

SUMMARY PAGE

STUDY 605: Designing a long-term monitoring program to track the status of fish communities and their habitats in Minnesota lakes, identify efficient indicators, and evaluate mechanisms.

PROCEDURES:

- JOB 605.1 Project coordination
- JOB 605.2 Predictive watershed and limnological modeling, and assessment of stressors
- JOB 605.3 Zooplankton indicators
- JOB 605.4 Aquatic plant indicators
- JOB 605.5 Fish indicators
- JOB 605.6 Status metric development
- JOB 605.7 Report preparation

SCHEDULE:

	Seg. 40 2008-09	Seg. 41 2009-10	Seg. 41 2011 –12	Seg. 42 2012-13	Seg. 42 2013-14	Job Total
JOB 605.1	\$30,200	\$31,590	\$32,915	\$34,355	0	\$129,060
JOB 605.2	38,280	35,700	37,170	45,910	\$1,500	158,560
JOB 605.3	0	0	0	0	0	\$0
JOB 605.4	26,715	31,585	34,460	43,505	0	136,265
JOB 605.5	44,510	46,655	49,880	51,375	0	192,420
JOB 605.6	18,070	18,770	20,160	21,710	0	78,710
JOB 605.7	0	0	0	0	65,158	65,158
Year Total	\$157,775					
		\$164,300	\$174,585	\$196,855	\$66,658	\$760,173
Seg. Total	\$157,775		\$338,895		\$263,515	\$760,173

GEOGRAPHIC LOCATION: Statewide, Minnesota

PERSONNEL:

- JOB 1 Ray Valley
- JOB 2 Tim Cross, Peter Jacobson, Andrew Carlson, GIS technician
- JOB 3 Jeff Reed, Jodie Hirsch
- JOB 4 Cindy Tomcko, Donna Dustin, Ray Valley
- JOB 5 Mike McInerney, John Hoxmeier, Donna Dustin, Nick Proulx
- JOB 6 David Staples

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SCHEDULE DETAILS: Figures in this table only include analysis, fleet, intern, and travel costs. Most field costs are to be covered under existing F29 plans. Job 3 will not be supported by DJ funds.

	Seg. 40 2008-09	Seg. 41 2009-10	Seg. 41 2011 –12	Seg. 42 2012-13	Seg. 42 2013-14	Total
JOB 605.1						
Ray Valley	\$23,800	\$24,800	\$25,740	\$26,780	0	
Fleet	1,800	2,000	2,200	2,400	0	
Meetings	4,600	4,790	4,975	5,175	0	
Total	\$30,200	\$31,590	\$32,915	\$34,355	0	\$129,060
JOB 605.2						
	\$16,990	\$17,670	\$18,370	\$19,110		
Pete Jacobson	12,740	13,250	13,780	14,330		
Tim Cross	4,550	4,780	5,020	5,270	\$1,500	
GIS Technician	0	0	0	2,700		
Andrew Carlson	4,000	0	0	4,500		
Meeting	\$38,280	\$35,700	\$37,170	\$45,910	\$1,500	\$158,560
Total						
JOB 605.3						
Jodie Hirsch	0	0	0	0		0
JOB 605.4						
Cindy Tomcko	\$2,840	\$2,950	\$3,060	\$4,780	0	
Intern	220	220	220	220	0	
GR Travel	950	990	1,020	1,060	0	
GR Fleet	775	850	930	1,025	0	
Donna Dustin	9,300	9,875	10,470	16,660	0	
DL Intern	880	3,200	4,520	4,700	0	
Travel	1,250	1,250	1,250	1,250	0	
DL Fleet	1,020	2,200	2,380	2,570	0	
Glenwd Fleet	500	610	670	750	0	
Hutch Intern	6,900	7,140	7,420	\$2,770	0	
Hutch Fleet	2,080	2,300	2,520	\$43,505	0	
Total	\$26,715	\$31,585	\$34,460		0	\$136,265
Details Cont'd						
JOB 605.5						
	\$28,660	\$30,090	\$31,600	\$33,170	0	
Mike McInerney	500	500	500	500	0	
Hutch. Travel	8,560	8,900	9,300	9,600	0	
Hutch. Travel	520	550	570	590	0	
John Hoxmeier	510	560	620	680	0	
L.C. Fleet	2,860	2,975	4,000	3,350	0	
Donna Dustin	960	1,000	1,040	1,080	0	
Steve Shroyer	910	940	980	1,020	0	
Dale Logsdon	250	300	350	375	0	
Waterville Fleet	380	410	450	500	0	
Duluth Travel	300	330	370	410	0	
Duluth Fleet	100	100	100	100	0	
Brainerd Fleet	0	0	0	0	0	
Bemidji Fleet	\$44,510	\$46,655	\$49,880	\$51,375	0	\$192,420
Nick Proulx						
Total						
JOB 605.6						
	\$17,570	\$18,220	\$19,550	\$21,040	0	
Dave Staples	500	550	610	670	0	
Fleet	\$18,070	\$18,770	\$20,160	\$21,710	0	\$78,710
Total						
JOB 605.7						
					\$6,300	
Ray Valley						
Fleet					500	
Cindy Tomcko					6,628	
Fleet					300	

John Hoxmeier					6,672	
Fleet					300	
Donna Dustin					6,960	
DL Fleet					600	
Jeff Reed					3,950	
Fleet					300	
Pete Jacobson					8,050	
Dave Staples					8,750	
Fleet					300	
Tim Cross					7,948	
Mike McInerney					7,000	
Hutch Fleet					600	
Total					\$65,158	\$65,158
Year Total	\$161,775	\$168,310	\$178,585	\$200,245	\$66,658	\$760,173

Note that the budget schedule on the summary page and the detailed budget on pages 2-3 cover only those activities for which we plan to use Federal funds by requesting reimbursement under F26. Several other agencies will be participating in this project to some degree; however, they will not be using Federal funds or requesting reimbursement. Those partners are listed on page 4 (Summary page part 2) with reporting category as NFA. Much of the field work will be done under approved F29 survey programs, but most of the analysis and monitoring design work will be done by this research project under F26.

Summary page part 2. List of all proposed sampling activities on the sentinel lakes, their funding reporting categories, and lead analyst. NFA denotes part or all of the sampling activity will not be supported by Federal Aid funds.

	Indicator	Reporting Category (survey)	Reporting Category (analysis)	Proposal Job
Surveys				
Ice cover duration	Climate	NFA ^b	F26	605.2
Lake levels	Climate	NFA ^b	F26	605.2
Precipitation	Climate	NFA ^b	F26	605.2
Thermal and oxygen structure	Habitat	F26 / NFA ^c	F26	605.2
Total Phosphorus	Habitat	F26 / NFA ^c	F26	605.2
Total Nitrogen	Habitat	F26 / NFA ^c	F26	605.2
Nitrates	Habitat	F26 / NFA ^c	F26	605.2
Chlorophyll a	Habitat	F26 / NFA ^c	F26	605.2
pH	Habitat	F26 / NFA ^c	F26	605.2
Total Suspended Solids	Habitat	F26 / NFA ^c	F26	605.2
Total Suspended Volatiles	Habitat	F26 / NFA ^c	F26	605.2
Total Organic Carbon	Habitat	F26 / NFA ^c	F26	605.2
Alkalinity	Habitat	F26 / NFA ^c	F26	605.2
Calcium	Habitat	F26 / NFA ^c	F26	605.2
Sulfate	Habitat	F26 / NFA ^c	F26	605.2
Agricultural practices	Land Cover	NFA ^d	F26	605.2
Land cover	Land Cover	NFA ^e	F26	605.2
Land cover projection	Land Cover	NFA ^f	F26	605.2
P loading	Land Cover	F26	F26	605.2
Silvicultural practices	Land Cover	NFA ^g	F26	605.2
	Morphometri			
Bathymetry	c	F26	F26	605.2
	Morphometri			
Watershed delineations	c	NFA ^h	F26	605.2
Zooplankton community	Habitat	NFA ^a	NFA ^a , F26	605.3
Aquatic plant species frequency	Habitat	F29	F26	605.4
Curly-leaf pondweed surveys	Habitat	F29	F26	605.4
Aquatic plant abundance mapping	Habitat	F26	F26	605.4
Fish Index of Biotic Integrity	Fish	NFA ^a	NFA ^a , F26	605.5
Northern pike surveys	Fish	F29	F26	605.5
Largemouth bass surveys	Fish	F29	F26	605.5
Community composition	Fish	F29	F26	605.5

^aDNR Division of Ecological Resources without using Federal funds or requesting reimbursement.

^bCitizen volunteer monitoring program administered by DNR Division of Waters without using Federal funds or requesting reimbursement.

^cMinnesota Pollution Control Agency without using Federal funds or requesting reimbursement. Discretionary PCA budgets will support the first two years of these assessments. Additional funding will be needed for years 3 and 4.

^dMN Dept. of Agriculture and US Dept. of Agriculture

^eUS Geological Survey (no reimbursement will occur via this proposal)

^fUS Forest Service (no reimbursement will occur via this proposal)

^gDNR Division of Forestry without using Federal funds or requesting reimbursement.

^hDNR Division of Waters without using Federal funds or requesting reimbursement.

STUDY 605: Designing a long-term monitoring program to track the status of fish communities and their habitats in Minnesota lakes, identify efficient indicators, and evaluate mechanisms.

PROBLEM: Fisheries lake surveys are conducted on most Minnesota lakes only once every three to six years and focus on sportfish, thus our ability to distinguish changes due to our management actions (e.g., aquatic plant management programs, fishing regulations, stocking programs) from those due to other human actions within the watershed (e.g., urbanization, agricultural changes, forest practices, invasive species), or those due to temperature fluctuations, is limited. We lack clear measures of how fish habitats and food-webs respond to many natural environmental gradients or human disturbances. The crux of the problem is that we do not know which of the many possible measures would be the most reliable indicators of changes that will alter sportfish populations, how the key indicators vary within and among lakes, how the key indicators respond to natural environmental gradients versus human disturbances, or how often we need to sample to detect change in fisheries or their habitats,

Early detection and rapid response to changes on the landscape and in lakes will be required to accomplish our mission of maintaining high quality fisheries in Minnesota. With very high certainty, early detection and rapid response will not occur without a robust long-term monitoring program.

GOALS: The goals of this study are to identify the best indicators to assess the overall status of Minnesota lakes—those that most reliably measure habitat quality for native sportfish populations—and to establish baseline monitoring of 24 Minnesota lakes that span a range of geomorphic and disturbance conditions. This four-year pilot project complements our current lake survey program and uses a split-panel design that should allow us to more reliably detect change to lake habitats and fish communities and predict results of large-scale ecological stressors.

OBJECTIVES: Augment existing fisheries assessment protocols by developing an integrated, long term monitoring program for lakes based on water quality, habitat, zooplankton, and fish; to analyze properties of the monitoring program and its constituent metrics; and to assess the performance of the metrics as indicators of disturbance.

JUSTIFICATION: More frequent and detailed study of 24 sentinel lakes will help identify the most reliable indicators with which to detect habitat changes and help link changes in fisheries to causal mechanisms. With better indicators, earlier detection of changes, more rapid and appropriate response measures, and more objective evaluation of effectiveness become possible. Early adaptation and mitigation at multiple levels are the best ways to cope with the consequences of environmental change (Figure 1). A long-term monitoring program focusing on tracking environmental stressors and the status of sensitive indicators is needed to accomplish our mission of maintaining high quality fisheries in Minnesota.

