

# Environment and Natural Resources Trust Fund (ENRTF) 2010 Work Program

**Date of Report:** November 24, 2009 (Revisions December 18, 2009)

**Date of Next Progress Report:** June 30, 2012

**Date of Work Program Approval:** (blank as requested)

**Project Completion Date:** June 30, 2012

**I. PROJECT TITLE:** Sustainable, Cost-Effective Approaches to Management of Shallow Lakes

**Project Manager:** Mark A. Hanson

**Affiliation:** Wetland Wildlife Populations & Research Group, Minnesota DNR

**Mailing Address:** 102 23<sup>rd</sup> Street NE

**City / State / Zip:** Bemidji, MN 56601

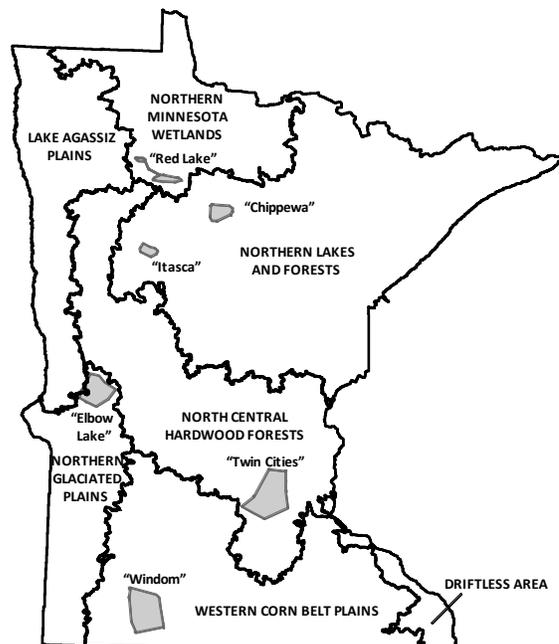
**Telephone Number:** 218.308.2049

**E-mail Address:** mark.alan.hanson@state.mn.us

**FAX Number:** 218.755.2604

**Web Site Address:** none

**Location:** 6 study areas as indicated below



**Figure 1. Map showing locations of proposed study landscapes (shaded gray) in relationship to Minnesota's aquatic ecoregions (thick black lines).**

<b>Total ENRTF Project Budget:</b>	<b>ENRTF Appropriation</b>	<b>\$</b>	<b>262,000</b>
	<b>Minus Amount Spent:</b>	<b>\$</b>	<b>0</b>
	<b>Equal Balance:</b>	<b>\$</b>	<b>262,000</b>

**Legal Citation:** ML 2010, Chap.[\_\_\_\_], Sec.[\_\_\_\_], Subd.\_\_\_\_\_.

**Appropriation Language:**

**II. PROJECT SUMMARY AND RESULTS:**

Minnesota’s shallow lakes provide numerous direct human benefits such as clean water, hydrologic storage to limit flooding, recreational opportunities, and access to unique wild areas. They also contribute valuable ecosystem services including carbon sequestration and habitat for native species. Unfortunately, water and habitat quality of Minnesota’s shallow lakes have deteriorated dramatically during the past century. Conversion from native upland covers, widespread wetland drainage and surface-water consolidation to facilitate agricultural and urban/residential development have been implicated as major causes for these changes. We propose to study approximately 150 shallow lakes in 5 ecological regions of Minnesota to:

- Identify major factors leading to deterioration
- Evaluate results of specific lake restoration approaches, including cost-effectiveness of various combinations of lake management strategies
- Assess the impacts of increased surface water connectivity on fish invasions and resulting habitat quality

Our efforts will include: comprehensive sampling of shallow lakes to identify direct and indirect causes of deterioration, evaluation of approximately eight lakes currently undergoing rehabilitation, and economic analyses to determine which restoration strategies are likely to produce the greatest improvements in water quality and other lake characteristics per unit cost. Research results will provide to lake managers scientific synthesis and practical guidance for shallow lakes throughout Minnesota and will be made available in the form of scientific publications and a synthesis document especially for lake management. Ultimately, our results will help guide municipalities, state, county, and local governments, and private organizations in identifying cost-effective approaches for maintaining and restoring ecological integrity of shallow lakes throughout Minnesota. Special attention will be directed towards development of regionally-specific recommendations for sustainable lake management.

**III. PROGRESS SUMMARY: November 24, 2009**

**IV. OUTLINE OF PROJECT RESULTS:**

**RESULT 1:** Identify and estimate major factors responsible for deterioration of shallow lakes in 6 areas of Minnesota

**Description:** We propose to gather data from, and characterize watershed features of approximately 140 shallow lakes (hereafter Extensive lakes) from 6 regions of Minnesota (Figure 1). Lakes will be sampled once each summer (July) to assess general ecological features and determine whether basins exhibit characteristics of clear- or turbid-water regimes. Lake watershed characteristics associated with each study lake will also be determined by creating and

applying numerous lake watershed variables via GIS technology and interpretation of aerial photography. Resulting data will be used to develop models to identify combinations of variables that explain most variability in shallow lake characteristics, especially water quality features and lake regime status (turbid or clear). Special attention will be given to assessing influences of resident fish populations, extent of surface-water connectivity associated with study lakes, and proportion of agriculture in lake watersheds because these are believed to be major determinants of water quality in Minnesota's shallow lakes. Resulting data will help identify and estimate magnitude of major factors responsible for deterioration of water quality and ecological characteristics in our regional subsets of study lakes.

**Summary Budget Information for Result 1:** ENRTF Budget: \$ 124,000  
Amount Spent: \$ 0  
Balance: \$ 124,000

<b>Deliverables</b>	<b>Completion Date</b>	<b>Budget</b>
<b>A. Provide a clear understanding of specific roles of fish as determinants of shallow lake water quality and habitat features along regional gradients. This will require us to:</b>		
1. Identify and select approximately 140 shallow lakes for use as study sites (Winter 2009-2010)		Non-LCCMR
3. Purchase field work supplies	Aug 30, 2011	\$ 6,000
4. Travel/lodging to research sites in Minnesota	Aug 30, 2011	\$ 25,000
2. Gather biological, chemical, and physical data samples from approximately 140 lakes (support for 4 field interns during July 2010- August 2011; methods described in Research Addendum)	Aug 30, 2011	\$ 36,000
5. Processing samples in lab; catalog resulting data (Sept 2010-March 2011); construct models relating shallow lake characteristics to features of lake watersheds and physical properties of basins (support for 4 lab interns during Sept 2011-March 2011; methods described in Research Addendum)	Mar 30, 2012	\$ 18,000
6. Investigator summer salary (Kyle Zimmer, Univ St. Thomas-1.5 mo.)	Aug 30, 2011	\$ 10,000
7. Technician salary (Univ MN; 50% - 1 yr)	Aug 30, 2011	\$ 29,000
<b>B. Develop and distribute recommendations for management to improve habitat conditions in shallow lakes. To accomplish this, we will:</b>		
1. Integrate results to form a project synthesis document to convey research results directly to shallow lake managers in Minnesota		Non-LCCMR
2. Convene a regional workshop for communication and information exchange with technical experts and lake managers		Non-LCCMR
2. Develop manuscripts for publication in scientific		Non-LCCMR

literature		
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**Result Completion Date: June 30, 2012**

**Result Status as of December 31, 2010**

**Result Status as of June 30, 2011**

**Result Status as of December 31, 2011**

**Result Status as of March 31, 2012**

**Final Report Summary: June 30, 2012**

**RESULT 2:** Evaluate and refine specific strategies for improving water quality and ecological characteristics of shallow lakes across Minnesota

**Description:** We propose to evaluate responses of 8 shallow lakes (hereafter Intensive lakes) currently undergoing lake restoration treatments such as draw downs or fish community manipulation. Ecological characteristics of Intensive lakes will be sampled monthly from May-August during 2 summers, including all components measured in the 140 Extensive sites. Identical landscape-level analyses will be conducted on these areas to determine upland cover and surface-water connectivity in lake watersheds using GIS analysis and aerial photography interpretation. Combining results and data from Intensive and Extensive lakes (Result 1), we will estimate water quality improvements in response to various combinations of treatments including upland restoration and within-lake-basin measures such as fish community manipulation. Specific efforts will be directed to evaluating responses of the Intensive lakes to management applied on each lake. Resulting empirical data from Extensive (140) and Intensive (8) lakes will be integrated and used in an economic analysis comparing various combinations of management costs and lake water quality outcomes. Empirical and economic analyses will provide guidance useful for refining and maximizing efficacy of future lake management efforts with specific attention to variability in lake responses and costs of rehabilitation techniques across different ecological regions of the state.

