2010 Project Abstract
For the Period Ending June 30, 2012

PROJECT TITLE: Assessment of Shallow Lake Management
PROJECT MANAGER: Mark A. Hanson
AFFILIATION: Wetland Wildlife Populations & Research Group, Minnesota DNR
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WEB SITE ADDRESS: none
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2010, Chap. 362, Sec. 2, Subd. 5g
APPROPRIATION AMOUNT: $ 262,000

Overall Project Outcome and Results: Assessment of Shallow Lake Management
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 many valuable ecosystem services including carbon sequestration, habitat for native species, and unique recreational opportunities. 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. To facilitate better conservation of these areas, we studied approximately 140 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 included: 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 help managers identify which restoration strategies are likely to produce the greatest improvements in water quality and other lake characteristics per unit cost. Our key findings were as follows:

- High nutrient levels and dense populations of undesirable fishes favor water quality deterioration. These influences increase along a NE-SW gradient. Turbid lakes more often occur in prairie than in forested regions.
- Fish removal via rotenone, water control structures, and drawdowns improve water quality and wildlife habitat. Deteriorated conditions often recur; this underscores need for long-term approaches that reduce nutrient loading.
- Fish removal via rotenone and drawdown are effective methods for improving lakes in the short-term (5-10 years). Because improvements may not persist, watershed restoration to reduce nutrient loading is also necessary. More monitoring of rehabilitated

lakes is necessary. Region-specific guidelines are not yet possible, but in-lake measures will be most beneficial in short-term, regardless of where lakes are located.
- Limiting surface connectivity is critical to controlling distribution of undesirable fishes including invasive species.

These findings were used to develop improved modeling and produced a series of recommendations to guide future efforts to maintain and rehabilitate shallow lakes throughout Minnesota. This information is being disseminated through future presentations and publications and through the Minnesota DNR Data Deli website (http://deli.dnr.state.mn.us/).

Project Results Use and Dissemination

We anticipate preparation of 5-8 peer reviewed manuscripts to be developed from data gathering and analyses completed during the present study. We are also planning to develop a shallow lake workshop for lake managers and other conservation partners to be held in central Minnesota during July or August 2013. We expect to offer a day-long technical program that will center on results of the present LCCMR-funded research, allow discussion of lake rehabilitation strategies, and will offer opportunities for project managers and collaborators to present study findings directly to lake and landscape managers and other conservation partners in Minnesota. Presently, the Minnesota Chapter of the Wildlife Society has agreed to sponsor this workshop and to coordinate meeting and facilities requirements.

Results and synthesis from this work have been presented at annual meetings of the American Society of Limnology (Lake Biwa, Shiga, Japan, July 2012), the Ecological Society of America (Portland, Oregon, Aug 2012), and at various regional meetings of DNR staff and others. In addition, results have been distributed to DNR staff, other professionals, and the general public via annual project summaries from the Wildlife Research Unit, Minnesota DNR. We expect to develop 5-8 manuscripts for publication during the next 2-3 years.

Environment and Natural Resources Trust Fund (ENRTF)
2010 Work Program – Final Report

Date of Report: August 14, 2012
Final Report
Date of Work Program Approval:
Project Completion Date:

I. PROJECT TITLE: Assessment of Shallow Lake Management

Project Manager: Mark A. Hanson
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FAX Number: 218.755.2604
Web Site Address: none

Location: 6 study areas as indicated below

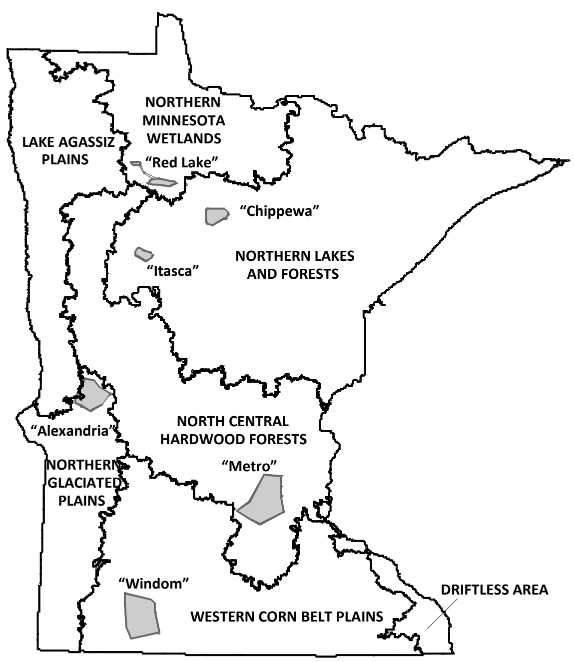

Figure 1. Map showing locations of proposed study landscapes (shaded gray) in relationship to Minnesota's aquatic ecoregions (thick black lines).

Total ENRTF Project Budget:	**ENRTF Appropriation**	**$**	**262,000**
	Minus Amount Spent:	**$**	**261,390**
	Equal Balance:	**$**	**610**

Legal Citation: M.L. 2010, Chap. 362, Sec. 2, Subd. 5g

Appropriation Language:
$262,000 is from the trust fund to the commissioner of natural resources to evaluate the major causes of deterioration of shallow lakes in Minnesota and evaluate results of current management efforts. This appropriation is available until June 30, 2013, by which time the project must be completed and final products delivered.

II. and III. FINAL PROJECT SUMMARY

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 many valuable ecosystem services including carbon sequestration, habitat for native species, and unique recreational opportunities. 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. To facilitate better conservation of these areas, we studied approximately 140 shallow lakes in 5 ecological regions of Minnesota to:

- Identify major factors leading to deterioration
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- Assess the impacts of increased surface water connectivity on fish invasions and resulting habitat quality

Our efforts included: 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 help managers identify which restoration strategies are likely to produce the greatest improvements in water quality and other lake characteristics per unit cost. Our key findings were as follows:

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- Fish removal via rotenone, water control structures, and drawdowns improve water quality and wildlife habitat. Deteriorated conditions often recur; this underscores need for long-term approaches that reduce nutrient loading.
- Fish removal via rotenone and drawdown are effective methods for improving lakes in the short-term (5-10 years). Because improvements may not persist, watershed restoration to reduce nutrient loading is also necessary. More monitoring of rehabilitated lakes is necessary. Region-specific guidelines are not yet possible, but in-lake measures will be most beneficial in short-term, regardless of where lakes are located.

- Limiting surface connectivity is critical to controlling distribution of undesirable fishes including invasive species.

These findings were used to develop improved modeling and produced a series of recommendations to guide future efforts to maintain and rehabilitate shallow lakes throughout Minnesota. This information is being disseminated through future presentations and publications and through the Minnesota DNR Data Deli website (http://deli.dnr.state.mn.us/).

IV. OUTLINE OF PROGRESS RESULTS

Description of study efforts here are described in cumulative fashion, and reflect chronological development of our study results during past 2 years. This was required by our research approach, and by our analysis which also developed throughout the study. To convey details of our findings, periodic project updates were retained in this final project summary. As above, key findings for each Result are summarized in a text block at the beginning of each Result Status section of this final report.

PROGRESS SUMMARY: December 31, 2011

The period of July – December 2011 marked significant progress in all major areas of this research. Despite the ~3 week shut-down of state government, we were able to complete almost all scheduled sampling, including fish and submerged plant surveys and collections of invertebrates and water chemistry at the Extensive lakes as planned. However, we were only able to sample Intensive lakes once during June 2011, and a second time during July-August, instead of monthly sampling during June, July, and August as originally planned.

Significant progress was also made toward development and summarization of GIS watershed delineations and other spatial features including land cover types, surface connectivity networks, and categorization and quantification of degree of connections among study sites and upstream and downstream water bodies (i.e., potential fish sources).

We again made progress on our economic comparisons of lake rehabilitation strategies. Data sets comprising key elements of lake condition, including chlorophyll *a* (Chla), total phosphorus, land cover proportions (e.g., % agriculture in the watershed), and fish biomass per unit effort have been compiled electronically and were sent to our staff biometrician for statistical analysis. We also have preliminary linear mixed models (lake was treated as random effect to account for repeated observations) describing relative influences of within-lake drivers (e.g., fish) versus watershed land use in determining lake condition (expressed in terms of Chla). Simultaneously, we are gathering information on "costs" of watershed restoration and within-basin management activities, and intend to develop models that bridge the benefit and cost sub-models. In the next six months, our goal is to develop a tool that allows managers and planners to identify cost-effective rehabilitation strategies for Minnesota shallow lakes.

PROGRESS SUMMARY: June 30, 2011

Priority during January – June 2011 was given to data development and analysis for the Extensive portion of our research (128 lakes). We emphasized laboratory, data entry, and GIS-related accomplishments, along with development and integration of data from lakes in the Red Lake region. Interns made major progress enumerating aquatic invertebrates in samples collected during field season 2010; electronic data files were updated and archived accordingly. GIS was used to refine and complete watershed delineations for all remaining study lakes in Metro, Windom, Itasca, and Chippewa study areas (Figure 1). We gave special attention to identifying surface connectivity features of study lakes, updating digital data with observations made during field reconnaissance in 2010. Additionally, we completed delineation of land cover types within 100-m buffers adjacent to all study lakes in the same 4 areas. We are currently preparing to sample all Extensive lakes again during July 2011.

As part of our efforts to assess lake responses to prior rehabilitation, we are again sampling all Intensive lakes in 2011. During May 2011 we sampled for water transparency, phytoplankton abundance (Chla), and aquatic invertebrates (as summarized in Table 1). We plan to continue sampling Intensive lakes at approximately monthly intervals through August 2011. Along with work on intensive lakes, we made progress on our economic comparisons of lake rehabilitation approaches. To date, we have developed a conceptual framework for this effort and compiled an extensive bibliography summarizing related literature.

PROGRESS SUMMARY: December 31, 2010

Our research is aimed at describing characteristics of shallow lakes in Minnesota, identifying factors influencing key ecological features and potential deterioration of these sites, comparing costs of possible management alternatives, and synthesizing results in a way that provides guidance for shallow lake management in Minnesota. We selected two groups of lakes for sampling and evaluation. A first group of 127 lakes were distributed among 6 regions of the state and represented a range of water quality and upstream watershed conditions. A second group of 8 lakes were selected based on their management history; each had been enhanced to improve habitat conditions using combinations of drawdown and reflooding, rotenone treatments, and piscivore stocking during the past 2-3 years. In each study lake, we sampled fish populations, abundance of submerged aquatic plants, aquatic invertebrates, water transparency, and a suite of chemical constituents in lake waters. Samples from lake water columns were collected in the field and are being tested for nitrogen, phosphorus, dissolved inorganic and organic carbon, Chla (as a proxy for phytoplankton biomass), and other limnological characteristics. Results of these analyses should give us comprehensive views of plant and animal communities and water quality characteristics of shallow lakes across Minnesota, and should help us identify factors affecting characteristics of these lake sites. We also plan to describe how influencing mechanisms differ among ecological regions of the state, and we expect to compare potential effectiveness of alternative management approaches based on ecological relationships and regional variation in magnitude of key influences.

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: $ 145,160.62
Amount Spent: $ 144,550.92
Balance: $ 609.70

Deliverables	**Completion Date**	**Budget**
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:		
1. Identify and select approximately 140 shallow lakes for use as study sites (Winter 2009-2010)		Non-LCCMR
2. Purchase field work supplies	Aug 30, 2011	$ 9,455
3. Travel/lodging to research sites in Minnesota	Aug 30, 2011	$ 17,000
4. 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	$ 76,000
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	$ Included above (#4)
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. Develop and distribute recommendations for management to improve habitat conditions in shallow lakes. To accomplish this, we will:		

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 literature		Non-LCCMR

Final Result 1 Summary: June 30, 2012

Overview of Result 1: A key finding from studies of Extensive Lakes was high variability among the 6 study regions in nearly all variables summarized to date including background nutrient levels, phytoplankton and zooplankton, aquatic macroinvertebrates, fish community characteristics, and other features. This means that even obvious features of shallow lakes should be expected to differ across ecological regions of the state. Background nutrient levels, surface water connectivity patterns, fish community characteristics, and perhaps other land use aspects influence liklihood of shallow lake transitions from clear- to turbid-water regimes. Data gathered here, along with findings from other investigators, support the hypothesis that potential for turbid shifts (and reduced water quality) increases with higher phosphorus concentrations, more extensive surface-water connectivity, and higher mass of planktivorous and benthivorous fishes (fish mass). In-lake phosphorus levels and fish mass appear to have major influences on shallow lake communities and dramatically influence potential for shifts to turbid regime conditions. Broadly, this indicates that vulnerability of shallow lakes to turbid-shifts increases with increasing lake productivity, higher fish densities, and perhaps greater landscape development for agriculture along a NE – SW gradient statewide. Turbid lakes more often occur in prairie than in forested regions although turbid lakes are present in forested areas. Fish mass and perhaps historical patterns of land use and climate appear to mask effects of present day land use, making it difficult to identify relationships between land cover characteristics in lake watersheds and lake community features.

Key Findings:

A. Provide a clear understanding of specific roles of fish as determinants of shallow lake water quality and habitat features along regional gradients. Along with high levels of nutrients, dense populations of planktivorous and benthivorous fishes (such as minnows, bullheads, carp, and other species) are important causes of water quality deterioration in shallow Minnesota lakes. Influence of high levels of phosphorus and undesirable fishes are more widespread along a NE-SW gradient, but these factors can also be important deterrents to lake quality in forested regions of the state. Increased surface-water connectivity is one key factor leading to widespread nuisance fish populations in Minnesota's shallow lakes.

B. Develop and distribute recommendations for management to improve habitat conditions in shallow lakes. Specific recommendations for lake managers will be distributed at a day-long workshop to be held during summer 2013 (sponsored by the Minnesota Chapter of the Wildlife

Society). Lake management guidelines will emphasize controlling surface water connectivity and in-lake measures as means of regulating undesirable fish populations.

Result Status as of December 31, 2010

A. Provide a clear understanding of specific roles of fish as determinants of shallow lake water quality and habitat features along regional gradients

Collaboration and Site Selection: Extensive sampling of lakes in 6 geographic areas of Minnesota required collaboration among research partners (Herwig, Zimmer, Bowe, Cotner, Vaughn, Welle, and others identified in our Research Addendum) and with private land owners, city and county land managers, MN DNR Wildlife Managers, representatives from the Red Lake and Leech Lake Indian Reservations, and US Fish and Wildlife Service Wetland Management Districts. Our project spending plan requires research contracts with the University of St. Thomas (UST, St. Paul, through Dr. Zimmer) and the University of Minnesota (UM, through Dr. Cotner). Currently, we are finalizing the contract with UST; contracting with UM has already been completed.

Using methods described in our work plan, we selected study lakes in 6 landscape areas distributed among 5 Ecoregions of Minnesota. The following numbers of lakes were selected for study (after Figure 1): Twin Cities 22, Windom 22, Alexandria 23, Itasca 22, Chippewa 15, and Red Lake 23. We sampled a total of 127 lakes for this extensive aspect (Result 1) of our study. We had planned to sample approximately 17 more lakes during 2010, but this was not practical due to low-water conditions, unexpected characteristics of lakes (such as alteration due to damming by beavers, extreme depth, or other features not noted until field visits), and because in at least one case land ownership changed before onset of our study.

Data Gathering: All sites were sampled during July-early August 2010. At each study lake (as described in our work plan), we sampled fish populations, abundance of submerged aquatic plants, aquatic invertebrates, water transparency, and a suite of chemical constituents in lake waters (Table 1). Samples from lake water columns were collected in the field and are being tested for turbidity and concentrations of dissolved inorganic and total nitrogen, dissolved and total phosphorus, dissolved inorganic and organic carbon, Chla (as a proxy for phytoplankton biomass). Additional laboratory analyses are being conducted on water column particulate matter (seston) to determine concentrations of carbon, nitrogen, and phosphorus suspended in lake water columns. Field crews collected approximately 1,260 samples of aquatic invertebrates from study lakes. Samples are currently being processed and we expect that resulting electronic data sets will be developed by summer 2011.

Table 1. Summary of lake variables sampled during summer 2010. Similar data were gathered from Extensive (N=127) and Intensive (N=8) lakes except that Intensive lakes were sampled during June, July, and August. Extensive lakes were sampled a single time during July.

Biological	Physical	Chemical
Fish abundance (gill and trap nets)	Turbidity	Total Nitrogen

	Submerged aquatic plants (rake and mass) methods	Specific Conductivity	Dissolved Inorganic Nitrogen
	Aquatic invertebrates (sweep nets, column samplers)		Total Phosphorus
	Phytoplankton abundance (chlorophyll a)		Dissolved Phosphorus
			Dissolved Inorganic Carbon
			Dissolved Organic Carbon
			Seston Phosphorus
			Seston Carbon
			Seston Nitrogen

Earthworm Sampling in Itasca Study Area: We investigated the influence of earthworms on lake productivity and soil properties in ten small watersheds within or near Itasca State Park, Minnesota. Worms were extracted from soils to measure biomass, and soil properties and lake properties characterized. We observed a wide range of worm impact among the sampled lakes Dissolved organic phosphorus (DOP), dissolved organic carbon (DOC), and total nitrogen (TN) in the lakes was highest at intermediate worm biomass in the surrounding soils, suggesting that intermediate biomass sites are active invasion zones where worms are releasing high amounts of previously tied up nutrients. In the soils, we measured wet bulk density, percent water, total organic matter and organic phosphorus (P) and found that at intermediate worm biomass, organic P levels decreased in the soil, while bulk density increased. We hypothesize that extremes in biomass represent different degrees of invasion with fewer anecic worms (e.g. the soil dwelling, vertical burrowing common nightcrawler, *Lumbricus terrestris*) at the low extreme and higher abundances at the intermediate and high end, but at this extreme more of the nutrients have already been removed from the soil. This implies that earthworms have potential to contribute most to aquatic eutrophication as anecic worms are actively invading.

Preliminary Data Trends: (Data presented here are from 5 of 6 study regions; we have not yet summarized data from our Red Lake sites although we expect to receive them in the near future. We caution that data and summaries presented below are preliminary; results and interpretation may change with additional data and analyses.)

Total phosphorus – As expected, TP values in study lakes showed a weak increasing trend along a general north-south gradient from Itasca to Windom areas, with highest median values recorded for lakes within the Windom core. Smallest variation in TP values among lakes was observed within the Itasca study area, where mean and range values were < 5 um L^{-1}. Median values in the Metro were comparable to those observed in other study areas, but showed greater variability due to one record of extremely high TP (>20 um L^{-1}).

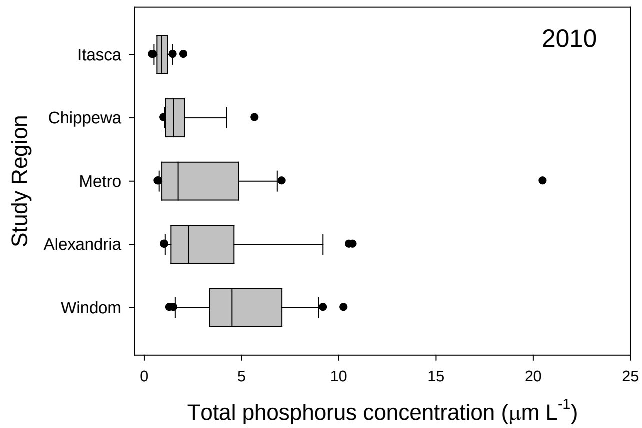


Figure 2. Box plots showing mean abundance of total phosphorus (TP) for 127 shallow lakes sampled within 5 study regions during 2010. Vertical lines within boxes depict median TP values for each study region; extent of boxes depict 25th and 75th percentiles. Whiskers show 10th and 90th percentiles, with dots indicating more extreme values.

Submerged aquatic plants, phytoplankton, and regime implications – In general, phytoplankton was more abundant in lakes in west-central and southern study regions, especially in Windom lakes, where values approached 100 ug L^{-1}. Other recent research on shallow Minnesota suggested that lakes below 22 and above 31 ug L^{-1} were most often characterized as clear- or turbid- regimes sites, respectively (Zimmer et al. 2009). Comparing our current lakes to those threshold values suggests that lakes in Itasca, Chippewa, and Metro study areas were most often characterized by phytoplankton levels falling within the range expected for clear-regimes. In contrast, many Alexandria and Windom lakes showed phytoplankton levels in excess of thresholds expected for turbid-regime lakes (Figure 3). This indicates higher probability for lakes in Alexandria and Windom to show characteristics associated with turbid regimes.

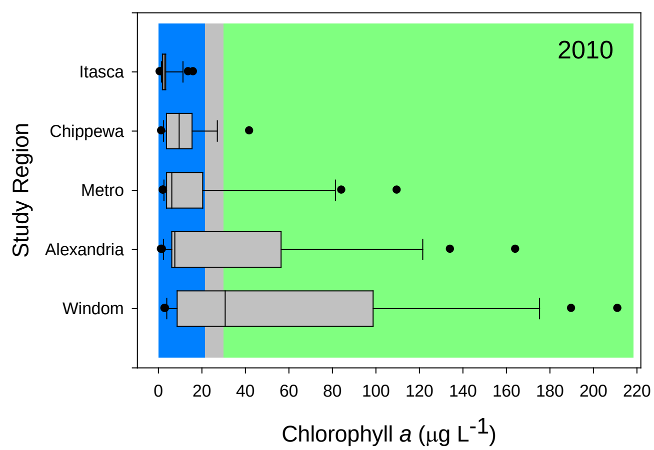


Figure 3. Box plots showing mean abundance of phytoplankton (chlorophyll *a* concentration) for 127 shallow lakes sampled within 5 study regions during 2010. Background colors depict expected chlorophyll *a* regions for clear- (blue), transition (grey), and turbid-regimes (green) based on threshold values after Zimmer et al. (2009).

Submerged aquatic plants are key ecosystem components of lakes and dense plant communities are known to favor clear-water regimes in Minnesota's shallow lakes. Our preliminary data show that abundance of submerged plants varies widely from lake-to-lake and among study regions in Minnesota. Lakes supporting high mass of submerged plants showed relatively low abundance of phytoplankton (chlorophyll a); alternatively no lakes with chlorophyll a concentrations above 50 ug l^{-1} showed high abundance of submerged macrophytes (Figure 4). Preliminary data also suggested that these patterns vary considerably among study regions. For example, most Windom, Alexandria, and Metro-area lakes had high abundance of either macrophytes or phytoplankton. In contrast, lakes in our Itasca and Chippewa study region were dominated by macrophytes, but abundance was much lower than in other ecoregions. This suggests macrophyte abundance in Itasca and Chippewa regions were limited by otherfactors such as nutrient availability.

Regional patterns in fish communities – Data gathered during 2010 indicated presence of complex fish communities in lakes of all study areas summarized thus far. We sampled no fishless lakes in our Chippewa study area, while a large number of fishless sites were found in our Itasca study area; a small number of fishless sites were observed in all other areas (Figure 5). Highest fish species richness was observed in Metro, Windom, and Alexandria study areas, where we sampled lakes containing up to 8, 10, and 8 species respectively. Common carp (*Cyprinus carpio*) were less widely distributed among our lakes than we expected, with carp occurring in 23, 14, and 14 % of lakes in Windom, Metro, and Alexandria areas, respectively; carp were not collected from lakes in Itasca and Chippewa regions. Bullheads were collected from lakes in all 5 study areas, with highest numbers (> 46 %) in lakes in Windom, Metro, Alexandria, and Chippewa regions, but were found in only 9% of Itasca lakes.

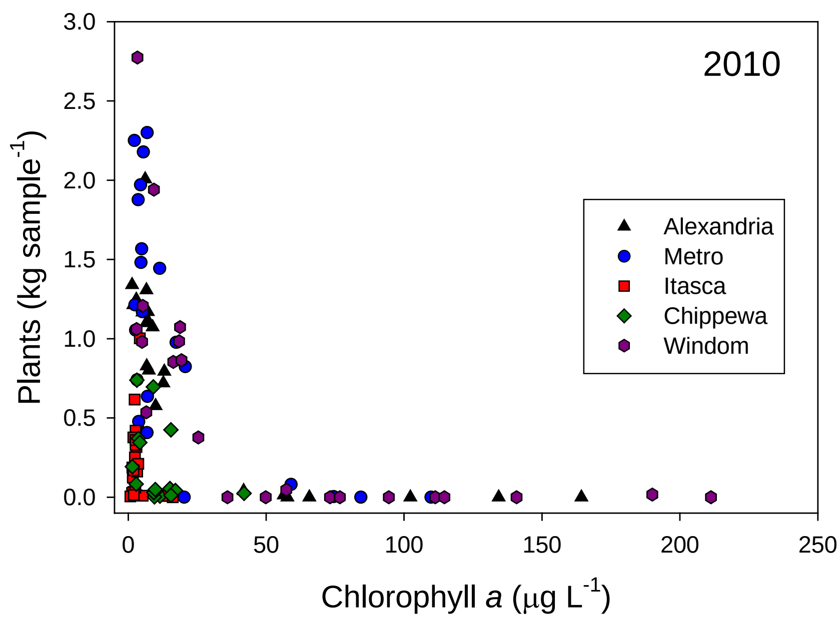


Figure 4.   Abundance of phytoplankton (chlorophyll *a* concentration) and submerged macrophyte biomass for 127 shallow lakes in 5 study regions during 2010. Plant mass indicates average wet weight of plants collected on rake casts in each lake. Colors depict study area as indicated in caption.

We also summarized fish relative abundance (mean total mass sampled) of predominant fish feeding guilds (planktivores [e.g. fathead minnows, sunfish], benthivores [e.g. bullheads, common carp], piscivores [e.g. northern pike, walleye, largemouth bass]) for lakes within each study area (Figure 6). In general fish mass was roughly comparable among Windom, Alexandria, and Chippewa lakes, but showed a trend toward lower abundance in Metro and Itasca areas. Highest mass of planktivorous fishes was collected from lakes in Chippewa and Windom areas; piscivores were usually collected in lower numbers than other guilds, but apparently outnumbered benthivorous species in Itasca lakes, and were also high in Chippewa lakes. Dense populations of planktivores (shiners, yellow perch) and benthivores (bullheads) were sampled in Chippewa lakes, although conventional wisdom suggests that these species are more abundant in prairie regions.

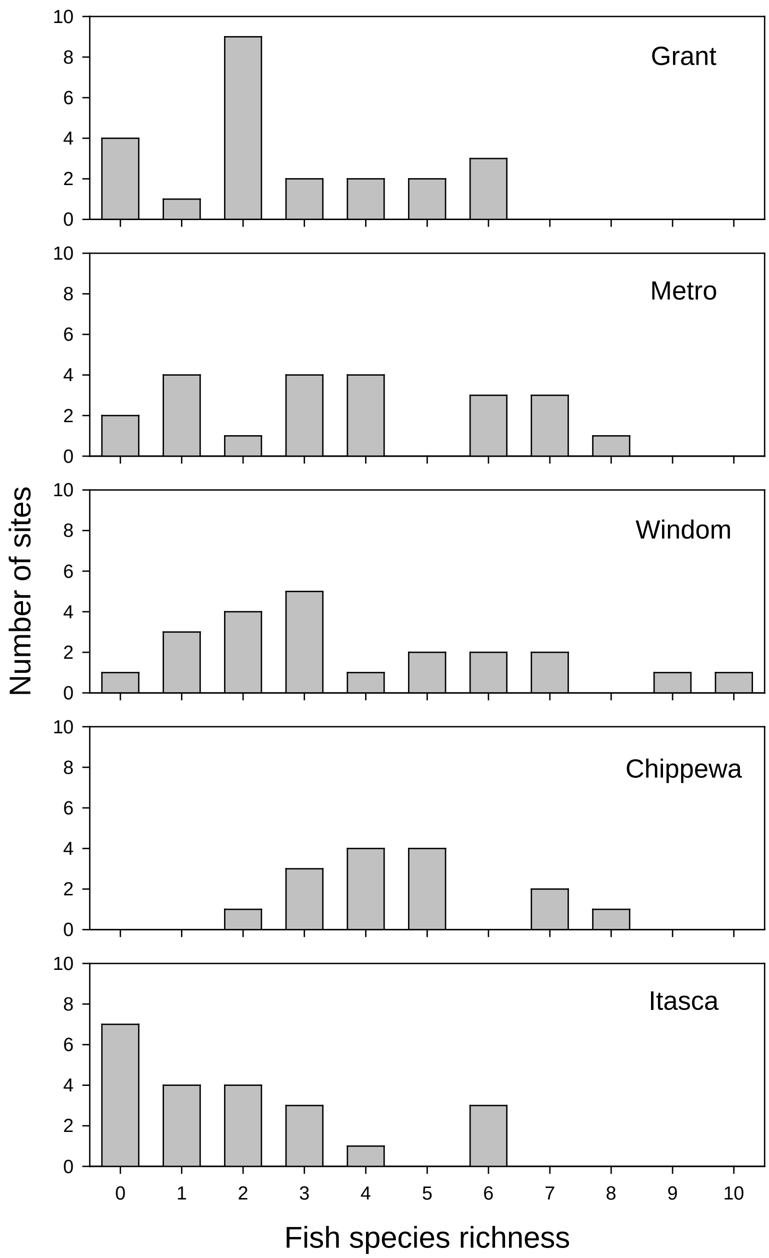


Figure 5. Fish species richness for 127 shallow lakes in 5 study regions during 2010. Height of bars on x-axis depicts number of lakes in which corresponding number of fish species were collected.

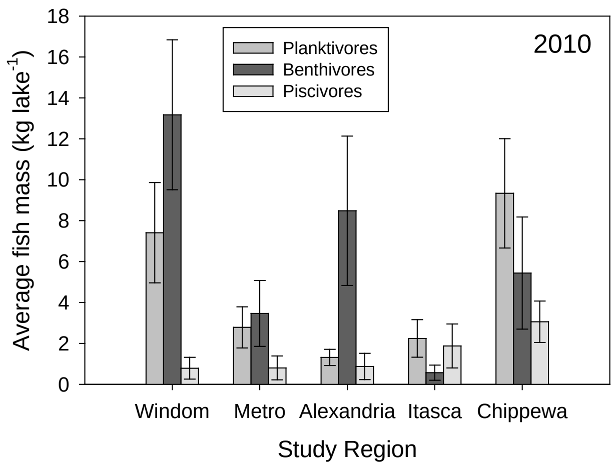


Figure 6. Summary of fish relative abundance for 127 shallow lakes in 5 study regions during 2010. Height of bars on x-axis depicts average weight (mass) for each of 3 major fish feeding guilds common in these lakes (planktivores, benthivores, piscivores).

B. Develop and distribute recommendations for management to improve habitat conditions in shallow lakes – to be done pending completion of A

Result Status as of June 30, 2011

Efforts during January-June 2011 were directed towards summary and integration of data from lakes within the Red Lake study region. It is now possible to compare patterns in phytoplankton abundance (chlorophyll a), submerged aquatic plants, and fish communities across all study regions.

Total phosphorus – Our data show an obvious trend toward increasing total phosphorus (TP) in lakes along a gradient from northern Red Lake sites to lakes in southern study regions. Highest TP levels were observed in Metro, Alexandria, and Windom study regions (Figure 2.1). This implies higher productivity in these southern-region lakes.

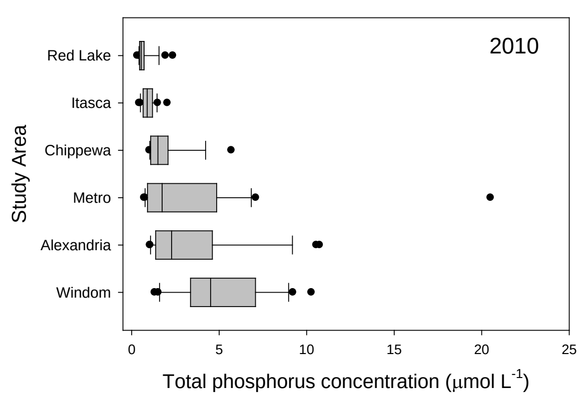


Figure 2.1 Box plots showing mean abundance of total phosphorus (TP) for 127 shallow lakes sampled within 6 study regions during 2010. Vertical lines within boxes depict median TP values for each study region; extent of

boxes depict 25th and 75th percentiles. Whiskers show 10th and 90th percentiles, with dots indicating more extreme values.

Submerged aquatic plants, phytoplankton, and regime implications – Given the lower apparent productivity of Red Lake and Itasca sites, it is not surprising that lowest phytoplankton abundance (chlorophyll a) was observed in these sites (Figure 3.1). As with TP, highest median values were observed in Metro, Alexandria, and Windom lakes. These gradients have implications for regime dynamics in these lakes as described in our December 31, 2010 update and Figure 4. Higher July levels of TP and Chlorophyll *a* implies that lakes in Metro, Alexandria, and Windom regions are more susceptible to shifts toward turbid regimes. Collectively, these data indicate that lakes in Red Lake are unlikely to occur as turbid-regime sites. Low levels of nutrients, chlorophyll a, and submerged plants in many lakes in Red Lake, suggesting that plant communities in lakes here may be limited more by nutrients than by regime dynamics (Figure 4.1).

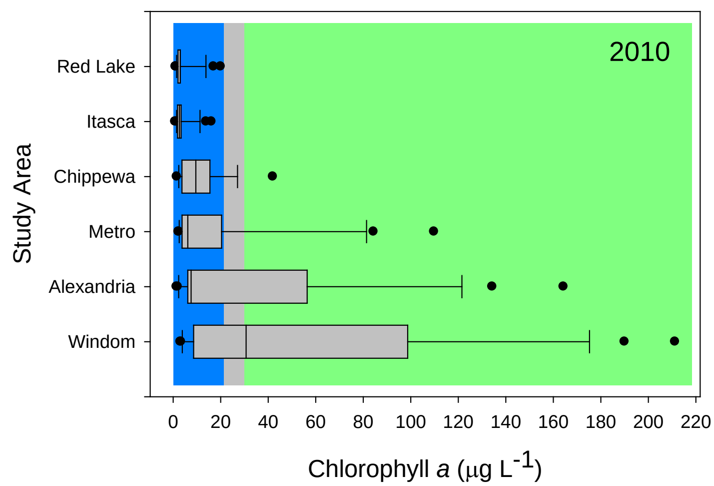


Figure 3.1 Box plots showing mean abundance of phytoplankton (chlorophyll *a* concentration) for 127 shallow lakes sampled within 6 study regions during 2010. Background colors depict expected chlorophyll *a* regions for clear- (blue), transition (grey), and turbid-regimes (green) based on threshold values after Zimmer et al. (2009).

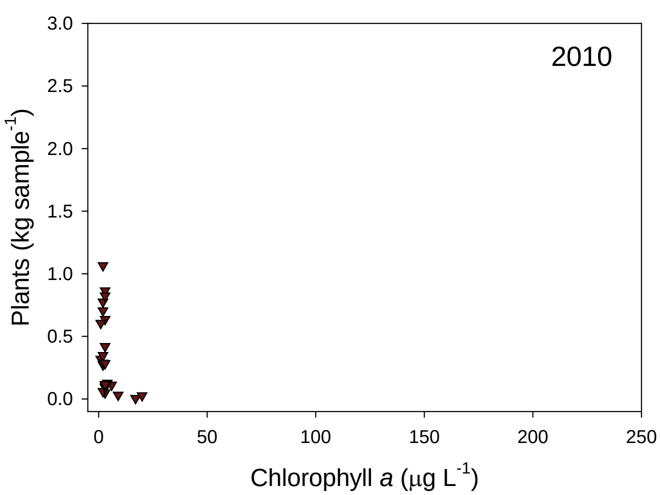


Figure 4.1 Abundance of phytoplankton (chlorophyll *a* concentration) and submerged macrophyte biomass for 23 shallow lakes in the Red Lake study region during 2010. Plant mass indicates average wet weight of plants collected on rake casts in each lake.

