Environment and Natural Resources Trust Fund

Research Addendum for Peer Review

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Project Title: Assessing the consequences of ecological drivers of change on water quality and habitat dynamics of deep-water lakes with coldwater fish populations.

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Abstract

Water quality, habitat, and fish in Minnesota lakes are or will be facing substantial levels of stress primarily due to two very large drivers of change: land use changes (both urban and agricultural) and climate change. Incorporating several aspects of the recently completed Statewide Conservation and Preservation Plan recommendations and complementing efforts of ongoing LCCMR-funded work (e.g., NRRI climate change project), we propose a 3-yr cooperative study in several sentinel lake watersheds throughout the state that will help us understand, predict, and monitor the consequences of climate change and land cover alterations on lake habitats. Multiple national, state, and local government and academic partners are currently enrolled in a fledgling, large-scale effort called Sustaining Lakes in a Changing Environment (SLICE) that includes a focus on monitoring basic watershed, water quality, habitat, and fish indicators in 24 sentinel lakes across a gradient of ecoregions, depths, and nutrient levels. SLICE represents a promising new direction towards lake assessment and monitoring; an approach that national leaders in water resource science are currently advocating. LCCMR support represents solid, initial funding for a long-term investment in SLICE and will help us better understand dynamics of lakes with coldwater fish populations and identify threats to these unique resources. Here we outline our overall approach to SLICE, how this LCCMR project fits within this framework, and specific activities for which we are requesting LCCMR funding.

Background

The case for SLICE

Sustaining Lakes in a Changing Environment (SLICE) will require a comprehensive approach that addresses all drivers that together are changing the condition of our lake resources. We must identify and mitigate the consequences of stressors we have some control over (e.g., development and agricultural policies, prevention of the introduction of non-native species), and adapt to those we don't (climate change, establishment of non-native species populations after introduction). Below we articulate major drivers of ecological change, how they are affecting lake habitats and fish populations, and what we feel is the most prudent response as professionals charged with sustaining aquatic resources for future generations.

Cumulative effects of land alterations - 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 parts of a lake, the shore, littoral habitat, water, etc. because of the importance of how all the parts interact. In Canada, laws prohibit "harmful alteration, disruption, or destruction" of fish habitat and follow 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; Smokorowski and Pratt 2007).

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 McInerny (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 how black crappie and largemouth bass select 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.

Climate change - Climate change has the potential to exacerbate the cumulative impacts of human activities (Schindler et al. 2001). 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 CO_2 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.

Invasive species - 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 (Hooper et al. 2005). 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 both 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 are inevitable and in situations where habitat suitability for native species has been permanently altered, will actually be necessary to provide basic ecosystem services and functions (e.g., primary and secondary production; Hooper et al. 2005).

Sentinel sites and the "split-panel" design for assessment and monitoring

In recent years, water resource scientists have been making the case for focused assessments and monitoring of "sentinel" systems (Jassby 1998, Carpenter et al. 2007, Magner and Brooks 2007, Williamson et al. 2008). Lakes and their contributing watersheds are highly complex. Mechanistic understanding of the basic physiology of lakes and how stressors affect watershed and lake processes and communities can only occur by taking a large-scale and long-term, adaptive approach towards water resource and fisheries questions (Magnuson et al. 2006). Despite the importance of intensive monitoring a few representative systems to understand cause-effect mechanisms, there is still a great need to assess the spatial extent of change to water resources and fisheries by periodic sampling of many systems. The split-panel design of environmental monitoring represents a powerful combination of both approaches (McDonald 2003, Figure 1) and is a break from Minnesota natural resource agencies' traditional focus on judging status by solely relying on infrequent snapshots in many systems. Efforts in the sentinel lakes during the first phase of SLICE (2008 – 2011) will inform the implementation of a split-panel design for DNR Fisheries' long-running Lake Survey Program during the second phase. In other words, lessons learned in the sentinel lakes during the project period about how various environmental indicators behave naturally from year-to-year and how they covary will inform final monitoring recommendations and schedules.

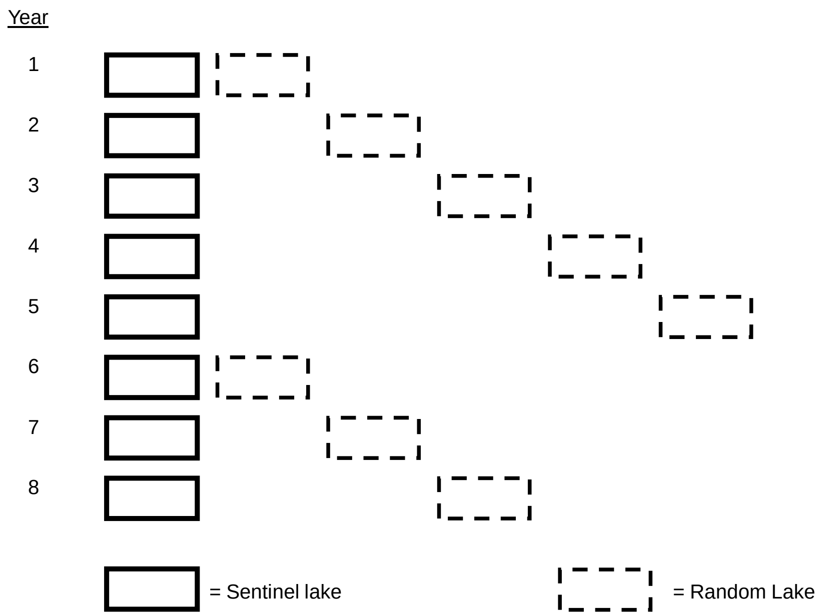

Figure 1. Split-panel design of SLICE. Sentinel lakes will be targets of intensive long-term monitoring of stressors and indicators gaining information on cause-effect mechanisms of high temporal resolution. Coupling sentinel lakes monitoring with less intensive monitoring of a few key indicators across a wider range of lake types will provide information about the status of water resources across wider geographic regions than can be inferred from the sentinel lakes.

Sentinel lake selection - 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 (NLF), Northern Central Hardwoods (NCHF), and Western Corn Belt Plains (WCBP). 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 Northern Glaciated Plain 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 $\geq$ 4.5 were classified as likely thermally mixed (unstratified) throughout the open water season and lakes with geometry ratios $\leq$ 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 to ecoregion-specific 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 three lakes from each mixing class (stratified or unstratfied) 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. Sentinel lakes.

Lake	DOW	Acres	Max depth (ft)	P-level	Stratification	Cold Water*
Bearhead	69025400	674	46	med	stratified	No
Elephant	69081000	724	30	high	stratified	No
Echo	69075700	1139	10	high	mixed	No
Tait	16038400	338	15	low	mixed	No
Trout	16004900	257	77	low	stratified	Yes
White Iron	69000400	3238	47	med	mixed	Yes
Belle	47004900	856	25	med	mixed	No
Carlos	21005700	2598	163	med	stratified	Yes
Cedar	49014000	243	88	low	stratified	Yes
Pearl	73003700	746	17	low	mixed	No
Peltier	2000400	465	18	high	mixed	No
South Center	13002700	898	109	high	stratified	No
Elk	15001000	305	93	med	stratified	Yes
Hill	1014200	907	48	high	stratified	No
Portage	29025000	412	17	high	mixed	No
Red Sand	18038600	516	23	med	mixed	No
South Twin	44001400	1000	29	low	mixed	Yes
Ten Mile	11041300	4669	208	low	stratified	Yes
Artichoke	6000200	1964	16	high	mixed	No
Carrie	34003200	81	26	low	stratified	No
Madison	7004400	1439	59	high	stratified	No
Shaokotan	41008900	994	10	med	mixed	No
St James	83004300	221	16	low	mixed	No
St Olaf	81000300	99	33	med	stratified	No

*Lakes are classified as “Cold Water” if they support cold water fish populations such as cisco, or lake trout.