<b>Summary Budget Information for Result 2:</b>	<b>ENRTF Budget:</b>	<b>\$ 123,000</b>
	<b>Amount Spent:</b>	<b>\$ 0</b>
	<b>Balance:</b>	<b>\$ 123,000</b>

<b>Deliverables</b>	<b>Completion Date</b>	<b>Budget</b>
<b>A. Evaluate current shallow lake restoration strategies using a case study approach to document responses of selected reclamation lakes</b>		
1. Select approximately 8 lakes presently undergoing rehabilitation for use as case-study sites (Winter 2009-2010) in association with efforts of Ducks Unlimited, the Minnesota DNR Shallow Lakes Program, and perhaps other groups		Non-LCCMR

2. Purchase field work supplies	Aug 30, 2011	\$6,000
3. Purchase 2 14-ft aluminum boats with small outboard motors-for use sampling 8 intensive lakes	July 10, 2010	\$ 8,000
4. Travel/lodging to research sites in Minnesota	June 30, 2011	\$ 25,000
5. Intensively sample biological, chemical, and physical data samples from 8 case-study lakes (support for 4 field interns during July 2010- August 2011; methods described in Research Addendum)	Aug 30, 2011	\$ 36,000
6. Processing samples in lab; catalog resulting data (support for 4 lab interns during Sept 2010-March 2012); construct models relating shallow lake characteristics to features of lake watersheds and physical properties of basins (Sept 2011-March 2012)	June 30, 2012	\$ 18,000
<b>B. Develop region-specific guidelines useful for identifying cost effective reclamation approaches enabling optimization strategies</b>		
1. Review 8 case-study responses; combine with data from previous lake rehabilitation efforts in Minnesota to develop summary of generalized responses of shallow lakes to various management approaches		Non-LCCMR
2. Conduct cost-benefit analyses comparing water-quality improvements to be expected from various combinations of lake rehabilitation practices (Contract with P. Welle, Bemidji State University)	June 30, 2012	\$ 30,000
3. Convene a regional workshop for communication and information exchange with technical experts and lake managers		Non-LCCMR
4. Incorporate results a project synthesis document (identified for Result #1 above) to convey research results directly to shallow lake managers in Minnesota		Non-LCCMR

**Result Completion Date: June 30, 2012**

**Result Status as of December 31, 2010**

**Result Status as of June 30, 2011**

**Result Status as of December 31, 2011**

**Result Status as of March 31, 2012**

**Final Report Summary: June 30, 2012**

**RESULT 3:** Identify surface connectivity elements threatening water quality and biodiversity in shallow lakes

**Description:** The health of shallow lakes is a reflection of their upstream and downstream watersheds and the hydrologic connectivity within those watersheds. Increased surface water connectivity due to drainage, ditching, road construction, and other anthropogenic activities is known to increase the transfer of organisms, especially undesirable fishes, among shallow lakes in Minnesota. Such connectivity probably also provides major pathways for the spread of invasive species, which threaten native communities.

This effort will identify, delineate and digitize unmapped natural and human created water conveyance features that constitute present-day surface water connectivity. Using data from the Extensive (140) and Intensive-lakes (8), we propose to document water quality, biodiversity, and habitat characteristics and measure their response to various surface water connectivity scenarios. This will allow the development of models useful for assessing probable results from increased surface water connectivity within the watersheds. We believe this will provide useful data and guidance for natural resource managers who frequently must respond to specific requests for landscape modifications that increase surface-water connectivity, runoff and channelized flow contributing to decreased water quality and ecological conditions in shallow lakes throughout Minnesota.

**Summary Budget Information for Result 3:** ENRTF Budget: \$ 15,000  
Amount Spent: \$ 0  
Balance: \$ 15,000

<b>Deliverables</b>	<b>Completion Date</b>	<b>Budget</b>
A. Delineations of shallow lake watersheds and surface connectivity networks; determine extent of land cover types within watersheds; summarize resulting data (1 mo. Salary support – hydrologist - Sean Vaughn)	June 30, 2011	\$ 15,000
B. Distribute resulting electronic data through DNR (Division of Waters) web links		Non-LCCMR
C. Construct models relating lake watershed characteristics to lake watershed size, surface connectivity, and flow patterns to biological and chemical characteristics of shallow lakes		Non-LCCMR
D. Incorporate recommendations for improved strategies for controlling spread of invasive species by identifying key connectivity elements needed to preserve natural biodiversity of shallow lakes into final synthesis document (identified for Result #1 above)		Non-LCCMR

**Result Completion Date: June 30, 2012**

**Result Status as of December 31, 2010**

**Result Status as of June 30, 2011**

**Result Status as of December 31, 2011**

**Result Status as of March 31, 2012**

**Final Report Summary: June 30, 2012**

**V. TOTAL ENRTF PROJECT BUDGET:**

**Personnel:** \$ 192,000

**Contracts:** \$ 0

**Equipment/Tools/Supplies:** \$ 18,000

**Acquisition (Fee Title or Permanent Easements):** \$ 0

**Travel:** \$ 52,000

**Additional Budget Items:** \$ 0

**TOTAL ENRTF PROJECT BUDGET: \$ 262,000**

**Explanation of Capital Expenditures Greater Than \$3,500:** Repeated sampling of 8 “Intensive lakes” will require two 14-ft flat bottom boats with small outboard motors.

**VI. PROJECT STRATEGY:**

**A. Project Partners:** Our project team has 11 collaborators representing one NGO, state, university, and tribal representatives. Scientific investigations will be lead by S. Bowe (Red Lake DNR), J. Cotner, (UM), N. Hansel-Welch, M. Hanson, B. Herwig (MDNR), P. Welle (Bemidji State University), J. Younk (MDNR), and K. Zimmer (University of St. Thomas). Logistical and financial support also will be provided by Ducks Unlimited (DU, R. Heiniger and J. Schneider) and NSF (through REU to Cotner). Hydrological interpretations, data summaries, and analysis will be conducted and overseen by S. Vaughn (MDNR). Along with an extensive set of 140 shallow lakes, study areas will include approximately 8 lakes currently targeted for restoration by MDNR, USFWS, and MN DU using new LOHC funds.

**B. Project Impact and Long-term Strategy:** Shallow lakes in Minnesota have deteriorated. Numerous factors work together to reduce water quality and ecological characteristics of these areas; some of these influences are well known, others are not. For example, carp and other undesirable fishes are known to limit water quality and reduce plant diversity in shallow lakes, yet mechanisms contributing to distribution of carp and other fish species in shallow lakes are poorly known. Also, contributions of other factors such as extent and condition of upland cover types within lake watersheds, influences of ecological regions and regional gradients, and interactions among key drivers are not known. Presently, lake managers are in need of scientific evidence and practical guidelines for future management of shallow lakes throughout Minnesota. More specifically, managers need regionally-specific guidance to identify lake management strategies that are cost-effective and have high probability of success in various ecological regions of the state.

**C. Other Funds Proposed to be Spent during the Project Period: \$ 428,686**

**D. Spending History:** *None*

**VII. DISSEMINATION:** We anticipate several peer-reviewed publications from major aspects of this research. In addition, we plan to develop a project summary that will provide regionally-specific guidelines for shallow lake managers in Minnesota. Due to length of time required to process and analyze biological samples, manuscripts for peer-review journals will be developed after June 2012.

**VIII. REPORTING REQUIREMENTS:** Periodic work program progress reports will be submitted not later than at 6 mo. intervals as described. A final work program report and associated products will be submitted between June 30 and August 1, 2011 as requested by the LCCMR.

**IX. RESEARCH PROJECTS:** Research Addendum attached

# Environment and Natural Resources Trust Fund

## Research Addendum for Peer Review

Project Manager Name: Mark A. Hanson

Project Manager Email address: mark.hanson@dnr.state.mn.us

Project Title: Sustainable, Cost-Effective Approaches to Management of Shallow Lakes

Project number: 020-A3

**Abstract** - Minnesota's shallow lakes provide numerous valuable ecosystem services and habitat for native species along with direct human benefits including clean water, recreational opportunities, and carbon sequestration. Unfortunately, water and habitat quality of Minnesota's shallow lakes have deteriorated dramatically during the past century. Conversion from native upland covers, widespread wetland drainage and surface-water consolidation to facilitate agricultural and urban/residential development have been implicated as major causes for these changes. We propose to study approximately 150 shallow lakes in 5 ecological regions of Minnesota to 1) identify major factors leading to deterioration, 2) evaluate results of specific lake restoration approaches, including cost-effectiveness of various combinations of lake management strategies, and 3) assess the impacts of increased surface water connectivity on fish invasions and resulting habitat quality. Our efforts will include extensive sampling of shallow lakes to identify direct and indirect causes of deterioration, evaluation of approximately eight lakes currently undergoing rehabilitation, and economic analyses to determine which restoration strategies are likely to produce the greatest improvements in water quality and other lake characteristics per unit cost. Ultimately, our results will allow municipalities, state, county, and local governments, and private organizations to identify cost-effective approaches for maintaining and restoring ecological integrity of shallow lakes throughout Minnesota. Special attention will be directed towards development of regionally-specific recommendations for sustainable lake management.

**Background** - Minnesota has approximately 4,000 lakes characterized by mean depth  $\leq 15$  ft and surface area  $> 40$  acres (Nicole Hansel-Welch, personal comm.) and many thousands of smaller waters technically classified as "prairie wetlands"; the latter are functionally indistinguishable from the larger analogues (Potthoff et al. 2008). Collectively, these shallow lakes represent an international resource, providing critical waterfowl habitat and ecological benefits within Minnesota and the Mississippi Flyway. Currently, only 40 of these lakes  $> 40$  acres are formally designated for wildlife management, however many others are focus areas for various wildlife habitat and conservation practices. Due to concerns over wetland/lake water quality, seasonal duck abundance and habitat use, and hunter satisfaction, MN DNR recently proposed a collaborative plan to Recover Ducks, Wetlands, and Shallow Lakes ([http://files.dnr.state.mn.us/outdoor\\_activities/hunting/waterfowl/duck\\_plan\\_highlights.pdf](http://files.dnr.state.mn.us/outdoor_activities/hunting/waterfowl/duck_plan_highlights.pdf)). This plan targets restoration of 1,800 shallow lakes in Minnesota. At the same time, restoration strategies for shallow lake managers remain limited and often ineffective; in addition, reliable data on baseline conditions of shallow lake characteristics and regional patterns of variability are often unavailable, especially for northern areas. This means that lake and wildlife managers are frequently unsure of the current status of lakes they manage, and whether ecological characteristics of these areas may be limiting use by waterfowl and other wildlife. In general,

managers receive little technical guidance useful for management and restoration of these lakes, or for implementation of rules for managing increased development and other anthropogenic influences in these areas.

Ecological characteristics of shallow lakes, along with their suitability for ducks and other wetland wildlife species, result from integrated influences of within-site and landscape-mediated processes. Effects of key variables operate at multiple spatial scales, sometimes result from off-site influences, and no doubt vary regionally throughout the state. Ecologists have long held that prairie wetlands (including our “shallow lakes”) are strongly influenced by gradients of hydrology (or hydrogeomorphic setting) and climate (especially precipitation) (Euliss et al. 2004). However, within boundaries established by hydrology and climate, biological interactions, especially wetland fish communities, also exert major structuring influences on communities and characteristics of prairie wetlands and shallow lakes (Hanson et al. 2005). This is not surprising given robust improvements known to follow removal of undesirable fishes from shallow Minnesota lakes such as Christina (Hanson and Butler 1994), and smaller wetlands (Zimmer et al. 2001).