Regional patterns in fish communities – We collected 6-10 fish species from among lakes in all study regions. Lakes in Metro, Windom, and Chippewa regions showed slightly higher fish species richness than did sites in other areas (Figure 5.1). Fish communities in lakes from all 6 regions included members of all 3 common feeding groups (Planktivores, benthivores, and piscivores) (Figure 6.1). Piscivorous species (northern pike, largemouth bass, etc.) and relative abundance appeared to be especially low in Red Lake sites.

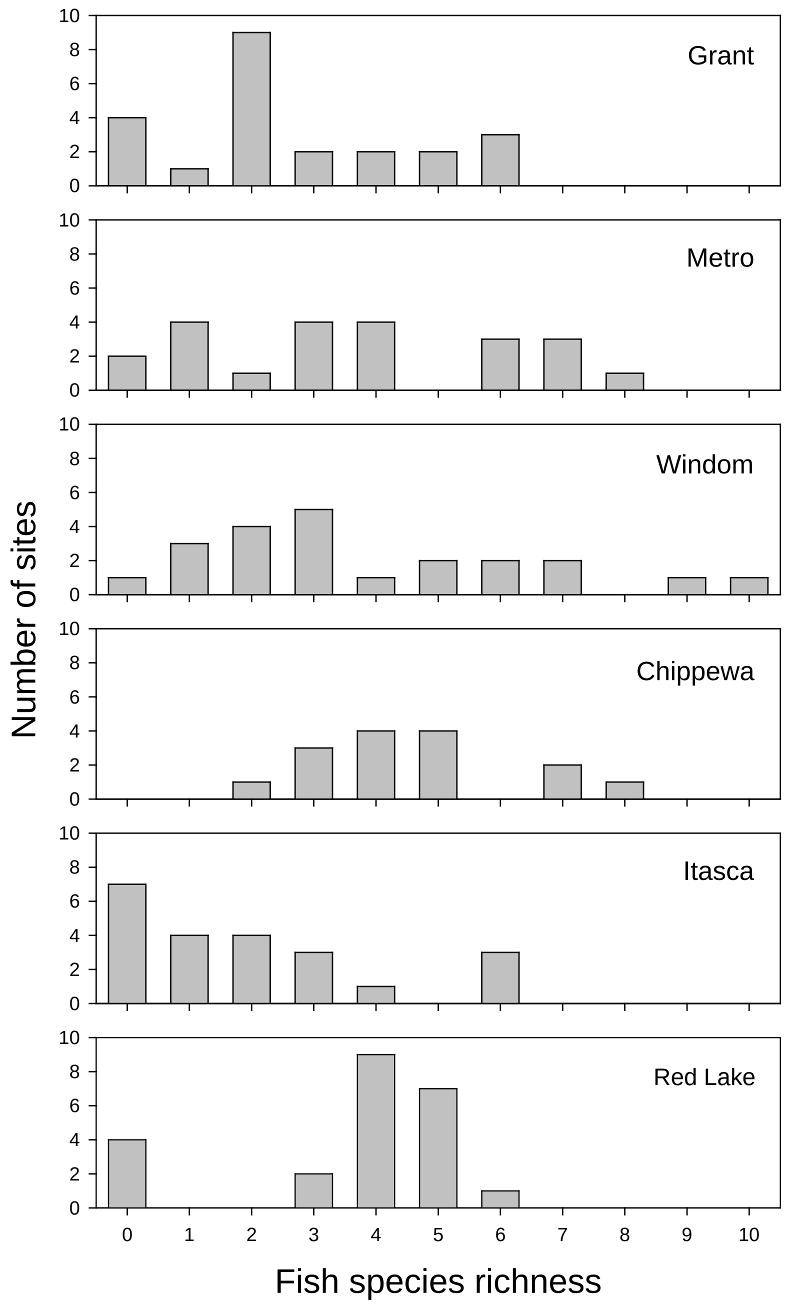


Figure 5.1 Fish species richness for 127 shallow lakes in 6 study regions during 2010. Height of bars on x-axis depicts number of lakes in which corresponding number of fish species were collected.

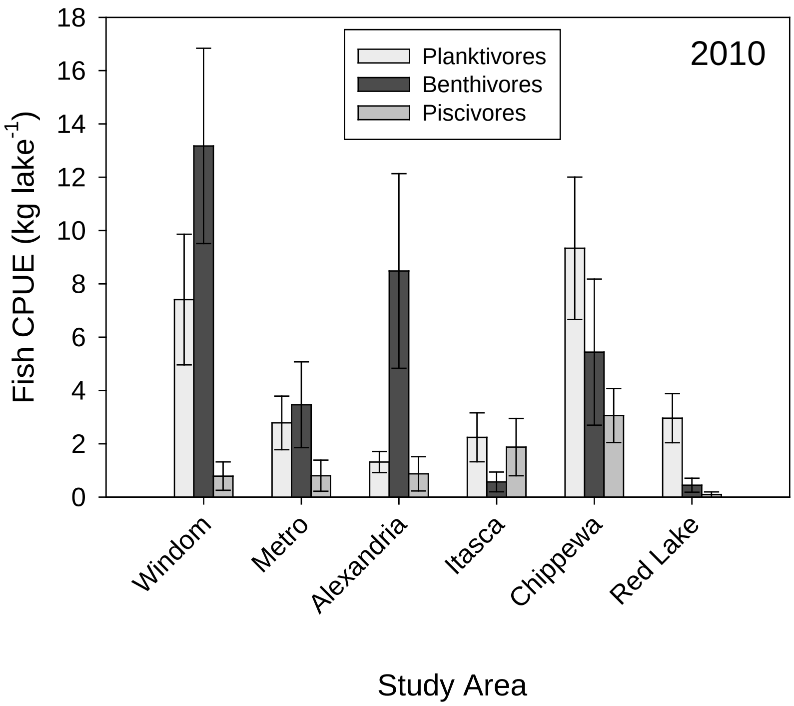


Figure 6.1 Summary of fish relative abundance for 127 shallow lakes in 6 study regions during 2010. Height of bars on x-axis depicts average weight (mass) for each of 3 major fish feeding guilds common in these lakes (planktivores, benthivores, piscivores).

Result Status as of December 31, 2011

Submerged aquatic plants, phytoplankton, and regime implications – Chlorophyll *a* (Chla) showed a similar pattern throughout summers 2010-2011, with a trend toward higher values in Alexandria and Windom study areas and lowest average values observed from lakes in Red Lake and Itasca regions. One exception was Metro area lakes; Chla values here appeared somewhat higher than we observed during 2010, but remained intermediate (between Alexandria and Chippewa). A trend toward higher values in Metro lakes during 2011 may reflect reduced stability, perhaps portending shifts to turbid conditions in some of these lakes. In general, during both study years (and especially in 2011), Chla levels associated with turbid lake regimes were more often observed in Alexandria, Chippewa, and Metro study regions (Figure 3.2). Highest individual lake Chla was observed in Windom study lakes each year (Figure 3.2).

Overlays of submerged plant abundance (mass in samples) and Chla are useful for identifying regime patterns across our 6 research areas (Figure 3.2). These plots illustrate extent to which study lakes express either high phytoplankton abundance (Chla) or high plant mass in a given year, but not both. Along with regime areas depicted in Figure 3.1, this probably reflects regime behavior of these lakes as described by Zimmer et al. (2009). Alternatively, during 2011, some lakes showed intermediate levels of Chla and plant abundance, perhaps because a portion of our sites were in transition between clear and turbid regimes during this second study year. It is also obvious that numerous study sites in Metro, Alexandria, and Windom regions exhibited summer Chla levels known to be associated with turbid-regime conditions in shallow Minnesota lakes (Figure 3.2).

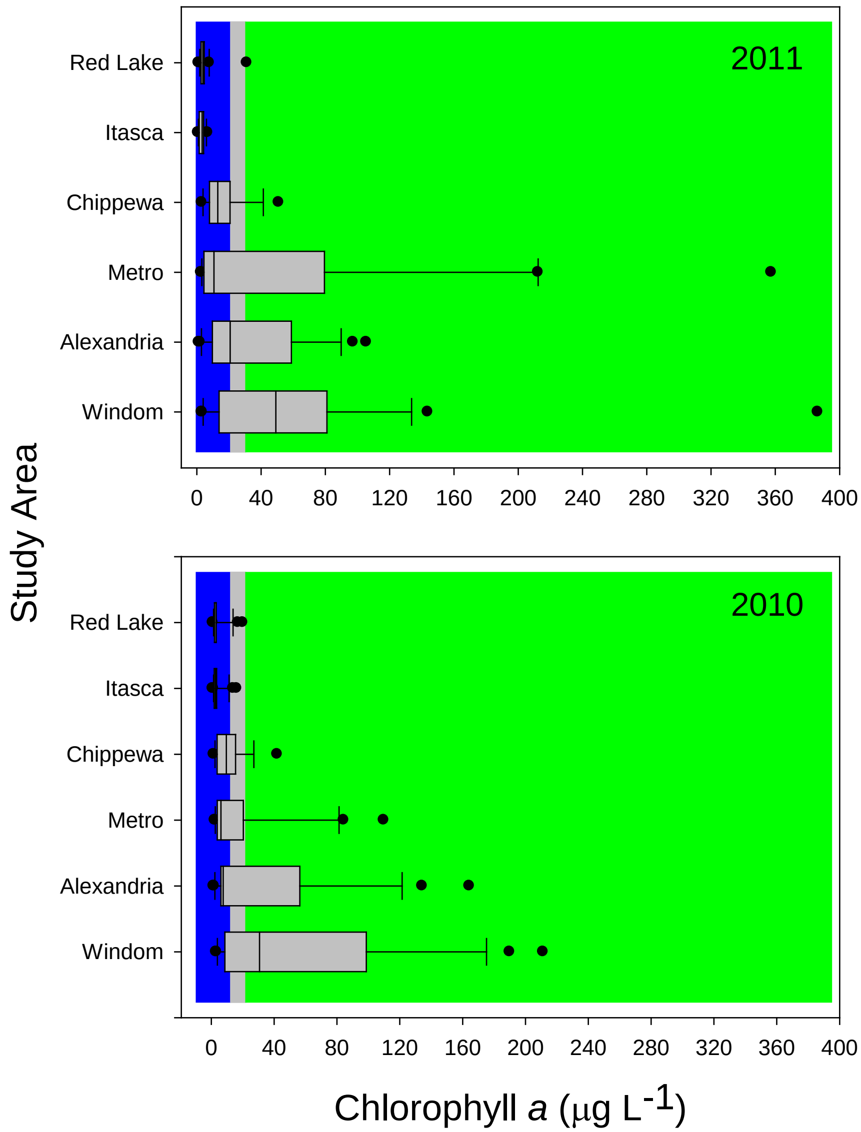


Figure 3.2 Box plots showing mean abundance of phytoplankton (chlorophyll *a* concentration) for 127 and 130 shallow lakes sampled within 6 study regions during 2010 and 2011, respectively. Background colors depict expected chlorophyll *a* regions for clear- (blue), transition (grey), and turbid-regimes (green) based on threshold values after Zimmer et al. (2009).

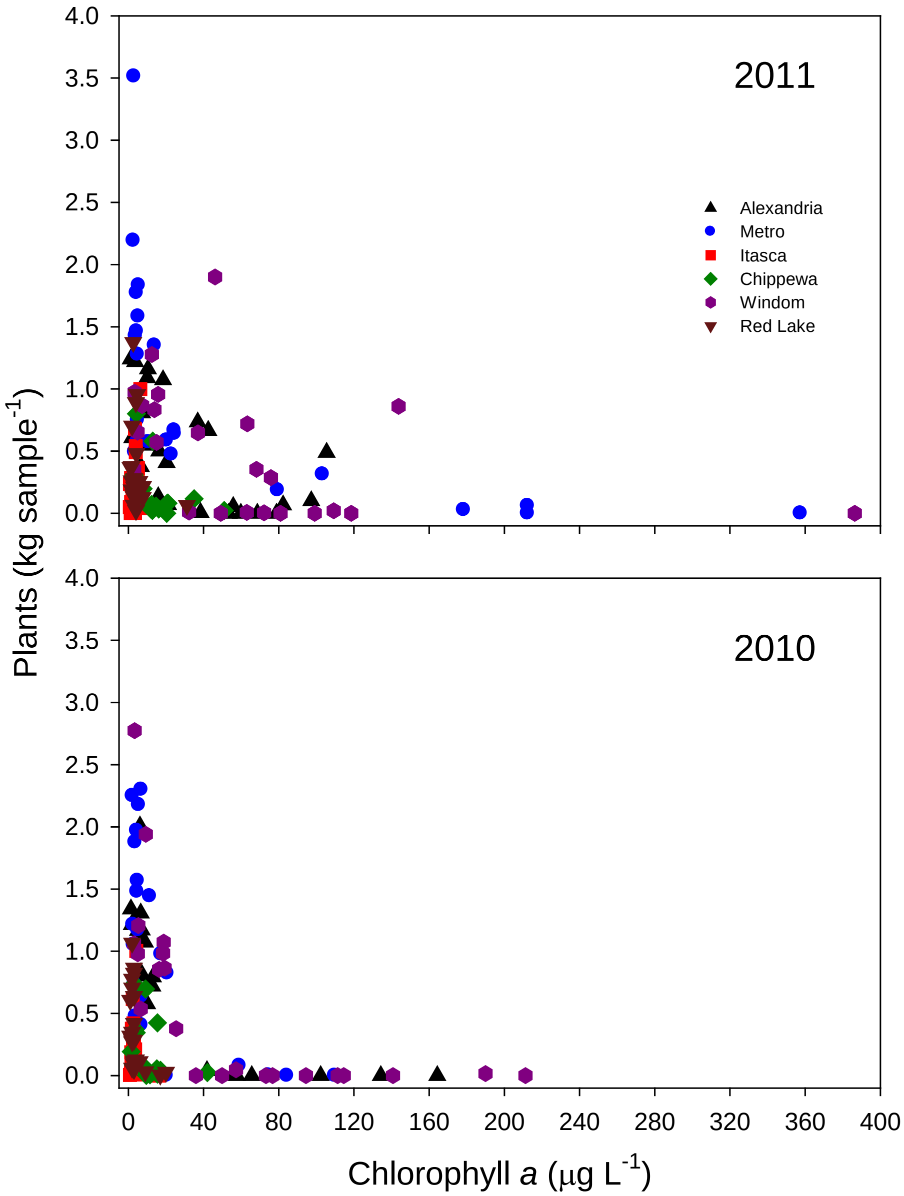


Figure 4.2 Abundance of phytoplankton (chlorophyll *a* concentration) and submerged macrophyte biomass for 127 and 130 shallow lakes in 5 study regions during 2010 and 2011, respectively. Plant mass indicates average wet weight of plants collected on rake casts in each lake. Colors depict study area as indicated in caption.

Regional patterns in fish communities – Fish communities were widespread and moderately complex in shallow lakes in all study regions during 2010-2011. Patterns in taxonomic richness (number of species) and relative abundance of functional feeding guilds (mass of benthivores, planktivores, and piscivores) were similar during both study years. Maximum species richness (12) was observed in a single Windom-area lake in 2011 (Figure 5.2). In no other instances did we detect more than 10 fish species in a single lake. Benthivorous species (especially bullheads) comprised the most abundant feeding guild in Windom, Metro, and Alexandria study areas during 2010 and 2011 (Figure 6.2). Planktivorous fishes (fathead minnows, dace, golden shiners, etc.) predominated biomass of lakes in Chippewa and Red Lake areas. Itasca lakes showed a trend toward relatively low fish abundance during both study years. Piscivorous fishes were present in lakes in all regions, but were less abundant than were planktivores and benthivores in all study areas except for Itasca, where piscivores were more abundant than benthivores or similar to benthivores and planktivores (Figure 6.2).

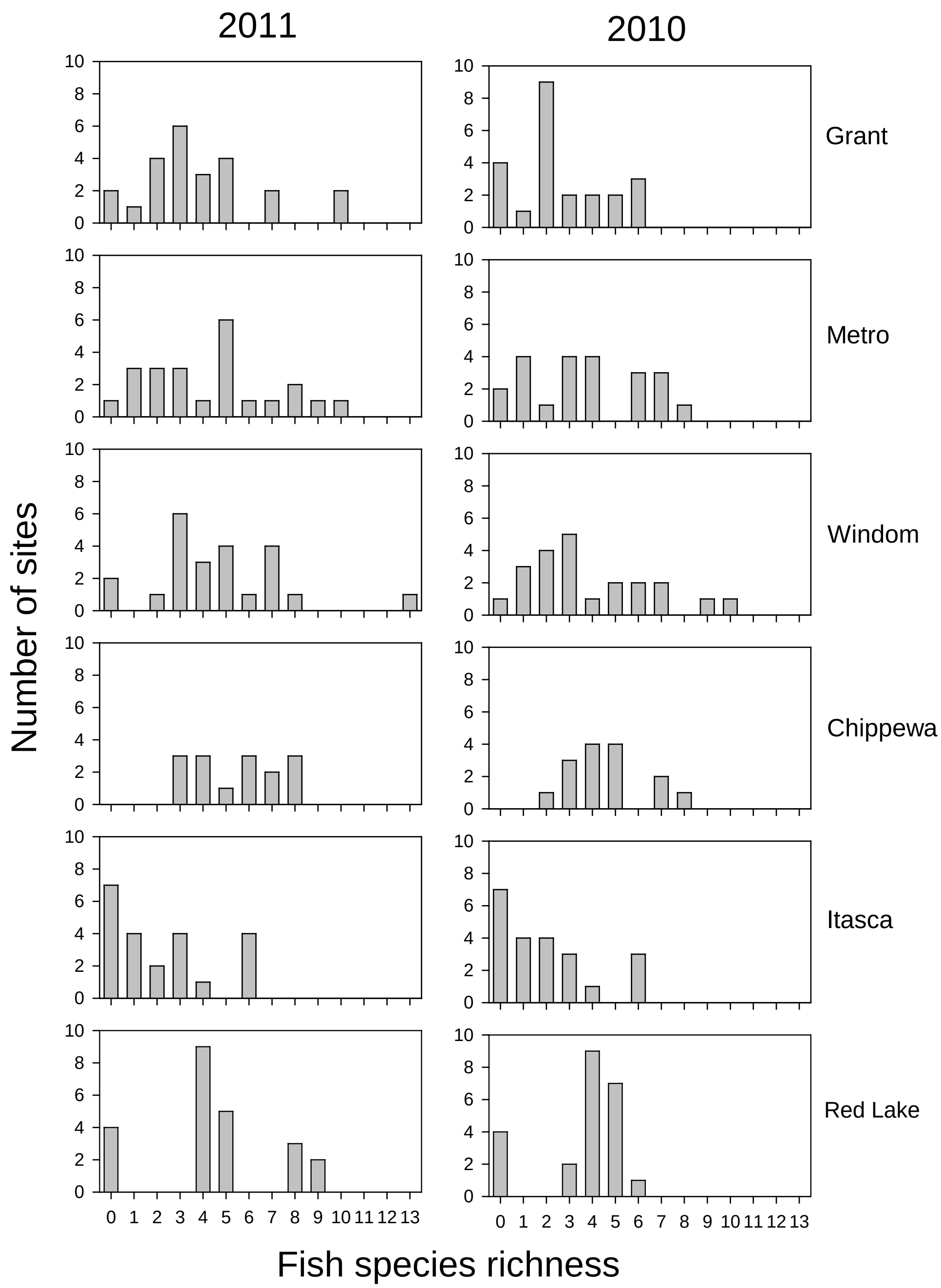


Figure 5.2 Fish species richness for 127 and 130 shallow lakes in 6 study regions during 2010 and 2011, respectively. Height of bars on x-axis depicts number of lakes in which corresponding number of fish species were collected.

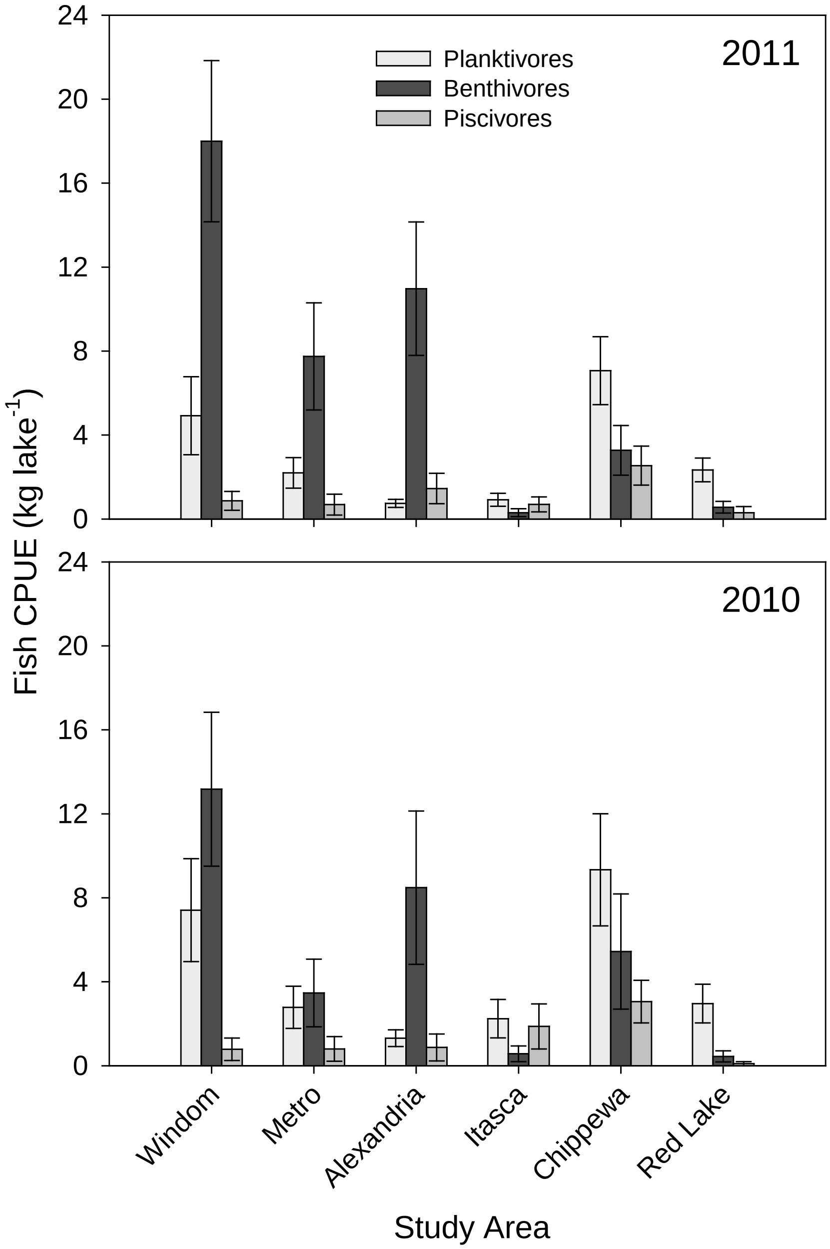


Figure 6.2 Summary of fish relative abundance for 127 and 130 shallow lakes in 6 study regions during 2010 and 2011, respectively. Height of bars on x-axis depicts average weight (mass) for each of 3 major fish feeding guilds common in these lakes (planktivores, benthivores, piscivores).

Earthworm Sampling in Itasca Study Area- We continued investigating the influence of earthworms on lake productivity and soil properties in ten small watersheds within or near Itasca State Park, Minnesota. In addition to field work, we conducted experiments where we manipulated worm biomass and examined effects on dissolved organic phosphorus (DOP), dissolved organic carbon (DOC), and total nitrogen (TN). The results of these experiments suggested that the presence of earthworms increased the availability of organic carbon and nitrogen in soils. One of the important implications of these results is that watersheds with abundant anecic worms are likely to have depleted organic carbon and nitrogen pools due to increased lability of organic matter and increased leaching into surrounding water bodies. In the coming months, we will examine the organic matter and nutrient content of lakes at our Itasca sites, focusing on the abundance of worms in the watersheds of these systems.

Report Summary: June 30, 2012

Submerged aquatic plants, phytoplankton, phosphorus concentrations and regime implications – Patterns in aquatic plants, phytoplankton abundance, and implications for regime status in study lakes were reviewed in our December 30, 2011 update. We also examined total phosphorus (TP) concentrations in study lakes, summarizing results for each of our 6 regions and allowing comparisons among these geographic areas (Fig. 7). Patterns in TP were generally similar during both study years with highest individual lake values observed in the Metro region, but highest median TP levels in Windom lakes. Alternatively, lakes in Itasca and Red Lake regions showed lowest TP levels during both study years. TP patterns among study regions almost certainly reflect nutrient concentrations in surrounding upland soils, as well as land use and extent of anthropogenic development and agriculture within watersheds of lakes in Metro, Alexandria, and Windom study areas.

Preliminary analyses indicated that phosphorus is usually the key limiting nutrient in these study lakes, especially in turbid-regime sites. Present data from Extensive Lakes also illustrated that the probability of an individual lake exhibiting clear or turbid regimes was related to in-lake TP levels and mass of planktivorous and benthivorous (Fig. 8). Implications of these relationships (Figure 8) are best illustrated by examples. A lake with high fish mass (relative abundance of >39 kg) and high TP levels (>495 ugl^{-1}) would almost certainly exhibit characteristics of a turbid regime (probability =100%). Alternatively, lakes exhibiting extremely low fish mass and low TP levels will likely be in a clear-water state. All this suggests that underlying fish community composition, TP gradients, and land-use within lake watersheds are probably important determinants of regional water quality patterns in shallow lakes across these regions of Minnesota. Generally, these findings support the hypothesis that the shallow lakes in western and southern regions of Minnesota are at greater risk of shifts to turbid regimes than are lakes in northern reaches of the state.

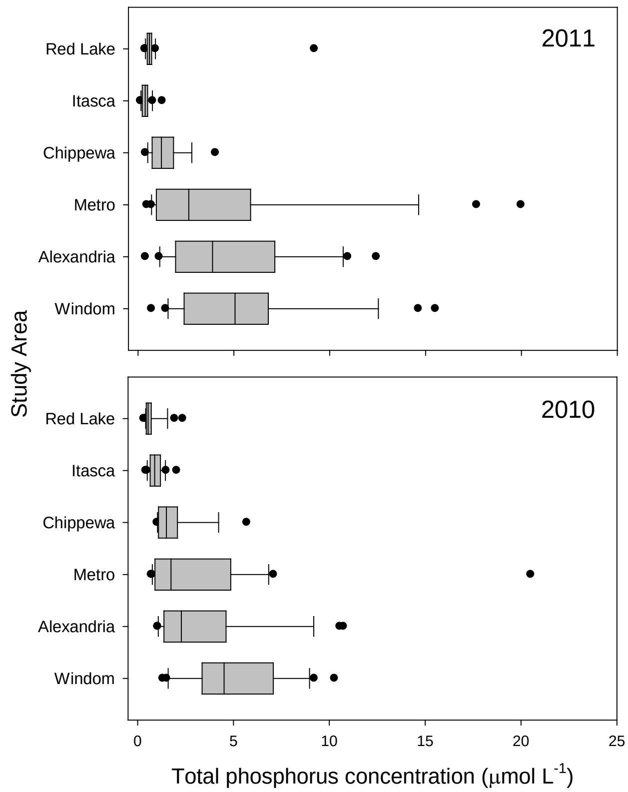


Figure 7. Box plots showing mean abundance of total phosphorus (TP) for 127 shallow lakes sampled within 6 study regions during 2010 and 2011. Vertical lines within boxes depict median TP values for each study region; extent of boxes depict 25th and 75th percentiles. Whiskers show 10th and 90th percentiles, with dots indicating more extreme values.

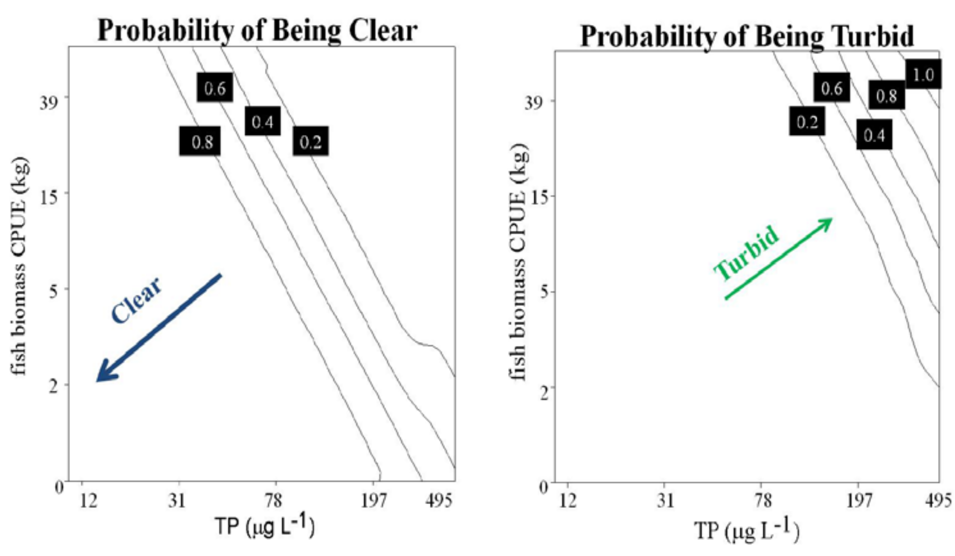


Figure 8. Isobars in panels indicate probability of lakes exhibiting characteristics of clear (left) or turbid regimes. Probabilities of turbid regime show positive relationship to TP concentrations and are based on data from 127 Extensive Lakes.

Regional patterns in fish communities- Fish populations were widespread and complex in lakes across all study regions (reviewed in June 30, 2011 update). We also explored whether fish community richness might be influenced by size (surface area) of lake basins or watersheds. Using model fitting methods, we assessed relationships between fish community species richness (across all 6 of our study regions) and surface area (size) of study lakes and watersheds. Fish community richness results were best fitted using negative binomial models which suggested that fish community richness increased with increasing lake and watershed size during both study years (Fig. 8), as might be expected from classic theory of island biogeography. However, patterns of fish community richness exhibited variability across all sizes of lakes and watersheds, suggesting other factors must also be important in influencing richness.

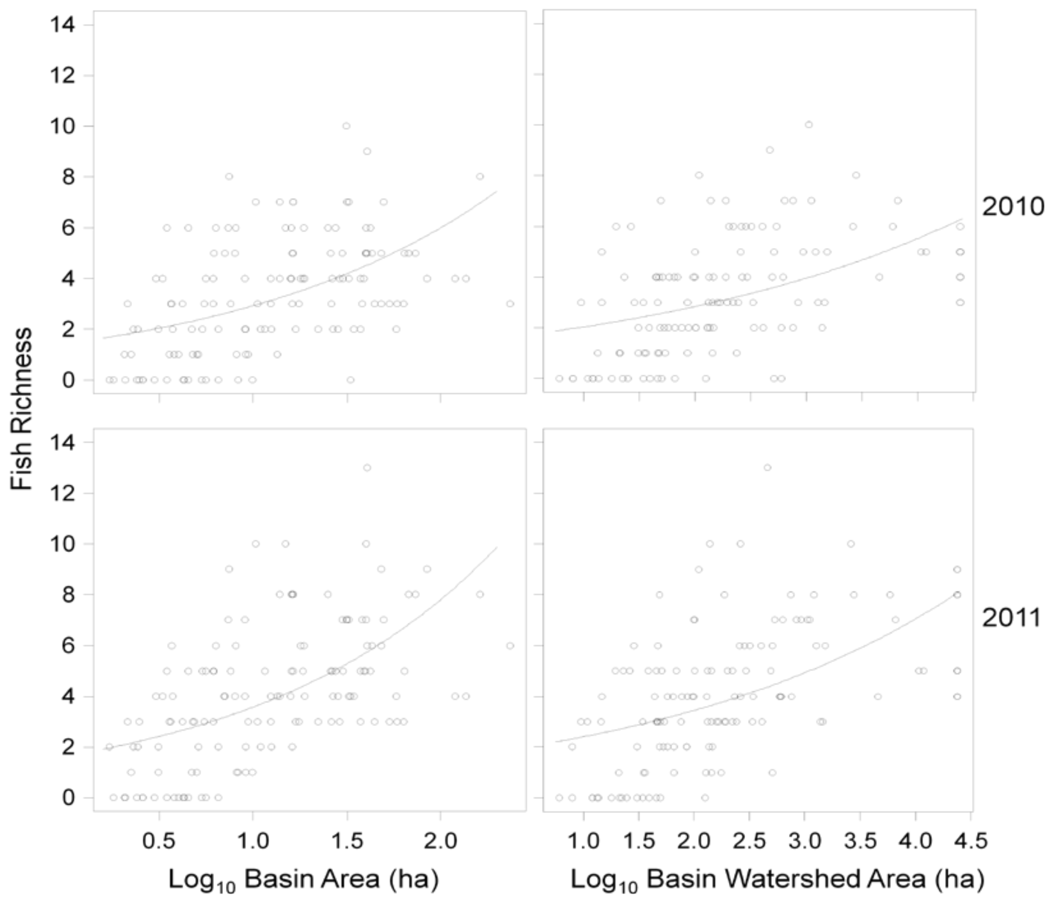


Figure 8. Relationships between fish community richness (vertical axis) and size of shallow lake basins and watersheds (ha). Number of fish taxa (species richness) for individual study lakes are depicted as circles; best-fit lines (negative binomial plots) determined by model selection procedures implemented using R.

Earthworms and lake nutrient patterns- To analyze the impact of *Lumbricus terrestris* on the nutrient availability and cycling of soil systems, we devised a simple microcosm experiment with two treatment groups. We filled 14 5-gallon buckets with homogenized soils obtained from the University of Minnesota greenhouse. Before the soil was distributed to the individual buckets, dried leaves were added to the soil and it was thoroughly mixed using a soil mixer. We distributed soil in equal amounts to each bucket and covered the buckets with lids. Each bucket had 16 air holes drilled into the top lid of the bucket to allow for air exchange. We stored the buckets in the 5th floor greenhouse of the Ecology building.

After allowing the buckets to settle for a week, we created the two treatments by adding 6 *L. terrestris* to 7 of the 14 buckets. To ensure that worms were not contaminating the buckets with the soil they were living in previously, the worms were flushed and allowed to live in a small amount of the experimental soil for one week. Before adding worms to each bucket they were counted and their masses were determined by weighing each worm on a balance.

Soil samples were collected from the buckets immediately prior to worm addition and 6 weeks after worm addition. We collected soil using a 50 ml falcon tube to extract soil cores. Each core was used to measure bulk density, soil moisture, and organic matter by loss-on-ignition.

To perform nutrient analysis, nutrients were extracted from the soils by placing approximately 3 grams of soil into 45 mL of nanopure water and incubating the samples for 48 hours at 4 degrees Celsius. After incubation, the sample was filtered through a 0.7 µm pore GF/F Whatman filter. From the filtered sample dissolved carbon, nitrogen, and phosphorus were then measured using standard methods.

