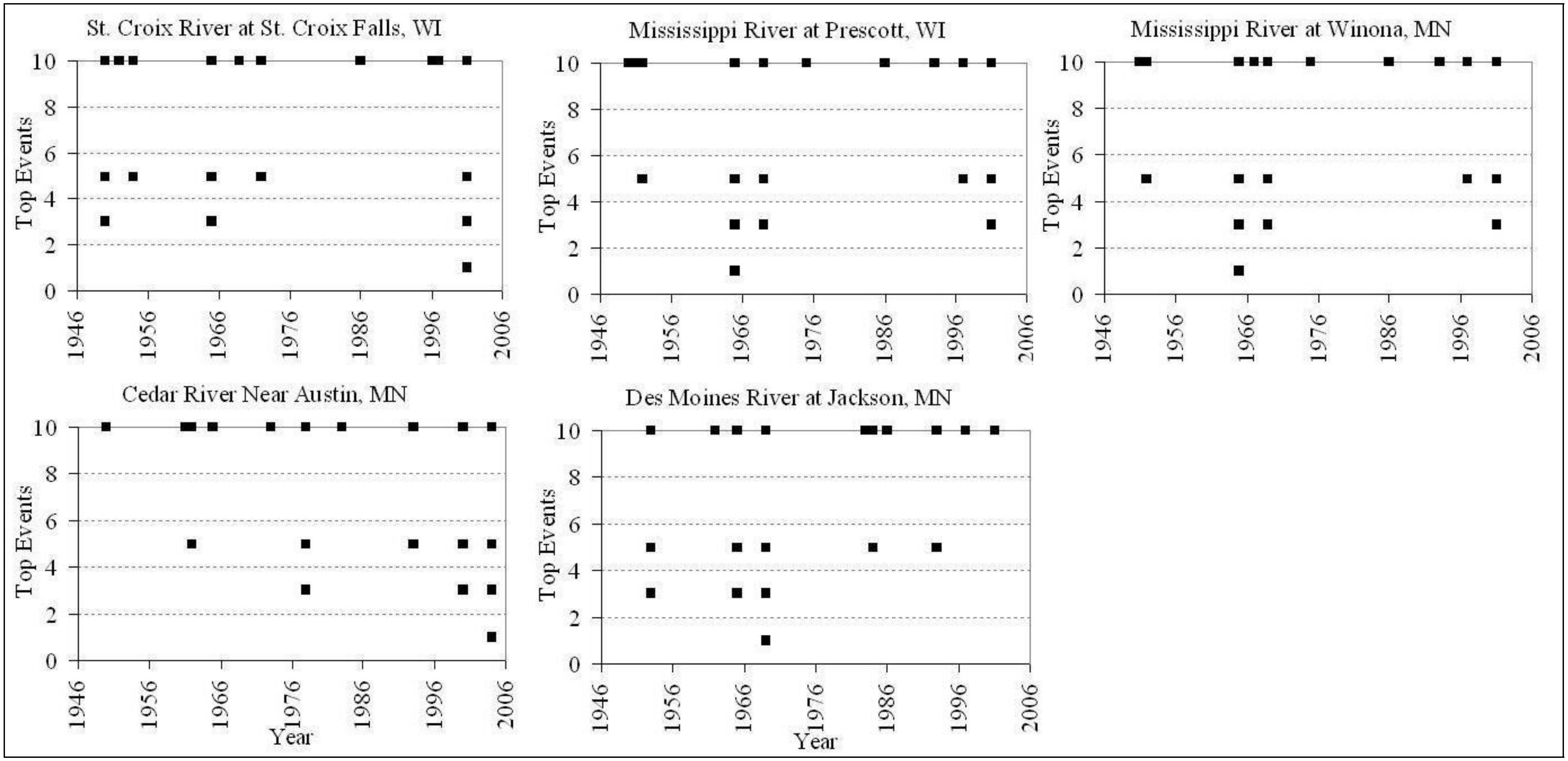

Figure 5.5b. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in the Upper Mississippi River Basin

6. RESULTS – OCCURRENCE OF RANKED ANNUAL 7-DAY (AVERAGE) LOW FLOWS

When 7-day (average) low flows occur in a stream, it is typical that water quality deteriorates and habitat conditions for many aquatic organisms become stressed. 7-day low flow events are therefore ecologically very significant. The 7-day low flows in some small streams in Minnesota have been zero in some years. Table 6.1 gives the number of years when the 7-day low flow fell to zero at the 36 stream gauging stations investigated.

Table 6.1. Stations that had zero 7-day average low flows during the 1946-2005 period.

USGS Gauging Station No.	Stream/River Name	Number of years 7-day average flow is zero
Minnesota River Basin		
05291000	Whetstone River Big Stone City, SD	3
05313500	Yellow Medicine River Granite Falls, MN	2
05315000	Redwood River Near Marshall, MN	8
Red River of the North Basin		
05054000	Red River of the North at Fargo, ND	1
05104500	Roseau River Near Milung, MN	5
Upper Mississippi River Basin		
05476000	Des Moines River at Jackson, MN	7

Low flows can also be ranked – from the lowest annual low flow to the highest annual low flow in the record.. The temporal distributions of the lowest 1, 3, 5, and 10 7-day (average) annual low flows that occurred at stream gauging stations located in the five main river basins of Minnesota over the period of record (1946-2005) are provided in Figures 6.1 to 6.5. These plots show qualitatively if the occurrence of low flow conditions shifted over the period of record from 1946 to 2005. To quantify the shift, the number and the percentage of stream gauging stations which had a smaller than the expected number of lowest 7-day (average) low flow events during the recent 1986-2005 period are given in Table 6.2.

The analysis of flow duration curves in Section 4 showed that low flows increased within the last 20 years in some regions of Minnesota. We therefore also analyzed the distribution of the top 1, 3, 5, and 10 highest 7-day (average) annual low flow events that occurred in the 1946-2005 period (Figures 6.6 to 6.10). We also quantified the shift by calculating the number and the percentage of stream gauging stations where more than the expected number of the highest 7-day (average) low flow events occurred (Table 6.3).

According to this analysis changes in 7-day (average) low flows were most evident in the Minnesota River Basin and the Red River of the North Basin, and somewhat evident in the Upper Mississippi River Basin.

In the Minnesota River Basin, the highest 1, 3, 5 and 10 7-day (average) annual low flows occurred more than expected in the 1986-2005 period at all 12 stations (Table 6.3). In agreement with this finding is that only 1 in 12 stations had the single lowest 7-day (average) annual low flow in the 1986-2005 period (Table 6.2).

In the Red River of the North Basin, the highest 1 and 3 7-day annual (average) low flows at all 6 stations occurred during the 1986-2005 period. All stations showed more than the expected top 1, 3, 5 and 10 7-day annual (average) low flow events in the last 20 years. All but one stations had at least 4 of the 5 highest and 7 of the 10 highest 7-day average low flows after 1985 (Table 6.3).

In the Upper Mississippi River Basin, 6 of the 11 stations had the highest 7-day annual (average) low flow between 1986 and 2005 and 7 stations had at least 2 of the 3 highest 7-day annual (average) low flows after 1985.

The highest 7-day (average) low flow occurred on both gauged tributaries to Lake Superior in the last 20 years, the 3, 5, and 10 highest flows did not. Similarly, no convincing trend was observed in the records of the stations located in the Rainy River Basin. Only 40% of the stations had more than the expected highest 5 and 10 7-day annual (average) low flow in the 1986-2005 period.

In summary, the low flow occurrence results for all five major river basins agree with the results from the flow duration curves (FDCs) in Section 4 – as they should. Both analyses indicate that changes in low flows have occurred in 3 of the 5 major river basins (Minnesota River Basin, Red River of the North Basin, and Upper Mississippi River Basin).

Table 6.2. Number and percentage of stations which had more than the expected number of lowest 7-day (average) low flow occurrences in the 1986-2005 period.

	Number of lowest low flow events in (1946-2005) record	**1**	**3**	**5**	**10**
	Number of events expected in the (1986-2005) period	**0**	**1**	**2**	**3**
Minnesota River Basin (12 sta)	Number of sta below expected	1	0	0	1
	Percent of sta below expected	8	0	0	8
Red River of the North Basin (6 sta)	Number of sta below expected	2	0	0	1
	Percent of sta below expected	40	0	0	20
Rainy River Basin (4 sta)	Number of sta below expected	2	2	1	4
	Percent of sta below expected	33	33	17	67
Lake Superior Tributaries (2 sta)	Number of sta below expected	1	0	1	2
	Percent of sta below expected	50	0	50	100
Upper Mississippi River Basin (11 sta)	Number of sta below expected	2	2	1	1
	Percent of sta below expected	18	18	9	9

Note: “Number below expected” is the number of stream gauging stations at which fewer than the expected number of low flow events occurred. “Percent below expected” is the number of stream gauging stations at which fewer than the expected number of low flow events occurred, divided by the total number of stream gauging stations in the river basin

Table 6.3. Number and percentage of stations which had more than the expected number of highest 7-day (average) low flow occurrences in the 1986-2005 period.

	Number of low flow events in (1946-2005) record	**1**	**3**	**5**	**10**
	Number of events expected in the (1986-2005) period	**0**	**1**	**2**	**3**
Minnesota River Basin (12 sta)	Number of sta above expected	12	12	12	12
	Percent of sta above expected	100	100	100	100
Red River of the North Basin (6 sta)	Number of sta above expected	6	6	6	6
	Percent of sta above expected	100	100	100	100
Rainy River Basin (4 sta)	Number of sta above expected	0	0	2	2
	Percent of sta above expected	0	0	40	40
Tributaries to Lake Superior (2 sta)	Number of sta above expected	2	1	1	1
	Percent of sta above expected	100	50	50	50
Upper Mississippi River Basin (11 sta)	Number of sta above expected	6	7	7	9
	Percent of sta above expected	55	64	64	82

Note: "Number above expected" is the number of stream gauging stations at which more the expected number of low flow events occurred."Percent above expected" is the number of stream gauging stations at which more than the expected number of low flow events occurred, divided by the total number of stream gauging stations in the river basin.

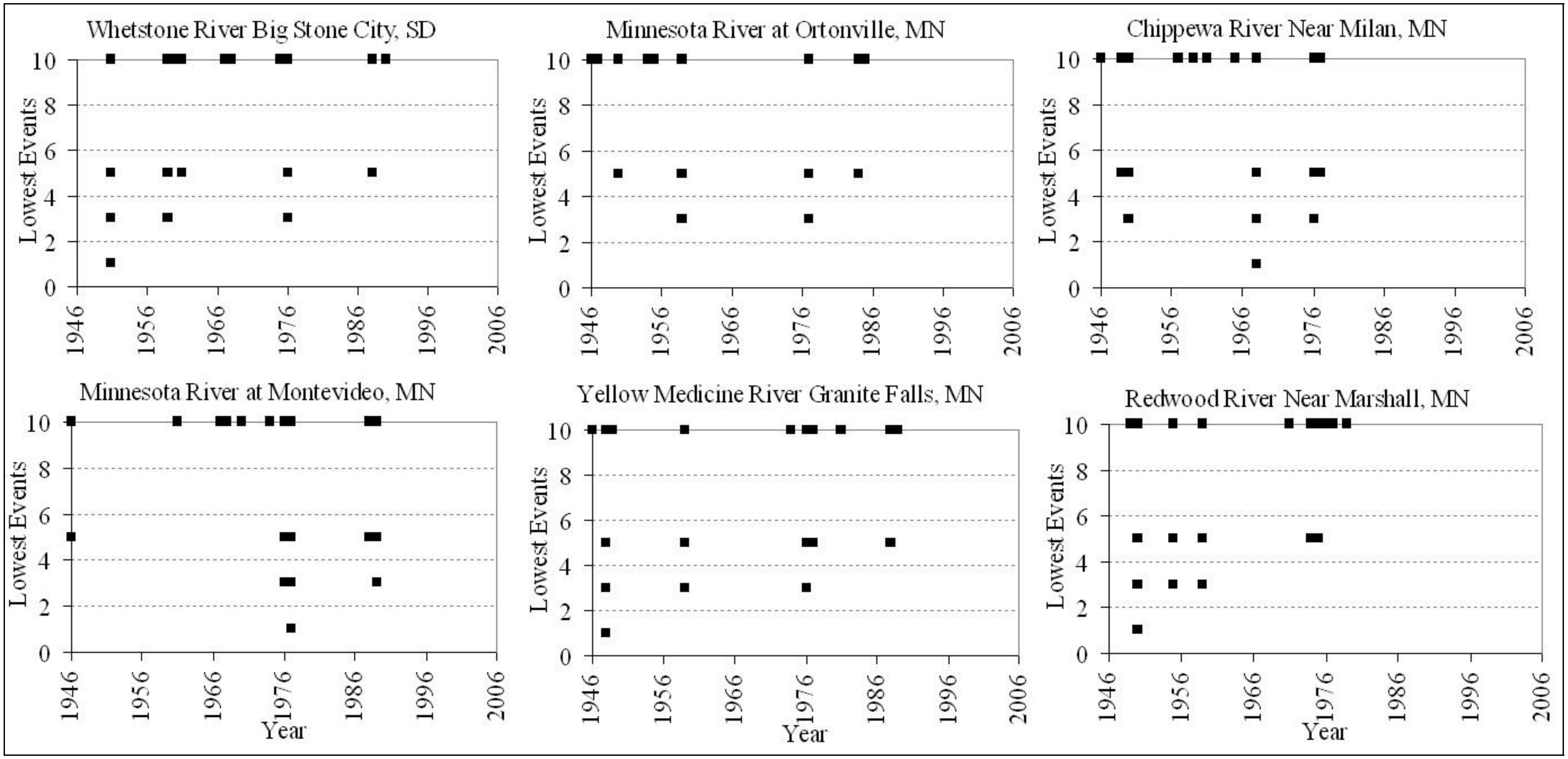

Figure 6.1a. Occurrence of the 1, 3, 5, and 10 lowest 7-day average low flows in the 1946-2005 period in the Minnesota River Basin

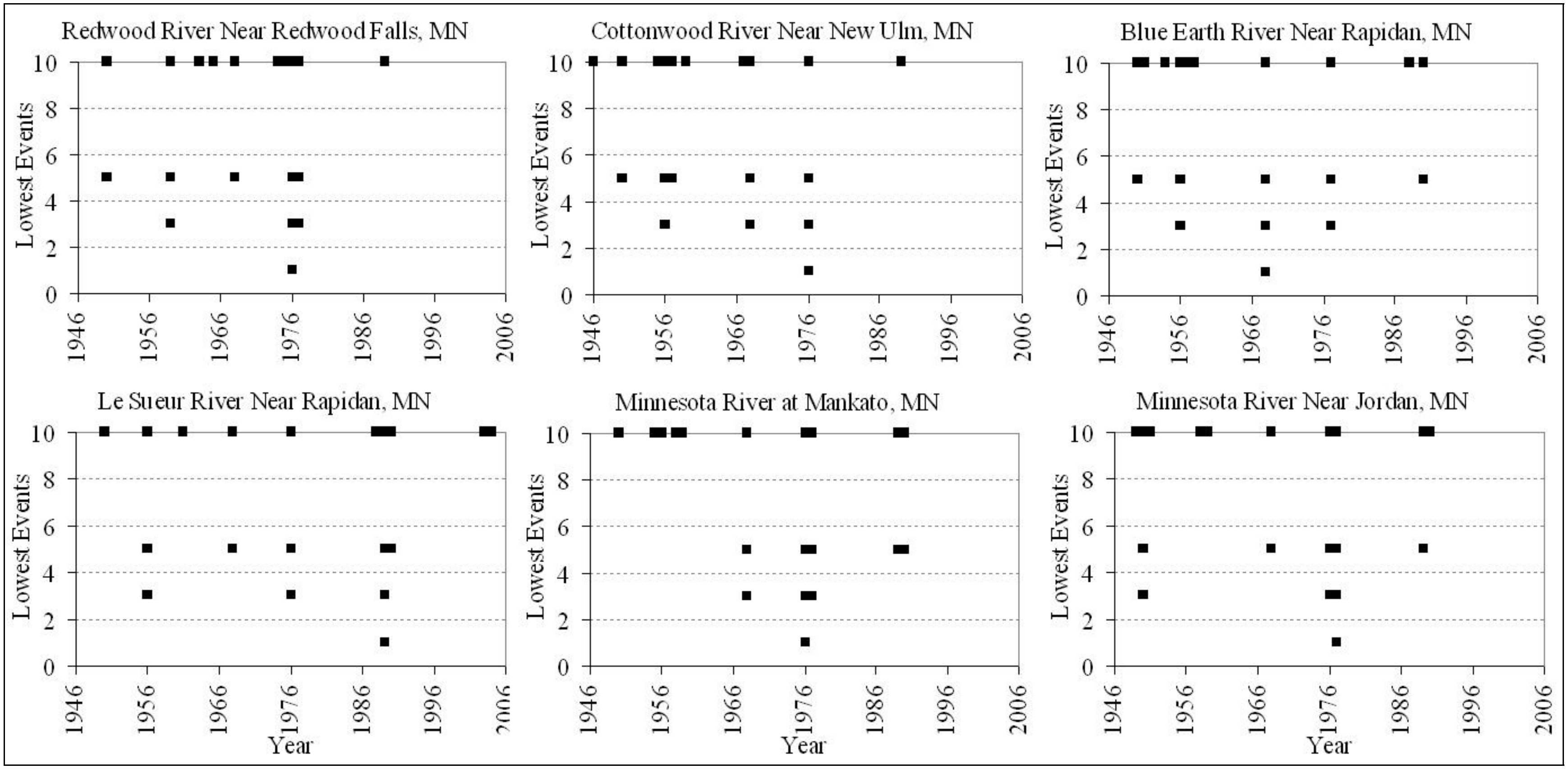

Figure 6.1b. Occurrence of the 1, 3, 5, and 10 lowest 7-day (average) low flows in the 1946-2005 period in the Minnesota River Basin

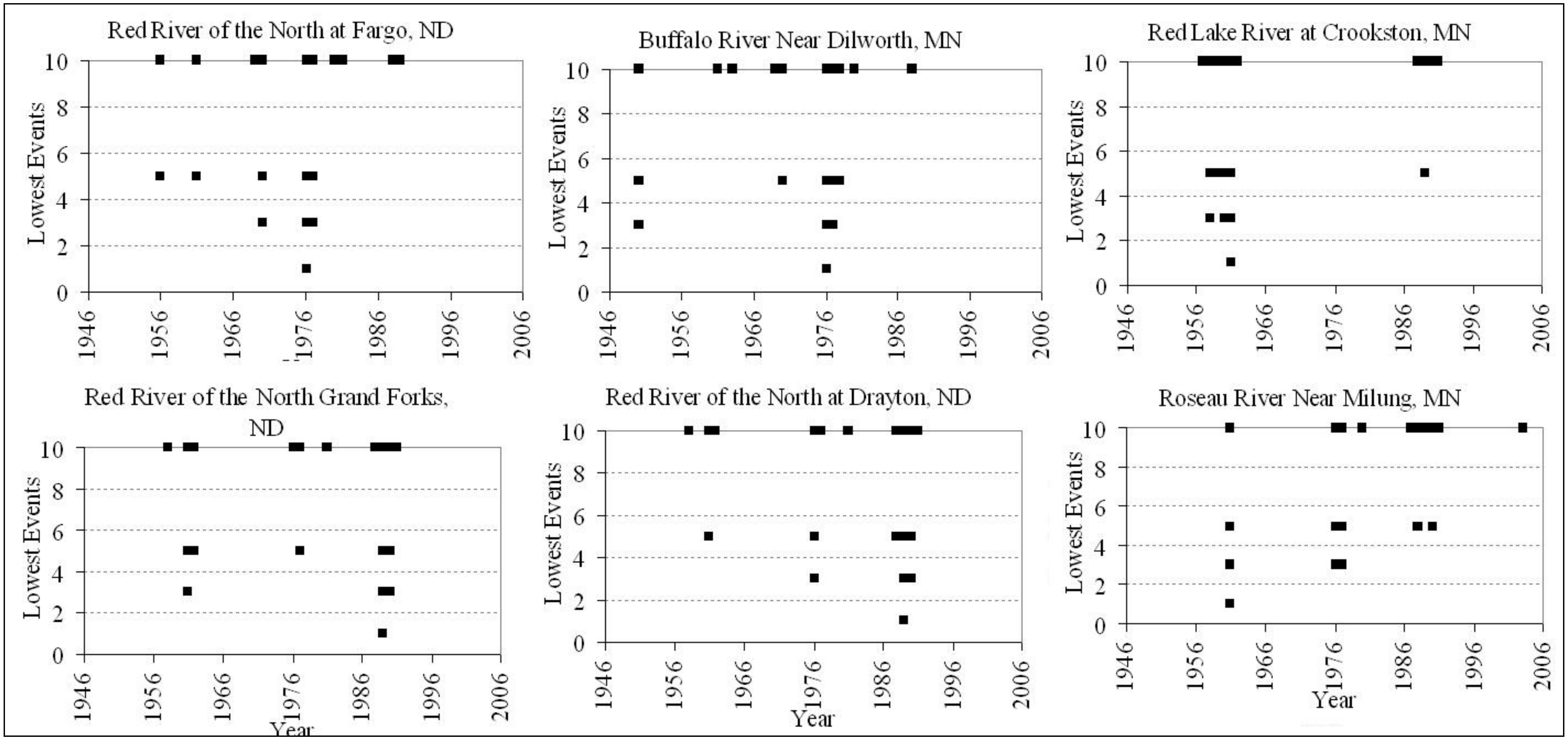

Figure 6.2. Occurrence of the 1, 3, 5, and 10 lowest 7-day (average) low flows in the 1946-2005 period in the Red River of the North Basin

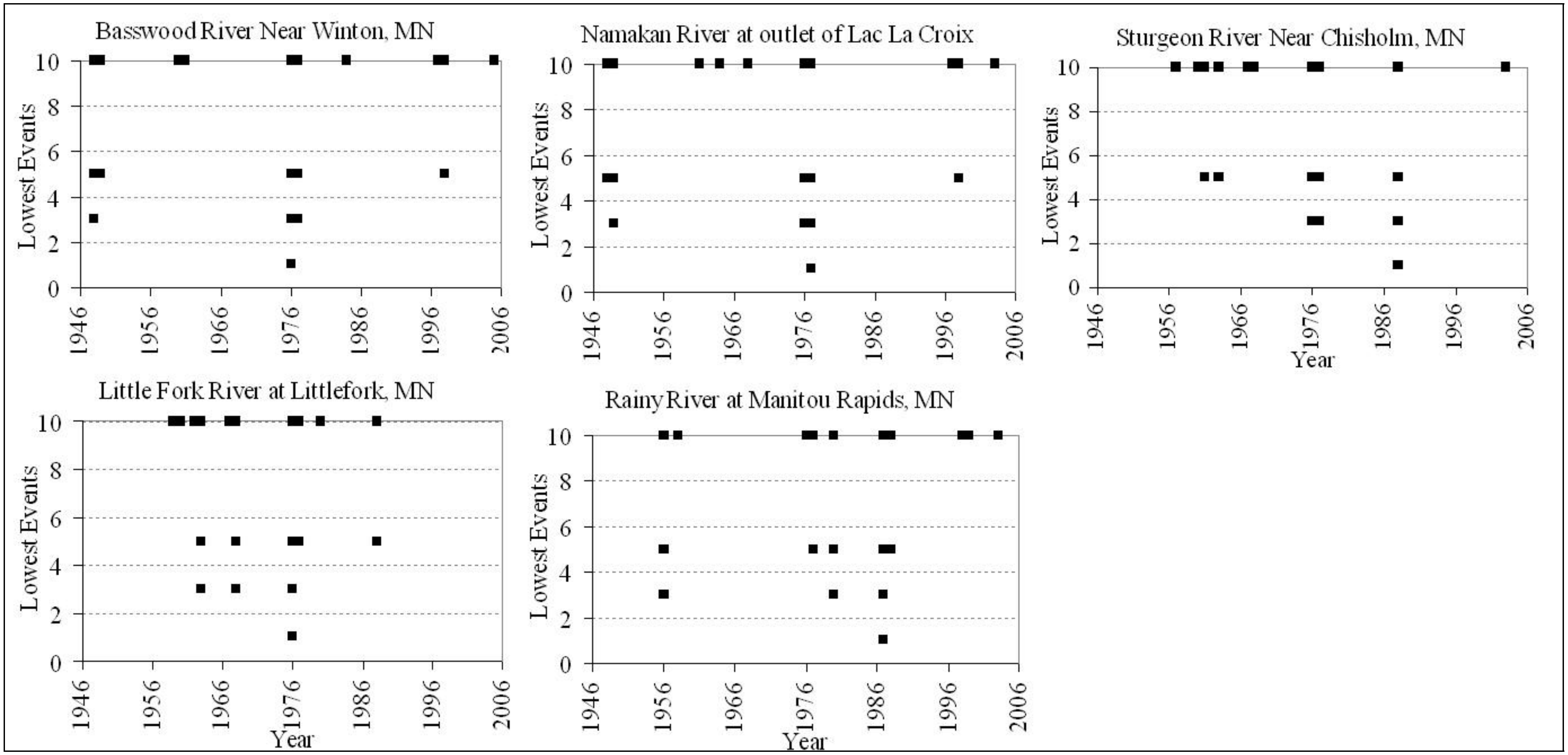

Figure 6.3. Occurrence of the 1, 3, 5, and 10 lowest 7-day (average) low flows in the 1946-2005 period in the Rainy River Basin

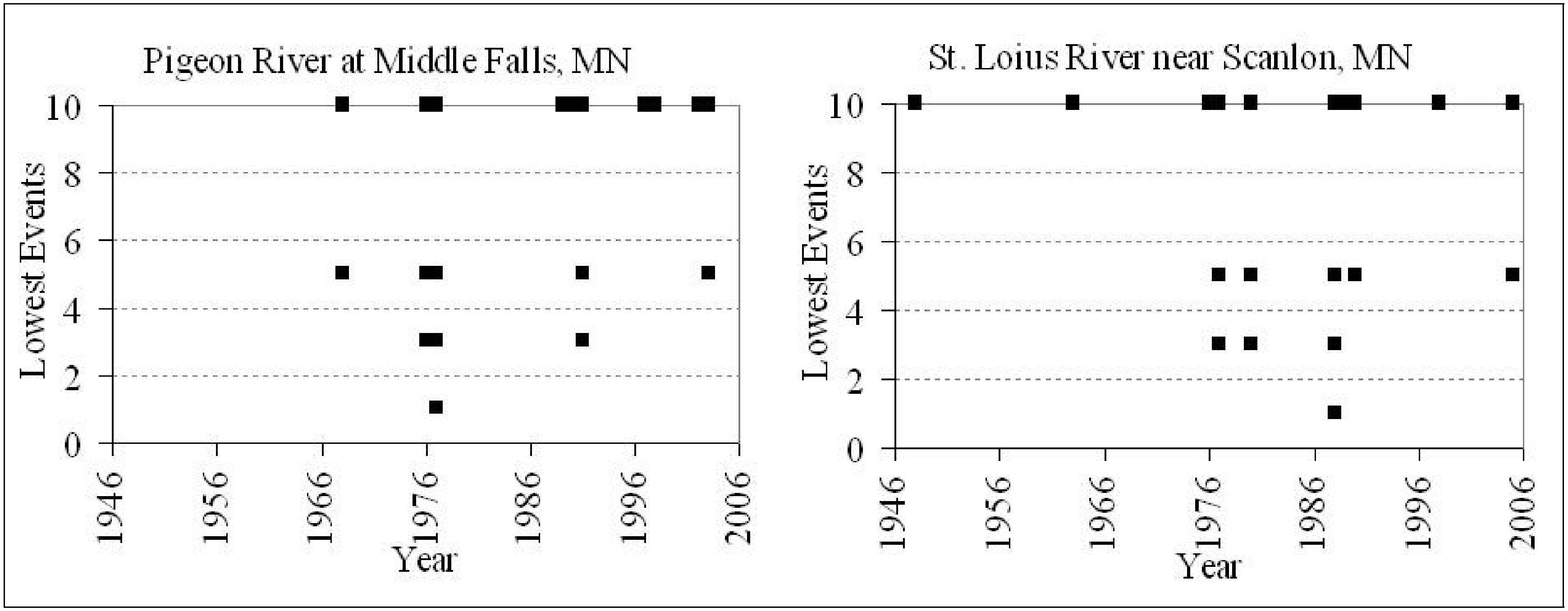

Figure 6.4. Occurrence of the 1, 3, 5, and 10 lowest 7-day (average) low flows in the 1946-2005 period in tributaries to Lake Superior

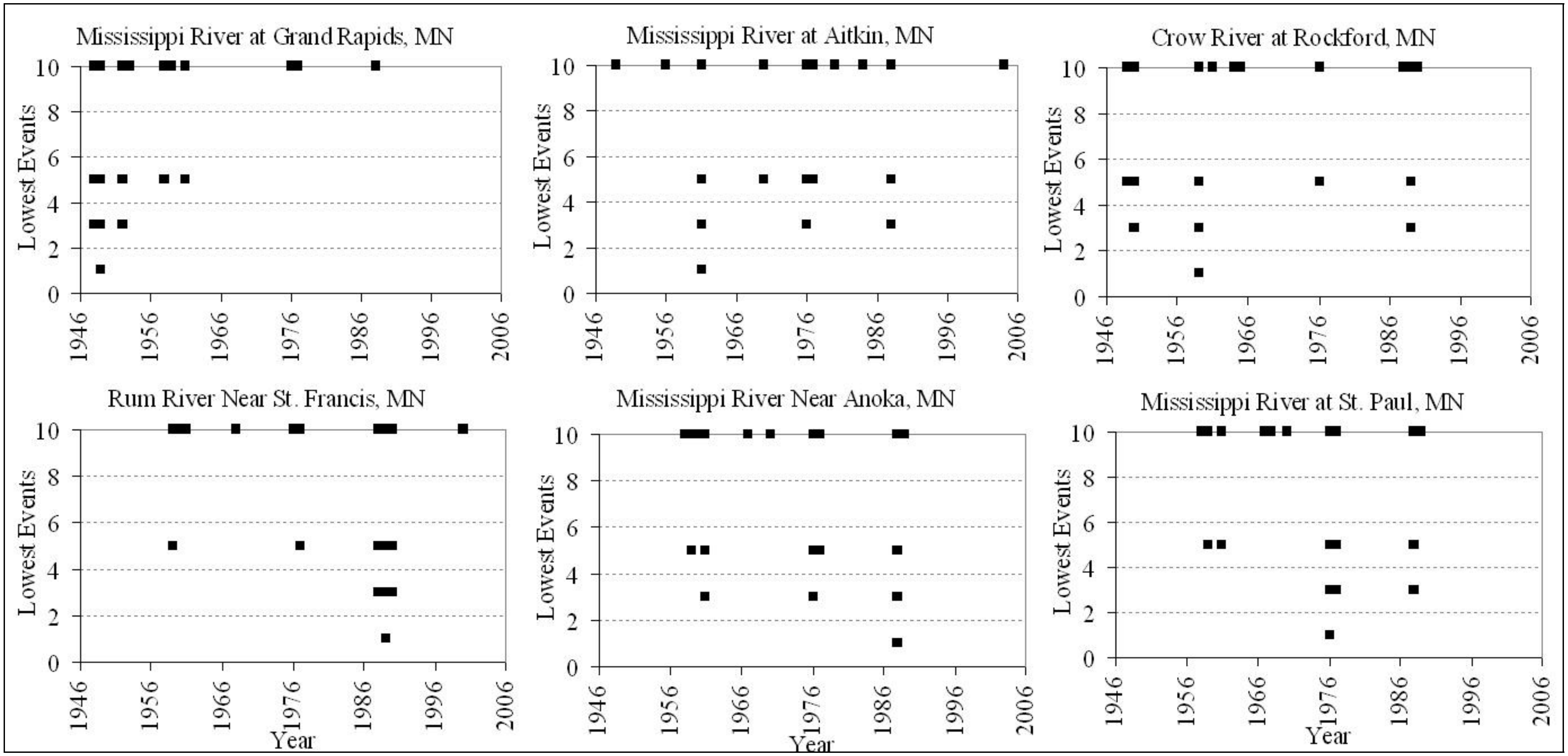

Figure 6.5a. Occurrence of the 1, 3, 5, and 10 lowest 7-day (average) low flows in the 1946-2005 period in the Upper Mississippi River Basin.

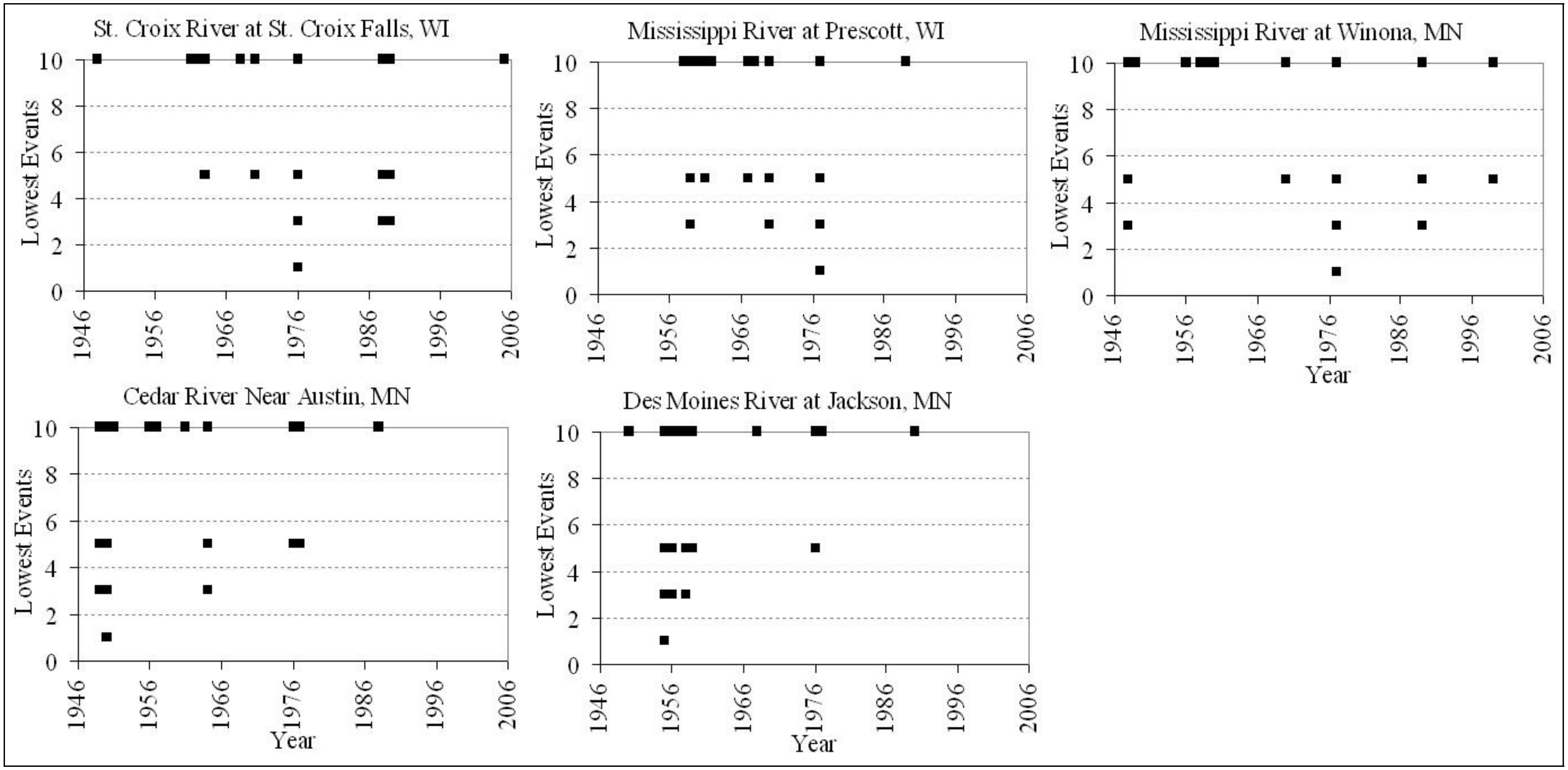

Figure 6.5b. Occurrence of the 1, 3, 5, and 10 lowest 7-day (average) low flows in the 1946-2005 period in the Upper Mississippi River Basin.