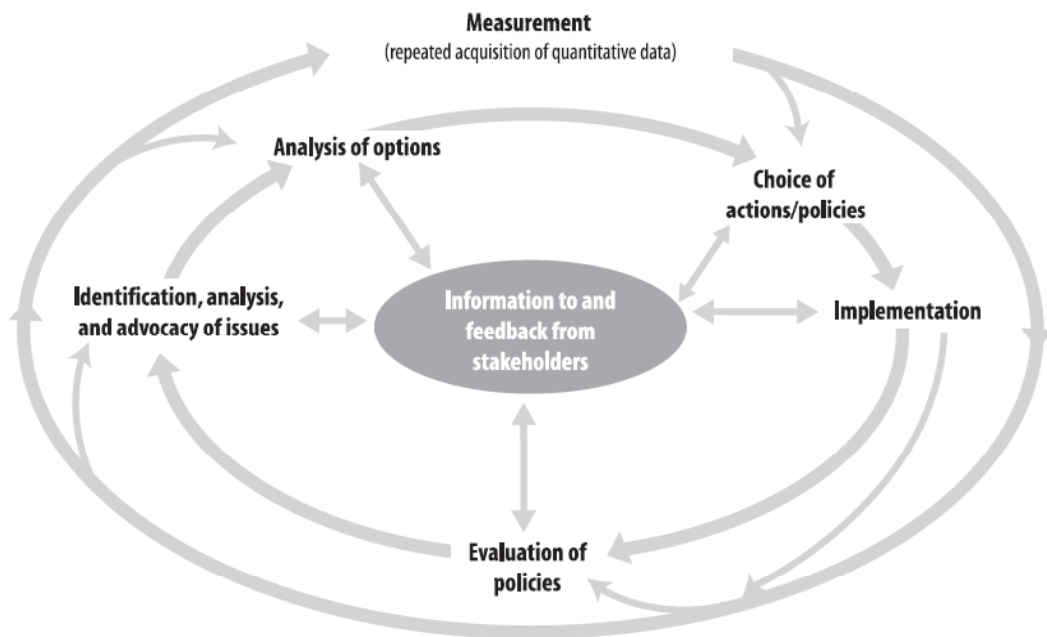


Figure 1. The adaptive management cycle (From Lovett et al. 2007)

Lovett et al. (2007) and Magnuson et al. (2006) identified several general reasons why a well-designed long-term monitoring program is a highly efficient and necessary use of agency resources: 1) costs of monitoring are small compared to value of the resource it protects and the policy it informs; 2) a long-term monitoring program allows for evaluation of policies and management decisions; 3) time-lags between environmental disturbances (or from management policies) and their outcomes hinder studies; and 4) lake ecosystems are dynamic over time and space, thus their status cannot be evaluated out of spatial or temporal context. More specifically, the indicators identified should not only improve evaluation of aquatic plant management, stocking, and fishing regulations, but also identification of biological hot-spots, measurement of fisheries gains or declines, establishment of biological criteria and assessment of impacts of human activities.

STATUS: Both large- and small-scale stressors have been shown to impact lake habitats and aquatic communities. Studies in Wisconsin found localized disturbances, such as human altered lakeshore habitats, impacted fish assemblages on a local scale (Christiansen et al. 1996; Jennings et al. 1996; Engel and Pederson 1998). However, Jennings et al. (1999) also reported that fish assemblages responded more strongly at larger spatial scales, when many diverse incremental changes have accumulated within a basin over time. Jennings and Emmons (2001) summarized many of the problems and information needs regarding cumulative effects in WI lakes and stressed the importance of maintaining habitat function of all the parts of a lake, the shore, littoral habitat, water, etc. because of the importance of how all the parts interact. The importance of fish habitat is believed so great

that Canadian legislation prohibits “harmful alteration, disruption, or destruction” of fish habitat and follows a guiding principle of no net loss (DFO 1998). Consequently, work has been done in recent years in an attempt to measure fish response to changes in Canadian lake habitats (Minns 1997; Pratt and Smokorowski 2003).

Evidence suggests that human development activities are affecting habitat and fish populations in Minnesota lakes. Trophic status derived from diatom core samples indicate changes in lake trophic conditions corresponding to human settlement and watershed development in the North Central Hardwood Forest and Western Cornbelt Plains Ecoregions, but not the Northern Lakes and Forest Ecoregion (Heiskary and Swain 2002). Changes in fish populations have also been associated with human development activities. Cross and McInerney (1995, 2001) documented an influence of watershed land use on fish communities in a selected Central Minnesota ecological lake class (24). Radomski and Goeman (2001) and Radomski (2006) quantified losses of emergent and floating-leaf plant cover associated with shoreline development. Furthermore, these losses correlated with differences in the relative biomass and mean size of three species of sportfish. Shoreline development has also been linked to a reduction in black crappie and largemouth bass nest sites in lakes (Reed and Pereira, in press). Drake and Valley (2005) used a fish-based index of biotic integrity (IBI) to demonstrate a negative relationship between IBIs and trophic status and to identify patterns in IBI scores relative to land use. In forested watersheds, lakes were generally mesotrophic with a high proportion of species intolerant to disturbance. In contrast, we found a relatively high proportion of species tolerant to disturbance in eutrophic lakes in urban or agricultural watersheds (Drake and Valley 2005). Measuring change in fish communities is difficult because of inherent variability in population dynamics of fish and in their measurement. Identifying the reason for a change is even more difficult because multiple stressors interact simultaneously to alter habitat conditions for fish populations and the cumulative effects of multiple stressors can differ greatly from the sum of their independent effects. In addition, it is difficult to identify responses to specific stressors because fish species have complex life histories, utilize different habitats during different life stages, and exhibit large inter-annual fluctuations in abundance (Rose 2000).

Conventional agricultural activities (e.g., feedlots, ditching, tile drainage) also have had measurable consequences on macrophyte habitats and lake fish communities (Egertson et al. 2004, Egertson and Downing 2004). Lakes in prairie landscapes are often naturally eutrophic (Heiskary and Lindon 2005), however, runoff from agriculture and livestock operations have led to greater eutrophication, loss of macrophytes, and a shift to benthivorous fish communities (Scheffer and Carpenter 2003, Egertson et al. 2004, Egertson and Downing 2004). Future demands for energy and food production will affect both the quantity and quality of water resources. Of course, this has large implications for sportfish production.

Climate change has the potential to exacerbate the cumulative impacts of human activities. In north temperate lakes, much work over the past decade has focused on modeling habitat changes as a result of warming water temperatures and predicting the consequences for fish populations and communities (Stefan et al. 1996, DeStasio et al. 1996, Casselman 2002, Shuter et al. 2002, Jackson and Mandrak 2002). Stefan et al. (1996) projected seasonal average epilimnetic water temperatures will increase by approximately 3° C with a doubling of CO₂ concentrations. This could lead to a 41% reduction in coldwater habitat in northern Minnesota. The Intergovernmental Panel on Climate Change (IPCC) predicts this doubling could happen as early as 2030 under continued rates of emission and population growth (IPCC 2007). Minnesota populations of coldwater species such as Lake Trout and Cisco could experience the greatest reduction in inland lakes because of their narrow

thermal and dissolved oxygen habitat requirements. With a temperature increase of 3° C, Casselman (2002) projected recruitment of coolwater species will decline by a factor of 18 and recruitment of warmwater species would increase approximately 15 fold. This would result in the displacement of coolwater species by warmwater species. Jackson and Mandrak (2002) project these temperature changes will result in the loss of fish biodiversity along with shifts in species assemblages.

Finally, cumulative impacts from development, agriculture, climate change, and a mobile human society will continue to favor the establishment of opportunistic non-native invasive species in ecosystems. Non-native invasive species cause environmental damage and economic losses in excess of \$137 billion in the United States alone (Pimentel et al. 2000). Humans are directly and indirectly altering ecosystems at a scale not seen since the last ice age. In response to these stressors, there will be winners and losers as species sort themselves out (IPCC 2007). Some invasions and declines are inevitable and will be necessary to provide basic ecosystem functions (e.g., primary and secondary production).

Establishing sentinel sites for ongoing monitoring - Across Minnesota's major ecoregions, lakes vary widely with respects to their geomorphology and fish communities (Schupp 1992). Likewise, ecological and anthropogenic forces shaping lake habitats and fish communities are regional in nature. These regional differences must be accounted for in a monitoring program. During pre-project planning, we focused sentinel lake selection in three of Minnesota's major ecoregions (level III; Omernik 1987), Northern Lakes and Forest (Level III: NLF), Northern Central Hardwoods (Level III; NCHF), and Western Corn Belt and Northern Plains (Level III WCBP and Level III Northern Glaciated Plain NGP). Within NLF we separated the Boundary Lakes and Hills ecoregion (level IV: BLH) from the rest of the level III ecoregion giving us four study regions. Also, we merged the WCBP level III ecoregion with the NGP ecoregion. Based on lake size and depth (Geometry ratio; Stefan et al. 1996) we determined the likely mixing status of potential study lakes. Lakes with geometry ratios ≥ 4.5 were classified as likely thermally mixed (unstratified) throughout the open water season and lakes with geometry ratios ≤ 2 were classified as likely thermally stratified throughout the open water season. Mixing status is less clear for geometry ratios in between. Lake mixing is important because it controls the degree that nutrients such as phosphorus are cycled within a lake. We also determined the relative productivity classes (e.g., low, medium, high) of potential lakes according level III ecoregion-specific relative phosphorus levels. Because these classes were derived from ecoregion-specific phosphorus levels, the observed range of phosphorus in each class differs among ecoregions. For example, low phosphorus in the WCBP is much greater than low phosphorus in NLF. Total or epilimnetic phosphorus reflects the major human stressor impairing water quality, fish habitat, and fish community integrity in Minnesota lakes (Drake and Valley 2005; Heiskary and Wilson 2005). Six lakes were then chosen from each study region with 3 lakes from each mixing class (stratified or unstratified) and within each mixing class one lake was from each productivity class (low, medium, high). This resulted in 24 sentinel lakes. Pre-existing long-term datasets, opportunities for local partnerships, and workload considerations also contributed the selection of the 24 sentinel lakes (Table 1; Figure 2).

Table 1. Proposed sentinel lakes.