Nutrient Analysis from Bucket Experiments

The data for organic matter, bulk density, dissolved carbon, and dissolved phosphorus showed no significant differences between treatment types (p-values of 0.245, 0.647, 0.082, and 0.23 respectively, Figure L-1 and Figure L-2). In contrast, both nitrogen availability and soil moisture varied significantly across treatment type. Dissolved extractable nitrogen was roughly 3 parts per million (PPM) higher in the treatment with worms compared to the treatment without worms (Figure L-3, $p= 0.002$). Soils with worms present were also 2% moister (measured as moisture content by weight) than soils without worms after six weeks (Figure L-4, $p= 0.012$).

Significance

The increased nitrogen availability due to the presence of worms in the microcosm experiment has some potential extended significance. For example, worms are potentially increasing the availability of limiting nutrients in the soil, thus may explain some of the changes in understory plant communities observed when earthworms invade northern forests. Another potential impact of increased nitrogen availability is that it could exacerbate the amount of nutrient runoff from forest soils over time. Because worms are increasing the amount of extractable nitrogen in the soils, there is potential for nitrogen leaching from soils during rainfall events into the surrounding watershed. This leaching could result in increased downslope and downstream transport of nutrients and ultimately more fertile lakes. Preventing further introductions of non-native earthworms will not only protect forest soils, but may also help maintain the integrity and functioning of our northern forest lake systems.

The soil moisture data suggest that worms are also influencing how water is circulated in the soil system. Because our sampling method only collected soils from the uppermost layer of the buckets, we believe that difference in soil moisture between treatment groups could be explained by mixing associated with burrowing activities. *L. terrestris* is a vertical burrowing worm, so this species likely transfers soils from the lower soil column to the upper soil column. When no worms were present the upper soils became drier after water had filtered into deeper soil layers; however, when present worms brought moist soil from the bottom of the bucket back to the top mixing it with the drier upper soil. In natural systems, this could mean that worms may increase the evaporative loss of water from the soils as they continually bring moist soils to the surface.

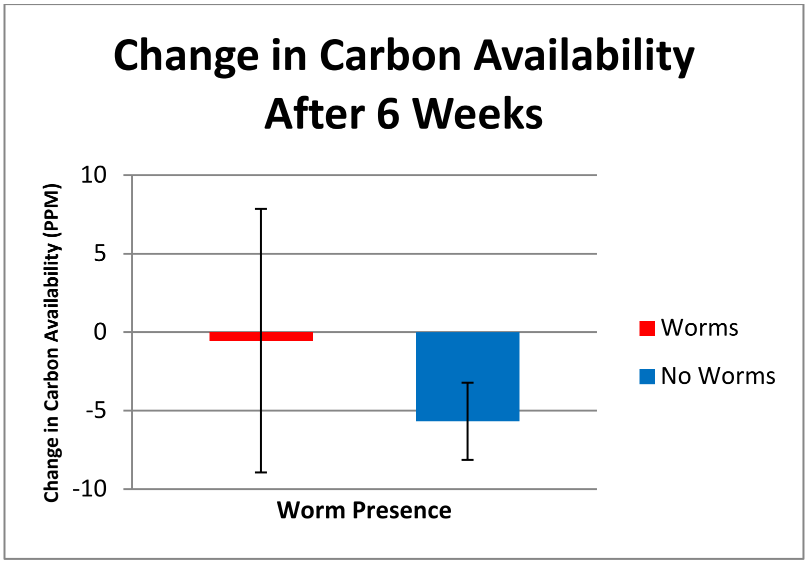


Figure L-1: Bars show the change in carbon availability after 6 weeks. Two sample t test showed no significant difference between treatment groups (p= 0.082). Carbon was measured by extractable dissolved organic carbon.

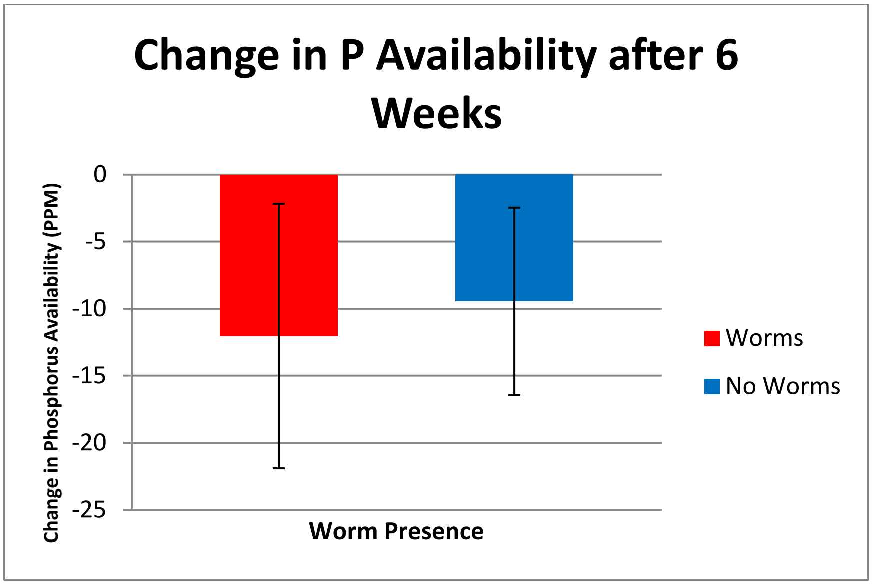


Figure L-2: Bars show the change in phosphorus availability after 6 weeks. Two sample t test showed no significant difference between treatment groups (p= 0.23). Phosphorus was measured as total dissolved phosphorus.

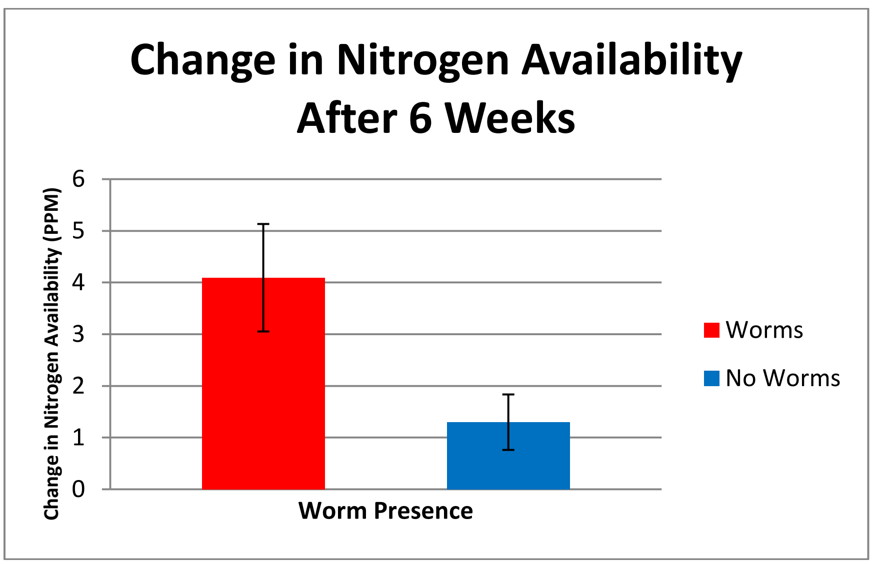


Figure L-3: Bars show change in nitrogen availability after 6 weeks. Soils with worms present showed an increase in nitrogen availability compared to soils without worms present (p= 0.002). Nitrogen was measured by total dissolved nitrogen.

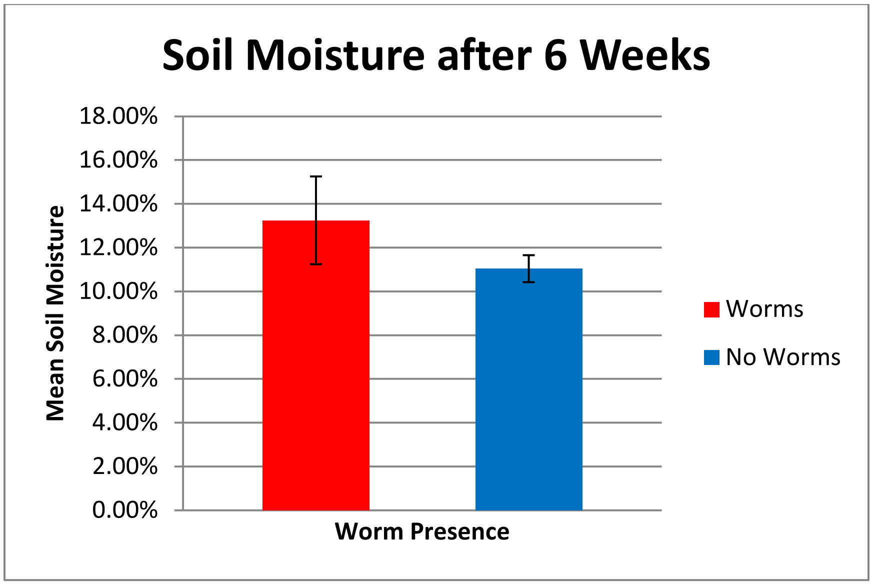


Figure L-4: Moisture of the two treatment groups after 6 weeks. Soils with worms are significantly moister than soils without worms (p= 0.012). Moisture was measured as mass loss per unit of dry weight.

Aquatic invertebrates: regional patterns and major influences - Abundance of zooplankton and macroinvertebrates was extremely variable in Extensive Lakes, and this was evident both among and within study regions (as evidenced by confidence intervals, Fig. 8a,b). The most dramatic differences between study years were observed in lakes within Windom, Metro, and Alexandria regions. However, aquatic Diptera (flies) in Chippewa and Red Lake areas also showed high variability between years and were highly abundant during 2010 (Fig. 9b). General patterns toward higher abundance of both zooplankton and macroinvertebrates in Windom, Metro, and Alexandria lakes (relative to lakes in Itasca, Chippewa, and Red Lake regions) was also evident during 2010 and 2011 (Figs. 8-11).

To the best of our knowledge, ours is one of the first studies to compare relative abundance of zooplankton and macroinvertebrates from shallow lakes across multiple Ecoregions of Minnesota. Patterns in regional trends seem to suggest that higher invertebrate abundance across taxonomic groups reflects productivity, with phosphorus availability typically increasing in Minnesota lakes along a NE-SW gradient (Heiskary 1997), hence higher background phosphorus and Chla in Windom and Alexandria lakes. High variability in relative abundance of shallow lake zooplankton and macroinvertebrates has also been reported from smaller, previous studies of wetlands and shallow lakes in the Midwestern US (Turner and Trexler 1997, Miller et al. 2008) and it certainly has implications for lake management. Overall, data seem to suggest that shallow lake invertebrate communities show higher temporal variability in Windom, Alexandria, and Metro study areas, at least relative to lakes in northcentral regions. This may reflect greater tendency of southern lakes to alternative between clear and regimes as has been shown for shallow lakes in western Minnesota and elsewhere (Hanson and Butler 1994, Scheffer 2004, Zimmer et al. 2009, Hobbs et al. 2012). Because it is likely that fish populations and plant communities fluctuate in response to lake-wide regime shifts, it is plausible that invertebrate communities also reflect high variability between years.

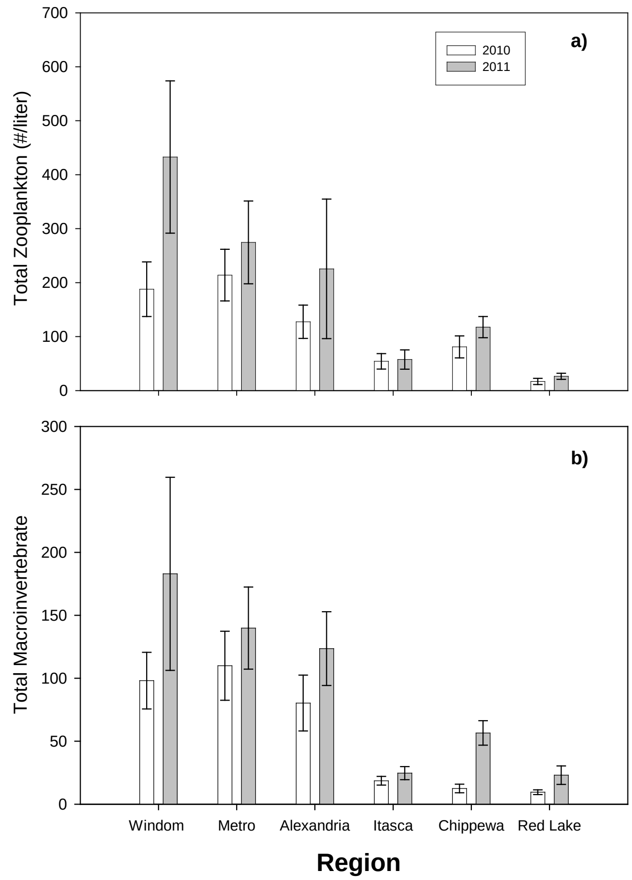


Figure 9. Total numbers of zooplankton (a) and macroinvertebrates (b) captured in Extensive Lake study sites during 2010 and 2011 for all 6 study regions. Vertical bars represent ± 1standard error.

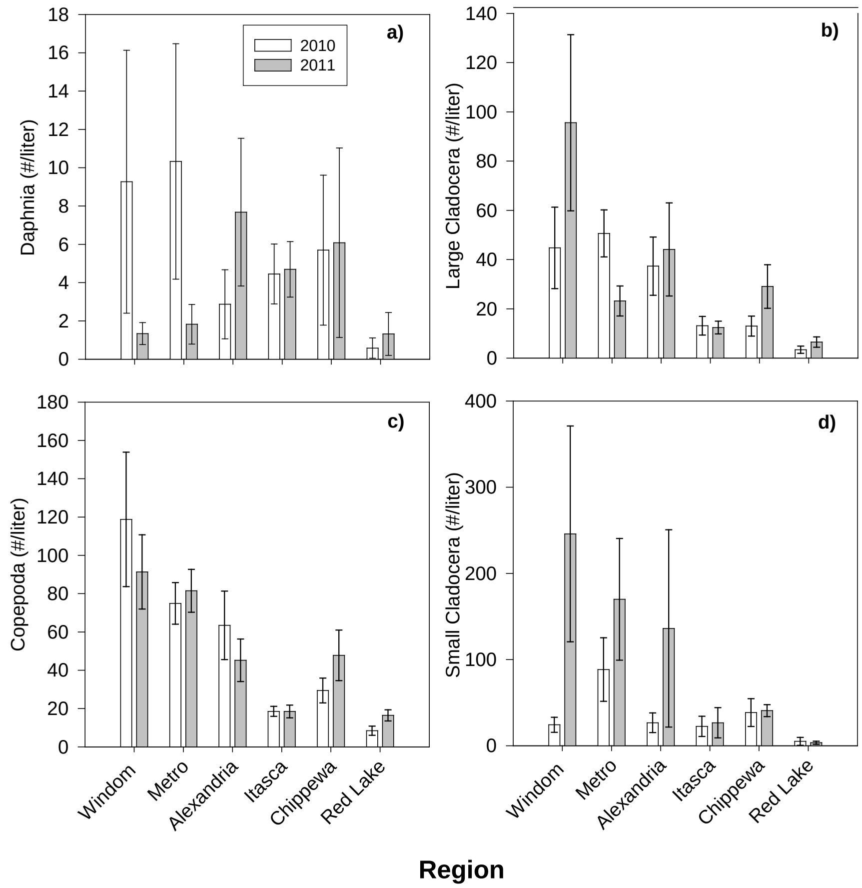


Figure 10. Abundance of zooplankton collected in Extensive Lake study sites during 2010 and 2011 for all 6 study regions. Panels show density of *Daphnia*, all large cladocera, Copepoda, and small cladocera (a-d, respectively). Vertical bars depict 1 standard error.

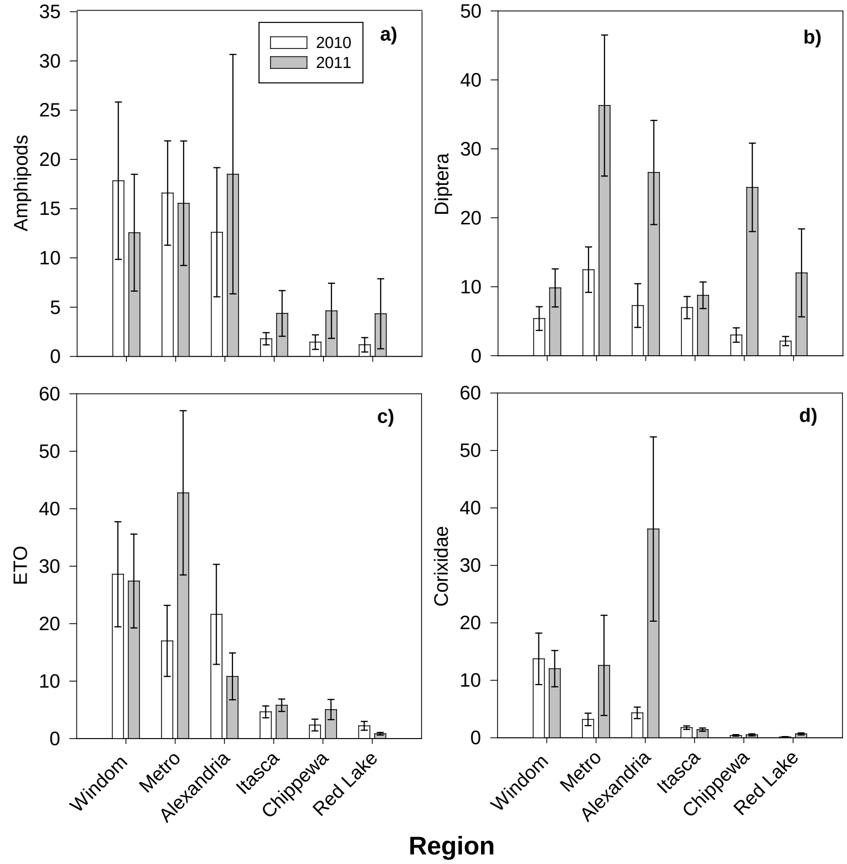


Figure 11. Abundance of selected macroinvertebrate taxa collected in Extensive Lake study sites during 2010 and 2011 for all 6 study regions. Panels show relative abundance of Amphipoda, all Diptera, variable combining Ephemeroptera, Trichoptera, and Odonata, and Corixidae (a-d, respectively). Vertical bars depict 1 standard error.

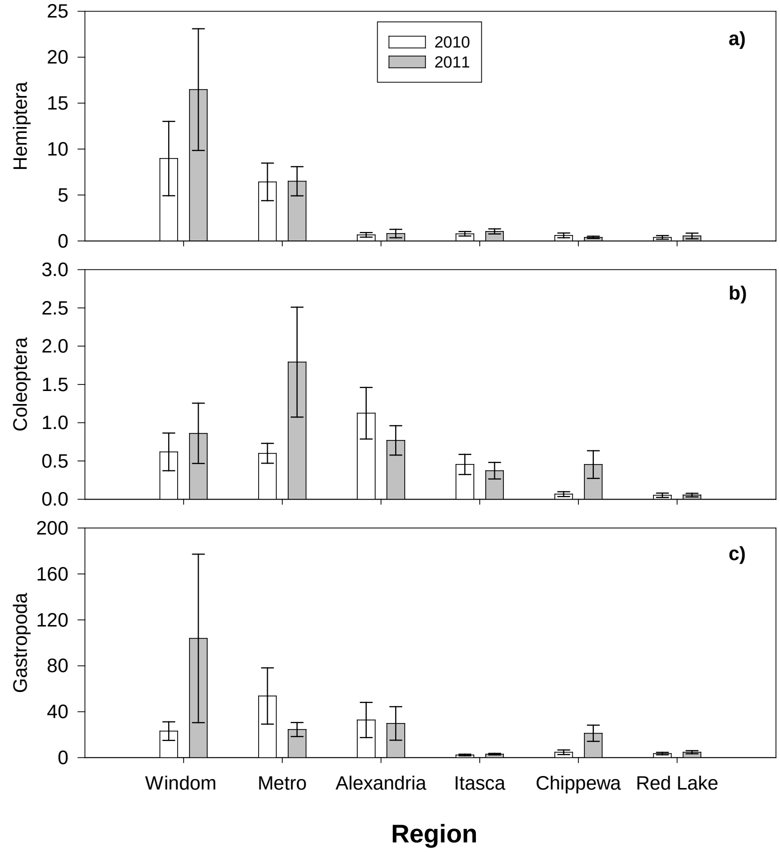


Figure 12. Abundance of selected macroinvertebrate taxa collected in Extensive Lake study sites during 2010 and 2011 for all 6 study regions. Panels show relative abundance of Hemiptera, Coleoptera, and Gastropoda (a-c, respectively). Vertical bars depict 1 standard error.

Causal Factors; what are the constraints on aquatic invertebrate communities?

To improve broad understanding of factors controlling ecological characteristics of shallow lakes, we are exploring relationships among factors likely to be influential for aquatic invertebrate communities in these systems. Using robust regression procedures (Hanson et al. 2012), we have modeled effects of watershed area, relative abundance of planktivorous + benthivorous (P+B) fishes, lake productivity (Chla), and extent of agricultural development within lake watersheds. Preliminary results suggest that abundance of P+B fishes and, in some cases, lake productivity (Chla) showed most obvious influences across a range of aquatic invertebrate taxa (Fig. 13). Present extent of agriculture within watersheds appeared to have an influence only on the abundance on small cladocerans, copepods, and aquatic Diptera, but showed no relationship for other taxa.

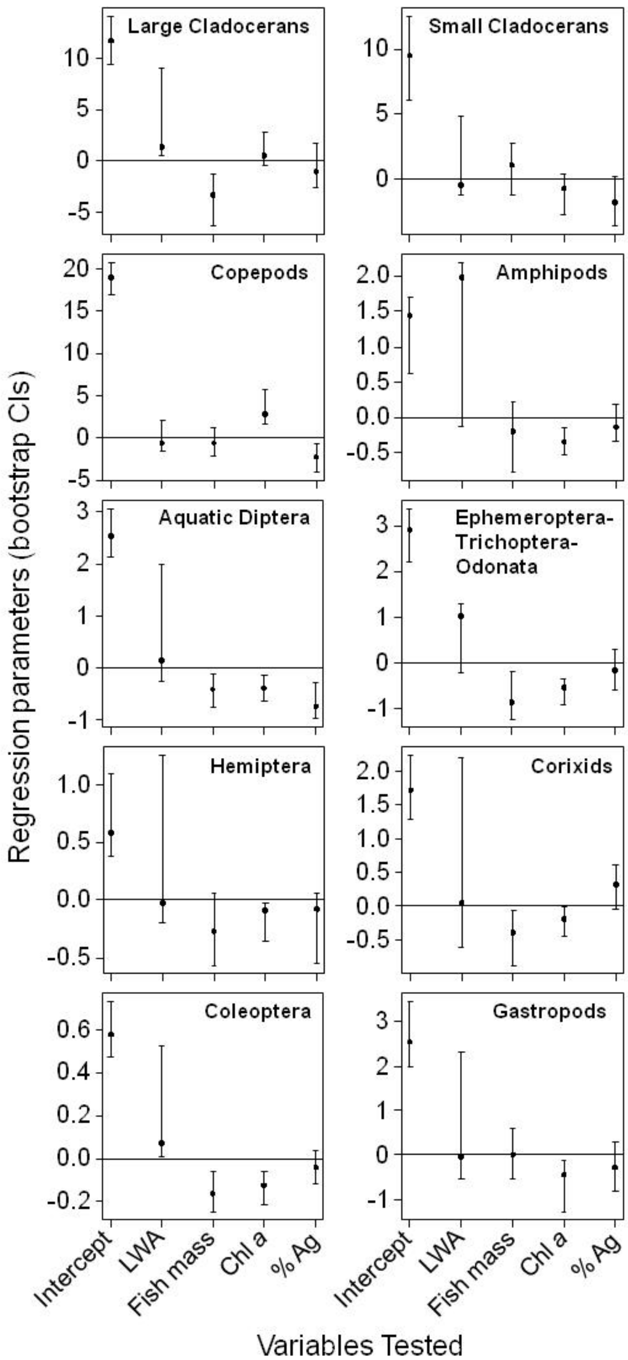


Figure 13. Summary of parameter estimates from robust regression models fit to sqrt abundance of major invertebrate taxa, using centered and scaled predictors (so, parameter estimate departures from 0 reflects abundance change per a 1 sd change in the respective predictor). Mean values are shown, along with confidence intervals (CI; +/- 2 SD); CI overlapping 0 indicate lack of significance for estimated parameter. Predictor variables used in models are summarized on x-axis as follows: LWA = lake watershed area; Fish mass = total mass of planktivorous and benthivorous fishes sampled in each study lake; Chl a = chlorophylla (ugl^{-1}); % Ag = percentage of agriculture comprising study lake watershed.

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.

Summary Budget Information for Result 2:	**ENRTF Budget:**	**$ 107,545**
	Amount Spent:	**$ 107,545**
	Balance:	**$ 0**

Deliverables	**Completion Date**	**Budget**
A. Evaluate current shallow lake restoration strategies using a case study approach to document responses of selected reclamation lakes		
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	$5,000
3. Purchase 2 14-ft aluminum boats with small outboard motors-for use sampling 8 intensive lakes	July 10, 2010	$ 7,545
4. Travel/lodging to research sites in Minnesota	June 30, 2011	$ 21,000
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	$ 44,000
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	June 30, 2012	$ Included above (#5)

features of lake watersheds and physical properties of basins (Sept 2011-March 2012)		
B. Develop region-specific guidelines useful for identifying cost effective reclamation approaches enabling optimization strategies		
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

Final Result Summary – June 30, 2012

Overview of Result 2: A key finding from studies of Intensive Lakes and historical analysis was that shallow lake responses to rehabilitation are sometimes favorable, but results were also extremely variable in both Alexandria and Windom study regions. This included trends in phytoplankton abundance (Chla), aquatic invertebrates, and especially submerged plants, the latter often considered to be reliable indicators of regime status (clear or turbid) and water quality conditions in shallow lakes. Our data clearly illustrate needs for careful monitoring of lake projects before and after rehabilitation efforts in order to refine management techniques, establish regional criteria for evaluating lake responses, and better define realistic outcomes, especially extent and duration of lake responses.

Our evaluation of Intensive Lakes was limited by several factors. First, the small number of sites and lack of pre-manipulation data precludes statistical comparisons; Intensive Lakes (and responses to rehabilitation) must be viewed as case studies. Second, rehabilitation strategies actually used varied widely among lakes. Some sites were treated only via drawdown; others received rotenone, and still others were managed using combined drawdown and rotenone approaches. Finally, the 2-year timeframe of our project also limited potential for evaluating duration of responses or, perhaps, identification of favorable responses that may develop during years immediately following lake rehabilitation. Our economic analysis, along with accompanying simulations and historical evidence, suggested that within-lake measures such as rotenone treatments, fish barriers, and water-control structures are important tools necessary for achieving short-term improvements in water quality and habitat suitability in shallow lakes. We also emphasize the importance of watershed improvements to decrease nutrient loading to shallow lakes as a critical strategy to favor long-term improvements in lake water quality and habitat suitability.

Key Findings:

A. Evaluate current shallow lake restoration strategies using a case study approach to document responses of selected reclamation lakes. Our case-study review, along with historical evidence examined below, indicates that in-lake restoration such as fish removal via rotenone, use of water control structures to facilitate water-level management, and drawdowns can trigger improvement in water quality and wildlife habitat values in shallow lakes. Unfortunately, these efforts are sometimes unsuccessful, and when they do work, these measures usually produce relatively short-term improvement in shallow lake characteristics. Deteriorated conditions often recur within 5-10 years. This resilience of deteriorated, turbid conditions in underscores the need for development of long-term approaches that effectively reduce nutrient loading from watersheds associated with shallow lakes.

B. Develop region-specific guidelines useful for identifying cost effective reclamation approaches enabling optimization strategies. We suggest that future efforts to restore shallow lakes in Minnesota must focus on several complementary approaches. First, in-lake measures such as fish removal via rotenone and drawdown appear to be the most effective available methods for improving water quality characteristics of shallow lakes in the short-term (5-10 years). Second, because improvements in response to in-lake methods rarely persist (beyond 5-10 years), restoration of watersheds to reduce nutrient loading, sedimentation, and other influences is necessary to favor long-term improvements. Finally, variability in lake responses is extreme and more rigorous monitoring of rehabilitated lakes is necessary in order to better document extent and duration of specific lake improvements.

Contrary to original expectations, region-specific guidelines are not yet possible given the scope and variability of data that were available for the present analyses. However, our ecological and economic analyses to date suggest overwhelming support for the notion that in-lake measures (in contrast to restoration of watershed cover types) will be most beneficial in the short-term, regardless of where shallows are located.

Result Status as of December 31, 2010

A. Evaluate current shallow lake restoration strategies using a case study approach to document responses of selected reclamation lakes

Site Selection: On February 10, 2010, we met with our project partners (Minnesota DU, DNR Shallow Lakes Program staff), local DNR Area Wildlife Managers, and US Fish and Wildlife Service managers to discuss recent shallow lake restoration (hereafter enhancement) projects in Minnesota and specific lakes for possible inclusion as case studies. Collectively, we identified 28 candidate lakes. After the meeting, it was decided that lake enhancements must have been completed within the past 4 years, that there exists at least one year of pretreatment data on lake condition, and that lakes should fall within no more than two spatial aggregations for two reasons. First, time, budget, and personnel logistics would not allow us to travel between lakes located at great distance from one another. Second, aggregating sites into geographic areas provides replication, thus should allow statistical comparisons of lake responses. Final study sites included Nora, Sedan and Wilts lakes in the "Alexandria" study area, and Augusta, Hjermstad, Maria, Spellman and Teal lakes in the "Windom" study area. Table 2 summarizes specific enhancement activities implemented at each of the study lakes. Treatments and timing varied, but generally included combinations of either partial or full drawdown, rotenone additions, and in some cases stocking of piscivorous fish (e.g. walleye).

Table 2. Narrative describing shallow lake enhancement strategies implemented on selected case study lakes.

Lake	**County**	**Size (acres)**	**Enhancement Strategy**	**Years Post-Treatment in 2010**
Nora	Pope	60	Full drawdown implemented in 2007. Began to refill in 2008, 40-50% open water by 2009. Metal half-riser structure with stoplogs functions as a fish barrier.	3 yrs
Sedan	Pope	62	Partial drawdown began in 2007, with a full drawdown occurring in 2008. Began to refill in 2009. Concrete variable crust structure with stoplogs regulates water level.	2 yrs
Wilts	Grant	55	Water levels were low in 2008 and lake is isolated, thus a decision was made to rotenone-treat the lake in fall 2008. Isolated basin.	2 yrs
Augusta	Cottonwood	499	This lake has a long history of drawdown to achieve wildlife benefits (pre-2004), but the most recent full drawdown occurred in 2008. Lake was re-flooded in 2009. Water control structure exists on lake outlet; control structures and high-velocity fish barrier installed on other adjacent waters within immediate watershed.	2 yrs
Hjermstad	Murray	60	Partial drawdown implemented in 2008, and lake was rotenone-treated under the ice during 2008-09. Fathead minnows persisted, so the lake was stocked with piscivores (walleye fry) in 2009 to attempt to suppress antecedent minnow populations. Water control via weir with stop logs; hanging finger fish barrier in place.	2 yrs
Maria	Murray	425	Full drawdown implemented from fall 2006 through fall 2007. Electric barrier was placed at lake outlet, but fish remain in the basin. Lake was rotenone-treated under the ice in February 2007. As of 2010, water levels remain low, and much of lake is remains covered with very dense stands of emergent cattail. Water control via weir with stop logs; electric fish barrier in place.	3 yrs

Spellman	Yellow Medicine	300	A managed drawdown occurred on this basin from 2006-08. 2009 was the first year with full water in the south basin. Box inlet culvert, outlet pipe, and finger-gate fish barrier in place.	2 yrs
Teal	Jackson	91	Partial drawdown implemented in 2008, and lake was rotenone-treated under the ice during winter 2008-09. Water control structure allows partial drawdown; no fish barrier in place at present.	2 yrs

Data Gathering: All intensive lakes were sampled once monthly during June, July, and August. Because project funding did not begin until July 1, we were unable to sample in May as originally proposed, but we were able piece together DNR funds from existing Fisheries Research, Wetland Wildlife Population and Research Group, and University of St. Thomas budgets to sample intensive lakes during June. At each monthly visit, we sampled aquatic invertebrates, phytoplankton abundance, water transparency, and chemical constituents in lake waters (see Table 1). In July only, we also sampled fish populations and abundance of submerged aquatic plants. Hard copy data of fish populations and submerged aquatic plants have been converted to electronic data sets, and will be summarized during this upcoming winter. Samples of aquatic invertebrates collected by field crews are currently being processed and we expect that electronic data sets will be developed by summer 2011.

Preliminary Data Trends: Data not yet available from efforts of Result 2.

B. Develop region-specific guidelines useful for identifying cost effective reclamation approaches enabling optimization strategies - pending completion of A.

Finalizing discussions among project investigators were held to clarify personnel and data needs and a sub-contract for economic analysis with Dr. Welle at BSU has been executed. Dr. Welle's assignment for next semester includes duties to work on the conceptual framework for cost-effectiveness analysis of methods to restore shallow lakes. A graduate assistant has been hired to work with Dr. Welle beginning in Jan. 2011.

Result Status as of June 30, 2011

Progress was made toward developing the conceptual framework for cost- effectiveness analysis of shallow lake rehabilitation alternatives. The goal of this analysis was to provide the Minnesota Department of Natural Resources and LCCMR valuable economic information that can be used to formulate policy to maintain and restore the integrity of these aquatic ecosystems in the most cost effective way. Preliminary results will be presented to project collaborators and will be integrated with empirical data from Extensive and Intensive Lakes.

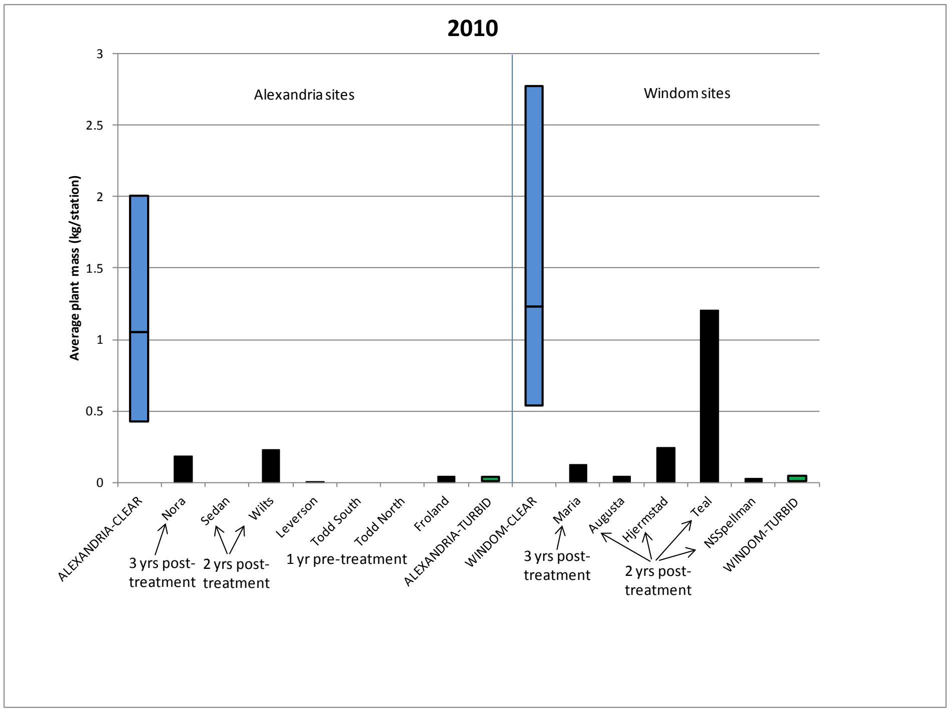
Result Status as of December 31, 2011

Cost-effectiveness modeling- The cost-effectiveness assessment will be further developed in two stages. First, data and model products from Extensive lakes will be used to develop regression models relating fish mass and upland cover characteristics (percentage agriculture) to algal abundance (chla) in study lakes (model details discussed above). Parameter estimates from these and other models will be used to predict potential rates and extent of chla improvements following fish removal (in-lake) or, alternatively, conversion of upland agriculture back to grasslands (in-watershed). Data on chla and fish mass are essential for preliminary models and were gathered for all Extensive and Intensive lakes during June-August 2011. Presently, we have most necessary data on fish abundance, extent of upland cover types in study lake watersheds, and we are entering and organizing resulting electronic data files. Final chla data should be available within the next 6 weeks. This should provide two years of data from approximately 130 Extensive and 12 Intensive lake sites (see below). Extensive lake data should provide comparisons useful for evaluating potential improvements resulting from in-lake vs. in-watershed approaches to shallow lake rehabilitation in Minnesota.