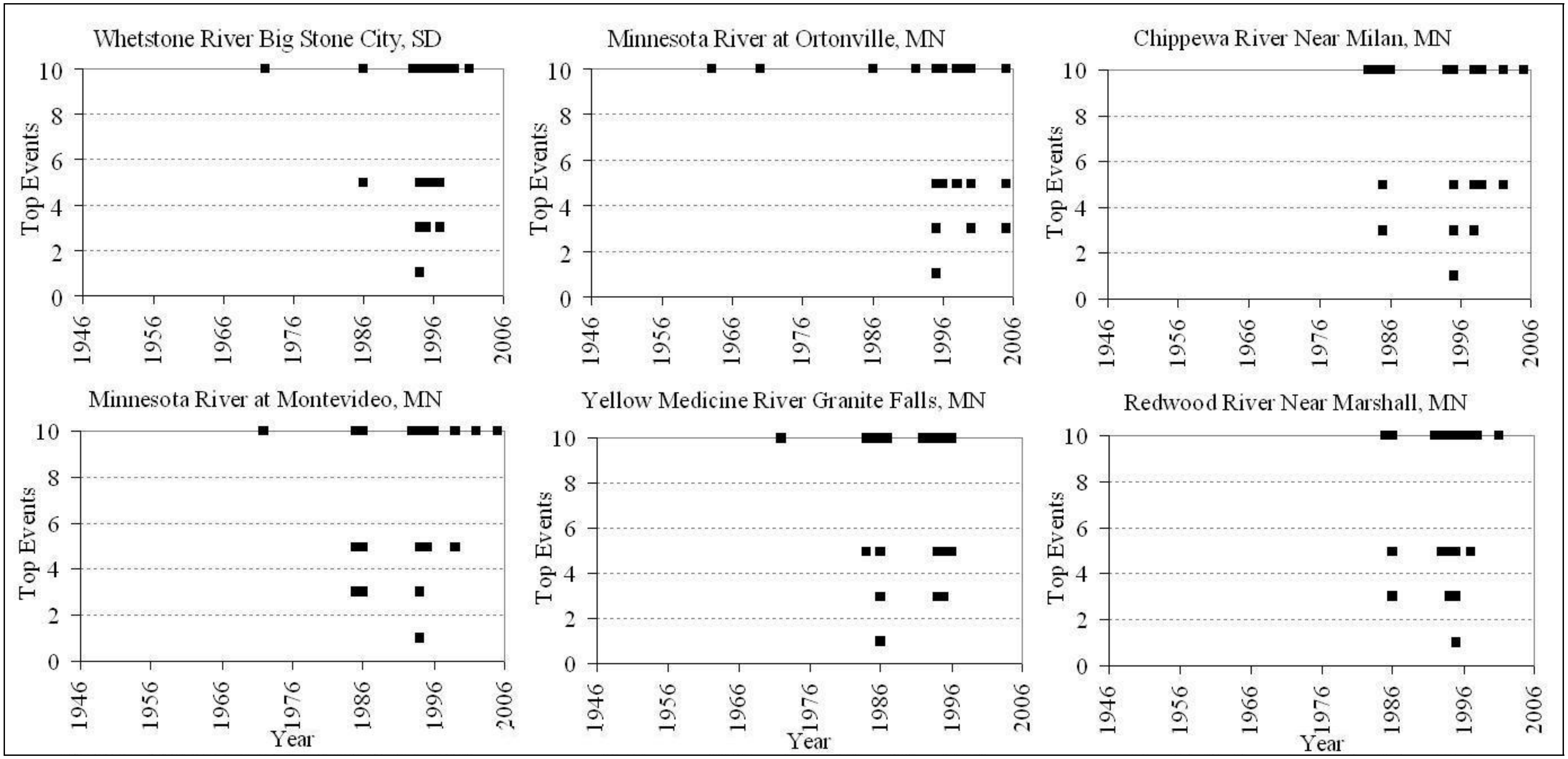

Figure 6.6a. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in the Minnesota River Basin

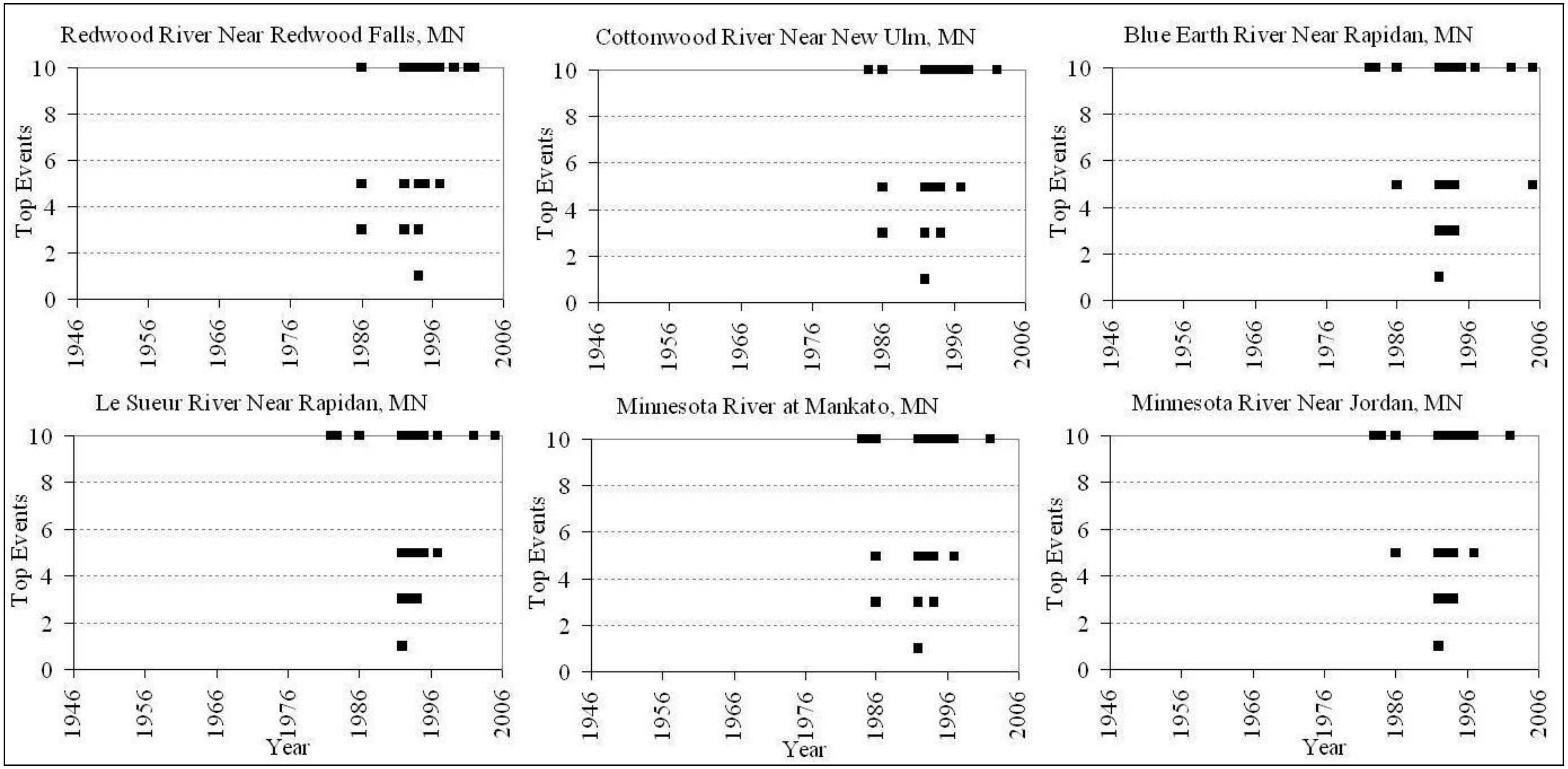

Figure 6.6b. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in the Minnesota River Basin

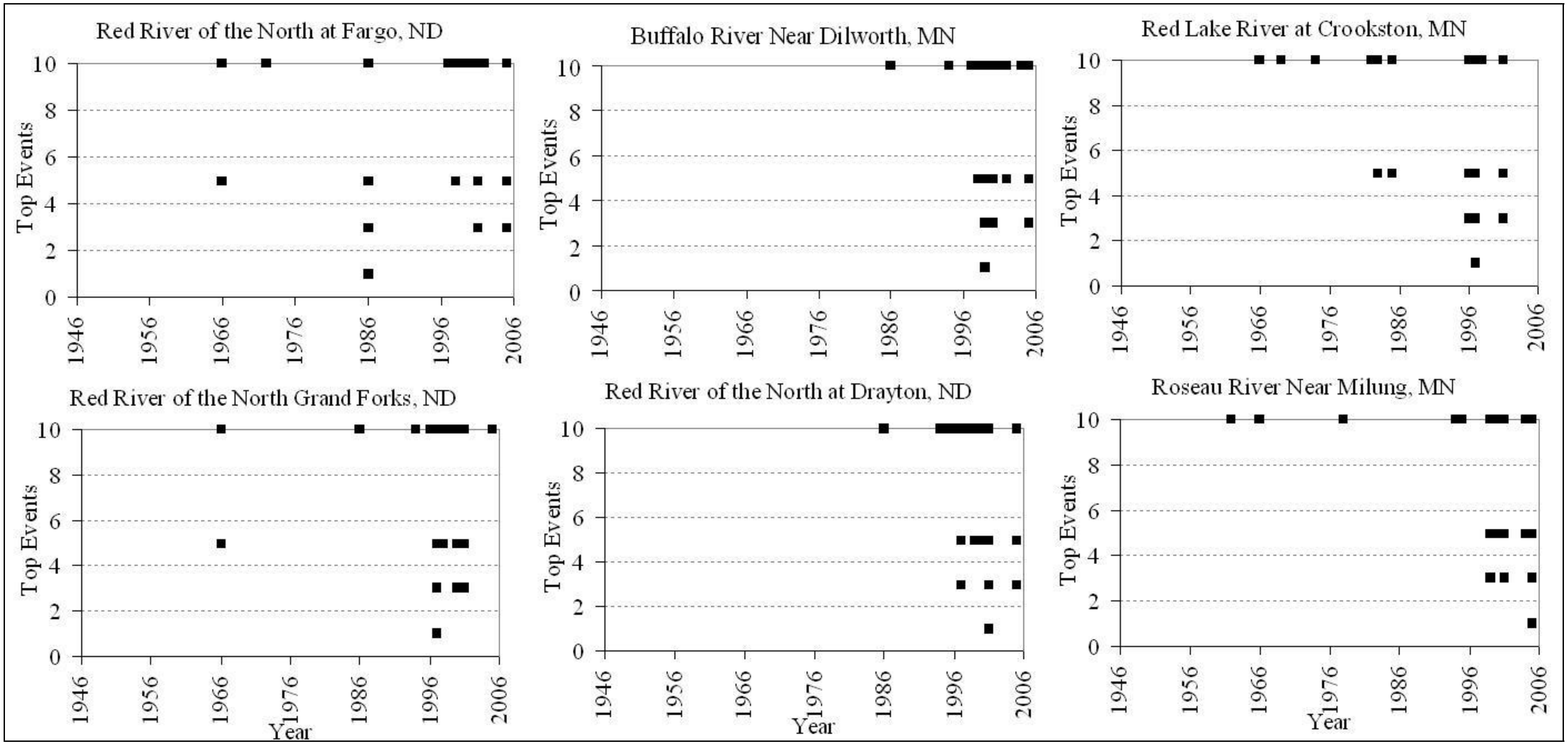

Figure 6.7. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in the Red River of the North Basin

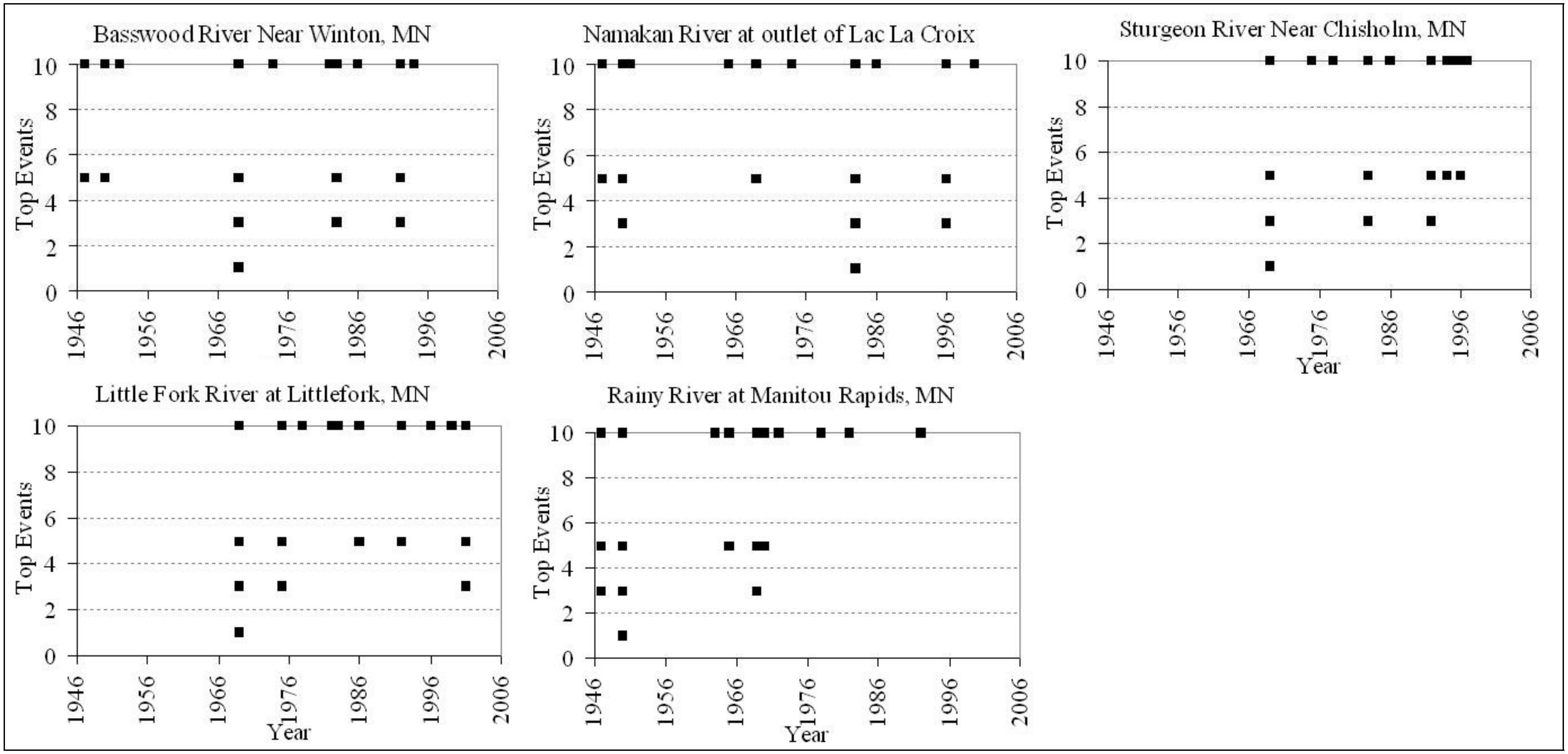

Figure 6.8. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in the Rainy River Basin

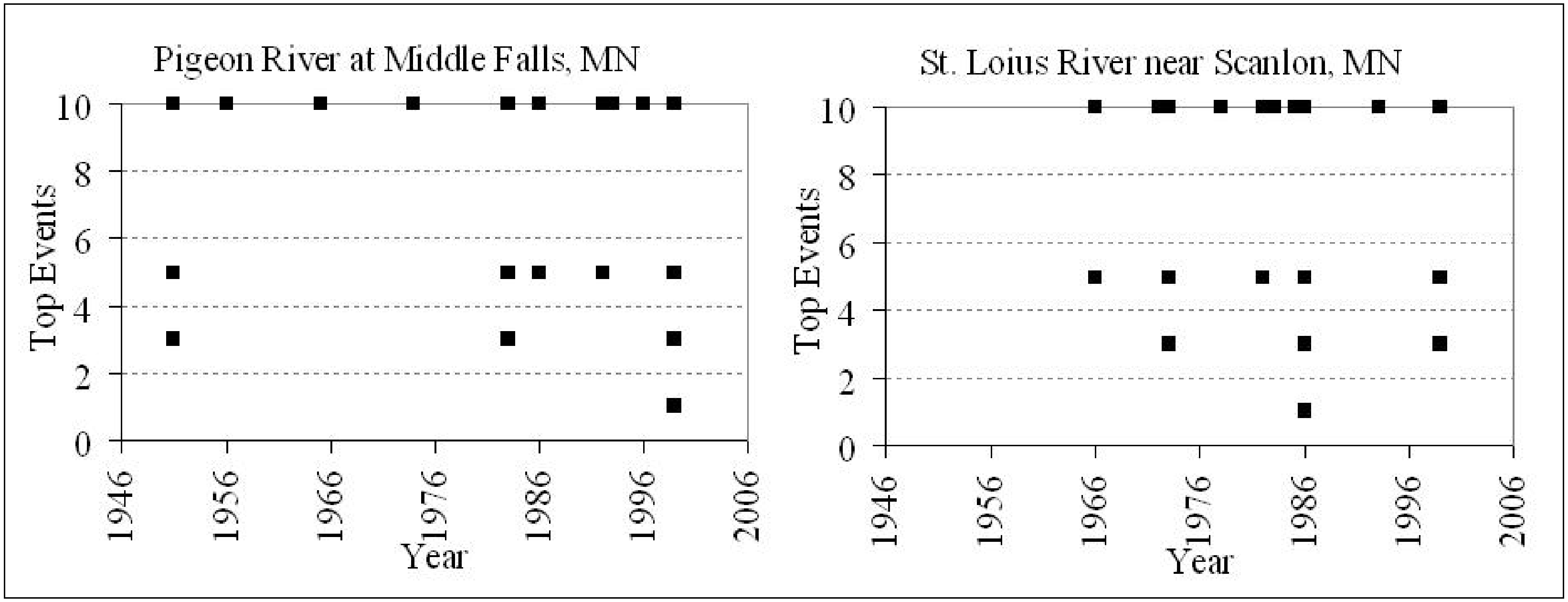

Figure 6.9. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in tributaries to Lake Superior

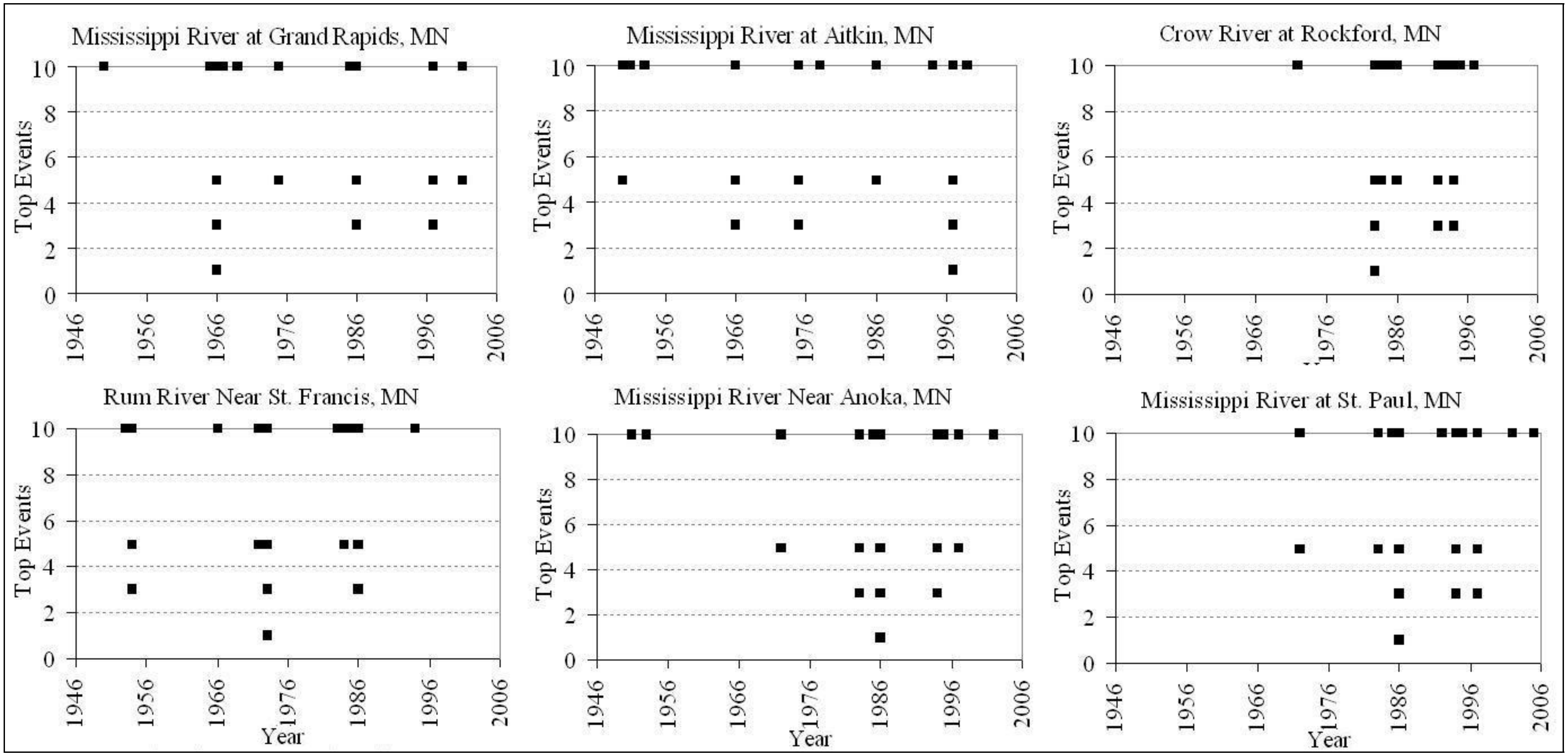

Figure 6.10a. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in the Upper Mississippi River Basin.

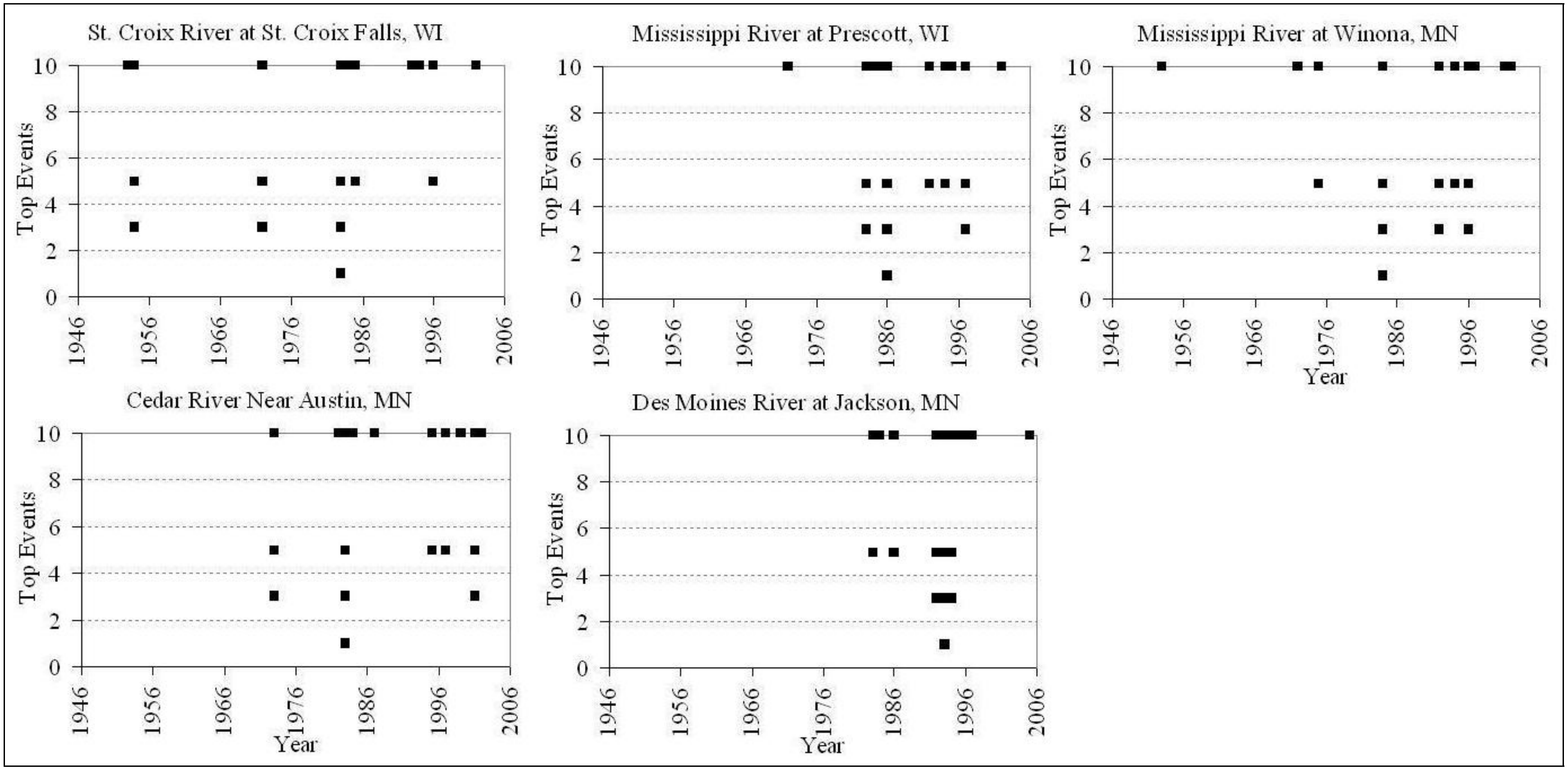

Figure 6.10b. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in the Upper Mississippi River Basin.

7. RESULTS - FLOOD FREQUENCIES

Floods pose a risk to human life, they cause large economic losses, and they are disruptive to ecosystems. In an earlier section we analyzed the timing of peak flows in the period of record from 1946 to 2005. In this section we report results of flood frequency analyses (FFA) which were conducted on the annual peak flows in the 1946-1965 and 1986-2005 periods. Results for all stream gauging stations will be presented by river basin. Intermediate computational results are given in Appendix C. The magnitudes of floods with return periods from 1 to 25 years (small to moderate floods) were estimated in the analysis and provided in Appendix D. It would not make much sense to extrapolate flows of a higher recurrence interval from a data base of 20 years. Also many flow conveyance structures such as storm sewers in cities (not flood protection works) are designed to handle flows of this average recurrence.

7.1. Flood frequencies in the Minnesota River Basin

Flood frequency analysis (FFA) of the annual maximum flows in the periods 1946-1965 and 1986-2005 gave the results graphed in Figures 7.1a and b, and listed in Appendix D for the Minnesota River Basin. Table 7.1 summarized the changes in flood flows. Flood frequency distributions changed substantially from the 1946-1965 to the 1986-2005 period for eight of the 12 stream gauging stations in the Minnesota River Basin.

In a first group of stream gauging stations, representing the upstream portion of the Minnesota River Basin, flood flows with 1- to 25-year return periods were higher in the 1986-2005 period. This group includes stream gauging stations in the Minnesota River at Ortonville and at Montevideo, and the Chippewa River near Milan. The changes (%) in flood flows between the 1946-1965 and 1986-2005 periods for these three stations were in the range of 3% to 209% (Table 7.1).

In the second group of stream gauging stations representing the lower portion of the Minnesota River Basin magnitudes of the 1- to 5-yr floods became slightly higher but the magnitude of 25-yr flood remained pretty much the same in the 1986-2005 period. This group includes the Minnesota River near Jordan, the Minnesota River at Mankato, the Cottonwood River near New Ulm. The increases in the 1- to 10-yr flood flows were from 4% to 70%, and the decrease in the 25-yr flood floods from 1% to 7%.

In the third group of stream gauging stations, including the Redwood, the Blue Earth and the LeSueur Rivers in the middle reach of the Minnesota River, flood flows with 1- and 2-year return periods increased as for the second group, but flood flows with10- and 25-yr return periods became significantly lower in the last 20 years. The Yellow Medicine River showed the same behavior, except that the flood flows for all return periods showed a decrease.

Overall, in the Minnesota River Valley, floods with 1-yr and 2-yr return periods, i.e., floods of moderate magnitude that occur pretty much every year became, on average, 20-30% higher, while rarer floods with return periods of 10 to 25 years remained pretty much unchanged or became lower from 1946-1965 to 1986-2005 (Table 7.1). The median increase in 1-yr flood flows between 1946-1965 and 1986-2005 in the Minnesota River was 50% (with much variation between individual stream gauging stations), the median decrease in the 25-year flood flows was only 4% (range for individual stations was from -53% to 220%) (Table 7.1).

Table 7.1. Change (%) in flood flows in the Minnesota River Basins from (1946-1965) to (1986-2005).

	Return Period (years)				
Gauging Station	**1.01**	**2**	**5**	**10**	**25**
Whetstone River Big Stone City, SD	-69	3	48	77	112
Minnesota River at Ortonville, MN	3	86	136	168	209
Chippewa River Near Milan, MN	50	72	73	72	70
Minnesota River at Montevideo, MN	12	38	54	64	77
Yellow Medicine River Granite Falls, MN	45	-12	-24	-29	-34
Redwood River Near Marshall, MN	505	25	-4	-11	-14
Redwood River Near Redwood Falls, MN	220	25	-10	-23	-35
Cottonwood River Near New Ulm, MN	48	13	3	-2	-7
Blue Earth River Near Rapidan, MN	153	4	-24	-35	-45
Le Sueur River Near Rapidan, MN	2760	94	-8	-35	-53
Minnesota River at Mankato, MN	44	21	10	4	-2
Minnesota River Near Jordan, MN	70	27	13	6	-1
Median	**49**	**25**	**6**	**1**	**-4**

Average	**320**	**33**	**22**	**21**	**23**
Standard Deviation	**782**	**34**	**47**	**62**	**79**

Note: Change (%) is the flow in the (1986-2005) period minus the flow in the (1946-1965) period divided by the flow in the (1946-1965) period times 100%.

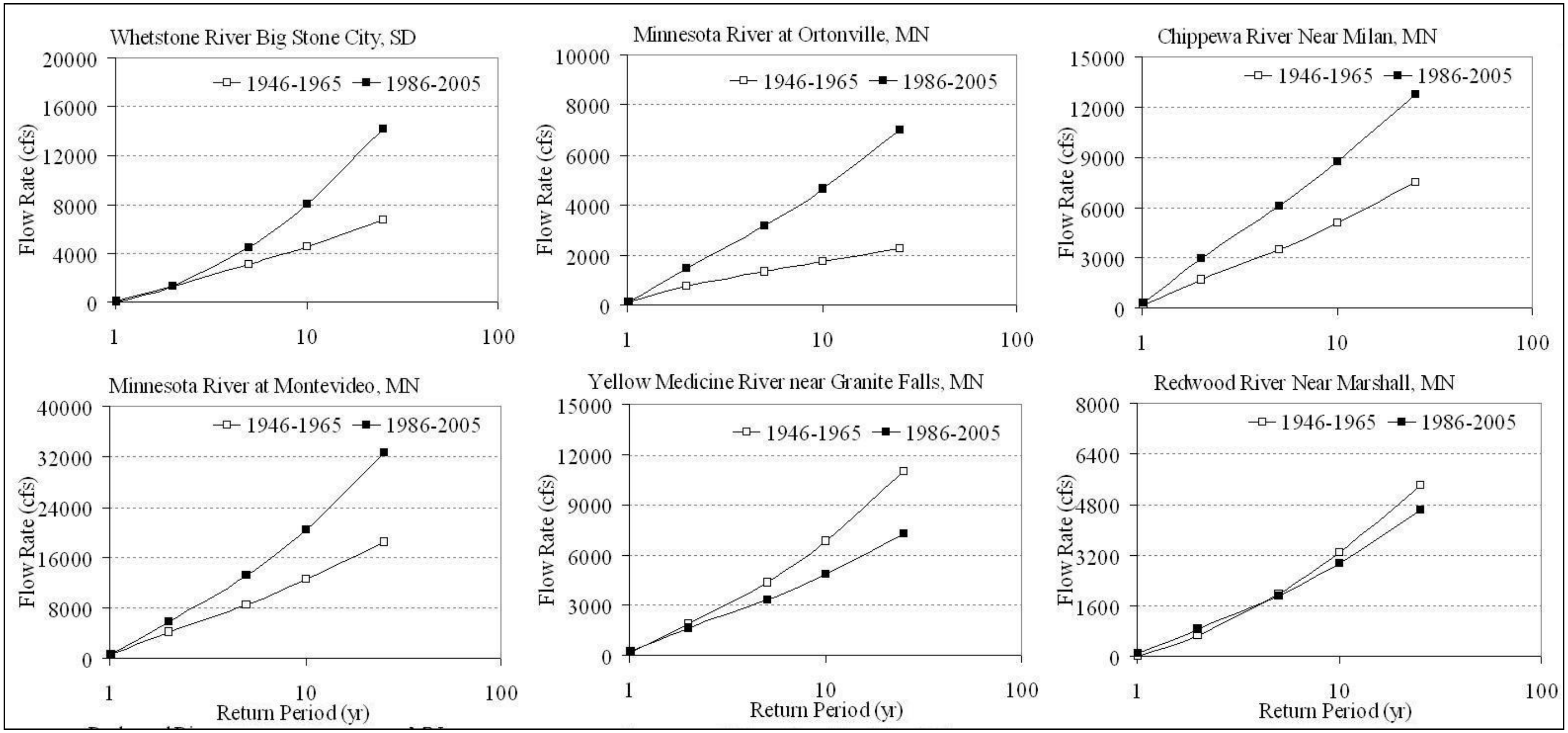

Figure 7.1a. Flood frequencies in the Minnesota River Basin

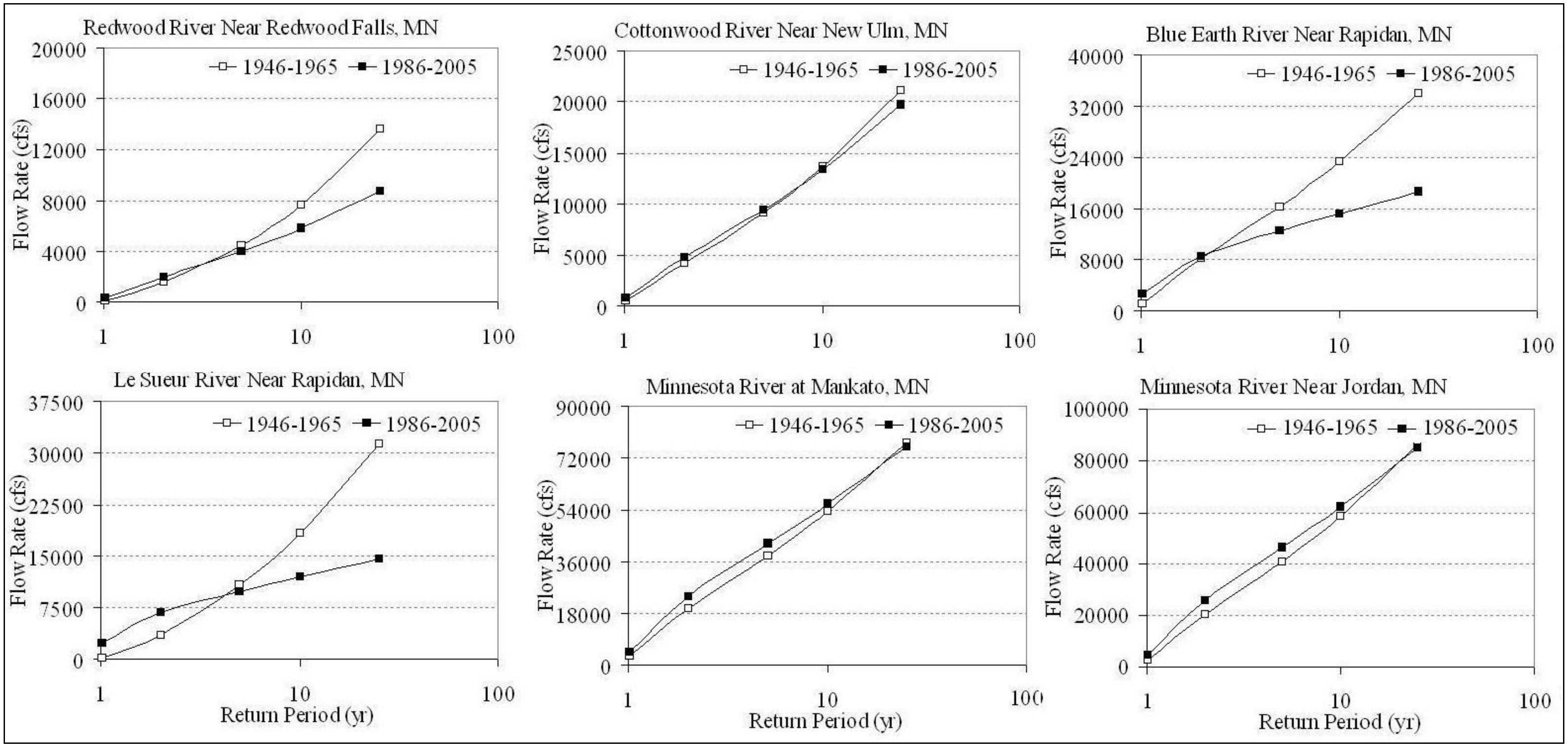

Figure 7.1b. Flood frequencies in the Minnesota River Basin

7.2. Flood frequencies in the Red River of the North Basin

In the Red River of the North Basin, 1-yr (annual) flood flows decreased in magnitude between the 1946-1965 and 1986-2005 periods while flood flows with higher return periods (2- to 25-year floods) became higher (Figure 7.2 and Table 7.2). The patterns and magnitudes of changes were consistent for all stations. The decrease in magnitude of 1-yr flood was in the range of 1% to 65% with a median of 11% (average of 21%) for the six stream gauging stations. The median and the average increases of flood flows with 2- to 25-yr return periods were from 30% to 60%.

Table 7.2. Change (%) in flood flows in the Red River of the North Basin from (1946-1965) to (1986-2005).

	Return Period				
Gauging Station	**1.01**	**2**	**5**	**10**	**25**
Red River of the North at Fargo, ND	-1	57	70	74	76
Buffalo River Near Dilworth, MN	-18	22	34	38	42
Red Lake River at Crookston, MN	-35	6	17	21	25
Red River of the North Grand Forks, ND	-4	54	73	82	91
Red River of the North at Drayton, ND	-5	36	43	45	46
Roseau River Near Milung, MN	-65	27	66	84	100
Median	**-11**	**30**	**54**	**60**	**60**
Average	**-21**	**34**	**50**	**57**	**63**
Standard Deviation	**25**	**19**	**23**	**26**	**30**

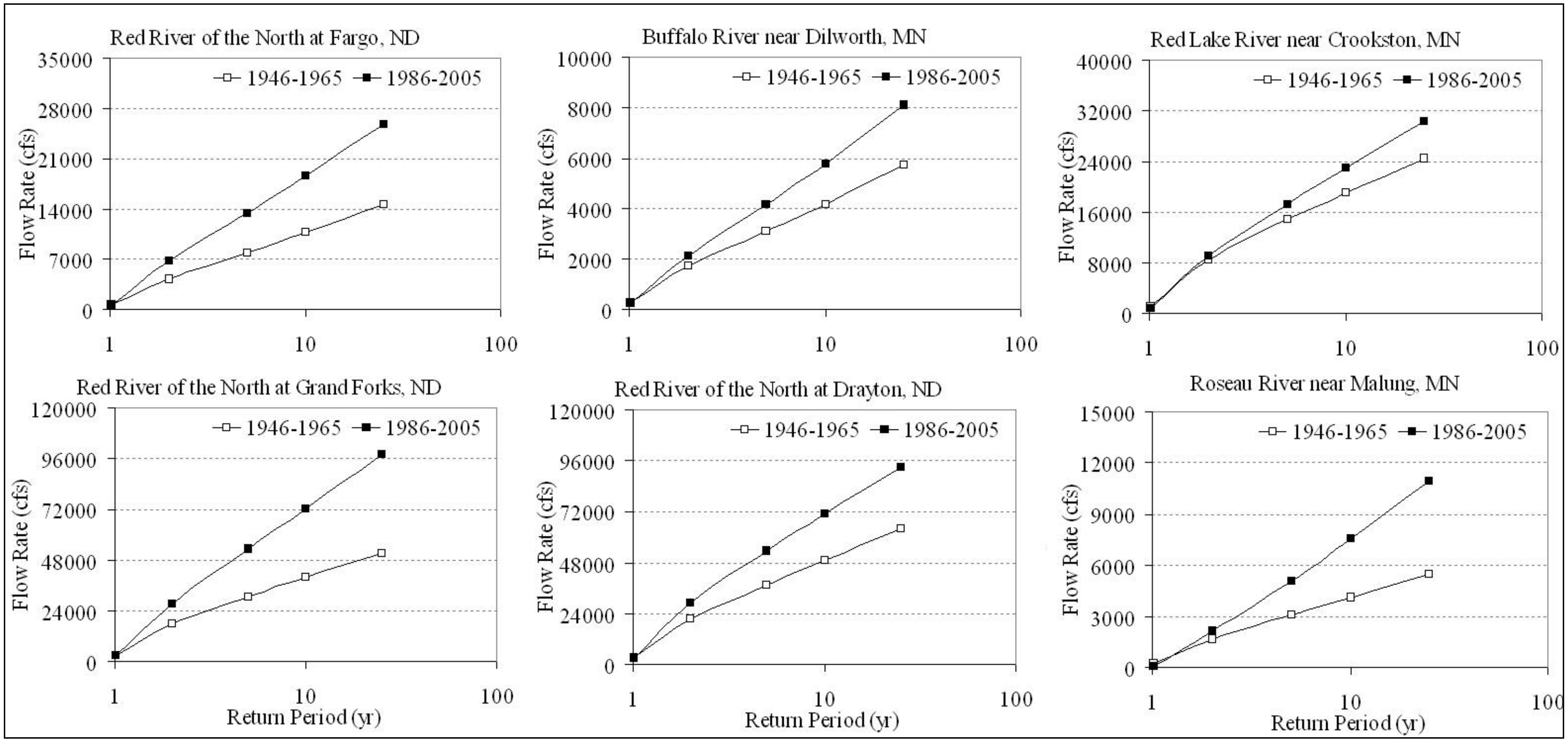

Figure 7.2. Flood frequencies in the Red River of the North Basin

7.3. Flood frequencies in the Rainy River Basin

In two of the station (Sturgeon River near Chisholm, MN, and Little Fork River at Littlefork, MN) in the Rainy River Basin, floods corresponding to 1, 2, 5, 10, and 25-yr floods became lower in the 1986-2005 period (Figure 7.3 and Table 7.3). The decrease in magnitude of 1-yr flood was the largest and the rate of decrease became smaller as return period increased (Table 7.3). In Basswood River near Winton, MN, magnitude of 1-yr flood became 19% lower in the 1986-2005 period, but 2 to 25-yr floods became higher. In Rainy River at Manitou Rapids, MN, magnitudes of 1 and 2-yr floods decreased with a rate of 47% and 19% respectively from 1946 to 2005 while 5, 10 and 25-yr floods increased by about 3-5% (Figure 7.3).