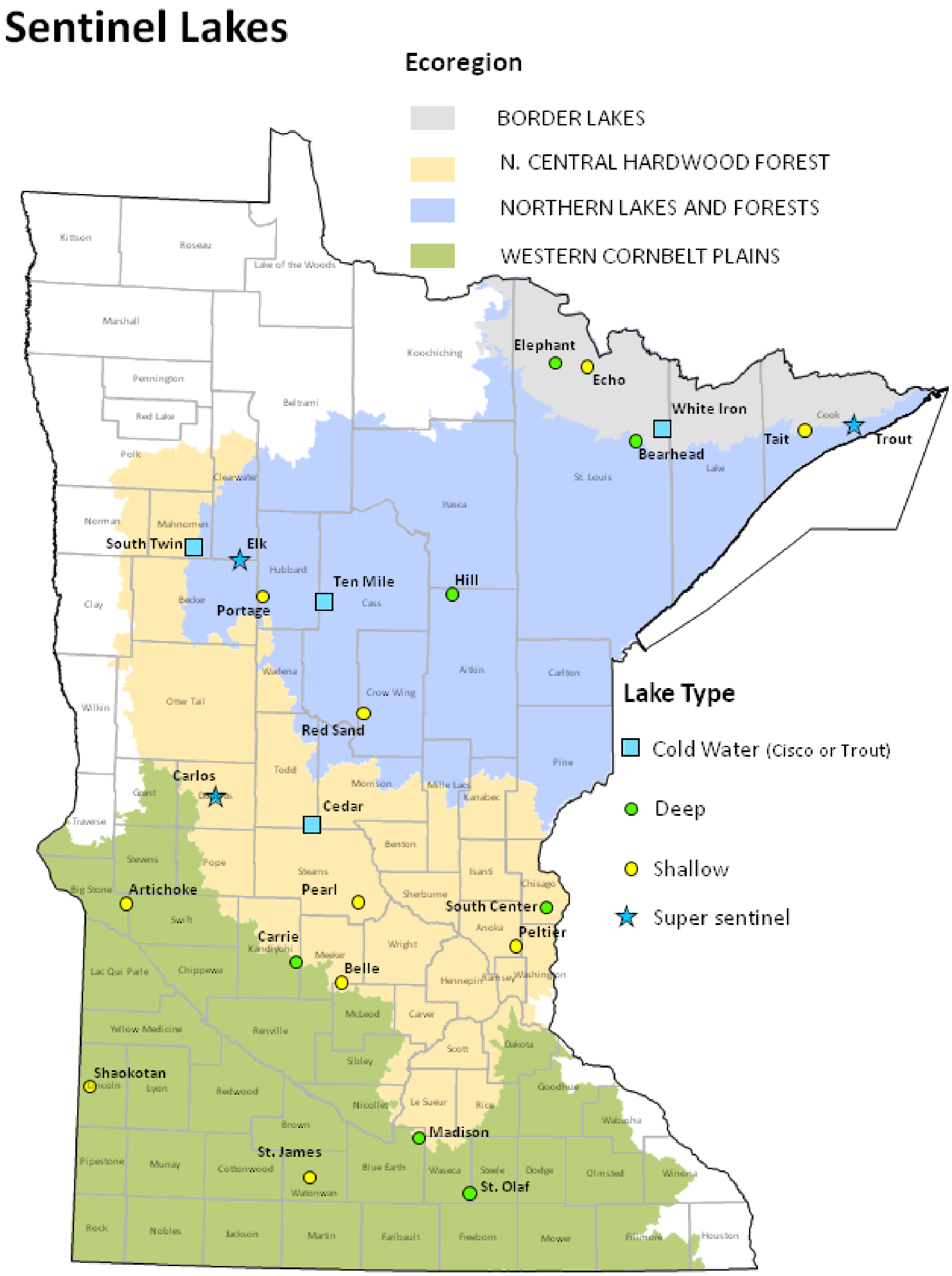

Figure 2. Major ecoregions and sentinel lakes. The coldwater sentinel lakes will be the focal point for most work detailed in this LCCMR proposal.

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.

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. NRRI's phase I and II climate change LCCMR study that is nearing completion will provide guidance on which indicators may be most sensitive to climate stressors, yet robust to interannual variability.

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	Slow, cumulative	Rapid

	patchiness		
	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
	Fish species/community traits[b]	Slow, cumulative	Slow
	Status of indicator species[c] ▪ Growth ▪ Age at maturation ▪ Size structure ▪ Mortality	Varied, cumulative	Slow

[a]Temperature is an indicator that will be most affected by climate change.
[b]Specific traits to be evaluated will be determined in part from the outcomes of NRRI's soon to be completed climate change indicator research project
[c]Indicator species include, cisco, walleye, northern pike, largemouth bass, smallmouth bass, white sucker, black crappie, bluegill, rock bass, pumpkinseed, and yellow perch

SLICE program goals

Strategically addressing the challenges posed by the myriad of stressors on MN lake resources requires working towards concrete objectives nested within short-term goals nested within long-term goals. Over the long-term, the goals of SLICE are to:

1) Monitor relevant landcover, climate, and other environmental stressors.
2) Monitor the effect of stressors on lake habitats and biotic communities.
3) Forecast changes to lake habitats and biotic communities given possible changes in stressor levels.
4) Use results to inform and evaluate appropriate adaptation policies.

Progress towards these long-term goals will require integrated efforts among multiple partners and probably multiple funding mechanisms (Environmental Trust Fund, Game and Fish Fund, Clean Water Legacy, Lessard Outdoor Heritage, Federal grants and matching dollars, etc.). In the short-term, during the first phase of SLICE (2008-2012), we've identified six immediate goals that we will be pursuing through a combination of LCCMR funds, Game and Fish funds, and other in-kind resources from our partners:

1. Evaluate historic and recent changes to habitat and biotic communities in a set of sentinel lakes representative of Minnesota.
2. At the most appropriate biological scale, identify key proxies that indicate changes in nutrient loading, water temperature, hydrologic flows, removal of upland and submersed vegetative or woody cover, human recreation and exploitation, and non-native species invasions.
3. Using lake and watershed models simulate the outcomes of urban development, agricultural practices and climate change on habitats in the sentinel lakes.
4. Identify a set of habitat and fish indicators that are most responsive to land use and climate stressors.
5. Evaluate the current status of habitat and fish indicators in each sentinel lake compared with the range of indicator values in similar lakes where data are available.
6. Design of a robust, long-term SLICE program that will give us statewide inference into current status of lakes and forecast change due to different environmental and management scenarios.

Role of proposed LCCMR project in the SLICE framework –Synergy and efficient use of resources is essential if we are to effect positive change for our water resources and fisheries. The partnerships outlined within the LCCMR proposal and the strong infrastructure and in-kind resources that go along with these partnerships will maximize the return on LCCMR's investment (Table 3). Below we highlight in detail our LCCMR investment needs. Aspects of goals 1, 3, and 4 fall outside of DNR's current scope of work current budgets can support. More specifically, this proposal focuses on lake and watershed assessment and modeling, reconstruction of historical habitat conditions, and assessment of zooplankton and cisco indicators. This work will supplement other ongoing analyses of indicators and stressors supported by DNR Fisheries and PCA Environmental Analysis and Outcomes Division operational budgets.

Below, we outline background, hypotheses, methodology, results and deliverables, and dissemination and use for results that were outlined in the 2-page LCCMR proposal that was recommended for funding. More focus is placed on data collection and assessment with LCCMR funds of seven cold-water lakes supporting cisco populations, an important forage species and indicator of disturbance (Figure 2; blue squares and stars). We are requesting less LCCMR support for work in the 17 other sentinel lakes (Figure 2; yellow circles), mostly restricted to a small budget for water chemistry analysis and intern time for data collection efforts. For the other activities described in Table 3, we plan to reprioritize workloads to get this work done. At the end of the addendum, we outline an itemized budget and attach credentials of each major investigator.

Given the scale and complexity of this project, a communication plan and organizational structure for information exchange and decision-making will be critical for success. This will be one of the key responsibilities of the project coordinator, Ray Valley. A steering committee of DNR Fisheries leaders will provide overall project oversight and guidance; identifying and mitigating institutional hurdles that may hinder project progress. Meetings will be scheduled quarterly with the steering committee to track progress and make adjustments if needed. An advisory team of DNR Fisheries management and research personnel and PCA research staff was responsible for the initial design of SLICE and will continue to be engaged with major project design elements as they come up. Local coordination and implementation is accomplished through the Area DNR Fisheries Offices and locally assigned PCA technical staff. Partners on this proposal mostly serve as technical team leaders and will focus on the specific tasks outlined below. Finally, the project coordinator will work with DNR staff on public information products (website, project updates to partners) and database management. Near the end of the LCCMR project period (July 2012), we propose a DNR-sponsored meeting of partners to discuss project outcomes and outline next steps, consistent with an adaptive management and evaluation framework.