A second stage will involve summarizing physical costs associated with each of our Intensive lakes and using these to valuate benefits of lake improvements following specific rehabilitation measures. Through contacts with project collaborators (Ducks Unlimited, Minnesota DNR, US FWS, and others), we have initiated the process for securing data to support the larger cost-effectiveness analysis and we expect to receive and compile needed data by this spring. In addition, we received data from 4 additional lakes, useful here because these sites were rehabilitated (using fish removal via rotenone) during our current Intensive study. This increases our population of Intensive Lakes to 12 and should increase potential for generating accurate cost-effectiveness estimates. We expect that collaborators will also provide lake-specific costs of fish removal methods, installation and maintenance of water level control structures, seasonal water level drawdown, conservation easements, staff time, and other various physical and operational needs required for completion of these rehabilitation projects. We believe this combined approach (using costs and observed chla results from Extensive and Intensive lakes) has the best potential for reflecting cost details associated with lake rehabilitation, and should ultimately allow cost-effectiveness comparisons of in-lake vs. in-watershed approaches.

Presently, watershed cover type summaries, along with lake-scale fish mass and phytoplankton abundance data (chla) have been summarized and delivered to a biometrician for development of stage 1 models for Extensive lakes. Results will be used in economic models and other analyses to be completed during winter 2011.

Evaluation of Intensive Lakes- We have begun compiling data on aquatic plants, fish communities, and other characteristics of intensive sites so lake responses can be assessed. We



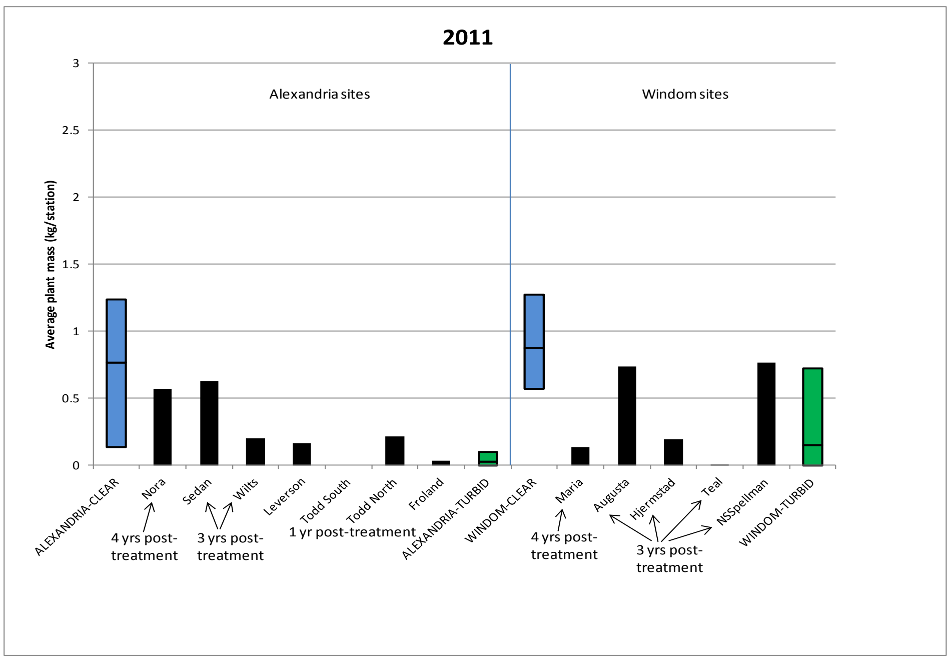


Figure 7.2 Relative abundance of submerged aquatic plants (average mass per sampling station) in Intensive Lakes in Alexandria and Windom study regions during 2010 (top panel) and 2011 (bottom panel). Blue bars indicate means and ranges of regional Extensive Lakes in clear-water regime; green bars indicate means and ranges of regional Extensive sites in turbid-water regime (based on threshold values of Zimmer et al. 2009).

emphasize that we are evaluating these 12 lakes as case studies. This is essential because the small number of sites and variable treatment histories prohibits use of rigorous statistical analysis. Instead, we depicted relative abundances of plants and fish to allow comparisons between community characteristics of individual Intensive Lakes and those of Extensive Lakes within the same study region (Windom or Alexandria). We included Extensive Lake data averages and ranges of clear and turbid sites as a basis for general comparisons with specific Intensive Lakes. Resulting patterns indicate that plant communities are generally less robust in Alexandria Intensive Lakes than in most regional Extensive sites in 2010 (Figure 7.2). By 2011, 2 of 3 lakes rehabilitated 3 or more years ago showed improvement in submerged macrophytes, while ½ of the sites treated the year previous with rotenone application showed improvement. Plant communities in Windom Intensive Lakes showed variable improvements when compared to regional data ranges. Initial improvements in one lake (Teal) faded between 2010 and 2011; two lakes saw improvements with an additional year post-treatment (cf. Augusta and NS Spellman in 2010 and 2011), and one lake (Maria) had plant biomass similar to regional turbid lakes throughout 2010-11 (Figure 7.2). More detailed analysis of the plant data (spp-composition and abundance) will be necessary to determine extent to which these trends reflect favorable responses to previous lake rehabilitation efforts, inherent year-to-year variability, or sampling biases.

Relative abundance of planktivorous and benthivorous fishes was variable and often high in Intensive Lakes, especially in Windom (Figure 8.2). Fish abundance was also extremely variable in Extensive Lakes in both regions, so comparisons between Intensive and Extensive Lakes may be less informative than expected. Still, Windom sites showed an obvious trend toward higher abundance of planktivorous and benthivorous fishes than did Alexandria lakes and this was evident during 2010 and 2011. High fish abundance in 3 or 4 Windom sites was well within the range indicated for regional turbid lakes, probably indicating that fish successfully re-colonized these lakes during 2 or 3 years following drawdown and reflooding (Figure 8.2). Interestingly, one of the Windom sites (Teal) has consistently low fish abundance, and yet water quality (as measured by plants – Figure 7.2) remains low, suggesting something other than fish is influencing the regime status of this lake, perhaps watershed land use, internal nutrient loading, or both. All of these preliminary data patterns should be investigated in more detail as additional data become available.

Status of Intensive Lakes- Relatively low plant and high fish abundance indicate that 3 or 4 Windom Intensive Lakes show characteristics of turbid regimes. Using our data, is not possible to determine whether these sites failed to respond to rehabilitation (via drawdown and reflooding) or if fish quickly recolonized and caused lakes to tend back towards turbid conditions prior to onset of our study. It is notable that relative abundance of submerged plants and fishes may not reflect regime characteristics of Intensive sites. This is because shallow lakes exhibit stability in both turbid and clear regime conditions, so fish or plant mass may not be closely correlated with regime conditions in any single year. It is also important to note that we have not yet summarized data on nutrients or phytoplankton abundance from Intensive Lakes. Those data should be available within the next several weeks and we expect they will help clarify details of Intensive Lake responses and comparisons with Extensive sites.

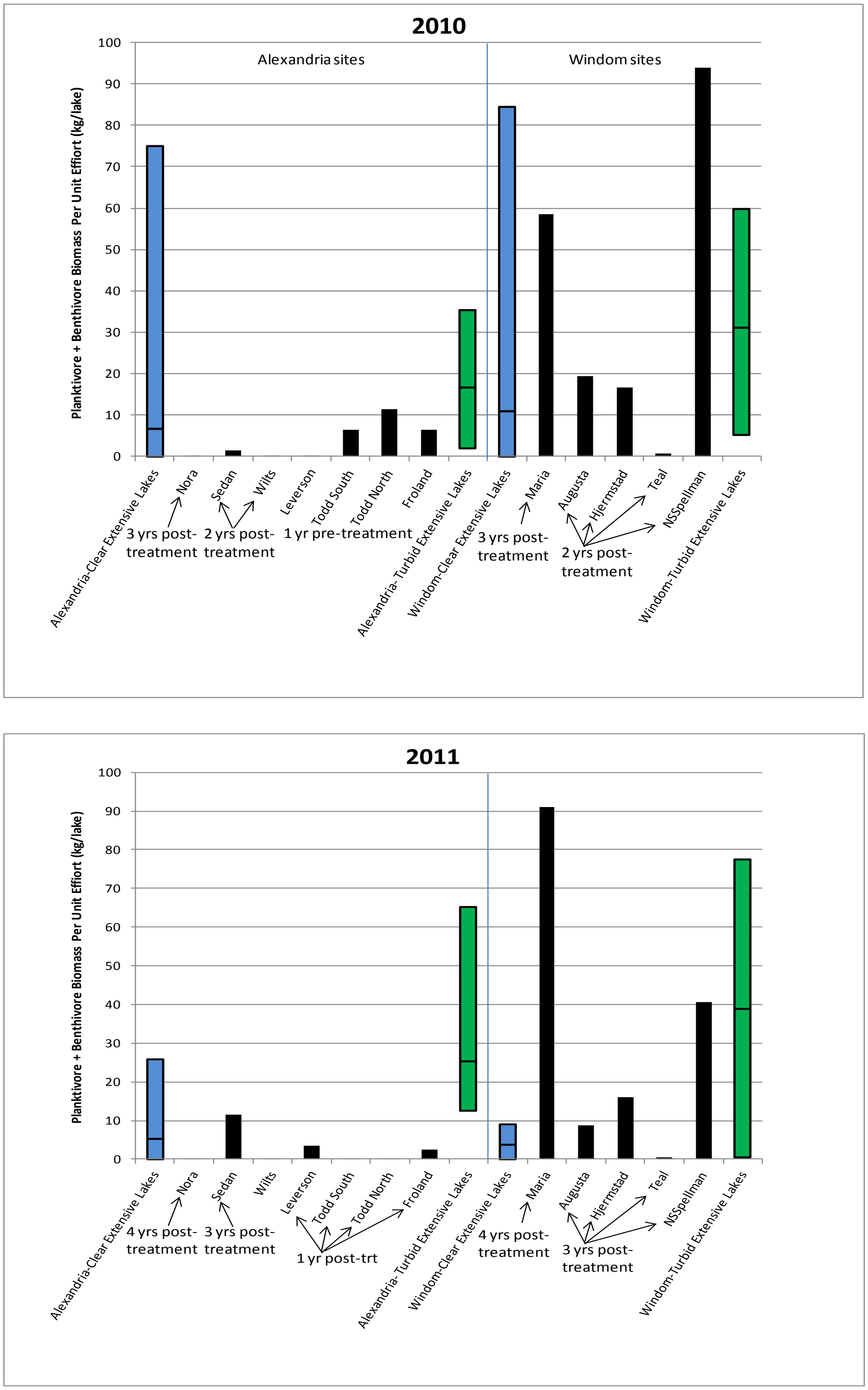


Figure 7.2 Relative abundance of planktivorous and benthivorous fishes (average mass per lake) in Intensive Lakes in Alexandria and Windom study regions during 2010 (top panel) and 2011 (bottom panel). Blue bars indicate means and ranges of regional Extensive Lakes in clear-water regime; green bars indicate means and ranges of regional Extensive sites in turbid-water regime (based on threshold values of Zimmer et al. 2009).

Final Report Summary: June 30, 2012

Evaluation of Intensive Lakes: Patterns in abundance of submerged aquatic plants and fish communities in Intensive lakes were described in previous project updates. In general, we observed highly variable responses of Intensive Lakes following rehabilitation with several of our sites showing characteristics of turbid regimes. Plant abundance often fluctuated widely between study years and, along with the short duration of our study, this made interpretation of lake responses extremely difficult. However, submerged plant abundance in Intensive sites was often within the range of values observed for regional Extensive Lakes in clear regimes, perhaps indicating favorable responses to rehabilitation.

Phytoplankton abundance is a good indicator of regime status (clear or turbid) in regional lakes. Intensive Lake-Chla levels were relatively high in both Windom and Alexandria, with extreme values tending higher in Windom (Fig. 13). Analysis of current data indicates that 100% of Extensive Lakes exhibiting Chla values > 46 ppb showed evidence of turbid regimes.

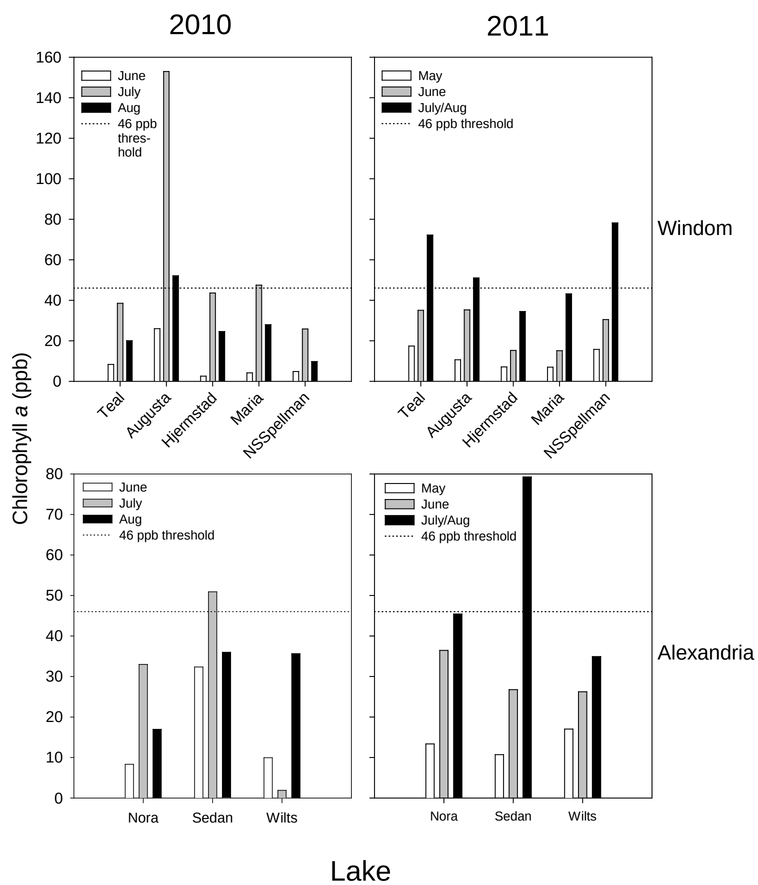


Figure 14. Bars depict chlorophyll a concentrations in Intensive Lakes in Windom and Alexandria study regions during 2010 and 2011. Threshold value is Chla level above which 100% of lakes in present study showed characteristics of turbid regime.

Applying that threshold to Chla levels depicted here indicates that rehabilitated lakes in both study regions approached (or exceeded) this Chla value (Fig. 13). For reasons unknown to us, Augusta (Windom) and Sedan (Alexandria) developed extreme algal blooms during 2010 and 2011 respectively (Fig. 13).

We also assessed the relative abundance of zooplankton and aquatic macroinvertebrates in study lakes because these communities are known to reflect ecological characteristics of shallow lakes, and also show contrasting characteristics between clear- and turbid-water regimes. Zooplankton abundance tended to be higher in Alexandria lakes (Nora, Sedan, Wilts) during both 2010 and 2011, although numbers fluctuated widely between regions and study years (Fig. 14). Macroinvertebrates showed an even more variable pattern, with high- and low- abundance lakes in each study region and no clear trends. Highest relative abundances of macroinvertebrates were observed in Hjermstead (Windom, 2010) and Wilts (Alexandria, 2011), but extreme variability limits interpretation of these data, at least with aggregated taxonomic groups used in these preliminary summaries (Fig. 15). We did not observe obvious trends in abundance of zooplankton or macroinvertebrates in response to apparent differences in fish communities in Invensive Lakes, but this may reflect high variability more than causal mechanisms. Additional analyses based on specific taxa may help clarify data trends and identity ecological responses in rehabilitated lakes.

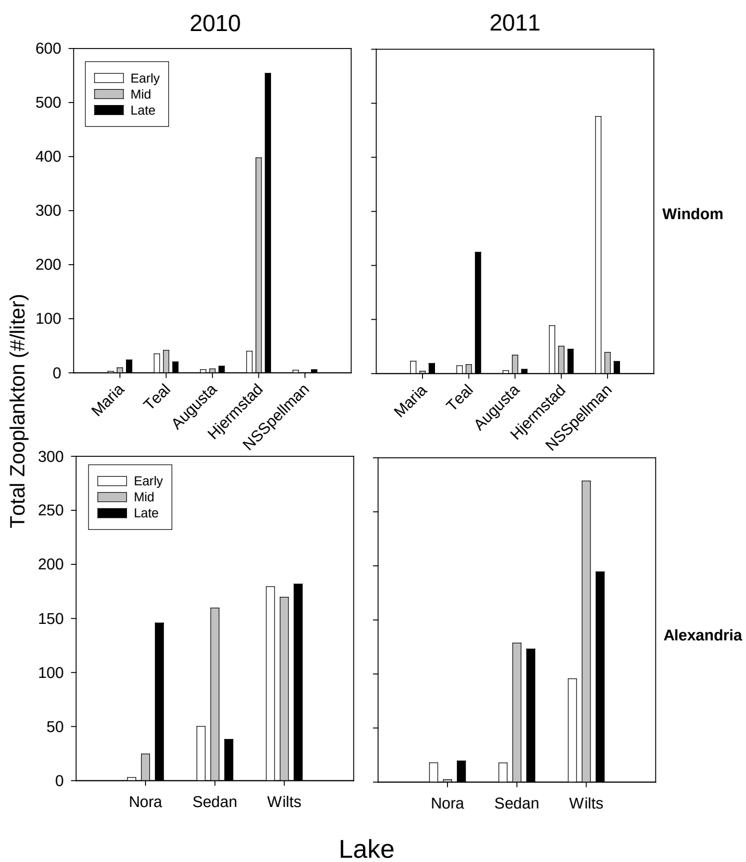


Figure 15. Density of all zooplankton in study lakes in Windom and Alexandria regions during 2010 and 2011.

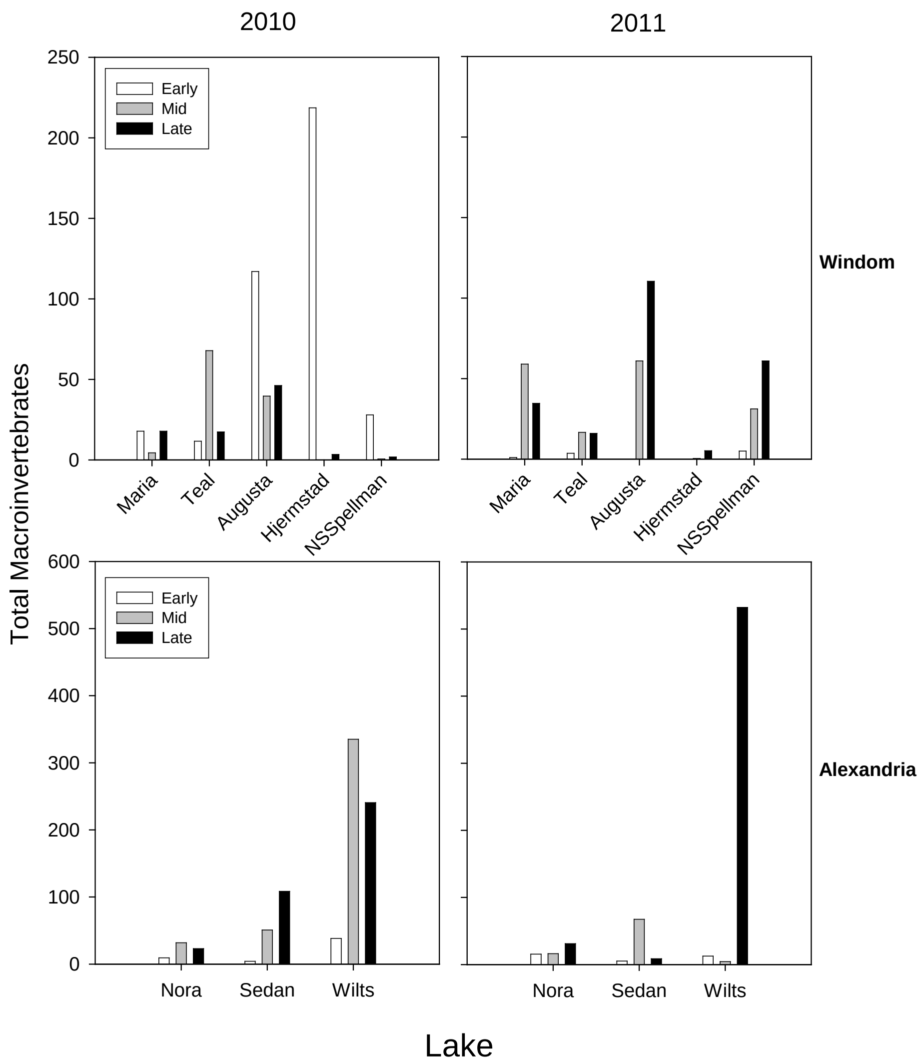


Figure 16. Relative abundance of macroinvertebrates in study lakes in Windom and Alexandria regions during 2010 and 2011.

*Cost-Effectiveness of Lake Management Approaches-Cost- Effectiveness of Methods to Rehabilitate and Protect Shallow Lakes **

(*submitted by Patrick G. Welle, Ph.D. Professor of Economics and Environmental Studies, Bemidji State University, Bemidji, Minnesota. Research assistance was provided by Brett Nelson. Mr. Nelson composed the annotated bibliography in Appendix C. Dr. Welle is also grateful to others who assisted this work, especially Mark Hanson who directed the overall project and provided technical material for this document, including Appendix B. Brian Herwig, Kyle Zimmer, John Fieberg and other members of the project team shared findings and ideas upon which this analysis is based. The research benefited from information provided by Nicole Hansel-Welch, Suzann Willhite and Polly Remick. Jon Schneider from Ducks Unlimited was extremely helpful and accommodating in providing cost information on projects involving Ducks Unlimited. Ducks Unlimited also provided partial funding through a grant from the McKnight Foundation.)

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EXECUTIVE SUMMARY

The goal of this analysis is to provide the Minnesota Department of Natural Resources (DNR) and the Legislative-Citizens Commission on Minnesota Resources (LCCMR) valuable economic information that can be used to formulate policy to maintain and restore the integrity of shallow lake ecosystems in the most cost effective way. This paper presents both a conceptual framework to understand the economic trade-offs and cost implications of available methods to restore shallow lakes as well as empirical evidence comparing costs of methods across lakes and regions of the state. This report contains both conceptual and empirical findings integrating the biological knowledge of restoration effectiveness with economic insights and quantification of costs.

Cost-effectiveness analysis is a subset of benefit-cost analysis in that it shares the objective of measuring net economic benefits to society but it measures the benefits in merely physical terms rather than attaching dollar values to them. Attaching dollar values to the private and public benefits provided by shallow lakes in Minnesota would be extremely challenging and beyond the scope of this study. Instead this study focuses on physical measures of lake quality rather than dollars of benefits. So the objective of cost-effectiveness can be expressed either as

minimizing the cost for a given improvement in shallow lake quality or maximizing the improvement per dollar spent. For practical reasons given the biological measures of shallow lake quality the latter formulation is used, so that the physical measure of improvement is placed in the numerator with dollars of costs in the denominator. The biological findings on improvements offer three alternative measures: 1. reduction in chlorophyll *a* (Chla), 2. increase in submerged aquatic vegetation (macrophytes), and 3. increase in the probability of the lake being in a clear state rather than a turbid state over a designated period of time.

While generating and analyzing primary data on the dollar value of economic benefits from improving Minnesota's shallow lakes is beyond the scope of this study, it is informative to refer to benefit estimates in the literature. This study lays out the underlying concepts for defining economic benefits, such as theoretical components of value. Benefits estimation techniques are also highlighted. Empirical evidence found in the literature on the benefits of shallow lakes is summarized.

Given variables that represent background characteristics of shallow lakes and their watersheds, the theoretical cost-effectiveness model is expressed as:

MODEL: (Y= reduction in Chla/cost) = *f* (IL, WB, PA, CLI, NL, BIO, PHYS, LF, LU, MORPH)

where the independent variables are respectively: In-Lake characteristics, Watershed-Based characteristics, Public Awareness, Climate, Nutrient Levels, Biological conditions, Physical conditions, Landscape Features, Land Uses, and Morphometric features.

Findings indicate cases in which methods implemented on some lakes have little to no impact on Chla. In the extreme this means marginal product of the methods approaches 0, so that marginal cost approaches infinity. The conceptual framework identifies variables that tend to influence the marginal product or the conditions under which improvements may or may not be achieved. This is a topic ripe for further research. Possible thresholds that would push MP toward 0 and MC toward infinity would be:

- High internal nutrient cycling (so only limited amount of nutrients can be removed)
- Unfavorable surrounding land uses/watershed characteristics that make it ineffective to allocate resources to improve lake conditions (determined by % agriculture/%urban)
- Geomorphology and hydrology that make reductions in fish biomass difficult to achieve or sustain for more than a few years (i.e. lakes connected to large river systems or "downstream" in large watersheds)

This investigation into the cost-effectiveness of restoration strategies is based in large part on specific evidence from methods that have been implemented on eight intensive study lakes. These are the lakes with the best evidence on the improvement (or lack thereof) and the closest monitoring of the costs involved. A more expansive group of lakes involves 14 case-study lakes bringing to 22 the group of lakes with good data on improvements and/or costs of methods. A third group of 64 lakes was defined based on data provided by Ducks Unlimited on the costs of projects in which they partnered. Including these lakes expands the sample size and geographic coverage of projects in terms of costs of various strategies, but for most of these lakes, ecological improvements have not yet been estimated.

When the costs of methods are combined with the three alternative physical measures, the resulting cost-effectiveness metrics become:

1) units of algae reduced [µg/L Chla] per dollar spent on enhancement method,
2) increase in submerged aquatic vegetation (macrophytes) per dollar spent on enhancement method, and
3) increase in the probability of the lake being in a clear state per dollar spent on enhancement method.

The total costs of projects implemented over the last decade or so are approximately $20 million. Project costs vary a great deal across lakes. On the smaller subset of lakes where responses have been monitored, a great deal of improvement has occurred. Some lakes had high existing water quality and treatment efforts succeeded in protecting it. In other cases, high-quality conditions have been achieved and maintained. A few lakes have stayed in a low-quality condition despite rehabilitation efforts.

The metric, costs of methods per acre feet implemented, is the most informative comparison across lakes because it controls for water volume. The cost-effectiveness measure best supported by the science and available data is the number of years likely to be in a clear state per $ spent on an acre foot. The percentage of submerged plant coverage gained per $ spent on an acre foot also yields useful quantification of responses to rehabilitation efforts. The two measures are consistent in identifying lakes with the most and least cost-effective treatments.

Development of the conceptual framework enhanced understanding of ways to integrate biological and economic principles. Insights developed here should stimulate further progress in integrating ecological and economic contributions to shallow lake research. Conceptual principles can be better realized through time as data limitations are ameliorated through more extensive data collection and intensified focus on monitoring both ecological and economic returns.

In comparing ecoregions, factors converge that make improvements in southern Minnesota more difficult to achieve ecologically and more expensive to implement. The fertility of the soil is related to the fertility of the lakes and their watersheds and this also leads to higher land values and easement rates due to levels of agricultural productivity.

Patterns across time are merely suggestive based on the limited data available. But further comparisons are warranted as more results are forthcoming with completion and monitoring of more projects in the future. The balance between methods that yield short-term versus long-term improvements is complex. Rotenone treatment may turn around a lake quickly but need to be repeated often or lake quality will not last. And rotenone treatments are not 100% effective, sometimes needing re-application to get even a short-term response.

Erecting fish barriers tends to have a longer lasting effect, but still may be undermined by high water conditions that allow undesirable fish species to return. If a longer term perspective is adopted - implying a lower discount rate on future benefits and costs - higher initial investment in methods such as water control structures and long-term reductions in nutrient loads from better land-use practices may be warranted opposed to repeated expenses on short-term fixes. Judgments about discount rates depend on public preferences, but given that long-term methods may also generate broader types of benefits to the public - such as improved habitat across a landscape scale, rather than merely improving individual lakes - the relative advantages may turn in favor of the long-term perspective.

The biological portion of this project has generated evidence suggesting that changing water quality to a clear state in some lakes may be difficult if not impossible, by solely reducing external nutrient loads. By extension these methods would be too expensive for many lakes due to too much nutrient tied up in the lake sediment and water column. But watershed strategies to reduce nutrient loads may be complementary over the long term to in-lake management in some watersheds. Identifying lakes where long-term reduction in nutrient loads could eventually improve water clarity requires complicated analysis. But this may more accurately reflect reality rather than regarding as futile attempts to reduce nutrient loads in all shallow lakes. For those lakes that will respond positively to nutrient reductions, it may be more cost-effective long-term to reduce root causes of turbidity rather than repeated applications of rotenone that improve conditions for only a few years before needing to be redone.

INTRODUCTION, BACKGROUND AND PURPOSE OF STUDY

Over the past few decades the degradation of Minnesota's shallow lakes has become painfully evident to the point that the State of Minnesota has mounted considerable efforts to protect and restore these lakes and the ecological services they provide. These shallow lakes provide many direct economic, recreational and ecological benefits plus many economic impacts with multiplier effects in the macroeconomic realm. The Minnesota Department of Natural Resources (DNR) has devoted substantial research efforts to enhancing the understanding of shallow lakes and has implemented various management strategies to reverse the environmental degradation that has occurred. (A recent DNR public education piece on shallow lakes can be found at http://www.shallowlakes.info/images/Shallow_Lakes_Booklet_rev12.pdf. For a European perspective on the immense public value of shallow lakes, along with threats to future quality, see Moss.)

The goal of this analysis is to provide the Minnesota Department of Natural Resources and Legislative-Citizens Commission on Minnesota Resources (LCCMR) valuable economic information that can be used to formulate policy to maintain and restore the integrity of these aquatic ecosystems in the most cost effective way. This paper presents both a conceptual framework to understand the economic trade-offs and cost implications of available methods to restore shallow lakes as well as empirical evidence comparing costs of methods across lakes and regions of the state. This report contains both conceptual and empirical findings integrating the biological knowledge of restoration effectiveness with economic insights and quantification of costs.

COST-EFFECTIVENESS ANALYSIS AS A SUBSET OF BENEFIT-COST ANALYSIS

Cost-effectiveness analysis is a subset of benefit-cost analysis in that it shares the objective of measuring net economic benefits to society but it measures the benefits in merely physical terms rather than attaching dollar values to them. According to a highly regarded book on benefit-cost analysis by Boardman, et al., cost-effectiveness analysis is an economic method used to "compare mutually exclusive alternatives in terms of the ratio of their costs and a single quantified, but not monetized, effectiveness measure" (Boardman, et al.) Important examples of cost-effectiveness measures in the literature are costs per lives saved or costs per ton of pollution abated. In these examples, the ratio puts dollars of costs in the numerator so the most net benefit to society would come from minimizing costs per unit gained. The same results can be achieved by maximizing the physical units gained per dollar spent, where the ratio has physical units in the numerator and costs in the denominator, for example lives saved per million dollars spent on highway safety. For further discussion of these two equivalent specifications of the cost-effectiveness ratio see the discussion of the dual below in the section on the model.

In this study of shallow lakes the objective can be expressed either as minimizing the cost for a given improvement in shallow lake quality or maximizing the improvement per dollar spent. For practical reasons given the biological measures of shallow lake quality the latter formulation is used, so that the physical measure of improvement is placed in the numerator with dollars of costs in the denominator. The biological findings on improvements offer three alternative measures: 1. reduction in chlorophyll *a* (Chla), 2. increase in submerged aquatic vegetation (macrophytes), and 3. increase in the probability of the lake being in a clear state rather than a turbid state over a designated period of time, such as 20 years.

It is rare that analogies from popular culture can be drawn to provide non-technical examples of economic techniques. But the recently released film "Money Ball" and the book it is based on provide such an opportunity. The story of the success of the Oakland Athletics in assembling a highly successful major league baseball team by innovatively applying economics is an example of cost-effectiveness analysis. In the statistically rich world of major league baseball, the Oakland Athletics management advanced the use of statistics to find players that were exceptionally productive in relation to their salaries. This was done by combining various measures to quantify a player's productivity (contribution to runs scored) divided by the salary to generate a highly informative measure of runs contributed per dollar spent. This is a variation of the fundamental economic principle of production efficiency under which the best input to hire is the one with the highest marginal product per dollar spent, found by dividing the marginal product by the price of the input. This is often referred to in the vernacular as "the most bang for the buck". In Money Ball, it is "the most runs for the buck."

The similarities are very strong between the "Money Ball" innovation and this study's cost-effectiveness analysis of methods to improve shallow lakes. The first major stage of this study is to assemble various measures to quantify a method's contribution to improving a shallow lake. At the first stage, methods can be compared in terms of their contribution to lake improvement. But economics implies that a second stage is needed to better inform management strategies. Once these quantitative measures of lake improvement are derived, the second stage is to compare various methods in terms of dollars spent. So the units of improvement are divided by the costs of the methods to put improvement in terms of costs per dollar. The formulae involved will be expressed more formally below, but to conclude this explanation of the cost-effectiveness comparison of methods to rehabilitate shallow lakes the basic measure is:

improvement per dollar spent = improvement/cost of method.

The point that cost-effectiveness analysis quantifies benefits in physical terms and not dollar values is also shown in the "Money Ball" analogy. Just as shallow lake improvements are not monetized in this study, so to in "Money Ball" the value of a run in terms of income to the team is not measured.

RECOGNITION OF BROADER PUBLIC BENEFITS

While it is beyond the scope of this cost-effectiveness analysis to put dollar values on all of the public benefits of improving the quality of shallow lakes, a conceptual discussion of benefits is warranted. This section describes the components of values the public enjoys from shallow lakes and refers to empirical findings in the literature without generating primary estimates of economic benefits from shallow lakes in Minnesota.

Future goals for managing shallow lakes are articulated in the Minnesota DNR document "Managing MN Shallow Lakes for Waterfowl and Wildlife"
http://files.dnr.state.mn.us/recreation/hunting/waterfowl/shallowlakesplan.pdf
The stated priorities are much broader than the three physical measures of quality identified above. Recognition of these broader aspects of quality and their contributions to public benefits is essential to qualify cost-effectiveness analysis and its limited scope. The plan relates improved shallow lake quality to increased waterfowl abundance, habitat improvements for game and non-game wildlife, enhanced quality of public lands containing or adjacent to shallow lakes and the goal of returning areas that have historically contained wild rice to their natural state. The specific objective concerning wild rice is stated in the shallow lakes plan as "Increase awareness of the historic, cultural and natural resource benefits of wild rice." This quote highlights both the appeal of cost-effectiveness analysis in avoiding the troublesome monetization of benefits that would be extremely difficult to express in dollar terms and the limitations of the technique due to the important aspects it excludes.