Overall, the flood frequency analysis indicated no increase in flood flows with 1- to 25-yr return periods in the Rainy River Basin. Flood flows on two of the tributaries (Basswood River and Little fork River) decreased, Flood flows on the mainstem (Rainy River at Manitou Rapids) and one tributary (Sturgeon River near Chisholm, MN) remained unchanged. On average, flood flows with 1- to 25-yr return periods were smaller in the 1986-2005 period compared to the 1946-1965 period. The median decreases were from 5% to 36% (average from 8 to 25%).

Table 7.3. Change (%) in flood flows in the Rainy River Basin from (1946-1965) to (1986-2005).

	Return Period				
Gauging Station	**1.01**	**2**	**5**	**10**	**25**
Basswood River Near Winton, MN	19	-12	-21	-25	-29
Sturgeon River Near Chisholm, MN	-47	-11	-4	-3	-3
Little Fork River at Littlefork, MN	-46	-27	-18	-13	-7
Rainy River at Manitou Rapids, MN	-27	-2	3	5	5
Median	**-36**	**-12**	**-20**	**-8**	**-5**
Average	**-25**	**-13**	**-10**	**-9**	**-8**
Standard Deviation	**31**	**10**	**11**	**13**	**15**

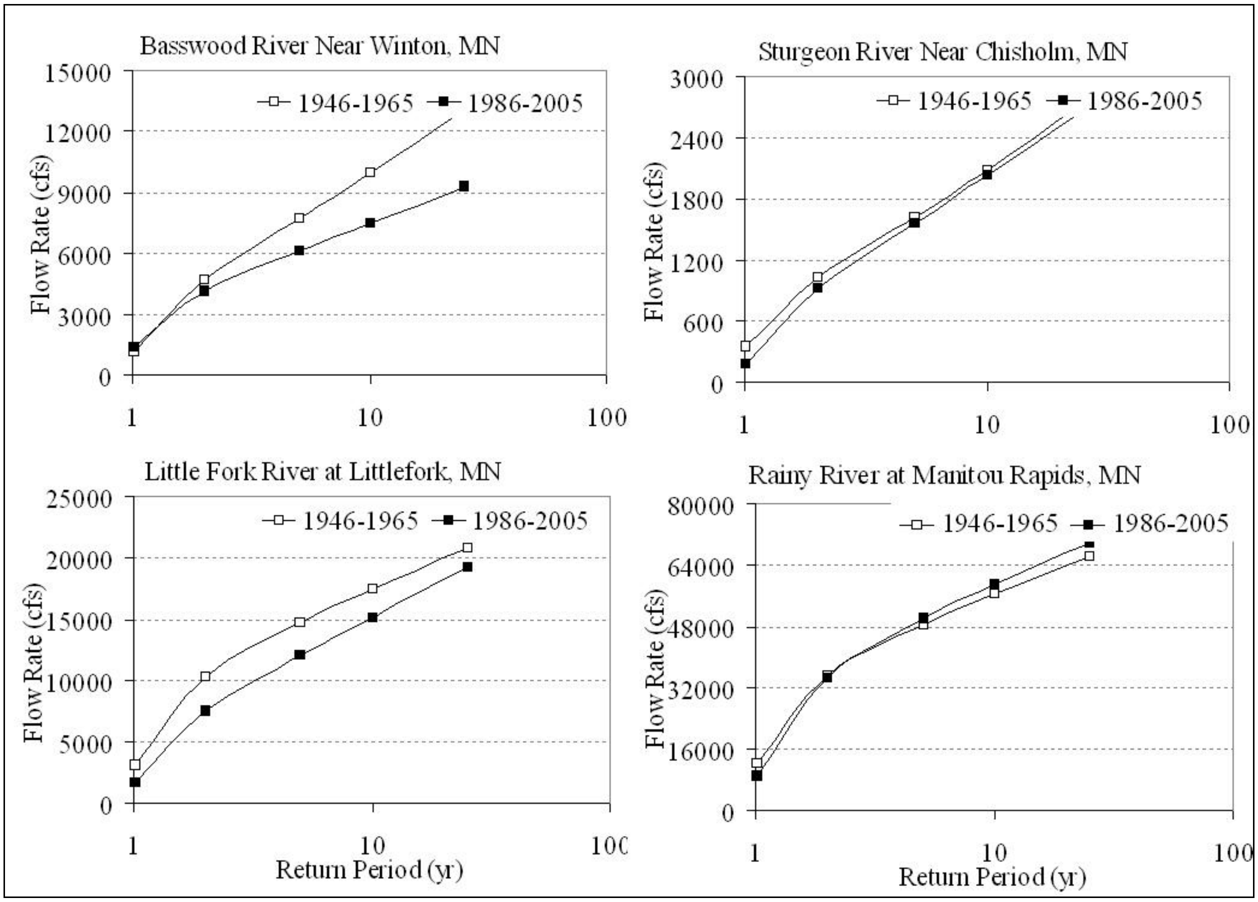

Figure 7.3. Flood frequencies in the Rainy River Basin

7.4. Flood frequencies in tributaries to Lake Superior

Two tributaries to Lake Superior showed inconsistent patterns of changes (Figure 7.4 and Table 7.4). At Pigeon River at Middle Falls, MN, the 1-yr flood flow increased (91%) in the 1986-2005 period, while the 2- to 25-yr flood flows decreased (range of 13% to 58%). In the St. Louis River near Scanlon, MN, the 1- and 2-yr flood flows became lower (38% and 9%, respectively), while the 10-yr and 25-yr floods became higher (4% and 8%, respectively). The 5-yr flood did not show any change. Overall, no significant increase in flood flows was found from the sparse data in the Lake Superior Basin.

Table 7.4. Change (%) in flood flows in tributaries to Lake Superior from (1946-1965) to (1986-2005).

	Return Period				
Gauging Station	**1.01**	**2**	**5**	**10**	**25**
Pigeon River at Middle Falls	91	-13	-33	-41	-48
St. Louis River at Scanlon, MN	-38	-9	0	4	8
Average	**26**	**-11**	**-17**	**-19**	**-20**
Standard Deviation	**91**	**3**	**23**	**32**	**40**

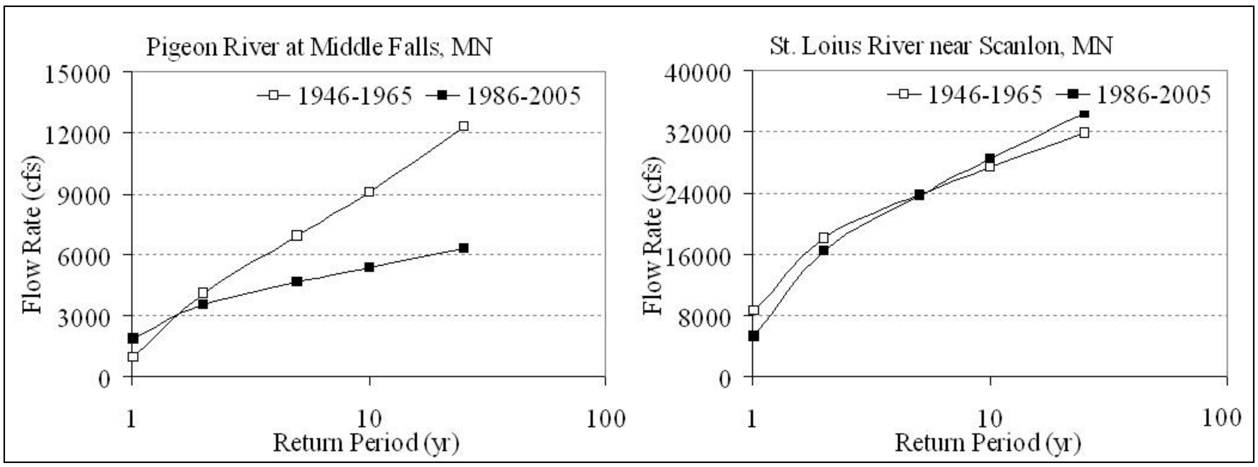

Figure 7.4. Flood frequencies in tributaries to Lake Superior

7.5. Flood frequencies in the Upper Mississippi River Basin

The flood frequency analysis predicted found no overwhelming changes in the 1- to 25-yr return flood flows in the Upper Mississippi River Basin. Although the identified changes were not consistent among all of the 11 stream gauging stations (Figure 7.5), some common patterns are apparent.

On the Mississippi main stem, changes between 1946-1965 and 1986-2005 in annual flood flows (1-year return period) varied from +51% (Grand Rapids,MN, to -9% Prescott,WI). Flood flows with return periods of 2- to 25-years decreased at the three upstream stations (Grand Rapids, Aitken, and Anoka, MN), showed only minor (almost 0%) change at the two stations in the middle reach (St. Paul,MN, and Prescott, WI), and an increase (between 2% for the 25-year return period and 20% for the 2-year return period) at the most downstream station (Winona, MN). The increases in flood flows at St. Paul and Winona, MN. for 2- to 25-year return periods were in the range of 1% to 20%. In other words, there is no indication in increases of major flood flows on the main stem of the Mississippi River.

On the five tributaries to the main stem the changes were relatively modest and mostly negative, i.e. lower flood flows in the 1986-2005 period. For the annual (1-yr return period) flood flow changes had a median of +26%. Floods with 2-year to 25-year return periods changed between +25% and -18% at individual stations with median values from -1% to -6% depending on the return period. The Crow River at Rockford had increased flood flows for all return periods and the Rum River at St. Francis and the St. Croix River at Croix Falls,WI, had decreased flood flows for all return periods above 2-years. The decreases in flood magnitudes were in the range of 3% and 20% (Table 7.5)

Table 7.5. Change (%) in flood flows in the Upper Mississippi River Basin from (1946-1965) to (1986-2005).

	Return Period				
Gauging Station	**1.01**	**2**	**5**	**10**	**25**
Mississippi River at Grand Rapids, MN	51	-1	-20	-30	-39
Mississippi River at Aitkin, MN	28	-14	-15	-12	-8
Crow River at Rockford, MN	26	25	14	6	-2
Rum River Near St. Francis, MN	-14	-18	-18	-16	-14
Mississippi River Near Anoka, MN	-3	-9	-11	-12	-14
Mississippi River at St. Paul, MN	11	13	8	5	1
St. Croix River at St. Croix Falls, WI	-19	-17	-13	-10	-6
Mississippi River at Prescott, WI	-9	0	0	-1	-2
Mississippi River at Winona, MN	16	20	13	8	2
Cedar River Near Austin, MN	82	-1	-3	-1	5
Des Moines River at Jackson, MN	80	17	1	-6	-13
Median	**16**	**-1**	**-3**	**-6**	**-6**

Median (6 stations on the mainstem)	**13**	**-5**	**-5**	**-6**	**-5**
Median (5 tributaries)	**26**	**-1**	**-3**	**-6**	**-6**
Average	**23**	**8**	**-1**	**-3**	**-4**
Standard Deviation	**34**	**15**	**12**	**11**	**12**

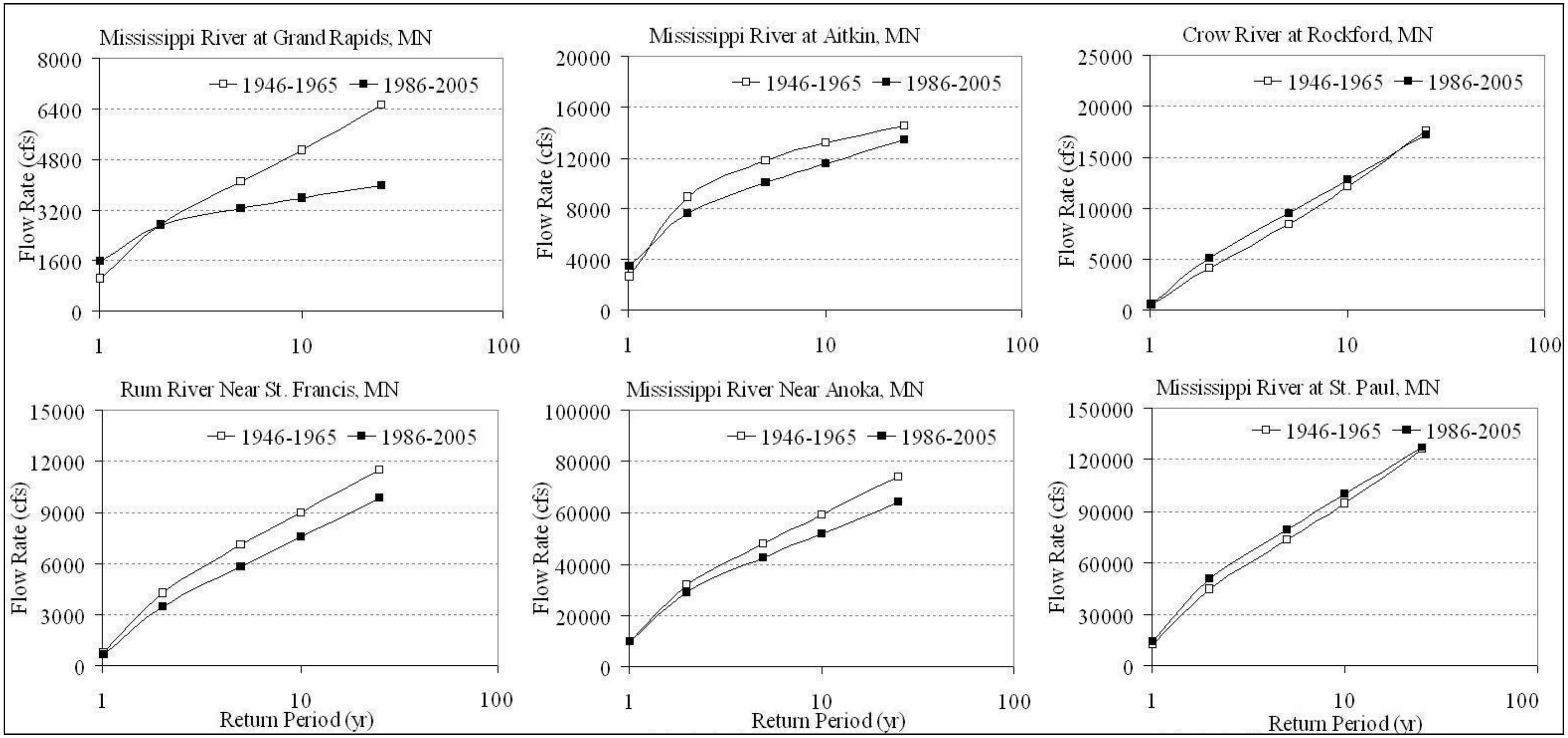

Figure 7.5a. Flood frequencies in the Upper Mississippi River Basin

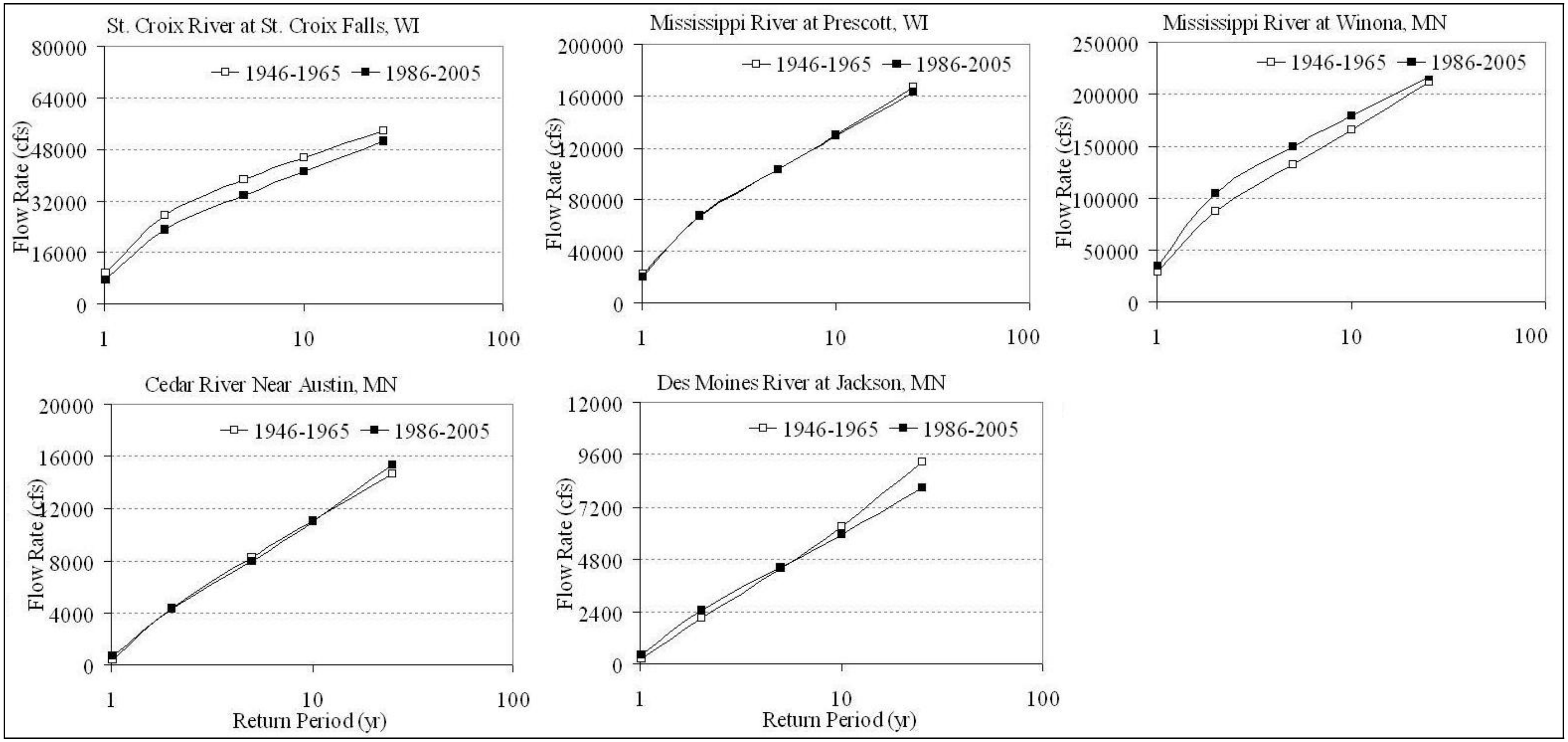

Figure 7.5b. Flood frequencies in the Upper Mississippi River Basin

7.6. Summary of results from flood frequency analysis

Floods with 1- to 25-yr return periods (small to moderate floods) were calculated using recorded stream flow data sets from 36 stream gauging stations in Minnesota for the two 20-year periods (1946-1965) and (1986-2005). The flood frequency analysis showed that observed flood flow characteristics in five river basins of Minnesota changed from 1946 to 2005, but the patterns and magnitudes of changes are not consistent throughout Minnesota. Changes in flood flows in the Rainy River Basin and the Lake Superior Basin had to be determined from a modest data base, and the results showed no consistent or alarming change in flood flows with return periods from 1- to 25-years. There are no definite patterns and the estimated changes are smaller than in the other three river basins. In these three other and major basins in area (Minnesota River, Red River of the North, and Upper Mississippi River Basins) changes were more detectable.

The analysis provided the most consistent results for the Red River of the North Basin. In this basin, magnitudes of 1-yr to 25-yr floods increased at all six stream gauging stations between the two periods analyzed. In the Minnesota River Basin and the Upper Mississippi River Basin, it was found that moderate increases in the magnitude of the most frequent and lowest floods (1-year to 5-year return period) had occurred, while floods of rarer occurrence (10-year and 25-yr return period) had decreased in the 1986-2005 period at many of the stream gauging stations. With regard to the 10- and 25-year floods, the Red River of the North Basin, and the upstream reach of the Minnesota River Basin (which together cover the northwestern portion of Minnesota) therefore showed results opposite to those found in the Upper Mississippi River and the lower Minnesota River Basins. In the Mississippi and lower Minnesota river Basins there were far more stream gauging stations where the 10- and 25-year floods had decreased in magnitude in the 1986-2005 period relative to the 1946-1965 period.

8. RESULTS – LOW FLOW FREQUENCIES

7-day annual (average) low flows corresponding to 2, 5, 10 and 20-year return periods were calculated for the 1946-1965 and 1986-2005 periods. Table 8.1 provides the changes in low flows from 1946-1965 to 1986-2005. We omitted the extreme values (i.e., values higher than 500%) from this table and provided the actual magnitudes of low flows in Appendix E.

The most consistent and largest changes in low flows were observed in the Minnesota River Basin. 7Q2, 7Q5, 7Q10, and 7Q20 values showed an increase at all stations from the 1946-1965 to the 1986-2005 period. The changes were largest for 2-year 7-day annual (average) low flows (most frequent low flows) and comparatively smaller for the 7-day annual (average) low flows of rarer occurrence (corresponding to 5-, 10- and 20-yr return periods). The largest changes in 7Q2, 7Q10 and 7Q20 values were observed at the Le Sueur River near Rapidan and the largest change in 7Q5 was observed in the Redwood River near Redwood Falls.

Considerable changes in 7-day average low flows were also observed in the Red River of the North and Upper Mississippi River Basins from the 1946-1965 to the 1986-2005 period. The changes although not as large as the changes observed in the Minnesota River Basin followed a similar pattern. In both river basins 7Q2, 7Q5, 7Q10, and 7Q20 values were larger in the 1986-2005 period at the majority of the stations. The changes were largest for most frequent low flows and smaller for rarer occurrence low flows.

Changes observed in the Rainy River Basin and Tributaries to Lake Superior were small and variable.

The results of the low flow frequency analysis support the findings obtained from flow duration curves and the analysis of 7-day annual (average) low flow occurrence in the earlier sections of this report. The Minnesota River Basin, the Red River of the North Basin, and the Upper Mississippi River Basin experienced bigger changes in low flows than the Rainy River Basin and Tributaries to Lake Superior.

Table 8.1. Changes (%) in 7-day (average) low flows of 2-, 5-, 10-, and 20- year return periods from 1946-1965 to 1986-2005.

	Return Period (yr)			
Stream/River Name	**2**	**5**	**10**	**20**
Minnesota River Basin				
Whetstone River Big Stone City, SD	131	63	33	11
Minnesota River at Ortonville, MN	159	69	30	4
Chippewa River Near Milan, MN	209	191	197	-
Minnesota River at Montevideo, MN	171	107	76	-
Yellow Medicine River Granite Falls, MN	319	198	148	112

Redwood River Near Marshall, MN	625	424	332	269
Redwood River Near Redwood Falls, MN	-	-	-	-
Cottonwood River Near New Ulm, MN	145	52	56	-
Blue Earth River Near Rapidan, MN	117	41	9	-13
Le Sueur River Near Rapidan, MN	-	-	-	360
Minnesota River at Mankato, MN	-	382	173	61
Minnesota River Near Jordan, MN	-	-	-	-
Average	**215**	**170**	**117**	**115**
Standard Deviation	**121**	**145**	**105**	**145**
<u>Red River of the North Basin</u>				
Red River of the North at Fargo, ND	-27	-86	-100	-
Buffalo River Near Dilworth, MN	81	24	-4	-
Red Lake River at Crookston, MN	78	30	3	-17
Red River of the North Grand Forks, ND	39	41	44	50
Red River of the North at Drayton, ND	124	81	61	45
Roseau River Near Milung, MN	110	64	40	22
Average	**68**	**26**	**8**	**25**
Standard Deviation	**50**	**54**	**53**	**26**
<u>Rainy River Basin</u>				
Basswood River Near Winton, MN	-13	-14	-14	-15
Namakan River at outlet of Lac La Croix	39	23	13	5
Sturgeon River Near Chisholm, MN	82	51	18	-13
Little Fork River at Littlefork, MN	9	10	9	7
Rainy River at Manitou Rapids, MN	6	5	4	5
Average	**25**	**15**	**6**	**-2**
Standard Deviation	**37**	**24**	**12**	**11**
<u>Tributaries to Lake Superior</u>				
Pigeon River at Middle Falls	-29	-	-54	-59
St. Louis River at Scanlon, MN	-4	-93	-35	-
Average	**-16**	**-**	**-44**	**-**

Standard Deviation	**18**	**-**	**13**	**-**
<u>Upper Mississippi River Basin</u>				
Mississippi River at Grand Rapids, MN	37	135	244	383
Mississippi River at Aitkin, MN	61	29	6	-
Crow River at Rockford, MN	373	-	-	-
Rum River Near St. Francis, MN	66	59	54	51
Mississippi River Near Anoka, MN	24	16	12	8
Mississippi River at St. Paul, MN	31	14	1	-
St. Croix River at St. Croix Falls, WI	9	3	-2	-6
Mississippi River at Prescott, WI	25	10	1	-8
Mississippi River at Winona, MN	9	7	2	-4
Cedar River Near Austin, MN	227	128	79	43
Des Moines River at Jackson, MN	-11	-1	10	23
Average	**77**	**40**	**41**	**61**
Standard Deviation	**117**	**51**	**76**	**132**

9. DISCUSSION

In the Minnesota River, Red River of the North, and Upper Mississippi River Basins an upward shift in stream flow rates appears to have occurred between 1946 and 2005. The 7-day average low flow appears to have become significantly higher, but annual peak flows have also increased at the majority of the stream gauging stations analyzed in these three basins. Annual (1-year return period) flood flows seem to fit this trend also, but rarer floods with 10- or 25-year return periods appear to have increased in magnitude only in the northwestern region of Minnesota (Red river of the North and upper Minnesota River). In the Rainy River Basin and in tributaries to Lake Superior, we found smaller and inconsistent changes in stream flow characteristics from 1946 to 2005.

These results are consistent with previous studies by Changnon and Kunkel (1995), Schilling and Libra (2003) in Iowa and Gebert and Klug (1996) in Wisconsin. Changnon and Kunkel (1995) found upward trends in flood flows that occur either in the warm-season (May-November) or in the cold-season (December-April) in Minnesota. An analysis of historical stream flow records from 38 USGS stream gauging stations in Minnesota (Novotny and Stefan, 2007) showed significant upward trends in seven stream-flow statistics including mean annual flows, peak and low flows, and number of days with high and low flows. Peak flows due to rainfall and low flows throughout the year were found to be increasing, but regional differences were pronounced. Stream flow changes in three river basins of Minnesota (Minnesota River, Upper Mississippi, and Red River of the North) were significantly larger than in two other basins (Rainy River and Lake Superior). This regional difference agrees with the findings of this study.

Although not an objective of this study, there are potentially multiple causes for the changes or the lack of changes in the observed stream flows. Precipitation is one obvious potential cause. An upward trend in precipitation in the midwestern region of the U.S. has been documented (Karl et al., 1996; Lettenmaier et al., 1994). The increase in precipitation for Minnesota was reported to be 10% to 20% per century (Karl et al., 1996). Heavy-precipitation amounts in Minnesota (e.g., from 7-day precipitation events at the 1-yr recurrence level) increased from 1921 to 1985 according to Changnon and Kunkel (1995). Novotny and Stefan (2007) reported strong correlations between mean annual stream flow changes and total annual precipitation changes. Figures 9.1 and 9.2 show annual average air temperature and annual precipitation in 9 climate divisions of Minnesota for the 1917-2002 period (Novotny and Stefan 2007).

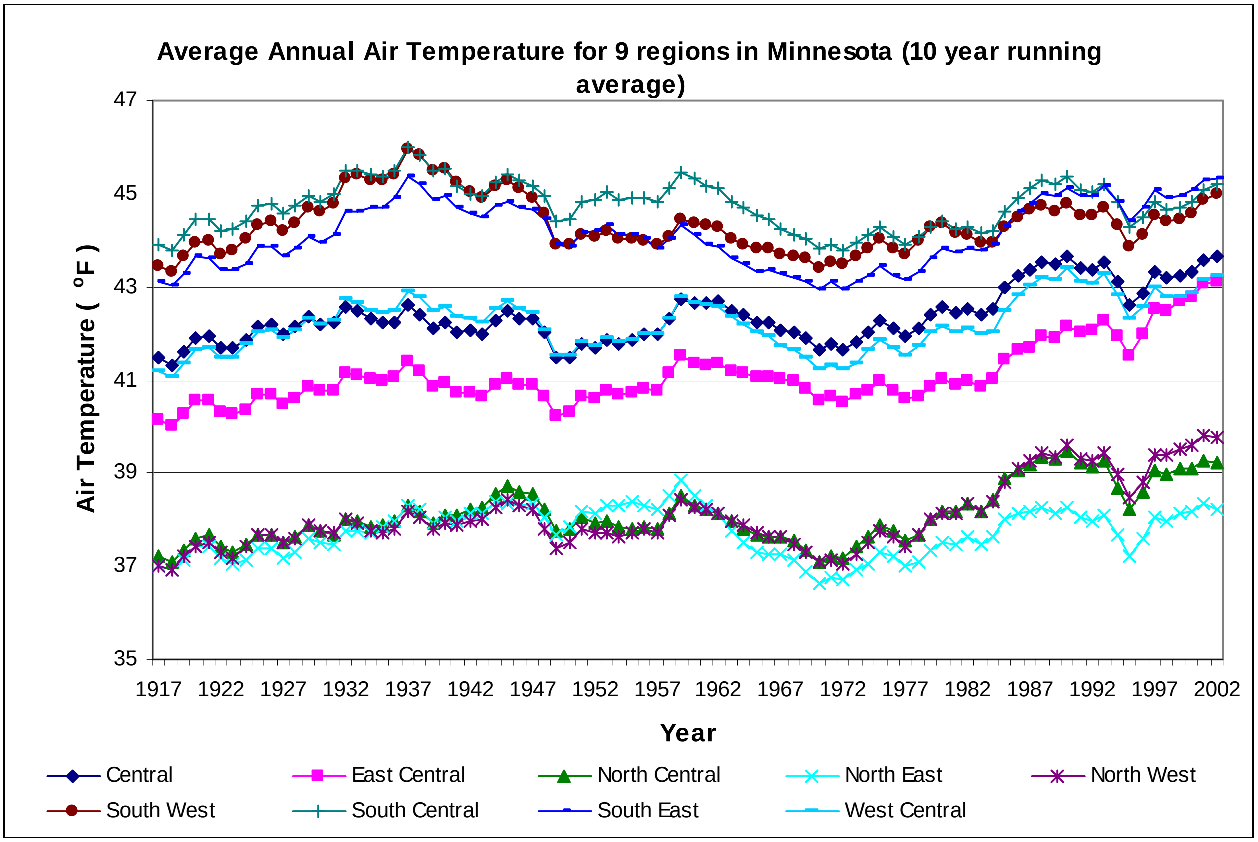

Figure 9.1. Average annual air temperature for 9 climate divisions of Minnesota (10 year running average) (from Novotny and Stefan 2007)

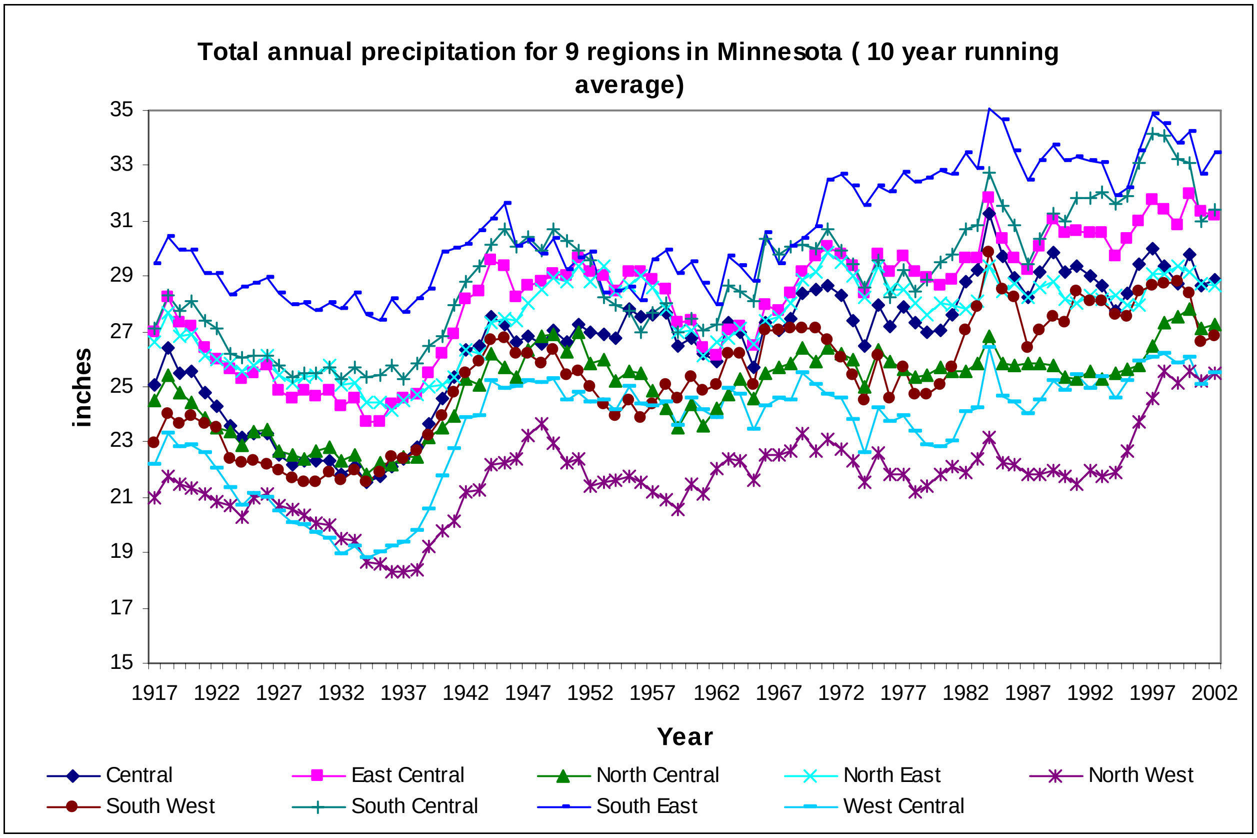

Figure 9.2. Total annual precipitation for 9 climate divisions of Minnesota (10 year running average) (from Novotny and Stefan 2007)

We also calculated the trends in precipitation and air temperature in the nine climate divisions of Minnesota (Figure 2.1) for the 1946-2005 period using a linear regression method. Precipitation showed an upward trend for all nine divisions from 1946 to 2005 (Table 9.1). The trends in precipitation in divisions 1, 5, 6, 7, 8, 9, and SD3 (South Dakota division 3) were significant at the 0.1 level. The largest increase in precipitation was in division 9 (0.114 in yr^{-1} or 2.89 mm yr^{-1}) and the lowest in division 3 (0.005 in yr^{-1} or 0.13 mm yr^{-1}). Precipitation trends, i.e., increases in precipitation, are more evident in the southern portions of the Minnesota. Air temperatures also had an upward trend for the 1946-2005 period (Table 9.1). All trends, except for divisions 3, 8, and SD4 (South Dakota division 4) were significant. The highest rate of temperature increase was observed in division 6 (0.047 ^{o}F yr^{-1} or 0.026^{o}C yr) and the lowest in division 3 (0.005^{o}F yr^{-1} or 0.003^{o}C yr). The rates of air temperature increase seem independent of geographic location. The increase in division 6 is probably linked to urbanization (Twin cities metropolitan area).

Table 9.1. Trends in precipitation and temperature from 1946 to 2005 (* indicates that the trend is significant at the 0.1 level).

Climate Division	Trend in Precipitation (in yr^{-1})	Trend in Temperature ($^{o}F\ yr^{-1}$)
1	0.060*	0.048*
2	0.032	0.035*
3	0.005	0.005
4	0.030	0.031*
5	0.068*	0.039*
6	0.079*	0.047*
7	0.072*	0.021*
8	0.094*	0.008
9	0.114*	0.030*
SD 3	0.077*	0.029*
SD 4	0.016	0.013
WI 1	0.053	0.026*

Our analysis showed that the river basins which showed the largest increases in stream flows drain climate divisions where significant increases in precipitation have been observed, while the basins which show little or no change in stream flows drain climate divisions where changes in precipitation have not been significant. For example, the drainage area of the Minnesota River Basin includes the climate divisions 4, 5, 7, 8 of Minnesota (Figure 2.1) and two climate divisions of South Dakota (SD 3, and SD4). Upward trends in precipitation were observed in climate divisions 5, 7 and 8 and SD4. Climate division 1 had a significant increase in precipitation, and covers the Red River of the North Basin. The Rainy River Basin and the Lake Superior Basin drain climate divisions 2 and 3, where no significant increase in precipitation has been recorded.

Changes in agricultural drainage and crop patterns can contribute significantly to changes in stream flows. A study conducted in the LeSueur and Cottonwood River watersheds in the Minnesota River Basin indicated that increases in baseflow, stormwater runoff, and 7-day low flows after 1950s are most likely due to the intensification of agricultural drainage and corn and soybean cultivation rather than climatic change (Ennaanay, 2006).