As evidenced by whole-lake manipulations such as those summarized above, shallow lake food webs often differ dramatically in response to density and community structure of associated fish populations. Fish-mediated influences on invertebrate community structure and water transparency are often pronounced (Bendell and McNicol 1987; Zimmer et al. 2000, 2001). Recent studies in Minnesota’s Prairie Pothole Region (PPR) documented the strong negative influences of fathead minnows on invertebrate populations (Zimmer et al. 2000, 2001, 2002). Consequent reductions in herbivorous zooplankton (resulting from fish predation) allowed increases in phytoplankton densities and turbidity consistent with predictions of the recent models of Scheffer et al. (1993) and Scheffer (1998). These models propose that shallow-water ecosystems exist in one of two alternative conditions, either a clear-water, macrophyte-dominated state, or a turbid-water, phytoplankton-dominated state (Scheffer et al. 1993). Minnesota PPR wetlands largely conform to a binomial distribution (clear or turbid), rather than a normal distribution of features along a theoretical continuum (Zimmer et al. 2001; Herwig et al. 2004; Zimmer et al. 2009).

Composition of fish assemblages may also mitigate the relative influence of fish on shallow lake communities, and may dictate the success of remediation efforts. For example, stocking of piscivorous fish often results in a reduction of planktivorous fish (especially soft-rayed minnows), which may indirectly increase water transparency (Walker and Applegate 1976; Spencer and King 1984; Herwig et al. 2004). Similarly, in small lakes in northern Wisconsin containing natural fish communities, piscivores (largemouth bass *Micropterus salmoides* or northern pike *Esox lucius*) and cyprinids often occupy unique and separate assemblages. This pattern is thought to reflect the elimination of minnows via predation, and further suggests that biotic interactions can be important in structuring fish assemblages (Tonn and Magnuson 1982; Rahel 1984). In contrast, populations of large-bodied benthivorous fish species (e.g., black bullhead *Ameiurus melas*, white sucker *Catostomus commersoni*, and common carp *Cyprinus carpio*) are often resistant to predation, and are frequently associated with high turbidity and loss of rooted aquatic plants (Hanson and Butler 1994; Braig and Johnson 2003; Parkos et al. 2003). Due to the important but very different influences of planktivorous and benthivorous fishes on water quality, and the potential for restoration success given different fish assemblages, managers would benefit from tools that linked fish assemblages to landscape features and environmental characteristics of shallow lakes themselves.

Many lake and wetland studies have reported that landscape setting directly influences characteristics of embedded waters. For example, the watershed position sets boundaries on a variety of physical, chemical, and biological attributes of both deep lakes (Kratz et al. 1997) and prairie wetlands (Euliss et al. 2004). These lake properties include potential responses to drought, predominant groundwater interactions, water chemistry and concentrations of dissolved constituents, and biological communities. Other landscape features that have been found to influence lake water quality are wetland extent in the lake watershed (Detenbeck et al. 1993; Prepas et al. 2001), and extent of agricultural land use, the latter being correlated with higher trophic state index in associated lakes (Detenbeck et al. 1993). In many cases, off-site influences probably interact with site-level wetland features and processes so that observed community characteristics reflect simultaneous influences operating within the local context of lake nutrient status (Scheffer et al. 1993; Bayley and Prather 2003; Jackson 2003), surface area (Hobæk et al. 2002), depth (Scheffer et al. 1993), and biological properties such as abundance of macrophytes (Scheffer et al. 1993; Paukert and Willis 2003; Zimmer et al. 2003).

Our previous work (2005-06) confirmed that landscape characteristics can influence lake communities, interact with within-basin processes, and may be important determinants of shallow lake characteristics in Minnesota. These landscape effects are direct and indirect. For example, both presence of downstream fish sources and depth were useful for predicting fish presence/absence (Herwig et al. In review), and landscape control on distribution of fish species limited the ability of predatory fish to control prey fish and improve water quality conditions (Friederichs et al. In review). Proportion of agricultural lands in upstream lake watersheds interacted with fish mass in our best models and together these attributes were useful for predicting algal biomass in adjacent shallow lakes (Gorman et al. In prep.), and fish were also the best predictors of amphibian site occupancy and abundance in shallow lakes (Herwig et al. In Prep.). In addition, results from our previous study provided new insights that will help elucidate mechanisms associated with important in-lake processes such as identifying thresholds at which shallow lakes shift from turbid- to clear-water regimes, and clarifying roles of benthivorous fish in these well-known lake dynamics (Zimmer et al. 2009). Preliminary results from earlier work indicate that fish abundance and community structure exert major influences on shallow lake invertebrates, yet this relationship varies widely across ecological region. We are also comparing relative influences of within-site and landscape-scale characteristics on shallow lake invertebrate communities. Contributions from Sean Vaughn (Division of Waters, MDNR) and Robert Wright (Section of Wildlife, MDNR) provided new spatial analysis tools (delineating lake watershed boundaries, spatial analysis, etc.) that were not only critical for the recently-completed study, but will have direct application to questions and hypotheses posed in this current effort.

Major goals of our previous study were to develop conceptual and empirical models linking landscape features, environmental influences and wetland fish assemblages, to assess influences of these factors on the community characteristics in shallow lakes, and to clarify specific influences of within-lake processes that influence ecological characteristics of shallow lakes. An overarching finding of the prior work was that regional differences often constituted the largest source of variance in characteristics of shallow Minnesota lakes. This is not unexpected given findings of others studying deeper lakes (Carpenter et al. 2007), or perceptions of staff from the MDNR shallow lakes program indicating that baseline characteristics of shallow lakes differ dramatically across regions of the state (Nicole Hansel-Welch, pers. comm.). Regional

differences not only contribute to major variability in obvious lake characteristics, but they probably influence extent and nature of lake responses to landscape constraints such as surface-water connectivity, as well as within-lake processes in regime responses to thresholds of phytoplankton and fish mass. For example, it is likely that combinations of increased benthivorous fish mass and/or decreased macrophytes will often induce regime shifts in prairie lakes, and these changes probably portend shifts to turbid-water states. However, we speculate that increased fish mass is much less likely to induce turbid-states in north-central Minnesota lakes, and turbid states may not even be possible in northern lakes where low ambient nutrient levels prevail. Additional work is needed to document extent and patterns of regional variation, and to assess how it influences key structuring mechanisms such as surface connectivity, fish community characteristics, stability of phytoplankton- and macrophyte-dominated states, and proportion of lakes in clear- vs. turbid-water states.

**Hypotheses** - Our overall, general working hypothesis is that 6 fundamental “drivers” are ultimately responsible for most of the variation in ecosystem characteristics of Minnesota shallow lakes: climate, ambient nutrient levels, fish abundance and community type, landscape features, land use, and morphometric features of individual lakes. These 6 factors, in turn, induce strong, predictable spatial gradients in shallow lake characteristics across the state of Minnesota. Thus, we expect shallow lakes will exhibit wide ranges of features (and responses to lake management) at a statewide scale as the influence of some drivers increase while others decrease. Additionally, inter-annual variability in precipitation and temperature will have strong influences on shallow lakes, and this inter-annual variability will also exhibit spatial patterns across the state. Thus, we hypothesize these 6 drivers generate predictable spatial and temporal patterns in shallow lakes across the state of Minnesota. Overall, we believe that understanding and predicting ecosystem characteristics of shallow lakes (fish, waterfowl, plant and invertebrate communities, water quality, carbon cycling, etc.), along with lake responses to rehabilitation efforts, requires understanding the influence of these drivers, as well as synergistic combinations of influences arising from two or more drivers. Within-lake interactions, such as those associated with fish, have strong influences on shallow lakes (Scheffer et al. 2006; Verant et al. 2007; Potthoff et al. 2008). However, we hypothesize that the types and strengths of these interactions are also a function of our 6 main drivers, such that within-lake interactions will also exhibit spatial and temporal patterns that can be predicted from these influences.

We believe it is also especially important to test hypotheses regarding stability regimes in shallow lakes. Previous work (Hanson and Butler 1994) suggests that shallow lakes in MN conform to general models of alternative states developed for European lakes (Scheffer et al. 1993, Scheffer 1998) and these relationships have recently been confirmed from our prior work on Minnesota lakes (Zimmer et al. 2009). However, in Minnesota, it is likely that regime dynamics and stability thresholds will vary along regional gradients. We expect that companion models may need to be developed that extend the concept of basin states to include patterns of variance in invertebrate communities and other lake characteristics. Resulting data and modeling outcomes from tests of our specific hypotheses will be synthesized and applied to address needs and provide results identified in our accompanying Work Plan. For example, results from all study lakes will be used to estimate the magnitude of major factors responsible for deterioration of shallow lakes within the 6 study regions. Comparisons among management outcomes on 8 Intensive lakes (Result 2) will allow generalizations about relative usefulness of these lake rehabilitation approaches. Using a combination of data and outcomes from Extensive and Intensive lakes, our economic analysis will compare cost-effectiveness of various management approaches and will provide guidelines useful for maximizing future lake restoration and

management decisions, including suggestions as to how more cost-effective approaches vary across the state. Finally, all resulting data will be used to assess extent to which surface connectivity among surface waters influences ecological characteristics of shallow study lakes. We emphasize that our combination of specific hypothesis is necessary to address lake management needs identified in our proposal and work plan.

The following specific hypotheses are couched within general working hypothesis. Extent to which all specific hypotheses can be tested will be determined by characteristics and management plans of actual study lakes.