Ecoregion	Lake	DOW	Acres	Max depth (ft)	P-level	Stratification	Fish mgt area
Border	Bearhead	69025400	674	46	med	stratified	Tower
Border	Elephant	69081000	724	30	high	stratified	International Falls
Border	Echo	69075700	1139	10	high	mixed	International Falls
Border	Northern Light	16008900	433	8	low	mixed	Grand Marais
Border	Trout	16004900	257	77	low	stratified	Grand Marais
Border	White Iron	69000400	3238	47	med	mixed	Tower
CHF	Belle	47004900	856	25	med	mixed	Hutchinson
CHF	Carlos	21005700	2598	163	med	stratified	Glenwood
CHF	Cedar	49014000	243	88	low	stratified	Little Falls
CHF	Pearl	73003700	746	17	low	mixed	Montrose
CHF	Peltier	2000400	465	18	high	mixed	East Metro
CHF	South Center	13002700	898	109	high	stratified	Hinckley
NLF	Elk	15001000	305	93	med	stratified	Bemidji
NLF	Hill	1014200	907	48	high	stratified	Aitkin
NLF	Portage	29025000	412	17	high	mixed	Park Rapids
NLF	Red Sand	18038600	516	23	med	mixed	Brainerd
NLF	South Twin	44001400	1000	29	low	mixed	Detroit Lakes
NLF	Ten Mile	11041300	4669	208	low	stratified	Walker
WCB	Artichoke	6000200	1964	16	high	mixed	Ortonville
WCB	Carrie	34003200	81	26	low	stratified	Spicer
WCB	Madison	7004400	1439	59	high	stratified	Waterville
WCB	Shaokotan	41008900	994	10	med	mixed	Windom
WCB	St James	83004300	221	16	low	mixed	Windom
WCB	St Olaf	81000300	99	33	med	stratified	Waterville

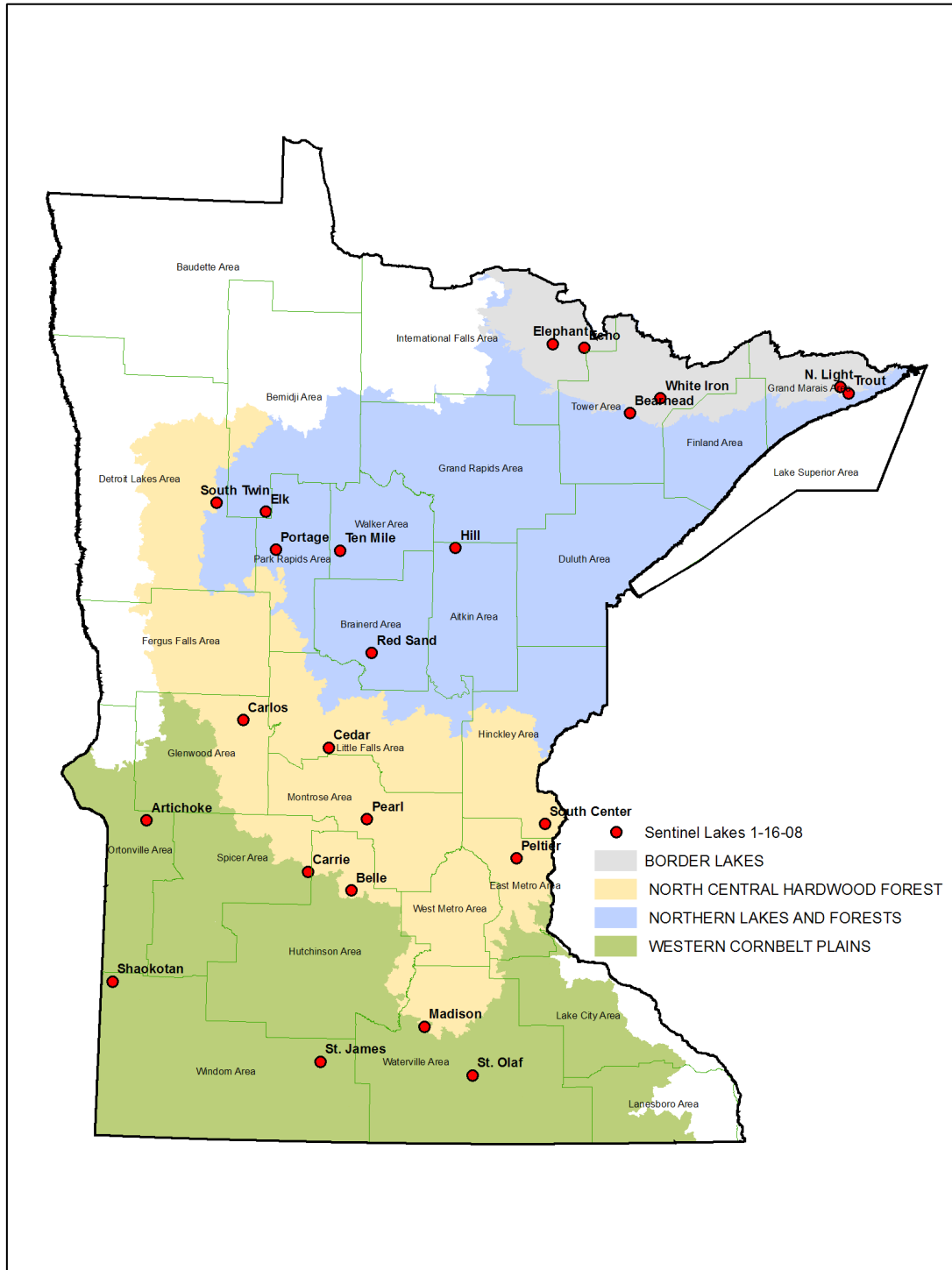


Figure 2. Major ecoregions and proposed sentinel lakes.

Establishing potential indicators to be monitored – Detection of ecological change in fish habitat and fish populations requires selection of the appropriate stressor measures and robust, yet sensitive indicators (Danz et al. 2006; Niemeijer and Groot 2008). Stressors are physical, chemical, or biological perturbations to a system that are either foreign to that system or natural to the system but occurring at an excessive or deficient level (Gucciardo et al. 2004). For the Great Lakes Basin, Danz et al. (2006) grouped 86 variables related to five classes of anthropogenic stress: agriculture, atmospheric deposition, human population, land cover, and point source pollution. In this study, we will focus our attention on stressors most relevant to each sentinel lake. For example, agricultural stressors are not relevant for lakes in the federally protected forests of the BLH ecoregion. Rather, these systems are threatened most by climate change and possibly the introduction of non-native invasive species. We will mine publicly-available datasets to find metrics that may best reflect sediment or phosphorus loading or recycling, water temperature, or physical removal of habitat (e.g., aquatic plant removal by lakeshore owners) and identify critical information gaps (e.g., irregular or infrequent assessments of landcover across the state).

During pre-project planning, we identified several potential fish, invertebrate, and habitat-related metrics to evaluate for use as potential indicators (Table 2). The response of indicators to disturbances likely varies according to the type and scale of disturbance, which is why it is important to monitor multiple indicators over time. Use of multiple indicators also increases the likelihood of early detection as indicators with shorter lifecycles may respond more quickly to stressors than longer-lived organisms that integrate cumulative stressors. Sampling error combined with natural variability may limit the utility of some metrics as indicators. At the conclusion of the study, we will identify a set of metrics that are robust to sampling error and interannual variability (i.e., high signal:noise ratio; Jassby 1998) and demonstrate a potential to respond to stressors in a predictable manner. These metrics will be used as indicators in a long-term monitoring program where their performance as indicators can be further evaluated.

Predicting potential responses to large scale drivers of change - The ability to project the potential outcomes of a range of large scale drivers of change, such as watershed land use alterations or climate change, is needed to proactively manage fish populations in Minnesota lakes. For example, the amount of phosphorus recycled within a lake is a key limiting factor for fish habitat quality. If we can predict the consequences of various watershed land use alterations on phosphorus loading and lake mixing, it will enable us to provide decision makers with information on the trade-offs of various management actions. This in turn will allow them to make informed decisions regarding land use practices. In addition, projecting potential responses to various climate change scenarios will enable us to identify factors that may help to minimize the impact of climate change on our fisheries, identify thermal refuges that warrant special protection, and identify management efforts that have little chance of longterm success. MNDNR will begin collection of data needed to model the response of lake dynamics to large-scale drivers of change. We will use existing standard watershed and lake modeling tools to describe basic lake dynamics. Unfortunately, MN DNR Fisheries does not possess the expertise in-house to develop the more complex models needed to fully explore lake dynamics. Therefore, we will begin organizing a consortium of experts on watershed and lake modeling that through partnerships and data sharing can accomplish mutual objectives.

Table 2. Proposed indicators and hypothesized responses to disturbances. All indicators are hypothesized to change slowly as a result of climate-influenced stressors.

Class of Indicator	Indicator	Response to local disturbance	Response to watershed disturbance
Water Quality	Epilimnetic P	Slow, cumulative	Rapid
	Dissolved O ₂	Slow, cumulative	Rapid
	Temperature ^a	NA	NA
	Chlorophyll a	Slow, cumulative	Rapid
Physical Habitat	Density and distribution of emergent macrophytes	Locally immediate Lake-wide, slow	Slow
	Density and distribution of submerged macrophytes	Locally immediate Lake-wide, slow	Rapid
	Max depth of veg. growth	Slow, cumulative	Moderate
	Macrophyte IBI	Slow, cumulative	Moderate
	Stability of macrophyte patchiness	Slow, cumulative	Rapid
	Distribution, quantity, and quality of coarse woody habitat	Locally immediate Lake-wide, slow	No response
	Substrate composition	Slow, cumulative	Locally rapid Lake-wide, slow
Invertebrates	Pelagic zooplankton community composition	Slow, cumulative	Moderate
	Pelagic zooplankton size-structure	Slow, cumulative	Moderate
	Macroinvertebrate community structure	Locally immediate Lake-wide, slow	Moderate
Fish	Fish IBI	Slow, cumulative	Slow
	Status of indicator species ^b <ul style="list-style-type: none"> ▪ Growth ▪ Age at maturation ▪ Size structure ▪ Mortality 	Varied, cumulative	Slow

^aTemperature is an indicator that will be most affected by climate change.

^bIndicator species include, cisco, walleye, northern pike, largemouth bass, smallmouth bass, white sucker, black crappie, bluegill, rock bass, pumpkinseed, and yellow perch.

EXPECTED RESULTS AND BENEFITS:

1. Robust design of a long-term lake monitoring program that will facilitate rapid detection of changes to fish populations and habitat.
2. Identification of the most reliable indicators of habitat changes that will alter sportfish populations, based on variability within and among lakes.
3. Description of how key indicators of fish habitats and food-webs respond to natural environmental gradients and human disturbances.
4. More appropriate management responses to habitat and fishery changes.
5. Better evaluation of management actions (e.g. aquatic plant management, stocking, regulation change, identification of biological hot-spots, measurement of fisheries gains or declines, establishment of biological criteria and assessment of impacts of human activities).
6. Revisions to the DNR's lake survey program that will increase efficiency, be more informative about the status of habitat and fish in lakes, and improve identification of local and statewide trends in stressors, habitat, and fish populations.
7. Building of long-term partnerships (e.g., within and among DNR divisions, among local, state, and federal agencies, and among citizen groups) to address ecological drivers of change that go well beyond Fisheries jurisdictional boundaries and areas of expertise.
8. Aquatic education – the sentinel lakes will serve as 24 lake laboratories where educators and students can learn about watershed and lake processes and how human activities on the landscape can affect fish and fishing.
9. Synergy in lake resource management – the sentinel lakes will serve as a focal point for collaborative research. For example, the PCA is evaluating questions related to how mercury moves through food webs as a response to land use and climate change in a range of Minnesota lake types, and is exploring possible work in the sentinel lakes.
10. Understanding mechanisms driving habitat conditions and fish populations.

JOB 605.1: Project Coordination

OBJECTIVES: 1. Communication and coordination with internal and external partners, 2. Schedule and coordinate surveys, 3. Oversee data collection and management, 4. Provide direction and support to field staff, 5. Dissemination of findings.

PROCEDURES:

1. Organize annual fall joint meetings with research and management staff to debrief from the previous field season and adjust sampling plans where necessary for the following field season
2. Communicate findings and activities with external partners and the public through meetings, press releases, managing a website, and other public information products (will involve working closely with our information officer)
3. Work with administrators of aquatic databases to ensure data gets entered into the appropriate databases (Table 3).
4. Manage a schedule of all DNR Fisheries-related field activities and provide logistic support where necessary.
5. Lead preparation of annual progress and a final report. Facilitate publication of results in the peer-reviewed scientific literature.
6. As project manager, manage study direction through teams with assigned responsibilities (Figure 3).

Table 3. Databases where data from 605 will be housed and administrators of the databases.