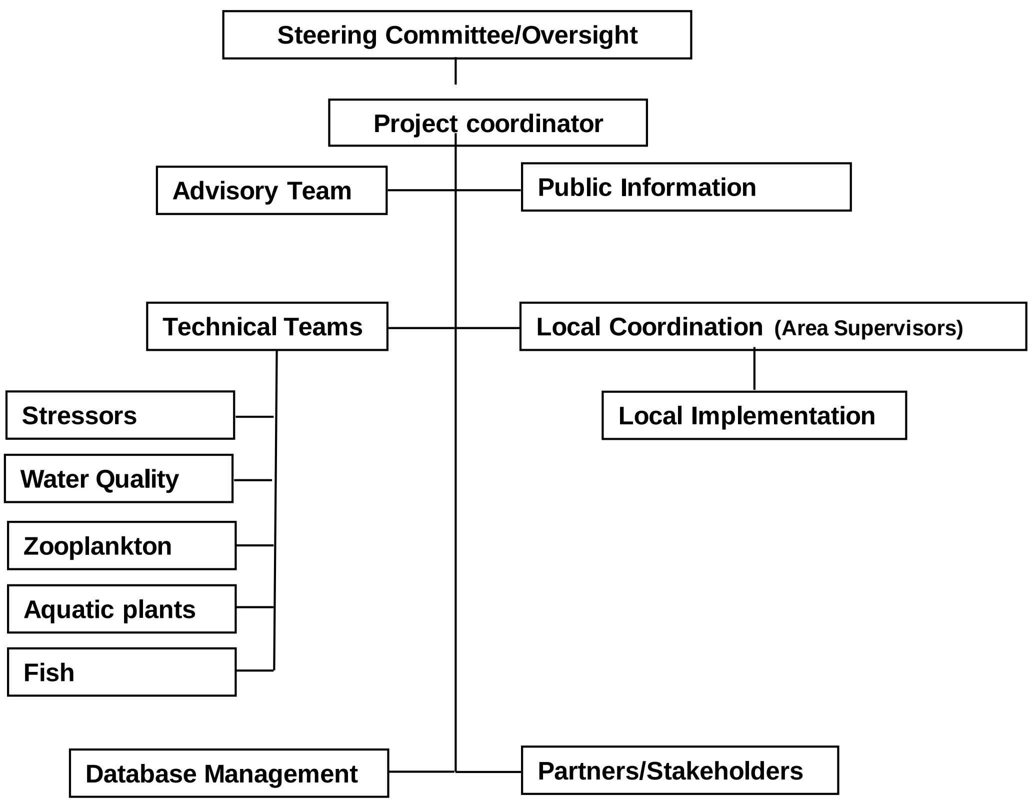

Figure 3. Organizational structure of the SLICE program.

Table 3. Proposed data collection activities in all sentinel lakes. Activities supplemented with LCCMR dollars are also indicated.

Surveys	Indicator	All Sentinel	Cold-water only	Super Sentinel	Sampling Method	Frequency	LCCMR support	Leader
Evaporation rates	Climate			x	Automated sampling buoy	Continuous	x	State Climatology Office
Ice cover duration	Climate	x		x	Direct observation	Daily		State Climatology Office
Lake levels	Climate	x		x	Lake gauging stations	Weekly		DNR Waters
Precipitation	Climate			x	Automated sampling buoy	Continuous	x	USGS
Relative humidity	Climate			x	Automated sampling buoy	Continuous	x	USGS
Solar radiation	Climate			x	Automated sampling buoy	Continuous	x	USGS
Tributary stream flow	Climate			x	Automated flow gauging stations	Continuous	x	USGS
Wind energy	Climate			x	Automated sampling buoy	Continuous		USGS
Fish Index of Biotic Integrity	Fish	x		x	Standard Methodology	Annually		DNR Ecological Resources
Northern pike surveys	Fish	x		x	Ice-out trapnets or Gillnets	Annually		DNR Fisheries
Largemouth bass surveys	Fish	x		x	Electrofishing	Annually		DNR Fisheries
Cisco surveys	Fish		x	X	Hydroacoustics	Annually	x	UMD, DNR Fisheries
Community composition	Fish	x		x	Standard Fisheries methodology	Annually		DNR Fisheries
Thermal and oxygen structure	Habitat			x	Automated vertical profiling buoy	Continuous	x	USGS
Thermal and oxygen structure	Habitat	x			Manual temperature and DO profiles	Monthly		PCA/DNR Fisheries
Thermal and oxygen structure	Habitat	x			Epilimnetic temperature loggers	Continuous		DNR Fisheries
Total Phosphorus	Habitat	x		x	Standard Methodology	Monthly	x	PCA
Total Nitrogen	Habitat	x		x	Standard Methodology	Monthly	x	PCA
Nitrates	Habitat	x		x	Standard Methodology	Monthly	x	PCA
Chlorophyll a	Habitat	x		x	Standard Methodology	Monthly	x	PCA
pH	Habitat	x		x	Standard Methodology	Monthly	x	PCA
Total Suspended Solids	Habitat	x		x	Standard Methodology	Bi-monthly	x	PCA
Total Suspended Volatiles	Habitat	x		x	Standard Methodology	Bi-monthly	x	PCA
Total Organic Carbon	Habitat	x		x	Standard Methodology	Bi-monthly	x	PCA
Alkalinity	Habitat	x		x	Standard Methodology	Bi-monthly	x	PCA
Calcium	Habitat	x		x	Standard Methodology	Bi-monthly	x	PCA
Magnesium	Habitat	x		x	Standard Methodology	Bi-monthly	x	PCA
Sodium	Habitat	x		x	Standard Methodology	Bi-monthly	x	PCA
Potassium	Habitat	x		x	Standard Methodology	Bi-monthly	x	PCA

Sulfate	Habitat	x		x	Standard Methodology	Bi-monthly	x	PCA
Chloride	Habitat	x		x	Standard Methodology	Bi-monthly	x	PCA
Zooplankton community	Habitat	x		x	Standard Methodology	Monthly		DNR Ecological Resources
Aquatic plant species frequency	Habitat	x		x	Point-intercept rake sampling	Annually		DNR Fisheries
Curly-leaf pondweed surveys	Habitat	x		x	Point-intercept rake sampling	Twice annually		DNR Fisheries
Aquatic plant abundance mapping	Habitat	x		x	Hydroacoustics	Variable		DNR Fisheries
Historical productivity	Habitat		x	x	Fossil diatom reconstruction of Total P	initial	x	Science Museum of MN
Sedimentation	Land Cover		x	x	Paleolimnological estimation	initial	x	Science Museum of MN
Agricultural practices	Land Cover	x		x	GIS and agricultural records	Annual		MN Dept. of Ag, USDA
Land cover	Land Cover	x			Landsat land use delineation	every five years		USGS
Land cover projection	Land Cover	x		x	Demographic change projections	decadal		NRRI
P loading	Land Cover			x	Intensive P loading estimation	annual	x	USGS
P loading	Land Cover	x			P loading estimation	every five years		PCA, USGS
Silvicultural practices	Land Cover	x		x	GIS and forestry records	annual		DNR Forestry/USFS
Bathymetry	Morphometric	x		x	Hydroacoustics	Once		DNR Fisheries
Watershed delineations	Morphometric	x		x	Standard methodology	Initial		DNR Waters
Groundwater dynamics	Morphometric			x	Piezometers		X	USGS, U of MN

LCCMR Project Components

Lake and watershed assessment and modeling

Background

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 Minnesota lakes. A number of regional and state-wide lake modeling studies have illustrated the potential linkages between climate change, lake morphology, and fish habitat in the form of temperature and dissolved oxygen distributions for Minnesota and the north-central United States (e.g., see summaries in Stefan et al. 1995; De Stasio et al. 1996; Fang et al. 1999). These models have documented the relative importance of lake-basin geometry, ice-free season, thermal stratification, dissolved oxygen stratification and wind-driven mixing to the development of sustainable fish habitat in deep-water lakes of the region. However, the potential trophic-dynamic response to simultaneous changes in climate and land-use is less well understood, as is the response of specific lakes to these historical and hypothetical changes. Questions also remain as to how the complex food webs that support fish guilds within these modeled systems will respond to the predicted physical changes in fish habitat (De Stasio et al. 1996).

Our proposed work will develop predictive tools to evaluate the trophic response of three sentinel lakes ("super" sentinel lakes – Figure 2) to current climate and watershed land-use conditions. We will accomplish this by developing watershed-loading models coupled with in-lake water quality models. Calibrated lake models will be used to forecast changes to water quality and deep-water thermal habitat conditions under changing climate and land-use scenarios. Where data are sufficient, models will be used with historic land use and climate data to provide historical benchmarks for comparison with output from scenario models.

By the conclusion of the study, we will outline the steps needed to take this result from a highly technical exploration to something in a more usable format for land use planners and policy makers. 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 or land use practices. In addition, we will project potential responses to various climate change scenarios which will enable us to identify factors that may help to minimize the impact of climate change on fisheries, identify thermal refuges that warrant special protection, and identify management efforts that have little chance of long-term success. Interactive web-tools may be a promising mechanism by which local planners, policy makers, and even educators and students could "plug-n-play" different scenarios and evaluate the potential consequences of policy decisions on water quality and fish habitat.

Forecasting various scenarios and where to concentrate mitigation measures is not unique to this project and many groups at various scales are currently engaged in developing lake or watershed assessment tools. These groups include the Midwest Glacial Lakes Partnership (a regional subsidiary of the National Fish Habitat Initiative), North Central Lakes Collaborative, NRRI, and DNR Ecological Resources-U of MN (http://www.dnr.state.mn.us/watershed_tool/index.html).

The likelihood of more efforts given new clean water legacy amendment funding is high. The need for coordination of these activities for maximum mutual gain with minimum redundancy is obvious. By completion of the LCCMR project, we will draft a proposal outlining other similar efforts and tools in development and how these efforts can be coordinated or adapted for web tools that focus on watershed-lake links. Modeling efforts coupled with long-term monitoring and recalibration of watershed and lake models could be used to form a strong empirical basis for these tools.