**Specific hypothesis 1:** Ambient nutrient levels will be highest in Windom (Figure 1), moderate in Twin Cities, and Elbow Lake, and lowest in Itasca and Red Lake, and this will have strong indirect effects on resident fish populations.

Explanation: Geological influences result in a natural gradient of phosphorus levels in lake sediments and topsoil within lake watersheds, with highest levels occurring in the southwestern part of the state and decreasing toward the northeast. Additionally, agriculture will be highest in Windom and Elbow Lake, and lowest in Itasca and Red Lake, while Twin Cities will be highest in extent of developed land. Winterkill effects will be most intense, but most variable in Windom due to fluctuating winter severity and high ambient nutrient levels (thus high biological oxygen demand in winter), whereas frequent, low intensity winterkills will occur throughout Red Lake and Itasca due to more consistent winter weather patterns.

**Specific hypothesis 2:** Spatial patterns in ambient nutrient levels, fish communities, and landscape features will cause spatial and temporal variability in proportional frequency of alternative states and stability of these regimes throughout Minnesota's shallow lakes.

Explanation: Windom will be dominated by stable turbid regimes, Red Lake and Itasca dominated by stable clear regimes, with a more equal frequency of regimes in Elbow Lake, and Twin Cities in the central part of the state. Furthermore, frequency of regime shifts will be highest in Elbow Lake, and Twin Cities, and lowest in Windom, Itasca, and Red Lake. High ambient nutrients and fish biomass will increase resilience and resistance of the turbid regime in Windom, while low nutrients and fish biomass promote resilience of clear regimes in Red Lake and Itasca.

**Specific hypothesis 3:** Functional influences of fish will decrease northward, along a spatial gradient from Windom to Red Lake.

Explanation: Dominance of benthivores will decrease along this same gradient, while planktivores increase. Concurrently, influence of piscivores on fish abundance will also increase along this gradient. Overall, species diversity of fish will peak at moderate level of ambient nutrient levels in Elbow Lake.

**Specific hypothesis 4:** Thresholds at which changes in fish biomass induce shifts between alternative regimes will vary across the state due to interactions between ambient nutrient levels and fish.

Explanation: Our previous work on shallow lakes in central Minnesota indicated that interannual proportional change in biomass of planktivores and benthivores is a threshold for regime shifts in shallow lakes (Zimmer et al. 2009). We predict similar thresholds for Elbow Lake, but lower biomass thresholds for Windom and Twin Cities, and higher thresholds in Itasca and Red Lake.

**Specific hypothesis 5:** Differences in landscapes features and land use among the 6 study areas will influence the relative importance of extinction and colonization as processes controlling distribution and abundance of fish in shallow lakes.

Explanation: High incidence of surface-water connectivity in Windom and Twin Cities will result in fish present in lakes, independent of lake depth and size, while a low prevalence of surface-water connectivity in Itasca and Red Lake will limit fish to deeper, larger lakes. Thus, long-term success in inducing regime shifts via biomanipulation may require installation of fish barriers in southern lakes, but not in the more isolated northern lakes.

**Specific hypothesis 6:** Benthivores and planktivores exert different relative influences on key characteristics of shallow lakes, with planktivores stabilizing turbid regimes, while benthivores both stabilize and induce shifts to the turbid regime.

Explanation: Planktivores stabilize a turbid regime, but do not induce shifts from clear to turbid regimes. Thus, we will not observe planktivore-only lakes shifting clear to turbid, but winterkill in planktivore lakes will cause a shift from turbid to clear. In contrast, benthivores stabilize turbid regimes and induce shifts to turbid regimes. Lakes with benthivores may shift clear to turbid, and winterkill in benthivore lakes will cause a shift from turbid to clear. We also hypothesize that influences will differ between the two dominant benthivore species in these systems: common carp and black bullhead. Carp distribution will be more limited, but will be more closely associated with turbid regimes.

**Specific hypothesis 7:** Shallow lake responses to biomanipulation will depend on ambient nutrient levels.

Explanation: Relative to high nutrient lakes (Windom), lakes with low nutrient levels (Itasca, Red Lake) will exhibit faster responses in water clarity and submerged macrophytes. The clear-water regime will also be more stable through time in low nutrient lakes, and more resistant to influences of subsequent recovery of planktivorous or benthivorous fish. We also predict that low nutrient lakes will require less reduction in fish mass for regime shifts (due to lower overall fish biomass), and the overall success rate will be higher in these systems.

**Specific hypothesis 8:** Water clarity and stability of clear-water regimes will be higher in *Chara* dominated lakes relative to lakes dominated by submerged angiosperms. We also predict a spatial gradient of *Chara* lakes, with highest occurrence in the Itasca-Red Lake and lowest in Windom.

Explanation: *Chara* species are very sensitive to changes in light intensity. They require high light intensity, and are expected to be more prevalent in clear lakes. Other submerged macrophytes are generally less sensitive to low light, thus are expected to decrease in abundance at higher critical turbidity thresholds than *Chara* spp.

**Specific hypotheses 9:** *Chara* species will become less abundant along the gradient from Itasca-Red Lake-Windom, while overall macrophyte biomass will increase along that gradient.

Explanation: *Chara* species are typically limited to relatively low-nutrient systems. Increasing nutrient availability along the Itasca-Red Lake-Windom gradient will thus decrease the relative abundance of *Chara* along that gradient. At the same time, higher nutrient availability will favor the biomass production of larger macrophytes, such as *Potamogeton* species.

**Specific hypothesis 10:** Efficacy of lake watershed restoration (e.g. converting row crop agriculture to native grasslands) and biomanipulation to reduce algal abundance will vary among study areas. Interactions between ambient nutrient levels, land use, and fish communities will make manipulations of fish more effective as you move toward the southwestern portion of the state, and management of lake watersheds more effective as you move north.

Explanation: Figure 2 (below) shows results from our previous study of high nutrient lakes near Elbow Lake, and low nutrient lakes west of Bemidji. Inset box show the ranges of fish biomass and agriculture in lake watersheds actually observed for the low nutrient lakes. The area below the

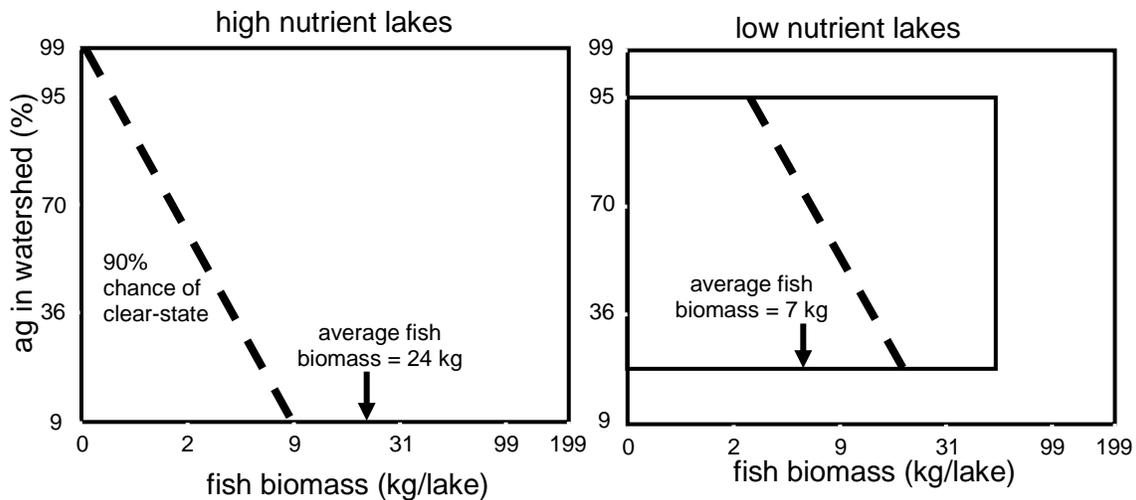


Figure 2. General relationships showing likelihood of achieving clear-water regimes under various combinations of extent agriculture (in lake watershed) and total fish biomass (per lake) in high and low nutrient lakes. Lakes falling left of dashed lines have a 90 % chance of being clear (based on unpublished data from K. Zimmer). Inset box for low nutrient lakes shows the actual range of agriculture in lake watershed and fish biomass observed in those lakes.

dashed line shows combinations of agriculture in the lake watershed and fish biomass (summed biomass of benthivores and planktivores) that allow a 90% chance of a lake being in a clear-water regime. Combinations above the line don't necessarily guarantee a turbid regime, but the probability of being clear declines as you move up and to the right the right from the dashed line. These results show that, in high nutrient lakes, efforts reducing agriculture result in a 90% chance of clearing lakes only if fish biomass is <9 kg. In contrast, reducing agriculture has potential to induce clear shifts in low nutrient lakes lakes with up to 25 kg of fish. Moreover, the average fish mass was higher than the 9 kg threshold for high nutrient lakes, while average mass was lower than the threshold for low nutrient lakes. These patterns indicate that lake watershed management will be more broadly applicable in low nutrient lakes. Eliminating fish should work in both areas, but improving water quality via fish reduction may also be more difficult in high nutrient lakes. For the upcoming study, we predict an even lower fish-mass threshold (for 90% chance of being clear) in Windom, where average fish biomass in shallow lakes is likely to be high. In contrast, Itasca and Red Lake should have higher fish thresholds, and lakes here should contain lower fish biomass due to lower productivity. Overall, this would indicate that restoration of lake watersheds contributing to shallow lakes is most effective in Itasca and Red Lake, fish and watershed management are both viable in Elbow Lake, while fish management is

most effective in Windom and Twin Cities. Additionally, we predict the amount of fish reduction needed to generate 90% chance of being clear will be highest in Windom, and lowest in Red Lake.

**Specific hypothesis 11:** Feeding activities of exotic earthworms increase concentrations of orthophosphate and ammonia in lake watersheds, while reducing concentrations of dissolved organic carbon in soil. The net result is worms increase autochthonous production in shallow lakes by increasing nutrient loading from lake watersheds, while simultaneously reducing loading of allochthonous organic matter from the watershed.