Cost-effectiveness analysis of various methods to rehabilitate shallow lakes (even comparison of broad categories of methods such as in-lake strategies versus watershed management strategies) is limited in that it cannot capture other public benefits beyond the physical measure of quality. For example, watershed management strategies that reduce nutrient loads may not only contribute to surface water quality but might also enhance upland wildlife habitat. Fish eradication through lake drawdown or rotenone application may appear comparable to better land-use practices in a watershed in terms of enhanced water clarity but would not be comparable when other benefits are included, such as enhanced upland habitat and increased nesting cover for waterfowl.

The objective for wild rice is an excellent example demonstrating the strengths and weaknesses of cost-effectiveness analysis. Methods that generate comparable improvements in Chla may be very different in terms of other benefits yielded, such as enhanced wild rice beds. The greater the importance placed on multiple benefits such as restoring wild rice to more of its historical range and enhancing wildlife habit, the greater the weakness of the cost–effectiveness approach in that it reduces the gain to one quantitative measure. The further out on this continuum, the greater the justification for switching to multi-goal analysis as the preferred technique.

Wild rice also provides the opportunity to raise awareness of the diverse perspectives held within the public in terms of its cultural significance and that of lakes in general. The interconnections in nature understood by those with indigenous environmental knowledge presents a contrasting worldview to an economic approach that expresses impacts in one dollar measure of net benefits or a biological approach measuring improvement in one parameter. Still with the proper degree of intellectual modesty, conventional metrics used in economics and biology can enhance understanding as long as their limitations are recognized as a proxy for broader impacts that may or may not be quantifiable.

Even within mainstream economics, there are different schools of thought on how well dollar measures capture net benefits to society. While economic efficiency is accepted as a major economic goal, equity or economic justice takes on varied levels of importance in these schools of thought. The intellectual distance is not great to extend the economic debate on justice to issues of environmental justice.

Here too, wild rice serves as a prime example. The fact that degradation of shallow lakes in Minnesota has led to degradation of wild rice has created a disproportional loss to the Anishinaabe people. Traditional practices that depend on natural processes and ecosystem services from shallow lakes are diminished or disappear with the degradation of these lakes. These losses can be better understood from a long-term perspective, at least as long as half a century. The degradation of shallow lakes and wild rice has occurred mainly in the last 50 years and plans for reversing these trends extend out similarly into the future. This raises the challenge of putting shallow lakes management in the context of Intergenerational Equity. The Anishinaabe ethic of considering impacts on "The Seventh Generation" provides an important worldview on fairness between generations. The book by Foushee and Gurneau, Sacred Water, celebrates cultural traditions and practices centered around water and highlights environmental threats to water such as acid rain and mercury. These perspectives should inform efforts to improve shallow lakes, but are not incorporated within cost-effectiveness analysis.

Recognizing the strengths and weaknesses of cost-effectiveness analysis suggests that while this approach is informative for better understanding ways to maximize the potential improvements in shallow lakes given the limited resources available, the application to shallow lakes does not meet the textbook standards for the ideal situations to apply the technique. In a nutshell, this discussion demonstrates that the benefits of shallow lakes are difficult to reduce to one quantitative measure of quality and that, contrary to the quote from Boardman et al. above, the methods available to improve shallow lakes are not always "mutually exclusive alternatives." Rather multiple methods can be complementary, such as reducing fish biomass and nutrient loads in concert.

This discussion aims to identify the various components of value that people place on shallow lakes. The discussion is extended to include indications of the magnitude of benefits found in the literature, even though primary estimation of benefits will not be conducted in this study. The effort and funding being devoted to shallow lakes is what economists refer to as "public revealed preference" indicating the substantial value these aquatic resources have for the public. The concept is that committing money to a resource reveals that people prefer to have it protected, or value it as least as much as the spending that has been approved. Allowing damage to these lakes runs counter to the evidence on the importance and value of these lakes revealed in public policy, especially in "The Land of 10,000 Lakes."

There are about 4,000 lakes in Minnesota with characteristics that fit the shallow lake classification. While some might conclude that there are many substitutes for any particular shallow lake so that it has little value by itself, economic analysis indicates the contrary. Rather than devaluing a resource such as this because of available substitutes, conventional wisdom in economics and ecology indicates that resources can be essential in reaching critical mass to provide ecological services. The famous statement "If you've seen one redwood, you've seen them all" is just as erroneous if applied to shallow lakes.

The growing literature in economics on shallow lakes internationally is a testament to the value the public places on these lakes. (For example see Fish and Game New Zealand for an application to shallow lakes in that country and Louette et al. for an analysis from Belgium.) It is also a result of growing recognition of the vulnerability of these ecosystems to degradation, especially to the greater susceptibility of shallow lakes (compared to other types of lakes) to undergo dramatic switches in quality – referred to by aquatic ecologists as "regime change." (A Dutch analysis by Hein models economic aspects of regime change.) In all types of lakes water clarity is emerging as a proxy for regime change in that surpassing a threshold or tipping point for water clarity can change the entire character of a lake. Turbid lakes with algae blooms are often referred to as "pea soup." The characteristics of shallow lakes, especially the lower water volume in most cases, amplify the likelihood of occurrence of a "threshold effect." Socioeconomic modeling of management strategies given this threshold effect can be found in Salerno, et al.

As background for identifying public benefits from shallow lakes, it is worth noting the general characteristics of shallow lakes listed in the state plan.

- At least 50 acres in size
- No more than 15 feet in depth
- 300 are currently managed for wildlife resource benefits
- Many are prairie lakes or deep lakes that contain extensive shallow littoral zones
- Tend to provide critical habitat for many different plant species (cattail, bulrush, sedge) and waterfowl species (canvasbacks, mallards, redheads, ruddy ducks, lesser scaup, ring-necks)
- Over 20 other species that use shallow lakes are conservation priorities
- Shallow lakes comprise a crucial component of "Long Range Recovery Duck Plan" (Duck Plan) over 50 years to achieve breeding and migration improvements
- As part of the plan for duck populations, 1,800 lakes need to be protected to meet the goals of recovery
- Also key to Minnesota Statewide Conservation and Preservation Plan
- Also a focus of the Clean Water Act and Total Maximum Daily Loads approach to enhancing water quality by managing nutrients within an entire watershed and nutrient loading internal to the surface water as well

A list of benefits to the public emanating from quality shallow lakes would include:

- Recreational values from hunting (microeconomic activity) and expenditures to engage in hunting and tourism as well as related purchases such as equipment that also have a macroeconomic impact
- Wild rice production (with various public values that are direct, cultural, historic, and seeding)
- Other recreation values such as bird and wildlife watching
- Bait trapping
- Biodiversity and ecological integrity maintained and enhanced by providing critical mass of native species in order to prevent establishment of invasive species

These benefits and others defined below are discussed in the Shallow Lakes Plan and are seen as increasing in priority for lakes that are adjacent to high public use areas such as state parks, WMAs, etc.

Conceptual Framework for Valuing Shallow Lakes

Management strategies to rehabilitate or protect shallow lakes will have consequences that may span just a few years or could last many years. Comparing benefits and costs needs to include future values. If impacts are to be estimated for the foreseeable future, anticipated benefits and costs in years to come would need to be discounted into present value terms.

The standard formulation is:

Net Present Value (N*PV*) defined as:

$NPV = PV\ of\ Benefits\ - PV\ of\ Costs = B_t / (1 + i)^t - C_t / (1 + i)^t$

Where B = Benefits and C= costs

t = time (years into the future) and

i = discount rate

Identifying benefits must be well grounded in a comprehensive conceptualization of the components of value the public enjoys from the activities and ecological services supported by the resource in its natural vs. degraded state. A shallow lake in a high-quality state provides a multitude of benefits that can be conceptualized as economic goods. Among these benefits are recreational experiences to individuals but also non-consumptive enjoyment and ecological services that do not require action by the citizen and so provide collective benefits that fit the economic definition of "public goods."

In thoroughly defining the economic goods associated with environmental resources and services it is important to recognize that some benefits are revealed through commercial expenditures but other benefits are not: some of these economic goods are valued by the public but are not exchanged through market transactions. So preferences for these goods and services are not typically observable because often people do not spend dollars in markets for these effects. One example is valuing the fact that shallow lake habitat exists for an endangered species. Nonetheless, such public values of environmental services are economic goods in a very real sense in that an improvement in human well-being is yielded. Accurate benefit-cost analysis must not exclude public values that people receive just because they are not revealed in market transactions.

Economic goods vary in the degrees to which they are comprised of two principal components of value: "use value" and "passive-use value". Use value accrues when someone gets satisfaction from some form of direct interaction with the resource. For example, people in these watersheds engage in activities such as hunting and fishing. The use value comes from consumptive uses. Use values can also come from non-consumptive uses such as boating or bird watching. Economic loss occurs when the quantity or quality of surface waters such as a shallow lake become less suitable for these activities and so decreases the quantity of goods that people value.

Value can also be generated due to preferences that are entirely separate from use of the resource in a conventional sense. Some people may derive satisfaction from knowing that measures are being taken to ensure ecosystem health, whether or not they pursue "user" activities (such as hunting). These people derive economic value in a passive manner, hence the term "passive-use value": also referred to as non-use value or intrinsic benefits. Substantial attention in the literature has been devoted to several possible motives underlying these values with existence value capturing the intrinsic value of preservation while a subset of altruism toward future generation is sometimes distinguished as bequest value. Existence value has been identified in a variety of contexts, including preservation of natural resources, places of historic significance, legal precedent and great works of art.

Methods for Inferring Economic Value

Methods for estimating the willingness to pay (WTP) for environmental services fall into two classes: revealed-preference techniques and stated-preference techniques. Revealed-preference approaches involve examining peoples' behavior and using this information to draw conclusions about WTP. Stated-preference approaches involve the use of surveys to elicit information that can be used to estimate WTP. The principal stated-preference technique for environmental-policy analysis is the contingent valuation method (CVM). CVM employs a survey method that characterizes the object of choice (e.g., the bundle of effects associated with a policy change). CVM is designed to produce a monetized value for the defined object of choice. Under circumstances where the object of choice is properly framed and the credibility conditions are satisfied, the stated choices provided by respondents provide the basis for estimating benefits. In the context of court proceedings to assign damages, the National Oceanic and Atmospheric Administration determined that natural resource damage assessment can include passive-use values estimated using CVM.

Counting Indicators of Public Values Once, and Only Once

The components of value described above apply to shallow lakes. Shallow lakes, in condition of high quality, provide substantial use values. They also provide ecological services that generate passive-use values. For some shallow lakes, primary data is available to directly calculate losses in recreational values such as duck hunting. Relevant secondary data is also available to estimate losses of passive-use values through benefits transfer techniques. While estimating the dollar value of benefits is beyond the scope of this study, estimates from the literature are cited below.

Studies must be designed to fully count benefits to the public by including all components of value. But reliable estimation must also not err on the high side by adding dollars that measure part or all of the same benefits: this would result in the mistake referred to as double counting. Willingness to pay for a day of duck hunting is a preferred measure of this type of use value, but to add it to what the hunter paid for travel and equipment would be two different monetary indicators of the same enjoyment so to add these would be double counting.

Another common example of the potential for double counting occurs when defensive expenditures have been made, such as the DNR monitoring changes and applying herbicides in an attempt to minimize degradation. These defensive expenditures are warranted by the public values that are at stake. Again this is a form of public revealed preference. Defensive expenditures are often treated as a lower-bound estimate of the values the public has at stake. But from an efficiency standpoint it would be double counting to add these defensive expenditures to the public's willingness to pay (WTP) to undo degradation. Conventional benefit-cost analysis would only include the WTP for benefits once and exclude other spending to avoid double counting.

The literature cited below provides estimates of typical expenditures for these types of recreational activities and reports the economic impacts of these. These are important macroeconomic effects, and the businesses that lose these might want to be compensated for the loss. But benefit-cost analysis is in the microeconomic realm, so conventional microeconomic practices exclude these economic impacts from estimates of economic efficiency. In other words, changes in net benefits provide the theoretically correct measure of changes in economic well-being.

Selected Literature Relevant to Economic Analysis of Shallow Lakes

Episodic bounces in water levels are part of the natural cycle for many shallow lakes. Through time, water control structures have been installed on many lakes, including large reservoir lakes, so that water levels have been kept artificially high and uniform on many lakes. A relevant case of unnaturally low water levels being maintained is reported in a study titled "Lake Drawdown: A Debate on the Value of 2 Inches of Water" by Russell Kashian. He uses hedonic pricing of lakeshore around Lake Koshkonong in Wisconsin to show the disproportionally large loss in economic value for a relatively small loss in lake depth. The quality of the lake was impaired disproportionally to the percentage drop in the volume of water. It demonstrates the danger of misapplying an economic approach that treats all changes as incremental and regards marginal damages as movements along a smooth, constantly sloped function. This was a "permanent" reduction in water level, rather than the type of temporary drawdown applied to many shallow lakes, resulting in a threshold effect. That is, the lake moved to the impaired side of regime change. Sometimes such changes are referred to as non-convexities and irreversibilities, both in terms of ecological and human impacts.

Both ecological and human tipping points are important when applied to shallow lakes. As noted above, the ecological literature establishes that shallow lakes are susceptible to regime changes in water quality, in contrast to a simple, proportional incremental effect. Various perturbations can result in abrupt decreases in ecological services. And when a biological threshold is passed, such as diminished conditions for duck hunting, a dramatic change in human behavior can also occur. Duck hunters may quit using a degraded lake, or the "behavioral regime change" can be more dramatic when enough lakes are degraded in an area to cause a duck hunter to give up the sport all together.

Another important study sets an upper-bound on the magnitude of economic benefits yielded by shallow lakes. Duffield et al. (2011) recently completed a multi-faceted analysis of the economic value of the Great Salt Lake. Of course this lake generates values on an entirely different scale and magnitude compared to the shallow lakes in Minnesota. It is correct that the authors state repeatedly that Great Salt Lake is of "hemispheric importance." Still the study provides a conceptual framework and methodology for properly assessing the public loss from decreased duck hunting. Duffield et al. (2011) employs CVM as described above. It asks water fowlers their willingness-to-pay (WTP) but also tracks trip expenditures, equipment purchases and economic impacts, including macroeconomic multiplier effects. As such it provides a foundation for various estimates of benefits generated by high-quality shallow lakes in Minnesota, though it only includes duck hunting as one use value and ignores other non-consumptive use values (such as bird watching) and passive use-values (such as protecting endangered plants.)

Hunter responses yielded an average trip expenditure per day for "public" hunters of $180. The other group of "private" hunters use private clubs which causes them to spend more. The authors note that this is substantially higher than the estimates from the US. Fish and Wildlife Service (USFWS) based on the survey of Fishing, Hunting and Wildlife-Associated Recreation conducted every 5 years. The higher Utah estimates are presented by the authors as more realistic given the more thorough methodology and larger sample size they used compared to the USFWS estimates. Furthermore the authors cite evidence that their numbers are more consistent with the range found in the literature. (See Loomis, et al. and Hay.)

The Duffield et al. study analyzes net benefits to provide an alternative measure consistent with the neoclassical approach to economic efficiency. Net benefits, also listed as Net Economic Value (NEV) is derived by subtracting from WTP the amount actually spent. If the consumer is willing to pay more than was actually spent, the consumer got a bargain. This excess of willingness to pay over actually spending measures the net gain to the consumer from the activity, called consumer surplus. The estimate for average consumer surplus for the public sample of Utah hunters is $76 per day. This leads to net benefits of $9.5 million per year from hunting the lake. The authors note, "Non-hunter values which are not represented in the estimate are potentially large, and are a subject for future research." (Duffield, et al., 2011, p. 14.) Alternative measures of economic value from the study are direct trip expenditures of $26.5 million plus $35.4 million in equipment expenditures for a total of $61.9 million in 2010. With a modest multiplier the economic impact is calculated to be $97 million in 2010.

A study conducted for the USFWS, titled "Economic Analysis of the Migratory Bird Hunting Regulations for the 2008-2009 Season", provides further review of the literature on estimates of the value of duck hunting. They compare various estimates noting the average of 17 estimates of WTP came to $67 per day converted to 2007 dollars. Hay did extensive work with the USFWS survey data and found consumer surplus estimates ranging from $36 - $58 per day, again in 2007 dollars. When narrowed down to the Mississippi Flyway, which includes Minnesota, the range of consumer surplus values was $42 - $54 per day of duck hunting and yielded $110 - $141 million in consumer surplus.

The USFWS survey generates highly regarded economic estimates for recreational activities. The 2008 addendum to the 2006 report on the economic impact of waterfowl hunting shows 52,000 hunters in Minnesota that engaged in 897,000 days of waterfowl hunting. Nationwide it is estimated that 1,306,000 waterfowl hunters spent over $900 million leading to total industry output of over $2.3 billion. The 2006 estimates for Minnesota are trip and equipment expenditures of nearly $29 million and total output of over $43 million.

The USFWS also provides a 2008 addendum to the 2006 report which includes economic analysis of the impact of birding in the US. Being many shallow lakes are within or adjacent to WMAs it is important to consider the loss to the public of values of these ecological services, especially degradation of habitat. The report shows Minnesota to have the fourth highest percentage of residents who watch birds, at 33%. Total birders are listed at 1,448,000 in the state, with 93% resident and 7% non-residents. These figures indicate that there are roughly 30 times more birders in Minnesota than there are waterfowl hunters. Responses also show that waterfowl are the most popular type of bird sought by bird watchers. This is relevant to understanding the importance of the ecological services that are provided by many shallow lakes.

To compare and contrast the economic impacts of birding to waterfowl hunting, the following quote from the birding addendum is informative: "Birders spend money on a variety of goods and services for trip-related and equipment-related purchases. Trip-related expenditures include food, lodging, transportation, and other incidental expenses. Equipment expenditures consist of binoculars, cameras, camping equipment, and other costs. By having ripple effects throughout the economy, these direct expenditures are only part of the economic impact of birding."

In 2006 "Birders spent an estimated $12 billion on trip expenditures and $24 billion on equipment expenditures. For trip expenditures, 57 percent was allocated for food and lodging, 35 percent was spent on transportation, and 7 percent was spent on other costs such as guide fees, user fees, and equipment rental. Equipment expenditures were relatively evenly distributed among wildlife watching equipment (29 percent), special equipment (35 percent), and other items (33 percent). Auxiliary equipment accounted for only 3 percent of all equipment expenditures." "The trip and equipment expenditures of $36 billion in 2006 generated $82 billion in total industry output across the United States. Total industry output includes the direct, indirect, and induced effects of the expenditures associated with bird watching."

Nationwide the spending for bird watching is over thirty times greater than for waterfowl hunting. This ratio is similar to the ratio of water fowlers to birders in Minnesota and provides a basis for treating individual trip and equipment expenditures in Minnesota as similar between the two groups.

A cautionary note is in order regarding all three types of estimates of benefits - recreational expenditures, WTP and consumer surplus – in that these measures are more problematic when applied to situations where benefits are lost due to shallow lakes being degraded. The economics literature reaches consensus that, for many environmental damages, the conceptually appropriate welfare measure would be willingness to accept compensation for the loss rather than WTP to avoid it. The value should be based on what the harmed citizen would accept as compensation to allow the losses to occur. This fits because the property rights endowment lies with the public so that they should not have to pay to avoid damage. However, in practice, valuation techniques such as CVM are problematic when asking respondents for willingness to accept (WTA) as it could be infinity or at least very large relative to WTP. WTP is constrained by the person's ability to pay based on income and wealth, while WTA is not. So conventional practice, (see NOAA and WRC cites below) estimates values for things such as resources, goods and services using WTP being it is easier to work with empirically. However, for the degradation of shallow lakes that has occurred, it is philosophically more appropriate to value the losses using WTA.

It is worth considering how total WTP may be separated into use and passive-use values. Over the past three decades evidence has emerged demonstrating that passive-use values are too significant to ignore. In the early 1980s the USEPA summarized numerous studies at that time, focusing on the value of water quality, and determined that users tended to have passive-use values that were 50% of use values, and developed a benefits transfer method using this as the passive-use value for non-users as well. (See Fisher and Raucher.) So an estimate of use value per user could be translated into another 50% for passive-use value to users. Added to the use value and passive-use value to users is the passive-use value to non-users, calculated by multiplying that 50% value times all the non-users in the relevant population. This extrapolation of the non-use values that accrue to users and non-users based on estimates of average use values enjoyed by users has been referred to as the 50% proportionality rule. Applying this 50% proportion to estimate non-use values based on the estimates of use values to duck hunters of the Great Salt Lake yields dollar values of huge economic significance. For shallow lakes in Minnesota that generate substantial use values, similar high proportions of non-use values would be reasonable to expect.

Being estimating monetary values of benefits from improving shallow lakes is beyond the scope of the present study, this discussion of conceptual and empirical evidence found in the literature on the benefits of shallow lakes is provided to partially fill that void.

THE COST-EFFECTIVENESS MODEL

This section formulates the conceptual framework for measuring the cost-effectiveness of shallow lake rehabilitation methods. It is more encompassing and frames broader comparisons of methods than could be supported given the available data. As such the additional conceptual ideas that could not be applied here provide implications for further research.

1. Specifying Costs (Y)

(Y)– costs of improving shallow lakes in Minnesota over a 50 - year time frame (reduction in Chla per dollar or - the dual specification - cost per unit of reduction of Chla) This cost-effectiveness approach uses the quantity of Chla as a proxy for a broader measure of benefits that typically would be expressed in monetary terms.

2. Identifying Methods (X)
(X) – Methods/strategies influence variables that indicate improvements in the quality for the shallow lake. Methods may affect various measures of water quality but overall lake quality can also be assessed with measures that are not defined by water quality, strictly speaking. Methods are outlined in the Shallow Lake Management Plan found at
http://files.dnr.state.mn.us/recreation/hunting/waterfowl/shallowlakesplan.pdf
Appendix A of the plan contains maps showing various categories of shallow lakes by the four ecoregions. These ecoregions from northeast to southwest are: Laurentian Mixed Forest, Tallgrass Aspen Parklands, Eastern Broadleaf Forest, and Prairie Parkland. Methods are analyzed for spatial patterns on both lake quality improvements and costs of certain methods, especially land easements, using these four ecoregions.

3. Types of Costs over time
Total Cost Formula = CC (capital costs) + OMC (Operation and Maintenance costs)

Costs will be conceptualized and projected as varying by methods over a "long" time frame, such as twenty years. The temporal aspects of these strategies will be expressed using the common denominator of present value, converting all future costs into current dollars. This approach will reveal **patterns of relative cost advantages thru time of specific methods by ecoregions**, using sensitivity analysis to determine if conclusions are influenced by alternative discount rates.

Present Value (*PV*) is defined such that
$PV(C) = C_t / (1 + i)^t$
C= costs
t = time (years into the future)
i = discount rate

4. Specifying Restoration Methods
a) In–Lake (IL)
(Y)=*f* (• IL)
- Water control structures or temporary pumps/siphons (IL_1) (Total Cost)

- Upfront material and construction costs (CC)
- Wages to install and maintain (OMC)
- Longevity of structures
  - Rotenone treatment (fish population control) (IL_2) (Total)

- Costs of chemicals (OMC)
- Wages to apply/ survey effectiveness (OMC)
- How many years between treatments?
  - Water level control from natural sources (beaver dams and inlet/outlet channels) (IL_3)

- Removal/dredging costs (CC & OMC)
- Wages (OMC)
  - Seeding of aquatic vegetation (i.e. wild rice) (IL_4)
  - Invasive species control (aside from rotenone treatments) (cattail, loosestrife, milfoil- biocides, pesticides, herbicides, mechanical, direct removal, biomanipulation) (IL_5)

- Cost of chemicals (OMC)
- Wages (OMC)
  - Fish barriers (specified in proposal) (IL_6)

- Cost of materials/construction/maintenance (CC & OMC)
- Wages (OMC)
  - Piscivore fish stocking (control of benthivores and planktivores) (IL_7)

- Cost of fry, fingerlings, adults etc. (CC)
- Wages (OMC)
  - Migratory bird structures (feeding and resting devices, wave control) (IL_8)

- Cost of materials (CC)
- Wages (OMC)
  - Tighter regulation on motor use (wave control) (hard to estimate costs) (IL_9)
  - Future or other in – lake methods developed in the feature (IL_{10})

b) Watershed Based Approaches (WB) (Dependent upon characteristics) (Total Cost)

(Y)=*f* (• WB)

- Upland grass restoration/protection (WB_1)

-Cost of plants (CC)
-Salaries/wages to survey/plant/manage? (CC & OMC)
-Land out of production (on-going opportunity cost)

- Conservation easements (non-profits/farm bill) Working Lands Initiative (WB_2)

-Cost of land rights (OMC)

- BMPs dealing with drainage issues (WB_3)

It should be noted that the cost data available to DNR in the recently changed financial tracking system did not provide anywhere near the degree of cost specificity contained in this conceptual framework. The same is true for many of the "other factors" and biological parameters suggested in item c) below for monitoring improvements. Again this discussion may serve as "food for thought" in its implications for further research.

c) Other Factors Influencing Costs
Public Awareness (PA) (Total Cost)
(Y) = *f* (• PA) (all variable)

- News releases
- Environmental education videos and seminars
- Upkeep of DNR website
- Shallow lake ecology posters/articles (State Parks, Conservation Volunteer)
- Scheduled meetings, workshops & conferences regarding shallow lake management

Climate (CLI)
(Y) = *f* (• CLI) – *Note: • CLI may positively or negatively influence Y*

- Long-term Weather Patterns
- Koppen Classification (south-Dfa humid continental (hot summers), north – Dfb humid continental (mild summers))

Ambient Nutrient Levels (NL)(Chemical) (Thresholds for Total Phosphorus have been established)
(Y) = *f* (• NL) – *Note: • NL may positively or negatively influence Y*

- Total Nitrogen
- Dissolved Inorganic Nitrogen
- Total Phosphorus
- Dissolved Phosphorus
- Dissolved Inorganic Carbon
- Seston Phosphorus
- Seston Carbon
- Seston Nitrogen

Biological Sampling Results (BIO)
(Y) = *f* (• BIO) – *Note: • BIO may positively or negatively influence Y*

- Fish abundance (gill and trap nets)
- Submerged aquatic plants (rake and mass methods)
- Aquatic invertebrates (sweep nets, column samplers)
- Phytoplankton abundance (Chla)

Physical Characteristics of Sampled Lakes (PHYS)
(Y) = *f* (• PHYS) – *Note: • PHYS may positively or negatively influence Y*

- Turbidity
- Specific conductivity

Landscape Features (LF)
(Y) = *f* (LF)

- Structural and Spatial Attributes of Landscapes used by Wildlife
- Hydrologic, Geologic, Vegetation

Land Uses (LU)
(Y) = *f* (LU)

- National Land Cover Classification

Morphometric Features of Individual Lakes (size and shape) (MORPH)
(Y) = *f* (• MORPH) – *Note: • MORPH may positively or negatively influence Y*

- Lake Depth
- Lake Surface Area (aerial photo techniques)

- Dilution Capacity
- Volume (surface area X mean depth)
- Lake Formation

Given these variables the theoretical cost-effectiveness model is:
MODEL: (Y= reduction in Chla/cost) = *f* (IL, WB, PA, CLI, NL, BIO, PHYS, LF, LU, MORPH)

In the middle stages of this project, this conceptual framework stimulated discussion and enhanced understanding among members of the project team about the best ways to merge ecological findings on lake improvements with available data on costs of methods. An important finding that deserves major emphasis is that certain lakes possess characteristics that may make it too expensive to improve conditions. Or put another way, some lakes will not improve even if technologically and economically feasible methods were implemented. So if no improvement can be achieved, a zero response in the cost-effectiveness formulation means the return on any expenditure would be zero. Or the dual specification putting cost in the numerator and improvement in the denominator indicates that cost per unit improved becomes infinity when no improvement occurs.

Other documents provided for this study demonstrate that for many lakes the in-lake accumulation of nutrients has been too great for too long for any reasonable reduction in nutrient load to trigger improvement, so that changing lake regimes from turbid to clear cannot be accomplished by watershed-based methods alone. While long-term improvements might still be possible with a combination of reduced nutrient loads from the watershed and in-lake manipulations to reduce fish biomass, even a combination of methods may not generate a discernible response in ecological services or habitat. A more extreme method to reduce nutrients within these systems would be to dredge sediment. Given the high costs of dredging, for all practical purposes, lakes such as this may be regarded as beyond rehabilitation.

Also, some lakes can only be improved to a certain point until little if any further improvement can be gained. As further efforts are applied, the marginal investment is no longer cost effective. In economics this is referred to as diminishing returns or diminishing marginal product and is represented by the following equation.
MP = • Q/• X > 0 but declining, so marginal costs per unit of improvement are increasing
where *MP* = Marginal Product,
• *Q* = Change in quantity of output produced (Chla reduced)
• *X* = Change in the input (one unit change in X variable is one more unit of the method)

Or MC = C/• *Q*
Where MC = Marginal Cost of one unit of improvement
And C = cost of the method

As noted above, findings indicate cases in which methods implemented on some lakes have little to no impact on Chla. In the extreme this means MP approaches 0, so that marginal cost approaches infinity. Using the notation above, MP = 0 implies • *Q/*• *X* = 0 and when • Q = 0, C/• Q = infinity.

The conceptual framework has advanced understanding already on the variables that tend to influence the marginal product or the conditions under which improvements may or may not be achieved. This is a topic ripe for further research. Possible thresholds that would push MP toward 0 and MC toward infinity would be:

- High internal nutrient cycling (so only limited amount of nutrients can be removed)
- Unfavorable surrounding land uses/watershed characteristics that make it ineffective to allocate resources to improve lake conditions (determined by % agriculture/%urban)
- Geomorphology and hydrology that make reductions in fish biomass difficult to achieve or sustain for more than a few years (i.e. lakes connected to large river systems or "downstream" in large watersheds)

This conceptual framework focuses on the inverse relationship between MP and marginal cost and, when combined with biological results, draws attention to the need to better understand the interaction of restoration methods with features of the lakes as well as other factors that impact improvements and hence cost-effectiveness.

In economic theory, cost-effectiveness analysis is an approach to achieving constrained optimization. That is, an objective is defined subject to constraints on the means for achieving those ends. So if cost minimization is identified as the objective, that goal is subject to the constraint of achieving a target level of water quality improvement. Cost minimization per unit gained is the most intuitive version in most people's minds. However, these constrained optimization problems are recognized in economic theory to have an alternative specification called the Dual (i.e. a second, equivalent way to define the problem that will generate the same optimal solutions.)

The dual to cost-minimization for achieving improvements in shallow lakes is to specify the improvement (lower Chla) as the objective to be maximized subject to a certain amount of costs that can be afforded. Hence, the cost-effective solution is also the option that achieves the maximum improvement for the set amount of costs. And again in either of these dual specifications of the problem, a method that has MP approaching 0 and marginal costs approaching infinity will not be included in the optimal solution set.

Production Function: $Q = f(X_1, X_2, X_3, \ldots, Xn)$
Q = quantity of output
X's = quantities of factor inputs (restoration methods)

Given the ecological results and the three alternative measures of improvement utilized here, for ease of discussion, the production function approach is employed. So the primary model is:
MODEL: (Y= reduction in Chla/cost) = f (IL, WB, PA, CLI, NL, BIO, PHYS, LF, LU, MORPH)

And the secondary model is:
MODEL: (Z= Cost/Chla reduced) = *f* (IL, WB, PA, CLI, NL, BIO, PHYS, LF, LU, MORPH)

METHODS OF EMPIRICAL ANALYSIS

This investigation into the cost-effectiveness of restoration strategies is based in large part on specific evidence from methods that have been implemented on eight intensive study lakes. These are the lakes with the best evidence on the improvement (or lack thereof) and the closest monitoring of the costs involved. A more expansive group of lakes involves 14 case-study lakes bringing to 22 the group of lakes with good data on improvements and/or costs of methods. A third group of 64 lakes was defined based on data provided by Ducks Unlimited on the costs of projects in which they partnered. Including these lakes expands the sample size and geographic coverage of projects in terms of costs of various strategies, but for most of these lakes, ecological improvements have not yet been estimated.

The eight intensive lakes and descriptions of management efforts are as follows:

Augusta [Full Drawdown, Re-Flooding, Water Control Structure, Adjacent Fish Barriers]

Augusta is a 499 acre lake located in Cottonwood County. This lake is unique in that pre-2004 it was already subjected to drawdown. In 2008 a full drawdown was implemented and it was re-flooded in 2009. A water control structure already exists on the lake outlet. High velocity fish barrier was installed on adjacent waters within the immediate watershed.

Hjermstad [Partial Drawdown, Rotenone Treatment, Piscivore Stocking, Water Control Device, Fish Barrier]

Hjermstad is a 60 acre lake located in Murray County. In 2008 partial drawdown techniques were implemented, followed by a rotenone treatment during the winter of 2008-09. In 2009 piscivore stocking (walleye fry) took place to attempt to suppress surviving fathead minnows. Also in place is a water control structure, which is a weir with stoplogs and hanging finger fish barrier.

Maria [Full Drawdown, Rotenone Treatment, Electric Fish Barrier, Water Control Device in Place]

Maria is a 425 acre lake located in Murray County. From the fall of 2006 to the fall of 2007 a full drawdown was implemented. An electric fish barrier was placed at the lake outlet and rotenone treatment occurred in February 2007. Currently, lake water levels remain low and are covered with dense stands of emergent cattails. Also in place is a water control structure via weir with stoplogs. A 640-acre acquisition of land on the lake was also completed, with tilled land restored to native grassland and wetlands.

Nora Lake [Full Drawdown, Metal Fish Barrier Installed]

Nora is a 60 acre lake located in Pope County. In 2007 a full drawdown hydrology strategy was implemented. In 2008 the lake began to refill and by 2009, approximately 40-50% was classified as open water. In addition a metal half-riser structure with stoplogs was installed, serving as a fish barrier.

Sedan [Mixed Drawdown, Concrete Water Level Regulation Device Installed]

Sedan is a 62 acre lake located in Pope County. Partial drawdown techniques were employed in 2007, followed by a full drawdown in 2008. In 2009 the lake began to refill. In addition a concrete variable crest structure with stoplogs was installed to regulate water levels.

Spellman [Managed drawdown, Pipe/Culverts Installed, Fish Barrier in Place]

Spellman is a 300 acre lake located in Yellow Medicine County. From 2006 – 07 a managed drawdown took place and 2009 was the first year with full water in the south basin. In addition box inlet culverts, outlet pipes, and finger-gate fish barriers are in place.

Teal [Partial Drawdown, Rotenone Treatment, Water Control Structure in Place]

Teal is a 91 acre lake located in Jackson County. In 2008 a partial drawdown was implemented, followed by a winter rotenone treatment from 2008 – 09. In addition a water control structure is in place, which allows partial drawdown.

Wilts [Naturally Low Water Levels, Rotenone Treatment]

Wilts is a 55 acre lake located in Grant County. This lake is an isolated basin and 2008 water levels were naturally low, so rotenone-treatment was implemented in the fall of 2008.