Hypotheses

1. We will use the calibrated, carbon-based water quality models to test the predictions of previous models that deep-lake fish habitat is insensitive to lake trophic status.

2. Where possible, we will use the calibrated water quality model to test the reconstructed trophic status of lakes as predicted by sediment core geochemistry and diatoms analysis.

3. Where possible, we will use the calibrated lake models to test for the occurrence of past deep-lake fish habitat bottlenecks using historical climate data from Minnesota

Methodologies

The two-dimensional, numerical model CE-QUAL-W2 (W2) will be used to simulate the hydrodynamics and water quality of the three super sentinel lakes in this proposal. The model has been used in a number of systems to assess the effects of eutrophication and to evaluate the alternative lake-management scenarios. It has been successfully combined with different watershed models (e.g., SWAT and HSPF) to evaluate how well BMPs will function in reducing constituent loading to lakes.

The biophysical components of the model incorporate mechanistic consumer-resource interactions. This enables to model to simulate trophic dynamics with high vertical spatial resolution while providing very good estimates of carbon-based production dynamics. Algal population growth kinetics are modeled using the Monod formulation and are constrained by functional light and temperature limits. W2 also incorporates realistic stoichiometric constraints into algal growth kinetics and into nutrient and carbon cycling, while allowing for biological complexity in estimates of primary production.

In addition to the ability to simulate 21 water quality state variables, CEQUAL- W2 builds on the proven hydrodynamic solution techniques of its predecessors, the Laterally Averaged Reservoir Model (LARM) and the Generalized Longitudinal and Vertical Hydrodynamics and Transport (GLVHT) model. The capability of the model to reliably predict changes in water quality in two dimensions (longitudinally and vertically) for multiple branches was among the characteristics which made CE-QUAL-W2 particularly suited to simulation of Lake Carlos, the largest and most complex of the three super sentinel lakes to be studied. Its ability to handle additional inputs will also make the model flexible in dealing with the substantial ground-water inputs into Elk Lake.

CE-QUAL-W2 was developed and supported by the U.S. Army Corp of Engineers Waterways Experiment Station (USACE-WES; Cole and Buchak, 1995). The current release of the model (W2 V3.6; 2008) was developed under the supervision of Dr. Scott Wells, Portland State

University (PSU), under contract with the USACE-WES. The current model release includes executables, source codes, and examples for the W2 V3.6 model and preprocessor. There is also a stand-alone V3.6 GUI preprocessor available for download at http://www.ce.pdx.edu/w2/. Model Capabilities listed on the website include longitudinal-vertical hydrodynamics and water quality in stratified and non-stratified systems, multiple algae species, epiphyton/periphyton, zooplankton, macrophyte, CBOD, and generic water quality groups, internal dynamic hydraulic structures (weirs, spillways) algorithms including submerged and 2-way flow over submerged structures, internal calculations of equilibrium temperatures and coefficients of surface heat exchange; heat exchange between the water/sediment interface; linear interpolation of inputs; and improved ice cover algorithm.

Proposed tests using model output – Fang et al. (1999) used the MINLAKE96 model to simulate suitable fish guild habitat under past (1961-1979) and predicted future (2 X CO_2) climate scenarios for 27 Minnesota lake types and three generalized fish guilds. In their study, fish habitat contours were derived from temperature and dissolved oxygen (DO) profiles produced by the MINLAKE96 model output. Contours of fish habitat were compared with temperature and DO habitat criteria derived from the literature for the three fish guilds (warm, cool, and cold water fish guilds).

Based on their study, good-growth habitat areas (GGHA) and volumes (GGHV) were predicted to increase under climate change for cool and warm-water fish guilds in all lake types, with the greatest increases observed in northern Minnesota lakes. Cold-water fish also were predicted to have a small percent increase in good growth spaces for deep ($Z > 24$ m) lakes due mostly to a significant increase in the length of the stratification period (e.g., a 25% increase in good growing season length (GSL) from 150 days to 190 in two lakes > 24 m deep in northern Minnesota). However, medium depth lakes ($Z = 13$ m) were predicted to have a decrease in good growth spaces for cold-water fish because of the interaction between the length of the stratification period and lake DO metabolism. In general, the same physical forcing factor (i.e, increase in length of stratified period) produces opposite outcomes for cold-water fish habitat based on lake morphometry and correlates of lake metabolism (heat loss / gain and oxygen dynamics).

This gradient of positive and negative responses of generalize cold-water fish habitat to physical forcing from climate change needs to be examined more fully with a more detailed model to address the following questions:

A. **How do changes in primary and secondary production associated with changes in prolonged stratification in deep water lakes affect the distribution of thermal and dissolved oxygen habitat criteria for specific cold-water fish species?**

   This question was not addressed by Fang et al.(1999) because MINLAKE96 does not include important biological and chemical feed-back mechanisms in lake metabolism and because they used habitat criteria associated with broad cold-water fish guilds. Biological and chemical feed-back mechanisms in lake metabolism are amplified under higher temperatures and long (> 30 days) periods of stratification. Long periods of stratification also increase water column stability which in turn amplifies depth-dependant metabolic processes.

Fang et al. (1999) used habitat criteria associated with broad cold-water fish guilds to evaluate habitat gain and loss, but our study is aimed at evaluating the response of sentinel indicator species (e.g., *Coregonus* sp.) to the types of changes in fish habitat their model has predicted.

Our methodology is to expand on Fang et al. (1999) by using a two-dimensional, laterally averaged, biologically and chemically explicit carbon-based model. Our model estimates net primary production and produces ecosystem-based estimates of deep-water dissolved-oxygen concentrations, allowing us to map deep-water fish habitat based on ecosystem processes. We will collect the data necessary to develop calibrated models for three deep-water lakes and will use associated model output to test the predictions of the Fang et al. (1999) MINLAKE96 model for the same class of lakes. Model calibration statistics will be calculated following Flowers et al. (2001). The mean error (ME,) absolute mean error (AME), and the root mean square error (RMSE) will be used to evaluate model performance for each calibration variable. The absolute mean error (AME) gives an indication of how close on either side of the observed values the predicted values lie while the root mean square error (RMSE) is a measure of the variability between observed and predicted concentrations.

We will use our calibrated model output of temperature and DO profiles to map fish habitat under current conditions and then simulate changes in lake productivity to evaluate the effects on fish habitat using the GSL, GGHA and GGHV metrics. We will compare our results from these simulations with the range of values observed from historical and climate change simulations performed by Fang et al. (1999) in order to evaluate the importance of trophic status on deep-water fish habitat.

B. **How do areas of GGHA and GGHV vary in space and time over a specific lake as watershed characteristics change?**

We will use our calibrated model output of temperature and DO profiles to map deep-water fish habitat in space and time under current conditions and then simulate changes in lake productivity associated with changes in watershed inputs of nutrients. We will accomplish this by running model scenarios based on land use or land cover changes and then evaluate the affect of these changes on fish habitat using the GSL, GGHA and GGHV metrics. We will compare our results from these simulations with the range of values observed from historical and climate change simulations performed by Fang et al. (1999) in order to evaluate the importance of trophic status changes associated with land use or land cover change on deep-water fish habitat.

Data sources – Model choice will be evaluated using an existing USGS dataset from Shingobee Lake, MN, during the first four months of the project. Shingobee Lake provides a strong basis for evaluating the capability of W2 to model a Minnesota Lake with significant groundwater contributions (e.g. Elk Lake) while simultaneously handling the significant longitudinal transport of water and constituents associated with the Shingobee River (e.g., Lake Carlos). The Shingobee Lake model will also provide an evaluation of the density of data required to adequately model system behavior.

Data collection for each super sentinel lake will consist of continuous temperature data from multiple depths for each major sub-basin in the lake during the ice-free season as well as one multiple-parameter data platform for the collection of continuous water quality data during the ice-free season. The data platform will provide the continuous meteorological (MET) and water quality data necessary to populate the model. MET data collection will include wind speed and direction at the surface of the lake, air temperature, net radiation, rainfall, and photosynthetically-active radiation (PAR). Water quality data collection from the platform will include standard four-parameter water quality sonde data (temp., DO, cond., pH) plus chlorophyll a in vivo fluorescence (IVF). Data will be collected at multiple depths a number of times per day. Up to three platforms will be available for deployment in Lake Carlos if individual sub-basins display individual behavior.

Ambient water quality sampling will also take place at regular intervals. In addition to the standard sentinel lakes water quality parameters, dissolved and particulate nutrients and algal group abundance will be determined.

Surface water inflow at up to four locations in each watershed will be estimated using temporary, continuous streamflow gages. Locations will be chosen to provide the best estimates of loading to and discharge from the lakes in question. All three lakes have well-define outlets. Even-mean constituent loads will be estimated using flow-weighted sampling of seasonal storm event.

Groundwater contributions will be estimated for Elk Lake as part of a separate research study by the University of Minnesota. Groundwater constituent concentrations will be measured directly using shallow groundwater wells and up-gradient surveys with mini-peizometers (Jones 2006). Water balance calculations and model calibration will also provide an estimate of groundwater contribution in all three lakes.