Explanation: Exotic earthworms have been referred to as ‘ecosystem engineers’ due to their profound effects on soil properties (Frelich et al. 2006). They are capable of decreasing the organic layer horizon of soils, increasing the rates of carbon, nitrogen and phosphorus cycling as well as altering the aboveground plant composition (Frelich et al 2006; Suarez et al. 2004; Dominguez et al. 2004). Little work has examined the effects of earthworms on adjacent aquatic ecosystems but given their profound effects on biogeochemical dynamics in soils, it is also likely that they are having important effects on aquatic systems. Given the increased rates of soil metabolism and nutrient leaching, it is quite probable that earthworms mobilize nutrients for transport into lakes and rivers, facilitating the rates of eutrophication of water bodies where they are most abundant. Preliminary work in lakes at Itasca State Park suggest that lakes with increased worm abundance are more productive and less likely to be limited by phosphorus, perhaps suggesting that earthworms are increasing the availability of P in these lakes.

Below we describe our methods for research on both Extensive (140) and Intensive (8) lakes, the latter undergoing various management efforts to improve ecosystem characteristics. Similar field methods will be used in both the extensive and intensive aspects of this project, allowing us to use the data from the 140 lakes in our assessment of improvements in the 8 lake study.

## **Methodology-**

### *Study Areas*

A key goal of our study is to increase understanding of spatial patterns of shallow lake characteristics across Minnesota. Shallow lakes here occur across a wide range of lake watershed characteristics (agriculture and urban land uses, native cover types, etc.), phosphorus concentrations, and water transparency gradients. We propose to use an aquatic ecoregion approach for characterizing shallow lake features (sensu Heiskary et al. 1987). We plan to use classifications based on Omerik’s (1987) Level III ecoregion delineations denoting areas of general similarity in the type, quality, and quantity of environmental resources. Under this approach we will establish a study area (or “study landscape”), each containing a cluster of study sites, within each of the five ecoregions that collectively encompass the vast majority of lakes and wetlands in Minnesota: Northern Minnesota Wetlands (NMW), Northern Lakes and Forests (NLF), Northern Glaciated Plains (NGP), Western Corn Belt Plains (WCP), and North Central Hardwood Forests (CHF). As previously mentioned, there are large gradients in in-lake phosphorus (P) and nitrogen concentrations across these ecoregions. For example, in a survey of 1,062 lakes, Heiskary et al. (1987) found median P concentrations of 23 ppb (NLF), 50 ppb (CHF), 121 ppb (WCP), and 177 ppb (NGP). No information was available for NMW, but we expect lower P concentrations here, perhaps intermediate between NLF and CHF. Cover types also vary widely, ranging from heavily forested, with some marshlands (NLF) to nearly level marsh, containing both boreal vegetation and expansive swamps (NMW), to principally cropland

agriculture (WCP & NGP), to a mosaic of cover types, including forests, wetlands and lakes, cropland agriculture, pasture, grasses, and urban development (CHF) (Omerik 1987).

Our study will focus on 6 landscape areas distributed across five aquatic ecoregions within Minnesota as follows: (1) the NMW study area (hereafter “Red Lake”) will be located within the boundaries of the Red Lake Indian Reservation in far northern Clearwater and west-central Beltrami counties, (2) the NLF study area (hereafter “Itasca”) will be focused within and around Itasca State Park in south-eastern Clearwater County, (3) sites located in western portions of the Chippewa National Forest in far western Itasca County, (4) the NGP study landscape (hereafter “Elbow Lake”) will be located in the southern portions of Grant County, extending into the northern and western margins of Stevens and Douglas counties, respectively (we have a long time series here, dating back the mid 1990’s), (5) the WCP study area (hereafter “Windom”) will be centered around Windom, MN, and thus roughly split between Cottonwood and Jackson counties, (6) the CHF study landscape (hereafter “Twin Cities”) will be located in the Hennepin-Carver county metro area (Figure 1).

Our study landscapes are also positioned in several different major river watersheds. In some cases, study areas fall within two or more drainages. For example, Red Lake is entirely within the Red River drainage, Itasca is entirely within the Upper Mississippi River drainage, but Twin Cities is within both the Upper Mississippi River and Minnesota River drainages. Similarly, Windom is within the Minnesota River and Lower Mississippi River drainages, and Elbow Lake is within the Red River and Minnesota River drainages.

### *Individual Study Sites*

Within each study landscape, up to 25 shallow lakes will be selected for measurement of fish assemblages, wetland characteristics, and surrounding landscape attributes. Study lakes will be distributed across both public and private ownerships. We expect that all lakes will be of semipermanent or permanent (type IV or V) duration of flooding (Shaw and Fredine 1956; Stewart and Kantrud 1971). Within these broad classifications, shallow lakes will be selected so as to span a range of values of surface area, depth, and adjacent upland cover types.

### *General Data Collection Approaches*

#### Development of land use and lake watershed variables using GIS and photo interpretation

Our approach relies on methods developed by Minnesota DNR Waters (Watershed Delineation Project [DNR-WDP]) which created a unique watershed methodology that incorporates three techniques: traditional on-paper; modern on-screen; and GIS-automated delineation into one comprehensive methodology. Merging these three techniques involves a complex, iterative process of heads-up on-screen digitizing and utilizes as many as 30 different datasets, sources of information and field reviews. Resulting products are best described as manually derived, human interpreted, “off-site” height of land watershed delineation, developed and maintained using GIS technology.

GIS data layers will be used to derive metrics that characterize features of the landscape associated with each study site. Both upstream and downstream hydrologic connectivity of each study site will be identified, delineated and digitized for analysis. Lake watershed boundaries

will be delineated for each site. When possible, existing land cover layers will be overlaid and summarized for the individual lake watersheds. GIS data layers will be used to derive metrics that characterize features of the lake watershed associated with each study site. Data summaries will be developed as needed. These will primarily include connectivity attributes, and watershed characteristics (e.g. surface area of different cover types, inter-lake surface connection distances, watershed:lake area ratios).

Landscape/watershed connectivity analyses may include but are not limited to the following: 1) presence of upstream/downstream connections to surface waters capable of supporting fish populations, 2) modeled upstream/downstream connections of surface water from digital elevation models (DEM) to surface waters capable of supporting fish populations, 3) network distances to represent “as the fish swims” to surface waters capable of supporting fish populations (horizontal and vertical dimensions), and 4) rank variable for type and degree of connectivity to other surface waters (also a potential proxy for geomorphic setting).

### Fish assemblages

Fish species composition and relative abundance (biomass per unit effort) will be determined using a combination of gears deployed overnight. All fish sampling will be done during July and August each year. Three mini-fyke nets (6.5 mm bar mesh with 4 hoops, 1 throat, 7.62 m lead, and a 0.69 X 0.99 m rectangular frame opening into the trap) will be set overnight in the littoral zone of each lake. One experimental gill net (61.0 m multifilament net with 19, 25, 32, 38, and 51-mm bar meshes) will be set along the deepest depth contour available in lakes less than 2 m deep or along a 2 m contour in lakes with sufficient depth. The protocol outlined above has been shown to be effective in sampling fish assemblages in shallow lakes in Minnesota (Herwig et al. In review) as well as small lakes from other regions (Tonn and Magnuson 1982; Rahel 1984; Jackson and Harvey 1989; Robinson and Tonn 1989). This should enable us to capture both small- and large-bodied fish, and species from all of the major trophic guilds (e.g., plankivores, benthivores, piscivores) potentially present in the study wetlands. All fish sampled will be sorted by species, rated (counts per unit weight), and weighed in bulk. Fish data will likely be summarized as the summed total biomass of each species collected in all four nets. Voucher specimens will be collected and returned to the laboratory for identification when field identification cannot be made.

### Aquatic invertebrates

Zooplankton will be sampled once per year in July concurrent with fish sampling by collecting two replicate vertical column samples (Swanson 1978) at 5 locations in each wetland. Estimates will be made of density and taxon richness. Relative abundance of macroinvertebrates will be sampled concurrent with other sampling in July using sweep net samples (Murkin et al. 1983) at 0.75m depth at 5 randomly selected locations in each lake. Abundance and taxon richness of macroinvertebrates will be measured.

### Nutrients, specific conductance, light attenuation, and phytoplankton

Surface (dip) water samples will be taken from the center of each lake once during July concurrent with other sampling. Samples will be frozen and transported to the University of St. Thomas (Dr. Kyle Zimmer’s lab) for analysis of chlorophyll *a*, total nitrogen, total phosphorus and total dissolved phosphorus. Turbidity will be measured in the field with a portable

nephelometer. Phytoplankton biomass will be estimated from chlorophyll *a* (Strickland and Parsons 1972). Collection of samples for chlorophyll *a* simultaneously with measurement of turbidity will allow assessment of the contribution of phytoplankton to turbidity, and ultimately to light attenuation.

### Submerged macrophytes

Abundance of submerged macrophytes and *Chara* spp. will be assessed using modified techniques of Jessen and Lound (1962), and Deppe and Lathrop (1992). In each lake, submerged macrophytes will be sampled at 15 stations located equidistant along four transects running the width of each basin in July or August of each year. Two throws of a weighted plant rake will be made at each station, and dragged along 3 m of lake bottom. Plants collected on the first throw will be weighed (all taxa combined) and frequency of occurrence (1 = sampled on one throw, or 2 = sampled on both throws) will be recorded for each plant species sampled. Plant data will be summarized as mass and frequency of occurrence (all taxa combined) averaged across the total number of throws used for each metric.

### Earthworms

We will collect earthworms in soils surrounding the study wetlands using a liquid extraction method with a solution of mustard powder (Laurence and Bowers 2002). Three 35 cm x 35 cm areas will be cleared of surface duff and immersed with a saturated solution of mustard. Extracted worms will be collected, preserved in 75% ethanol and identified into their ecological classification (Hale et al. 2005). We will correlate worm ecological classifications and abundances with the productivity and water quality characteristics of nearby water bodies.