Data	Database	Web URL	Administrator/Contact
Climate	MN Climatology Working Group	http://climate.umn.edu/	DNR Waters and U of MN
GIS data layers	GIS Data Resource Site	http://deli.dnr.state.mn.us/	DNR Fisheries
Lake Levels	Lake level database	http://www.dnr.state.mn.us/lakefind/results.html	DNR Waters
Flow and temperature	HYDSTRA	http://www.dnr.state.mn.us/waters/csg/index.html	DNR Waters
Water Quality	STORET	http://www.epa.gov/storet/	PCA
Zooplankton	Zooplankton	None	DNR Ecological Resources
Aquatic plants	Lake Survey Database	None	DNR Fisheries
Fish	Lake Survey Database	None	DNR Fisheries

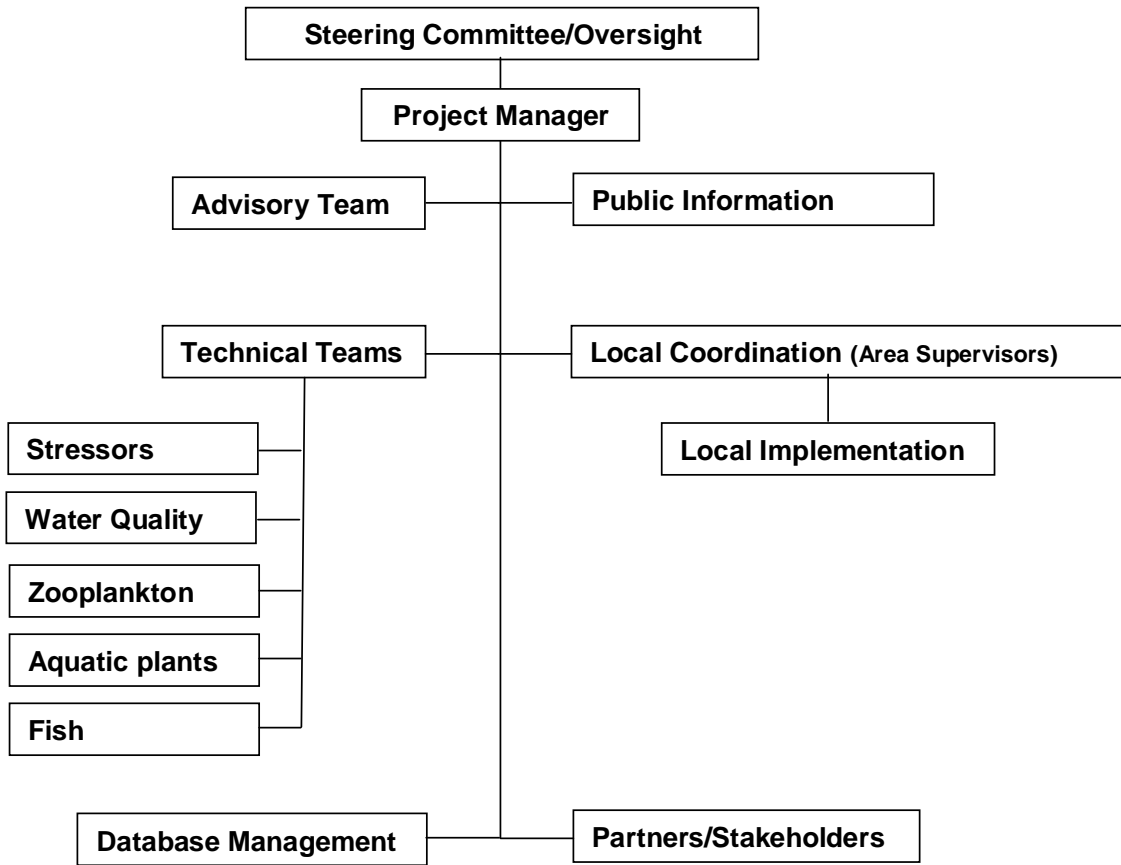


Figure 3. Study 605 Organizational chart

JOB 605.2: Predictive watershed and limnological modeling, and assessment of stressors

OBJECTIVES: 1. To identify and measure important physical, chemical, and biological stressors borne from land use and climate drivers that may affect habitat and fish indicators in the sentinel lakes. 2. Organize a consortium of experts to identify watershed and limnological modeling strategies and potential collaborations. 3. Develop and execute a modeling approach for the sentinel lakes that will give us inference into effects of future changes of land use and climate change on sentinel lake habitats and fish communities.

PROCEDURES:

Organizing a consortium of modelers - The four-year pilot project will explore and identify the critical parameters that need to be measured to effectively monitor how large-scale ecological stressors affect lakes in Minnesota. A 'stressor' is any physical, chemical, or biological property or process that exists outside of its normal range and impacts ecosystem structure or function (Gucciardo et al. 2004). Possible parameters and processes that will be considered are presented in Table 4. Most of these parameters are basic components of ecological or food web models. Potential sampling frequencies suggested in Table 4. are specified separately for the standard sentinel lakes and for a smaller set of 'super' sentinel lakes. Super sentinel lakes will be sites of additional intensive monitoring to allow modeling of how nutrients move through watersheds, lakes, and aquatic food webs. Given the intensity and sophistication of mechanistic watershed and lake modeling, the additional work in the super sentinel lakes (over that in the other sentinel lakes) will require collaboration with outside University experts, and additional funding that we will seek outside this F26 proposal. Accordingly, we will organize a consortium of experts and hold two coordination meetings to guide future direction in mechanistic watershed and lake modeling. Outcomes of these meetings will include a long-term approach to monitor stressors and model their effects on lake habitats and fish populations, and future partnerships to execute the approach.

A number of different potential partners have been identified that could collaborate with the design and implementation of several components of the monitoring. Limnologists, water engineers, and landscape ecologists at the University of Minnesota (both Twin Cities and Duluth campuses) have expertise in automated sampling buoys, in-lake water chemistry/thermal habitat modeling, and watershed modeling. The University of Minnesota is also a world leader in remote sensing of land use and water quality. The St. Croix Watershed Research Station has several experts on paleolimnological reconstruction of water quality. The United States Geological Survey (USGS) has extensive expertise in stream gauging and hydrologic modeling that could be useful in developing monitoring systems designed to measure phosphorus-loading rates. The State Climatology Office is the primary data clearinghouse for ice up/ice out statistics for lakes around the state and is interested in remote, automated methods for determining ice status. Partnerships with these outside collaborators that bring expertise beyond the DNR and PCA will be a key component of the project.

Assessment of stressors

Collection and retrieval of watershed land use, hydrologic, and climate data will be an important for developing the tools in 605.2. Data summaries will be in conjunction with Minnesota DNR GIS and outside GIS experts (e.g. the University of Minnesota). Lake watershed land use (e.g.: Minnesota land cover NLCD 2001) will be summarized by categories at appropriate spatial scales. Useful methodologies for measuring land use/land cover applicable to this project are outlined by Wolter et al. (2006). Climate data will focus on precipitation, evaporation, temperature, solar radiation, and wind speed and direction. Recent climate data (temperature and precipitation) interpolated at a resolution of 1 square

km and correcting for effects of elevation (Hijmans et al. 2005) will be explored as well. The hydrologic characteristics of each watershed will include data on connectivity and tributary characteristics, soil and hard surface permeability, and potential runoff rates (water yield). The Minnesota DNR Division of Waters (DOW) has delineated individual lake watersheds for most Minnesota lakes including the sentinel lakes. Additional land use data (e.g., DNR pre-settlement vegetation data and multitemporal Landsat derived land use – see Yuan et al. 2005) also holds promise for reconstructing historical P loading rates. As with physical and chemical lake measurements, collaboration and outside sources of data describing lake habitat stressors will be invaluable.

Watershed and limnological modeling

Developing tools for understanding how ecological stressors at multiple scales directly affect ecological processes within the sentinel lakes is an important goal of this project. Accordingly, we will collaborate with various experts specialized in watershed and lake modeling in order to develop and refine predictive models describing relationships between these ecological stressors and physical-chemical lake habitat parameters. This will involve modeling hydrologic processes determining the contribution of surface runoff and ground water (if applicable) contributions of sediment, nutrients, and chemicals to lakes. In addition, modeling will also be done to address in-lake dynamics of physical and chemical parameters measured in Job 605.2 as influenced by watershed inputs, climatic factors, and invasive organisms (if applicable).

Table 4. Potential parameters, properties, and processes affected by climate and land use change that could be monitored on sentinel lakes, along with suggested sampling frequencies and collaborating partners.

Property/Process	Stressor	Super		Sampling Method	Sampling Frequency	Additional Budget	Potential Technical Expertise
		Sentinel	Sentinel				
Bathymetry	Baseline	x	x	Detailed bathymetric measurement	initial		DNR Fisheries
Hydrologic network	Baseline	x	x	Hydrologic watershed delineations	initial		DNR Waters
Lake history	Baseline	x	x	Written and oral records	initial		
Air temperature	Climate change		x	Automated sampling buoy	continuous	x	U of M
Evaporation rates	Climate change		x	Automated sampling buoy	continuous	x	State Climatology Office
Ice cover duration	Climate change	x	x	Direct observation	daily		State Climatology Office
Lake levels	Climate change	x	x	Lake gauging stations	weekly		DNR Waters
Precipitation	Climate change		x	Automated sampling buoy	continuous	x	U of M
Relative humidity	Climate change		x	Automated sampling buoy	continuous	x	U of M
Soil freeze/thaw cycles	Climate change		x				U of M?
Solar radiation	Climate change		x	Automated sampling buoy	continuous	x	U of M
Thermal and oxygen structure	Climate change		x	Automated vertical profiling buoy	continuous	x	U of M
Thermal and oxygen structure	Climate change	x		Manual temperature and DO profiles	monthly		PCA/DNR Fisheries
Thermal and oxygen structure	Climate change	x		Epilimnetic temperature loggers	continuous		DNR Fisheries
Tributary stream flow	Climate change		x	Automated flow gauging stations	continuous	x	DNR Waters, USGS
Wind energy	Climate change		x	Automated sampling buoy	continuous		U of M
Agricultural practices	Land use change	x	x	GIS and agricultural records	annual		Dept. of Ag, USDA
Epilimnetic water chemistry	Land use change	x	x	Total P, Chl-a, Secchi	monthly		PCA/DNR Fisheries
Groundwater dynamics	Land use change		x	Piezometers		x	DNR Waters, USGS
Historical hypolimnetic oxygen	Land use change		x	Fossil chironomid reconstruction	initial	x	St. Croix Wshd Research Station
Historical productivity	Land use change	x	x	Fossil diatom reconstruction of Total P	initial	x	St. Croix Wshd Research Station
Land use	Land use change	x		Landsat land use delineation	every five years		U of M
Land use	Land use change		x	Intensive land use delineation	every five years	x	U of M, UMD
Land use projection	Land use change	x	x	Demographic change projections	decadal		
P loading	Land use change		x	Intensive P loading estimation	annual	x	USGS
P loading	Land use change	x		P loading estimation	every five years		PCA, USGS
Sedimentation	Land use change		x	Acoustic estimation	decadal		DNR Fisheries
Sedimentation	Land use change		x	Paleolimnological estimation	initial	x	St. Croix Wshd Research Station
Silvicultural practices	Land use change	x	x	GIS and forestry records	annual		DNR Forestry/USFS
Total phosphorus	Land use change	x	x	Standard PCA protocols	monthly		PCA
Chlorophyll a	Land use change	x	x	Standard PCA protocols	monthly		PCA

The ability of generalized models to account for differences among disparate landscapes in Minnesota and be extended to other lakes around the state will be assessed. These different landscapes include agricultural ecoregions where water diversion, cropping practices, and manure management are important; forested landscapes where silvicultural practices can affect watershed processes; and urbanized landscapes, where impervious surfaces and storm water drainage are key factors. Birr and Mulla (2001) present a reasonable approach that that could be used to develop and evaluate watershed models for application at a regional scale in Minnesota, and Schussler et al. (2007) provide a watershed phosphorus mass balance model that also has utility for use with this project. In addition to surface water modeling, models of ground water hydrology may also be needed, especially for seepage type lakes that depend heavily on ground water recharge, and where ground water withdrawals affect water availability. Ultimately, we will gain the most robust understanding of how climate and landuse stressors will affect lake habitats and fish communities by using general models in conjunction with future mechanistic models in the super sentinel lakes. Model development will include verification and calibration with observations.