Recent Relevant USGS Work

Nustad, R. A. and J. D. Bales. 2006. Simulation of Constituent Transport in the Red River of the North Basin, North Dakota and Minnesota During Unsteady-Flow Conditions, 1977 and 2003-04. U. S. Geological Survey Scientific Investigations Report 2006–5296, 58.

Results and Deliverables

From LCCMR 2-page proposal

Result 1: Establish 7 deep sentinel lakes and their associated watershed as focal points of collaborative long-term monitoring, research, and environmental education (see attached map).
Budget request: $298,143
Deliverable (Completion Date: July 2009):

1. Network of 7 sentinel monitoring and research sites
2. Installation of flow, climate, and water quality monitoring systems lakes: Carlos L., Douglas Co.; Elk L., Clearwater Co.; and Trout L., Cook Co.
3. Project coordinator to maintain and manage partnerships, and coordinate reporting.

Result 3: Utilize watershed and lake mixing models to forecast future water quality conditions in deep lakes with cold-water fish populations given different climate change and land-use scenarios. Budget request: $14,135
Deliverable (Completion Date: July 2012):

1. Models to form an empirical foundation for the development of watershed best management practices and climate change adaptation policies that will protect the resiliency of deep-water lakes.
2. Strategies for building future interactive web-applications of these models for state policy makers, educators, and local land use planners.

The LCCMR grant secures a temporary focus on at least 7 cold-water sentinel lakes for assessment and monitoring. However, realizing the full potential of SLICE (and thus preservation of deep cold water lakes) over the long term necessitates a focus on a wider range of lake conditions. DNR and PCA will continue to search for funds to maintain a suite of 24 sentinel lakes and an ongoing partnership with USGS to maintain a subset of super-sentinel lakes where data collection is ongoing and models will be continually verified and refined (Result 1 Deliverable 1).

Timetable

	2009		2010	2011			2012	
Tasks	August	October	Ice-free	Ice-free	Sep.	Dec.	April	June
Platform Deployment	x	x						
Water-level gages		x	x	x				
Data Collection	x	x	x	x				
W2 model calibration					x			
W2 model validation						x		
NWIS data publication							x	
Final report								x
Web applications proposal								x

Dissemination and Use

- Data streams from sentinel lakes into the National Water Inventory System and EPA's STORET databases (Result 1 Deliverable 2)

- Reports, presentations to technical and agency audiences, and manuscripts of results for publication will be produced for Result 3 Deliverable 1.

- LCCMR proposal(s) to coordinate, build, or refine interactive web-based watershed and lake assessment tools (Result 3 Deliverable 2).

Reconstruction of post-European to present water chemistry, sedimentation and erosion.

Background

To complement modern sampling and inform modeling of future lake responses, we will partner with the Science Museum of Minnesota to comprehensively evaluate post-European colonization changes in lake conditions and evaluate major environmental events that coincided with these changes using analysis of biogeochemical signals preserved in sediment cores the seven cold-water sentinel lakes. The sediment record of a lake faithfully preserves chemical and biological clues or proxies that can be used to reconstruct the environmental history of a lake and its watershed. With any environmental assessment programs such as the SLICE, it is important to have a basic understanding of natural fluctuations within the system. Reliable long-term data sets, on the order of 30 - 50 years, are generally not available for most regions of the country, let alone most lakes in Minnesota. Using paleolimnological techniques and quantitative environmental reconstructions, we can estimate past environmental conditions and natural lake variability. In Minnesota, paleolimnological techniques, especially diatom-based analyses, have been used throughout the state to quantitatively reconstruct historical environmental conditions, including nutrient concentrations (Ramstack et al. 2003; Edlund and Kingston 2004), inform TMDLs and nutrient reduction targets (Edlund et al. 2009), and to develop nutrient criteria specific to ecoregion and lake-type (Heiskary and Wilson 2008). These successes have been based on paleolimnological analysis of only about 200 of Minnesota's 13000 lakes. Although lake environmental histories vary across the wide range of ecoregions and land uses in Minnesota, major periods of change are generally associated with initial Euroamerican settlement and land clearance, post-WWII changes in agricultural practices, (sub)urbanization, and climate change, although other site-specific land uses (e.g., lakeshore development, damming) have also been identified as drivers of change.

Hypotheses

1. We hypothesize that the major period of ecological and geochemical changes in the sentinel lakes will be associated with Euroamerican settlement and initial land clearance/logging.

2. We hypothesize that recent (1970-present) ecological and geochemical changes in the sentinel lakes can be attributed in part to climate changes

Methodology

Core collection

A 1.0-1.8-m long sediment core will be collected from each of the seven sentinel lakes to recover sediments deposited over the last 200-500 years. Cores will be collected during the open-water season from an anchored boat using piston-coring methods that recover the very loose uncompacted sediment surface without disturbance (Wright 1990). Each sediment core will be initially extruded vertically from the coring tube in 1-cm increments. Extrusion of the upper unconsolicated sediment will be done on-site (in the field), and the remaining core sealed in the core barrel and returned to the laboratory for 4° C storage.

Core description, subsampling and magnetics

Cores will be transported to the Limnological Research Center (Univ. of MN), horizontally extruded, split lengthwise, physically described, and photographed. Cores will be subdivided into 1.55-m long sections for magnetic susceptibility logging on a Geotek Standard MSCL with an automated trackfeed. Susceptibility measures are taken at 1-cm intervals, which integrate a signal over a 5-10-cm length of core. Data will be spliced at core breaks for plotting. Following susceptibility logging, cores will be split lengthwise, physically described, and digital images taken of each core section using a Geoscan Corescan-V. Split cores can be secondarily scanned for magnetic susceptibility using a Geotek XYZ MSCL split-core logger if greater magnetic detail is needed. Magnetic susceptibility provides a non-destructive measure of relative quantity and size of ferro-magnetic minerals. Increases in magnetic susceptibility signatures may be correlated with land use changes including land clearance, increased terrestrial-derived sediments, and paleosols. Decreases in magnetic susceptibility often accompany increased carbonate and organic fluxes to the sediments from increased in-lake productivity.

Loss-on-ignition and Lead-210 dating

Dry-density (dry mass per volume of fresh sediment), water content, organic content, and carbonate content of sediments will be determined by standard loss-on-ignition techniques (Dean 1974). Up to 40 core increments will be analyzed.

Cores will be analyzed for ^{210}Pb activity to determine age and sediment accumulation rates for the past 150 years. Lead-210 will be measured at 16-20 depth intervals by ^{210}Po distillation and alpha spectrometry methods, and dates and sedimentation rates will be determined according to the c.r.s. (constant rate of supply) model (Appleby and Oldfield 1978, Binford 1990).

Diatom analysis

A total of 15 or more core increments will be analyzed for diatom microfossils; ten of the samples will be concentrated in the upper part of the core representing about the last 120-150 years (ca. 15-year resolution). The remaining five samples will be taken at core intervals representing 10-20 year resolution from pre-European settlement times (pre-1850). Samples will be treated with dilute HCl to remove carbonates followed by addition of 30% H_2O_2 and heating for two hours at 85°C. Following cooling, samples will be rinsed once daily for four days to remove oxidation byproducts, the remaining sample dried onto microscope coverslips, and the coverslips mounted on microslides using Naphrax. Diatoms and chrysophyte cysts will be identified to species level using light microscopes with full immersion optics capable of 1200X magnification at an N.A. of 1.4. A minimum of 400 diatom valves will be counted in each sample. Lake-water total phosphorus (TP) will be reconstructed from fossil diatom assemblages using a diatom-phosphorus calibration model and weighted averaging calibration and regression techniques (Ramstack et al. 2003). A diatom-TP model developed by Ramstack et al. (2003) and others from a suite of 145 Minnesota Lakes will be available for this study. Diatom analysis will be further used determine the timing and extent of major ecological changes in each lake including shifts between benthic and planktonic dominance, shifts between diatoms and chrysophytes, and modern analogues based on diatom communities. These multivariate ordination techniques will help identify the ecological trajectory of the lake, a useful tool for understanding environmental drivers of change and recent trends in lake condition. To attribute historical changes in diatom communities to various environmental and human stressors, we will try variance partitioning analysis (Brocard et al. 1992, Hall et al. 1999) to determine whether potential explanatory variables (e.g., climate, land use) have had significant unique and/or interactive effects on structuring the historical diatom communities.

Results and Deliverables

From LCCMR 2-page proposal

Result 2: Reconstruct post-European to present water chemistry, sedimentation and erosion.
Budget request: $90,000
Deliverable (Completion Date: July 2012)

1. Reconstruct historical water quality and habitat conditions in the deep sentinel lakes.
2. Report explaining how past landuse and major environmental cycles (wet/dry, warm/cool) of the recent past shaped current water quality and habitat conditions in each sentinel lake.