### Intensive sampling

In consultation with MN Ducks Unlimited staff, we will identify 8 case study lakes to evaluate effectiveness of restoration strategies typically used by state, federal, and private organizations working on shallow lake management. Study sites will include lakes undergoing management manipulations during 2010-11. Specifically, we plan to assess the effectiveness either alone, or in combinations, of installation of fish barriers, water level draw downs, rotenone, and perhaps other measures to be prescribed by lake managers.

We will collect one year of data before and for one year after the management activity during the two years of LCCMR funding. We will measure the same predictor and response variables as described above in the *General Data Collection Approaches* section. The only difference is that response variables will be measured monthly from May through August for two years in the Intensive lakes, while the Extensive lakes are to be sampled only once in July of each year.

We will measure the effectiveness of the various management activities by assessing changes in ecosystem features following the specific manipulation to the lake. Variables to be assessed include water clarity, nutrient levels in the water column, and abundance and species composition of phytoplankton, submerged macrophytes, zooplankton, macroinvertebrates, and fish. The relative improvement in each of these variables will be assessed using data from our larger Extensive study for lakes in the same ecoregion. For example, it is difficult to quantify the degree of “successfulness” if lake-drawdown causes phytoplankton abundance to drop from 88 ug/L to 23 ug/L. However, the Extensive (140) lake study will help to quantify this change as

the lake shifting from a probable turbid-water state to a probably clear-water state following the drawdown. Interpreting lake response in the context of natural regional variability should also facilitate assessment of success across ecoregions where lake features naturally vary.

### *Data Analysis*

We anticipate applying a suite of analysis strategies to evaluate the various hypotheses outlined above. This is necessary because no single approach we are aware of allows for identification and measurement of multiple complex linkages discussed above. Our approach will include gradient analysis (ter Braak 1995; ter Braak and Smilauer 1998; McCune and Grace 2002), classification and regression tree techniques (Breiman et al. 1984, De'ath and Fabricus 2000), variance partitioning (Borchard et al. 1992; ter Braak and Wiertz 1994), mixed effect linear models (Littell et al. 2006), piecewise regression (Toms and Lesperance 2003), information-theoretic model selection techniques (Burnham and Anderson 1998; Anderson et al. 2000), and traditional parametric approaches (SLR, ANOVA) (Zar 1999). Collectively, our analyses are intended to provide evidence whether ecological features of study lakes differ in predictable ways (thus whether lakes can be grouped) and, if so, whether fish communities, landscape and lake watershed features, cover types, ambient nutrients, lake basin morphology, and climate and other regional patterns account for observed differences among groups. Analyses will likely include situations where data are pooled from all landscapes to ensure a considerable range of values in both predictor and response variables, and situations where analyses will be developed for each study landscape separately, especially if separate modeling improves predictive ability, or if region-specific prediction and models are required. Below we have highlighted four major statistical approaches that will be used: gradient analysis, classification and regression trees, variance partitioning via constrained ordination, and model selection using information-theoretic approaches.

Ordination techniques (principal components analysis or correspondence analysis) will be used to identify whether unique wetland fish assemblages exist among our study lakes (ter Braak 1995; ter Braak and Smilauer 1998). Once assemblage types are identified, we will use classification and regression tree (CART) analysis (a binary recursive partitioning technique) to develop two separate decision tree models to predict fish presence/absence, and type of fish assemblage present within a lakes based on environmental and landscape attribute variables (Breiman et al. 1984). Our response variables will be categorical; therefore, classification trees will be constructed. In classification tree analysis (CTA), the estimated probability for each response level is the fitted value, and the most significant split is determined by the largest likelihood-ratio chi-square statistic (Breiman et al. 1984). The splits are chosen to maximize the difference in the responses between the two branches of the split. Also, CART may perform well using input data, but model prediction may be very poor for new data sets (Lookingbill and Urban 2005). Several techniques will be used during tree building and pruning to avoid overfitting the data, and ensure parsimonious models, including 1) setting the minimum split value (minimum size split allowed, defined as a proportion of total sample), 2) setting the minimum number of cases included in a terminal node, and 3) overbuilding the trees, and then pruning back until k-folded (k=25) cross-validation errors plateau, or until there was no remaining residual error, and 4) model validation via comparison of misclassification rates for learning and validation data sets, where 30% of sites are left out as the validation set.

We will use direct gradient analysis (ter Braak 1986, 1995; ter Braak and Smilauer 1998) to relate major drivers (climate, ambient nutrients, landscape features, land use, lake morphometric

features, and more proximately, fish populations) to a suite of ecological characteristics of study lakes. More specifically via constrained ordination, we will use driver variables to predict lake responses such as water transparency, phytoplankton biomass, water-column nutrient concentrations, extent of submerged macrophytes, invertebrate abundance and community features, and other characteristics of each lake study site. Preliminary ordinations will be conducted using detrended correspondence analysis. This will be necessary to assess length of environmental gradients, thus to determine whether linear (redundancy analysis, RDA) or unimodal (canonical correspondence analysis, CCA) response models are likely most appropriate for analysis of these data (Van Wijngaarden et al. 1995). Previously, we have successfully used both linear and unimodal forms of gradient analysis on data sets similar to that described here (Zimmer et al. 2000, 2003; Hanson et al. 2005). Where necessary, response variables (water quality and invertebrate data, and others) will be log-transformed prior to analysis to equalize variances (Van Wijngaarden et al. 1995; ter Braak 1995). We anticipate using variance partitioning to assess the comparative importance of major drivers and the spatial scales at which they are functionally important (Borchard et al. 1992; ter Braak and Wiertz 1994). This will allow us to assess the relative contribution (“pure effect”) of each predictor variable, and to assess the statistical significance of each using Monte Carlo simulation procedures. Where necessary, we will use Bonferroni corrections (Rice 1990) to maintain experiment-wise Type 1 error rates of 0.05. All gradient analyses and variation partitioning will be performed using CANOCO 4.0 (ter Braak and Smilauer 1998).

Finally, we will also assess the relative strength of relationships among external drivers (e.g., climate, ambient nutrients, land use), within-lake drivers (morphometry, fish communities) and key ecosystem characteristics, such as water clarity or abundance of submerged macrophytes using an information-theoretic (IT) approach (Burnham and Anderson 1998; Anderson et al. 2000). Model selection involves consideration of problems associated with both overfitting (low-precision models due to too many parameters) and underfitting (models biased due to insufficient numbers of parameters) the data. The IT approach assesses the relative strength of support for competing models, and selects the most parsimonious model that adequately fits the data, representing the optimal tradeoff between over- and under-fitting the data (Hillborn and Mangel 1997). The IT approach is based on Akaike’s information criterion and it avoids pitfalls associated with more traditional approaches to model selection in multiple regression and ordination (i.e., forward and backward selection), as well as the problems inherent in use of null hypothesis testing (Johnson 1999; Anderson et al. 2000).

Using the techniques described above we also expect to test and evaluate data and models from our previous study by ecoregion. Various data combinations will be used to assess model performance and whether our approaches will be useful for different landscapes and, perhaps, for different time periods. Such analyses will be useful for determining whether or not management and restoration strategies need to be tailored to specific regional settings or be modified over time.

#### *Economic Analysis – Assessing Cost-Effectiveness of Management Options for Maintaining and Restoring Shallow Lakes*

An economic analysis will be conducted using the empirical data from all study lakes in identifying the water quality improvements (such as cost per unit of algae reduced [ $\mu\text{g/L}$  chlorophyll *a*]) resulting from various application of various management options being utilized or considered within Minnesota. We plan to quantify the costs of applying various combinations

of upland vegetation restoration (conversion of agriculture to grass) and in-lake habitat enhancements (fish removal, installation of barriers, etc.) to achieve a given measure of lake water quality improvement. We expect that costs of management options will vary widely among ecological regions due to regionally variability in lake characteristics, lakesheds, upland easement costs, property values, and other attributes of lakes and adjacent uplands.

Comparison of restoration costs will be informative and will help elucidate trade-offs on temporal and spatial scales. Some options may generate quick results but may need to be repeated frequently, so that variations in long-run costs (over multiple decades) will be important to consider. Easement costs for land to be restored to vegetative buffers are known to vary across regions of the state. Cost data for the management options being studied are known to be currently available or obtainable.

### **Synthesis and research products**

We will use data from 8 Intensive and 140 Extensive lakes and from characterization of associated watersheds to address specific hypotheses above. Along with results from our economic analysis, we will specifically address Results 1-3 as summarized in the attached Work Plan to develop and suggest management guidelines for shallow lakes based on data and outcomes from specific ecological regions of the state. Study results will be synthesized and distributed in the form of several peer-reviewed manuscripts and a project summary, the latter to be developed specifically for shallow lake managers in Minnesota.

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- Zimmer, K.D., Hanson, M.A., and Butler, M.G. 2001. Effects of fathead minnow colonization and removal on a prairie wetland ecosystem. *Ecosystems* 4: 346-357.
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**Mark A. Hanson**

Wildlife Research, Wetland Wildlife Populations & Research Group,  
Division of Fish & Wildlife, Minnesota Department of Natural Resources  
102 23<sup>rd</sup> NE, Bemidji, MN 56601  
ph. (218)308-2283; fax (218)755-2604; [mark.hanson@dnr.state.mn.us](mailto:mark.hanson@dnr.state.mn.us)

**Current Position:** Research Scientist and Project Leader, Wetland Wildlife Populations & Research Group

**Education:**

- B.A. in Biology, Cedarville College (OH), 1979
- M.A. in Biology, Bemidji State University (MN), 1982
- Ph.D. in Zoology, North Dakota State University, 1990

**Research Experience and Perspective:**

My research has long been directed toward development of ecologically-based management strategies for wetlands and shallow lakes. I have focused broadly on wetland ecology, relationships among wetland-dependent wildlife species, and interactions between wetland and shallow lake communities and landscape features. Long-term research themes have centered on food web interactions and effects of fish as structuring influences on native communities of invertebrates and water quality features of prairie wetlands and shallow lakes. Most recently, with collaborators and students, I have sought to identify and measure influences of upland vegetation features on communities and hydrological processes in small wetlands, and to use scale- and watershed-dependent landscape characteristics to model fish and invertebrate communities, and regime dynamics (shallow- v. clear-water states) in shallow lakes.