Along with climate change and land use, invasive plants and animals will be addressed as another key stressor impacting physical and chemical lake habitat properties. Including effects of invasive organisms in predictive models of physical and chemical lake parameters will involve obtaining data on invasive organisms and using it in the modeling process to improve predictive accuracy. When applicable, we plan to incorporate data from other Study 605 jobs that assess populations of invasive organisms in predictive models of physical and chemical lake parameters. Some key invasive organisms to assess in lake modeling could include common carp (*Cyprinus carpio*) and their impact increasing turbidity and nutrient levels (Parkos et al., 2003) and curly-leaf pondweed (*Potamogeton crispus*), which goes through a phase of rapid nutrient release in mid summer (Bolduan et al. 1994). Invasive invertebrate species are also known to directly impact physical and chemical lake parameters and could be factored into lake modeling efforts. For example, rusty crayfish (*Orconectes rusticus*) reduce plant cover in lakes and their presence is positively related to human use and connectivity of other lakes containing rusty crayfish (Puth and Allen 2004) and zebra mussels (*Dreissena polymorpha*) increase water clarity as a direct result of their filter feeding on phytoplankton (Idrisi et al. 2001). Zebra mussels do not presently occur in any sentinel lakes; however, it would be useful model the impacts of these and other potential invaders in likely future scenarios combined with climate change projections.

JOB 605.3: Evaluating potential zooplankton indicators

OBJECTIVE: 1. Identify patterns in zooplankton metrics relative to inherent lake characteristics and stressor gradients. 2. Quantify within lake temporal variation for each metric. 3. Identify patterns in metric variation relative to inherent lake characteristics and stressor gradients. 4. Quantify the minimum detectable difference for each metric and sampling effort needed to detect a range change for each metric, if necessary by lake type or stressor level. 5. Determine potential indicators based on 1-4.

STATUS: Despite the importance of zooplankton to food chains in north temperate lakes (see Rusack et al. 2002, Beisner et al. 2003, and Olden et al. 2006), few studies have examined the linkages of zooplankton populations to environmental conditions or to fish populations in inland lakes in Minnesota. Westerlund et al. (1998) were unable to link fish community structure with limnetic zooplankton abundance in Minnesota, yet their work provides a baseline for designing a long-term monitoring study and a first comparison for new results. Zooplankton abundance and species composition were found to have no

influence on recruitment of yellow perch or black crappie in four Minnesota lakes (Parsons et al. 2004), but large fluctuations in recruitment of all sportfish remain unexplained. Zooplankton variability among lakes is generally greater than variability within lakes (Rusack et al. 2002, Olden et al. 2006). This suggests zooplankton characteristics will respond to changes in lake conditions with a good signal-to-noise relationship during long-term monitoring. In addition, the short generation times of zooplankton allow a rapid response to perturbation. Zooplankton are thus sensitive to environmental conditions in ways that make them potentially valuable leading indicators for changes that will affect sportfish.

PROCEDURE: The DNR Division of Ecological Resources will be contributing to this project, but will not be using Federal funds or requesting reimbursement, thus the budget schedule on page one shows \$0 for Job 605.3. Ecological Resources has agreed to dedicate 400 hours (~\$4,000 / year) to the zooplankton portion of the Sentinel Lakes Study. Each of the 24 lakes will be sampled monthly from ice-out (April or May) through October (6 times). Zooplankton samples will be collected on the same dates that water quality samples are collected by the same personnel. A total of 288 samples will be collected and sent to the Ecological Resources laboratory. The processing of the 288 samples should be completed well within the hours that have been dedicated by Ecological Resources.

On each lake, two vertical tows will be taken with an 80 μm mesh Wisconsin zooplankton net, ideally at the deepest portion of the lake. The boat will be anchored to insure a vertical haul. The net will be lowered to within 0.5 meter of the bottom and hauled up at a rate of approximately 0.5 m/sec. Contents will be rinsed into sample bottles labeled with date, lake name, site location, and tow depth. Samples will be preserved with 100% reagent alcohol and shipped to the Ecological Resources Biology Laboratory for analysis.

Zooplankton samples will be adjusted to a known volume by filtering through 80 μm mesh netting and rinsing specimens into a graduated beaker. Water will be added to the beaker to a volume that provides at least 150 organisms per 5 ml aliquot. A 5 ml aliquot will be withdrawn from each sample using a bulb pipette and transferred to a counting wheel. Specimens from each aliquot will be counted, identified to the lowest taxonomic level possible, and measured to the nearest 0.01 mm using a dissecting microscope and an image analysis system. Densities and estimated biomass will be calculated with the aid of the zooplankton analysis system ZCOUNT (Charpentier and Jamnick 1994).

Potential indicators will include, but not be limited to, the following:

- Relative density or biomass of major groups: cladocerans vs. copepods. calanoids vs. cyclopoids, or calanoids vs. cladocerans (Gannon and Stemberger 1978).
- Total zooplankton abundance (Pace 1986, Attayde and Bozelli 1998).
- Total zooplankton biomass (Hanson and Peters 1984, Pace 1986, Gamble et al. 2006).
- Relative size of individual zooplanktors, especially large cladocerans (Pace 1986, Harig and Bain 1998).
- Relative abundance of large *Daphnia* (Harig and Bain 1998).
- Size structure and/or biomass of fish-edible zooplankton during mid to late summer when young of the year fish food is limited (Tessier and Woodruff 2002).

- Species diversity or functional group diversity (Hoffmann and Dodson 2005, Barnett and Beisner 2007).
- Presence of possible indicator species (Gannon and Stemberger 1978).

Evans and Sell (1983) found that spatial variance of zooplankton within Lake Michigan was greatest in the summer. With only two tows per sampling date, we will have very limited ability to quantify how much spatial variation there is within lakes. Nevertheless, after examination of seasonal variation and differences among lakes, this study should provide guidance about the adequacy of this number of tows.

Two key questions guide our sampling design and analyses. First, how much variation is there among zooplankton samples collected at different times of the year? Sampling effort throughout the open water season should be at a maximum, as zooplankton populations generally have short generation times, and rapid changes can occur in community composition, density and biomass throughout the season. In Lake Michigan, temporal differences (monthly sampling) were a greater source of variation in zooplankton communities than differences among years, subsamples, and replications (Evans and Sell 1983). Second, how much variation is there in a zooplankton community from year-to-year? It is important for this to be a multi-year study even though year-to-year variation is often low. Olden et al. (2006) suggest that single year studies may be adequate to document differences in zooplankton communities among lakes, especially if they differ greatly in their productivity; however, multi-year studies are needed to detect changes.

JOB 605.4: Evaluating potential aquatic vegetation indicators

OBJECTIVES:

1. Identify patterns in aquatic vegetation metrics relative to inherent lake characteristics and stressor gradients. 2. Quantify within lake temporal variation for each metric. 3. Identify patterns in metric variation relative to inherent lake characteristics and stressor gradients. 4. Quantify the minimum detectable difference for each metric and sampling effort needed to detect a range change for each metric, if necessary by lake type or stressor level. 5. Determine potential indicators based on 1-4.

PROCEDURE: Point intercept (Madsen 1999) and hydroacoustic surveys (Valley et al. 2005) will be conducted on each of the 24 sentinel lakes to estimate composition, percent coverage, and biovolume of submersed aquatic vegetation and to compute vegetation indicator metrics.

Point-intercept methodology

In lakes not infested with curly leaf pondweed (CLP), we will survey each of the sentinel lakes once annually during a window of peak vegetation biomass (typically July-August). In sentinel lakes infested with CLP, we will sample lakes twice annually (spring and summer). A point grid of regularly patterned GPS locations will be generated prior to the survey to designate the locations where plant species will be recorded. Point density will be set at 0.7 points per littoral acre based on species accumulation curves for nine previously sampled lakes (Figure 4). Estimated point density requirements were made using Monte Carlo resampling techniques. The analysis showed that 80% of all species sampled were detected at 0.7 points per littoral acre (Figure 4). We saw diminishing returns in numbers of species with greater levels of effort. Because our limited resources will not allow us to

intentionally oversample aquatic plants (e.g., > 2 pts per acre; Figure 4), we must assume that 0.7 points per littoral acre is sufficient to characterize aquatic plant communities in the sentinel lakes.

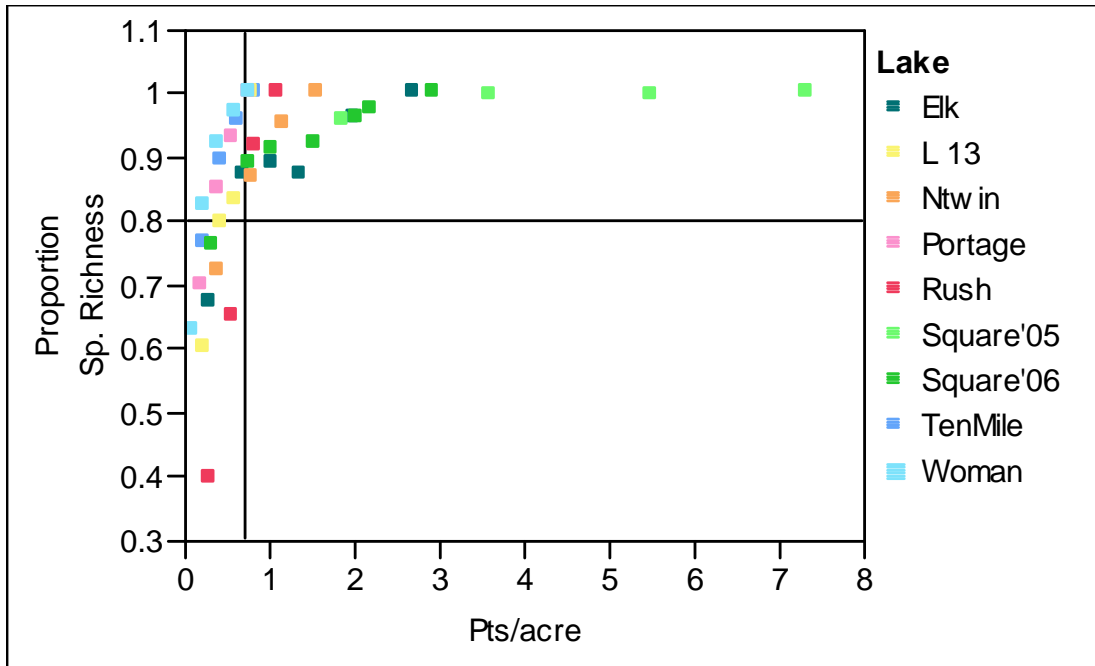


Figure 4. Proportion of species detected as points from nine lakes were systematically reduced.

Hydroacoustic methodology

We plan to survey all 24 lakes at least once during the four-year study and will select a subset of 4-6 sentinel lakes for annual sampling. For curly leaf lakes, spring and summer hydroacoustic surveys will be conducted in each lake during two of the four years, with half of the lakes surveyed each year. For hydroacoustic surveys, we will use methodologies described by Valley et al. (2005). Briefly summarized, we will use a BioSonics Inc. (Seattle, WA) DEX-6000 echosounder equipped with a 430 kHz 6° split-beam transducer mounted on a 16-foot flat-bottom boat. We will collect hydroacoustic vegetation data (pulse rate = 5 pings/s; pulse width = 0.1 ms) over transects perpendicular to the longest shoreline and spaced 40 - 100 m apart. Boat speed will be 1.5 – 2.5 m/s, separating differentially corrected GPS reports by 3 – 5 m. Each point in the GIS point coverage represents a 3 – 5 m cross-section of transect (i.e., the size of our sampling unit or our survey resolution), and will include 10 – 11 pings. The location for each point is calculated as the mid point between DGPS reports (i.e. 5 - 6 pings on either side of the calculated location). Average transect location error from previous fixed-transects experiments in Square Lake was 1.1 m (R.D. Valley unpublished data). The echosounder collects plant data in depths as shallow as 0.5 m. In most cases, we can collect hydroacoustic samples to within 10 m of the shore.