When looking at the different management strategies implemented, the two stages of comparisons required for cost-effectiveness analysis will be conducted. The first stage is comparing the physical improvements. Each method on each lake will be evaluated in terms of the amount of algae removed (μg/L Chla). Chlorophyll *a* is used as a proxy for phytoplankton biomass. Proposed strategies include watershed strategies (such as the purchase of land easements with the goal of converting agricultural land to native grassland and restoring drained wetlands) and various in–lake habitat enhancements (such as fish removal and/or installation of fish barriers). The second stage includes the cost of the methods so that the ultimate measure is the following ratio: amount of algae removed (μg/L Chla) per dollar of cost.

In order to find the optimal management strategy, ideally each potential method should be compared to the others for each study site. However, multiple methods have not been implemented and monitored on most lakes so ideal comparisons are not possible. Rather comparability assumptions are made across lakes so that the success of methods can be contrasted. Results are then generalized to discern spatial and temporal patterns. These findings should allow the most cost effective rehabilitation methods to be applied to other lakes with similar characteristics.

Three Alternative Measures of Shallow Lake Enhancements

The evidence on improvements indicates that other measures should also be included in addition to tracking changes in Chla. To broaden the analysis, three alternative measures of improvement are utilized: 1) reduction in Chla, 2) increase in submerged aquatic vegetation (macrophytes), and 3) increase in the probability of the lake being in a stable clear-water state rather than a turbid state. A stable clear-water state signifies being clear over a designated period of time. The appropriate time frame to define "stable" should vary by region and by the degree of connectivity of the lake to other surface waters.

When the costs of methods are included the three alternative measures become:

4) units of algae reduced [µg/L Chla] per dollar spent on enhancement method,
5) increase in submerged aquatic vegetation (macrophytes) per dollar spent on enhancement method, and
6) increase in the probability of the lake being in a clear state per dollar spent on enhancement method.

A useful context for understanding shallow lake degradation as well as the effectiveness of methods to reverse negative trends in quality is provided in the following list of possible causes of shallow lake degradation:

- Prior water quality degradation
- Extent of surface-water connectivity
- Population increases (water demand)
- Climate change
- Alteration of cover types within watersheds
- Urban development
- Intensive agriculture
- Exotic species
- Feedlots, ditches or tiles, impervious surface, near shore development, watershed size, crop coverage

A caveat is in order regarding the conclusion that reducing nutrient loads may be insufficient to change the lake regime to the clear state. The production function version of the model is best at illustrating that multiple inputs can be employed simultaneously toward the desired effect. For shallow lakes, strategies to reduce nutrient loads can be complementary to in-lake management strategies. This may be especially true in the long-term.

Before proceeding to the Results Section, it should be repeated that the improvements that occur may be difficult to capture in one proxy measure such as chla. As an extension, watershed strategies are far more complicated and diverse than can be captured in one variable such as % agriculture. As a proxy this relates most directly to the amount of nutrient load in the watershed. Another perspective would focus on land uses that reduce nutrient loads for any given % agriculture in a watershed.

The following two paragraphs from the 2012 Shallow Lakes report to the Legislature summarize criteria for identifying lakes that are good candidates for protection and those that could be rehabilitated:

"Criteria to consider for targeting lakes for direct protection are: quality of existing habitat, size of watershed (smaller the better), waterfowl use, water level management potential, and proximity to features that would contribute to a wetland habitat complex.

Such tools can also be applied to degraded lake systems as a part of a comprehensive habitat restoration plan that includes in-lake management. Research on shallow lakes demonstrates that while watershed restoration is usually not sufficient to restore in-lake habitat quality due to internal nutrient loading, reducing the external sources of nutrients can aid and extend the benefits of in-lake management. In addition, wetland and grassland restoration and protection provides additional benefits by forming habitat complexes of shallow lakes, wetlands and grasslands. These complexes are a key component of achieving the goals of the 2006 Duck Recovery Plan." (MNDNR, 2012, p. 24.)

RESULTS AND DISCUSSION

Some concepts and variables framed in the original model could not be operationalized in the empirical analysis given limitations of available data. Still the conceptual framework is useful in shaping thinking and in pointing to ways empirical analysis could be strengthened in the future. Many potential insights from cost-effectiveness analysis are supported by the empirical analysis conducted on the data available at this time. At this juncture, many of the resources devoted to the shallow lakes program have been committed to surveying conditions on hundreds of lakes, so that management strategies have not yet been identified nor implemented. In that sense, with many management decisions yet to come, it is a good time for cost-effectiveness analysis. But the patterns of cost-effectiveness will be revealed more soundly and thoroughly in the future as more evidence is generated on improvements that result as more methods are applied and projects are completed on a greater number of lakes.

This study may point to potential future benefits of devoting more resources to monitoring responses to future management strategies and to detailing cost components (between and within capital, operating and maintenance categories.) Much of the categorization of costs in the original conceptual model cannot be tracked with the cost data available to date.

The empirical analysis that follows is limited by:

1) A small number of lakes where management strategies have been implemented
2) An even smaller number of lakes where responses to management strategies have been monitored or where sufficient time has elapsed to observe responses
3) The inability to track costs of management strategies in some cases because costs are recorded by project, not by lake, which makes it difficult to retrieve cost figures for methods implemented on particular lakes. This retrieval is further complicated by recent changes in the financial information system, making it more difficult to bridge to project costs from past years.
4) These management projects are often difficult to implement, both technically and politically. Planning and implementation can span several years, which can add to the difficulty in tracking costs.
5) The level of detail on costs recorded within the state financial system makes it difficult to identify cost categories for most projects. Even in instances where cost types are distinguished - such as labor, supplies, travel, equipment - it is difficult to connect to the type of method applied, such as rotenone, fish barrier or water control structure. Future emphasis should be placed on connecting costs with the type of method implemented. In the future perhaps more complete data will be kept and it will be easier to track as familiarity grows with the new financial information system.

Results on Improvements: Three Alternative Measures of Lake Quality

Chlorophyll a

Marginal reasoning from economics points to Chla as an appealing measure of physical improvement for cost-effectiveness analysis. It is theoretically tidy to imagine this as the marginal product of management efforts, moving monotonically along a smooth function showing steady decreases in Chla. Unfortunately such responses do not align with reality in the world of shallow lake ecology where there are threshold effects in the amount of Chla that translate into tipping points in ecological services. Dramatic changes occur in the qualities that the public cares about, meaning the ecological and public benefits are not proportionate to changes in the amount of phytoplankton. What matters to lake health and ecological services is whether Chla is above or below the threshold that allows for a clear water state, natural abundance of desirable aquatic vegetation, and habitat for species including many waterfowl. So using Chla as a measure of improvement oversimplifies the outcome sought by shallow lake management strategies. Even a large decrease in Chla under some conditions can lead to no response in terms of lake quality and in other cases a small decrease can lead to favorable outcomes if near the tipping point to a clear water regime.

Rather than measuring absolute or relative changes in Chla, members of the research team devised ways to capture whether the change in Chla might lead to favorable outcomes in the lake, such as shifting to a clear state or greater percentage of coverage of desirable aquatic plants. Those approaches are shown in the other two measures of improvements involving vegetation and probability of a clear regime. But background levels of Chla for selected lakes are worth considering as a context for how much of a reduction would be needed. Note from Figure 1 that lakes in the northern counties have levels that explain their clear water conditions, while most of the lakes in the southern area near Windom would require huge decreases to see a change toward better quality, if achievable at all.

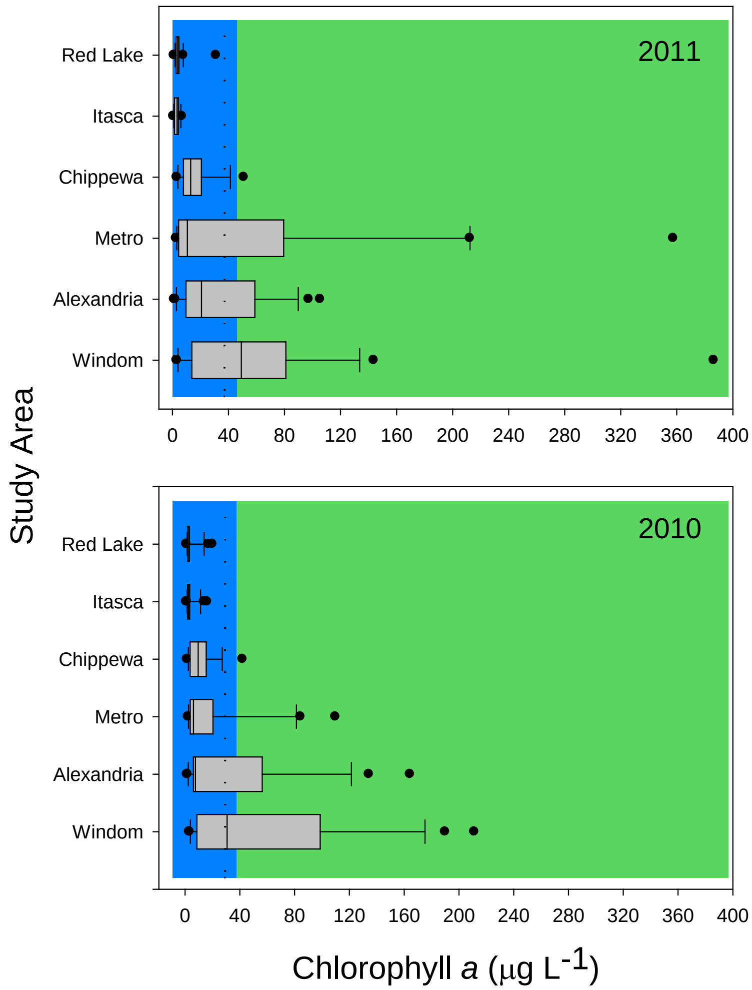

Figure A-1. Box plots show mean abundance of phytoplankton (Chla) for shallow lakes sampled within 6 study regions during 2010 and 2011. The right border of the blue bar depicts threshold values for chlorophyll *a* of lakes in a clear state, and the green area shows region of Chla values indicative of a turbid regime. Note that the box plots indicate lakes in the different regions are very different in terms of sensitivity to shifts between clear and turbid regimes.

Plant Coverage

Another important measure of ecosystem health in shallow lakes is the percentage of the lake bottom that has desirable aquatic plants rooted in the lake bottom. Shallow lakes are surveyed by casting a plant rake at points on the lake (identified by putting the lake map on a grid) to assess plant presence. Recording the percentage of points that have desirable aquatic plants present before and after management treatment is a good indicator of response to treatment, or the improvement that occurred. Table 1 below reports the change in percentage of aquatic plants present and change in water clarity as measured by Secchi disk transparency. Figure 2 graphs these numerical changes.

Table 1. Adapted from Hanson, et al. 2012, Unpublished data

Program Lakes	Gain in % Plant Coverage	Gain in Feet of Secchi Transparency
Augusta	13.3	1.2
Bear	80.6	0.6
Buffalo	17.0	1.1
East Twin	62.0	1.8
Geneva	92.0	2.5
Hjermstad Slough	97.1	3.0
Little Towner	66.7	2.2
Maria	92.6	2.8
Mott	33.5	1.3
Nora WMA	5.7	0.3
Pickerel	100.0	2.6
Golden	0.0	-0.4
Sunset	0.0	-1.4
Sedan Pond	0.0	-2.1
South Spellman	3.0	1.74
South Twin	34.3	0.8
Swan	2.4	1.9
Teal	-3.3	0.0
Towner Lake	94.0	3.4
Wilts	0.5	2.1

Comparisons of vegetative coverage before and after treatment sometimes show big gains and are useful for illustrating complexity of interpreting lake responses. Top lakes in terms of improvement are Pickerel, Towner, Hjermstad, Maria and Geneva. These gains for the smaller number of intensive lakes are depicted in Figure 2. So if costs of management strategies across these lakes were equal, the biggest bang for the buck would have occurred in Pickerel and the others that switched regimes based on increased abundance of desirable aquatic plants. While most lakes showed vast improvement after treatment, Swan was already of high quality so the pre-emptive treatment is associated with only a slight improvement. The relevant comparison would be to how it would have deteriorated without treatment in response to sudden appearance of carp. Teal showed less plant coverage and less clarity after rehabilitation so, by these measures the quality of Teal declined. This is an example of the fallacy of pre-post comparisons (not cause and effect) in that Teal's decline is due to complex background factors and was not caused by treatment. Golden, Sunset and Sedan Pond are high-quality basins managed by the U.S. Fish and Wildlife Service. They had 100% vegetation both before and after management so no gain was shown. Secchi transparency was to the bottom before and after treatment: Secchi measures declined due to lower water levels. If there were valid cases of no gain, the cost for improvement would be infinity. If loss occurred the cost-effectiveness measure would actually be negative, technically negative marginal product per dollar spent.

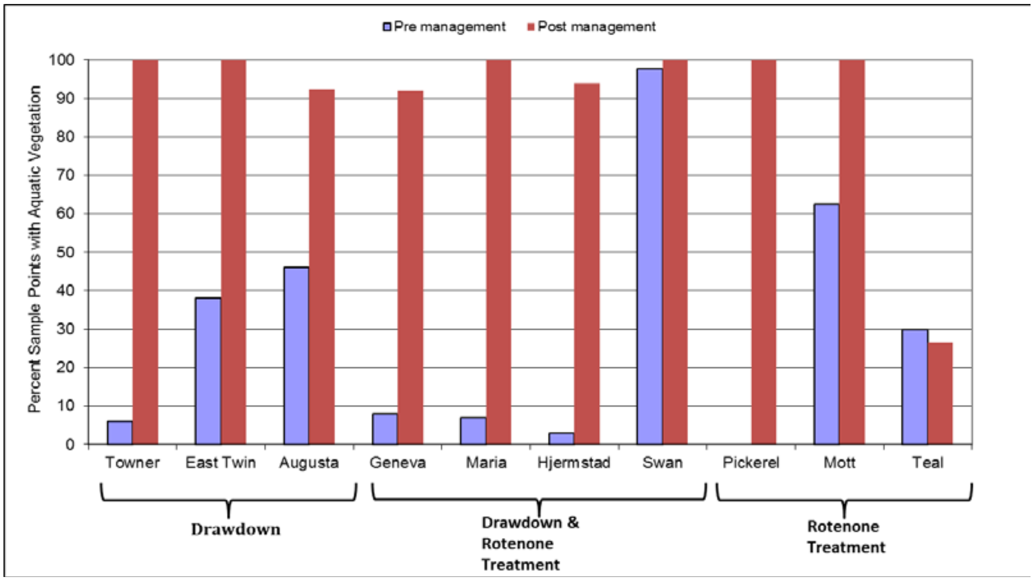

Figure 2. Aquatic Macrophyte Coverage in Managed Shallow Lakes: Pre and Post Treatment (data from 2002-2012; data summarized from MDNR Shallow Lake Report, 2012).

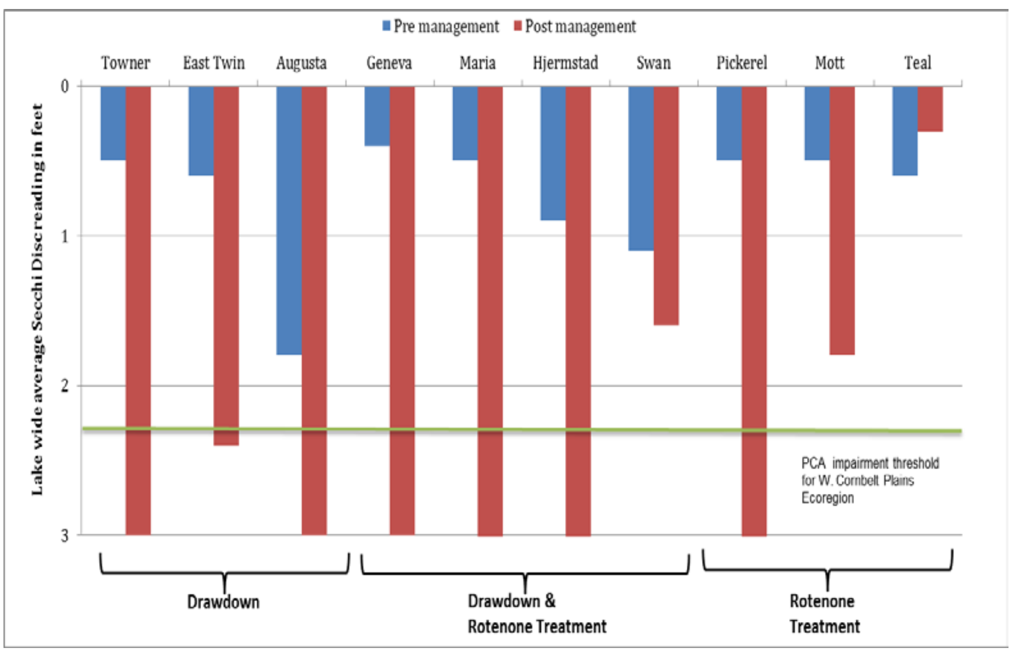

Figure 3. Secchi Transparency: Pre and Post Treatment (data from 2002-2012; data summarized from MDNR Shallow Lake Report, 2012).

Table 2: Results from 18 shallow lakes as summarized from MDNR Shallow Lake Report, 2012). Response indicates that lake shifted to clear regime following rehabilitation. Duration indicates years in clear-water state. Text and colors depict rehabilitation as follows: B = pre-treatment; 0 = turbid; 1 = clear; red = rotenone application in open-water; red shade = rotenone application under ice; tan = drawdown; tan shade = partial drawdown.

Lake	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2010	2011	RESPONSE	DURATION
Augusta					B-1	?	?		?	1	1	?	1	1	Y	2
Bear			B-0		0	1	?	?	0	0	0	?			Y	1
Buffalo				B-1		?	?	?	?		1	?			?	
East Twin			B-0	?	?		?	?	1	?	?	1			Y	1
Nora								B-1	1	1	1	?	1	1	?	
Sedan Pond								B-1		1	1	?	0	1	?	
South Spellman					B-1	?	?	?		1	1	?	0	1	?	
South Twin								B-1		1	1	1			?	
Towner	B-0							1	1	1	1	1			Y	4
Swan				B-1		?	1	1	1	1	1	?			?	5
Geneva			B-0	?	?	?	?	?	1	1	1	1			Y	4
Hjermstad									B-0	1	1	1	1	1	Y	3
Little Towner					B-0	1	1	1	1	1	1	1			Y	6
Maria				B-0	0	0	B-0	?	1	1	1	1	1	1	Y	4
Mott				B-1	?	?	?	?	B-1	1	1	?			?	
Pickeral			B-0	?	?	?	?	?	?	B-0	1	1			?	2
Teal							B-0			0	?	?			N	
Wilts							B-1	1	1	1	1	1	1	1	?	

Probability of Stable Clear-Water States

There are huge differences in water clarity and its importance in shallow lakes compared to deep lakes. Krysel, et al. (2003) studied the economic value of increased water clarity in deep lakes. Hedonic pricing was utilized to measure the greater market value placed on frontage feet of lakeshore on lakes with greater water clarity as measured by Secchi disk transparency . Protecting water quality to yield one meter more in clarity would lead to millions or tens of millions of dollars of greater property values on many of the 36 Headwaters lakes included in the study. Extrapolating to lakes in north-central Minnesota alone, preventing pollution that could cause reductions of one meter of water clarity on hundreds of lakes would enhance property values by roughly a billion dollars.

But a one meter improvement in Secchi disk transparency of deep lakes does not often indicate a regime change from turbid to clear, whereas for shallow lakes it usually would. For most deep lakes a change of a few feet is just a movement along a continuous function, whereas for shallow lakes there is a discontinuity so a change is not proportional, but rather all or nothing. A transparency improvement of even just a foot or two may extend light penetration to the average depth of a shallow lake. This represents a dramatic change from not being able to see much below the surface to being able to see the bottom. More importantly for lake health, it probably would induce a regime shift from turbid to clear. For deep lakes, a one meter improvement in clarity can have substantial value driven by aesthetics. For shallow lakes, regime change to a clear state means recapturing valuable environmental services, such as regaining favorable conditions for wild rice.

As noted above, members of the research team devised ways to capture whether the change in Chla would lead to favorable outcomes in the lake, in this case the probability that the lake would be in a clear state rather than a turbid one. Analysis of Chla conditions indicated that Chla levels less than 37 ppb would most often be associated with a clear state. This is a classic example of a threshold effect. This measure of improvement was formulated as dramatically increasing the odds of clear lake conditions. The analysis was extended further by investigating the number of years where those odds were enhanced.

For lakes where actual responses were monitored, the year-by-year conditions as being clear vs. turbid can be tracked. The results are shown in the table below for lakes for which this analysis is possible. In general it illustrates that treatments often did result in a clear state, at least for a couple of years. Results are limited by not having enough years elapsed to observe duration of improvement. The most immediate and longest lasting improvement thus far is shown by Little Towner Lake. It switched to clear from turbid the year after treatment and has maintained it for six years. As with the measures reported above on chla, vegetation, and water clarity, Teal Lake showed no consistent improvement in any measure. In terms of years where the regime changed to clear after treatment, other big winners are Towner, Geneva and Maria. Pickerel Lake was treated more recently so had only two years of improvement thus far. Recall Pickerel showed the biggest gain in healthy vegetation. Swan is noteworthy among the lakes that were treated while in a clear state and that condition was maintained.

<u>Probability of Clear State Following Lake Rehabilitation: Simulating Possible Outcomes</u>

Using data gathered from our Extensive cross-sectional study lakes during 2010, we identified high and low fish mass values (planktivores and benthivores), and high and low agriculture sites (as a % of watershed area), by selecting 75th and 25th percentile values from Alexandria and Windom study regions. We assumed in-lake rehabilitation (rotenone, drawdown, etc.) would reduce fish abundance by 50% and 90% (lakes with low fish abundance are unlikely to be rehabilitated). We also assumed upland restoration in lake watersheds could be achieved by reducing agriculture (as percent, through conversion to grass or similar cover types). Next, we used regression models to simulate chla from 24 combinations of fish mass (planktivores + benthivores) and extent (%) of watershed agriculture using data from Extensive Lakes.

We simulated likelihoods that lake rehabilitation either by fish removal or upland restoration would result in chla levels similar to values observed in association with clear-water regimes in our Minnesota study lakes (<37 chla ug L^{-1}, updated threshold value from most recent analysis of present study data). Simulation results were summarized as the proportion of lake response outcomes for which ending chla values (following lake management) were ≤ thresholds known for clear-water shallow lakes in Minnesota (Figure 5).

Results allow comparisons of simulated lake chla reductions following lake rehabilitation via in-lake measures (drawdown or rotenone to reduce benthivorous and planktivorous fish) in contrast to improvements resulting from restoration of upland cover (replacing row crops with grass). For example, results indicate that fish removal to 10 kg has approximately 70% likelihood of reducing chla levels to 37 ug L^{-1}, a level observed to be associated with clear-water regimes in Extensive Lakes (Figure 5). Results also indicate that a wide range of chla responses are likely in response to reductions in watershed agriculture, and that short-term chla reductions to 37 ug L^{-1} may be less likely (and more difficult to predict) in response to upland cover restoration than to fish removal. In other words, simulations suggest that within-lake rehabilitation has higher potential for reducing chla in shallow lakes than does conversion of watershed cover types.

Several notes of caution must be emphasized. First, we acknowledge that many other fish/cover-type combinations are possible, but our objective was simply to identify a set of possible outcomes based on conditions observed in Extensive Lakes during 2010. Second, simulations only estimated likelihood of chla values (and resulting regimes) previously observed in our Extensive (cross-sectional) study lakes. Model simulations cannot accurately predict probability of actual lake outcomes as those are influenced by many factors working together to influence lake responses in ways that are impossible to estimate given use of our existing data. We also emphasize that simulated results reflect short-term reductions in chla. This is not surprising given that lake rehabilitation by drawdown or rotenone application is known to induce only brief increases in lake water quality. Most likely, restoration of grass in lake watersheds will ultimately favor long-term, sustainable reductions in chla and other water quality improvements, but improvements following watershed-scale enhancements are almost certain to be delayed due to nutrient accumulation in lake sediments or other factors. Watershed restoration will do little to control invasive fish particularly carp, which are known to increase internal nutrient cycling (Hobbs et al. 2012).

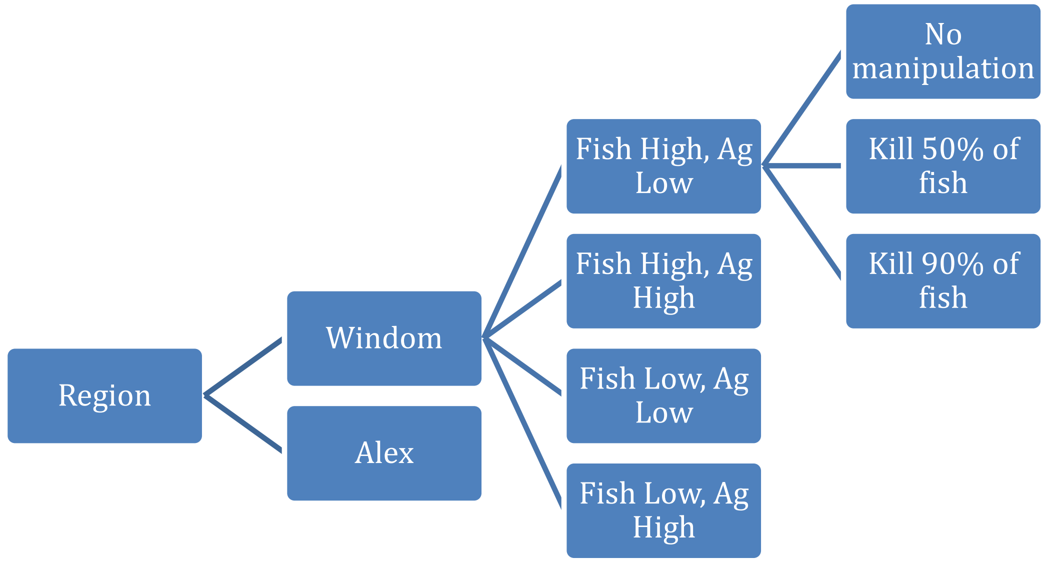

Figure 4. 24 scenarios (12 for each Region). These scenarios capture two different values of %Ag (25th and 75th percentiles from within each region), two different starting levels of fish biomass, and 3 possible management scenarios (no reduction in fish biomass, 50% reduction, 90% reduction).

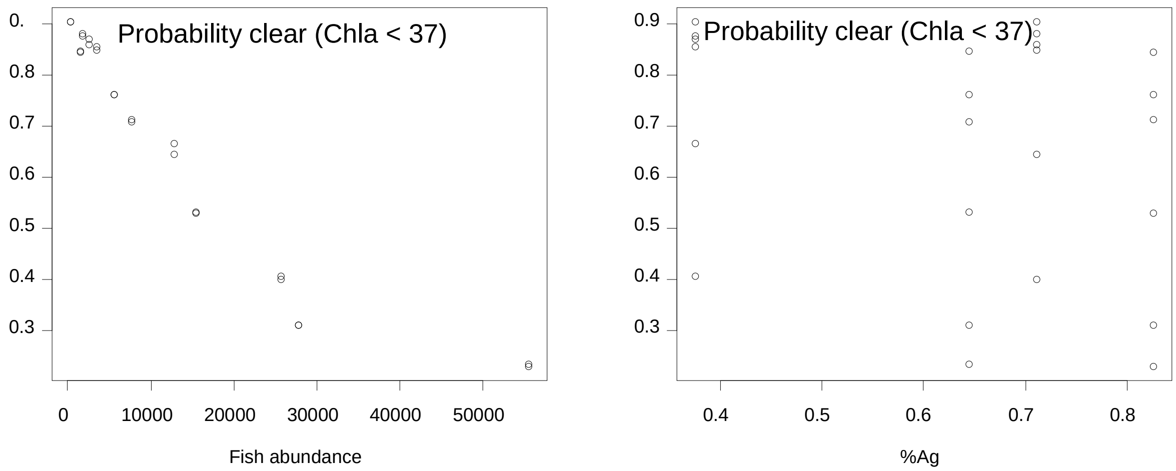

Figure 5. Summary of simulation results (probability of clear state [Chla < 37] as a function of ending fish abundance [planktivore + benthivore fish mass] and %Ag.

Having considered the three alternative measures of shallow lake improvement, it is important to note that lake size must be factored into calculating lake gains. Both the ecological benefit and the consequent public benefit vary proportionally with lake size. In an economic sense, the measure of marginal product (MP) must quantify the amount of lake area that has been improved. Partners on the research team determined that for some treatments, such as rotenone, the relevant lake unit is acre feet, to reflect volume of water improved, rather than surface area.

Foreshadowing the combination of improvement measures and costs, it is possible to conceptualize a measure of cost effectiveness as improvement times acre feet divided by costs, to get a metric that compares lakes by the number of acre feet, showing a quantity of improvement per dollar spent. The greatest bang for the buck would be the most improvement over the most acre feet per dollar. A more simple specification is used below which accounts for acre feet in the cost measure. In the section on costs that follows, treatment methods are compared both in terms of absolute costs and costs per acre foot of treatment. Algebraically the two expressions are interchangeable because putting the acre feet term in the denominator of the denominator is the same as multiplying by acre feet in the numerator: MP x acre feet / costs = MP/cost per acre feet

Results on Costs of Methods

Descriptive statistics on costs for all lakes are shown in Table 3. Projects date back about a decade, so it should be noted that the sum of costs is in nominal dollars, meaning more recent expenditures are somewhat higher due to inflation. Expressing all values in present value terms, such as 2011 dollars, would have been preferred. But costs that occurred over multiple years and missing data on the year when expenditures occurred did not support this adjustment.

There were a total of 86 lakes in the combined cost data bases provided by the DNR and Ducks Unlimited, but one, Nora, had no cost information. Many of the lakes had management projects that were partnerships between the DNR and Ducks Unlimited involving cost sharing with full or partial reimbursement to Ducks Unlimited from state and/or federal sources. On projects where the cost-sharing arrangement could be quantified, the sum of Ducks Unlimited costs is $16,000,217 with total reimbursements from state and federal sources of $12,259,533, indicating that the share from public funds is about 77%. The sum of all costs from both data sources is shown below in Table 3 to be $18,087,213.94 which includes a bit over $2 million of spending by the state on projects that were not in the Ducks Unlimited data base.

The measures of dispersion shown in Table 3 indicate a great deal of variability in spending across lakes due to the various strategies that have been implemented and due to the different sizes of the lakes. Treatments such as rotenone vary proportionally to lake size. However there is more similarity among cost methods such as fish barriers or water control structures that are not so closely related to lake size. Costs for individual lakes are shown in Table A-1 in the Appendix. The top five lakes for costs all exceed $500,000 and they are, in descending order: Lake Christina at over $2 million, Big Stone Pool 7 at about $1.8 million, Little Elk Main Pool, Bear and Wolf. Lowest costs for project were incurred on a half dozen lakes where less than $30,000 was spent. These lakes, in ascending order, are Wilts, Fulda Lake , Bradshaw WMA, Birchdale WMA, Sedan Pond, and Niemackl Lake – Ohlsrud.

Costs per acre foot control for the variation in lake size. Descriptive statistics on cost per acre foot are shown in the second cost (rightmost) column in Table A-3. Costs per acre foot for individual lakes are shown in Table A-2. The most expensive lakes in terms of costs per acre foot in descending order are Fenmont WMA, Lindsey Lake WPA, Wolf Lake, Harder Lake and Wiley WPA. Lakes with the lowest cost per acre feet in ascending order are Swan, Simon, Niemackl Lake – Ohlsrud, Big Slough and Fulda Lake.

Table A-3: Descriptive Statistics on Total Costs and Costs per Acre Foot

		sum costs lake	Costs per acre foot
N	Valid	85	55
	Missing	77	107
Mean		212790.7522	427.3905
Median		134534.7200	291.4771
Std. Deviation		279361.26662	524.11083
Variance		7.804E10	274692.161
Minimum		7090.00	13.58
Maximum		2222050.60	3273.70
Sum		18087213.94	23506.48
Percentiles	25	83478.4200	107.2498
	50	134534.7200	291.4771
	75	258788.3300	528.0910

The combination of high water quality and large size makes Swan Lake in Nicollet County an interesting case study. The largest lake in the study in surface area and volume, it was identified for management because of its importance and opportunity to protect, rather than rehabilitate, a lake that has good quality. Swan Lake ranks in the upper quartile in project costs for lake drawdown using an existing outlet structure and rotenone treatment. For such a large lake, the costs of a water control structure or forthcoming fish barriers do not increase proportionally with size, while rotenone treatment does. It is an interesting case because the decision was made to invest shortly after carp were first identified in the lake, in attempt to keep quality from deteriorating. This appears to be another among so many examples where protecting the environment is cheaper than cleaning it up after it has been degraded. Swan Lake is also interesting in exhibiting that a higher than average project cost is quite a bargain when looking at acre feet of quality water. It is the least costly in terms of costs per acre feet.

Given available data it is difficult to compare costs between methods. For most lakes the method is not recorded and in other cases multiple methods were employed over multiple years. Table A-3 shows total costs and costs per acre foot by method. Costs per acre foot for rotenone application varied between $50 and $100 on a few lakes tracked by the DNR (DNR communication) depending on whether the labor costs of application were charged to the project.

Table A-3 shows that costs of constructing water control structures varied between $46,000 and about $490,000. Costs of fish barriers ranged between about $84,000 and $285,000. When controlling for acre feet, costs of constructing water control structures varied between $59 and about $583. Costs per acre feet for fish barriers ranged between about $26 and $291. The lowest cost per acre foot, again for Swan Lake, was a combination of rotenone and drawdown using an existing control structure. A fish barrier is being constructed because carp were observed previously, but the costs are not yet recorded.

Watershed-based management focuses on relationships between land-use practices and nutrient loads to the shallow lakes. For various analyses, project research employs a variable measuring the percentage of agricultural land use in a watershed as a proxy for nutrient loads. Of course, land-use practices are more nuanced than this and even refining the measure according to percentage in row crops could be more closely correlated with nutrient loads. In terms of costs to change this percentage, federal programs such as the Conservation Reserve Program (CRP) pay farmers to enter into contracts (many lasting ten years or longer) to take land out of production and plant it to prescribed vegetation. So a complementary measure might be the percentage of acres in the watershed in native vegetation.

Nutrient loads will vary based on a number of factors. Percentage in agriculture could be refined by splitting the percentage of working lands into those where conventional practices are employed versus those utilizing sustainable practices such as the best-management practices rewarded in the federal Conservation Security Program (CSP). Vegetative buffers and filter strips along the edges of crop fields and nutrient management plans are among the practices designed to protect surface waters within the watersheds of working farm lands. Tracking the complex constellation of programs directed at protecting surface waters from excess nutrient loads and integrating those with present results is beyond the scope of this study.

However, the costs of watershed-based management strategies can be understood by exploring payments made for conservation easements. This is a major form of payment to reduce nutrient loads (again it may also generate a multitude of other public benefits such as habitat enhancement.) Payments for land easements also serve as proxies for other costs, such as land prices, in that easement rates and land prices tend to be highly correlated. There are four rates paid per acre under the State RIM program, depending on whether it is in the straight Wetland Reserve Program (WRP) or combined RIM-WRP Program and whether the foregone opportunity is for crop or non-crop uses.