Timetable

Result 2 Tasks	Year 1	Year 2	Year 3
Core collection	x	x	
Core analysis	x	x	x
Annual report	x	x	
Final report			x

Dissemination and Use

Reports, presentations to technical and agency audiences, and manuscripts of results for publication will be produced for Result 2 Deliverables 1 and 2. Information from sediment cores that will be included in the final report will be a review of methodology, coring sites, descriptions and images of cores, 210-Pb date model of each core, estimation of historical sediment accumulation rates for dated cores, downcore distribution and flux of geochemical constituents (inorganic matter, organic matter, carbonates), stratigraphy of major diatom species, and ecological and quantitative interpretation of environmental changes in cores. It is anticipated that results from sediment cores will provide critical data on historical lake response that will be incorporated in further SLICE publications and help inform future management and climate-change adaptation policies.

Evaluating zooplankton indicators

Background

Zooplankton indices that correlate with water quality have been developed and reported in past studies (Gannon and Stemberger 1978, Hanson and Peters 1984, Pace 1986, Attayde and Bozelli 1998, Harig and Bain 1998, Hoffman and Dodson 2005, Gamble et al. 2006, and Barnett and Beisner 2007). However, despite their promise as indicators of changing environmental conditions and their importance to food webs in north-temperate lakes (Rusack et al. 2002, Beisner et al. 2003, and Olden et al. 2006), no studies have examined the linkages of zooplankton populations to environmental conditions in Minnesota inland lakes. We will investigate the sensitivity and robustness of common zooplankton indicators to changes in lake productivity along the gradient of the 24 sentinel lakes. The overall objective of this analysis is to identify which characteristics of pelagic zooplankton communities in Minnesota lakes change in consistent, predictable patterns in response to human disturbance or increased nutrient loading. To address this objective, we will ask the following questions

Questions/Hypotheses:

1. <u>Are patterns in Minnesota zooplankton communities similar to those observed in other north-temperate systems?</u>

In general as nutrient loading increases, many aspects of zooplankton communities change. These changes include *increases* in total zooplankton abundance and (Pace 1986, Attayde and Bozelli 1998) biomass (Hanson and Peters 1984, Pace 1986, Gamble et al. 2006) and *decreases* in relative size of individual zooplanktors, especially cladocerans and large daphnia (Pace 1986, Harig and Bain 1998), species or functional group diversity (Hoffman and Dodson 2005, Barnett and Beisner 2007), percent composition of calanoids (Gannon and Stemberger 1978), and mid-summer fish-edible zooplankton (Tessier and Woodruff 2002). We will explore whether patterns in Minnesota lakes fit these observations in other north-temperate systems and what patterns might mean for water quality and food-webs.

2. <u>Which indices are most sensitive to changes along a gradient of lake productivity, yet are robust to sampling error or natural changes within or among years (i.e., high signal:noise ratio, Jassby 1998)?</u>

In two studies examining zooplankton variation in north temperate lakes, spatial variation among lakes and regions generally exceeded yearly temporal variation within a lake (Rusack et al. 2002, Olden et al. 2006). Nested within yearly temporal variation is within-year variation. Zooplankton 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). Further nested within-year variability is within-basin variability. Ideally, to develop valid indices, this variance should be small. Variation will depend upon the size and morphology of the lake. A small lake with one basin would require fewer sites than a large one with multiple basins. In a Lake Michigan study testing temporal vs. spatial variation among zooplankton, between station variance was low compared to monthly temporal variance, but tended to be the highest in summer (Evans and Sell 1983). Unfortunately, limited labor resources allow us to only sample two sites on some lakes, thus affecting our ability to adequately address within basin variability. Nevertheless, the presence of very large differences between these samples will guide follow up assessments and studies.

3. Does variance in indices show patterns across lake productivity gradients?

Basic ecological theory coupled with empirical evidence from many aquatic and terrestrial systems suggests that in systems with minimal disturbance, “regimes” are relatively stable and resilient to modest natural perturbations (Beisner et al. 2003, Scheffer and Carpenter 2003). In lakes these regimes are generally characterized by conditions of clear water, large cladoceran zooplankton, and abundant aquatic plants. However, if nutrient loading increases over time, then this clear-water regime becomes less resilient and unstable, temporarily moving into different domains depending on local disturbances. Finally, if eutrophication continues unabated the lake can shift into a highly stable and resilient impaired state (e.g., turbid water with little to no aquatic plant growth (Beisner et al. 2003, Scheffer and Carpenter 2003). We will explore whether patterns of variation of the zooplankton community fit some of these models.

Methodology

Field Sampling Methods:
Each of the 24 sentinel lakes will be sampled for zooplankton once a month from ice-out (April or May) through October for three consecutive years. Samples will be collected by Minnesota Pollution Control Agency personnel. Two replicate vertical tows will be taken from each lake on each sampling date at the deepest location. (Samples may be collected from more than one site on some lakes, depending upon lake size and morphology). Zooplankton tows will be taken with a standard 80μm mesh Wisconsin zooplankton net from an anchored boat 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 DNR Ecological Resources- Aquatic Invertebrate Biology Laboratory for analysis.

Laboratory Methods
Each zooplankton sample will be adjusted to a known volume by filtering through 80μm 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 (most to species level) and measured to the nearest .01 mm using a dissecting microscope and an image analysis system. Densities (#/liter), biomass (μg/liter), percent composition by number and weight, mean length (mm), mean weight (μg) and total counts for each taxonomic group identified will be calculated with either the laboratory’s existing zooplankton counting program ZCOUNT (Charpentier and

Jamnick 1994), or a new program that is expected to be written to replace ZCOUNT. Data generated will be analyzed using appropriate statistical methods to test for potential zooplankton indices and correlated with water chemistry parameters.

Statistical Methods

Data will be analyzed with mixed effect linear models (Searle et al. 1992) utilizing transformations of the response variables as necessary to satisfy model assumptions. A mixed model has both fixed effects and random effects. For the fixed effects, we will adjust for year effects, evaluate hypothesized relationships from the literature, and characterize intra-annual patterns. Individual lakes will be modeled as random effects to account for repeated measures (Kutner et al. 2005) within each lake and to estimate an inter-lake variance parameter; this variance parameter is critical for power analyses of long-term lake monitoring designs. Schwarz's Information Criterion (Schwarz 1978) will be used to find the model with the best fit to the data. Diagnostic and residual analyses (Weisberg 2005) of the linear models will be used to detect heteroscedasticity or other patterns in variation across lakes, years, or environmental gradients.

Results and Deliverables

From LCCMR 2-page proposal

Result 4: Identification of a set of habitat and fish indicators sensitive to human-caused disturbances to serve as an early warning sign of lake ecosystem stress. Budget: $422,722

Deliverable (Completion Date: July 2012)

1. Use results to inform on-going monitoring programs in sentinel lakes and a broader-range of random lakes
2. **Assessment of zooplankton indicators.**
3. Evaluation of hydroacoustics to assess the status of cisco populations in inland lakes.
4. Evaluation of cisco habitat use and behavior.

For deliverable 2 we are requesting $44,640. Most of the remaining budget request of Result 4 is to support basic data collection needs (water quality, aquatic plants, fish) for all Results in this study.

Timetable

Tasks	Year 1	Year 2	Year 3
Data Collection	x	x	
Data analysis	x	x	x
Annual report	x	x	
Final report			x

Dissemination and Use

Reports, presentations to technical and agency audiences, and manuscripts of results for publication will be produced for Result 2 Deliverables 1 and 2. A voucher collection of identified zooplankton specimens and digital photographs will be constructed for verification and future use as taxonomic tools.

Cisco Assessment

Background

Cisco *Coregonus artedi* are an important component of the fish community in many Minnesota lakes. They provide a significant forage base for walleyes, northern pike, muskellunge, and lake trout (Ryder and Kerr 1978; Colby et al. 1987). Walleyes grow significantly faster when foraging on energetically rich cisco (Henderson et al. 2004), and more large northern pike are produced when cisco are present (Jacobson 1993). As a dominant planktivore in many lakes, cisco can play an important role in structuring zooplankton communities (Rudstam et al. 1993). Cisco also provide a winter sport fishery and are the target of a traditional gill net fishery in Minnesota.

Climate warming has the potential to reduce coldwater fish thermal resources through direct warming in increased hypolimnetic oxygen depletion in stratified lakes from extended periods of stratification (Magnuson and DeStasio 1997; Fang et al. 2004). Cisco are the most common and widespread coldwater cold water fish in Minnesota lakes. Gillnetting assessments found cisco in 648 lakes throughout central and northern portions of the state and across several ecoregions (Minnesota DNR files). The wide distribution suggests that cisco are somewhat more adaptable than other native coldwater fish such as lake whitefish *Coregonus clupeaformis* (sampled in 155 lakes), lake trout *Salvelinus namaycush* (124 lakes) and burbot *Lota lota* (233 lakes). The combination of their wide distribution and cold water preference make cisco an excellent sentinel species and indicator of climate change.