**Other Recent Projects:**

- 2004-2007 Functional linkages among landscapes and shallow lakes: evaluating roles of land use and fish on shallow lake characteristics. (with B. Herwig and K. Zimmer co PIs)
- 2000-2004 Efficacy of forested buffers for conservation of small wetlands (with B. Palik and others)
- 2000-2003 Evaluating use of walleye fry to suppress fathead minnow populations in shallow lakes (with B. Herwig and others).
- 1999-2005 Measuring responses of seasonal wetland communities to age structure and removal of adjacent forest (with students and others)

**Publications Related to This Proposal:**

- Zimmer, K.D., **M.A. Hanson**, B.R. Herwig, and M.L. Konsti. 2009. Thresholds and stability of alternative regimes in shallow prairie-parkland lakes of central North America. *Ecosystems* 12:843-852.
- Potthoff, A.J., B.R. Herwig, **M.A. Hanson**, K.D. Zimmer, M.G. Butler, J.R. Reed, B.G. Parsons, and M.C. Ward. 2008. Cascading effects of piscivore introductions in shallow lakes. *Ecological Applications* 45: 1170-1179.
- Hanson, M.A.**, K.D. Zimmer, M.G. Butler, B.A. Tangen, and N.H. Euliss, Jr. 2005. Biotic Interactions as determinants of ecosystem structure in prairie wetlands. *Wetlands* 25:764-775.
- Zimmer, K.D., **M.A. Hanson**, and M.G. Butler. 2003. Relationships among nutrients, phytoplankton, macrophytes, and fish in prairie wetlands. *Canadian Journal of Fisheries and Aquatic Sciences* 60:721-730.
- Angeler, D.G., P. Chow-Frazer, **M.A. Hanson**, and S. Sanchez-Carillo. 2003. Biomanipulation: a useful tool for freshwater wetland mitigation? *Freshwater Biology* 48:2203-2213.
- Zimmer, K.D., **M.A. Hanson**, and M.G. Butler. 2001. Effects of fathead minnow colonization and removal on a prairie wetland ecosystem. ***Ecosystems* 4:346-357.**
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- Hanson, M.A.**, and M.G. Butler. 1994. Responses of plankton, turbidity, and macrophytes to biomanipulation in a shallow prairie lake. *Canadian Journal of Fisheries and Aquatic Sciences* 51:1180-1188.

### **Brian R. Herwig**

Fisheries Research, Populations and Community Ecology Group,  
Division of Fish & Wildlife, Minnesota Department of Natural Resources  
2114 Bemidji Avenue, Bemidji, MN 56601  
ph. (218)308-2333; fax (218)755-4076; brian.herwig@state.mn.us

#### **Current Position**

Sr. Fisheries Research Biologist, Division of Fish & Wildlife, Minnesota DNR

#### **Education**

B.S. (Forest Science), 1995, University of Wisconsin, Madison, WI.

M.S. (Natural Resources and Environmental Sciences), 2002, University of Illinois, Champaign-Urbana, IL.

#### **Research Experience**

My current research focuses on the ecology of shallow lakes at community-, ecosystem-, and landscape-scales. I am especially interested in the ecology and influences of fish populations in shallow lakes.

Current and recent research projects include:

- 2004-2007. Evaluating functional linkages among landscapes and wetland attributes: assessing the roles of geomorphic setting, land use, and fish on wetland community characteristics. (M. Hanson and K. Zimmer co PIs)
- 2000-2003. Evaluation of walleye to suppress fathead minnow populations in Type V wetlands (M. Hanson, J. Reed, B. Parsons co PIs).

#### **Publications Relevant to This Proposal:**

- Zimmer, K.D., M.A. Hanson, **B.R. Herwig**, and M.L. Konsti. 2009. Thresholds and stability of alternative regimes in shallow prairie-parkland lakes of central North America. *Ecosystems* 12:843-852.
- Potthoff, A.J., **B.R. Herwig**, M.A. Hanson, K.D. Zimmer, M.G. Butler, J.R. Reed, B.G. Parsons, M.C. Ward, and D.W. Willis. 2008. Cascading food web effects of piscivore introductions in shallow lakes. *Journal of Applied Ecology* 45:1170-1179.
- Ward, M.C., D.W. Willis, **B.R. Herwig**, S.R. Chipps, B.G. Parsons, J.R. Reed, and M.A. Hanson. 2008. Consumption estimates of walleye stocked as fry to suppress fathead minnow populations in west-central Minnesota wetlands. *Ecology of Freshwater Fish* 17: 59-70.
- Herwig, B.R.**, and K.D. Zimmer. 2007. Population dynamics and prey consumption by fathead minnows in prairie wetlands: importance of detritus and larval fish. *Ecology of Freshwater Fish* 16:282-294.
- Zimmer, K.D., **B.R. Herwig**, and L.M. Laurich. 2006. Nutrient excretion by fish in wetland ecosystems and its potential to support algal production. *Limnology and Oceanography* 51:197-207.
- Hanson, M.A., K.D. Zimmer, M.G. Butler, B.A. Tangen, **B.R. Herwig**, and N.H. Euliss. 2005. Biotic interactions as determinants of ecosystem structure in prairie wetlands: an example using fish. *Wetlands* 25:764-775.

## **Kyle D. Zimmer**

Department of Biology, University of St. Thomas  
Mail # OWS390, 2115 Summit Avenue, St. Paul, MN 55105  
ph. (651)962-5244; fax (651)962-5201; kdzimmer@stthomas.edu

### **Current Position**

Associate Professor, Department of Biology, University of St. Thomas

### **Education**

B.A. (Biology), 1992, Luther College, Decorah, IA.

M.A. (Biology, Fisheries Emphasis), 1994, St. Cloud State University, St. Cloud, MN.

Ph.D. (Zoology), 2001, North Dakota State University, Fargo, ND.

Postdoctoral Associate, 2001-2003, University of Minnesota, St Paul, MN.

### **Research Experience**

Dr. Zimmer's research focuses on community and ecosystem ecology of shallow lakes and wetlands. He is particularly interested in food-web interactions involving fish, and the subsequent effect of these interactions at the ecosystem scale. Current and recent research projects include:

2009 - 2012. Collaborative Research (RUI): Burial of organic carbon in temperate, shallow lakes. Funded by the National Science Foundation (K. Theissen, J. Cotner, and M. Edlund co PIs).

2005 - 2008. Carbon Sequestration in Minnesota's Wetlands: An Important Sink with Management Implications. Funded by the Initiative for Renewable Energy and the Environment (K. Theissen, J. Cotner, and S. Sugita co PIs).

2004 - 2007. Evaluating functional linkages among landscapes and wetland attributes: assessing the roles of geomorphic setting, land use, and fish on wetland community characteristics. (M. Hanson and B. Herwig co PIs).

### **Publications Relevant to This Proposal:**

**Zimmer, K.D.**, M.A. Hanson, B.R. Herwig, and M.L. Konsti. 2009. Thresholds and stability of alternative regimes in shallow prairie-parkland lakes of central North America. *Ecosystems* 12:843-852.

Potthoff, A.J., B.R. Herwig, M.A. Hanson, **K.D. Zimmer**, M.G. Butler, J.R. Reed, B.G. Parson, M.C. Ward, and D.W. Willis. 2008. Cascading food web effects of piscivore introductions in shallow lakes. *Journal of Applied Ecology* 45:1170-1179.

Verant, M.L., M.L. Konsti, **K.D. Zimmer**, and C.A. Deans. 2007. Factors influencing nitrogen and phosphorus excretion rates by fish in a shallow lake. *Freshwater Biology* 52:1968-1981.

Herwig, B.R., and **K.D. Zimmer**. 2007. Population dynamics and prey consumption by fathead minnows in prairie wetlands: importance of detritus and larval fish. *Ecology of Freshwater Fish* 16:282-294.

Scheffer, M., G.J. van Geest, **K.D. Zimmer**, E. Jeppesen, M.G. Butler, M.A. Hanson, M. Søndergaard, S. Declerck, and L. De Meester. 2006. Small habitat size and isolation can promote species richness: second-order effects on biodiversity in shallow lakes and ponds. *Oikos* 112:227-231.

**Zimmer, K.D.**, B.H. Herwig, and L.M. Laurich. 2006. Nutrient excretion by fish in wetland ecosystems and its potential to support algal production. *Limnology and Oceanography* 51:197-207.

Hanson, M.A., **K.D. Zimmer**, M.G. Butler, B.A. Tangen, B.H. Herwig, and N.H. Euliss. 2005. Biotic interactions as determinants of ecosystem structure in prairie wetlands: an example using fish. *Wetlands* 25:764-775.

**Zimmer, K.D.**, M.A. Hanson, and M.G. Butler. 2003. Interspecies relationships, community structure, and factors influencing the abundance of submerged macrophytes in prairie wetlands. *Wetlands*:717-728.

# James Bryan Cotner

Zimmer, K.D., M.A.  
2002. Effects of  
restoration on prairie

Department of Ecology, Evolution and Behavior  
University of Minnesota St. Paul, MN 55108

Hanson, and M.G. Butler.  
fathead minnows and  
wetland ecosystems.

Telephone: 612-625-1706/FAX: 612-624-6777 email: [cotne002@umn.edu](mailto:cotne002@umn.edu)

**Current position:** Professor, Department of Ecology, Evolution and Behavior, University of Minnesota

**Education:** Freshwater Biology 47:2071-2086.

B.A., Wittenberg University, Springfield, Ohio, 1981, Biology.