10. SUMMARY & CONCLUSIONS

We analyzed historical (1946 to 2005) flow records from 36 USGS stream gauging stations in Minnesota to identify changes in flow characteristics over the period of record. Flow duration curves, the occurrence of extreme peak and low stream flows, and flood and low-flow frequencies were analyzed. The basic data were mean and peak daily flow data from 36 USGS stream gauging stations (Table 3.1) located in five river basins of Minnesota (Minnesota River, Rainy River, Red River of the North, Lake Superior, Upper Mississippi River Basins). From these basic data, 7-day average low flows were extracted. The analysis period was 60 years, from 1946 to 2005. Because this study followed a previous study of Minnesota stream flows (Novotny and Stefan, 2007) this study focused on changes in two distinct periods, one from 1946-1965, and the other from 1986 to 2005. Most of the analysis was conducted on the data sets (7220 daily and peak stream flows) for these two 20-year sample periods. The results can be summarized as follows:

1) The largest stream flow changes were observed in the Minnesota River Basin, the Red River of the North Basin, and the Upper Mississippi River Basin from 1946 to 2005. In these river basins, low, medium, and high daily stream flows increased.
2) Magnitudes of floods, as exemplifies by the 25-yr floods, increased in the 1986-2005 period only in the Red River of the North and the Upper Minnesota River Basin. In all other Basins the magnitude of the 25-year floods decreased or remained more or less the same. Floods in Minnesota have often been due to snowmelt, sometimes combined with rainfall.
3) The occurrence of peak stream flow events may have shifted somewhat during the 1946 to 2005 period, at least in the Minnesota River Basin and the Red River of the North Basin. Six of the twelve stream gauging stations, all in the upper reaches of the Minnesota River Basin, had more than the expected number of annual peak flow events in the 1986-2005 period. In the Red River of the North Basin, up to 5 of 6 stations had more than the expected number of annual peak flow events in the recent period (1986 to

2005). In the Rainy River Basin and in tributary streams to Lake Superior the temporal distribution of annual peak flow events does not seem to have changed. In the Upper Mississippi River Basin the evidence of change is mixed: only 2 of 11 stream gauging stations show a shift in the occurrence of the rarest peak flow events, but peak flows that are in the top 10 have occurred more often at 6 of the 11 stream gauging stations on the Upper Mississippi River in the recent period (1986-2005).

4) The 7-day average low flows were higher in the 1986-2005 period than in the 1946-1965 period. Frequent 7-day annual (average) lows flows (i.e., low flows with 2-yr return period) increased more than the 7-day low flows of rarer occurrence (i.e., 20-yr return period).
5) Of the five river basins analyzed, the Minnesota River Basin has experienced the largest stream flow changes compared to the other four basins. In that basin high, medium, and low flows increased significantly from the 1946-1965 period to the1986-2005 period. The increases in Q5, Q50, and Q95 were on average 79%, 203%, and 148%, respectively. All 12 stations in this river basin had more than the expected number of 7-day (average) low flow events in the 1986-2005 period. Frequencies of occurrence of 7-day annual (average) low flows having 2 to 20 yr return periods were higher for all stations in the recent period too. At about half of the stream gauging stations, more than expected number of annual peak flow events was observed in the 1986-2005 period. Flood frequency analysis showed that, on average, magnitudes of the 1-, 2-, 5-, 10- and 25-yr floods increased by about 20 to 30%. The likely cause for these changes is not only the change in precipitation (climate) but also the change in agricultural practices.
6) In the Red River of the North Basin, Q5, Q50, and Q95 increased on average 55%, 62%, and 0%, respectively, from the 1946-1965 period to the1986-2005 period. All 6 stations in this river basin had higher than expected 7-day average low flows in the 1986-2005 period. At about 60% of the stations, more than expected number of annual peak flow events occurred in the 1986-2005 period. The 1-yr flood flow decreased on average about 20% while the 2-, 5-, 10- and 25-yr floods increased on the order of 30% to 60% in the 1986-2005 period.
7) In the Upper Mississippi River Basin, Q5, Q50, and Q95 increased on average 29%, 82%, and 435%, respectively, from the 1946-1965 period to the1986-2005 period. About

60% of the gauging station in this river basin had higher than expected 7-day average low flow events in the 1986-2005 period. An increase in the occurrence of peak flow events was not found. The 1- and 2-yr flood flows became, on average, about 20% and 8% higher, while the 5-, 10- and 25-yr flood flows did not change significantly in magnitude.

8) Changes in low, medium, and high flows in the Rainy River Basin and in tributaries to Lake Superior from 1946 to 2005 were determined from a relatively sparse data base, and were found to be lower (about 10 to 30%) compared to the other three basins.
9) There are potentially multiple causes for the changes or the lack of changes in the observed stream flows. Precipitation and land use changes are two potentially major causes for changes. Trends observed in precipitation data in the climate divisions of Minnesota support the findings from the analysis of stream flow records. However, more analysis is required to identify their roles individually.

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Appendix A: Flow Duration Curves for the exceedence of a given flow on Log-log plots for the periods 1946 - 1965 and 1986 - 2005.

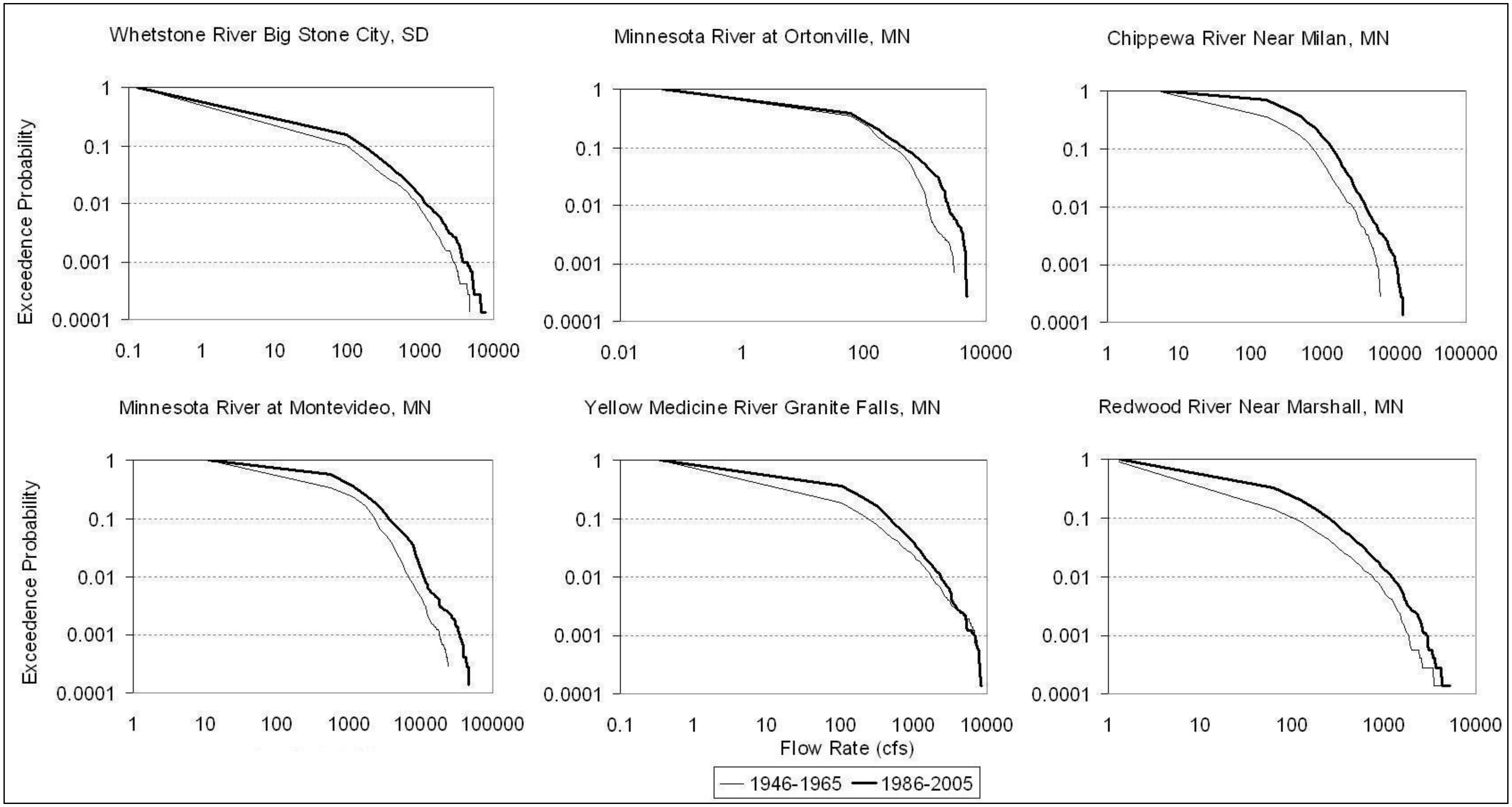

Figure A.1a. Flow Duration Curves for the Minnesota River Basin on Log-log plots.

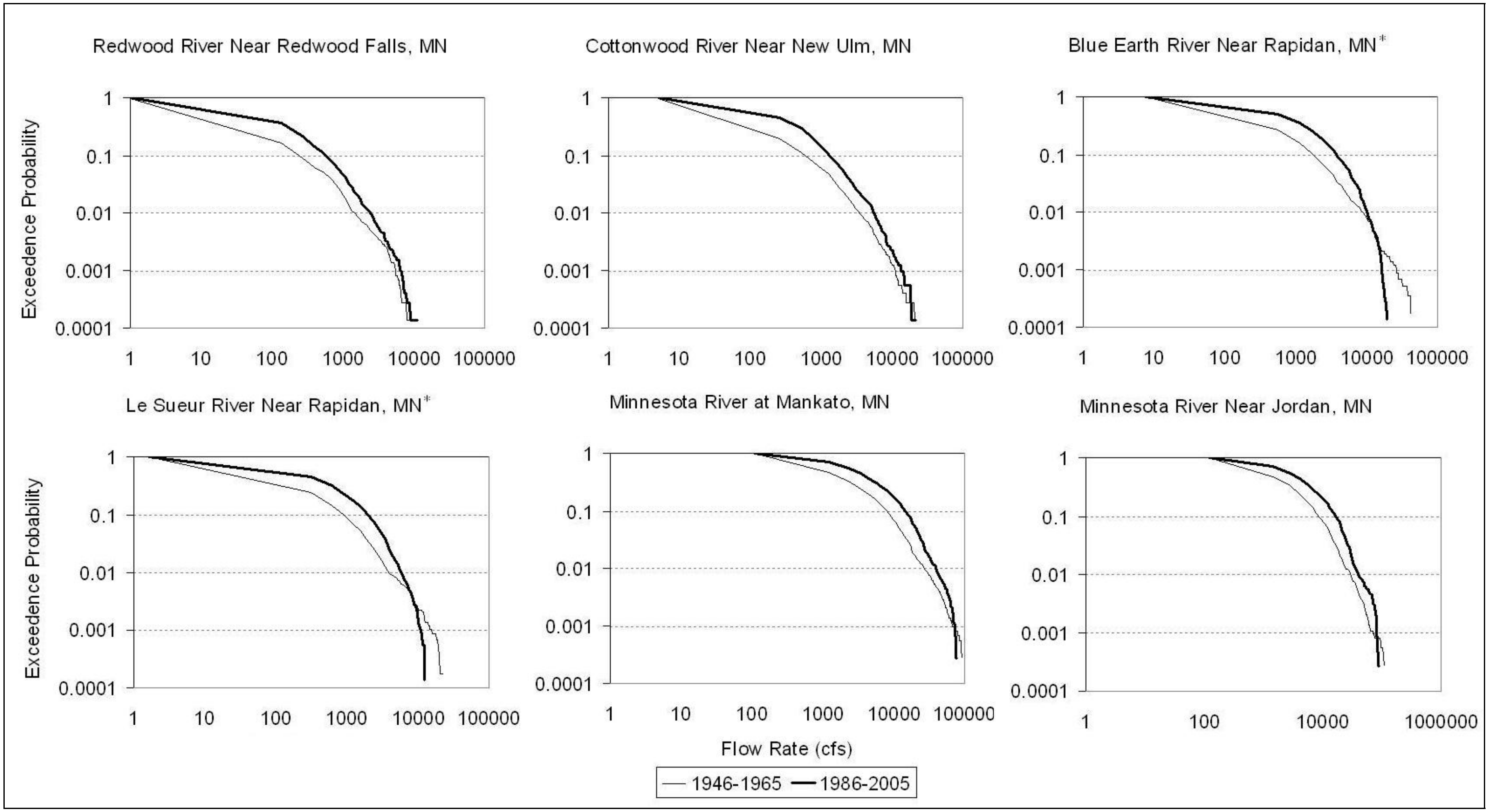

Figure A.1b. Flow Duration Curves for the Minnesota River Basin on Log-log plots.

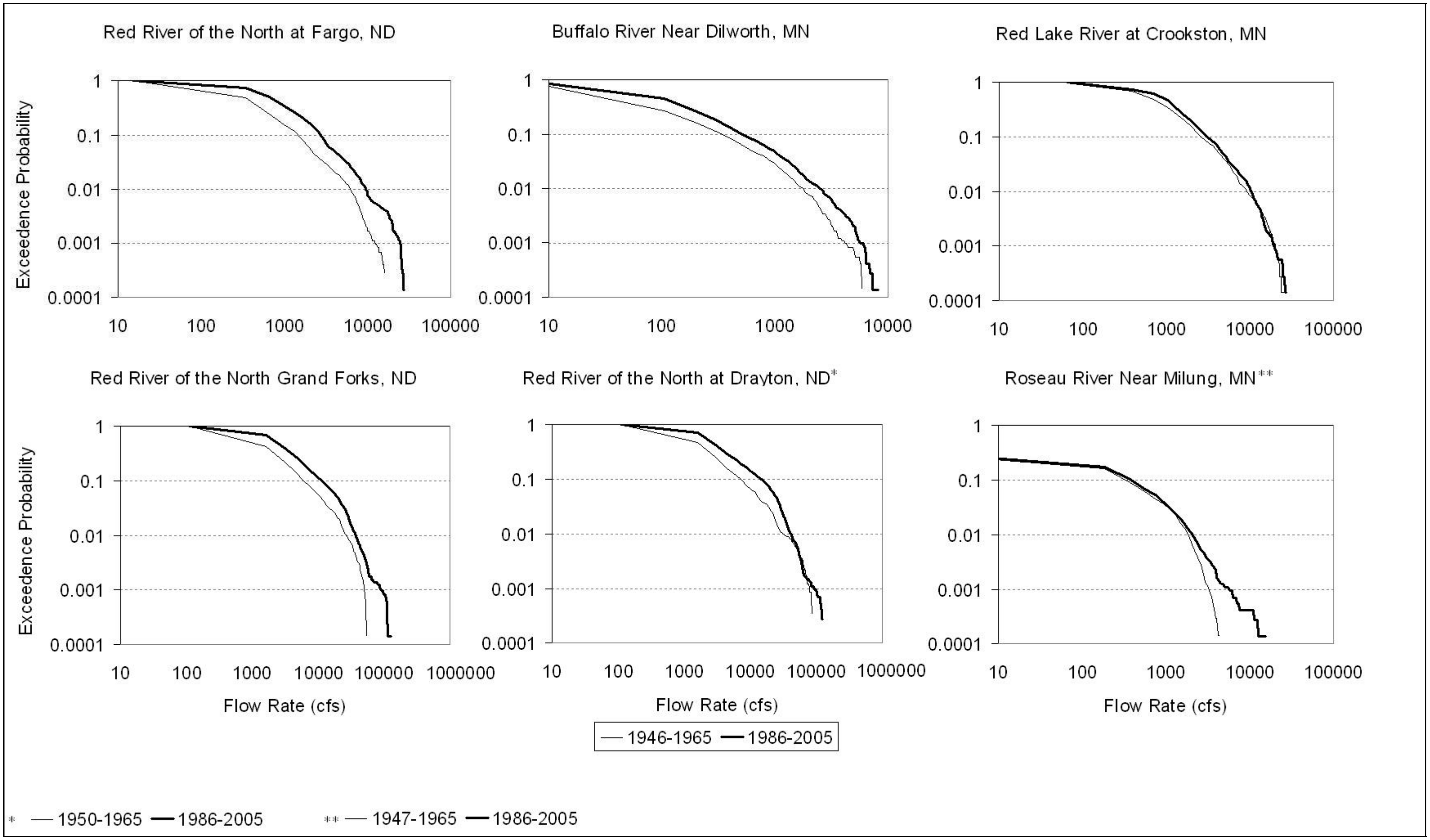

Figure A.2. Flow Duration Curves for the Red River of the North Basin on Log-log plots.

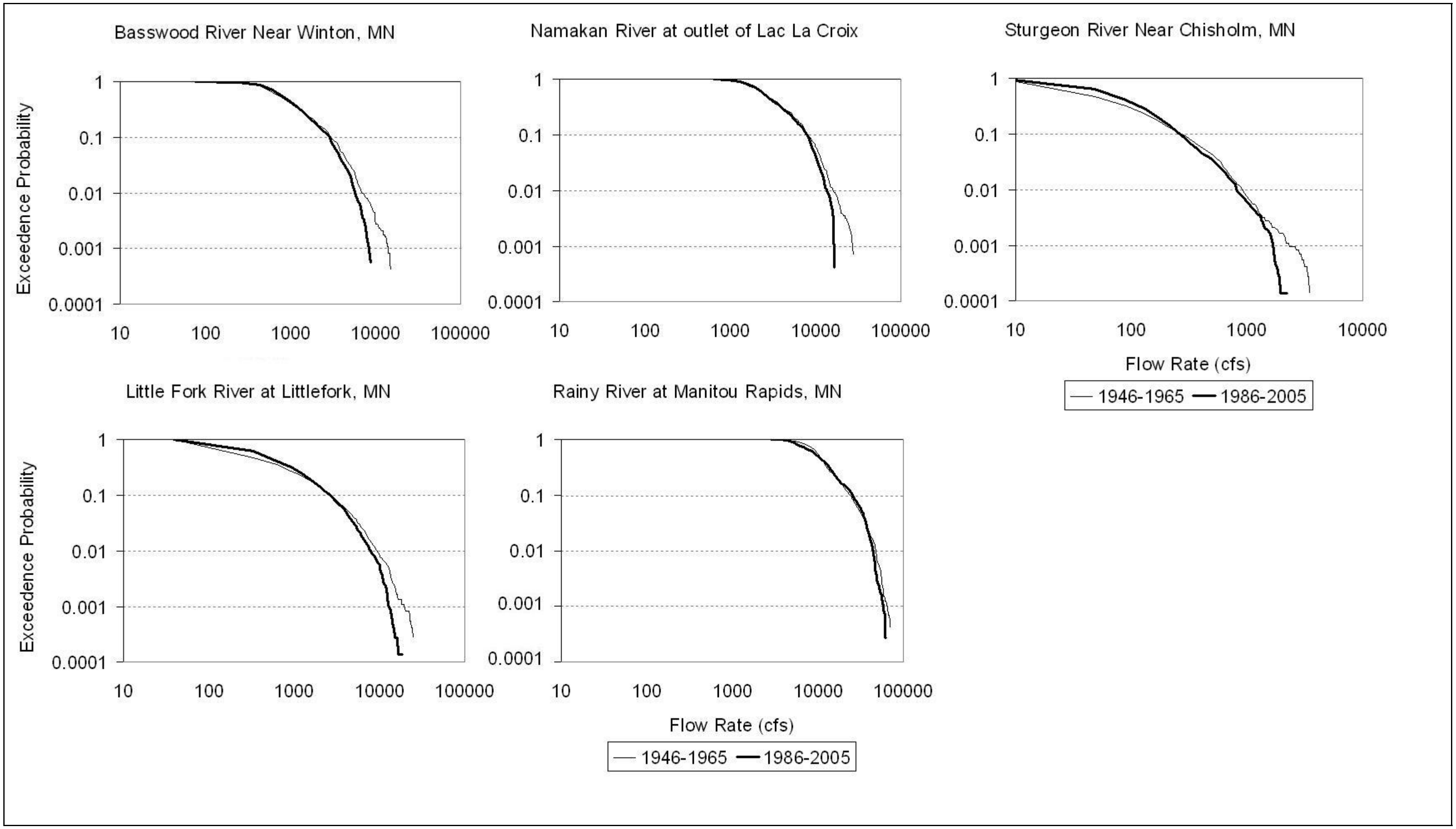

Figure A.3. Flow Duration Curves for the Rainy River Basin on Log-log plots.

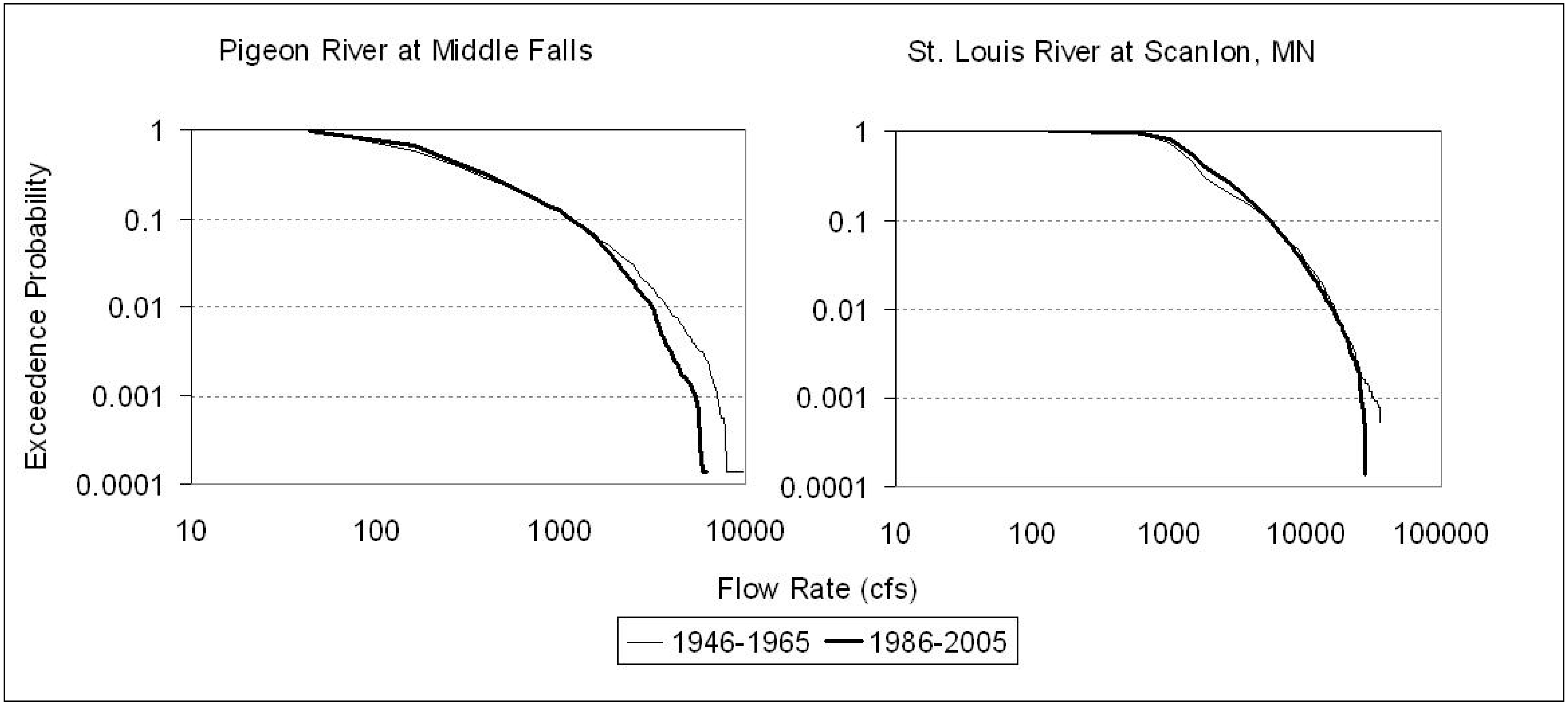

Figure A.4. Flow Duration Curves for tributaries to Lake Superior on Log-log plots.

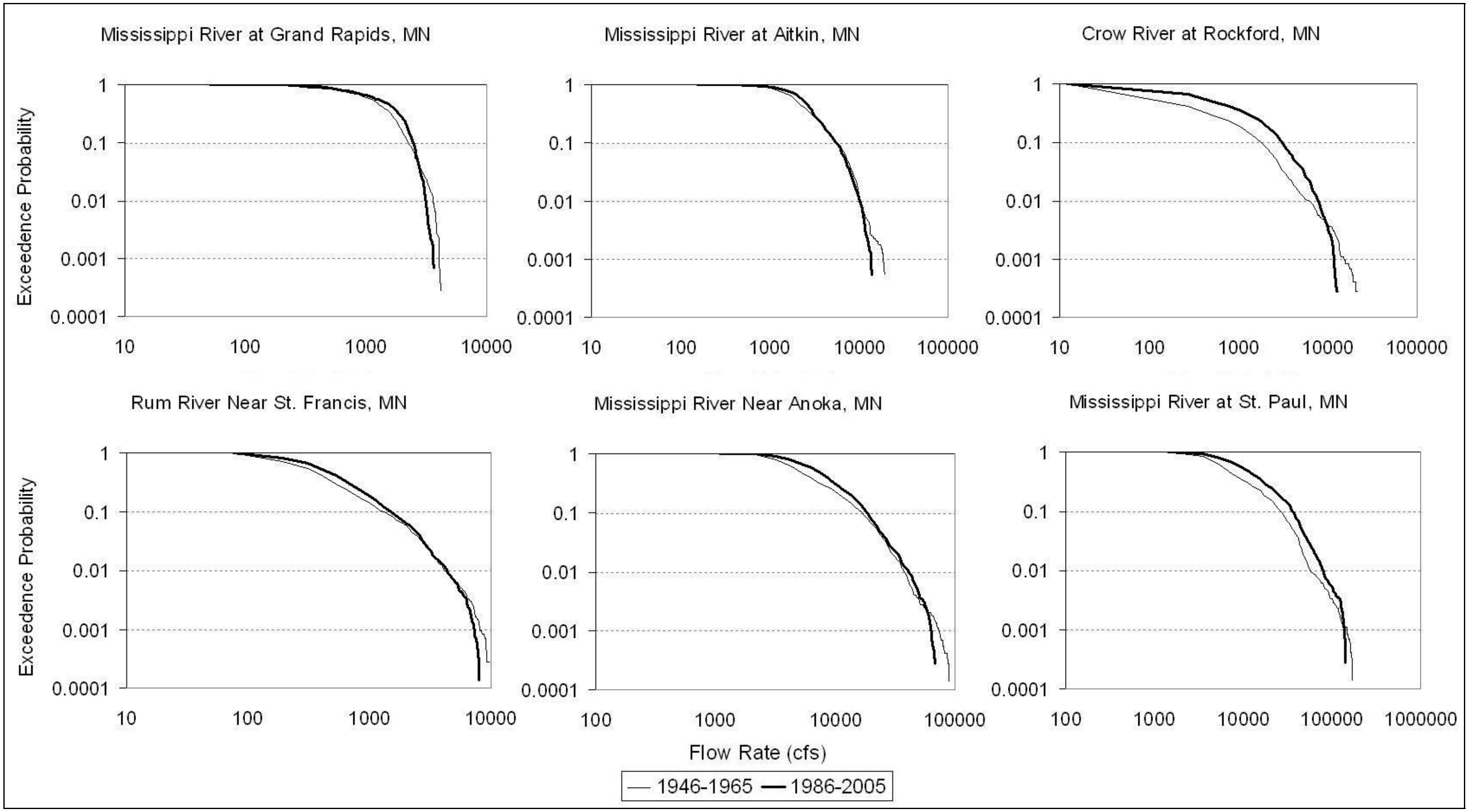

Figure A.5a. Flow Duration Curves for the Upper Mississippi River Basin on Log-log plots.

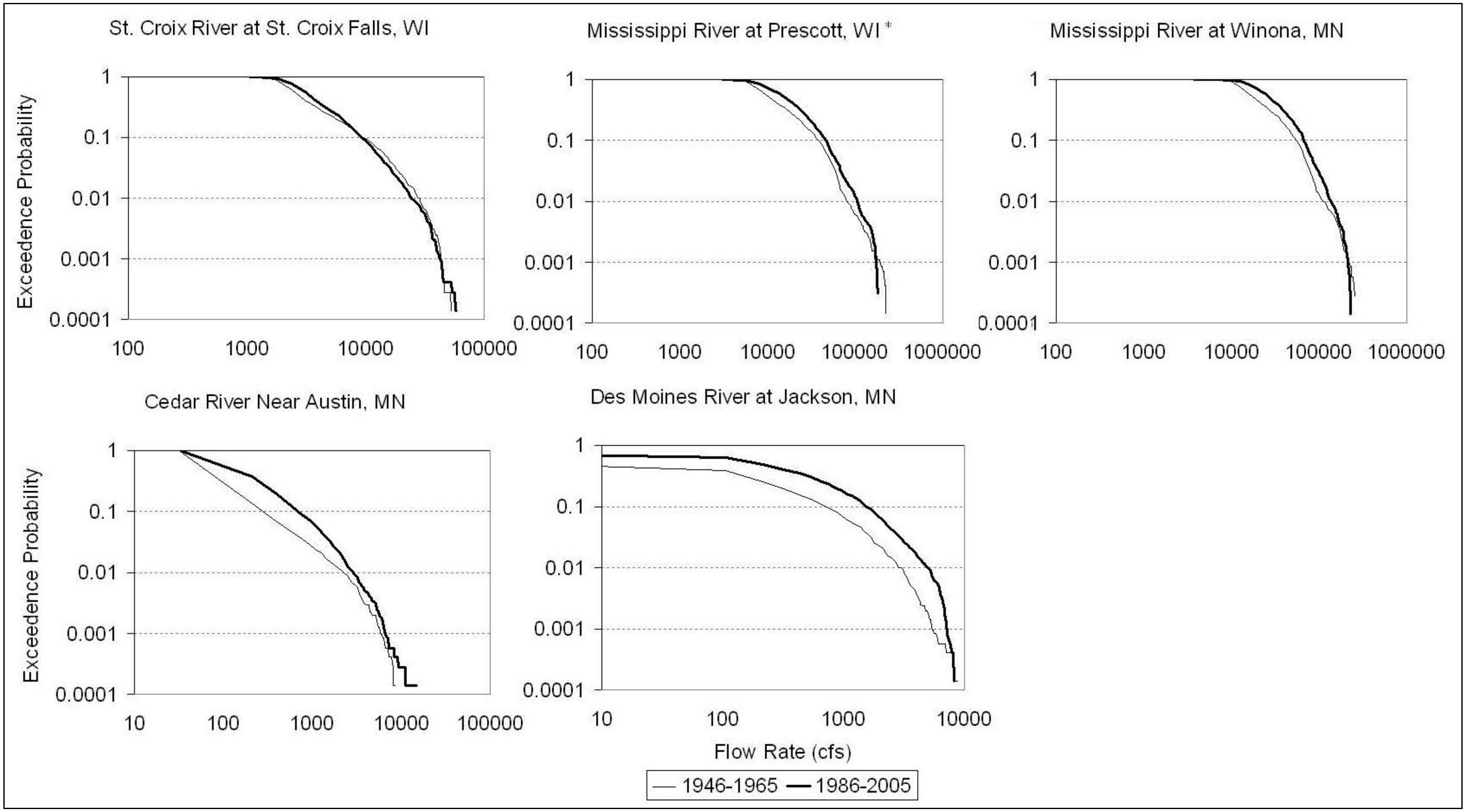

Figure A.5b. Flow Duration Curves for the Upper Mississippi River Basin on Log-log plots.

Appendix B: Flow Duration Curves for the non-exceedence of a given flow on Log-log plots for the periods 1946 - 1965 and 1986 - 2005.

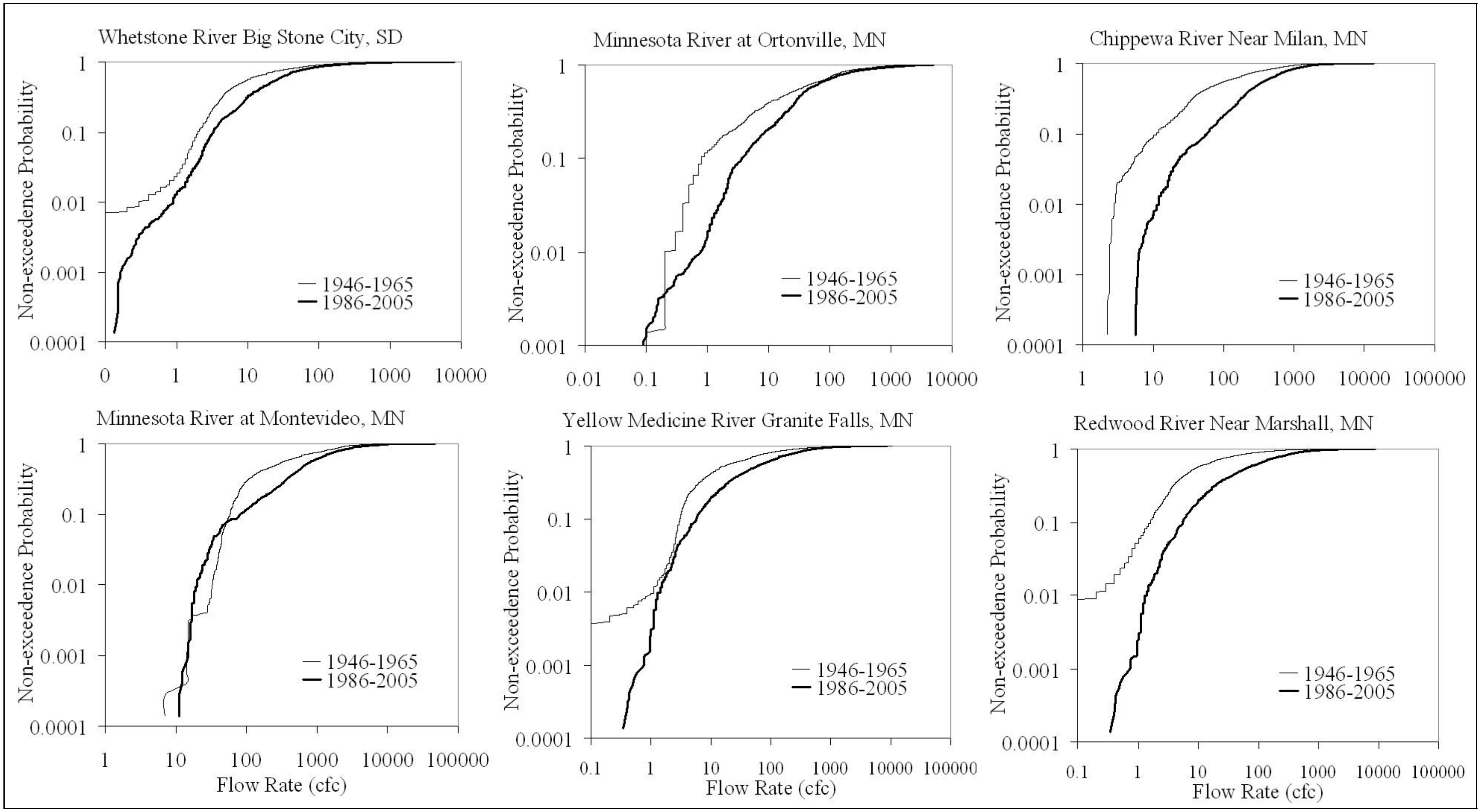

Figure B.1a. Flow Duration Curves for the Minnesota River Basin on Log-log plots for non-exceedence of a given flow.

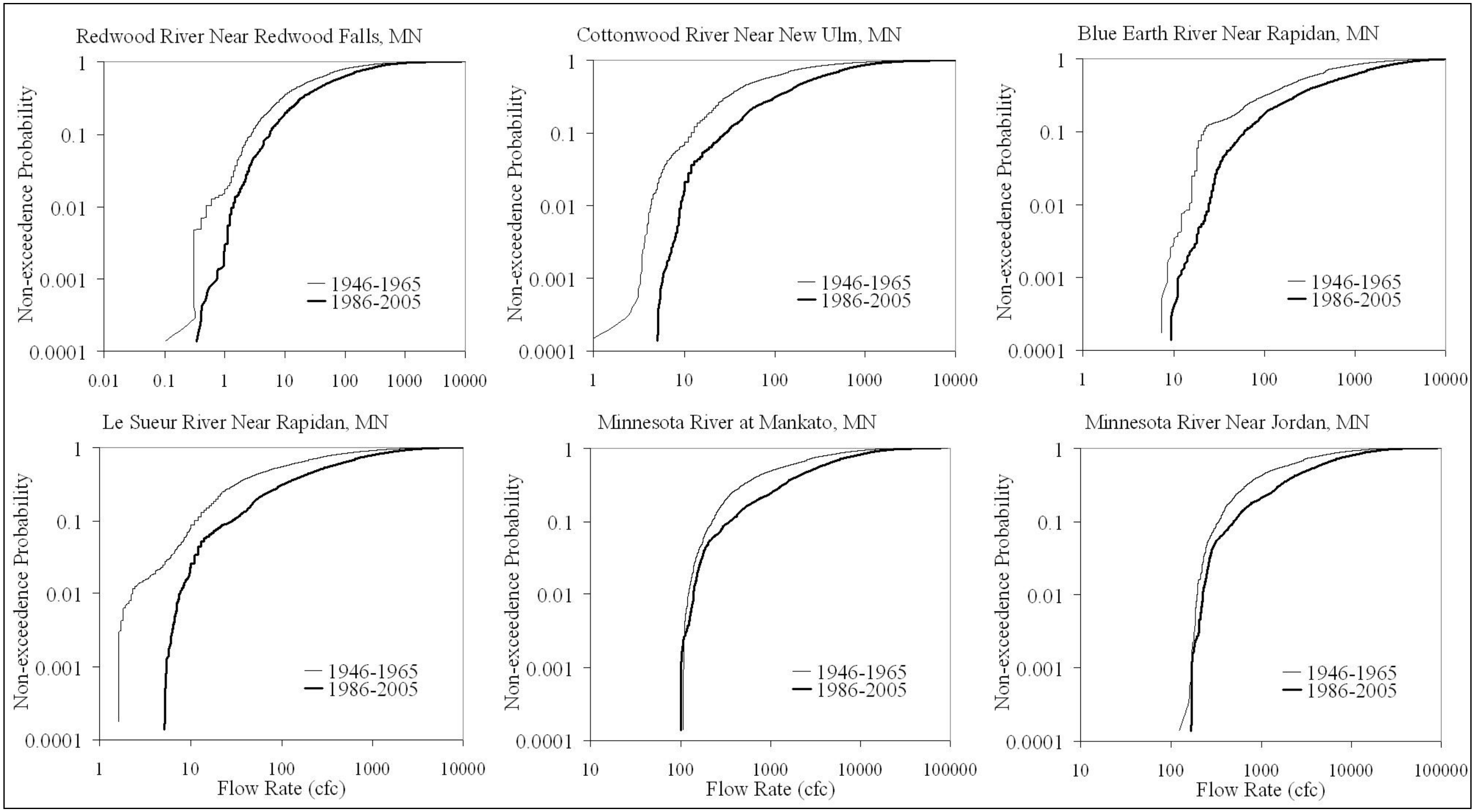

Figure B.1b. Flow Duration Curves for the Minnesota River Basin on Log-log plots for non-exceedence of a given flow.