Large littoral areas where much vegetation grows to the surface (i.e., topped-out) can not be sampled with hydroacoustics, thus manual sampling procedures will be used on a 80-m sampling grid to gather vegetation data. At each such grid point, we will anchor each end of the boat and recorded latitude and longitude. Then, we will visually estimate biovolume

along the length of the boat, and measure water depth with a survey rod. Manually collected data can then be appended to the hydroacoustic data for analyses.

To analyze hydroacoustic data we will use BioSonic's EcoSAV[®] software (BioSonics Inc. 2002) that produces georeferenced point-estimates of depth, vegetation cover, height, and biovolume. As per methods described by Valley et al. (2005) we will use non-parametric regression smoothers and geostatistics to model and interpolate vegetation biovolume and map lake-wide estimates of vegetation abundance.

Point intercept surveys provide more accurate estimates of plant species richness and coverage than those estimated from data collected using MNDNR Fisheries' traditional transect method. Data from the point intercept surveys will be used to explore potential indicator metrics. We will analyze each indicator to estimate sample sizes needed to detect a 10%, 25%, and 50% change in the indicator. We will also analyze various indicators for strong correlation with lake productivity, which is a likely outcome of climate and landuse changes (Drake and Valley 2005). Some of the indicators we will evaluate may include, number of species having frequencies > 10%, number of species having frequencies > 40% (dominance), FQI (Nichols 1999), frequency of curly leaf pondweed in spring surveys, average number of species per point, % exotics (McKee et al. 2002), % turbidity-tolerant species, % intolerant species, % Chara (a structurally complex macroalgae species important for water clarity and fish habitat), % fine-leaf aquatic species (Cross and McInerney 2001, 2005), and maximum depth of plants. These indicators will be evaluated separately as well as combined into an index of plant integrity (Nichols et al. 2000; Drake and Pereira 2002). The best plant indicator will exhibit minimal interannual variability, vary predictably along a lake productivity gradient, and correlate with fish performance indicators.

Hydroacoustic estimates of vegetation biovolume can offer insight into multi-scale patterns of vegetation abundance. Valley and Drake (2007) documented strong patterns of variability across a gradient of lake productivity. In this paper, we documented relatively stable spatial patterns of vegetation biovolume in mesotrophic lakes and variable patterns in eutrophic lakes. These results are consistent with the conceptual framework of alternative lake regimes outlined by Scheffer and Carpenter (2003). Basically, as lakes become more productive, they become less resilient to disturbance, unstable, and more prone to a highly resilient regime shift that is characterized by frequent algae blooms. These alternative lake regimes have large consequences for Minnesota fish communities (Cross and McInerney 2001, Drake and Valley 2005). Spatial patterns of vegetation biovolume may be a useful indicator of the status of fish habitat in lakes. Furthermore, patterns of variability of this spatial pattern may lend insight into the resilience and stability of plant habitats (Valley and Drake 2007). Using power analysis, we plan to explore a variety of indicators derived from hydroacoustic surveys (e.g., avg. plant biovolume, patchiness metrics derived from geostatistical models). Also as outlined in Job 605.4, we will correlate these metrics with fish performance indicators to judge their relevance to fish populations and thus their usefulness.

JOB 605.5: Evaluating potential fish indicators

OBJECTIVE:

1. Identify patterns in fish metrics, including catch per effort (CPUE), length at age, and age at maturation of target species and fish-based IBI, relative to inherent lake characteristics and stressor gradients.
2. Quantify within lake temporal variation for each metric.
3. Identify patterns in metric variation relative to inherent lake characteristics and stressor gradients.
- 4.

Quantify the minimum detectable difference for each metric and sampling effort needed to detect a range change for each metric, if necessary by lake type or stressor level. 5. Determine potential indicators based on 1-4. 6. Determine bias in back-calculated lengths at age of target fishes sampled with standard gill nets. 7. Estimate size selectivity of target species in standard sampling gears.

PROCEDURE: The DNR Division of Ecological Resources will be contributing to this job, but will not be using Federal funds or requesting reimbursement, thus the detailed budget on page three shows \$0 for Nick Proulx for Job 605.5. Target species will be sampled using standard MNDNR Lake Survey protocols including annual ice-out trap netting, annual assessment trap netting, assessment gill netting (annual or otherwise depending on lake sampling plan), or annual shoreline electrofishing in each sentinel lake during 2008 through 2011 (MNDNR 1993). Total lengths and weights of all fishes will be measured, sex determined, and ageing structures will be removed from target species following MNDNR Lake Survey guidelines (MNDNR 1993), except for some gill net samples (see below).

Before estimating variation in CPUE, we will first examine net and electrofishing catches of target species in order to determine catch distribution patterns (i.e. negative binomial, normal, other; if location affects catch, etc.). Catch per effort data collected from this four-year project plus data from standard MNDNR lake surveys and assessments since the new lake survey program was implemented (1993) will be used for these analyses. We will use appropriate literature on size-selectivity (i.e., Pierce et al. 1994; Anderson 1998; McInerney and Cross 1996, 2006) as well as examine annual catch curves to determine which lengths appear fully recruited to the appropriate gear for each species within each sentinel lake. After distribution and selectivities are evaluated, we will use the appropriate statistical method to estimate variation of CPUE of each target species within each lake. Then, the appropriate power analysis procedure will be used to optimize sampling effort (numbers of aging structures; nets, sample sizes for length distributions, etc.) needed to detect biologically meaningful changes (that amount remains to be determined) in a population parameter at each lake. Understanding net catch distributions within each sentinel lake will also help determine which past (before 1993) surveys and assessments are directly comparable to recent surveys and assessments.

Ages will be estimated with the most appropriate aging structure determined from other studies, and biases of back-calculated lengths at age from Rosa Lee phenomenon and the fixed-sampling protocol used to sample aging structures will be evaluated. Ages will be estimated either by Area staff or individuals selected to age all individuals of a particular target species. We will use length at age at the time of capture as an indicator of growth of target species sampled annually or every other year. However, we will use back-calculated lengths at age as an indicator of growth for northern pike, yellow perch, and walleye in lakes gillnetted less frequently than every other year. We will use the Fraser-Lee method to estimate back-calculated lengths at age. Either standard intercepts (when ages are estimated with scales) or intercepts developed from fish length to structure length regressions will be used. We will test for Rosa Lee phenomenon by comparing lengths at age data of the same year-classes of target species sampled with gill nets one or two years apart. Rosa Lee phenomenon is likely occurring if length at age estimates calculated from the earlier samples exceeds the lengths at age estimates of the same year class collected during the later sample that appear fully recruited to the gear. In those lakes not sampled annually or biannually with gill nets, aging structures of northern pike, walleye, and yellow perch will be collected in proportion to the gill net catch (P-sample) rather than from the standard fixed-sampling scheme (5 individuals per 1-cm length group for individuals less than 300 mm TL, 5 individuals per 2.5-cm length group for individuals 300 mm and longer;

F-sample) normally used (MNDNR 1993). We will calculate means plus measures of precision (standard errors or 95% confidence limits) of back-calculated lengths at age for each P-sample, and we will calculate means plus the same measures of precision from an F-sample drawn from the P-sample. The procedure providing the better precision (lower 95% confidence limits or standard errors) will be the one recommended for use in the long term monitoring program.

Because the proportion of large northern pike in the population may serve as a valuable fish indicator but is highly vulnerable to lethal sampling, we will examine catches of northern pike captured with non-lethal ice-out trap netting. We will determine the best sampling times and optimal effort for sampling large northern pike for each sentinel lake. Maximum and mean lengths at capture of northern pike will be calculated for each day of sampling. Surface water temperature will be measured each day, and weather and ice conditions will also be documented.

When opportunities arise, we will evaluate for variability in CPUE, species-selectivity, or size-selectivity in other sampling gears (e.g., short-term monofilament gill nets, shoreline electrofishing other than spring or fall, fall gill netting for cisco; small mesh trap netting) that could be used instead of standard gill netting or in addition to standard sampling.

Community indicators: In addition to population indicators, we will explore patterns in fish communities. For example, using historical and recent data for the sentinel lakes we will evaluate the relative biomass of different species groups, such as Coregonids/Salmonids, Percids/Esocids, Centrarchids, and Ictalurids, as a function of inherent lake characteristics and stressor gradients. Research at the University of Minnesota (Lead: Ray Newman) is evaluating similar questions with the MNDNR database for all Minnesota lakes, and we will coordinate this analysis with his lab.

We will use the index of biotic integrity developed for Minnesota lakes (Drake and Pereira 2002; Drake and Valley 2005) to calculate IBIs for all sentinel lakes except those in the BLH ecoregion. Annual variation in IBIs will be estimated and used to determine the minimum detectable change in IBI. Patterns in IBI and IBI variation will be evaluated relative to inherent lake characteristics and stressor gradients. Because most lakes in this study are larger than the lakes used to develop the lake IBI, we will need to determine if adjustments to IBI metric scoring criteria are needed. We expect fish IBI scores to decline with increasing lake productivity and this decline should be accompanied by a decline in intolerant species and an increase in tolerant species (Drake and Valley 2005). This trend is evident in minnow species from a large sample of Minnesota lakes compiled from MNDNR data (Figure 5). The lakes in BLH are in the softwater Canadian shield and have species communities that are naturally quite different from the alkaline glacial outwash lakes found in the NLF and CHF used to develop the IBI. Nevertheless, we will still sample the nearshore fish community in the BLH using lake IBI protocol, but rather than calculate IBIs we will explore patterns in catches of potential indicator species based on their tolerance to environmental disturbances. If the lake IBI protocol is not feasible in some lakes (i.e., shorelines are not seinable) other gears such as small mesh trap nets and boat electrofishing will be evaluated for sampling small fishes.