Descriptive statistics on conservation easement rates paid by the State of Minnesota as crop rates for WRP are shown in Table 4. Raw data by county was aggregated into the four ecoregions, with counties straddling ecoregions placed in the ecoregion containing the majority for the county. N in Table 4 indicates the number of payments made in that ecoregion. As would be expected, just as land prices vary widely across regions of the state, so do easement rates. These spatial differences in costs are shown using Analysis of Variance (ANOVA) across the four ecoregions as defined in the shallow lakes plan. ANOVA results are statistically significant across the ecoregions and pairwise comparisons of means show each pair is significantly different from the other, using the strict Bonferroni standard. The pattern mimics the gradient of land prices from lowest in the north to highest in the south moving across the state.

The other three per acre rates of easement costs (WRP non-crop, RIM-WRP crop and RIM-WRP non-crop) all show statistically significant differences across four ecoregions using ANOVA to compare means. Pairwise t-tests to compare means of each pair of ecoregions show all are significantly different at the 1% level using the Bonferonni test. Selected tables of statistical output are provided in Appendix A, Tables A-4a-d.

Table 4: Easement Rates per Acre

WRP Crop rate

	N	Mean
Laurentian Mixed Forest NE	828	1543.33
Tallgrass Aspen NW	193	841.53
Eastern Broadleaf Forest	675	3392.78
Prairie Parkland SW	945	3558.98
Total	2641	2685.97

Combining Improvements and Costs: Comparing Improvements per Dollar spent Across Lakes, Ecoregions and Years

Cost-effectiveness analysis merges information on improvements with costs to yield the ultimate measure of improvements per dollar spent. In this section, patterns are explored showing combinations of high vs. low improvements achieved combined with high to low costs of methods toward the objective of identifying high improvements per dollar spent.

Cost-effectiveness analysis identifies the option with the most bang for the buck as having the greatest MP/cost. So in comparing methods on two lakes, A and B, the better option is shown to be rehabilitating Lake A when MP for A/cost on A > MP for B/cost on B or (MP for A/cost on A)/(MP for B/cost on B) > 1. The economic theory of production efficiency also restates this condition as relative comparisons of the ratios of the marginal product and the costs. Comparing these ratios shows that the preferred option has a ratio of MP greater than the ratio of costs. So the alternative expression is: (MP for A/MP for B) > (cost on A/cost on B).

Any calculation of ratios of improvement to costs per acre feet needs to account for the three alternative physical measures of gain. As discussed above, improvement in Chla has quantitative appeal but is not necessarily associated with movement to a clear regime. The other two measures - vegetation and years switched to a clear regime – indicate the biggest improvements occurred on Pickerel, Towner, Hjermstad, Maria and Geneva. Swan was also protected from potentially turning turbid being the presence of carp had been verified. The most tangible measure of physical improvement may be the gain in the percentage of the lake covered by submerged aquatic vegetation. Recall from Table 1 that Pickerel Lake showed a 100% gain in coverage (from none to complete) and Hjermstad Slough was second, gaining 97.1 percentage points in coverage. Pickerel presents a strong example of cost-effectiveness in that it could be regarded as having the greatest physical improvement and, while its total costs are a bit above the mean, costs per acre feet are in the lowest quartile. The cost-effectiveness ratio for Pickerel (vegetative gain/costs per acre foot) would be 100%/$104.76 or just under a 1% increase in vegetative cover per dollar spent.

Table 5 below shows the ratios for lakes that have data on plant differences and cost per acre foot. The results are limited by the number of lakes with available data, but it is suggestive of cost-effectiveness comparisons between lakes. As noted above methods on Pickerel were among the most cost-effective, but Geneva is the most cost-effective by this measure given its high plant gain and very low cost per acre foot. East Twin is second best given its moderate improvement in vegetative coverage but even lower cost per acre foot. Teal is shown as the other extreme in that plant coverage actually declined and the costs per acre foot were in the upper quartile. Ratios like this raise questions about some lakes being "money pits." Lakes that have two characteristics would tend to be poor investments: 1) huge watersheds with a small fraction of surface water to total watershed size and 2) great connectivity to other surface waters that could be routes for re-introduction of undesirable fish. However Teal Lake does not have the characteristics that would indicate poor return on rehabilitation expenditures. This example highlights the difficulties of predicting responses to management in complex ecological systems.

Table 5. Ratios of Increase in %Plant Coverage/Costs Per Acre Feet

Lake	%Plant Diff.	Costs Per Acre Foot	% Plant Gain per $ spent on an acre foot
Augusta	13	155.24	.09
Bear	81	165.39	.49
Buffalo	17	92.38	.18
East Twin	62	59.43	1.04
Geneva	92	79.41	1.16
Hjermstad Sl	97	646.88	.15
Little Towner	67		
Maria	93	362.95	.26
Mott	34	206.55	.16
Nora WMA	6		
Pickerel	100	104.76	.95
Golden	0	922.89	.00
Sunset	0	365.22	.00
Sedan Pond	0	450.41	.00
South Spellman	3	291.48	.01
South Twin	34	341.62	.10
Swan	2	13.58	.18
Teal	-3	582.57	-.01
Towner Lake	94	320.77	.29
Wilts	1	52.52	.01

Care should be taken in interpreting these ratios given their dependence on pre/post-treatment conditions. For lakes like Swan that were good to begin with and stayed that way, the assumption about the alternative condition (the counterfactual) that would have occurred without treatment is crucial. If carp had not been eradicated, Swan may have lost its vegetation, implying that the more accurate gain from treatment was 100% plant coverage that was preserved. Under that scenario, Swan presents another strong example of gain per dollar spent per acre foot given its high quality and the lowest cost per acre foot.

It is informative to conceptualize a matrix of conditions that would reveal the best bang for the buck (highest improvement per dollar spent) and conditions under which the polar opposite would occur, (i.e. worst bang for the buck) due to low improvement and high cost. Under any measure of improvement, lakes such as Teal where quality does not improve have had treatments that have not been cost-effective.

The results on conservation easements above provide a major example of spatial variation of costs. It is plausible that other variables could cause cost variations across lakes, ecoregions or years. Other than land values and easement rates that vary substantially across regions, it seems implausible that costs such as rotenone vary across regions. The non-land costs of control structures and fish barriers and the electricity to run them would not be expected to exhibit much spatial variation either. Regional patterns of costs would be worth further exploration in the future.

Regional patterns of effectiveness of methods do seem to exist. The literature as well as the accumulation of evidence from this project and the shallow lakes program shows that lakes in the south are less stable, and therefore harder to keep in clear state for long periods of time. Hence regional patterns in cost-effectiveness may be driven more by background biological conditions than by variations in costs, other than land values.

In terms of improvements through time, tracking the number of years that a lake is in a clear regime is most informative. It is encouraging that a number of lakes that have been monitored remain in a clear state after treatment. More time to observe how long these lakes persist in a clear state is needed to better understand trade-offs through time.

Trade-offs between methods through time may be informed by the comparison of methods that could be viewed as "band-aid" approaches versus methods that address root causes. Long-term costs may be minimized by taking systemic approaches that may cost more initially but generate longer lasting returns. This perspective suggests that improvements in the south may not occur from reduced nutrient loads alone because of nutrients already present in the lakebed and suspended in the water column, made worse by high biomass of undesirable fish. Manipulation of fish may yield short-lived improvement, if any at all. For lakes in the south a combination of tools is likely necessary to get improvement, and long-term reduction of nutrient loads in conjunction with repeated manipulation of fish populations may be needed for extended improvements in lake quality. Over decades repeated fish manipulations may be more costly than more systemic solutions, but the available cost data at this point make it difficult to demonstrate potential trade-offs.

Suppose the objective through time becomes to spend money to maximize the number of acre feet that are in the clear state at a point five years from now. Some lakes in the south (being less stable) could have undergone shifts to clear regimes due to fish management but reverted back to turbid states before five years have elapsed. This possibility shows the flaw in applying a **static** approach to tracking clear vs. turbid status. Rather the approach must be **dynamic** in tracking change over time. It is more appropriate to count the number of years within that five-year period that lakes were in a clear state. But the temporal trade-offs of fish-management strategies vs. watershed-based strategies can be more fully understood using a longer time horizon, even as short as twenty years. Even among in-lake strategies temporal trade-offs may be important.

Sensitivity analysis could be employed to determine if conclusions are influenced by alternative discount rates. Rotenone is a short-term fix that will need repeated applications over a 20-year period while water control structures may last for decades, with occasional operating and maintenance expenses. In comparing costs of methods through time, it must be noted that rotenone treatments not only have limited time spans of effectiveness, but sometimes are not effective at greatly reducing fish abundance. To reduce the fish population sufficiently, multiple applications of rotenone could be needed which doubles or triples the cost of the treatment. Thus rotenone is not the preferred option for wildlife managers, but it is used when managing water levels is difficult or impossible.

Combining spatial and temporal analysis of costs may stack the decks against management efforts in the south versus other parts of the state where lakes are closer to or still in a clear state. Lakes in the south are disadvantaged given: 1) the background characteristics of the watersheds, 2) the amount of accumulated nutrients they have received over many years, 3) the higher land costs in the area and 4) carp are more abundant and widely distributed there. It might be tempting to say that very few candidates for cost-effective shallow lake management exist in the southern part of the state. While this might be concluded based on some of the quantitative comparisons on paper, it would be an oversimplification of the role of ecosystem integrity. It is important to keep sight of implications on a landscape scale. Restoring or protecting a high-quality shallow lake, such as Swan Lake, in an area where rehabilitating neighboring lakes may be technically or economically prohibitive, could still be a wise investment. The earlier quote from the report to the legislature argues for a more comprehensive perspective on the benefits of landscapes that contain "habitat complexes of shallow lakes, wetlands and grasslands. These complexes are a key component of achieving the goals of the 2006 Duck Recovery Plan." (MNDNR, 2012, p. 24.)

CONCLUSIONS AND IMPLICATIONS FOR FURTHER RESEARCH

The total costs of projects implemented over the last decade or so are approximately $20 million. Project costs vary a great deal across lakes.

On the smaller subset of lakes where responses have been monitored, a great deal of improvement has occurred. Some lakes had high existing water quality and treatment efforts succeeded in protecting it. In other cases, high-quality conditions have been achieved and maintained. A few lakes have stayed in a low-quality condition despite rehabilitation efforts.

The metric, costs of methods per acre feet implemented, is the most informative comparison across lakes. The cost-effectiveness measure best supported by the science and available data is the number of years likely to be in a clear state per $ spent on an acre foot. The percentage of submerged plant coverage gained per $ spent on an acre foot also yields useful quantification of responses to rehabilitation efforts. The two measures are consistent in identifying lakes with the most and least cost-effective treatments.

It is hoped that the conceptual framework developed here will stimulate further progress in integrating ecological and economic insights in shallow lake research. Conceptual principles can be better realized through time as data limitations are ameliorated through more extensive data collection and intensified focus on monitoring both ecological and economic returns.

In comparing ecoregions, factors converge that make improvements in the south more difficult to achieve ecologically and more expensive to implement. The fertility of the soil is related to the fertility of the lakes and their watersheds and this also leads to higher land values and easement rates due to levels of agricultural productivity.

Patterns across time are merely suggestive based on the limited data available. But further comparisons are warranted as more results are forthcoming with monitoring of more projects in the future. The balance between methods that yield short-term versus long-term improvement is complex, yet must be considered in comparisons of restoration approaches. Rotenone treatment may turn around a lake quickly but need to be repeated often or lake quality will not last. And rotenone treatments are not 100% effective, sometimes needing re-application to get even a short-term response.

Erecting fish barriers tends to have a longer lasting effect, but still may be undermined by surface water connectivity or by high water conditions that allow undesirable fish species to return. If a longer term perspective is adopted - implying a lower discount rate on future benefits and costs - higher initial investment in methods such as water control structures and long-term reductions in nutrient loads from better land-use practices may be warranted as opposed to repeated expenses on short-term fixes. Judgments about discount rates depend on public preferences, but given that long-term methods may also generate broader types of benefits to the public - such as improved habitat across a landscape scale, rather than merely improving individual lakes - the relative advantages may turn in favor of the long-term perspective.

Biological and empirical aspects of this project have generated evidence suggesting that changing water quality to a clear state in some lakes may be difficult if not impossible, by solely reducing external nutrient loads. By extension these methods would be too expensive for many lakes due to nutrient pools present in the lake sediment and water column. But watershed strategies to reduce nutrient loads may be complementary over the long term to in-lake management in some watersheds. Identifying lakes where long-term reduction in nutrient loads could eventually improve water clarity requires complicated analysis. But this may more accurately reflect reality rather than regarding as futile attempts to reduce nutrient loads in all shallow lakes. For those lakes that will respond positively to nutrient reductions, it may be more cost-effective long-term to reduce root causes of turbidity rather than repeated applications of rotenone favoring short-term improvements, but needing to be redone.

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APPENDIX A: SELECTED COST SUMMARIES FOR REHABILITATED SHALLOW LAKES IN MN

Table A-1. Cost summaries for shallow lakes rehabilitated in Minnesota. Values derived from data provided from MN DNR and MN Ducks Unlimited. Missing values were unavailable at time of reporting.

Lake	Cost	Cost per acre-foot
Albion WMA	119701.26	
Arends WPA	134534.72	
Ash	211362.66	269.32
Audubon Center	149147.02	
Augusta	285019.77	155.24
Bah Lakes WPA	140353.85	145.63
Bear	541811.00	165.39
Benson WPA	148551.57	
Big Slough	87635.18	34.17
Big Stone Pool 7	1180438.41	
Birchdale WMA	26390.78	
Blakesley WPA	104051.07	
Block WPA	55160.25	808.8
Bradshaw WMA	21170.49	
Buffalo	239761.22	92.38
Carlos Avery	379712.07	
Carlos Avery Pools15/17	58115.08	365.11
Christina	2222050.60	
Coon Creek WMA	299838.36	
Cory	217111.25	509.29
Cottonwood	123052.98	523.18
Curtis	374027.08	184.8
Denton	237083.49	501.76
Dovray WMA	149890.26	811.97
Duck	31108.13	40.14
East Park	325786.68	
East Twin	46000.00	59.43
Fenmont WMA	288085.23	3273.7
Fulda	12262.77	35.75
Geneva	491347.72	79.41
Gilfillin	321836.02	691.53
Gislason	146133.48	326.41
Goose	40555.41	40.60
Grey Eagle	116076.90	
Hanson Lake WPA	131689.58	368.88
Harder	124179.21	1349.77
Hjermstad	197763.75	646.88
Hjermstad South	76120.62	
Hurricane	301858.12	597.74
Jennie	311342.84	149.28
Kube-Swift WMA	125482.21	107.25

Lindsey	117935.60	1456
Little Elk Main Pool	701842.19	
Little Elk South Pool	117673.75	
Logue & Lick WMA	72982.58	
Long Lake E	95191.51	
LQP WMA dikes	115534.93	
Lyons WMA	70958.40	
Maria	412551.70	362.95
Mille Lacs Mikkelson	46440.11	
Mission	83068.69	
Moonan Marsh	189326.53	
Mott	92636.73	206.55
Mystery	89236.68	628.87
Nicholson WPA	127239.00	
Niemackl Ohlsrud	29866.91	28.63
Niemackl Towner	202662.96	
Noordmans WMA	129658.64	
Odens WPA	36323.23	
Olson Lake WPA	219685.85	528.09
Perch	217111.28	636.69
Pickerel	269647.00	104.76
Rice Blue Earth	165527.16	141.67
Rice Fairbault	244103.55	99.69
Ruff-Nik Robinson	166807.82	
Rydell Golden	75677.33	922.89
Rydell NWR	422324.29	
Rydell Sunset	89478.30	365.22
Sedan Pond	28894.00	450.41
Sherstad Slough	198608.00	360.58
Shetek-Round	149721.97	262.26
Simon	97711.31	25.84
Smith	247929.66	187.83
South Twin	60364.49	341.62
Spellman	134298.07	291.48
Steinlicht WPA	75608.09	357.99
Swan	329881.00	13.58
Swedzinski WPA	63012.81	
Teal	289753.96	582.57
Towner	202663.00	320.77
White Star	83888.15	291.28
Wiley WPA	289674.54	973.37
Wilts	7090.00	52.52
Wolf	513222.75	1437.6
Woman	119800.33	

Table A-2. Sum of costs per lake and costs per acre foot summarized by method.

	Method	N	Mean	Minimum	Maximum
sum costs lake	rotenone	1	269647.00	269647.00	269647.00
	structure	5	204352.85	46000.00	491347.72
	fish barrier	5	135947.32	83888.15	285019.77
	Structure and Fish Barrier	1	412551.70	412551.70	412551.70
	Rotenone and Drawdown	1	329881.00	329881.00	329881.00
	Total	13	208736.97	46000.00	491347.72
Costs per acre foot		1	104.76	104.76	104.76
	structure	5	270.90	59.43	582.57
	fish barrier	5	122.75	25.84	291.28
	Structure and Fish Barrier	1	362.95	362.95	362.95
	Rotenone and Drawdown	1	13.58	13.58	13.58
	Total	13	188.43		

Table A-3a. WRP Crop rate summarized by state regions.

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Laurentian Mixed Forest NE	828	1543.33	668.160	23.220	1497.75	1588.91
Tallgrass Aspen NW	193	841.53	398.635	28.694	784.94	898.13
Eastern Broadleaf Forest	675	3392.78	1250.963	48.150	3298.24	3487.32
Prairie Parkland SW	945	3558.98	1211.559	39.412	3481.64	3636.33
Total	2641	2685.97	1461.010	28.429	2630.23	2741.72

ANOVA

WRP Crop rate

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2.795E9	3	9.317E8	865.055	.000
Within Groups	2.840E9	2637	1077033.043		
Total	5.635E9	2640			

All pairwise comparisons of means using the Bonferroni test were significant at the 1% level.

Table A-3b. WRP Non crop rate summarized by state regions.

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Laurentian Mixed Forest NE	828	926.00	400.896	13.932	898.65	953.34
Tallgrass Aspen NW	193	504.92	239.181	17.217	470.96	538.88
Eastern Broadleaf Forest	675	2035.67	750.578	28.890	1978.94	2092.39
Prairie Parkland SW	945	2135.39	726.935	23.647	2088.98	2181.80
Total	2641	1611.58	876.606	17.058	1578.14	1645.03

ANOVA

WRP Non crop rate

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	1.006E9	3	3.354E8	865.055	.000
Within Groups	1.022E9	2637	387731.895		
Total	2.029E9	2640			

All pairwise comparisons of means using the Bonferroni test were significant at the 1% level.

Table A-3c. RIM-WRP crop rate summarized by state regions.

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Laurentian Mixed Forest NE	828	1929.16	835.200	29.025	1872.19	1986.14
Tallgrass Aspen NW	193	1051.92	498.293	35.868	981.17	1122.66
Eastern Broadleaf Forest	675	4240.97	1563.704	60.187	4122.79	4359.15
Prairie Parkland SW	945	4448.73	1514.448	49.265	4352.05	4545.41
Total	2641	3357.47	1826.263	35.537	3287.78	3427.15

ANOVA
RIM-WRP crop rate

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4.367E9	3	1.456E9	865.055	.000
Within Groups	4.438E9	2637	1682864.130		
Total	8.805E9	2640			

All pairwise comparisons of means using the Bonferroni test were significant at the 1% level.

Table A-3d. RIM-WRP non crop summarized by state regions.

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Laurentian Mixed Forest NE	828	1080.33	467.712	16.254	1048.43	1112.24
Tallgrass Aspen NW	193	589.07	279.044	20.086	549.46	628.69
Eastern Broadleaf Forest	675	2374.94	875.674	33.705	2308.76	2441.12
Prairie Parkland SW	945	2491.29	848.091	27.588	2437.15	2545.43
Total	2641	1880.18	1022.707	19.901	1841.16	1919.20

ANOVA
RIM-WRP non crop

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.370E9	3	4.565E8	865.055	.000
Within Groups	1.392E9	2637	527746.191		
Total	2.761E9	2640			

All pairwise comparisons of means using the Bonferroni test were significant at the 1% level.

APPENDIX B: HISTORICAL PROFILE OF LAKE CHRISTINA

Lake Christina is a large (about 4,000 acres), shallow lake located in west-central MN. The lake is among the most famous waterfowl habitats in North America and is especially well known as a feeding and resting area for diving ducks (especially canvasbacks). Accordingly, the lake also has a long history of waterfowl hunting and conservation efforts directed at maintaining high quality waterfowl habitat. An often-quoted report suggests that approximately 20 percent of North America’s canvasback population was observed on the lake during a single date during October 1949. A premier fall staging area for migrating diving ducks (and duck hunters) through the early 1950s, the lake has since experienced several rapid cycles of deterioration, each characterized by increased water turbidity, greatly reduced submerged aquatic plants (including duck food items), and dramatic declines in fall use by migrating diving ducks. Other changes with possible implications for the lake are also known from this period. For example, historical records indicate that small-scale farming practices may have contributed significant quantities of nutrients to the Lake Christina watershed prior to 1950. In addition, following drought in west-central MN early during the decade of the 1930s, a dam was constructed on the lake outlet (1936), probably in hopes of avoiding another severe drawdown in the event of future drought conditions.

Lake Christina habitat conditions have been monitored to varying extent since the 1940s, and key limnological features have been tracked closely since early 1985. Resulting data on extent of submerged aquatic plants, water clarity, phytoplankton abundance, and composition of aquatic invertebrates provides a unique and valuable basis for assessing long-term limnological patterns, habitat characteristics, and waterfowl use of the lake. This monitoring data clearly indicates that water quality declined and the lake tended toward characteristics of a turbid regime in 3 distinct cycles of deterioration since approximately 1950. Specific causes for these turbid shifts have been difficult to identify, but lake managers believe that sustained high water levels allowed proliferation of undesirable fish communities including high densities of bullheads, bigmouth buffalo, common carp (at times), and other fish species.

In response to these deterioration cycles, lake managers have induced 3 fish removals at Lake Christina (1965, 1987, 2003) using fall applications of approved piscicides. In each case, following improvements in water clarity, growth and extent of submerged aquatic plants, and fall use by migrating diving ducks have improved, sometimes dramatically (especially following the 1987 fish removal). However these reversals have been short-lived (5-10 years) and, in each case, were followed by returns to turbid regime conditions.

More recent paleolimnological studies of lake sediment (cores) confirmed the short-term nature of the 3 brief “recoveries” and suggested that Lake Christina actually persists in a “modern” regime with turbid-trending conditions since the mid-1950s, and that fish removals have succeeded only at inducing short-term reversals. This recent work also suggested that the long-term stability of the modern, turbid regime probably results from nutrients contributed to the lake (and perhaps surrounding watershed) during the period of approximately 1850-1950, now persisting in the sediments and providing in-lake nutrient loading that is extremely difficult to overcome in the long-term, at least using fish removal methods.

The Lake Christina case study helps illustrate the need for development of shallow lake rehabilitation strategies that include both in-lake and watershed-scale measures so as to induce short-term improvements, yet modify nutrient regimes so as to move lakes toward conditions favoring long-term stability in clear-water regimes. Detailed accounts of recent management history and of factors responsible for long-term trends in Lake Christina conditions have been summarized by Smith (1946), Ordal (1966), Hanson and Butler (1994), Hansel-Welch (2003), and Hobbs et al. (2012).

APPENDIX C: ANNOTATED BIBLIOGRAPHY

Bajer, P. G., Chizinski, C. J., & Sorensen, P. W. (2011) Using the Judas technique to locate and remove wintertime aggregations of invasive common carp. Fisheries Management and Ecology, 18, 497-505.

Bajer *et al* used method known as the Judas technique to locate aggregations of common carp and target them for removal in three Midwestern lakes. These methods can be another alternative to using whole-lake treatments using rotenone and water draw-downs. To locate the carp the researchers sampled fish then tagged them and employed multiple radio and acoustic telemetry techniques to track and record information about the fish habits. They found that during the summer and Autumn months the carp are more dispersed, were in the winter they tend to aggregate in tighter groups (usually when water temps fall below 10 degrees Celsius). The densities of the fish were calculated using nearest neighbor densities using ARC GIS. This and temperature data were then combined in a single regression calculation. During the winter months seining took place that proved to have success rates of 52%-94% in the lakes carp population. However, the success of seining appears to be associated with obstacles in the lake and precise and quiet capture. The results also show that by doing the proper prep work, bycatch biomass can be limited to low levels (<10% in study). This study is limited to Midwestern lakes (max depth 14m), but may be applied to other aquatic systems or other species of fish that tend to shoal like the Asian carp.

Balana, B. B., Vinten, A., & Slee, B. (2011). A review on cost-effectiveness analysis of agri-environmental measures related to the EU WFD: key issues, methods, and applications [Electronic version]. *Ecological Economics*, *70*, 1021 – 1031.

This study examines the European Water Framework Directive’s (WFD) water management strategies and policy decision-making approaches, with an emphasis on cost-effectiveness analysis (CEA) for agricultural non-point source pollution. First, the authors introduce the concept of CEA and compare it to other economic tools such as cost-benefit analysis (CBA) and multi-criteria analysis (MCA). The authors next explain how CEA is utilized by the WFD and that all member states’ bodies of water must be assessed by 2015. Next, CEA methodologies are discussed in terms of two separate models; cost minimization & benefit maximization. Both of these models get at the idea of ranking strategies by average cost per unit effectiveness. A brief overview of how CEA has been implemented in other studies and is then discussed and emphasizes the importance of choosing the right methodology based on data availability, environmental issue at hand, and the degree of uncertainty present in both cost and effectiveness information. Another important element explained is the amount of heterogeneity between member states and that there will be differences in mitigation types and scales that must be included in the WFD framework. To combat the stochastic nature of these strategies a wide-range of costs and effectiveness measures should be used. The main objective of these studies was looking at cost-effective management strategies that aimed primarily at reducing nitrogen-based pollution through changes in farming practices. It is worth noting that many shortfalls of CEA studies is the fact that many of them leave out the positive and negative externalities associated with pollution and management strategies.

Blackwood, J., Hastings, A., & Costello, C. (2010). Cost-effective management of invasive species using linear-quadratic control [Electronic version]. *Ecological Economics*, *69*, 519-527.

The focus of this study is looking at cost-effective management strategies for removing invasive species by using a spatial, dynamic economic optimization framework. The authors introduce a connected patch-base model with inter-patch heterogeneity. Then using linear - quadratic controls the researchers can model eradication strategies under different conditions. By doing so the authors can model the dependence between population size and the amount of removal, showing the costs will increase with the percentage of invasive removal. By applying discounting techniques optimal levels of control will then be revealed. The study additionally used a higher discount factor in early years due to expensive upfront removal costs. Therefore, areas with higher discount factors are likely to have more optimal eradication results. The two primary costs quantified in this analysis are the economic damage caused and the removal of the invasive species. This analysis can be used for the development of removal practices for invasive species with sedentary adults and dispersal of offspring, esp. s. alterniflora (Smooth Cordgrass). The model also allows for stochasticity and age or stage dependence. In conclusion, the results show that out of 1,000 linearly-aligned patches the optimal level would be around 500 patches and increase linearly away from patch 500.

Boardman, Anthony E., David H. Greenberg, Aidan R. Vining, and David L. Weimer. *Cost-Benefit Analysis: Concepts and Practice*. 3rd ed. Upper Saddle River, NJ:Pearson Prentice Hall, 2006. Print.

This textbook primarily focuses on the mechanics of cost-benefit analysis, but does go into some detail about cost-effectiveness analysis. This text also guides readers in how to value benefits and costs in primary and secondary markets. Also of importance is that the text introduces to idea of discounting benefits and costs for future time periods and the equations needed to do so. Lastly, for this study there will inevitably be some amount of uncertainty, this text provides a variety of different available options that may be used to help reduce this uncertainty.

Brady, M. (2003). The relative cost-efficiency of arable nitrogen management in Sweden [Electronic version]. *Ecological Economics*, *47*, 53-70.

The goal of this study is to introduce cost-effective measures that would help reduce anthropocentric nitrogen flows into the Baltic Sea to hopefully restore it to its pre-1950's state. The primary sources of this non-point pollution arise from the intensive use of fertilizers, field tillage, drainage systems and land cover conversion to cropland. The study area in this analysis is southern Sweden and looks at two alternatives, coordinated benchmark (best) and standard benchmark (second best). The model used in the study is a spatially distributed, nonlinear programming model linking changes in agriculture production practices to changes in net coastal nitrogen. The results of the analysis conclude that the most cost – effective approach to remove nitrogen would be through increasing subsidy (permanently) removing land from intensive commodity production or reducing area payments for commodity production.

Coops, H., Vulink, T. J., & Nes, E. (2004). Managed water levels and the expansion of emergent vegetation along a lakeshore [Electronic version]. *Limnologica*, *34*, 57-64.

Coops *et al* look at episodic drawdown techniques to trigger the expansion of helophyte stands in the Volkerak-Zoommeer (the Netherlands). The study area in this analysis is an artificial lake created in 1987 by closing part of the Oosterschelde estuary. To test their hypothesis the researchers closed off 3 ha of shoreline and exposed it to various drawdowns and re-flooding techniques over a three-year period. Inside the study area plots were established to look at with and without grazing on aquatic plant rhizomes during the winter months. The results of the study indicate that after a drawdown there will be an increase in salinity and a change in the composition of emergent vegetation. This salinity is then compensated for after the lake is reflooded with freshwater in which more freshwater species will take over. Another point mentioned is that winter grazing can have profound changes on plant biomass. Lastly, when considering anthropocentric water-level fluctuations, managers must consider other lake functions such as navigation, water-use for agriculture and the lake's water holding capacity.

Hansel-Welch, N., Butler, M. G., Carlson, T. J., & Hanson, M. A. (2003). Changes in macrophyte community structure in Lake Christina (Minnesota), a large shallow, following biomanipulation [Electronic version]. *Aquatic Botany*, *75*, 323-337.

The focus of this study is looking at the long-term changes to a large shallow lake after biomanipulation (i.e. rotenone treatment). To analyze the success of this treatment the authors looked at changes in plant communities from 1985 to 1998 and used the following techniques cluster analysis (CA), indicator species analysis (ISA), and canonical correspondence analysis (CCA). Other physical characteristics monitored were light attenuation, Secchi depth, turbidity, Chl *a*, total suspended solids (TSS), total phosphorus (TP), total Kjeldahl nitrogen and waterfowl presence. The results of this study indicate that Lake Christina changes through 'alternative stable state' following biomanipulation. This meaning that aquatic vegetation quickly repopulates the lake after treatment, but then continued to change over the following decade. The best variables explaining these changes were light attenuation, total phosphorus, and filamentous algae abundance.

Hein, L. (2006). Cost-efficient eutrophication control in a shallow lake ecosystem subject to two steady states [Electronic version]. *Ecological Economics*, *59*, 429-439.

This study investigates optimum eutrophication control strategies for 'De Wieden', a Dutch shallow ecosystem. This ecosystem provides services such as recreation and nature conservation and is home to the only population of the copper butterfly (Lyacena dispar).To understand the lake dynamics of De Wieden the study uses regression analysis using long-term water quality data. The two approaches used to control eutrophication are with and without biomanipulation and uses total-phosphorus as a control variable. The model follows a steady state approach and assumes after 25% of the lake bottom is covered by macrophytes it's now in a clear lake regime in a time period of 5 years. There are six management strategies and these are represented in terms of NPV with a discount rate of 5% over a 25 - year span. In this study the benefits of switching to a clear-lake regime from a eutrophic regime are monetized and measured in terms of utility using the same NPV calculation as the costs. Before making any conclusions the author explains the sources of uncertainty in the model by highlighting possible inaccuracies in the data, inaccuracies in the model equations, and uncertainty in the threshold values. From the analysis the researcher recommends that the most cost-effective approach would be to reduce nutrient loading in lakes with 3 tons total-P year in combination with biomanipulation. This would involve investment costs of 5 million euros and must produce benefits of at least 0.75 million euros/year.

Jayaweera, M., & Asaeda, T. (1995). Impacts of environmental scenarios on chlorophyll *a* in the management of shallow, eutrophic lakes following biomanipulation: an application of a numerical model [Electronic version]. *Ecological Engineering*, *5*, 445-468.

Jayaweera & Asaeda analyzed the results of removing 85% of current fish biomass from one section of the lake then restocked it with pike perch (*Stizostedion lucioperca*). Converse of this, another section of the lake was left untreated to be used as a control group. Using a comprehensive mathematical model the analysts looked at five environmental scenarios including: (1) the effect of fixed stoichiometry in terms of internal nitrogen and phosphorus that are tied up within algal cells; (2) the effects of external phosphorus limitation; (3) light limitation and external nitrogen limitation on algal growth; (4) probable consequences that have taken place within the chlorophyll-a biomass due to change in biomasses of various aquatic organisms; and (5) possible changes of chlorophyll-a biomass due to higher temperatures caused by global warming. To help limit the amount of error and uncertainty, performing regression to select the best fit for several coefficients and rate constants carried out sensitivity analysis. The results of the analysis indicate that fish removal/stocking improves water quality and shows positive and negative interactions among various biota. Meaning that either top-down or bottom-up manipulation will have effects on food-web cascades with expected results.

Kasprzak, P., Koschel, R., Krienitz, L., Gonsiorczyk, T., Anwand, K., Laude, U., & Wysukack, K., Brach, H., & Mehner, T.(2003). Reduction of nutrient loading, planktivore removal and piscivore stocking as tools in water quality management: The Feldberger Haussee biomanipulation project [Electronic version]. *Limnologica*, *33*, 190-204.

Kasprzak *et al* focus on the long-term dynamics of chemical characteristics and changes in plankton communities in response to reduced external nutrient loading and long-term biomanipulation. The goal is to see which strategy contributes the most to changes in water quality or if they are both acting in concert. The lake under investigation is the Feldberger Hausse a hard-water system located in the eastern part of Germany's Baltic lake district. During the early 1900's the lake used to be a low-nutrient clear water system, but due to input of a poorly treated sewage eutrophic conditions began to arise. Despite having the sewage diverted from the lake (resulting in a 90% nutrient reduction), eutrophic conditions remained due to nutrient cycling from the sediments. The biomanipulation technique employed consisted of 273 seine hauls from 1985 to 2000, which removed 107 metric tons of cyprinid fish. The results suggest that this also contributed to reductions in P- cycling either through excretion or sediment bioturbation, however by having r^2 values ranging from .526 - .392 indicates other factors are of importance. In conclusion the researchers attribute the reduction in phosphorus to external/internal nutrient loading and increased calcite precipitation, which led to improvements in water quality.

Paulsen, C. M., & Wernstedt, K. (1995). Cost-effectiveness analysis for complex managed hydrosystems: an application to the Columbia River Basin [Electronic version]. *Journal of Environmental Economics and Management*, *28*, 388-400.

This study focuses on cost-effective management strategies that aim to protect nearly 80 anadromous salmon and steelhead stocks that have been affected by hydropower development. The study site in this analysis concentrates on Columbia and Snake Rivers and their major tributaries located in the N.W. corner of the United States. The analysis identifies three different management strategies including passage actions, propagation actions, and harvest actions. The passage strategy includes three actions that increase migration through the main stem of the two rivers. The propagation actions are aimed at mitigating the degradation of spawning and rearing habitat in the sub-basins. Lastly, the harvest actions attempt to reduce the amount of fish that can be caught through a variety of regulations.

The results of the analysis suggest that no action taken will be cost effective under the scenarios presented in this study. However, other considerations including endangered species, distribution of costs, naturalness of mitigation actions and the process of reaching a policy decision are all important in terms of whether or not a project should be undertaken. The researchers conclude that the possible limitations in data and methodology are being addressed in ongoing work.