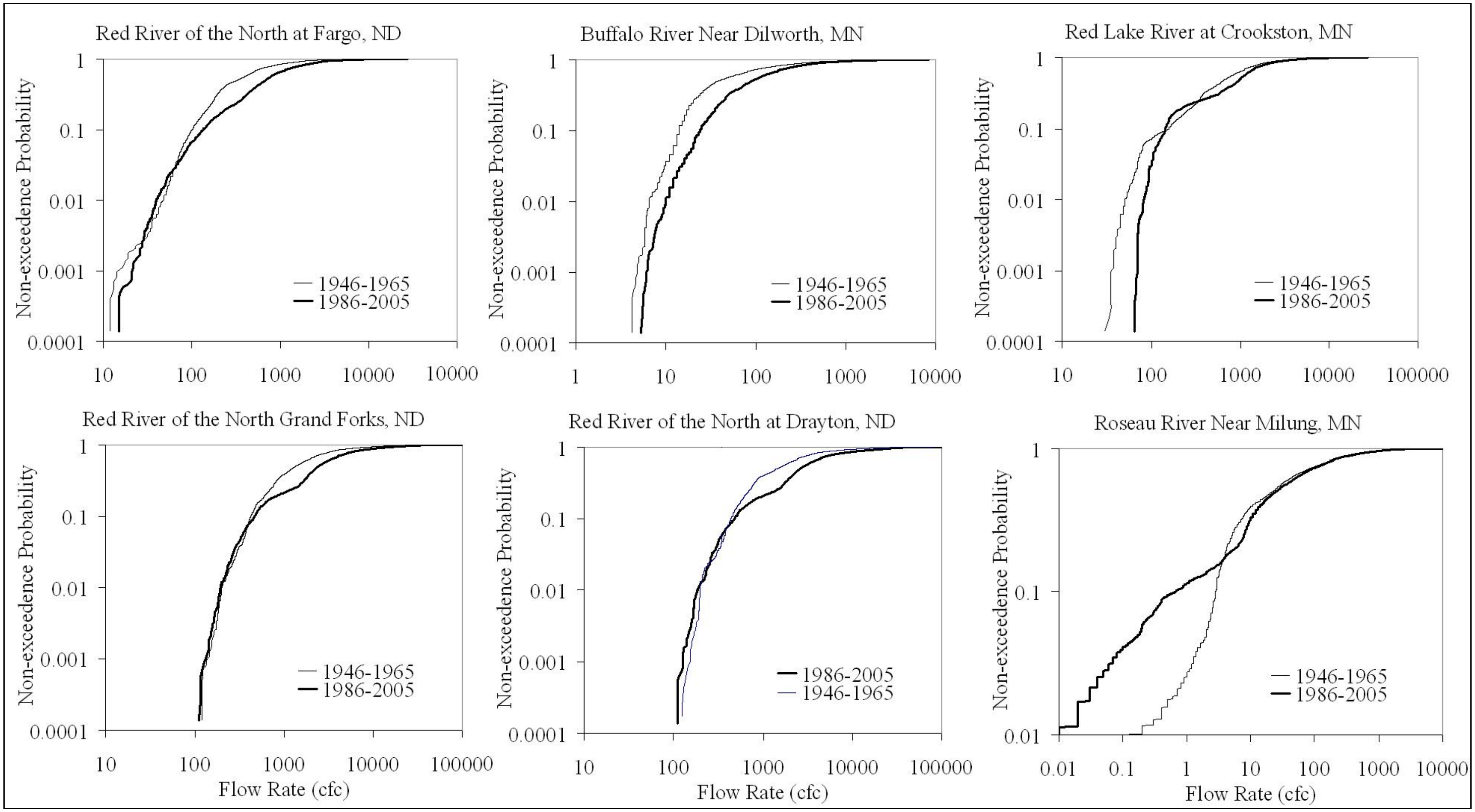

Figure B.2. Flow Duration Curves for the Red River of the North Basin on Log-log plots for non-exceedence of a given flow.

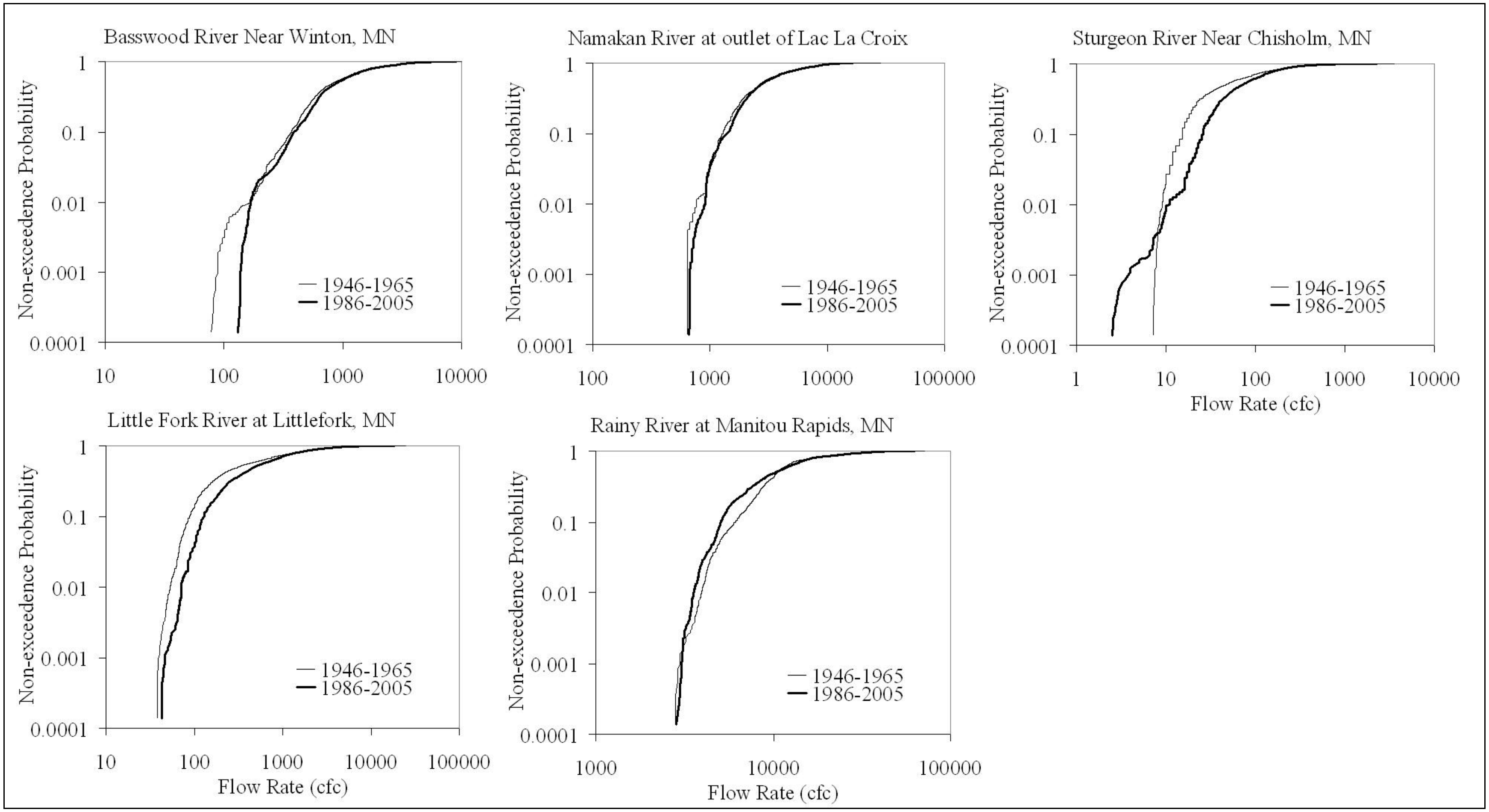

Figure B.3. Flow Duration Curves for the Rainy River Basin on Log-log plots for non-exceedence of a given flow.

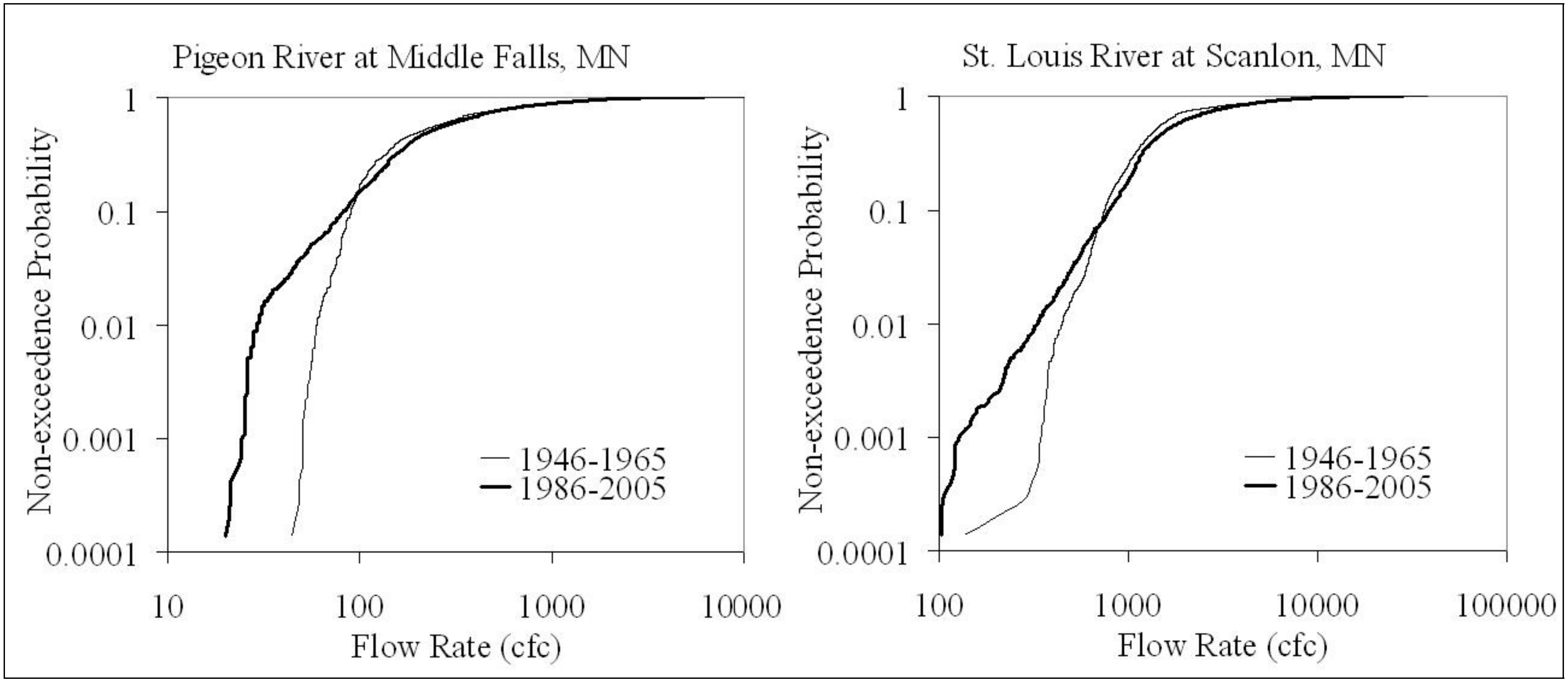

Figure B.4. Flow Duration Curves for tributaries to Lake Superior on Log-log plots for non-exceedence of a given flow.

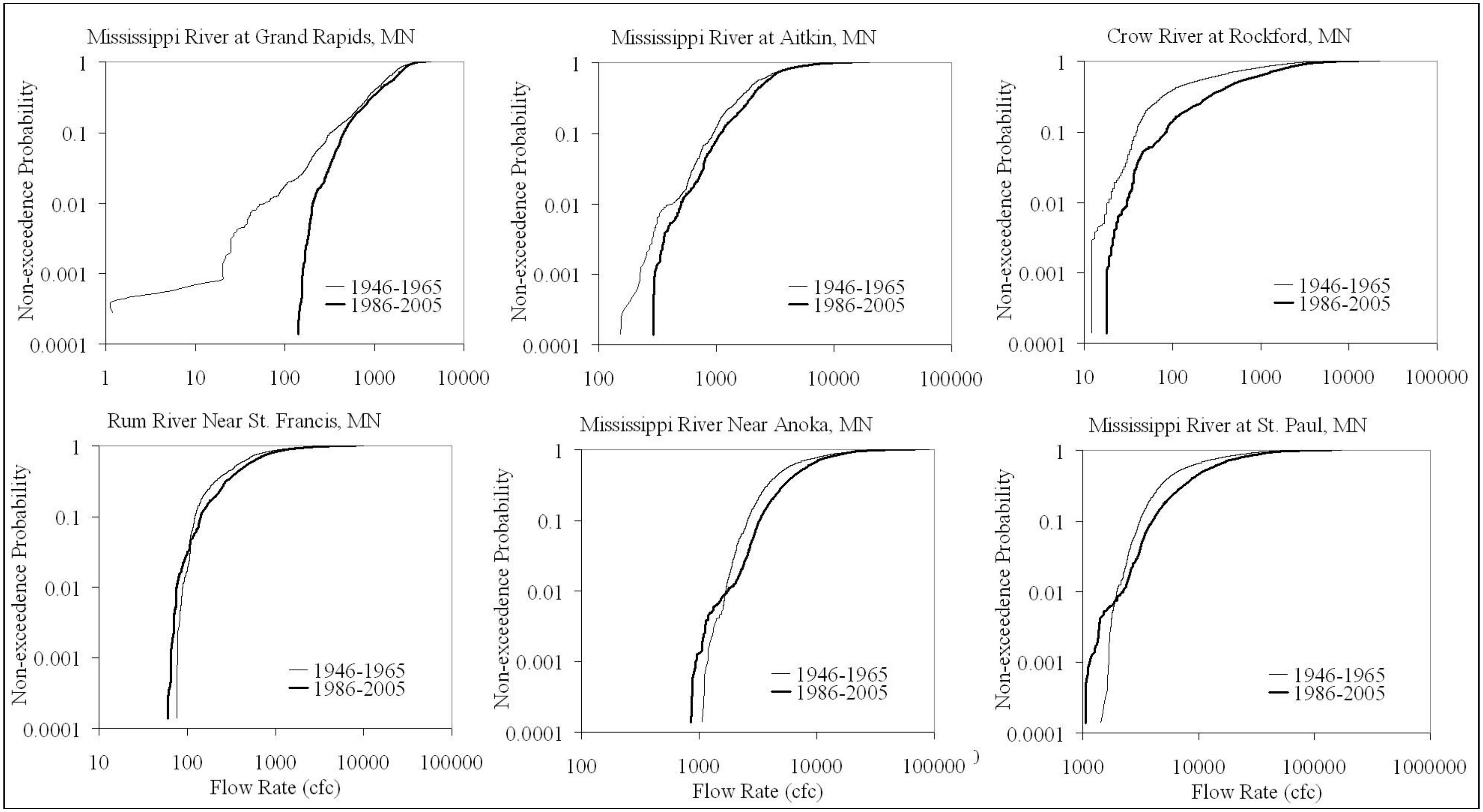

Figure B.5a. Flow Duration Curves for the Upper Mississippi River Basin on Log-log plots for non-exceedence of a given flow.

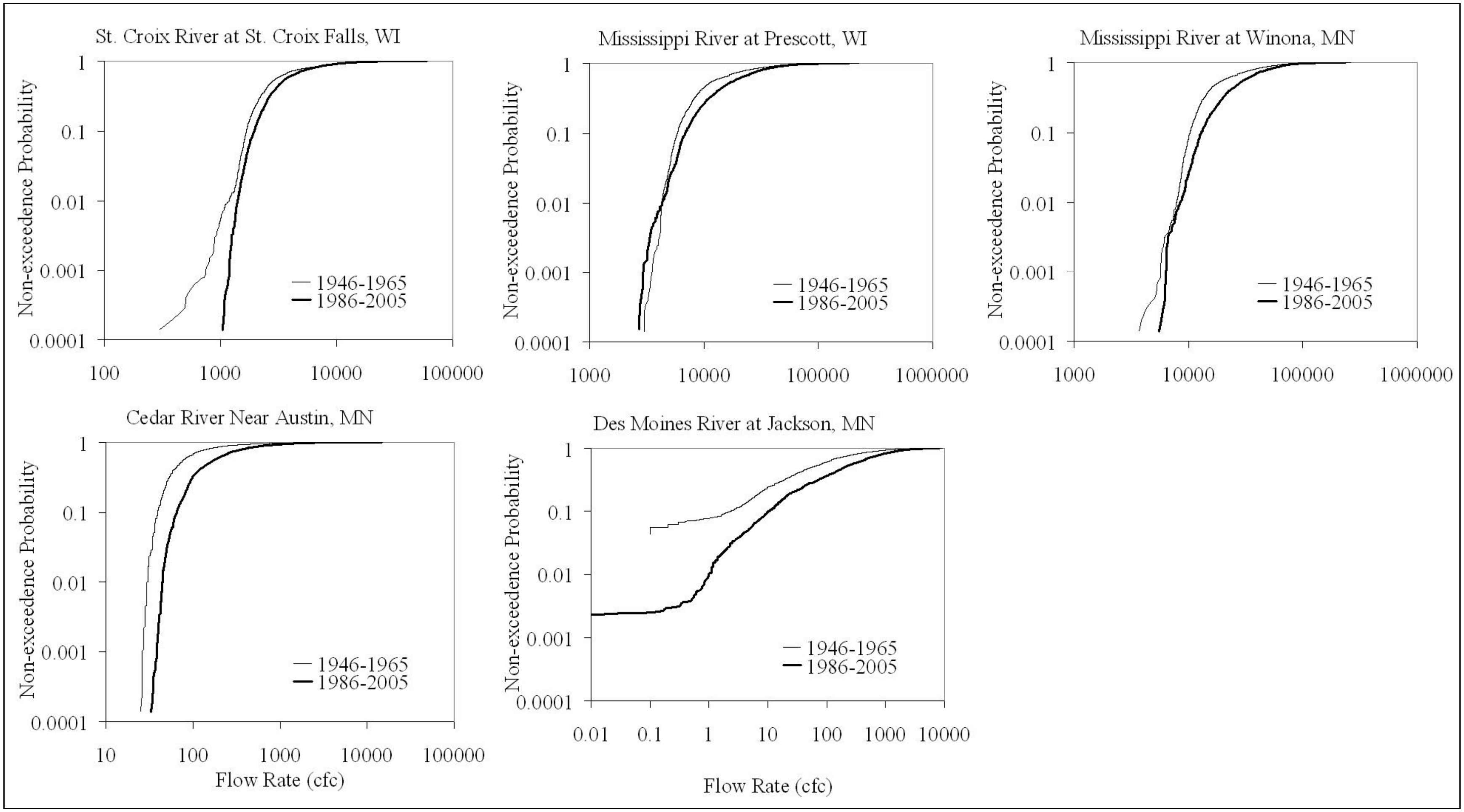

Figure B.5b. Flow Duration Curves for the Upper Mississippi River Basin on Log-log plots for non-exceedence of a given flow.

Appendix C: Mean, standard deviation, skew coefficient, and weighted skew coefficients of log-transformed stream flow data (log Q) for the 1946-1965 and 1986-2005 periods for 36 USGS stream gauging stations in Minnesota.

Stream/River name	**1946-1965**				**1986-2005**			
	Mean	**Std. Dev.**	**Skew Coeff.**	**Weighted Skew Coeff.**	**Mean**	**Std. Dev.**	**Skew Coeff.**	**Weighted Skew Coeff.**
Minnesota River Basin								
Whetstone River Big Stone City, SD	3.08	0.47	-0.78	-0.48	3.08	0.67	-0.64	-0.43
Minnesota River at Ortonville, MN	2.88	0.29	-0.30	-0.31	3.15	0.41	-0.74	-0.47
Chippewa River Near Milan, MN	3.23	0.38	0.03	-0.12	3.46	0.39	-0.21	-0.22
Minnesota River at Montevideo, MN	3.62	0.37	0.26	-0.02	3.77	0.42	0.49	0.06
Yellow Medicine River Granite Falls, MN	3.27	0.44	0.30	0.00	3.22	0.36	0.54	0.08
Redwood River Near Marshall, MN	2.79	0.60	-0.89	-0.47	2.94	0.41	0.48	0.04
Redwood River Near Redwood Falls, MN	3.21	0.53	0.35	0.04	3.31	0.36	0.57	0.11
Cottonwood River Near New Ulm, MN	3.62	0.40	0.25	0.03	3.68	0.35	0.28	0.04
Blue Earth River Near Rapidan, MN	3.91	0.36	-0.04	-0.09	3.93	0.20	-0.08	-0.11
Le Sueur River Near Rapidan, MN	3.51	0.61	-0.90	-0.37	3.83	0.19	0.06	-0.05
Minnesota River at Mankato, MN	4.30	0.34	0.29	0.00	4.38	0.29	0.02	-0.11
Minnesota River Near Jordan, MN	4.31	0.36	0.20	-0.03	4.41	0.30	0.07	-0.08
Rainy River Basin								

Stream/River name	1946-1965				1986-2005			
	Mean	Std. Dev.	Skew Coeff.	Weighted Skew Coeff.	Mean	Std. Dev.	Skew Coeff.	Weighted Skew Coeff.
Basswood River Near Winton, MN	3.67	0.26	-0.30	-0.06	3.61	0.20	-0.24	-0.04
Namakan River at outlet of Lac La Croix								
Sturgeon River Near Chisholm, MN	3.02	0.23	0.75	0.27	2.96	0.28	-0.47	-0.18
Little Fork River at Littlefork, MN	4.00	0.19	-0.55	-0.35	3.87	0.25	-0.29	-0.25
Rainy River at Manitou Rapids, MN	4.54	0.17	-0.39	-0.35	4.52	0.21	-1.08	-0.56
Red River of the North Basin								
Red River of the North at Fargo, ND	3.62	0.33	-0.06	-0.23	3.80	0.38	-0.51	-0.41
Buffalo River Near Dilworth, MN	3.23	0.31	0.13	-0.16	3.31	0.37	-0.19	-0.29
Red Lake River at Crookston, MN	3.91	0.31	-0.65	-0.52	3.92	0.37	-1.01	-0.63
Red River of the North Grand Forks, ND	4.23	0.30	-0.41	-0.43	4.41	0.37	-0.55	-0.49
Red River of the North at Drayton, ND	4.31	0.31	-0.29	-0.40	4.43	0.35	-0.69	-0.56
Roseau River Near Milung, MN	3.20	0.33	-0.23	-0.39	3.27	0.50	-0.85	-0.63
Streams Tributary to Lake Superior								
Pigeon River at Middle Falls	3.61	0.27	-0.84	0.03	3.55	0.13	-0.06	0.26
St. Louis River at Scanlon, MN	4.26	0.14	-0.01	-0.01	4.21	0.20	-0.59	-0.22
Upper Mississippi River Basin								
Mississippi River at Grand Rapids, MN	3.45	0.20	1.68	0.25	3.43	0.10	-0.13	-0.14
Mississippi River at Aitkin, MN	3.93	0.17	-0.45	-0.31	3.88	0.14	0.05	-0.11

Stream/River name	1946-1965				1986-2005			
	Mean	Std. Dev.	Skew Coeff.	Weighted Skew Coeff.	Mean	Std. Dev.	Skew Coeff.	Weighted Skew Coeff.
Crow River at Rockford, MN	3.60	0.38	-0.18	-0.18	3.68	0.35	-0.95	-0.44
Rum River Near St. Francis, MN	3.61	0.28	-0.67	-0.39	3.53	0.28	-0.67	-0.39
Mississippi River Near Anoka, MN	4.50	0.21	0.25	-0.02	4.46	0.20	0.17	-0.05
Mississippi River at St. Paul, MN	4.66	0.25	0.69	0.13	4.70	0.23	0.18	-0.05
St. Croix River at St. Croix Falls, WI	4.43	0.18	-0.46	-0.30	4.36	0.20	0.11	-0.07
Mississippi River at Prescott, WI	4.83	0.22	0.69	0.13	4.83	0.22	0.20	-0.04
Mississippi River at Winona, MN	4.95	0.21	0.68	0.12	5.01	0.19	-0.23	-0.21
Cedar River Near Austin, MN	3.60	0.36	-1.37	-0.55	3.63	0.32	0.29	-0.05
Des Moines River at Jackson, MN	3.31	0.38	-0.13	-0.15	3.38	0.31	-0.14	-0.15

Appendix D: Floods (in cubic feet per second) with 1-, 2-, 5-, 10-, and 25-year return periods for (1946-1965) and (1986-2005)

Return Period	1.01		2		5		10		20	
Stream/River Name	1946-1965	1986-2005	1946-1965	1986-2005	1946-1965	1986-2005	1946-1965	1986-2005	1946-1965	1986-2005
Minnesota River Basin										
Whetstone River Big Stone City, SD	65	20	1,305	1,341	3,048	4,521	4,535	8,037	6,693	14,210
Minnesota River at Ortonville, MN	136	140	780	1,450	1,338	3,163	1,741	4,672	2,274	7,016
Chippewa River Near Milan, MN	205	308	1,716	2,951	3,529	6,113	5,094	8,779	7,486	12,745
Minnesota River at Montevideo, MN	569	638	4,199	5,785	8,584	13,189	12,453	20,411	18,495	32,645
Yellow Medicine River Granite Falls, MN	176	254	1,863	1,645	4,378	3,330	6,842	4,846	11,012	7,262
Redwood River Near Marshall, MN	16	97	687	857	1,999	1,919	3,300	2,937	5,401	4,633
Redwood River Near Redwood Falls, MN	100	319	1,597	1,989	4,445	4,014	7,624	5,847	13,594	8,785
Cottonwood River Near New	509	755	4,196	4,752	9,100	9,382	13,674	13,430	21,139	19,730

Ulm, MN										
Blue Earth River Near Rapidan, MN	1,093	2,765	8,169	8,496	16,349	12,471	23,332	15,170	33,937	18,638
Le Sueur River Near Rapidan, MN	84	2,399	3,518	6,821	10,720	9,862	18,292	11,935	31,250	14,607
Minnesota River at Mankato, MN	3,240	4,669	19,857	24,082	38,216	42,179	53,789	56,152	77,418	75,845
Minnesota River Near Jordan, MN	2,876	4,882	20,429	25,980	40,995	46,318	58,838	62,320	86,335	85,208
Red River of the North Basin										
Red River of the North at Fargo, ND	640	634	4,297	6,734	7,929	13,441	10,479	18,667	14,702	25,882
Buffalo River Near Dilworth, MN	292	238	1,722	2,109	3,112	4,159	4,195	5,797	5,725	8,127
Red Lake River at Crookston, MN	1,178	772	8,554	9,064	14,801	17,286	19,083	23,104	24,427	30,447
Red River of the North Grand Forks, ND	2,767	2,655	17,957	27,591	30,836	53,260	39,822	724,411	51,297	97,779
Red River of the North at Drayton, ND	3,145	2,990	21,360	28,983	37,516	53,672	49,062	71,181	64,110	93,460
Roseau River Near Milung, MN	213	75	1,669	2,117	3,067	5,083	4,101	7,534	5,481	10,956

Rainy River Basin										
Basswood River Near Winton, MN	1,148	1,370	4,705	4,131	7,713	6,111	9,954	7,485	13,036	9,283
Namakan River at outlet of Lac La Croix		186		920		1,558		2,029		2,669
Sturgeon River Near Chisholm, MN	351	186	1,034	920	1,624	1,558	2,085	2,029	2,749	2,669
Little Fork River at Littlefork, MN	3,157	1,704	10,311	7,517	14,733	12,032	17,500	15,176	20,809	19,249
Rainy River at Manitou Rapids, MN	12,231	8,915	35,304	34,666	48,576	50,052	56,650	59,209	66,124	69,611
Tributaries to Lake Superior										
Pigeon River at Middle Falls	970	1,847	4,081	3,534	6,914	4,631	9,122	5,376	12,270	6,342
St. Louis River at Scanlon, MN	8,582	5,286	18,156	16,468	23,793	23,757	27,399	28,502	31,843	34,385
Upper Mississippi River Basin										
Mississippi River at Grand Rapids, MN	1,044	1,579	2,750	2,723	3,270	3,270	3,587	3,587	3,952	3,952
Mississippi River at Aitkin, MN	2,686	3,427	8,939	7,644	10,057	10,057	11,570	11,570	13,406	13,406
Crow River at Rockford, MN	459	577	4,092	5,097	9,549	9,549	12,845	12,845	17,219	17,219
Rum River Near St. Francis, MN	750	646	4,235	3,457	5,811	5,811	7,535	7,535	9,854	9,854

Mississippi River Near Anoka, MN	10,138	9,804	31,809	29,082	42,638	42,638	51,960	51,960	64,059	64,059
Mississippi River at St. Paul, MN	12,760	14,209	44,880	50,556	79,154	79,154	99,827	99,827	127,655	127,655
St. Croix River at St. Croix Falls, WI	9,371	7,607	27,641	22,941	33,700	33,700	41,077	41,077	50,628	50,628
Mississippi River at Prescott, WI	22,211	20,157	67,201	67,369	103,363	103,363	129,049	129,049	163,307	163,307
Mississippi River at Winona, MN	29,573	34,284	87,260	104,579	150,070	150,070	179,634	179,634	216,256	216,256
Cedar River Near Austin, MN	408	4,338	4,338	8,244	8,244	11,066	11,066	14,702	14,702	15,422
Des Moines River at Jackson, MN	239	2,108	2,108	4,369	4,369	6,316	6,316	9,281	9,281	8,055

Appendix E: 7-day (average) low flow (in cubic feet per second) with 2-, 5-, 10-, and 20-year return periods for (1946-1965) and (1986-2005)

	7Q2		7Q5		7Q10		7Q20	
Stream/River Name	**1946-1965**	**1986-2005**	**1946-1965**	**1986-2005**	**1946-1965**	**1986-2005**	**1946-1965**	**1986-2005**
Minnesota River Basin								
Whetstone River Big Stone City, SD	299	690	221	360	189	251	166	184
Minnesota River at Ortonville, MN	192	498	140	236	119	155	104	108
Chippewa River Near Milan, MN	11	35	4.99	14.5	3.05	9.05	-	6.1
Minnesota River at Montevideo, MN	29	79	16.2	33.6	11.9	21	-	14
Yellow Medicine River Granite Falls, MN	9	39	5.37	16	3.96	9.83	3.06	6.5
Redwood River Near Marshall, MN	2	15	1.11	5.82	0.75	3.24	0.52	1.92
Redwood River Near Redwood Falls, MN	1	6	0.14	3.54	0	2.65	0	2.1
Cottonwood River Near New Ulm, MN	3	6	1.57	2.39	0.91	1.42	0	0.91
Blue Earth River Near Rapidan, MN	51	110	32.7	46.1	25.4	27.7	20.3	17.6
Le Sueur River Near Rapidan, MN	8	78	3.68	30	2.52	15.8	1.87	8.61
Minnesota River at Mankato, MN	1	5	0.28	1.35	0.22	0.6	0.18	0.29
Minnesota River Near Jordan, MN	0	5	-	1.55	-	0.77	-	0.41
Red River of the North Basin								
Red River of the North at Fargo, ND	2	1.3	0.51	0.07	0.2	0	0	0
Buffalo River Near Dilworth, MN	460	834	277	344	209	201	-	124

Red Lake River at Crookston, MN	457	814	276	358	210	217	167	139
Red River of the North Grand Forks, ND	216	301	93.9	132	57.9	83.5	37.8	56.7
Red River of the North at Drayton, ND	12	28	8.43	15.3	6.75	10.9	5.54	8.02
Roseau River Near Milung, MN	82	173	42.1	68.9	28.6	40	20.4	24.8
Rainy River Basin								
Basswood River Near Winton, MN	5450	4720	4330	3740	3850	3310	3500	2990
Namakan River at outlet of Lac La Croix	77	107	59.3	72.8	51	57.7	44.7	46.8
Sturgeon River Near Chisholm, MN	13	23	9.85	14.9	8.58	10.1	7.65	6.68
Little Fork River at Littlefork, MN	1270	1390	966	1060	838	911	744	795
Rainy River at Manitou Rapids, MN	357	377	221	231	161	168	119	125
Tributaries to Lake Superior								
Pigeon River at Middle Falls	82	58	63.7	396	56.6	26.3	51.7	21.2
St. Louis River at Scanlon, MN	681	657	524	34.4	446	289	-	-
Upper Mississippi River Basin								
Mississippi River at Grand Rapids, MN	289	396	110	259	60.8	209	35.4	171
Mississippi River at Aitkin, MN	2750	4440	2180	2810	1930	2040	-	-
Crow River at Rockford, MN	3	14	0.04	2.63	0	0.82	0	0.04
Rum River Near St. Francis, MN	38	63	31.3	49.7	28.3	43.7	26.1	39.3
Mississippi River Near Anoka, MN	9740	12100	7970	9230	7110	7940	6440	6980
Mississippi River at St. Paul, MN	5450	7130	4630	5260	4280	4310	4020	-
St. Croix River at St. Croix Falls, WI	1650	1800	1440	1490	1350	1320	1280	1200
Mississippi River at Prescott, WI	2570	3200	1940	2140	1660	1670	1440	1330

Mississippi River at Winona, MN	147	160	98.2	105	81.5	82.9	70.6	67.5
Cedar River Near Austin, MN	34	112	21.8	49.6	17.4	31.1	14.5	20.8
Des Moines River at Jackson, MN	1030	920	587	583	418	460	308	379

Minnesota lake water quality on-line database and visualization tools for exploratory trend analyses

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I. Minnesota lake water quality on-line database and visualization tools for exploratory trend analyses

A. Background

Warming temperatures have been shown to have negative environmental impacts in both lakes and streams. In lakes, warmer temperatures may increase temperatures in the upper mixed layer (epilimnion) enough to affect algal, aquatic plant, invertebrate and fish communities. The IPCC analysis for the Upper Midwest (cite …p 117-122) suggested the following potential consequences of increased water temperatures due to increased air temperatures:

> *Earlier and longer period of density/thermal stratification in summer in deeper lakes, leading to longer periods of hypolimnetic "stagnation" and isolation from atmospheric oxygen mixing into the epilimnion. This can lead to the increased duration and magnitude of oxygen depletion in the hypolimnion, increasing the risk of developing a 'dead zone' and associated fish kills.*

These consequences were in part based upon more detailed models developed to predict potential climate change effects on Minnesota lakes (Stefan et al. 1993; Stefan et al. 2001; Fang and Stefan 1999).

In such cases, this increased duration of stratification can reduce oxygen inputs to bottom layers, increasing the risk of oxygen-poor or oxygen-free "dead zones" that will stress or kill fish and other organisms. In culturally nutrient-enriched lakes in particular, enhanced oxygen depletion would also be expected to increase phosphorus diffusion from bottom sediments leading to larger injections of bio-available phosphorus during periods of intermittent mixing in spring and summer, and during fall turnover. Such sudden inputs of P typically lead to large blooms of algae, in some cases producing noxious scums and increased likelihood of cyanobacterial (i.e. "bluegreen algae") toxins (e.g. MPCA 2007). Oxygen depleted bottom waters also are characterized by increased concentrations of chemically reduced nitrogen (ammonium-N) and sulfur (hydrogen sulfide); both can be toxic to fish and other aquatic animals at concentrations that often are found in such lakes, and the injection of ammonium along with phosphate into the epilimnion during mixing usually leads to more algal growth than would P alone. In lakes with contaminated sediments, warmer water and low-oxygen conditions may act to mobilize mercury and other persistent pollutants, potentially increasing health hazards for animals that eat fish from the lakes, including humans (e.g. Dodds 2002, Stefan et al. 2001, MPCA 2004). Poff et al. (2002) and Kling et al. (2003) list specific impacts to lakes that include an increase in nuisance algae, the reduction of fish habitat with the warming of lakes, and changes in runoff (both increases and decreases), that will in turn affect lake levels, and finally, expansion and contraction of aquatic species ranges.

The Water Quality component of the project was included in the following main objective:

<u>Summarize the follow variables in lakes and streams</u>:

(1) lake transparency (secchi depth);
(2) lake chlorophyll (a measure of algal abundance);

(3) lake total phosphorus (and nitrogenous nutrients when available);
(4) lake levels (see Appendix B);
(5) Stream flows, specifically annual mean flow, annual maximum flow, annual minimum daily low, and mean monthly flow (see Appendix D);
(6) Timing of stream flows, such as date of annual maximum daily flow, date of spring maximum daily flow, date of spring freshet (initiation of the spring/snowmelt runoff), date of annual minimum daily flow (see Appendix D); and
(7) Other ancillary water quality parameters, including temperature and total dissolved solids / specific conductance, dissolved oxygen, DOC/color, pH/alkalinity, TSS/turbidity

These parameters were selected for two reasons: a) their direct linkage to climate; and b) their potential direct impact on water quality and ecology (see Proposal Appendix A). Influences of land use changes, e.g. urbanization or agricultural use, have to be acknowledged, and to the extent possible based on funding limitations, will be taken into account in the interpretation of the results.

B**.** Lake Water Quality Trends Specific Objectives

The amount of lake water quality data that has been collected for Minnesota lakes is enormous and therefore, a series of meetings were held with project partners to distill down the scope of this task based on available funding 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 trend analyses on all available parameters.

As the project proceeded, using a third component became possible as a result of tools developed from other non-LCCMR funded projects:

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 water quality data.

C. Methods

1). Data compilation: Data from MPCA STORET files was re-organized and summarized in various ways (see below) in preparation for determining statistical associations with ice-out and ice-on data that was being compiled as a separate component of the overall project. With help from MPCA, we began by compiling data for an initial set of 26 lakes with long-term ice-out records compiled by co-PI V. Card. This set of lakes was then augmented to include an additional set of ~255 lakes for which ice-out records had been compiled. However, since the *ice-out record lakes set* had no *a priori* relationship to the amount of water quality data available for these lakes, we examined a larger set of lakes that contained at least 15 years of data for at least one parameter. This generated a set of 560 Minnesota lakes which ultimately grew to total

638 lakes totaling 1.9 million data records as other data bases were discovered that included quality assured data. Several water quality data sets were investigated, including those from MPCA (EDA), EPA (STORET), DNR Fisheries, Metropolitan Council, and our own (NRRI-UMD) cooperative work with Itasca County and Three Rivers Park District.

2). Water quality variables: Measured parameters comprise a primary *Core Suite* that includes the field sensor parameters that typically determine a meter-by-meter depth profile of temperature, dissolved oxygen (and a calculated percentage oxygen saturation), specific electrical conductivity (EC25, that estimates total salt/ion concentrations), and pH; and water clarity estimated by Secchi disk depth. Lake level is also considered to be a *Core* parameter, but trends in lake level were analyzed as a separate TASK by co-PI H. Stefan's group for the overall project (see Appendix B for details). 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 its limnologically relevant forms), dissolved and total organic carbon and/or color, SiO_2, Hardness, the major anions (ANC/alkalinity, SO_4, Cl) and the major cations (Ca, Mg, Na, K). These classifications derive from the *Vital Signs* program used by the National Park which was used by NRRI-UMD to structure analyses of historical water quality in the Great Lakes Network of National Parks (Axler et al. 2005, 2006; Pennoyer 2003). It is useful since there will be many more *Core* than *Advanced Suite* data available for Minnesota lakes and streams.