Despite the importance of cisco to Minnesota fisheries and the sensitivity of this species to climate change and eutrophication, relatively little is known about their habitat use and consumptive demand in Minnesota lakes. Furthermore, these pelagic species are difficult to sample with traditional survey gears (horizontal bottom gillnets), thus population status has been difficult to track. Hydroacoustics is an advanced assessment tool that has been proven effective for assessing population status of cisco in the Great Lakes and inland lakes in Wisconsin (Hrabik et al. 2006). Some Minnesota lakes harboring cisco do present some challenges to hydroacoustics (abundant populations of acoustically reflective *Chaoborus* zooplankton) that warrant exploration by a professional well versed in fisheries hydroacoustics. The seven cold-water sentinel lakes represent a wide range of conditions and will be good testing grounds for this technology. Accordingly, we will evaluate hydroacoustics as an assessment tool for cisco in Minnesota lakes while simultaneously exploring basic questions about their habitat use and diet.

Fish distribution may be influenced by a host of physico-chemical and biological variables including temperature and oxygen (e.g. Neil and Magnuson 1974, Magnuson et. al 1979, Crowder et al 1980, Rudstam and Magnuson, 1985), prey abundance, feeding or assimilation (Janssen and Brandt 1980, Werner et al. 1981, Crowder and Magnuson 1983, Wurtsbaugh and Neverman 1988, Munk et al. 1989), and predation risk (Eggers 1978, Werner et al. 1983, Clark and Levy, 1988, Hrabik et al. 2006, Jensen et al. 2006). Understanding how fish distribute themselves according to environmental gradients is a central interest of ecologists and managers who seek to predict effects of predator-prey interactions, the impact of an invading species, cultural eutrophication, climate change and the effect of community changes on foodweb structure and composition. Thus, the extent to which these interacting factors can be modeled to accurately predict planktivorous fish distribution *in situ* must be known before applications are possible.

Habitat quality may be defined as a function of prey density, prey encounter rates, thermal resources, and bioenergetic characteristics of a fish species that depict a growth rate potential (GRP) under a specific set of environmental conditions (e.g. Mason et. al 1995). Furthermore, the relative body condition of fishes has been linked to lipid content (Fetchelm et al. 1995) and growth rate (He et al. 1993) and is used to compare the health of populations of a given species (Neumann and Murphy 1991, Brown and Murphy, 1991, Fisher and Fielder 1998). Linkages have been identified between growth rate potential measures and piscivore body condition (Luecke et al. 1999). However, the linkages between relative body condition for planktivorous fishes and habitat quality have rarely been examined, and may vary with the extent to which predator avoidance behavior reduces foraging time. Measurements of each variable in a series of lakes with differing characteristics may offer a means to examine this possible relationship.

The objectives of this study are to:

1. Evaluate hydroacoustics as a cisco sampling tool across a range of lake types (hardwater and softwater, deep and shallow).
2. Assess cisco abundance across a range of lake conditions
3. Evaluate factors affecting cisco distributions, foraging behaviors, growth rate potential and body condition.

Hypotheses

In addressing objective one, we hypothesize that hydroacoustic sampling will provide accurate estimates of cisco population densities across lakes as has been shown in a variety of other ecosystems (Rudstam et al. 1993, Krueger and Hrabik 2005, Hrabik et al. 2006a). For objective two, we hypothesize that the density of cisco will be positively correlated to the volume of habitable area in each lake. Accomplishing objective three requires us to assess the predictability of cisco vertical distribution during the day and at night. To do so, we will use three basic competing models: 1) behavioral thermoregulation, 2) optimal foraging and 3) growth rate potential. Predictions from each of the models will be made with and without a predator avoidance component to assess the influence of predation risk on the distribution of cisco. We will also consider whether linkages exist between estimates of GRP and fish body condition and the extent to which predation avoidance behaviors decouple the possible relationship. Measurements of temperature-depth profiles, and prey distribution collected during the day and at night in each of the seven sentinel lakes harboring cisco populations will be the input for each model. Given previous studies (Hrabik et al. 2006, Jensen et al. 2006), we hypothesize that cisco distribution will be best predicted using foraging or GRP models with the predation risk component included.

Methods

The surveys on each study lake will systematically sample the open water area with the objective of uniformly covering the area of the lake > 6 m in depth. Our approach focuses on obtaining samples from open water sections within the survey area to estimate the abundance and biomass of open water prey species including cisco (Figure 1).

We will use a 70-kHz split beam echosounder to estimate pelagic fish target strength and fish density in each basin of the lake. We will sample approximately 0.1 km of transects per ha in each lake while actively pinging with the echosounder. This sample density will provide estimates of fish density with standard errors less typically than 20% of the sample mean (Hrabik unpublished data). Results from sampling with a spectrum of vertical gillnets (19, 25, 32, 38, 51 and 64 mm stretch mesh) conducted by MNDNR personnel in the deepest portions of each basin will be used to identify the composition of open water fish species detected with the echosounder.

Transect locations, acoustic information and gillnet locations will be geo-referenced using a global positioning system (GPS) system attached to the hydroacoustic unit. Raw acoustic data and gillnet information will be stored on computer hard drives and later copied to portable hard disks for data processing and archiving. Calibrations of the echosounder will be performed using a tungsten carbide reference sphere (Foote et al. 1987, Foote 1990). The speed of the sampling vessel will be approximately 3 knots while collecting hydroacoustic data.

Data Analysis and quality

Acoustic data will be collected using Biosonics Visual Acquisition software and analyzed using Echoview analysis software (v. 4.12, Sonardata Pty. Ltd). Prior to analysis, it will be necessary to manually edit each echogram to ensure that only true fish echoes were included in analysis. Each echogram will be examined for acoustic “noise” not likely attributable to fish backscatter (e.g., electrical interference, surface wave disturbance). Additionally, the Echoview bottom detection function will be used to exclude sound returned from the lake floor from echo integration and bottom echoes were identified by the algorithm throughout the survey area.

Echo Integration

Echo integration will be used to calculate the total amount of sound backscattered across all transects. The minimum raw echo-strength threshold will be set to –65 dB. These analyses will provide the Nautical Area Scattering Coefficient (NASC - a measure of the average amount of sound reflected by fish per square nautical mile) for each transect.

Single Target Detection

Fish density is calculated using the expected size of an acoustic fish to scale the NASC values. The single target detection algorithm of Echoview uses a suite of parameters to define raw echoes as likely fish targets. Echo strength for each target identified is then corrected for sound attenuation due to depth and angle off axis, providing a true measure of the sound reflected. Target strength will be estimated using data in the linear domain using the following equation:

$$\overline{TS} = 10\log_{10}\left(\frac{1}{N}\sum_{i=1}^{N}10^{\left(TS_i/10\right)}\right)$$

where:

TS or TS_{mean} is the mean target strength estimated for a given transect and TS_i is the target strength for single fish i.

From this, the average target strength (TS_{mean}) for each transect will be calculated.

Fish Density Calculations

Results from echo integration and single target detection will be used to calculate fish density for each transect using:

$$\text{Density}\ (^{fish}/_{ha}) = \frac{\text{NASC}}{4*10^{(TSmean/10)}*343}$$

where:

NASC is the nautical area scattering coefficient ($m^2*n.mi^{-2}$), $4*10^{(TSmean/10)}$ is the average backscattering cross-section of an acoustic target (m^2), and 343 is the number of hectares per square nautical mile.

The area of lake within our defined depth strata will be used to calculate the total number of fish in the lake during the survey period. We will estimate the abundance of fish in each lake by multiplying acoustic density (fish/hectare) by the number of hectares in the survey area (> 6 m depth).

We will estimate fish densities and the standard error about the mean estimate within each lake and depth strata. Transects will be divided into segments based on our ability to detect an average minimum of 30 single fish targets in each segment. In the past, fish densities estimated at 200m horizontal segments contained > 30 single targets and were not spatially auto-correlated (Hrabik unpublished data). We will use statistics derived from non-autocorrelated segments to estimate the density and associated variance for each lake. Depth distributions will be estimated using sigma obtained for a given 1-m vertical depth interval and sigma derived for that depth estimated on a lake wide basis.

Results and Deliverables

From LCCMR 2-page proposal

Result 4: Identification of a set of habitat and fish indicators sensitive to human-caused disturbances to serve as an early warning sign of lake ecosystem stress. Budget: $422,722

Deliverable (Completion Date: July 2012)

1. Use results to inform on-going monitoring programs in sentinel lakes and a broader-range of random lakes
2. Assessment of zooplankton indicators.
3. **Evaluation of hydroacoustics to assess the status of cisco populations in inland lakes.**
4. **Evaluation of cisco habitat use and behavior.**

For deliverables 3 and 4, we are requesting $100,000. Most of the remaining budget request of Result 4 is to support basic data collection needs (water quality, aquatic plants, fish) for all Results in this study.