Pipalova, I. (2002). Initial impact of low stocking density of grass carp on aquatic macrophytes [Electronic version]. *Aquatic Botany*, *73*, 9-18.

This study looks at the impacts of stocking grass carp (*Ctenopharyngodon idella*) at low densities to control for unwanted weed species. The study sites for this analysis took place in two eutrophic ponds in the Czech Republic in 1998 and 1999, where one was stocked with 10 year-old individual, while the other was left un-stocked to represent a control group. The aquatic plant biomass was assessed using the Shannon-Weaver index of diversity and the results were analyzed using three-way ANOVA where pond (fixed factor), year (random variable), and month (repeated measure). The results were reported at a $P < .05$ and were adjusted using the Bonferroni correction and showed that if stocked at low densities carp can have profound impacts on species composition, removing particularly filamentous algae and higher aquatic plants.

Qiu, D., Wu, Z., Liu, B., Deng, J., Fu, G. & He, F. (2001). The restoration of aquatic macrophytes for improving water quality in a hypertrophic shallow lake in Hubei province, China [Electronic version]. *Ecological Engineering*, *18*, 147-156.

Discussed in this article is the importance of submerged vegetation in terms of material cycling and both abiotic/biotic processes in these aquatic systems. Due to deteriorating water quality in lakes off the Yangtze River, this project was initiated to explored vegetation restoration for whole - lake rehabilitation using Lake Donghu as the study site. Results from sediment cores show that aquatic macrophytes used to dominate the system prior to the 1950's. However, nuisance algal blooms began to increase dramatically mainly due to increases in planktivorous fish (irrational fish stocking) and urbanization. In this study the researchers conducted experiments on three large-scale enclosures. The results of this experiment show that lakes with less eutrophic conditions will be better candidates for vegetation recovery if planktivorous fish stocking ceased. Under these conditions K-selected plants such as *Potamogeton maackianus* should be introduced, where more severely polluted lakes should have r-selected plants introduced (pioneer species).

Sazama, C. (2010). *A cost-effectiveness analysis of the actions taken by the participants of the mayors climate protection agreement to reduce greenhouse gas emissions with respect to selected city characteristics* (Master's thesis). July

In this study Sazama discussed the urgency of formulating policy that could help mitigate global climate change. The strategy of this was to perform a cost – effective analysis (CEA) on mitigation actions taken by participants of the Mayors Climate Protection Agreement based on survey results from 16 U.S. cities and 27 discrete actions. The survey respondents reported the effectiveness of their actions in terms of tons of GHG emissions reduced or amounts of kWh's reduced annually. Then based on the annual costs, cost effective ratios were set up for each action taken. Sazama also grouped each city into four population categories. The statistical analyses employed were descriptive statistics, ANOVA and Kruskal - Wallis Tests (due to small sample size needed to run non-parametric tests as well as parametric). After examining the cost effectiveness ratio it appeared that population, region, and action taken influenced the ratios. Lastly, the author created four hypothetical scenarios which cities could choose to take to reduce GHG or kWh use. The results show that whether or not cost effectiveness ratios are included in the decision making process can have major implications on GHG or kWh reduced annually.

Van Nes, E. H., Sheffer, M., Van Den Berg, M. S., & Coops, H. (2002). Aquatic macrophytes: restore, eradicate or is there a compromise? [Electronic version] *Aquatic Botany*, *72*, 387-403.

Van Nes *et al* explore the conflict between aquatic macrophytes populations in relationship to harvesting to meet human recreation needs. The plant under investigation in this analysis is *Chara aspera* Deth. ex Willd and is modelled using several logistic growth equations. The results of this study show that an optimal amount of aquatic biomass may not be feasible in terms of welfare for all lake users. They also conclude that there is no management strategy that could moderate biomass that would be feasible from an ecological view as well. As mentioned earlier to get at these conclusions the researchers used a minimal logistic model and a more complex realistic simulation model Charisma, which includes macrophyte dynamics. The reasoning discussed is that even if careful harvesting is practiced, positive feedbacks will occur due to increases in turbidity and will lead to complete loss of aquatic vegetation. From an economic perspective it would also be very costly for managers to harvest lakes at an intermediate level. Some other suggestions discussed are possibly assigning certain lakes for recreation and other for conservation, or at a smaller scale even dividing lakes in sections for the above. In most cases these alternatives will not be feasible either, which emphasizes that often political solutions do not coincide with optimal environmental economic solutions.

VerCauteren, K. C., Lavelle, M. J., & Hygnstrom, S. E. (2006). A simulation model for determining cost-effectiveness of fences for reducing deer damage [Electronic version]. *Wildlife Society Bulletin*, *34*, 15-22.

Vercauteren *et al* look to identify the benefits and costs associated with fence construction as a way to manage deer populations and whether or not it's cost-effective. Other ways to control deer populations have been hunting, but this is not effective in some cases. This study looks at seasonal fences and year-round ones that could be more effective on the long run. The results of this analysis show interactions that influence fence selection, which design will perform best in certain parameters, and will elucidate maximum damage reduction at minimal costs in terms of net present value (NPV). To come up with a best fence selection model the analysts used the computer program STELLA 8 consisting of three layers including an interactive controls layer, a model diagram layer, and an equations layer. In terms of fences there are twelve different fence types that are compared in terms of costs (materials/labor), height (m), efficacy (%), longevity (yrs), and maintenance (low/high). The results consider other attributes such as area of the plot, value of the crop, percentage of crop damaged annually prior to the fencing cost, cost of fence, and efficacy of the fence. This strategy is very useful in that future managers can easily determine the NPV associated with different fencing scenarios. One last point of importance is that the model is also capable of producing NPV for each year of the fence's life so an easy comparison can be made for different fences over time.

Yang, W., Wang, X., Gabor, S., Boychuk, L., & Badiou, P. (2008, October). Water quantity and quality benefits from wetland conservation and restoration in the Broughton's Creek Watershed. *Ducks Unlimited Canada*.

Yang *et al* looked to develop and employ a modeling system to evaluate environmental benefits of prairie wetlands at a watershed scale for Broughton's Creek in southwestern Manitoba. The study sites were lumped into hydrologic equivalent wetlands (HEW) and used a soil and water assessment tool (SWAT). In addition six - wetland restoration scenarios were evaluated that ranged from 10%-100% restoration. The levels were based on 1968 conditions as the upper limit and 2005 as the baseline or lower limit. The results of the model predict that the most cost-effective scenario would be restoration levels ranging from 50%-80% (2,689 – 2,875ha) in terms of benefit to wetland acreage ratios (peak discharges & sediment loadings). The model also predicted that total phosphorus and nitrogen could be reduced (2.4%-23.4%) under current or existing conditions.

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: $ 13,000**
Amount Spent: $ 13,000
Balance: $ 0

Deliverables	**Completion Date**	**Budget**
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	$ 13,000
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

Final Result Summary – June 30, 2012

<u>Overview of Result 3:</u> Key findings for Result 3 were positive relationships among lake and watershed size, surface connectivity, potential movement of aquatic organisms among habitats, and ultimately fish community richness (no. of fish species in a given lake). Larger lakes and watersheds had higher surface connectivity, more connections with other aquatic habitats, increased probability of fish presence, and higher richness of in-lake fish communities. These results have important implications for conservation of small isolated lakes, larger lakes and watersheds, and for practices that encourage surface ditching and increasing surface connectivity among waters. Our results support the contention that limiting surface connectivity among lakes and other waters is a key to controlling movement of undesirable fishes and invasive aquatic species.

Key Findings:

A. Delineations of shallow lake watersheds and surface connectivity networks; determine extent of land cover types within watersheds; summarize resulting data. These tasks are completed; data were used to develop findings described above and will be the subject of future publications

B. Distribute resulting electronic data through DNR (Division of Waters) web links. These data were incorporated into the Minnesota DNR data holdings available for public consumption as a GIS data layer via the Minnesota DNR Data Deli (http://deli.dnr.state.mn.us/). The watershed delineations exist as polygons within the DNR Level 08 Catchment GIS dataset as part of the DNR Watershed Suit. Metadata are available at: http://deli.dnr.state.mn.us/metadata.html?id=L390006150201. Specific questions regarding these watershed delineations, data availability and future updates should be directed toward Sean Vaughn, MN_iT services GIS Hydrologist (DNR Division of Ecological and Water Resources).

C. Construct models relating lake watershed characteristics to lake watershed size, surface connectivity, and flow patterns to biological and chemical characteristics of shallow lakes. Preliminary models depicting relationships between lake-watershed characteristics and surface water connectivity, fish presence and community richness (number of fish species), and abundance of key aquatic invertebrates (such as zooplankton and Amphipoda) have been developed and are included in this report. These and other results will be used in specific papers to be developed along with other final study products.

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. A key finding of this work is that controlling – even reducing – surface connectivity among lakes, streams, drainage ditches, etc. is extremely important in limiting distribution of undesirable fishes (such as minnows, bullheads, and carp) as well as invasive invertebrates and other species in Minnesota's shallow lakes. These results will be integrated in technical papers and will be presented to lake managers at the shallow lakes workshop to be held during summer 2013.

Result Status as of December 31, 2010

A. Delineations of shallow lake watersheds and surface connectivity networks

Within each lake watershed, surface water connectivity, along with land cover and land use patterns, are major influences on water quality, biological communities, and biodiversity in shallow lakes. Agriculture and urban development may negatively influence ecological characteristics of shallow lakes through direct and indirect mechanisms. Roads and culverts, drainage ditches and other human activities can alter natural conveyance features, typically increasing connectivity among surface waters. Surface water connectivity, in turn, dramatically affects shallow lakes by facilitating the transfer of aquatic plants, invertebrates, fishes, chemicals, and sometimes invasive species. Efforts to identify and delineate surface connectivity features affecting shallow lakes in Minnesota have been hindered because existing datasets do not capture surface hydrography or land cover classifications at large scales (i.e. 1:4,000). This necessitates hand delineation, review and integration of numerous GIS imagery and data resources, and field visits to all lake study sites and areas within their watersheds to confirm actual hydrologic and upland cover type features.

Since July 2010, we have used GIS and field reconnaissance procedures to: a) identify, delineate, and digitize unmapped natural and human created water conveyance features and to b) identify, delineate, and digitize landcover within each study site and DNR Basin Watershed. Our first step in delineating surface connections was to identify inlets and outlets for each study lake. This was accomplished by creating color paper maps for field crews visiting the study lakes. On these maps field crews identified water flow directionality and locations of road culverts. Using aerial photography, field notes, and GIS, all surface water connections within the Basin Watersheds were identified with directionality obtained from the field to create dendritic flow networks. Unlike the usual methods of creating an automated flow network in GIS, manual digitization of water conveyance features allows users to incorporate human alterations on the landscape such as culverts and ditches into the GIS analysis and the modeling environment. This digital hydrography illustrates how fish and other species might move from lake to lake. Our current upland cover classifications include grasslands, woodlands, shrubs, lakes, wetlands, streams, row crops, pasture, other agriculture, ditches, roads, driveways, other impervious surfaces, and residential development. Thus far, delineation of surface water connectivity features and land cover characteristics has been completed for upstream lake watersheds associated with 60 lakes in the Alexandria, Itasca, and Chippewa study regions. We anticipate completing similar delineations for all upstream lake watersheds by the end of summer 2011.

- *B. Distribute resulting electronic data through DNR (Division of Waters) web links – pending completion of A*
- *C. Construct models relating lake watershed characteristics to lake watershed size, surface connectivity, and flow patterns – pending completion of A*
- *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 – pending completion of A-C above*

Result Status as of June 30, 2011

Landcover and water conveyance features have been delineated, digitized, and reviewed for 45% of all the lake study sites (Itasca, Chippewa, and Windom regions completed). Landcover and surface connectivity for lakes in the Alexandria region have also been delineated and we are in the process of reviewing those efforts. In the Metro region, landcover delineations have been completed, and for 19 of 24 sites here we have completed delineation of water connectivity features including underground storm drainage systems. For fish modeling purposes, upstream water conveyance features have been delineated for 40% of the study lakes. We anticipate that all delineations and identification of surface connectivity features will be completed by 1 August 2011.

Result Status as of December 31, 2011

Landscape composition in study-lake watersheds is needed for all major objectives of this research, and is critical for Objectives #1 and 3, identifying relationships among surface connectivity, water quality, and biological characteristics of shallow lakes. During August-December 2011, using GIS, final delineations of lake watersheds, upland cover types within watersheds, aquatic habitats and surface-water connectivity features, extent of roads and residential development, agriculture, forest lands, and other features were completed for 143 study lakes in all 6 study regions. Results have been tabulated and summarized and are presently available for other Extensive and Intensive study objectives (summarized in Figures 7.2, 8.2).

Average land cover within Extensive lake watersheds differed dramatically among study regions. Agriculture dominated lake watersheds in Grant (52%) and Windom (66%) areas. Grasslands comprised 30% and 21% of Grant and Windom watersheds, respectively. Not surprisingly, woodlands were the most extensive upland cover type in lake watersheds in Chippewa, Itasca, and Red Lake areas, exceeding 60% of total areas in each region. Residential development was vastly more extensive in the Metro, comprising our 30% of lake-watershed areas. Red Lake watersheds showed the highest proportion of lakes and wetlands (33%) followed by Chippewa and Itasca (both 14%), Metro, Grant, and Windom with 10%, 8%, and 5%, respectively. Lake watershed cover types in our Metro study area were the most evenly divided, and included 6 land cover categories comprising 5+% of watershed areas. Red Lake watersheds, in contrast, consisted of 94% forested lands or lakes and wetlands, reflecting lack of anthropogenic development in this geographically remote region (Figure 7.2).

Land cover within Intensive lake watersheds reflected trends similar to those above, with agriculture predominating (on average) in both Grant (63%) and Windom (70%) regions, followed by extent of grasslands and lakes and wetlands (Figure 8.2). A curious finding was that lakes and wetlands comprised approximately twice the watershed area of study lakes in Alexandria relative to Windom regions (Figure 8.2).

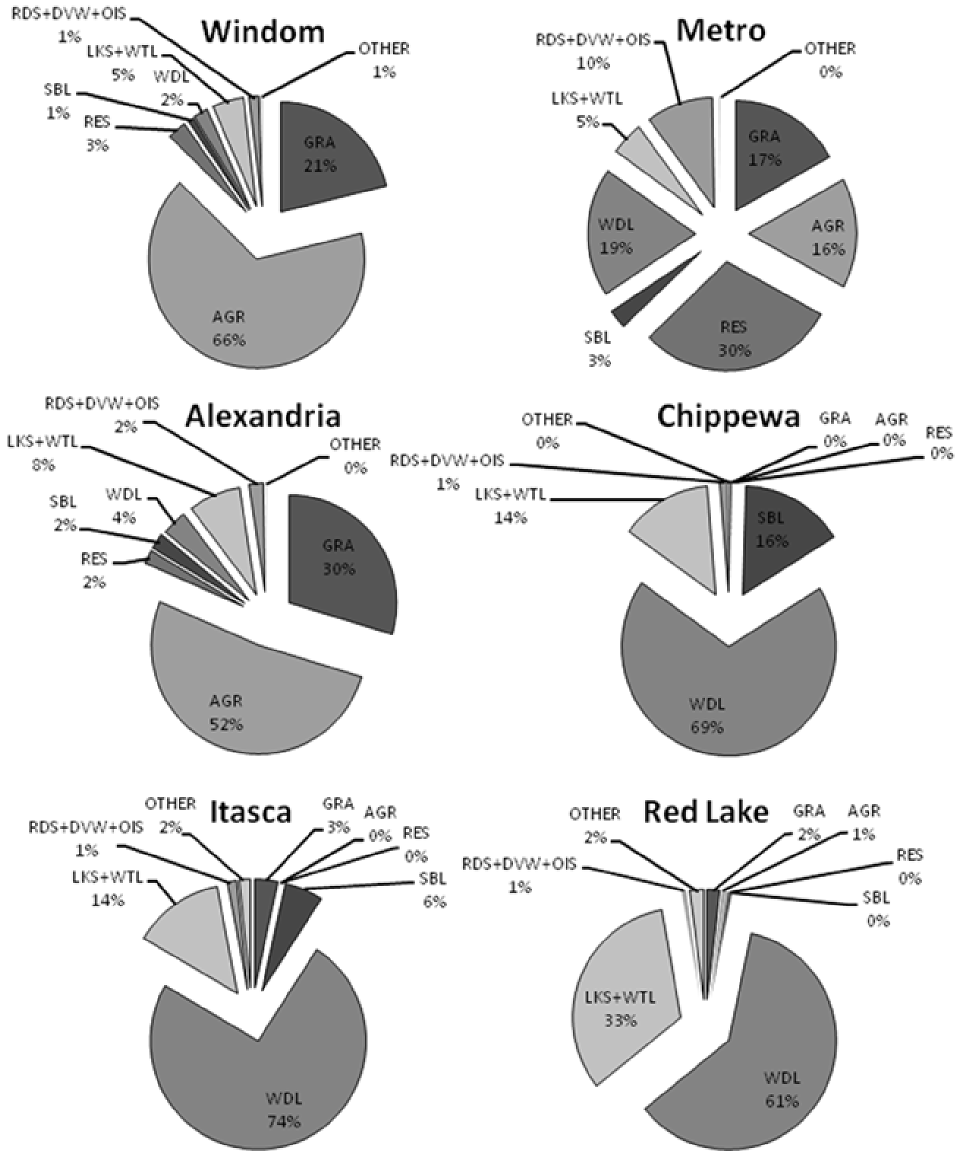
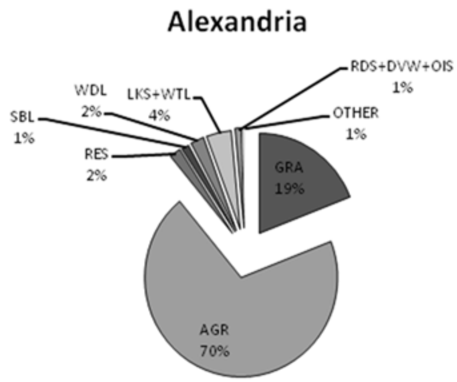


Figure 7.2. Average land cover composition within watersheds of Extensive lakes for each of the 6 study regions. Acronyms as follows: AGR = agricultural use, GRA = grassland, SBL = shrubland, LKS + WTL = lakes and all wetland types, RES = residential areas and rural farmsteads, including homes, outbuildings, and lawns/yards, RDS = roads, driveways, and other impervious surfaces such as commercial areas, parking lots, and gravel pits, OTHER = grasslands used for cattle grazing, islands within study sites, and streams.



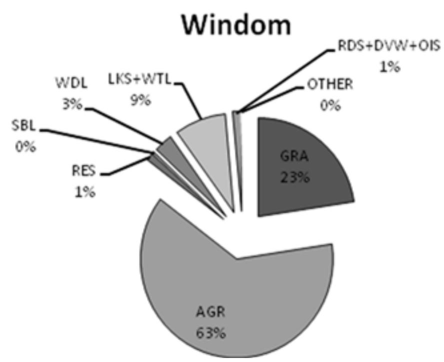


Figure 8.2. Average land cover composition within watersheds of Intensive lakes located near Elbow Lake, MN and Windom, MN. Acronyms as follows: AGR = agricultural use, GRA = grassland, SBL = shrubland, LKS + WTL = lakes and all wetland types, RES = residential areas and rural farmsteads, including homes, outbuildings, and lawns/yards, RDS = roads, driveways, and other impervious surfaces such as commercial areas, parking lots, and gravel pits, OTHER = grasslands used for cattle grazing, islands within study sites, and streams.

Final Report Summary: June 30, 2012

Lake and watershed characteristics - Delineation of study lake watersheds, composition and extent of upland cover types within lake watersheds, and extent of surface connectivity were completed and summarized as proposed and will be used in future analyses. Lake basin and watershed sizes are also summarized here to allow comparisons among study regions (Table 3). Largest and smallest study lakes occurred in Chippewa and Itasca study regions, respectively. Largest lake watersheds were associated with Red Lake study lakes; Itasca lakes were set within the smallest watersheds (an average) of our 6 study regions (Table 3).

Table 3. Average basin area and basin watershed area ± SE (minimum-maximum) of lakes in each of the six study areas.

Study Area	Basin Area (ha)	Basin Watershed Area (ha)
Red Lake	20.4 ± 4.8 (3.1-84.5)	12,521.4 ± 2545.6 (13.7-23,952.9)
Itasca	5.7 ± 1.0 (1.8-18.6)	124.5 ± 32.9 (6.1-599.9)
Chippewa	68.7 ± 16.9 (6.1-234.5)	1389.7 ± 488.4 (69.9-6592.6)
Metro	15.9 ± 2.9 (2.1-50.0)	438.8 ± 244.6 (9.6-5922.7)
Alexandria	20.3 ± 3.6 (1.7-63.9)	1301.1 ± 639.7 (8.0-11,811.1)
Windom	21.1 ± 3.5 (2.2-58.7)	260.4 ± 59.2 (12.1-1060.7)

Relationships among lakes, watersheds, surface connectivity patterns, and ecological communities - Extensive Lake data indicated that basin surface area (size) was strongly correlated with lake-watershed area (size). Watershed size, in turn, was significantly associated with downstream and upstream surface-water connections, and presence of both downstream and upstream potential fish sources. Modeling of current data, along with results from previous studies of regional shallow lakes (Fig. 17, Herwig et al. 2010), shows strong positive relationships between watershed size and surface connections to fish habitat, favoring immigration by fish populations. Increasing lake and watershed size increase likelihood for dispersal of fish and other aquatic organisms because more extensive surface connectivity typically accompanies increases in lake and watershed size. Data from Extensive Lakes confirm that both the probability of fish presence and the total number of fish species found in a given lake increased with increasing lake size (Fig.18).

Implications of lake and watershed size, and surface connectivity - Because larger lakes tend to develop more complex and interconnected surface networks, control of undesirable and even invasive fishes and other aquatic species is more complicated in these systems. Several considerations for lake management are especially important. First, potential transfer of undesirable aquatic organisms should motivate strategies for protecting relatively smaller, isolated shallow lakes and other waters. Second, managers should recognize increasing potential for transfer of aquatic organisms with increasing lake and watershed size, and with practices such as ditching which routinely connect surface waters. Finally, because planktivorous and benthivorous fishes have major influences in shallow lakes (and often increase potential for turbid-shifts), ecological implications of surface connectivity (and transfer of fish and aquatic organisms) should be considered as key decision criteria in all lake and surface water management projects.

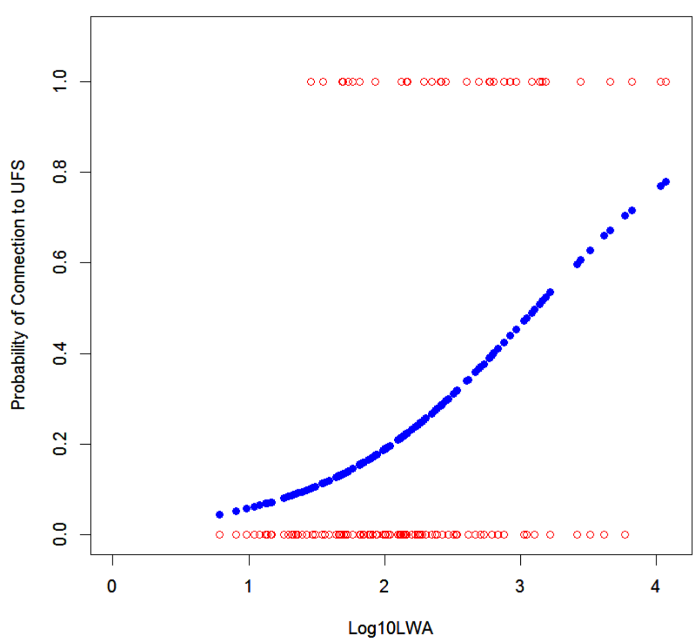


Figure 17. Relationship between lake watershed size and probability of upstream surface connections to fish habitat as determined for Extensive Lakes. Red circles indicate actual presence/absence of surface connections; solid blue circles show probability of surface connection to upstream fish source (UFS).

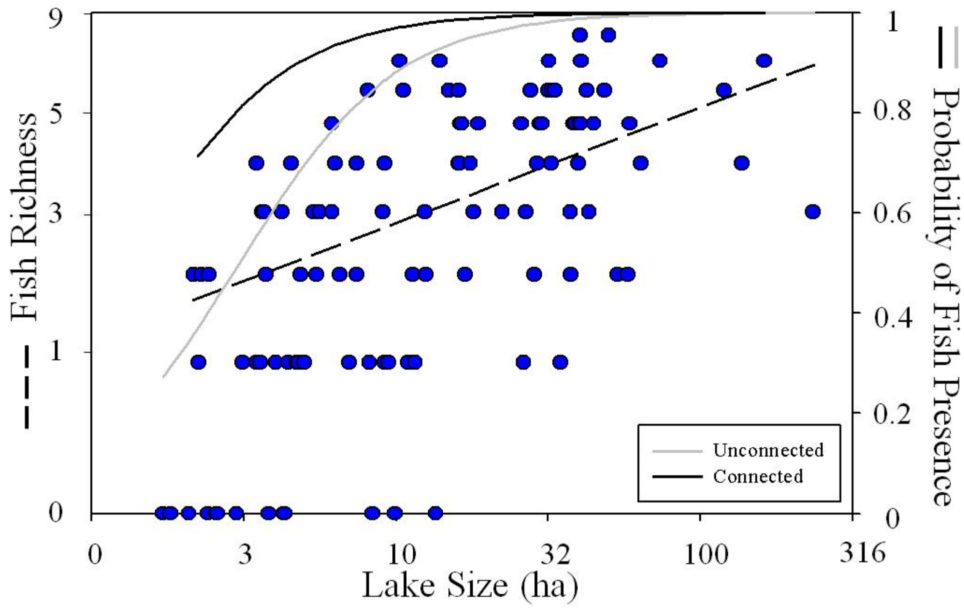


Figure 18. Relationship between lake size and fish richness in lakes where fish were found (dashed line, left axis) and probability of fish presence in both connected and unconnected lakes (solid lines, right axis).

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SUMMARY OF CURRENT AND EXPECTED STUDY PRODUCTS

We anticipate preparation of 5-8 peer reviewed manuscripts to be developed from data gathering and analyses completed during the present study. In addition to clarifying ecological relationships that regulate clear- and turbid-water regimes in shallow lakes, we anticipate a manuscript evaluating economic alternatives and other considerations for identification of shallow lake rehabilitation approaches. We are also planning to develop a shallow lake workshop for lake managers and other conservation partners to be held in central Minnesota during July or August 2013. We expect to offer a day-long technical program that will center on results of the present LCCMR-funded research, discuss lake rehabilitation strategies, and will offer opportunities for project managers and collaborators to present study findings directly to land and landscape managers. Presently, the Minnesota Chapter of the Wildlife Society has agreed to sponsor this workshop and to coordinate meeting and facilities requirements.

The following abstracts have been presented at scientific meetings during 2012:

Luke Ginger and many co-authors. 2012. Watershed versus within-lake characteristics as predictors of N:P ratios in shallow lakes. Presented at the summer meeting of the American Society of Limnology and Oceanography, Lake Biwa, Shiga, Japan, July 2012.

Langer, T.A., K.D. Zimmer, B.R. Herwig, M.A. Hanson, W.O. Hobbs, J.B. Cotner, R.G. Wright, and S.R. Vaughn. ´^{15}N of detritivores track nitrogen inputs from agricultural land into shallow Minnesota lakes. Presented at the summer meeting of the Ecological Society of America, Portland, OR, Aug 2012.

Probst, D.T., A.T. Goding, K.D. Zimmer, L.M. Domine, B.R. Herwig, J.B. Cotner, and W.O. Hobbs. Consumption of organic carbon from lake sediments by detritivorous fish: Implications for carbon sequestration in shallow lakes. Presented at the summer meeting of the Ecological Society of America, Portland, OR, Aug 2012.

Reuss, L.M., K.D. Zimmer, B.R. Herwig, and M.A. Hanson. Stability of alternative stable states in shallow lakes. Presented at the summer meeting of the Ecological Society of America, Portland, OR, Aug 2012.

Goetting, J.M., E.K. McHale, D. Martinovic, K.D. Zimmer, B.R. Herwig, M.A. Hanson, S.R. Vaughn, and R.G. Wright. Influence of watershed land-use on vitellogenin levels in fathead minnows (*Pimephales promelas*) in Minnesota shallow lakes. Presented at the summer meeting of the Ecological Society of America, Portland, OR, Aug 2012.

Buelt, C.A., K.D. Zimmer, M.A. Hanson, and B.R. Herwig. Community concordance among fish, aquatic invertebrates, and submerged aquatic plants in shallow lakes. Presented at the summer meeting of the Ecological Society of America, Portland, OR, Aug 2012.

Nolby, L.E., K.D. Zimmer, B.R. Herwig, M.A. Hanson, S.R. Vaughn, and R.G. Wright. Is island biogeography a poor fit to shallow Minnesota lakes? Presented at the summer meeting of the Ecological Society of America, Portland, OR, Aug 2012.

Finally, lake watersheds developed in support of Result 3 of this project were incorporated into the Minnesota DNR data holdings available for public consumption as a GIS data layer via the Minnesota DNR Data Deli (http://deli.dnr.state.mn.us/). More specifically, the watershed delineations exist as polygons within the DNR Level 08 Catchment GIS dataset as part of the DNR Watershed Suit. Metadata for this data is available at: http://deli.dnr.state.mn.us/metadata.html?id=L390006150201. Specific questions regarding these watershed delineations, data availability and future updates should be directed toward Sean Vaughn, MN_iT services GIS Hydrologist within the DNR Division of Ecological and Water Resources.

V. TOTAL ENRTF PROJECT BUDGET:

Personnel: $ 202,000 Funds requested here will not be used to support classified Minnesota DNR staff positions [costs of classified staff positions are summarized under VI. C below]. Project salary $$ will support 8-10 DNR student interns and 1 technician at University of MN (50%, 1 yr), along with 1.5 month salary support for K. Zimmer. No backfill will be necessary for any of these positions.
Contracts: $ 0
Equipment/Tools/Supplies: $ 22,000
Acquisition (Fee Title or Permanent Easements): $ 0
Travel: $ 38,000
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 undesireable 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: $ 433,686 Other state, non-state, University, and NGO support has been committed to the project. Pending support from Minnesota DNR Sections of Fisheries and Wildlife and Division of Ecological Resources will cover permanent staff salaries, research supplies and non-capital equipment, and travel to field research sites ($232,790). Secured support from The Red Lake Reservation Department of Natural Resources includes funds for permanent staff salary, support of a graduate student and student interns, non-capital research equipment and supplies, and travel and lodging expenses ($162,396). Support for non-capital equipment and undergraduate student assistants has been secured from the University of St. Thomas and the University of Minnesota ($28,500). Ducks Unlimited MN has committed funds and in-kind support for data gathering activities ($10,000).

D. Spending HIstory: *None*

VII. DISSEMINATION:

We anticipate preparation of 5-8 peer reviewed manuscripts to be developed from data gathering and analyses completed during the present study. We are also planning to develop a shallow lake workshop for lake managers and other conservation partners to be held in central Minnesota during July or August 2013. We expect to offer a day-long technical program that will center on results of the present LCCMR-funded research, allow discussion of lake rehabilitation strategies, and will offer opportunities for project managers and collaborators to present study findings directly to lake and landscape managers and other conservation partners in Minnesota. Presently, the Minnesota Chapter of the Wildlife Society has agreed to sponsor this workshop and to coordinate meeting and facilities requirements.

Results and synthesis from this work have been presented at annual meetings of the American Society of Limnology (Lake Biwa, Shiga, Japan, July 2012), the Ecological Society of America (Portland, Oregon, Aug 2012), and at various regional meetings of DNR staff and others. In addition, results have been distributed to DNR staff, other professionals, and the general public via annual project summaries from the Wildlife Research Unit, Minnesota DNR. We expect to develop 5-8 manuscripts for publication during the next 2-3 years.

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 can be found at
http://www.lccmr.leg.mn/PeerReview/2010/peerreview2010.html

Attachment A: Budget Detail for 2010 Projects - Final Update June 30, 2012												
Project Title: Cost-effective strategies for shallow lakes												
Project Manager Name: Mark A. Hanson												
Trust Fund Appropriation: $ 262,000												
2010 Trust Fund Budget	**Revised Result 1 Budget: 10 January 2012**	**Spent June 2012**	**Revised Balance**	**Revised Result 2 Budget:10 January 2012**	**Spent June 2012**	**Revised Balance**	**Revised Result 3: 10 Januaryl 2012**	**Spent June 2012**	**Revised Balance**	**REVISED TOTAL BUDGET: January 2012**	**Spent June 2012**	**Final Balance**
	dentify and estimatemajor factors responsible for deterioration of shallow lakes in 6 areas of Minnesota			**Evaluate and refine specific strategies for improving water quality and ecological characteristics of shallow lakes across Minnesota**			**Identify surface connectivity elements threatening water quality and biodiversity in shallow lakes**					
BUDGET ITEM												
PERSONNEL: wages and benefits												
Student Interns (4) - 8 Intensive lakes				$ 44,000.00	$ 44,000.00	$ -				$ 44,000.00	$ 44,000.00	$ -
Student Interns (4) - 150 Extensive lakes	$ 89,245.72	$ 89,245.72	$ 209.70							$ 89,245.72	$ 89,036.02	$ 209.70
Sean Vaughn (DNR Hydrologist-25%-1mo.)							$ 13,000.00	$ 13,000.00	$ -	$ 13,000.00	$ 13,000.00	$ -
Kyle Zimmer (Univ St. Thomas- 1.5 mo.)	$ 10,000.00	$ 10,000.00	$ -							$ 10,000.00	$ 10,000.00	$ -
1 UM technician (super. by J.Cotner-50% 1 yr)	$ 29,000.00	$ 29,000.00	$ -							$ 29,000.00	$ 29,000.00	$ -
Contracts												
Bemidji State University - Graduate student support				$ 30,000.00	$ 30,000.00	$ -				$ 30,000.00	$ 30,000.00	$ -
Other contracts												
Other direct operating costs *(for what? – be specific)*												
Non-capital Equipment / Tools *(what equipment? Give a general description and cost)*												
Office equipment & computers - NOT ALLOWED unless unique to the project												
Capital equipment over $3,500 *(list specific items)*												
2 14-ft aluminum boats for use sampling 8 intensive lakes				$ 7,545.00	$ 7,545.00	$ -				$ 7,545.00	$ 7,545.00	$ -
Land acquisition												
Easement acquisition												
Professional Services for Acq.												
Printing												
Supplies *(list specific categories)*												
Field sampling gear, nets, chemical supplies, sample jars, water quality monitoring equipment	$ 9,455.00	$ 9,455.00	$ 400.00	$ 3,427.68	$ 3,427.68	$ -				$ 12,882.68	$ 12,482.68	$ 400.00
Travel expenses in Minnesota												
Travel and perdiem 150 extensive lakes	$ 7,459.90	$ 7,459.90	$ -							$ 7,459.90	$ 7,459.90	$ -
Travel and perdiem 8 intensive lakes				$ 18,866.70	$ 18,866.70	$ -				$ 18,866.70	$ 18,866.70	$ -
Travel outside Minnesota												
Other DNR added governance @ 0.06												
COLUMN TOTAL	$ 145,160.62	$ 144,550.92	$ 609.70	$ 103,839.38	$ 103,839.38	$ -	$ 13,000.00	$ 13,000.00	$ -	$ 262,000.00	$ 261,390.30	$ 609.70