M.Sc., Kent State University, Kent, Ohio, 1984. Biology.

Ph.D., University of Michigan, Ann Arbor, 1990. Biology.

Post-doctoral research fellow, Great Lakes Environmental Research Laboratory and University of Michigan, Biological Limnology and Oceanography, 1990-1992.

**Research Experience:** The goal of my research program is to understand how bacteria and humans affect biogeochemical processes in aquatic systems. Microbes are incredibly important to ecosystem processes because of the great magnitude of their biomass and their diverse modes of heterotrophy and autotrophy. Because of this diversity of function, bacteria have significant impacts on the geochemistry of lakes, rivers and oceans. Humans have important effects on lakes and rivers through landscape and species alterations. Current research projects are focused on the Laurentian Great Lakes carbon and phosphorus cycling and the role of shallow lakes and wetlands in the global carbon cycle. Current funded projects:

*2007-09 NSF REU (\$224,000) for "Field Studies in Global Change at the Headwaters of the Mississippi" , PI: J. Cotner, co-PI: S. Cotner.*

*2009-2012 NSF Ecosystems RUI for "Burial of organic carbon in temperate, shallow lakes. (K. Theissen, J. Cotner, and M. Edlund co PIs).*

## **Publications relevant to this proposal:**

Cotner, J.B., J. Kenning and J.T. Scott. 2009. The microbial role in littoral zone biogeochemical processes: Why Wetzel was right. *Verh. Internat. Verein. Limnol.* 30 (6): 981-984.

Cotner, J.B., and B.A. Biddanda. 2002. Small players, large role: Microbial influence on auto-heterotrophic coupling and biogeochemical processes in aquatic ecosystems. *Ecosystems* 5, 105-121.

Biddanda, B.A., and J.B. Cotner. 2002. Love handles in aquatic ecosystems: Role of dissolved organic carbon drawdown, resuspended sediments and terrigenous inputs in the carbon balance of a Great Lake (Michigan). *Ecosystems* 5: 431-445.

Biddanda, B., M. Ogdahl and J.B. Cotner. 2001. Dominance of bacterial metabolism in oligotrophic relative to eutrophic waters. *Limnology and Oceanography* 46: 730-739.

Cotner, J.B., T.H. Johengen, and B.A. Biddanda. 2000. Intense winter heterotrophic production stimulated by benthic resuspension. *Limnology and Oceanography* 45: 1672-1676.

**Sean R. Vaughn**  
GIS Hydrologist  
Division of Waters, Minnesota Department of Natural Resources  
800 Oak Savanna Lane SW  
ph. (763)689-7106; fax (763)689-7120; [sean.vaughn@state.mn.us](mailto:sean.vaughn@state.mn.us)

***Current Position:*** GIS Hydrologist, DNR Watershed Delineation Project - Project Manager

***Education:***

B.S. Water Resources - Hydrology, University of Minnesota, St Paul, MN, 1989

***Experience and Perspective***

Over the long term, my work has focused on the identification, delineation and digitization of hydrologic features of the surface water system for client consumption and incorporation into GIS applications. As a GIS Hydrologist I have strived to produce watershed delineations that accurately represent the hydrology of the landscape. My intent is to produce watersheds that function as containers of hydrologic entities for modeling and GIS analysis. More recently, I have emphasized the importance of proper watershed data utilization associated with water quality and decision making processes through client and data-user education.

***Other Recent Projects:***

- 1998 – Present. DNR Watershed Delineation Project. I Developed all aspects of this intricate statewide project from the ground up, including: project design, GIS production, methodology design and documentation, problem solving, database design, hydrologic-GIS analysis and data development.
- 2004 – 2007. Evaluating functional linkages among landscapes and wetland attributes: assessing the roles of geomorphic setting, land use, and fish on wetland community characteristics. (with B. Herwig, M. Hanson and K. Zimmer co PIs)
- 1993 – 1998. Developed an inventory methodology to identify drained wetland boundaries in Chisago County, Minnesota employing the integration of aerial photography interpretation, National Wetlands Inventory, scope and effect of surface water channelization and hydric soil.

***Publications Related to This Proposal:***

Vaughn, S.R., 2009. DNR Watershed Delineation: *Project History, Methodology, Terminology & Data Attribution*. Minnesota Department of Natural Resources - Waters. Print

## VITA FOR PATRICK G. WELLE

**CONTACT INFORMATION:** Department of Economics, DH20, # 30  
Bemidji State University Bemidji, MN 56601  
(218) 755-3873, Fax: (218) 755-4107  
e-mail: pwelle@bemidjistate.edu

**PRESENT POSITION:** Professor of Economics & Environmental Studies  
Bemidji State University: Sept. 1982 - present

**EDUCATION:** Ph.D. Economics, 1986, Univ. of Wisconsin-Madison  
M.A. Economics, 1980, Univ. of Wisconsin-Madison  
B.A. 1978, St. John's Univ.-Collegeville, MN

### RECENT PUBLICATIONS:

- Boody, Gowda, Westra, van Schaik, Welle, Vondracek and Johnson, "Multifunctional Grass Farming: Science and Policy Considerations," forthcoming in the conference proceedings Farming With Grass, Soil and Water Conservation Society, 2009.
- Welle, Cloutman, Koch and Parson, "Biological and Shoreline Trend Monitoring at Tea Cracker Lake, Becker County, MN," technical report to the Minnesota Pollution Control Agency, December 2008.
- Welle and Hodgson, "Property Owners' Willingness To Pay For Restoring Impaired Lakes: A Survey In Two Watersheds of the Upper Mississippi River Basin," technical report to the Minnesota Pollution Control Agency, October 2008.
- Welle, Cloutman, Koch and Parson, "Biological and Shoreline Trend Monitoring at Beauty Lake, Hubbard County, MN," technical report to the Minnesota Pollution Control Agency, December 2006.
- Boody, Vondracek, Andow, Krinke, Westra, Zimmerman, and Welle, "Multifunctional Agriculture in the United States", BioScience, Vol. 55, No.1, January 2005.
- Krysel, Marsh Boyer, Parson and Welle, "Lakeshore Property Values and Water Quality: Evidence from Property Sales in the Mississippi Headwaters Region," technical report to the Legislative Commission on Minnesota Resources, June 2003.
- Welle, "Economic Perspectives on Water: Clean Water Makes Good Sense (Cents and Scents)," Focus on the Water, Vol. 13, No. 3, May 2002.
- Welle, "Multiple Benefits from Agriculture: A Survey of Public Values in Minnesota", technical report to the Legislative Commission on MN Resources, July 2001.

Attachment A: Budget Detail for 2010 Projects											
Project Title: Sustainable, Cost-Effective Approaches to Management of Shallow Lakes											
Project Manager Name: Mark A. Hanson											
Trust Fund Appropriation: \$ 262,000											
2010 Trust Fund Budget	Result 1 Budget:	Amount Spent (date)	Balance (date)	Result 2 Budget:	Amount Spent (date)	Balance (date)	Result 3 Budget:	Amount Spent (date)	Balance (date)	TOTAL BUDGET	TOTAL BALANCE
	Identify and estimate major factors responsible for deterioration of shallow lakes in 6 areas of Minnesota			Evaluate and refine specific strategies for restoring shallow lakes in Minnesota			Identify surface connectivity elements threatening water quality and biodiversity in shallow lakes				
<b>BUDGET ITEM</b>											
<b>PERSONNEL: wages and benefits</b>											
Student Interns (4) - 140 Extensive lakes (per each approximately 4 mos during each year)	54,000	0	54,000			0			0	54,000	54,000
Student Interns (4) - 8 Intensive lakes (per each approximately 4 mos during each year)			0	54,000	0	54,000			0	54,000	54,000
Sean Vaughn (DNR Hydrologist-25% time - 1			0			0	15,000	0	15,000	15,000	15,000
Kyle Zimmer (Univ St. Thomas- 1.5 mo.summer salary)	10,000	0	10,000			0			0	10,000	10,000
UM technician (1;supervised by J.Cotner-50% 1	29,000	0	29,000			0			0	29,000	29,000
<b>Contracts</b>			0			0			0	0	0
Bemidji State University - Graduate student support			0	30,000	0	30,000			0	30,000	30,000
<b>Capital equipment over \$3,500</b>			0			0			0	0	0
2 14-ft aluminum boats with small outboard motors-for use sampling 8 intensive lakes			0	8,000	0	8,000			0	8,000	8,000
<b>Supplies</b>			0			0			0	0	0
Field sampling gear, nets, etc.	3,500	0	3,500	3,500	0	3,500			0	7,000	7,000
Lab supplies, storage containers, etc.	2,500	0	2,500	2,500	0	2,500			0	5,000	5,000
<b>Travel expenses in Minnesota</b>			0			0			0	0	0
Travel (fleet/fuel costs) to 140 extensive lakes	18,000	0	18,000			0			0	18,000	18,000
Lodging to sample 140 extensive lakes	5,400	0	5,400			0			0	5,400	5,400
Per diem to sample 140 extensive lakes	1,600	0	1,600			0			0	1,600	1,600
Travel (fleet/fuel costs) to 8 case study lakes			0	18,000	0	18,000			0	18,000	18,000
Lodging to sample 8 case study lakes			0	5,400	0	5,400			0	5,400	5,400
Per diem to sample 8 case study lakes			0	1,600	0	1,600			0	1,600	1,600
<b>Other</b>			0			0			0	0	0
<b>COLUMN TOTAL</b>	<b>\$124,000</b>	<b>\$0</b>	<b>\$124,000</b>	<b>\$123,000</b>	<b>\$0</b>	<b>\$123,000</b>	<b>\$15,000</b>	<b>\$0</b>	<b>\$15,000</b>	<b>\$262,000</b>	<b>\$262,000</b>
Date: 12-29-09											