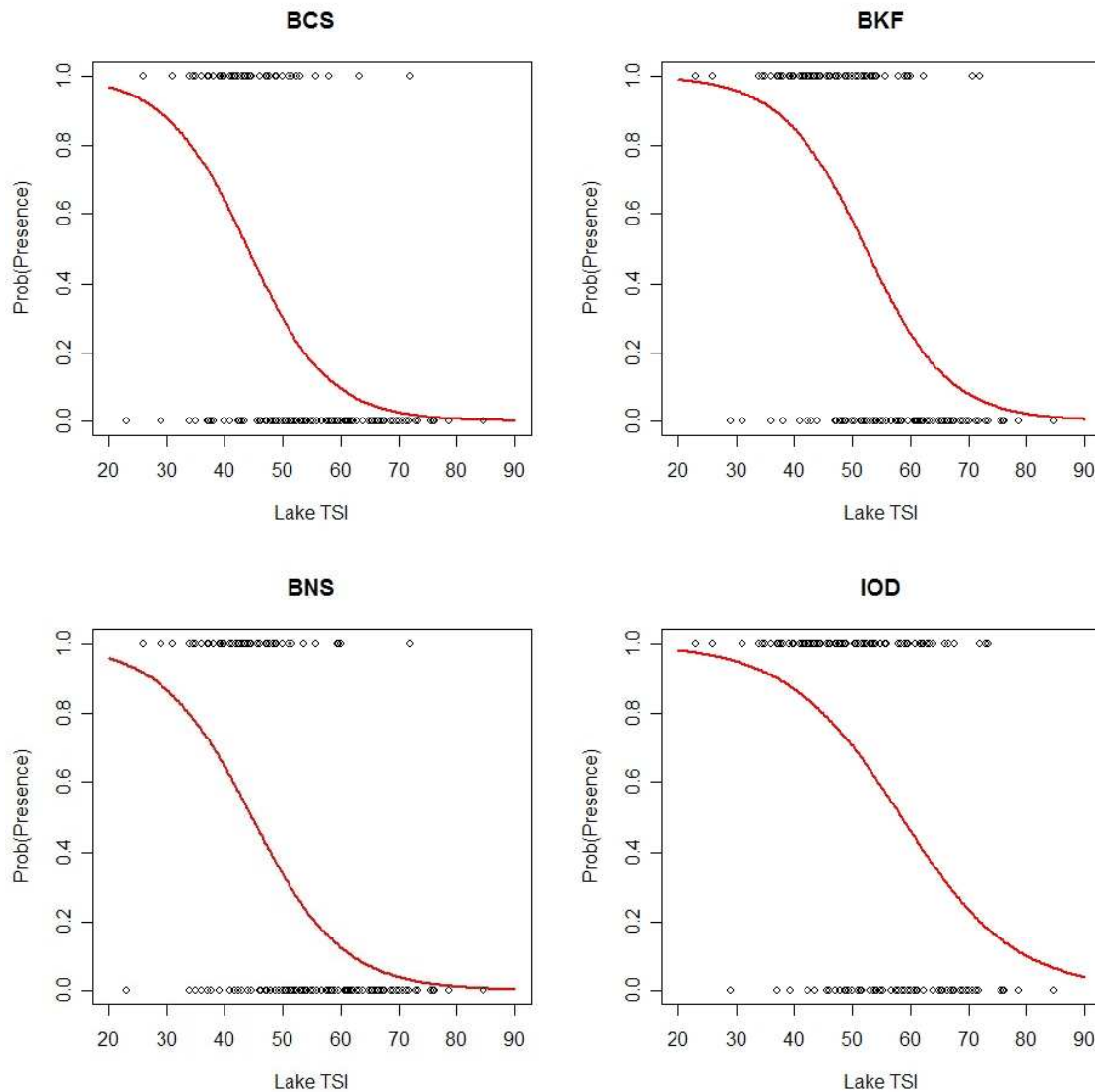


Figure 5. Logistic regressions of probability of occurrence versus lake trophic state index (TSI) for blackchin shiner (BCS), banded killfish (BKF), blacknose shiner (BNS), Iowa darter (IOD), least darter (LED), and pugnose shiner (PGS) from Minnesota lakes.

JOB 605.6. Develop a holistic metric of lake status.

OBJECTIVE: Develop a status metric applicable to lakes across Minnesota to summarize monitoring data into a comprehensive measure of the condition of lake habitats and fish communities relative to management goals. Use historical data in addition to modeling and data collection in this study to determine data necessary for calculating the status metric, as well as the sampling effort required for detecting important changes.

PROCEDURE: The overall goal of lake monitoring is to develop a framework to periodically evaluate lake status for the purpose of detecting adverse conditions in Minnesota lake ecosystems. This requires defining some metric of lake status, as well as how the status metric is calculated with monitoring data. Such a status metric should be applicable across

a wide range of spatial scales from statewide down to the individual lake level. Given the diversity of Minnesota lakes, the status metric should also be adaptable to lakes with varying fisheries potential and management goals.

We will use a hierarchical framework to summarize lake status, a heuristic example of which is given in Figure 6. At the highest level is an 'overall status metric' (OSM), which is flexible enough to be applied to lakes across Minnesota. For this example, the OSM is a dichotomous variable: Is the lake meeting management goals? This OSM relates directly to an individual lake, and the proportion of lakes meeting management goals can be used to describe the status of a given group of lakes. By relating lake status to management goals, the OSM inherently incorporates differences in environmental conditions and consequent management expectations for lakes across Minnesota.

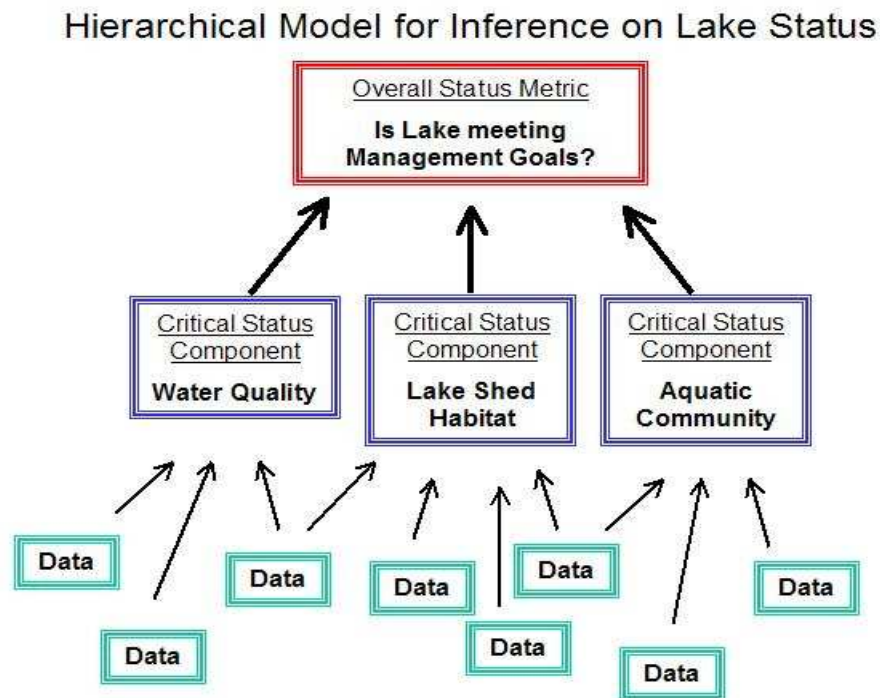


Figure 6. Conceptual model of measuring overall lake status with monitoring data.

The OSM will be calculated from a number of 'critical status components' (CSC) from the second level. For the example in Fig. 6, there are three CSC's: Water Quality, Lake Shed Habitat, and Aquatic Community. One simple way to calculate the OSM would be to determine if all three CSC's were in acceptable ranges for a given lake. The CSC's may be comprised of several metrics themselves; for example, there would have to have been acceptable measurements of chlorophyll-a, temperature, and dissolved oxygen for the Water Quality CSC to be acceptable. The CSC's could also represent different aspects of lake monitoring: in this example, the water quality component may be a short-term, immediate action component. In contrast, the lake shed habitat component may represent a longer-term outlook for lake status, while the aquatic community component could be geared toward evaluating management effectiveness for specific fish species.

We will consult with MN DNR fishery managers and research biologists to help develop a useful OSM and determine what CSC's are integral to its calculation. We will use historical data in addition to the sentinel lake data collection and model development in this study to evaluate the data and sampling intensity that are necessary to calculate critical status

components and the overall status metric. We will further explore the development of cursory lake status measurements that are reasonable to acquire for a larger sample of lakes for increased spatial inference on the status of Minnesota lakes.

The exact nature of the OSM is uncertain, we will explore the use of a dichotomous measure as in the above example in addition to categorical and continuous measures of lake status. For example, we could use an estimate of the probability that a lake will meet management goals for the next 10 years as the OSM, with the CSC's used as model inputs for calculating the OSM. This may be an effective strategy to accommodate the inter-relatedness of the critical status components (e.g., aquatic community may be affected by water quality which itself is a function of lake shed habitat). Such a model-based OSM would utilize current understanding about the lake system and current data to project future status of the lake. It would allow sensitivity and simulation analyses for the effect of specific changes in lake factors, and naturally lead to a truly 'adaptive management' framework via cycles of model predictions, evaluation, and refinement.

REFERENCES

- Anderson, C. S. 1998. Partitioning total size selectivity of gill nets for walleye (*Stizostedion vitreum*) into encounter, contact, and retention components. *Canadian Journal of Fisheries and Aquatic Sciences* 55:1854-1863.
- Attayde, J.L. and R.L. Bozelli. 1998. Assessing the indicator properties of zooplankton assemblages to disturbance gradients by canonical correspondence analysis. *Canadian Journal of Fisheries and Aquatic Sciences* 55:1789-1797.
- Beisner, B. E., C. L. Dent, and S. R. Carpenter. 2003. Variability of lakes on the landscape: roles of phosphorus, food webs, and dissolved organic carbon. *Ecology* 84:1563-1575.
- BioSonics Inc., 2002. *EcoSAV*[®] submersed aquatic vegetation detection and analysis. Seattle.
- Birr, A. S. and D. J. Mulla. 2001. Evaluation of the phosphorus index in watersheds at the regional scale. *Journal of Environmental Quality* 30:2018-2025.
- Bolduan, B. R., G. C. Van Eechhout, H. W. Quade, and J. E. Gannon. 1994. Potamogeton crispus – the other invader. *Lake and Reservoir Management* 10:113-125.
- Casselman, J. M. 2002. Effects of temperature, global extremes, and climate change on year-class production of warmwater, coolwater, and coldwater fishes in the Great Lakes basin. Pages 39-60. in N.A. McGinn, editor. *Fisheries in a changing climate*. American Fisheries Society Symposium 32. Bethesda.
- Charpentier, F. and B. H. Jamnick. 1994. ZCOUNT-A zoological counting program. Version 2.4 Voila Data Inc., Gloucester, Ontario.
- Christensen, D. L., B. J. Herwig, D. E. Schindler, and S. R. Carpenter. 1996. Impacts of lakeshore residential development on coarse woody debris in north temperate lakes. *Ecological Applications* 6:1143-1149.
- Cross, T. K., and M. McInerney 1995. Influences of Watershed Parameters on Fish Populations in Selected Minnesota Lakes of the Central Hardwood Forest Ecoregion. Minnesota Dept. of Natural Resources Division Fisheries Investigational Report No. 441, St. Paul.
- Cross, T. K., and M. C. McInerney. 2001. Spatial habitat influences on inshore fish communities in a selected Minnesota ecological lake class. Minnesota Department of Natural Resources, Section of Fisheries Investigational Report 494, St. Paul.
- Cross, T. K., and M. C. McInerney. 2005. Spatial habitat dynamics affecting bluegill abundance in Minnesota bass-panfish lakes. *North American Journal of Fisheries Management* 25:1051-1066.