3). Data quality assurance was assumed to have been properly completed prior to being stored in the MPCA EDA (Electronic Data Access) data base and EPA's STORET databases. However, numerous erroneous and anomalous values were uncovered during initial data screening that involved visually inspecting the data for outliers due to either entry error or changes in method detection limits. Outliers were identified based on best professional limnological judgment by NRRI staff and PI. In most cases, the problem was clearly due to a typographic error and was corrected. Ultimately, these outliers were either deleted from the data set used for statistical analyses, or allowed to remain in the database for lack of evidence to reject them. For some data we made assumptions about sampling depths based on maximum depths (Z_{max}) taken from MN DNR morphometry data available on the agency's Lake Finder website (http://www.dnr.state.mn.us/lakefind/index.html). Water quality parameter terminology follows standard limnological procedures (e.g. APHA 2003).

4). Depth strata: After data were manually reorganized and sorted into spreadsheets, a computer program was developed to automate the computation of depth stratum mean values, tabulation of data summaries, graphical presentation, and export to trend analysis software.

Each parameter from each site was averaged for all sampling dates and sampling periods for the following depth strata; 0m (surface values), 0-2m, 3-5m, 6-8m, 9-11m, 12-14m, 15-19m, 20-24m, 25-29m, 30-34m, etc. Strata were chosen for limnological reasons as well as data availability for the deeper strata in order to facilitate analyses of epi- meta- and hypolimnetic waters as manageable, but limnologically relevant "habitats" within a lake. These strata were selected to accommodate comparisons of lake trends across climatic regions and across groups of lakes classified by maximum depth. For example, our visual inspection of temperature and dissolved oxygen (DO) profiles from many shallow and deep, and productive and unproductive lakes has indicated that the strata 0-2, 3-5, 6-8 and 9-11m should capture the key seasonal and depth changes in temperature and DO for most lakes and eliminate the need for meter by meter comparisons of profiles. This also would eliminate about one third of the statistical analyses needed:

- [0-2m] - near-surface water in the mixed layer (epilimnion) where surface scums of algae can lead to supersaturated DO; averaging data from 0, 1 and 2m should also facilitate comparisons with chlorophyll and water chemistry measurements which have mostly been collected using 2m integrating tube samplers over the past 20 years.

- [3-5m] and [6-8m] – near-bottom water in polymictic shallow lakes (~4-8m bottom depth) and the thermocline region in stratified lakes whether the stratification persists throughout the ice-free growing season or not.

- [9-11m] - sub thermocline (uppermost hypolimnion) for most stratified lakes; may also be near-bottom for many lakes.

- [?-?] – undetermined for deeper hypolimnion strata. These analyses will likely focus on specific lakes within the set of ~ 255 lakes for which ice records exist.

- depth of the mixed layer (epilimnion depth for thermally stratified lakes); mean and maximum

- thermocline depth for stratified lakes - defined by the maximum temperature gradient with depth where the value exceeds 1 ^{o}C/meter (and 0.7 ^{o}C/meter); mean and maximum

- depth of anoxia – defined by DO $\leq$ 1 mgO_2/L; mean and maximum depth of acute warm, cool and cold water fish stress defined by values of 3 mgO_2/L, 5 mgO_2/L, and 7 mgO_2/L, respectively; these values are used as water quality criteria by the MPCA in various sections of Chapter 7050 (e.g. http://www.revisor.leg.state.mn.us/arule/7050/0222.html 7050.0222 SPECIFIC STANDARDS OF QUALITY AND PURITY FOR CLASS 2 WATERS OF THE STATE; AQUATIC LIFE AND RECREATION and http://www.epa.gov/waterscience/standards/wqslibrary/mn/mn_5_0150.htm 7050.0216 REQUIREMENTS FOR AQUACULTURE FACILITIES. As with temperature data, analyses will likely focus on specific lakes within the set of ~ 255 lakes for which ice records exist.

The statistics for each layer were calculated using the average of the daily averages within each time period. Note that stratum averages were not volumetrically weighted and only represent water column means for a site in the deepest portion of the lake.

5). Detection limit issues: We also needed to develop a set of "rules" for incorporating data listed as below detection into the database. This was particularly important for low nutrient lakes. There were two possibilities in the "raw" dataset extracted from the MPCA database -- "*Non-detect*" and "**Present <QL*", where QL is the *Quantitation Limit* for which the follow rules were adopted:

- If the record contains a value for "*MinDetectLimit*": use MinDetectLimit/2
- If the record contains a value for "*MinQuantLimit*": use MinQuantLimit/6
- Otherwise skip the record "*for now*"; we intend to examine this dataset more closely to see how important these deletions are to the results of the nutrient trends analyses.

6). *Secondary* parameters: In addition to the primary set of *Core* and *Advanced* suite water quality variables, several secondary, calculated parameters were generated for trend analysis:

- The Carlson Trophic State Index (TSI) was included because of its regulatory and management importance to lakes in Minnesota and its wide use in general. The index is actually three calculations based on midsummer secchi depth, surface TP and surface chlorophyll-*a* concentrations (details below in the Metadata).

- Algorithms were developed to calculate thermocline depth and the rate of change, or gradient, of temperature at the thermocline for over 500 lakes in the database since these are potentially important indicators of thermal trends in lakes. Thermal stratification and its stability (i.e. strength) act to structure habitat for aquatic organisms. This effort is also important because it provides a prototype for new calculated MPCA EDA (Electronic Data Access) thermal parameters since field temperature profiles are now simply entered into the database without further analysis.

- A third set of parameters compiled for each lake includes the various morphometric characteristics (e.g. surface area, maximum depth, mean depth, lake area to watershed area ratio, fetch, shoreline development, relative depth, et al.) as well as spatial classifications such as climate region and ecoregion.

7). Time intervals: Since this initial phase of the Climate Change project was intended to be exploratory, it was decided that trend analyses should be performed for a variety of potentially useful periods that could be used to characterize a particular year. For example, the MPCA has long requested Citizen Lake Monitoring Program (CLMP) volunteers, the group that has collected most of Minnesota's long-term Secchi disk water clarity data, to focus their measurements from June 15 – September 15. Therefore, all data within this time frame can be averaged to generate a single value for a particular year as has been routinely done by the agency for many years. Alternatively, a set of monthly or bimonthly mean values could be calculated and then analyzed singly for the year or considering their within-year variation. A monthly average for August, when algal biomass is usually thought to be at its peak could be useful to examine in comparison to weather patterns either at that time or perhaps over a longer period to include the contribution of spring runoff to the lake's nutrient loading. Similar arguments can be made for other ice-free months, or for any particular month, or two or three month period for that matter.
Limnological researchers have also used several different time periods and methods for generating annual averages, the most common periods perhaps being entire calendar year or the USGS *Water Year* defined as Oct 1 –Sep 30 of the following year, the *summer* (defined by the calendar season, or Jun-Aug, or Jun-Sep), or the *ice-free season* which on average could reasonably be defined as May through Oct (R.Axler, personal observations). Therefore, data was

compiled in a manner that would allow analyses to be performed using any or all of these time intervals. Consideration was also made of the potential for biasing averages if sampling was not spread evenly over a given interval and further statistical considerations of this issue are discussed below.

Initial examination of exploratory analyses focused on the following four time intervals:

- All data for the entire calendar year

- May through October 15, corresponding to the vast majority of the "ice-free growing season" for most lakes and most years.

- June 15 – September 15; the summer period as defined by MPCA for its Citizen Lake Monitoring Program (CLMP), CLMP-Plus, and most of its Lake Diagnostic studies. At least 4 monthly surveys will be required for this data set.

- June 1 – September 30; the "summer" as defined in Minnesota Rules, Chapter 7050, 7050.0150 DETERMINATION OF COMPLIANCE WITH WATER QUALITY STANDARDS AND WATER QUALITY CONDITION (http://www.epa.gov/waterscience/standards/wqslibrary/mn/mn_5_0150.htm)

- A midsummer window for some specified July – August period that is selected to maximize our use of data for a lake even if there was only a single survey for a year.

8). Trend analyses: Trends and trend rates over time were determined using the *Seasonal Kendall Trend Analysis* software developed by the U.S. Geological survey (2005; Computer Program for the Kendall Family of Trend Tests, Dennis R. Helsel, David K. Mueller, and James R. Slack SIR 2005-5275, U.S. Geological Survey; available at http://pubs.usgs.gov/sir/2005/5275) that allow for trend analyses both seasonally and regionally. The main advantage of the seasonal Kendall trend test is that it is a non-parametric, rank-based procedure suitable for non-normally distributed data, censored data, data containing outliers, and non-linear trends (Helsel et al. 2005; Helsel and Hirsch 1992; Hirsch and Slack 1984).

Sites were initially identified sites as "Qualifying" if they had records from at least 5 different years and with a level of significance of $p \leq 0.1$ for either a positive or negative trend over time. Additional exploratory trend summaries with accompanying mapping tools were generated for $p < 0.05$ and lakes having more years of data (8, 12 and >18 years).

It should be noted that in order to have been included in the original data set for which trend analyses were performed, a lake had to have "some" data for at least 15 different years and in virtually all cases, this long-term monitoring parameter was secchi depth clarity. Data records for all other parameters were considerably sparser.

9). Data, analyses, and visualization options: Mapping 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 and for the new

DNR/MPCA *SLICE* (i.e. sentinel) lakes. A comprehensive subproject website was constructed to make the trend results available to other project scientists. Our Minnesota Lake Trends website:

Minnesota Lake Trends Analyses website: ***http://mnbeaches.org/gmap/trends***

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). Detailed metadata were also created for the website and are included below.

The data are also incorporated into the larger project database that is now being used for more detailed examinations of geographic patterns, size and depth patterns, and associations with fish, macrophyte, weather, and ice cover data.

D. Results

1). Trend analyses: All statistical information is indexed at http://mnbeaches.org/gmap/trends/results/avg/index.html via a table with hyperlinks to specific statistical analyses (Figure 1). "Seasons" define how the data are averaged. For example, a one (1) season analysis computes the median of all data for a particular interval during the year, such as a single month, two months, or the generalized ice-free growing season (May 1 – Oct15). These analyses weight all data equally, even if there is a bias towards one period within the specified interval. In order to account for this potential bias, several additional "seasons" were defined, in particular the 3-"season" summer field season period that groups data into one month "seasons" from Jun15 - Jul15, Jul16 - Aug15, and Aug16 - Sep15, that collectively encompass the MPCA's historically defined Jun15 - Sep15 field season. Additional analyses were performed based on a standard 4-season year and a 12-month year, but we focused our initial conclusions on the results from the 3 season statistical analyses. In fact, because most data were collected during the period June through September, and distributed relatively uniformly in summer when multiple surveys were performed on a lake, the results from the 3-season analyses did not differ much from the 1-season Jun-Aug, 1-season Jun-Sep, or 1-season May-Oct15 interval results.

Figure 1. **MN Lake Trends - Seasonal Kendall Results**

These results were calculated by first averaging the results for each layer by day, then averaging those results for each time period (season).

Go to Metadata for details.

# of seasons per year	Season definition	≥ 5 yrs data & $p \leq 0.1$	≥ 5 yrs data & $p \leq 0.05$	≥ 8 yrs data & $p \leq 0.05$	≥ 12 yrs data & $p \leq 0.05$	≥ 18 yrs data & $p \leq 0.05$	≥ 8 yrs data & $p \leq 0.01$	≥ 12 yrs data & $p \leq 0.01$
12	Monthly	-X-	-X-	-X-	-X-	-X-	-X-	-X-
4	JanFebMar, AprMayJun, JulAugSep, OctNovDec	-X-	-X-	-X-	-X-	-X-	-X-	-X-
3	Jun15 - Jul15, Jul16 - Aug15, Aug16 - Sep15	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	May01 - Oct15	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	Jun15 - Sep15	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	Jun - Jul - Aug	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	Jun - Jul - Aug - Sep	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	May - Jun	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	Jun - Jul	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	Jul - Aug	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	Aug - Sep	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	April	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	May	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	June	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	July	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	August	-X-	-X-	-X-	-X-	-X-	-X-	-X-
1	September	-X-	-X-	-X-	-X-	-X-	-X-	-X-

- return to index -

This page was updated: 29-Jul-2009

Exemplary results for temperature are show in Figure 2 for the 3-season summer analysis where the criteria for a statistically significant trend required at least 5 years of data for the particular parameter of interest, and a significance level of 5% (i.e. $p \leq 0.05$). The row highlighted in the

Figure 2.

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MN Lake Trends

Seasonal Kendall Trend Analysis
3Periods_Jun15_thru_Sep15 Summary (3 seasons/year)

The statistics for each layer were calculated using the average of the daily averages of the result values within each time period.

Temperature, water

Qualifying sites: Sites with records from at least 5 different years and with p ≤ 0.05

[Download the complete results (csv)]

Summary type (averaged values)	Characteristic	Layer	[A] # of Sites with data	[B] # of sites with data from at least 5 different years	Sites with significant trends (p ≤ 0.05) & data from at least 5 different years			Trend direction				Map	List
					[C] Count	% of A	% of B	Count: Negative trend count	Count: Positive trend count	% of C: Negative trend percent	% of C: Positive trend percent		
3Periods_Jun15_thru_Sep15	Temp_H2O	00-00m	543	218	30	5.5%	13.8%	1	29	3%	97%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	00-02m	551	247	65	11.8%	26.3%	5	60	8%	92%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	03-05m	524	187	35	6.7%	18.7%	10	25	29%	71%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	06-08m	444	155	34	7.7%	21.9%	25	9	74%	26%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	09-11m	374	119	25	6.7%	21.0%	19	6	76%	24%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	12-14m	283	81	20	7.1%	24.7%	15	5	75%	25%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	15-19m	203	52	9	4.4%	17.3%	7	2	78%	22%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	20-24m	127	27	8	6.3%	29.6%	7	1	88%	13%	map	list
3Periods_Jun15_thru_Sep15	Temp_H2O	25-29m	67	8	1	1.5%	12.5%	1	0	100%	0%	map	list

red box shows summary trends data for these criteria for near surface temperature (the 0-2 m depth stratum). There were 551 lakes that had data for this stratum, of which 247 had at least 5 different years with data. Sixty-five (65) had a significant trend (26% of the 247 *qualifying* sites) and 92% of these showed a positive, i.e. warming trend. Clicking on the hyperlink **list** at the end of the row opens up a table listing all of the lakes by MDNR DOW #, shown in red if the trend was positive and blue if negative (see Figure 3) and grouped based on how many years of data each had (through 2007). The **map** hyperlink provides the *Googlemap*™ based geographic distribution of the lakes with significant trends, and if desired, of the entire set of lakes with data (Figure 4). Overlays of counties, MPCA Ecoregions and MDNR Ecoprovinces are also available. Markers denoting individual lakes are coded to indicate the sign, magnitude (%-ile), and level of statistical significance of the trend. Individual lake trends are shown as box and whiskers plots that show the data color coded and shown for each "season" according to the specific seasonal Kendall analysis, along with trend slope and its significance (Figure 5). Further description of the analysis outputs are found in the website METADATA below.

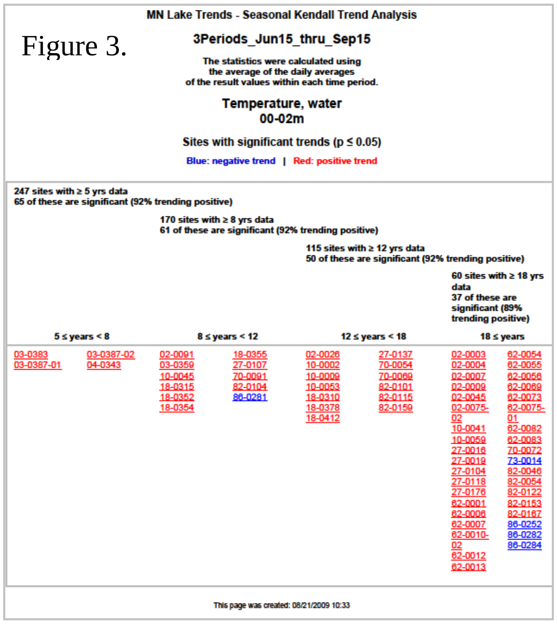

Figure 3.

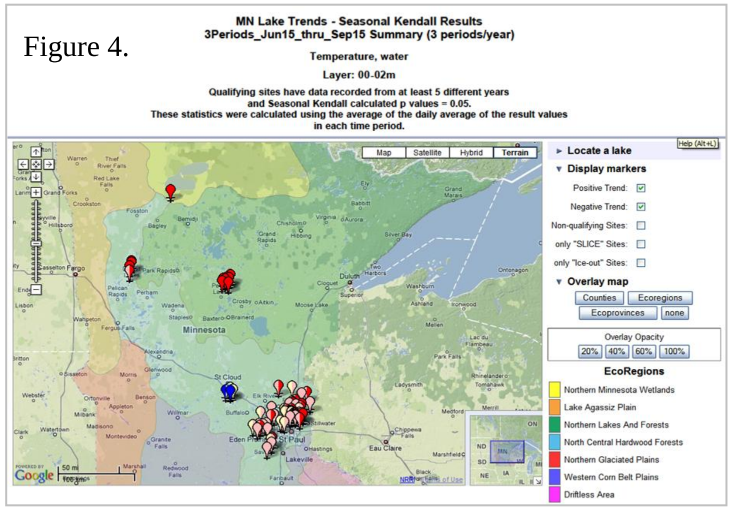

Figure 4.

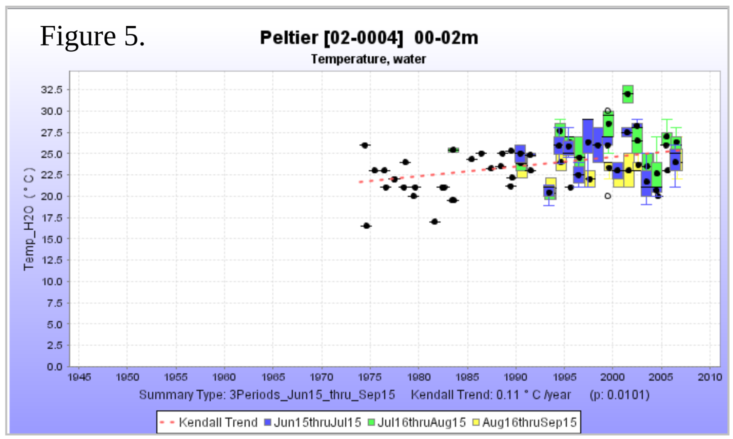

Figure 5.

2). <u>Comparison with MPCA Citizen's Lake Monitoring Program (CLMP) trends analyses</u>: This comparison was of immediate interest because the MPCA has been performing trend analyses for lakes with more than about 8-10 years of volunteer secchi data. The statistical basis for these analyses are apparently now being reviewed but it appears that MPCA has been using a similar type of Kendall analysis (details are currently unavailable). MPCA staff provided a spreadsheet summarizing the results of their trend calculations based on the average of the secchi readings taken each year between June 1 and September 30. Therefore, we compared our results with these for the identical time period as a "single season" in the sense of the Seasonal Kendall test software (see METHODS).

We initially examined sites that had the largest discrepancy between our calculated trends and theirs. We discovered that 7 of these sites had Secchi data that was improperly entered in STORET. Some of the readings were recorded in feet, but the units were entered as meters. MPCA had apparently caught these errors, and corrected them for their calculations and on their website where these data are posted (http://www.pca.state.mn.us/water/clmp/clmpSearch.cfm), but the corrections had not filtered back to STORET. These entries were corrected in our dataset and the trends were recalculated. This resulted in 274 sites showing significant trend results ($p \leq 0.1$) with 268 reported to show statistically trends by MPCA (% agreement, Figure 6).

Figure 7 displays the magnitude of the trend rate difference between the two analyses across all sites. All but 5 of the MPCA results were within 0.05 m/yr of the NRRI results and >90% were within 0.02 m/yr. These differences did not seem to be due to differences in the way annual means were computed since there was close agreement between NRRI annual means and those posted on the MPCA website- usually within 0.1 m for each year's average result which is approximately the method detection limit for volunteer secchi data. There were however, some differences in the methodology NRRI used to calculate the annual averages compared to MPCA. NRRI averaged all of the results for a site that were taken on the same day (i.e. from different stations) and then averaged all of these averages for the entire season. Most sites only have one reading for a given day, but there are some that have more than one. For example, site #29-0146 (the right-most data point in Figure 7) has 4-5 records in STORET for that StationID on some days, with different ActivityIDs and although NRRI averaged them all together for that day, MPCA seems to have only considered records with certain ActivityIDs, presumably using local information as a basis for their data editing. Three of the five sites with the largest discrepancy had identical data posted to what we used in our calculations. The differences seem to be explainable by the fact that MPCA did not use data from all of the years posted on their website when doing their trend calculations. For example, site #31-0424 has data posted from 13 years, but MPCA's summary spreadsheet indicates that only 8 were used in the calculation and unfortunately there are no notes explaining why this was done.

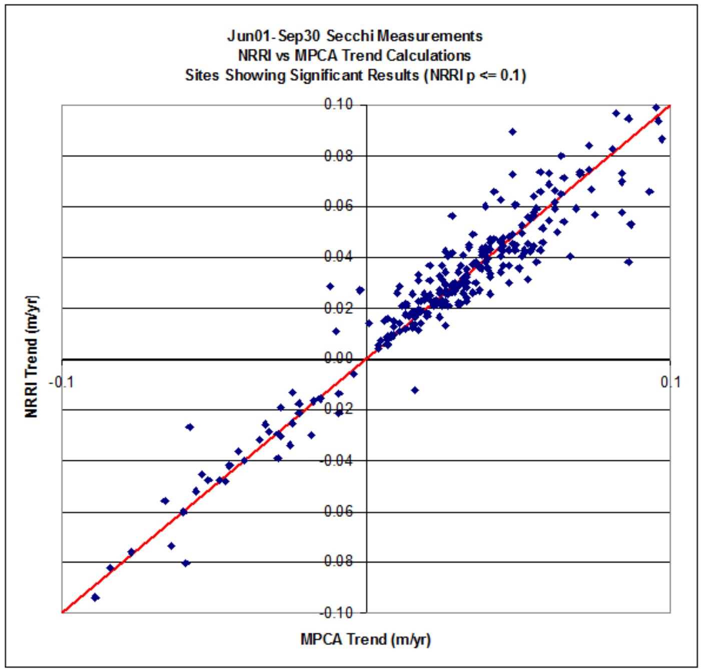

Figure 6. Comparison of Kendall analysis trend rates between NRRI (this study) and MPCA (CLMP, unpublished) for 274 lake sites selected on the basis of having at least 15 years of "some" data (see METHODS). Red line denotes 1:1 correspondence.

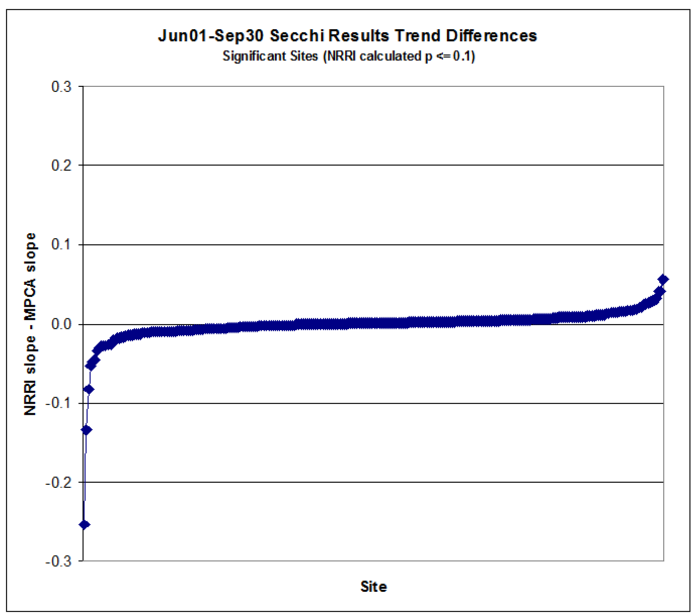

Figure 7. Magnitude of difference between NRRI and MPCA calculated trend rate for sites with ≥ 15 years of data.

Site #21-0106-01 shows the largest difference (-0.25 m/yr), even though the data used as input to the NRRI Kendall trend calculation is the same as what is shown on the MPCA website and so some of the data from the MPCA's EDA website suffers from the same unit-conversion errors mentioned above. MPCA seems to have corrected the data for their trend calculations, but not in the EDA database, so the discrepancy wasn't caught when we did our site by site comparisons. Figure 8 shows a plot of NRRI results, showing the effect of the erroneous values.

Although there are likely other uncaught errors, the close agreement between the two independent analyses is taken to be supportive of our approach to identifying the overall trends in Minnesota lakes.

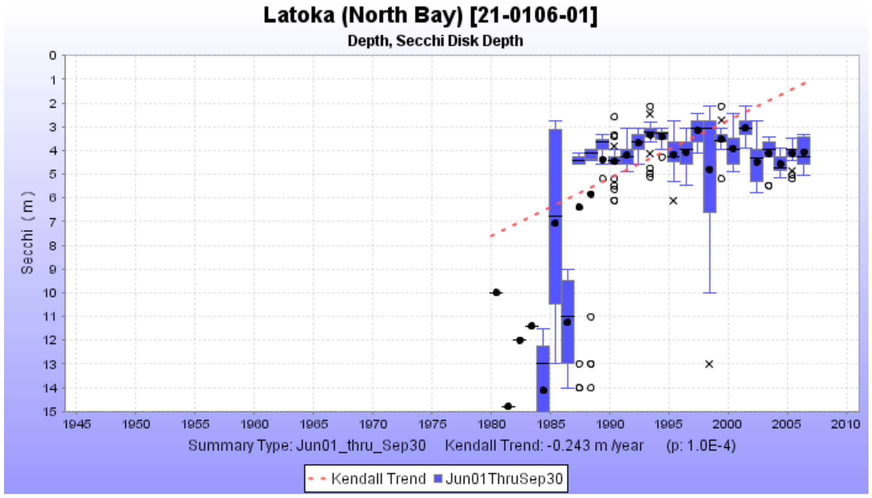

Figure 8. Secchi depth trend for site 21-0106-01 illustrating the effect of feet-to-meter conversion error the early years of the data record.

Discovering significant errors in the EDA and STORET databases almost exclusively due to *feet-to-meter* mis-conversions led us to conduct an extensive computerized and manual (visual) re-screening to identify and correct other secchi errors as well as for temperature, where we found additional unit errors from the *Fahrenheit-to-Celsius* conversion. All errors discovered as part of this project will be reported to MPCA for complete correction in the EDA and STORET databases.

3). A second confirmation of the web-reported trends was performed using the Mann-Kendall (MK) function in R from the Kendall software package written and maintained by McLeod (2005). The analysis was recreated from the NRRI website data summaries for near-surface temperature (0-2m), secchi depth, thermocline depth, TSI-Secchi, near-surface chlorophyll-*a* concentration (0-2m), and near-surface total phosphorus concentration (0-2m). Values for each parameter were averaged for the Jun15-Sep15 season (i.e. comparable to the 1-season analysis in Figure 1) and then the means for each lake and year were entered into the MK function as a vector. Table 1 compares the percent of lakes that showed a trend at a 5% level of significance for the different software analyses and indicates excellent agreement.

Table 1. Comparison of Helsel (2006; USGS) and McLeod (2005) trend analyses. Values indicate the percentage of lakes with at least 5 years of "some" data that showed a statistically significant trend at $p \leq 0.05$. RPD = relative percent difference.

	Helsel (2006)	McLeod (2005)	RPD
Secchi depth	32.3	32.1	0.6 %
Total Phosphorus	20.2	19.9	1.5 %
Chlorophyll-*a*	10.4	11.0	5.6 %
TSI-Secchi	31.3	31.2	0.3 %
Thermocline depth	10.3	9.6	7.0 %
Surface temperature	7.3	7.2	1.4 %

4). Summary of exploratory trend analyses (provisional observations, August 2009)

In the context of the climate change issue that spawned the present study, the most important result derived from the exploratory trend analyses has been that for lakes with significant time trends during the period June – September, more than 90% showed surface water warming as compared to cooling (Figure 9). 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 lakes with 18 years or more data. For the 37 lakes that showed statistically significant warming over their period of record, the mean trend was 0.080 $\pm$ ^{o}C/yr. This would project to an average increase of 0.8 ^{o}C (1.4 ^{o}F) in 10 years, and 3.3 ^{o}C (5.9 ^{o}F) by 2050.

Another important effect predicted from models of the thermal characteristics of lakes in response to climate change relates to the depth of the summer thermocline in deeper lakes and its thermal stability (i.e. resistance to wind mixing and destratification). Warmer growing season air temperatures have generally been predicted to decrease the depth of the thermocline (i.e. creating a shallower epilimnion) in most lakes as a consequence of increased warming of the epilimnion and increased thermal stability. The period of stable stratification is also predicted to begin earlier due to earlier ice-out and persist longer into the fall (e.g. Kling et al. 2003; Fang and Stefan 1999; Schindler et al. 1996). Both empirical and theoretical (i.e., modeling) studies have qualified these predictions because of the variability introduced by the uncertainty of wind velocities, site specific morphometry, and the potential effects of water color changes and light penetration due to changes in dissolved organic matter (DOM) loading and the effect of DOM on light absorption (i.e. heat storage) with depth (Parker et al. 2007; Fang and Stefan 1999).

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 (Figure 9). 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 (Figure 9). Together, these thermal effects over time suggest a shallower, but more stable depth of stratification, which is consistent with surface warming. The data also suggest that in those lakes, the hypolimnion could be more isolated from mixing of epilimnetic water although the population of lakes with such trends is relatively small. Trends in hypolimnetic water for depth strata below a depth of 6 meters, showed the opposite effect with about 20% of the lakes having at least 5 years of temperature profile data having statistically significant trends and more than 75% of those being negative (cooling)(data not shown but see http://mnbeaches.org/gmap/trends/results/avg/3Periods_Jun15_thru_Sep15Summary_5yrs-005p.html). 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. Both patterns, warming epilimnia and cooling hypolimnia when trends were found, were consistent across the many exploratory analyses that were performed for the period June through September, whether data were pooled for two or three months or examined for individual months (see http://mnbeaches.org/gmap/trends/results/avg/index.html)

The duration of thermal stratification was not investigated for this study and it is presumed that most of the lake data sets lack enough surveys during the ice-free season to assess potential trends in this important parameter. However, there may be some lakes with frequent enough summer sampling for enough years to warrant closer examination.

Trend results were less clear for dissolved oxygen (DO). The number of positive versus negative trends in surface waters was approximately similar although 60-75% showed increasing DO in the lakes with 12 to more than 18 yrs of data – an anomalous finding since one might have expected slightly decreasing DO due to warmer water (Figure 9). However, hypolimnetic strata for >20% of the lakes with available data showed significant trends with a clear (>75%) preponderance of increased DO.

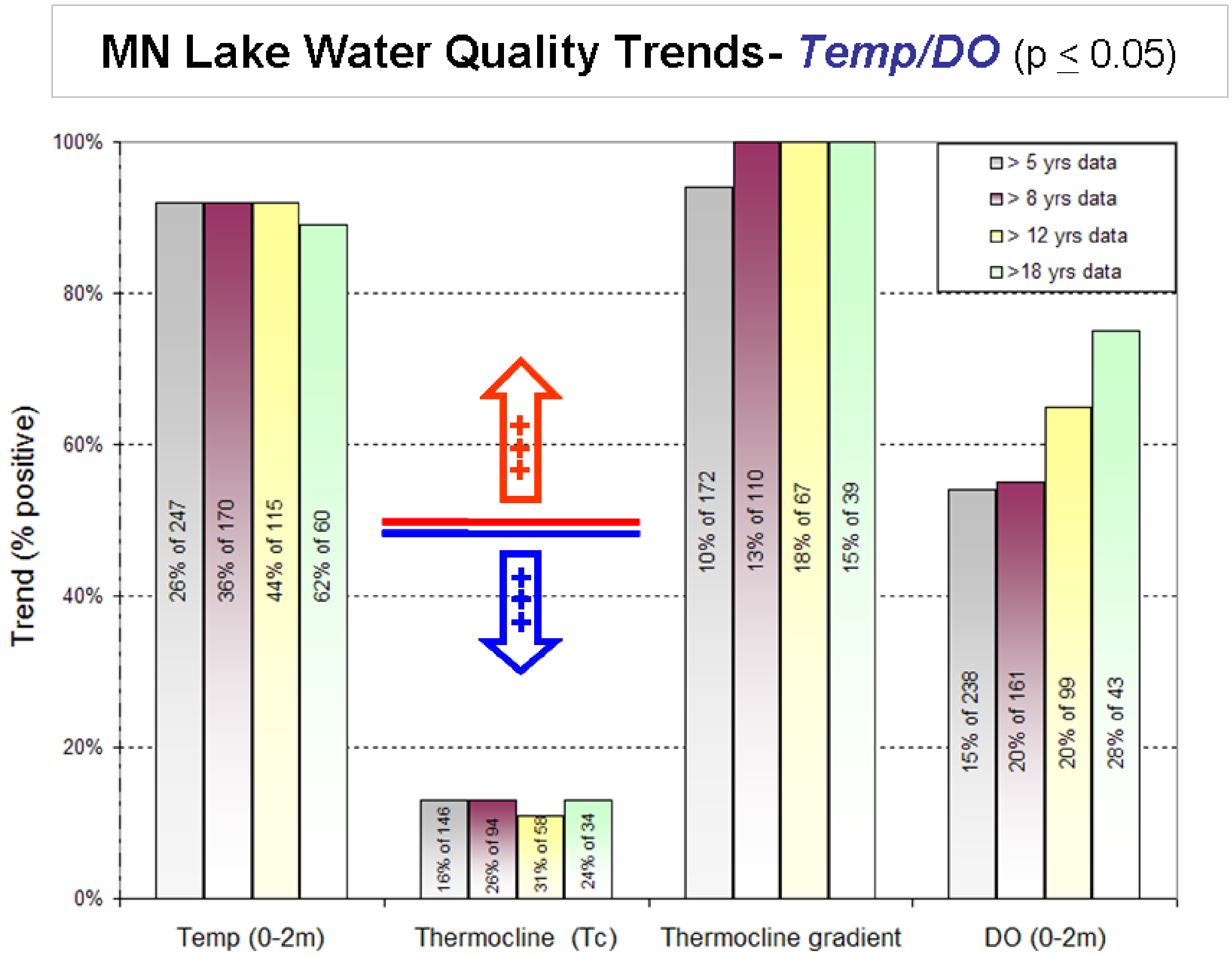

Figure 9. Summary of temperature and dissolved oxygen related trends for Minnesota lakes having at least 15 years of at least one water quality parameter. Bars indicate the percentage of statistically significant trends at $p \leq 0.05$ that were positive for sites with a given number of years of data. Bar colors denote the length of the parameter records; numbers inside the bars indicate the percentage of those sites that were statistically significant. A Trend value of 50% indicates equal likelihood of the significant trend being + or – This is show by the red (positive) and blue (negative) arrows.

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 (Figure 10). 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.

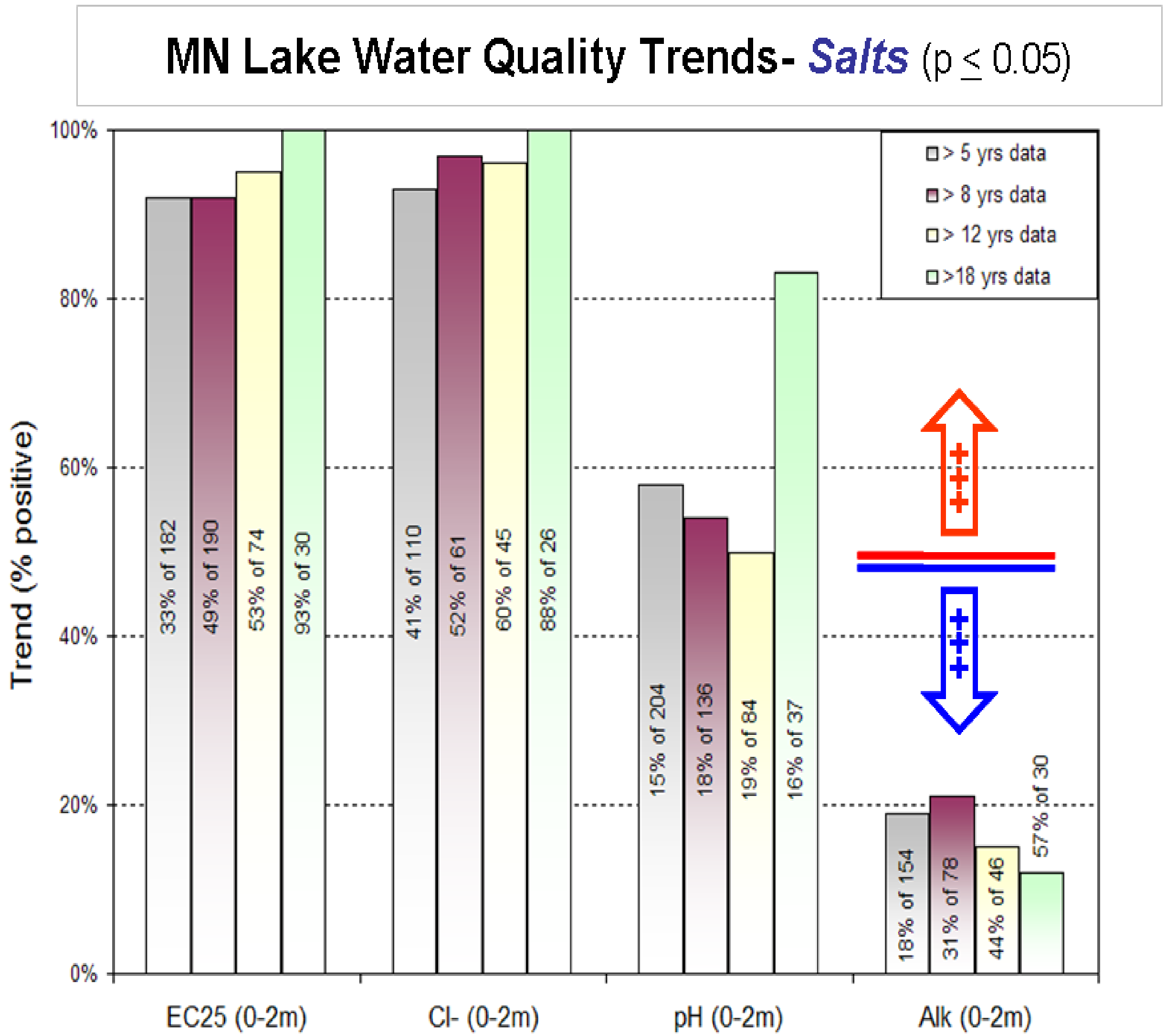

Figure 10. Summary of specific electrical conductivity (EC25), chloride concentration, pH and alkalinity trends for Minnesota lakes having at least 15 years of at least one water quality parameter. Bars indicate the percentage of statistically significant trends at $p \leq 0.05$ that were positive for sites with a given number of years of data. Bar colors denote the length of the parameter records; numbers inside the bars indicate the percentage of those sites that were statistically significant. A trend value of 50% indicates equal likelihood of the significant trend being + or – This is show by the red (positive) and blue (negative) arrows.