- Danz, N. P., G. J. Niemi, R. R. Regal, T. Hollenhorst, L. B. Johnson, J. M. Hanowski, R. P. Axler, V. J. Brady, G. E. Host, J. J. H. Ciborowski, T. Hrabik, J. R. Kelly, J. A. Morrice, J. C. Brazner, R. W. Howe, and C. A. Johnston. 2006. Integrated measures of anthropogenic stress in the U.S. Great Lakes basin. *Environmental Management* 39:631-647.
- Department of Fisheries and Oceans Canada (DFO) 1998. A decision framework for the determination and authorization of harmful alteration, disruption or destruction (HADD) of fish habitat. http://www.dfo-mpo.gc.ca/canwaters-eauxcan/infocentre/guidelines-conseils/guides/hadd/index_e.asp
- DeStasio, B.T. Jr., D.K. Hill, J.M. Kleinhans, N.P. Nibbelink, and J.J. Magnuson. 1996. Potential effects of global climate change on small north-temperate lakes: physics, fish, and plankton. *Limnology and Oceanography* 41: 1136-1149.
- Drake, M. T., and D. L. Pereira. 2002. Development of a fish-based index of biotic integrity for small central Minnesota lakes. *North American Journal of Fisheries Management* 22:1105-1123.
- Drake, M. T, and R. D. Valley. 2005. Validation and application of a fish-based index of biotic integrity for small central Minnesota lakes. *North American Journal of Fisheries Management* 25:1095-1111.
- Egertson, C. J., and J. A. Downing. 2004. Relationship of fish catch and composition to water quality in a suite of agriculturally eutrophic lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 61:1784-1796.
- Egertson, C. J., J. A. Kopaska, and J. A. Downing. 2004. A century of change in macrophyte abundance and composition in response to agricultural eutrophication. *Hydrobiologia* 524:145-156.
- Engle, S., and J. L. Pederson, Jr. 1998. The construction, aesthetics, and effects of lakeshore development: A literature review. Wisconsin Department of Natural Resources Research Report 177.
- Evans, M. S. and D. W. Sell. 1983. Zooplankton sampling strategies for environmental studies. *Hydrobiologia* 99:215-223.
- Gamble, A. E., R. Lloyd, J. Aiken, O. E. Johannsson, and E. L. Mills. 2006. Using zooplankton biomass size spectra to assess ecological change in a well-studied freshwater lake ecosystem: Oneida Lake, New York. *Canadian Journal of Fisheries and Aquatic Sciences* 63:2687-2699.
- Gannon, J. E. and R. S. Stemberger. 1978. Zooplankton (especially crustaceans and rotifer) as indicators of water quality. *Transactions of the American Microscopical Society* 97:16-35.
- Gucciardo, S., B. Route, and J. Elias. 2004. Conceptual models for long-term ecological monitoring in the Great Lakes Network. GLKN/2004/04, National Park Service, Ashland.
- Hanson, J. M. and R. H. Peters. 1984. Empirical prediction of crustacean zooplankton biomass and profundal macrobenthos biomass in lakes. 1984. *Canadian Journal of Fisheries and Aquatic Sciences* 41: 439-445.
- Harig, A. L. and M. B. Bain. 1998. Defining and restoring biological integrity in wilderness lakes. *Ecological Applications* 8: 71-87.
- Heiskary, S. A., and E. B. Swain. 2002. Water quality reconstruction from fossil diatoms: applications for trend assessment, model verification, and development of nutrient criteria for lakes in Minnesota, USA. Minnesota Pollution Control Agency, St. Paul.
- Heiskary, S., and M. Lindon. 2005. Interrelationships among water quality, lake morphometry, rooted plants and related factors for selected shallow lakes of west-central Minnesota. Minnesota Pollution Control Agency, St. Paul.
- Heiskary, S. A., and C. B. Wilson. 2005. Minnesota lake water quality assessment report: Developing nutrient criteria. Minnesota Pollution Control Agency, St. Paul.

- Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., and Jarvis, A. 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25:1965-1978.
- Hoffman, M. D. and S. I. Dodson. 2005. Land use, primary productivity, and lake area as descriptors of zooplankton diversity. *Ecology* 86: 255-261.
- Idrisi, N., E. L. Mills, L. G. Rudstam, and D. J. Stewart. 2001. Impact of zebra mussels (*Dreissena polymorpha*) on the pelagic lower trophic levels of Oneida Lake, New York. *Canadian Journal of Fisheries and Aquatic Sciences* 58:1430-1441.
- Intergovernmental Panel of Climate Change (IPCC). 2007. Climate change 2007: synthesis report. Valencia, Spain.
- Jassby, A. D. 1998. Interannual variability at three inland water sites: implications for sentinel ecosystems. *Ecological Applications* 8:277-287.
- Jennings, M., M. Bozek, G. Hatzenbeler, and D. Fago. 1996. Fish and Habitat in Duyfhuizen, T. editor, Shoreland Protection Study: A report to the Wisconsin State Legislature. Wisconsin Department of Natural Resources PUBL – RS-921-96.
- Jennings, M. J., M. A. Boser, G. R. Hatzenbeler, E. E. Emmons, and M. D. Staggs. 1999. Cumulative effects of incremental shoreline habitat modification on fish assemblages in north temperate lakes. *North American Journal of Fisheries Management* 19:18-27
- Jennings, M. J., and E. E. Emmons. 2001. Are we there yet? Effects of development on lakes. *Lakeline* 21:20-22.
- Madsen, J. D. 1999. Point intercept and line intercept methods for aquatic plant management. Army Corps of Engineers Waterways Experiment Station, Aquatic Plant Technical Note MI-02. Vicksburg.
- Magnuson, J. J., T. K. Kratz, and B. J. Benson 2006. Long-term dynamics of lakes in the landscape. Oxford University Press, New York.
- McInerney, M. C., and T. K. Cross. 1996. Seasonal and diel variation in electrofishing size-selectivity and catch per hour of largemouth bass in Minnesota lakes. Minnesota Department of Natural Resources Section of Fisheries Investigational Report 451, St. Paul.
- McInerney, M. C., and T. K. Cross. 2006. Factors affecting trap net catchability of black crappies in natural Minnesota lakes. *North American Journal of Fisheries Management* 26:652-664.
- McKee, D., and six other co-authors. 2002. Effects of simulated climate warming on macrophytes in freshwater microcosm communities. *Aquatic Botany* 74: 71-83.
- Minnesota Department of Natural Resources (MNDNR). 1993. Manual of instructions for lake survey. Minnesota Department of Natural Resources, Section of Fisheries Special Publication 147, St. Paul.
- Minns, C. K. 1997. Quantifying “no net loss” of productivity of fish habitats. *Canadian Journal of Fisheries and Aquatic Sciences* 54:2463-2473.
- Nichols, S. 1999. Floristic quality assessment of Wisconsin lake plant communities with example applications. *Journal of Lake and Reservoir Management* 15(2):133-141.
- Nichols, S., S. Weber, and B. Shaw. 2000. A proposed aquatic plant community biotic index for Wisconsin lakes. *Environmental Management* 26:491-502.
- Niemeijer, D., and R. S. de Groot. 2008. A conceptual framework for selecting environmental indicator sets. *Ecological Indicators* 8:14-25.
- Olden, J. D., O. P. Jensen, and M. J. Vander Zanden. 2006. Long-term dynamics of fish and zooplankton communities for among lake comparisons. *Canadian Journal of Fisheries and Aquatic Sciences* 63: 1812-1821.

- Omernik, J. M. 1987. Ecoregions of the conterminous United States (map supplement): *Annals of the Association of American Geographers* 77:118-125.
- Pace, M. L. 1986. An empirical analysis of zooplankton community size structure across lake trophic gradients. *Limnology and Oceanography* 31: 45-55.
- Parkos, J. J. III, V. J. Santucci, Jr., and D. H. Wahl. 2003. Effects of adult common carp (*Cyprinus carpio*) on multiple trophic levels in shallow ecosystems. *Canadian Journal of Fisheries and Aquatic Sciences* 60:182-192.
- Parsons, B. G., J. R. Reed, H. K. Fullhart, V. A. Snook, and J. K. Hirsch. 2004. Factors affecting black crappie recruitment in four west-central Minnesota lakes. Minnesota Department of Natural Resources, Section of Fisheries Investigational Report 514, St. Paul.
- Pierce, R. B., C. M. Tomcko, and T. D. Kolander. 1994. Indirect and direct estimates of gill-net size selectivity for northern pike. *North American Journal of Fisheries Management* 14:170-177.
- Pimentel, D., L. Lach, R. Zunigam, and D. Morrison. 2000. Environmental and economic costs of nonindigenous species in the United States. *Bioscience* 50: 53-65.
- Pratt, T. C., and K. E. Smokorowski. 2003. Fish habitat management implication of the summer habitat use by littoral fishes in a north temperate , mesotrophic lake. *Canadian Journal of Fisheries and Aquatic Sciences* 60:286-300.
- Puth, L.M., and T.F.H. Allen. 2005. Potential corridors for the rusty crayfish, *Orconectes rusticus*, in northern Wisconsin lakes: lessons for exotic invasions. *Landscape Ecology* 20:567-577.
- Radomski, P., and T.J. Goeman. 2001. Consequences of human lakeshore development on emergent and floating-leaf vegetation abundance. *North American Journal of Fisheries Management*.
- Radomski, P. 2006. Historical Changes in Abundance of Floating-Leaf and Emergent Vegetation in Minnesota Lakes. *North American Journal of Fisheries Management* 26:932-940.
- Reed, J. R., and D. L. Pereira. In press. Relationships between shoreline development and nest-site selection by black crappie and largemouth bass. *North American Journal of Fisheries Management*.
- Rose, K.A. 2000. Why are quantitative relationships between environmental quality and fish populations so elusive? *Ecological Applications* 10:367-385.
- Rusack, J. A., N. D. Yan, K. M. Somers, K. L. Cottingham, F. Micheli, S. R. Carpenter, T. M.Frost, M. J. Paterson, and D. J.McQueen. 2002. Temporal, spatial, and taxonomic patterns of crustacean zooplankton variability in unmanipulated north-temperate lakes. *Limnology and Oceanography* 47: 613-625.
- Scheffer, M., and S. R. Carpenter. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends in Ecology and Evolution* 18:648-656.
- Schussler, J., L. A. Baker, and H. Chester-Jones. 2007. Whole-system phosphorus balances as a practical tool for lake management. *Ecological Engineering* 29:294-304.
- Schupp, D. H. 1992. An ecological classification of Minnesota lakes with associated fish communities. Investigational Report 417, Department of Natural Resources, St. Paul.
- Shuter, B. J., C. K. Minns, N. Lester. 2002. Climate change, freshwater fish, and fisheries: case studies from Ontario and their use in assessing potential impacts. Pages 77-88 in N.A. McGinn, editor. *Fisheries in a changing climate*. American Fisheries Society Symposium 32. Bethesda.
- Stefan, H. G., M. Hondzo, X. Fang, J. G. Eaton, and J. H. McCormick. 1996. Simulated long-term temperature and dissolved oxygen characteristics of lakes in the north-central United States and associated fish habitat limits. *Limnology and Oceanography* 41: 1124-1135.

- Tessier, A. J. and P. Woodruff. 2002. Cryptic trophic cascade along a gradient of lake size. *Ecology* 83: 1263-1270.
- Tilman, D., R. M. May, C. L. Lehman, and M. A. Nowak. 1994. Habitat destruction and the extinction debt. *Nature* 371:65-66.
- Valley, R. D., M. T. Drake, and C. S. Anderson. 2005. Evaluation of alternative interpolation techniques for the mapping of remotely-sensed submersed vegetation abundance. *Aquatic Botany* 81:13-25.
- Valley, R. D., and M. T. Drake. 2007. What does resilience of a clear-water state in lakes mean for the spatial heterogeneity of submersed macrophyte biovolume? *Aquatic Botany* 87:307-319.
- Westerlund, J. E., P. C. Jacobson, H. K. VanOffelen, and J. K. Hirsch. 1998. Use of limnetic zooplankton sampling in assessments of fish community structure in Minnesota bass-panfish lakes. Minnesota Department of Natural Resources, Section of Fisheries Investigational Report 467, St. Paul.
- Wolter, P. T., C. A. Johnston, and G. J. Niemi. 2006. Land use land cover change in the U.S. Great Lakes basin 1992 to 2001. *Journal of Great Lakes Research* 32:607-628.
- Yuan, F., K. E. Sawaya, B. C. Loeffelholz, and M. E. Bauer 2005. Land cover classification and change analysis of the Twin Cities (Minnesota) Metropolitan Area by multitemporal Landsat remote sensing. *Remote Sensing and the Environment* 98:317-328.