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.

The Minnesota Lake Trends website also summarizes exploratory trend analyses for the major ions calcium, magnesium, potassium, sodium, and sulfate, hardness, color and dissolved organic carbon (see http://mnbeaches.org/gmap/trends/results/avg/3Periods_Jun15_thru_Sep15Summary_5yrs-005p.html for the 3-season period Jun15-Sep15). Most of these analyses either lack enough years of data to test for trends, or the number of statistically significant trends that were found were few enough that we are not confident in drawing even provisional conclusions at present.

Perhaps the most surprising result found in this study was that there was internal consistency within the group of trophic status indicators (secchi depth clarity, chlorophyll-a, total phosphorus and total Kjeldahl nitrogen) that suggests a strong overall improvement in water quality (Figure 11). 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 (Table 1) and also by cross-comparing our secchi trend rates with MPCA's estimates for CLMP lakes with more than 15 years of data (Figures 6 and 7). In both cases, the differences in results were negligible.

Additional analyses were performed on other nutrient fractions, including ammonium-, nitrate+nitrite-N, nitrate-N, nitrite-N, total Kjeldahl-N (TKN), and ortho-phosphorus. Ammonium-N, TKN and ortho-phosphorus also exhibited a predominance of negative relative to positive trends although there were fewer overall data. The other nutrient fraction data sets were inconclusive because of even fewer data (see http://mnbeaches.org/gmap/trends/results/avg/3Periods_Jun15_thru_Sep15Summary_5yrs-005p.html). Analyses of Carlson TSI's similarly indicated that about 80% of the lakes with > 5 years of data that had significant trends had shown improvement (data not show but available at http://mnbeaches.org/gmap/trends/results/avg/3Periods_Jun15_thru_Sep15Summary_5yrs-005p.html).

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.

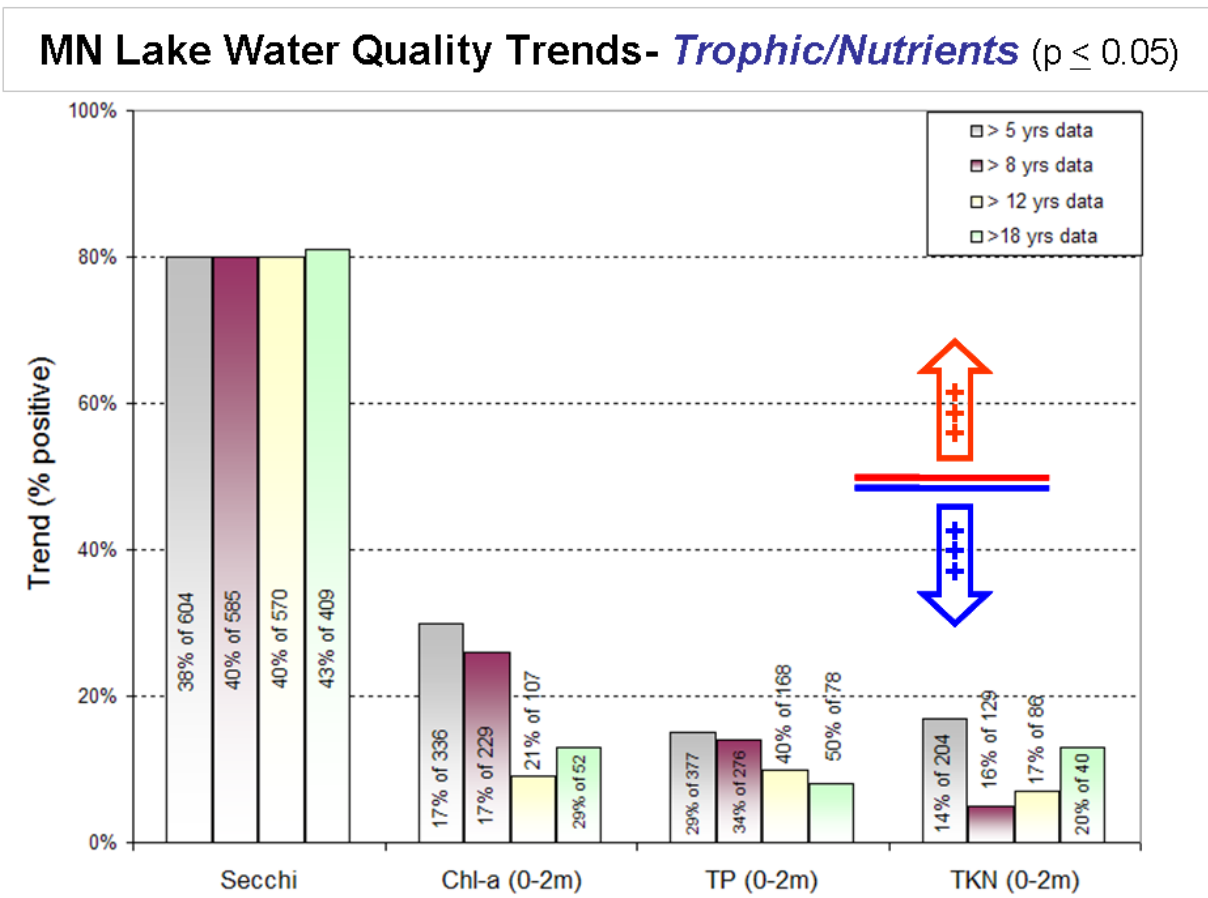

Figure 11. Summary of temperature and dissolved oxygen related trends for Minnesota lakes having at least 15 years of at least one water quality parameter. Bars indicate the percentage of statistically significant trends at $p \leq 0.05$ that were positive for sites with a given number of years of data. Bar colors denote the length of the parameter records; numbers inside the bars indicate the percentage of those sites that were statistically significant. A trend value of 50% indicates equal likelihood of the significant trend being + or – This is show by the red (positive) and blue (negative) arrows

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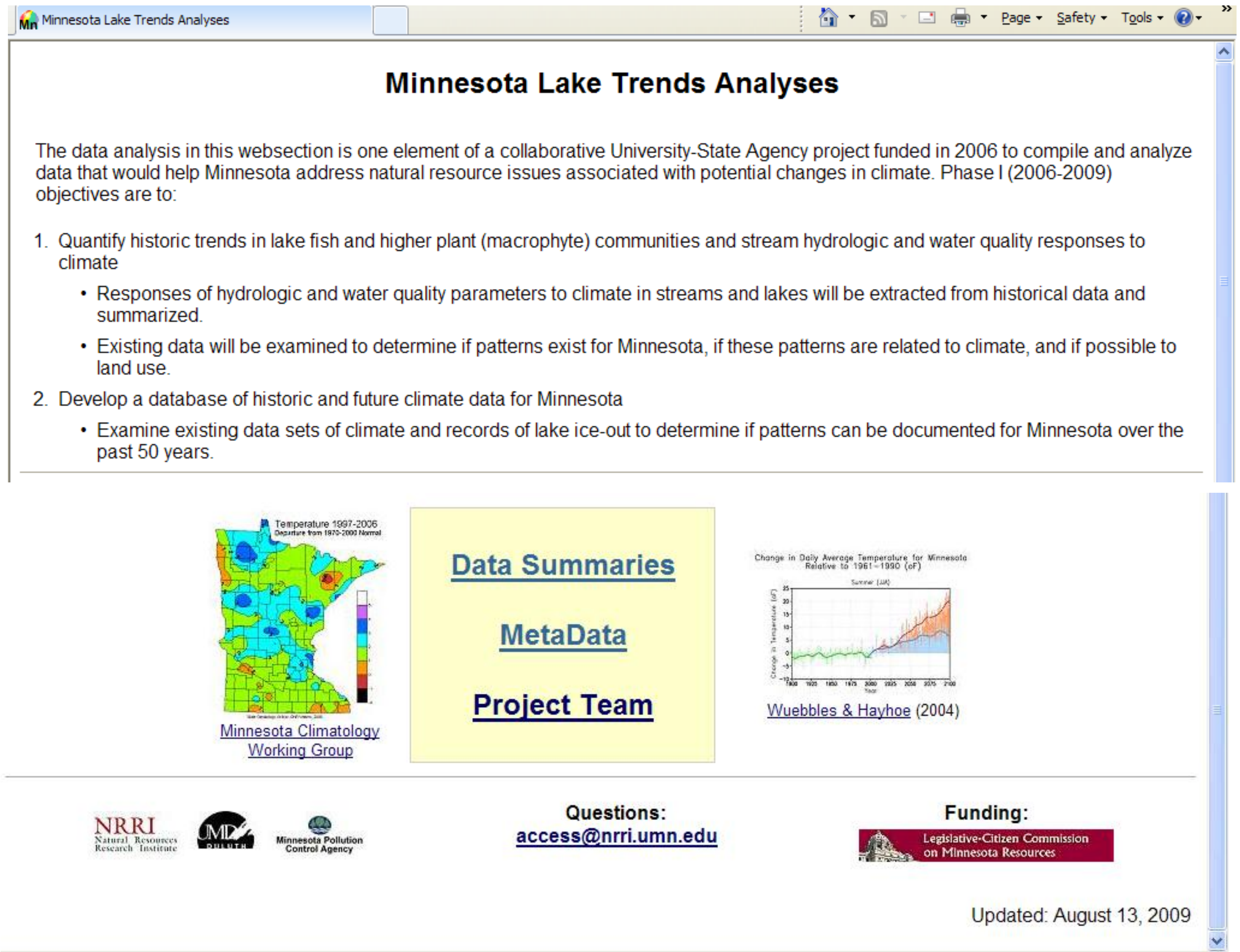
Attachment: Minnesota Lake Trends website home page and metadata:

: ***http://mnbeaches.org/gmap/trends***



Minnesota Lake Trends Analyses

Minnesota Lake Trends Analyses

The data analysis in this websection is one element of a collaborative University-State Agency project funded in 2006 to compile and analyze data that would help Minnesota address natural resource issues associated with potential changes in climate. Phase I (2006-2009) objectives are to:

1. Quantify historic trends in lake fish and higher plant (macrophyte) communities and stream hydrologic and water quality responses to climate
   - Responses of hydrologic and water quality parameters to climate in streams and lakes will be extracted from historical data and summarized.
   - Existing data will be examined to determine if patterns exist for Minnesota, if these patterns are related to climate, and if possible to land use.
2. Develop a database of historic and future climate data for Minnesota
   - Examine existing data sets of climate and records of lake ice-out to determine if patterns can be documented for Minnesota over the past 50 years.

Temperature 1997-2006
Departure from 1970-2000 Normal

Minnesota Climatology Working Group

Data Summaries

MetaData

Project Team

Change in Daily Average Temperature for Minnesota Relative to 1961–1990 (oF)

Wuebbles & Hayhoe (2004)

NRRI Natural Resources Research Institute

UMD Duluth

Minnesota Pollution Control Agency

Questions:
access@nrri.umn.edu

Funding:
Legislative-Citizen Commission on Minnesota Resources

Updated: August 13, 2009

Minnesota Lake Trends - Metadata

Page updated: Aug 13, 2009

I. Data sources

- STORET via MPCA retrieval
- Water quality data from lakes with >15 years of at least one water quality parameter to perform exploratory trend analyses on all available parameters
- Status (8/31/09): 638 Minnesota lakes having more than 15 years of at least "some" water quality data totaling 1.9 million data records.
- MPCA data is "current" through 2007
- Met Council data is "current" through 2006
-

II. Data screening

- Already screened for basic QA/QC via STORET data entry rules
- Further "visual, but non-systematic" scanning for errors, outliers, and anomalies
- After comparing NRRI trend analyses of secchi records with Minnesota Pollution Control Agency (MPCA) trends calculated for their Citizen Lake Monitoring Program (CLMP) on a lake-by-lake basis, a number of STORET errors were discovered. These had been previously corrected for the CLMP analysis, but not corrected in STORET. Errors were largely associated with the feet-to-meters conversion. Therefore, the entire MN Lake Trends data set was screened and corrected as needed. A similarly small but significant set of lakes also had Fahrenheit to Celsius conversion errors.

III. Data censoring rules

- For incorporating data listed as below detection into the database and this is particularly important for low nutrient lakes.
- There were two possibilities in the raw dataset -- "*Non-detect" and "*Present <QL", where QL is the Quantitation Limit:
    1. If the record contains a value for "MinDetectLimit": use MinDetectLimit/2 (one-half the specified detection limit). This technique has been widely used for decades and there is still no "accepted" guidelines for censoring below-detection data (e.g. EPA. 2004. Revised Assessment of Detection and Quantitation Approaches. EPA-821-B-04-005. October 2004. Office of Science and Technology, Office of Water (4303T), U.S. Environmental Protection Agency, Washington, DC 20460 (www.epa.gov/waterscience/methods/det/rad.pdf; Helsel, D. 2005. More

Than Obvious: Better methods for interpreting non-detect data. Environ. Sci. Technol., 2005, 39 (20), pp 419A–423A.).

2. If the record contains a value for "MinQuantLimit": use MinQuantLimit/6.6 based on the approximation that MDL ~ 3*SD and QL ~ 10*SD where SD is the Standard Deviation for a set of replicate water samples in the lower concentration range of interest (cf. EPA. 2004 above)
3. Otherwise skip the record "for now (7/14/09)"; we intend to examine this dataset more closely to see how important these deletions are to the results of the nutrient trends analyses if continued funding becomes available.

IV. Parameter groups

- ***Core Suite*** - field sensor parameters that typically determine a meter-by-meter depth profile of temperature, dissolved oxygen (and a calculated percentage oxygen saturation), specific electrical conductivity (EC25, that estimates total salt/ion concentrations), and pH; and water clarity estimated by Secchi disk depth.
- ***Advanced Suite*** - most of the other "routine" water quality variables such as chlorophyll-a, nutrients (TN [measured and calculated], TKN, [nitrate+nitrite]-N, ammonium-N, TP, ortho-P), dissolved and/or total organic carbon and/or color, SiO2, Hardness, major anions (ANC/alkalinity, SO4, Cl) and major cations (Ca, Mg, Na, K).
- We think this is a useful classification since there will be many more *Core* than Advanced Suite data available for Minnesota lakes and streams. This nomenclature was borrowed from the *Vital Signs* long-term monitoring program of the U.S. National Park Service.
- ***Calculated Indicators*** —

1. Carlson Trophic State Index (TSI) as individual TSI-secchi, TSI-TP, TSI-Chlorophyll-a; Mean-TSI (= [TSI-P + TSI-C + TSI-S]/3).
   - TSIs calculated for data collected only during the period May 1 - Oct 15;
   - if there is a 0-2m value, use it, otherwise use the value from the shallowest reading if it's < 5m, otherwise do not calculate the TSI;
   - any records for Secchi, Chlor, or TP that had result values of “0” were ignored because they would cause the TSI formulas to *explode* due to the log function. These records were probably data entry errors, obviously for Secchi depth.
   - The TSI values are calculated as show below (from MPCA;
   - *www.pca.state.mn.us/water/basins/305blake.html ; Carlson 1977*)

Secchi disk (SD): TSI (TSIS) = 60 - [14.41(natural log)(Secchi average)]

Total phosphorus (TP): TSI (TSIP) = [14.42 (natural log)(TP average)] + 4.15

Chlorophyll-a (chl-a): TSI (TSIC) = [9.81(natural log)(chl-a average)] + 30.6

(TP and chl-a in micrograms per liter (ug/L) and SD transparency in meters).

The index ranges from 0 to 100 with higher values indicating more eutrophic conditions. The TSI values were calculated for each variable, then averaged for each lake (Figure 1). Although *Mean TSI* values were calculated, they must be used with caution since this analysis assumes that water clarity is controlled by algal biomass, which is in turn controlled by available phosphorus as estimated by TP. TSIS, TSIP, and TSIC might be expected to diverge in lakes that are turbid due to high loads of suspended or re-suspended sediment, or when algal biomass is regulated by another factor such as nitrogen availability or grazing by invertebrates.

Figure 1. Carlson's Trophic State Index (TSI)

TSI <30	Classic Oligotrophy; Clear water, oxygen through the year in the hypolimnion, salmonid fisheries in deep lakes.
TSI 30-40	Deeper lakes still exhibit classical oligotraphy, but some shallower lakes will become anoxic in the hypolimnion during the summer.
TS 40-50	Water moderately clear, but increasing probability of anoxia in hypolimnion during summer.
TS 50-60	Lower boundary of classical eutrophy: Decreased transparency, anoxic hypolimnion during the summer, macrophyte problems evident, warm-water fisheries only.
TSI 60-70	Dominance of blue-green algae, algal scums probable, extensive macrophyte problems.
TSI 70-80	Heavy algal blooms possible throughout the summer, dense macrophyte beds, but extent limited by light penetration. Often would be classified as hypereutrophic.
TSI > 80	Algal scums, summer fish kills, few macrophytes, dominance of rough fish.

2. Actual thermocline depth – calculated directly from temperature profiles as the depth of the maximum temperature gradient provided it is > 1°C /meter for each site with a H2O Temp dataset.

For each profile in the dataset:

- combine any adjacent readings that are within 0.25 m into a single reading consisting of the averaged depths and temperatures

- calculate dtdz between adjacent readings in the profile,
- determine which is the maximum dtdz,
- ignore and move on to the next profile if dtdz_max is < 0.7 °C /m,
- otherwise:
    - create a record in the Thermocline_Rate dataset for the site,
    - set the upperDepth & lowerDepth variables to the depths of the 2 adjacent readings that gave dtdz_max,
    - if the dtdz for the previous (shallower) reading pair is within 0.05 of dtdz_max use its upper depth for upperDepth,
    - if the dtdz for the next (deeper) reading pair is within 0.05 of dtdz_max use its lower depth for lowerDepth,
    - calculate the thermocline depth = (lowerDepth + upperDepth) /2,
    - create a record in the ThermoclineDepth(rate $\geq$ 0.7 °C /m) dataset for the site,
    - if dtdz_max is >= 1.0 °C /m create a record in the ThermoclineDepth (rate $\geq$ 1.0 ^{o}C/m) dataset for the site

3. Predicted thermocline depth (to be done)– estimated based on lake morphometry from the equation developed in: Gorham, E. and F.M. Boyce, 1989. Influence of lake surface area and depth upon thermal stratification and the depth of the summer thermocline. Journal of Great Lakes Research, 15(2): 233-245.

V. Depth strata

- After data were manually reorganized and sorted into spreadsheets, a computer program was developed to automate the computation of depth stratum mean values, tabulation of data summaries, graphical presentation, and export to trend analysis software. Each parameter from each site was averaged for all sampling dates and sampling periods for the following depth strata; 0m (surface values), 0-2m, 3-5m, 6-8m, 9-11m, 12-14m, 15-19m, 20-24m, 25-29m, 30-34m, 35-39m, 40-49m, 50-59m, 60-69m, 70-79m, 80plus. Strata were chosen for limnological reasons as well as based on data availability for the deeper strata. The statistics for each layer were calculated using the average of the daily averages of the result values within each time period.

VI.Time intervals

- Since there are many periods of interest for these data, we performed trend analyses for a variety of periods that could be used to characterize a particular year. For example, the MPCA has long requested Citizen Lake Monitoring Program (CLMP) volunteers who have collected most of Minnesota's long-term Secchi disk water clarity data to take their measurements from June 15 – September 15. Therefore, all data within this time frame can be averaged to generate a single value for a particular year.

- Alternatively, a set of monthly or bimonthly mean values can be calculated and then analyzed singly for the year, or considering their within-year variation. A monthly average for August, when algal biomass is usually thought to be at its peak, would be useful to examine in comparison to weather patterns either at that time or perhaps over a longer period to include the contribution of spring runoff to the lake's nutrient loading.

- The statistical analysis software described below also permits the user to select a single period to characterize a year (e.g. the mean of data from the period Jun 15 – Sep 15 for each year), and also incorporate the variability from sub-periods within that period that are defined as "seasons". For example, each year can be characterized by its mean (or median) parameter value for the MPCA field season defined as all data from June 15 - September 15. Or, the variation from three separate month-long seasons from June15-July 15, July16 - August 15, and August 16 - September 15) can be identified and incorporated into the statistical analysis.

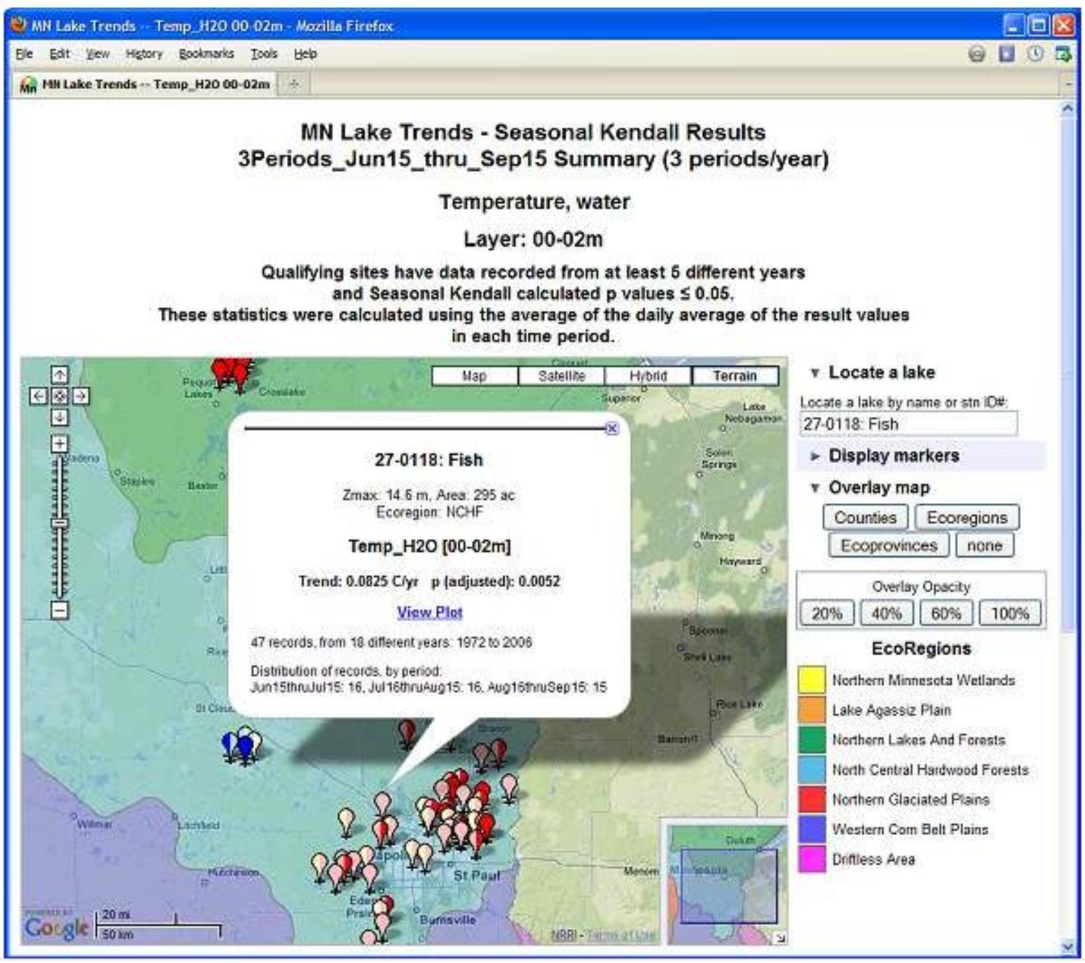
VII. Trend analyses

Trends and trend rates were determined using the Seasonal Kendall Trend Analysis software developed by the U.S. Geological survey (2005; Computer Program for the Kendall Family of Trend Tests, Dennis R. Helsel, David K. Mueller, and James R. Slack SIR 2005-5275, U.S. Geological Survey) that allow for trend analyses both seasonally and regionally. Sites were initially identified sites as "Qualifying" if they had records from at least 5 different years and with a level of significance of $p \leq 0.1$ for either a positive or negative trend over time. Additional exploratory trend summaries with accompanying mapping tools were generated for $p \leq 0.05$ and lakes having more years of data (8, 12 and ≥18 years).

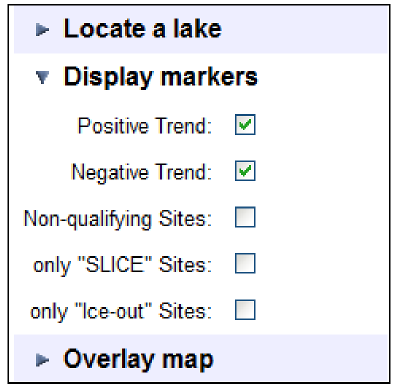
- Minnesota Lake Trends Analyses website*: http://mnbeaches.org/gmap/trends/*
- The USGS report “Computer Program for the Kendall Family of Trend Tests” and the computer program is available at *http://pubs.usgs.gov/sir/2005/5275/*

VIII. Graphical and tabular displays

- Data tabulated in *csv* format for easy import to spreadsheet and database software
- Data have been incorporated into "*Master*" NRRI-UMD Climate Change Database for association with other Project variables and use by other scientists
- Statewide distribution of lakes with statistically significant trends (e.g. p < 0.1 with >5 years of data) are denoted as tear drop shaped markers on a zoomable and scrollable map of Minnesota. Red denotes an increasing trend and blue a decreasing trend with half-tones to show the magnitude of the gradient for each plot based on quartiles for that plot. Levels of significance are shown as "hash" marks across the bottom of the tear drop.

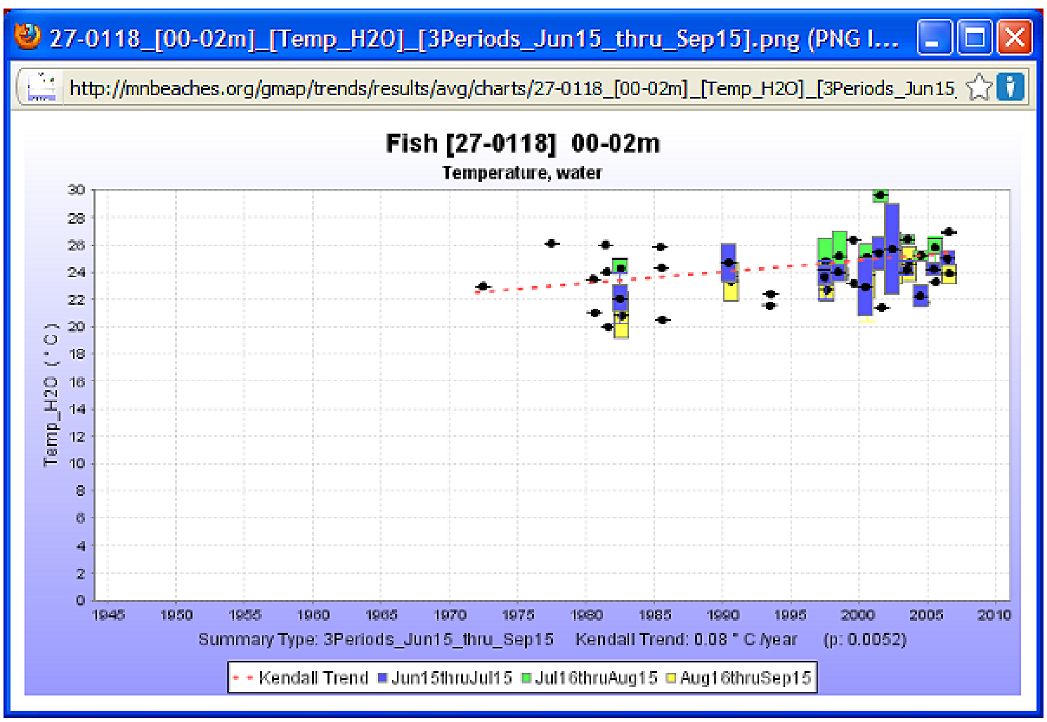


1. **Locate a Lake** is a search tool available for finding individual lakes by Lake Name or MDNR DOW #

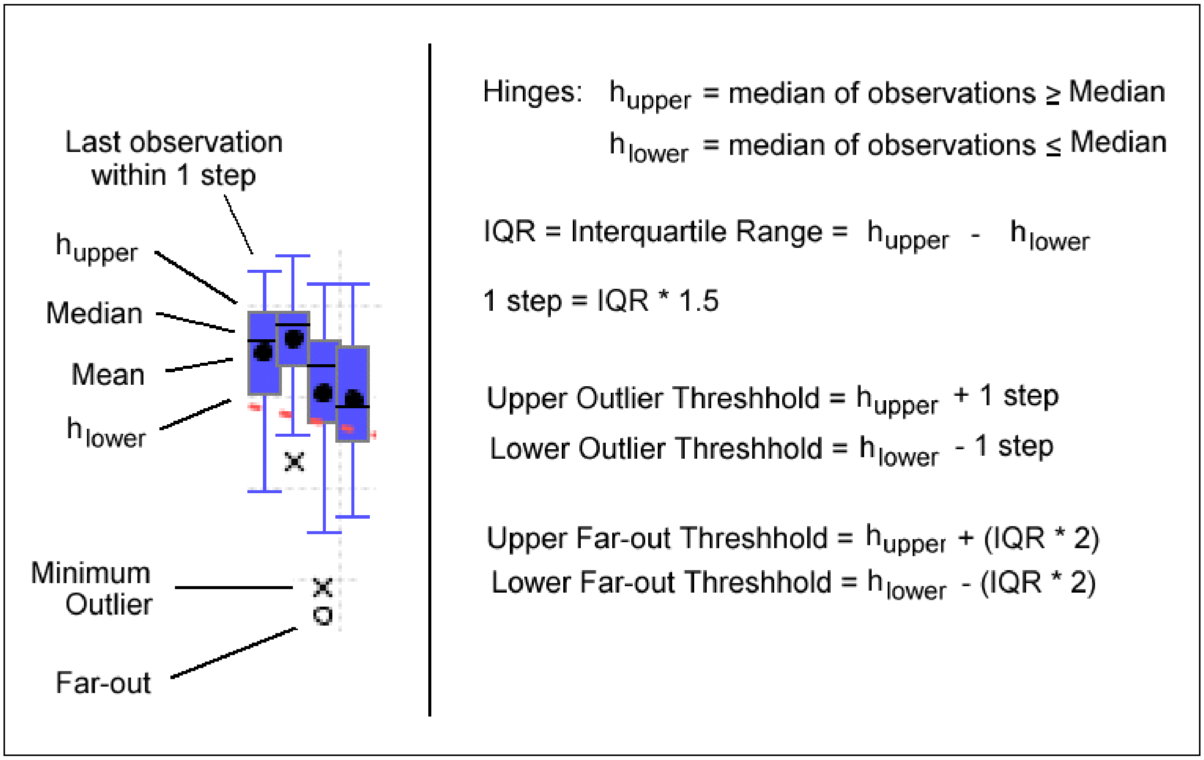


2. **Display Markers** offers choices for displaying markers on the map. Positive and negative trend sites were statistically significant; non-qualifying sites were not statistically significant or did not have data from enough years; "SLICE" sites refers to the 24 lakes from the MN DNR Sustaining Lakes in a Changing Environment (SLICE) project that includes a focus on monitoring basic watershed, water quality, habitat, and fish indicators in 24 sentinel lakes across a gradient of ecoregions, depths, and nutrient levels. "Ice-out" lakes refers to the set of lakes with long-term winter ice records that was compiled for the overarching U of MN Climate Change project.
3. **Overlay map** offers templates for county, ecoprovince and ecoregion boundaries. The data itself is classified in the main project database for these divisions but is not directly retrievable as such from the current MN Lake Water Quality Trends website.

- **Trend lines over time** are available by mouse clicking a particular lake on the map for a particular parameter x depth stratum x time period. This opens an information window with the lake name and MDNR DOW #, the trend slope and its significance, depth, area, ecoregion, and a link to open a box & whisker plot of the data and the calculated trend line:



- the data are color-coded and shown for each "season" according to the specific seasonal Kendall analysis.
- the box and whiskers depict the distributional characteristics of the independent measurements for that period are depicted as for that year



- return to the MN Lake Trends homepage -

Minnesota's Water Resources: Climate Change Impacts

Project Manager: Lucinda Johnson
Natural Resources Research Institute, U. of Minnesota-Duluth

- Co-Principal Investigators:
  - Richard Axler (NRRI/UMD)
  - Ray Newman, Heinz Stefan, Richard Skaggs, Katherine Klink (UM/TC)
  - Virginia Card (Metropolitan State University)
  - Patrick Welle (Bemidji State University)
- Agency Cooperators:
  - Edward Swain, Peter Ciborowski, Bruce Wilson (MPCA)
  - James Zandlo, David Wright, Kurt Rusterholz (MN DNR)
  - Clarence Turner (Forest Resources Council)
- Lake Water Quality Trends Subgroup (NRRI-UMD):
  - Rich Axler (subproject management, limnological review)
  - Jerry Henneck & Elaine Ruzycki (data acquisition, compilation, QA screening, interpretation)
  - Norman Will (trend analysis programming, graphing, summary and mapping; website development)
  - Jennifer Olker (database development)
  - Joe Swintek (statistical analyses)
  - MPCA cooperators: Nancy Flandrick & Jim Porter (providing source data)

- return to index -

Page updated: August 13, 2009

LCCMR Climate Change I & II
Mini-symposium
February 21, 2009 10 am – 5 pm
Natural Resources Research Institute, Duluth, MN

(Rm 435 #218-720-4241, L. Johnson #218-591-6598, J. Olker #218-428-0234)

Agenda

February 21 Saturday

10:00 Arrival at NRRI

10:00 – 10:15 Welcome and introductions

10:15 - 11:00 (Kenny Blumenfeld) Climate Tool tutorial

11:00 -11:10 (Dick Skaggs & Kenny Blumenfeld) Past & Future Climate

11:10 – 11:30 (Virginia Card) Ice-Out Records

11:30 - 12:00 (Ray Newman & Kristal Schneider) Fish Trends in Lakes with Long Records & Walleye Spawning Response to Ice-Out and Climate

12:00 – 12:45 BREAK (lunch)

12:45 – 1:30 (Heinz Stefan & Tim Erickson) Stream Flow Trends in Minnesota and Relationship to Climate & Lake Level and Lake Evaporation Response to Climate in Minnesota

1:30 – 2:00 (Rich Axler) Minnesota Lake Trends (analysis & website)

2:00 – 2:20 (Lucinda Johnson/Jennifer Olker/Dan Breneman) Trends in Fish Communities and Traits

2:20 – 2:30 (Patrick Welle & Rabi Vandergon) Progress report on economic analysis

2:30 – 2:45 BREAK

2:45 – 3:45 Discussion: Completing Phase I

3:45 – 4:30 Discussion: Phase II progress and future directions

4:30– 5:00 Discussion: Interactions with other programs (i.e. SLICE)

Participants

Natural Resources Research Institute
Lucinda Johnson
Rich Axler
Elaine Ruzycki
Jennifer Olker
Norm Will

St. Anthony Falls Laboratory
Heinz Stefan
Tim Erickson

Department of Geography
Dick Skaggs
Kenny Blumenfeld

Department of Fisheries, Wildlife, and Conservation
Ray Newman
Kristal Schneider

Metropolitan State University, St. Paul
Virginia Card

Bemidji State University, Bemidji
Patrick Welle
Rabi Vandergon

MN Department of Natural Resources
Don Pereira

MN Pollution Control Agency
Ed Swain

Project Abstract

Project Title: **Land Exchange Revolving Fund for Cass/Aitkin/Crow Wing Counties**

Project Manager: **Affiliation:** Mark Jacobs, Land Commissioner
Aitkin County Land Department
Mailing Address: 209 2nd St. NW Room 206
City / State / Zip : Aitkin, Mn. 56431
Telephone Number: 218-927-7364
E-mail Address: acld@co.aitkin.mn.us
FAX Number: 218-927-7249
Web Page address: co.aitkin.mn.us

Location: *Cass, Aitkin, and Crow Wing Counties*

Funding Source: Environment and Natural Resources Trust Fund.
Legal Citation: ML 2006, Chap 233, Sec. 20, Subd. 8.

In 2006, an inter-county revolving loan fund was established for the benefit of Aitkin, Cass and Crow Wing Counties. The objective of this fund was to improve public and private land-ownership patterns, which will increase public management efficiency, protect critical habitat, and reduce public service expenditures to isolated parcels; without reducing the local tax base

Under this program, the Counties purchased privately owned parcels that met certain project criteria. Tax forfeited land, of substantially equal value and better suited to private ownership, was sold to replenish the fund; resulting in the public/private land ownership base remaining stable.

A total of 174.6 acres of land plus a lot were purchased solving many easement issues and consolidating public ownership so that public service expenditures to these parcels would not exist.

During this process, land values dropped because of the recession which made it harder to recoup the funds from land sales. Parcels were put up for sale, but did not sell because of the economy. Purchases of recreational property was no longer a priority, when homes were being lost and people weren't sure about the future of their jobs.

Another item that caused some problems, was that as funds from the account were used, sometimes larger parcels were unable to be purchased as there was not enough in the account for purchase. Exchanges were not as favorably looked at as when a county parcel was exchanged, people thought that everyone should have the opportunity to purchase the parcel, not just the person doing the exchange.

Overall, the process was a good process. It gave counties the opportunity to cure problem parcels with a ready cash fund. No access properties, wetland properties that should not be developed, and recreational opportunities were all developed with a 'no cash out of the general fund' opportunity.

July 8, 2011
LCMR Work Program Update Report
ML 2006 Chapter 243 Section 20 Subdivision 8

LCMR 2006 Work Program   Final Report

Date of Report:	January 1, 2011 to June 30, 2011
Date of Next Status Report:	June 30, 2011
Date of Work program Approval:	
Project Completion Date:	June 30, 2011

I. PROJECT TITLE: Land Exchange Revolving Fund for Cass/Aitkin/Crow Wing Counties

Project Manager: **Affiliation:**	Mark Jacobs, Land Commissioner Aitkin County Land Department
Mailing Address:	209 2nd St. NW Room 206
City / State / Zip :	Aitkin, Mn. 56431
Telephone Number:	218-927-7364
E-mail Address:	acld@co.aitkin.mn.us
FAX Number:	218-927-7249
Web Page address:	co.aitkin.mn.us

Location: *Cass, Aitkin, and Crow Wing Counties*

Total Biennial LCMR Project Budget:	**LCMR Appropriation:**	**$290,000.00**
	Interest added:	**$ 14,206.92**
	Expenses:	**($ 705.61)**
	Paid back:	**$303,501.31**

Legal Citation: ML 2006, Chap 243, Sec. 20, Subd. 8.

Appropriation Language:
$145,000 in fiscal year 2006 and $145,000 in fiscal year 2007 from the trust fund to the Commissioner of Natural Resources for an agreement with Aitkin County for a six year revolving loan fund to improve public and private land ownership patterns, increase management efficiency, and protect critical habitat in Aitkin, Cass, and Crow Wing counties. By June 30, 2011, Aitkin County shall repay the $290,000 to the Commissioner of Finance for deposit in the Environment and Natural Resources Trust Fund.

II. PROJECT SUMMARY AND RESULTS:

A 5-year inter county revolving loan to be administered by Aitkin County for the benefit of the three counties that will improve public and private land-ownership patterns in participating counties, resulting in increased management efficiency and protection of critical habitat, without reducing the local tax base.

LCMR funds will expedite efficient responses to fee title purchase opportunities.

Under this program, counties will purchase privately owned parcels identified as critical habitat, public land access, or isolated. Then, tax forfeited land of substantially equal value which is better suited to private ownership, will be traded with the lands, purchased in fee, for purposes of transferring the tax forfeited status to the newly acquired county fee lands. This process will promote a stable public and private land ownership base.

Purchasing isolated, private lands in undeveloped areas of the County precludes development on those lands, which might result in additional public services such as road maintenance and school busing. When the purchased parcels adjoin property already in county management, land management is more efficient and lands better suited for natural resource benefits are protected.

Public lands selected for exchange and subsequent sale will be of substantially equal value to the private lands purchased (as defined by Class B land exchange process Mn Statute 94.344, Subdivision 3)

ENRTF funds(Environment and Natural Resources Trust Fund) will be placed in an inter county revolving fund account to be used for 5 years to facilitate / operate an acquisition - exchange - sale program. Notwithstanding the need to secure county board authorization to purchase, the land commissioners of Aitkin, Cass and Crow Wing Counties will review and approve all acquisition proposals. Upon completion of a purchase by a county, a reimbursement request will be submitted to the fiscal agent (Aitkin County). Only the cost of fee title acquisition will be eligible for reimbursement.

Aitkin County will be the fiscal agent representing the counties for this project. Aitkin County requests an advance for each year's allocation of LCMR funds. Aitkin County, as fiscal agent, will reimburse the State of Minnesota for the $290,000 plus any earned interest on the amount of LCMR funds received for this project by June 30, 2011.

III. SUMMARY OF PROGRESS AS OF June 30, 2011:

Under this program, the Counties purchased privately owned parcels meeting project criteria. Tax forfeited land, of substantially equal value and better suited to private ownership, was sold to replenish the fund; resulting in the public/private land ownership base remaining stable.

Aitkin County's purchases:

1. A 40 acre parcel landlocked by public land where a ¾ mile long easement was requested through county land. The purchase significantly reduced wetland impacts by an unbuildable parcel.
2. A 20 acre parcel landlocked by public land with an easement request through county forestland that contained high quality oak forests. The purchase addressed a legal access problem and avoided conflicts with forest management and public use.
3. A 37 acre parcel that was landlocked by public land. The purchase addressed a legal access problem, a potential recreation trail conflict, and consolidated public ownership.

Cass County's purchases:

1. A small lot that provides access to the Pine River for the public.
2. 6.75 acres of land with 980 feet of river and lake frontage. The aquatic area adjacent to this land is critical fish habitat and is mostly lowland hardwood

and marsh. This transaction helps protect the ecological integrity of Baby and Kid Lake.

3. 69.7 acres of forest land. The transaction substantially increased the forest productivity and recreation opportunities on county managed forest lands.

IV. OUTLINE OF PROJECT RESULTS*:*

RESULT 1: LAND ACQUISTION $290,000

- The funds were put in a revolving fund account which was used for 5 years to facilitate the acquisition-exchange-sale program.
- 173.45 acres were acquired in fee title. The counties making a purchase offered for sale tax forfeited parcels with a comparable value to maintain a balanced tax base.
- At the end of 5 years the entire sum plus any earned interest and minus administrative costs were returned to LCCMR.
- The funds were held in a separate interest bearing account and administered by Aitkin County.
- Aitkin County Auditor, as administrator of the funds, advanced funds to a county requesting reimbursement following a fee title purchase. Once the sale of property is completed, said county will pay back the Fiscal Agent for all monies loaned. This money will be put back into the revolving fund. There will be no prepayment penalty.

Summary Budget Information for Result 1:		**LCMR Budget**
		$ 290,000.00
	Allocated (Spent)	**$ 309,400.00**
	Interest	**$ 14,206.92**
	Repaid loan fund	**$ 309,400.00**
	Expenses	**$ 705.61**
	Balance repaid to ENRTF	**<u>$ 303,501.31</u>**

Expenses Itemized:

Total hours spent on LCCMR reports from 2006 to 2011 by Cathy Buhlmann – Aitkin Co.	**24.5 hours**	**$**	**694.09**
Postage costs		**$**	**11.52**
		Total expenses	**$705.61**

Completion Date: June 30, 2011

Result Status as of January 31, 2007
June 30, 2007
January 31, 2008
June 30, 2008
January 31, 2009
June 30, 2009
January 31, 2010
June 30, 2010
January 31, 2011

Final Report Summary: June 30, 2011

V. TOTAL LCMR PROJECT BUDGET:

All Results: Personnel:	**$0.00**
All Results: Equipment:	**$0.00**
All Results: Development:	**$0.00**
All Results: Acquisition:	**$309,400.00**
All Results: Other:	**$0.00**

TOTAL LCMR PROJECT BUDGET: $290,000

Explanation of Capital Expenditures Greater Than $3,500: na

VI. OTHER FUNDS & PARTNERS:

A. Project Partners: Aitkin County, Cass County, Crow Wing County

B. Other Funds being spent during the Project Period: $300,000 in kind and cash during the project -(ie. Staff time, attorney fees, recording fees, etc)

C. Required Match (if applicable): na

D. Past Spending: $309,400.00 in the past 5 years

E. Time: 5 years

VII. DISSEMINATION: na

VIII. REPORTING REQUIREMENTS: Periodic work program progress reports will be submitted not later than:
January 31, 2007, June 30, 2007
January 31, 2008, June 30, 2008
January 31, 2009, June 30, 2009
January 31, 2010, June 30, 2010
January 31, 2011

A final work program work and associated products will be submitted by June 30, 2011.

VIV. RESEARCH PROJECTS: na

Attachment A: Final Budget detail for 2006 projects

Proposal Title:

LAND EXCHANGE REVOLVING LOAN FUND – Cass / Aitkin / Crow Wing

Project manager name:

Mark Jacobs, Aitkin County Land Department

LCMR requested dollars: **$290,000**

1) see list of non-eligible expenses, do not include any of these items in your budget sheet
2) Remove any budget item lines not applicable

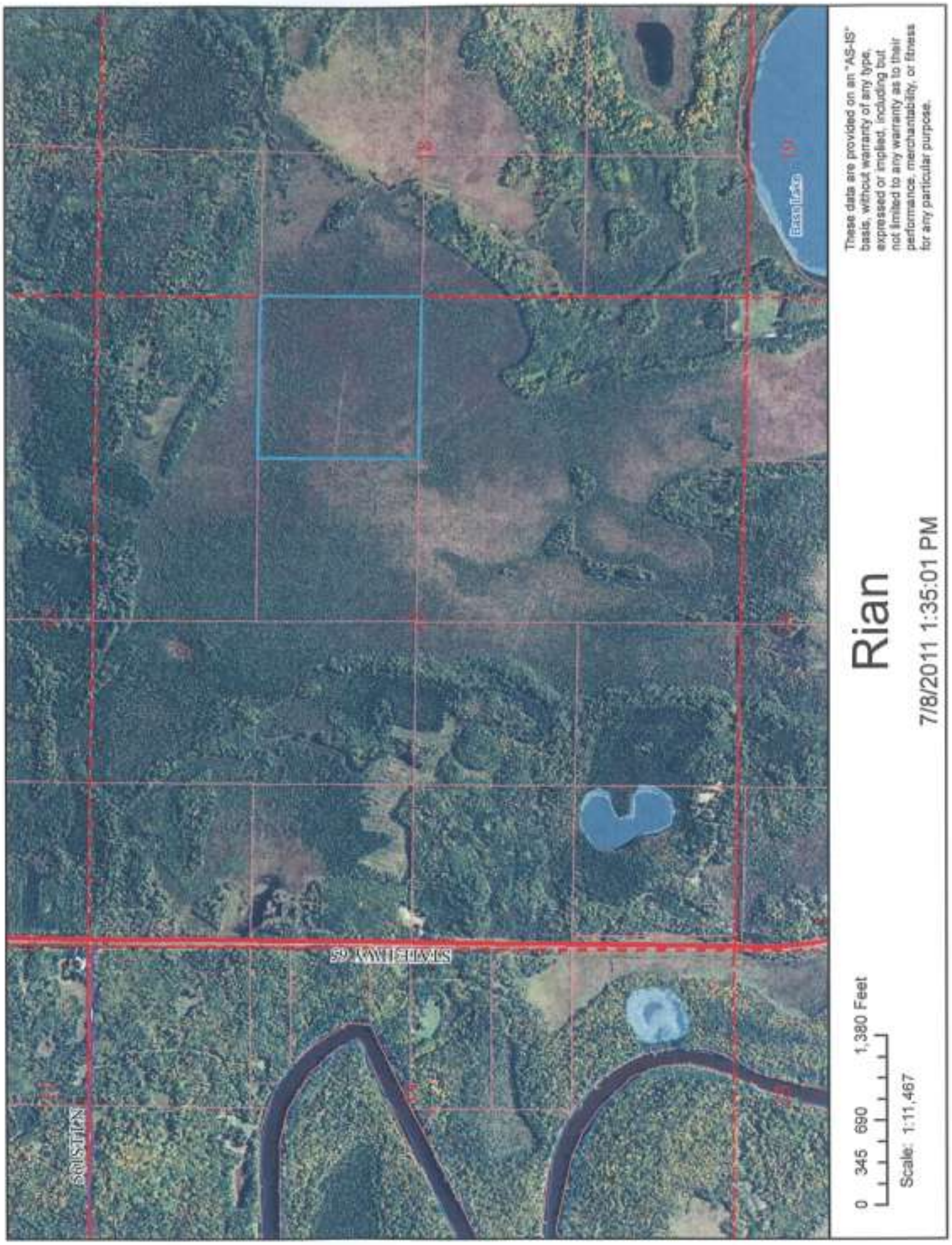
2006 LCMR Proposal Budget	Result 1 Budget: Land Acquisition	Amount Spent (to date)	Balance (to date)	Total For Budget Item
Revolving Loan Land Acquisition				
Land Acquisition – 250 acres	$290,000.00			$290,000.00
Interest to December 2006	$116.04			$290,116.04
Jan to June interest added	$5,215.57			$295,331.61
1-5-07 Troy Rian – Aitkin County		$9,800.00		$285,531.61
1-19-07 Steven Anderson – Aitkin County		$24,000.00		$261,531.61
2-9-07 Kellen – Cass County		$22,000.00		$239,531.61
4-16-07 Griffin – Cass County		$45,000.00		$194,531.61
June to December 2007 interest added	$5,461.14			$199,992.75
4-2-08 Stockman – Cass County		$160,000.00		$39,992.75
January to June 2008 Interest added	$2,442.54			$42,435,29
July to December 2008 interest added	$727.34			$43,162.63
January to June 2009 Interest added	$79.29			$43,241.92
July to December interest added	$26.28			$43,268.20
Aitkin County repayment of funds 12-31-2009	$33,800.00			$77,068.20
Cass County repayment of funds 6-14-2010	$67,000.00			$144,068.20
January to June 2010 interest added	$22.21			$144,090.41
July 2010 to December 2010 interest added	$76.19			$144,166.60
January to June 2011 Interest added	$36.75			$144,203.35
Cass County repayment of funds 6-30-2011	$160,000.00			$304,203.35

Aitkin County purchase of land (Heinzen)		$48,600.00		$255,603.35
Aitkin County repay of monies (Heinzen)	$48,600.00			$304,203.35
Postage charge 12-31-2006		$3.57		$304,199.78
Interest correction 12-31-2006	$3.57			$304,203.35
Administrative expenses from June 2006 to July 15, 2011		$702.04		$303,501.31
Column Total as of June 30, 2011	**$613,606.92**	**$310,105.61**		**$303,501.31**

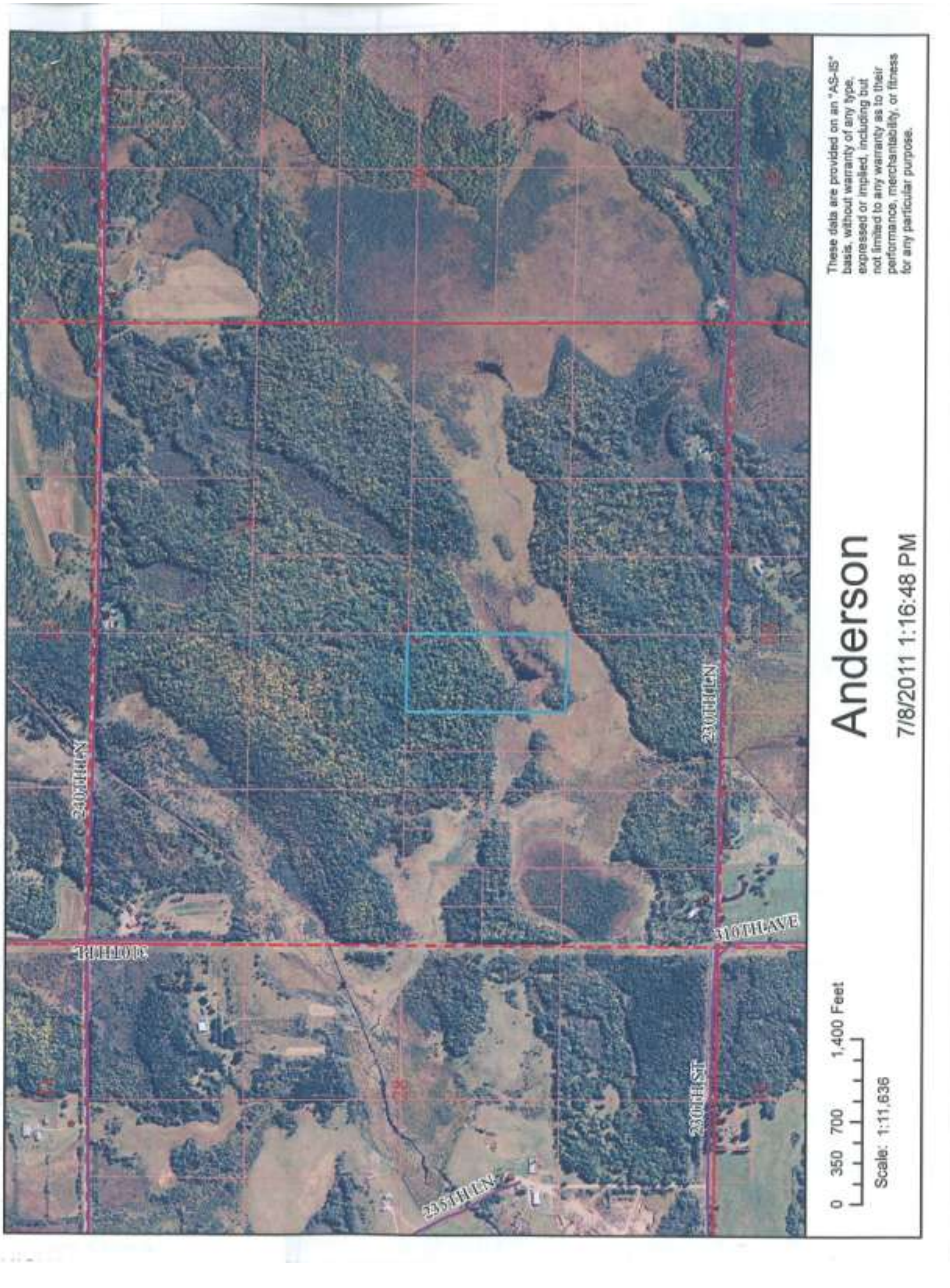
Land Exchange Revolving Fund for Aitkin/Cass/Crow Wing Counties
ML 2006 Chap. 243, Sec. 19, Subd. 8

Purchase Date	County	Parcel Name	Acres	Amount $	Final ownership	Notes
1-5-2007	Aitkin	Rian	40	$9,800	County owned	No access, non buildable parcel surrounded by tax forfeited, solved easement problem across wetlands
1-19-2007	Aitkin	Anderson	20	$24,000	County owned	No access, only access through high value oak forest on tax forfeited lands
6-30-2011	Aitkin	Heinzen	40	$48,600	County owned	Land locked parcel – purchase addressed access, recreation trail conflict, and consolidated land ownership
2-9-2007	Cass	Kellen	Lot	$22,000	County owned	Provides public access to a river and connects to public lands
4-16-2007	Cass	Griffin	6.75	$45,000	Reorganized and offered for sale	Parcel was subdivided for sale. Purchase of this allowed a nondivision of land and restrictive covenants to placed on the property.
4-18-2008	Cass	Stockman	67.9	$160,000	County owned	consolidated land ownership which increased forest productivity and recreation opportunities in Cass County –
	Crow Wing		0			No parcels acquired
		Total	174.65	$309,400		

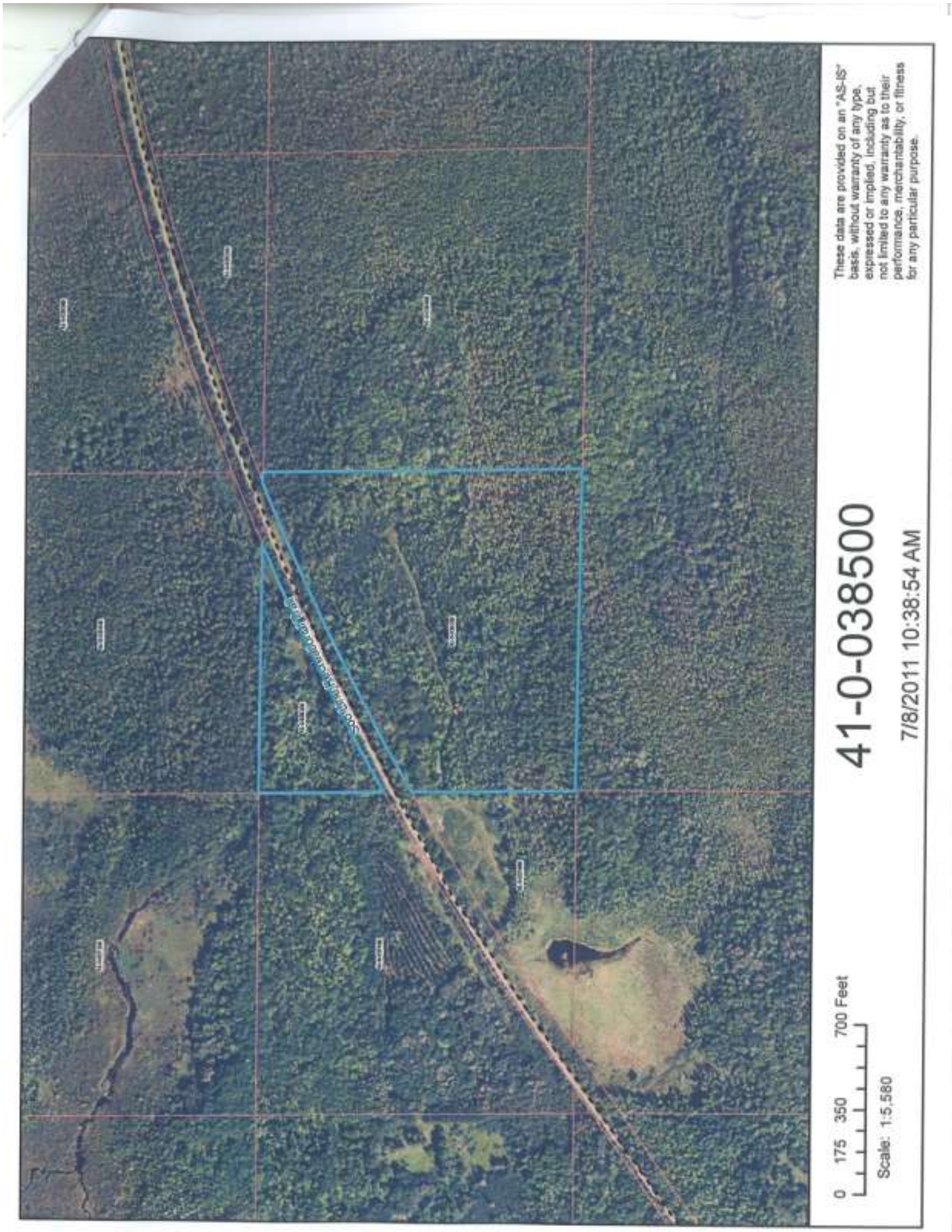
Aitkin - Rian


Rian
7/8/2011 1:35:01 PM
These data are provided on an "AS-IS" basis, without warranty of any type, expressed or implied, including but not limited to any warranty as to their performance, merchantability, or fitness for any particular purpose.
0 345 690 1,380 Feet
Scale: 1:11,467
STATE HWY 65
Bass Lake

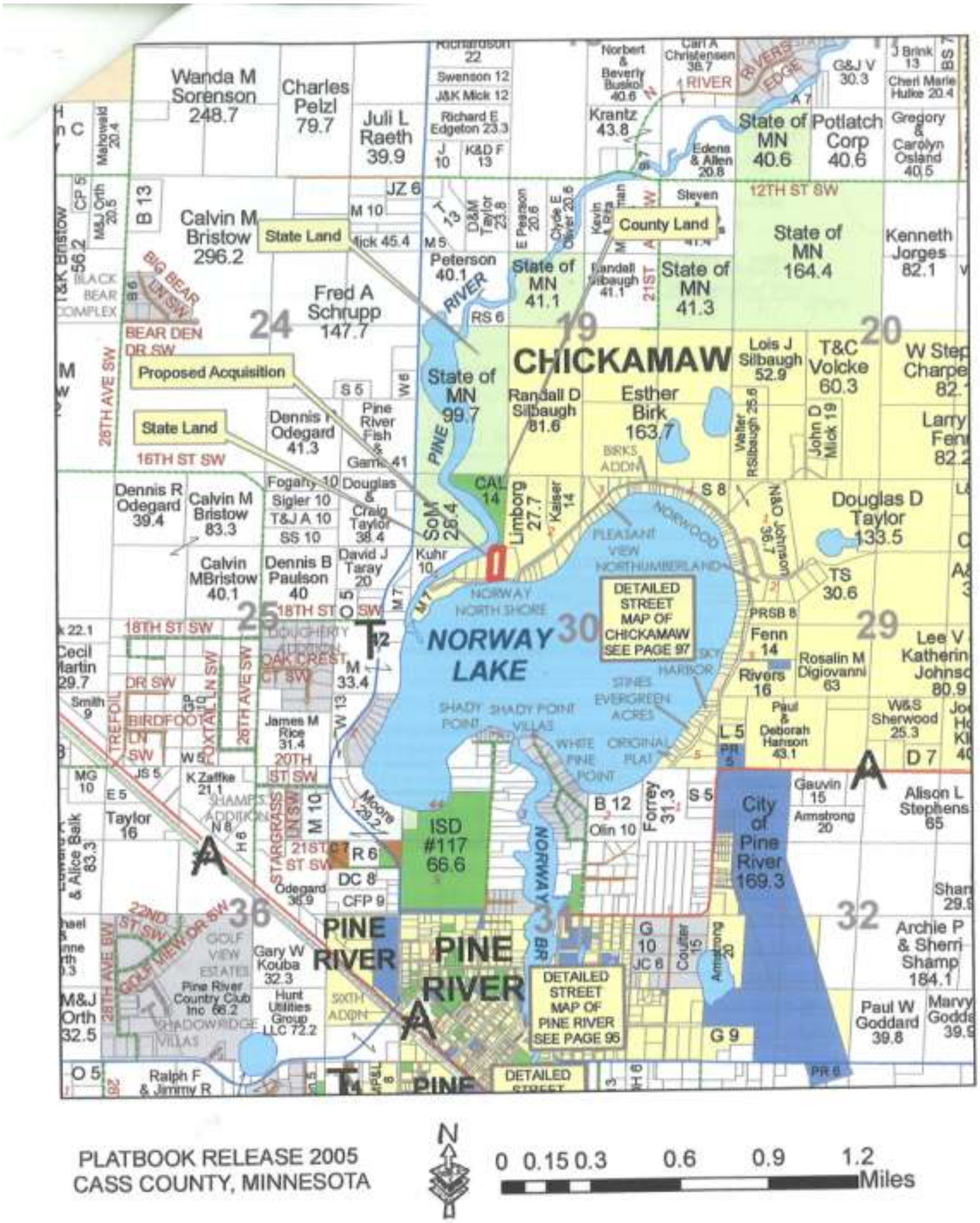
Aitkin - Anderson



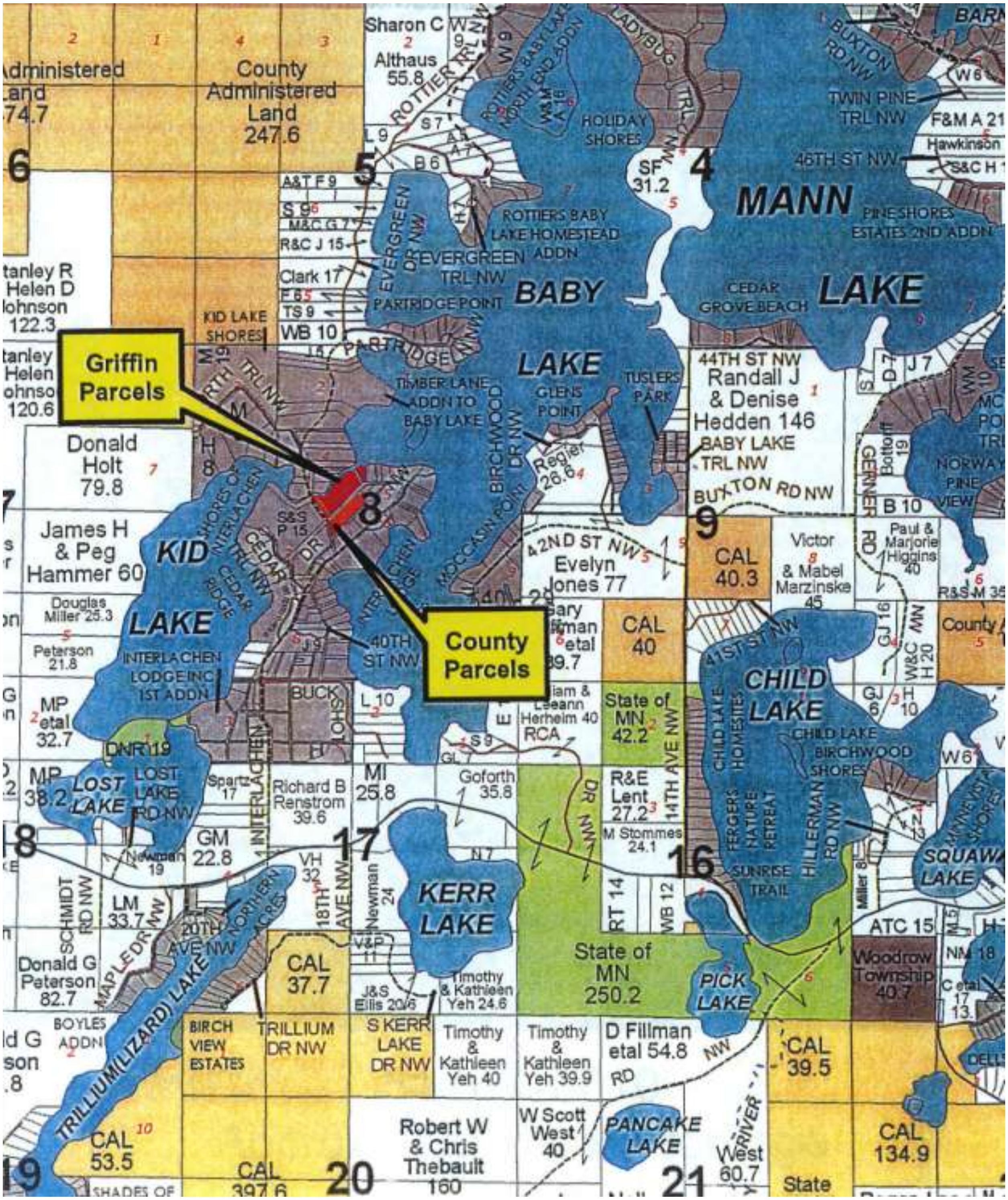
Aitkin Heinzen



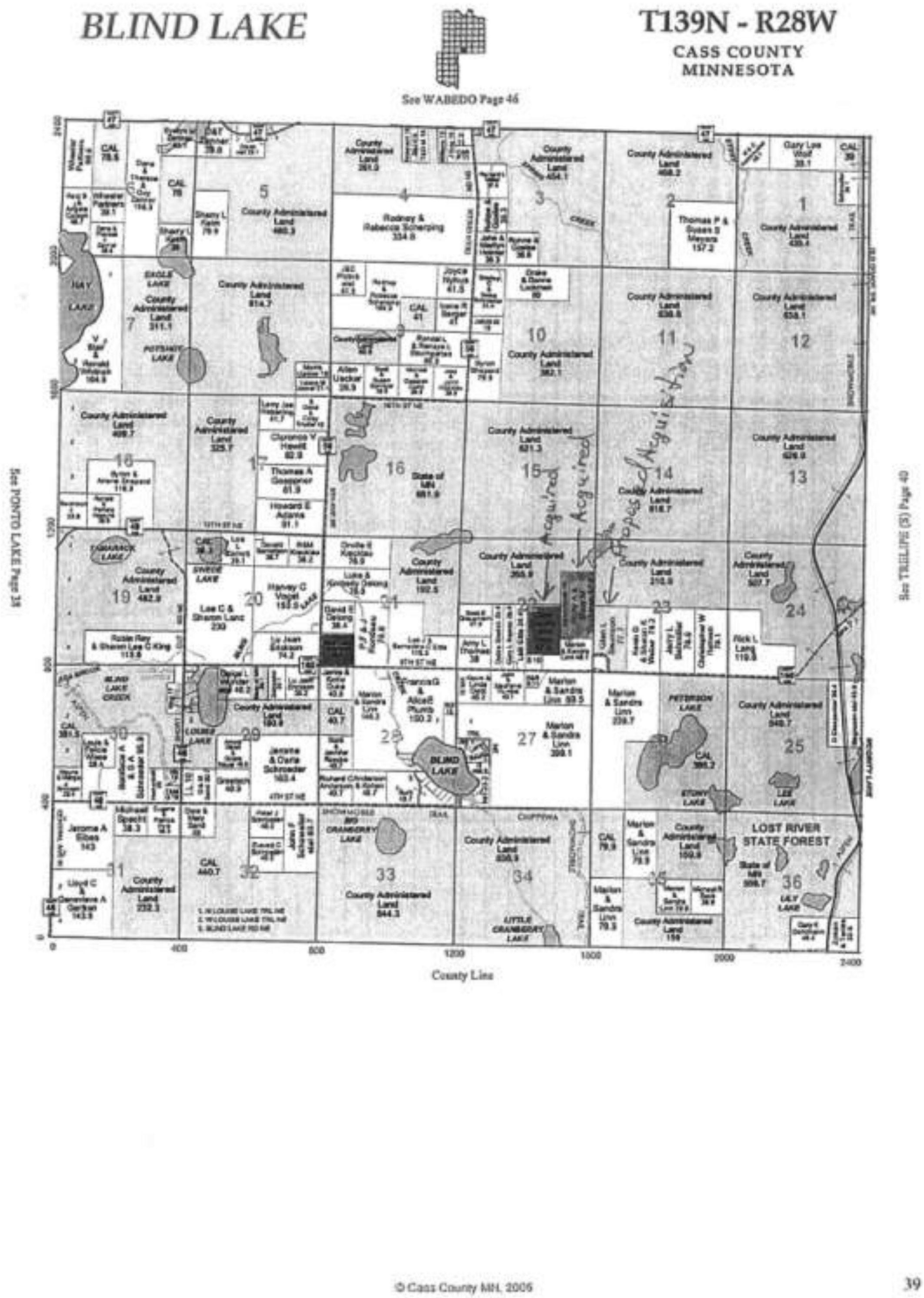
Cass - Kellen


CHICKAMAW
NORWAY LAKE
PINE RIVER
State Land
Proposed Acquisition
County Land
State of MN 99.7
State of MN 41.1
State of MN 41.3
State of MN 164.4
State of MN 40.6
Potlatch Corp 40.6
City of Pine River 169.3
ISD #117 66.6
DETAILED STREET MAP OF CHICKAMAW SEE PAGE 97
DETAILED STREET MAP OF PINE RIVER SEE PAGE 95
PLATBOOK RELEASE 2005
CASS COUNTY, MINNESOTA
0 0.15 0.3 0.6 0.9 1.2
Miles

Cass - Griffin



Cass - Stockman



LCMR Final Work Program Report

Date of Report: July 16, 2007
Date of Next Status Report: N/A
Date of Work program Approval: December 19,2006
Project Completion Date: January 31, 2008

I. PROJECT TITLE: Riparian Land Acquisition

Project Manager: Mike Halverson
Affiliation: Minnesota Department of Natural Resources (DNR)
Mailing Address: 500 Lafayette Road N
City / State / Zip: St. Paul, MN 55155
Telephone Number: 651-259-5209
E-mail Address: mike.halverson@dnr.state.mn.us
FAX Number: 651-297-4916
Web Page address: NA

Total Biennial LCMR Project Budget:

Fund		Year	Allocated	Liquidated	Balance
Riparian Land Acquisition Cleanwater Legacy (ETF) 2006					
	Fiscal Year	2006	$370,000	$370,000	$0
	Fiscal Year	2007	$270,000	$270,000	$0
Grand Total			$640,000	$640,000	$0

Legal Citation: ML 2006, Chapter 243, Sec. 20 Subd. 9.

Appropriation Language: Subd. 9. Riparian land acquisition. $370,000 in fiscal year 2006 and $270,000 in fiscal year 2007 are appropriated to the commissioner of natural resources for fee title acquisition and easements on high-priority, sensitive riparian lands that provide high value for watershed protection.

II. and III. Final Project Summary: This project resulted in a grand total of approximately 149 acres and 2.13 miles of lake and stream shoreline being acquired in fee title. Environmental and Natural Resources Trust dollars directly acquired 52.2 acres of the total, including 0.85 miles of lake and stream shoreline. Outside funds ($527,980) and other state monies ($2,025,220) leveraged with trust dollars totaled $2,553,200. These contributions helped acquire the remaining acres of the grand total including 79.4 acres and 1.05 miles using other state dollars, and 17.4 acres and 0.23 miles from outside funds.

This project complemented parcel acquisitions funded in the past with capital bonding, Trout Stamp, and Environmental Trust Fund dollars. The acquisition of aquatic management areas adjacent to lakes and streams ensures the protection of critical riparian habitat areas within sensitive watersheds and headwater areas, as well as, angler and management access. Acquisition under this project occurred in the following Counties: Bottle Lake in Hubbard, Rum River (Chuck Davis) in Mille Lacs, Dead Lake in Otter Tail, and Maple Lake in Douglas.

IV. OUTLINE OF PROJECT RESULTS: The DNR has collaborated with Basin Coordinators from the MPCA to determine which properties on the DNR's list of potential acquisitions would provide the greatest watershed protection value. Both DNR and MPCA staff believes that property that has never been developed and contains intact native vegetation will protect the riparian area and the water quality of the lakes and streams on which they are located, thereby supporting one aspect of the Clean Water Legacy Act (CWLA) which seeks to protect high quality water from becoming impaired.

Properties available for acquisition were ranked based on the following criteria:

- Whether or not the parcel contains undeveloped lakeshore/river bank with riparian and aquatic vegetation intact;
- The water quality of the rivers and lakes on which parcels are located;
- Whether or not the parcel contains critical habitat as described in MS 86A.05 (definition of AMA) and MR 6136.07 (Priorities for Acquisition and Improvement of Critical Natural Habitat – see Appendix B);
- User access (since these will properties will be publicly owned, how accessible the site is to the public is important); and
- the land value of the parcel (the DNR seeks to purchase land that offers the maximum land value to the state of Minnesota).

DNR has reviewed the ranked list and has selected those parcels that ranked as having the highest watershed protection value, contain critical habitat, provide the maximum land value and will be accessible for the public. The purchase of these lands will satisfy the aims of the CWLA, which seeks to protect high quality water from becoming impaired.

Result 1: Riparian Land Acquisition

Summary Budget Information for Result 1: LCMR Budget $640,000
Balance $0

Acquisition	Trust Acres	Trust Miles	Trust $	Other St Acres	Other St Miles	Other State $	Other Acres	Other Miles	Other $
Bottle Lake	6.26	0.09	$219,135	23.72	0.33	$830,155	10.02	0.13	$350,710
Chuck Davis	4.01	0.25	$178,200	0.00	0.00	$0	0.00	0.00	$0
Dead Lake	4.15	0.05	$100,000	48.48	0.63	$1,167,730	7.36	0.10	$177,270
Maple Lake	37.76	0.46	$142,665	7.24	0.09	$27,335	0.00	0.00	$0
Total	**52.18**	**0.85**	**$640,000**	**79.44**	**1.05**	**$2,025,220**	**17.38**	**0.23**	**$527,980**

Total Acres Acquired 149.0
Total Miles Acquired 2.13

V. TOTAL LCMR PROJECT BUDGET:

All Results: Personnel: $0
All Results: Equipment: $0
All Results: Development: $0
All Results: Acquisition: $640,000
All Results: Other: $0

TOTAL LCMR PROJECT BUDGET: $640,000

VI. OTHER FUNDS & PARTNERS:

A. Project Partners: NA

B. Other Funds being spent during the Project Period: $500,000 from the general fund (ML 2006, Chapter 258, Article 10 - Cleanwater Legacy) will be used in conjunction with the trust fund dollars to acquire the properties listed on Table I. The purchase of some properties will also likely involve donations of land value and/or cash received by the DNR from citizens or groups. Cash and land donations made to the DNR generate Reinvest in Minnesota Critical Habitat match dollars. If match dollars are generated, they will also be applied towards purchasing the properties listed on Table I.

C. Required Match (if applicable): NA

D. Past Spending: Nothing on this project.

E. Time: December 4, 2006 until January 31, 2008.

VII. DISSEMINATION: The proposed acquisitions will be fully described and designated as AMAs in the State Register. These AMAs will also be identified on Public Recreation Information Maps during the following year.

VIII. REPORTING REQUIREMENTS: Periodic work program progress reports will be submitted not later than January 31, 2007 and June 30, 2008. A final work program report and associated products will be submitted by January 31, 2008.

IX. RESEARCH PROJECTS: NA

Attachment A. Budget Detail **Final Report - Date: August 1, /2007**

Project Title: Riparian Land Acquisition Project

Project Manager Name: Mike Halverson

LCCMR Requested Dollars: $640,000

BUDGET ITEM	**Amount Budgeted ($)**	**Amount Spent ($)**	**Balance ($)**	**Comments**
ACQUISITION				
Land acquisition, trust fund *(fee title)*	$640,000	$640,000	$0	Fee title acquisition
Land transaction costs *(e.g., survey, title, appraisal, environmental, & legal)*	$0	$0	$0	
ACQUISITION - SUBTOTAL	$640,000	$640,000	$0	
TOTAL LCCMR Funding	$640,000	$640,000	$0	