The results of this project will provide a template for future hydroacoustic surveys in Minnesota lakes as well as direct estimates of population density of cisco in seven sentinel lakes in two consecutive years. DNR Fisheries is making a concerted effort towards establishing a hydroacoustics program to assess habitats and fish populations in Minnesota lakes. This much needed baseline work and close involvement with an expert in the field of fisheries acoustics will help support development of this important technology.

Furthermore, acoustic estimates will provide a baseline measurement of cisco density to which future surveys may be compared. The study will provide information on the extent to which cisco population size may be related to habitable space and identify the extent to which cisco distribution and habitat selection in a range of lakes is predictable using a set of environmental measurements. Given previous work on the topic (Hrabik 1999, Hrabik et al. 2006 and Jensen et al. 2006), we expect to find the strongest correlations between the vertical distribution of cisco and predictions from the foraging model and GRP model with predation risk components included. Furthermore, we expect to find a positive correlation between the body condition of cisco and the integrated measures of both foraging potential and GRP among lakes. Should these predictions hold true, it would indicate that GRP may be used as a measure of habitat quality for cisco and that this model may be used to simulate possible changes in cisco habitat quality with changes in thermal resources resulting from climate change and eutrophication.

Result 4, Deliverables 3 and 4 – Timeline

The study will be conducted by a graduate student in the Integrated Biosciences Program at the University of Minnesota, Duluth Campus advised by Dr. Thomas Hrabik. Field work will formally begin in summer 2010 and be completed by the end of summer 2011. This work will complement cisco research that is ongoing in DNR Fisheries research and the lead investigators (Mr. Peter Jacobson and Dr. Andrew Carlson, MN DNR Detroit Lakes and Brainerd, respectively) will collaborate with Dr. Hrabik and his graduate student on this deliverable through in-kind contributions.

Dissemination and Use

Results will be prepared for annual work program reports and culminate in a Master's Thesis. In addition, results will be presented at technical meetings and published in peer-reviewed ecological or fisheries journals after the project is complete.

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Project Manager – Dr. Donald Pereira

Dr. Pereira is the Fisheries Research and Policy Manager for the DNR. He obtained his B.S. in Biology from the University of Vermont, and graduate degrees (M.S. and Ph. D.) in Fisheries Science (Statistics minor) from the University of Minnesota. In his 28 years of experience in fisheries and aquatic sciences, he has co-authored 21 peer-reviewed articles related to fish behavior, recruitment, community ecology, and habitat interactions. Dr. Pereira spent 17 years as a DNR Research Biologist and 7 years as a Research Supervisor. He also currently maintains an adjunct faculty appointment at the University of Minnesota's Department of Fisheries, Wildlife, and Conservation Biology where we has advised five M.S. students and served on the graduate committees of ten students. In April 2007, Dr. Pereira was hired as the Fisheries Research and Policy Manager and currently oversees a research unit of 21 biologists and 3 Research Supervisors with extensive fisheries and aquatic research and management experience. Many of these biologists have been involved in the proposed project and along with our partners, will be involved with data collection, analysis, and dissemination of results through in-kind efforts.

Responsibilities

Dr. Pereira will be the primary administrator on the project who will work towards mitigating any bureaucratic hurdles that may challenge DNR's ability to deliver on the project. Dr. Pereira will oversee the budget and subcontracts. Furthermore, Dr. Pereira will be working internally to weave SLICE into DNR Fisheries' long standing Lake Survey Program supported by operational budgets.

Mr. Ray Valley is a Senior Research Biologist in the Division of Fish and Wildlife at DNR (currently reports to Dr. Pereira and Mr. Peter Jacobson, Fisheries Research Habitat Supervisor) and will be the project coordinator. Since October 2006, Mr. Valley has been at the center of the evolution and implementation of SLICE. With this project Mr. Valley will continue day-to-day coordination of partnerships, field work, and reporting. Up to now, Mr. Valley's work has largely been voluntary and has far exceeded what has been outlined in his position description. We are seeking to supplement with LCCMR funds, Mr. Valley's current 10L MAPE salary (Natural Resource Specialist Senior) with a salary commensurate to the work of a 14L MAPE Project Coordinator. Of course, Mr. Valley plans to spend much more time than the 7% FTE level of funding we are requesting from LCCMR (closer to 75% FTE). We would consider time not compensated by LCCMR as an additional in-kind contribution from DNR Fisheries

Ms. Shannon Lotthammer is the Program Manager for the Water Monitoring Section of the Environmental Analysis and Outcomes Division for the PCA. She will be overseeing all PCA operations and staff involved with collecting water quality information in the sentinel lakes. PCA will be responsible for the QA/QC and management of water quality data and coordinating lab analysis with the MN Department of Health. Water quality data collected in the sentinel lakes will follow standard protocols and be consistent with 303d (impaired waters list) assessment standards.

Most of Results 1 and 3 will fall under the direction of Dr. Richard Kiesling, a hydrologist with the Water Science Center at the US Geological Survey. Dr. Kiesling will oversee all USGS operations in the three in the super sentinel lakes including the assembly, installation and operation of water quality data platforms, the installation and operation of seasonal stream gages, and the collection and management of continuous and discrete water quality data associated with these installations. Dr. Kiesling will also direct and participate in the watershed and lake modeling efforts to develop dynamic lake water quality models in the super sentinel lakes. Dr. Kiesling will oversee one USGS hydrology technician (Ms. Meghan Roussel) who will be responsible for management of the platforms and gaging equipment and two hydrologists who will be responsible for the watershed and lake water quality models (Mr. Perry Jones). As the budget indicates, USGS budgets will match approximately 58% of what is requested from LCCMR for this work.

Result 2 will be led by Dr. Mark Edlund a paleolimnologist with the Science Museum of Minnesota's St. Croix Watershed Research Station.

Result 3 will be mostly be led by Dr. Kiesling. Dr. Kiesling will coordinate with NRRI and other entities adapting pre-existing climate and lake modeling tools to generate predictive watershed and lake models designed to model land use and climate change scenarios on lake habitats. Ray Valley will lead coordination efforts with other entities involved in lake and watershed modeling to develop a proposal for interactive web tools for planners and policy makers.

Result 4 has many facets and involves a significant amount of in-kind contributions from DNR staff and partners. Basic water quality, habitat, and fish data collection activities fall under this result. Mr. Steve Heiskary, Research Scientist at the PCA (reports to Shannon Lotthammer) will coordinate water quality data collection and management in the sentinel lakes.

Deliverable 2 - Ms. Jodie Hirsch, Invertebrate Biologist in DNR's Division of Ecological Resources will coordinate zooplankton data collection, processing and management. We are seeking LCCMR funds to pay her salary at the 10% FTE level. DNR Ecological Resources will plan to backfill Ms. Hirsch's time with a student worker or intern. We are also seeking funding from LCCMR to contract internally with DNR's Management Information Systems section or with an external contractor (we're still working out these details). Mr. Jeff Reed, Senior Research Biologist in DNR's Division of Fish and Wildlife will be responsible for much of the dissemination of the zooplankton results. Mr. Reed's contribution on Result 4 will be in-kind and supported by DNR Fisheries budgets.

Deliverables 3 and 4 - Dr. Tom Hrabik will lead a graduate research project evaluating hydroacoustic technologies to assess the status of cisco in the sentinel lakes. Dr. Hrabik and his TBA M.S. graduate research assistant will also collaborate with Mr. Peter Jacobson and Dr. Andrew Carlson in DNR Fisheries Research on questions surrounding cisco habitat use and behavior.

Other partners not explicitly involved in this proposal but who have and who will continue to provide significant in-kind contributions include many internal partners in DNR Divisions of Ecological Resources, Waters, and Parks, NRRI (Dr. Lucinda Johnson, Ms. Jennifer Olker, and Dr. Richard Axler), U of MN (Dr. Raymond Newman and Dr. Joe Magner), and the US Forest Service – Superior National Forest (Mr. Jason Butcher)

Participant Vitae

Dr. Donald P. Pereira
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Education:

Ph. D. Fisheries (Statistics minor) 1992, University of Minnesota, St. Paul, MN
M. S. Fisheries (Statistics minor) 1983, University of Minnesota, St. Paul, MN
B. S. Biological Sciences 1980, University of Vermont, Burlington, VT

Professional Employment:

2007-present – Fisheries Research & Policy Manager, Minnesota Department of Natural Resources, St. Paul, MN
2000-2007 – Fisheries Research Program Supervisor Senior, Minnesota DNR, St. Paul, MN
1993-present – Adjunct Assistant Professor, Graduate Faculty, University of Minnesota, Department of Fisheries, Wildlife and Conservation Biology, St. Paul, MN
1991-2000 – Senior Fisheries Research Biologist, Minnesota DNR, St. Paul, MN
1985-1991 – Senior Fisheries Research Biologist, Minnesota DNR, Glenwood, MN (educational leave from 1987 to 1991)
1983-1985 – Assistant Fisheries Research Biologist, Minnesota DNR, Grand Rapids, MN

Scientific and Professional Memberships:

American Association for the Advancement of Science; American Fisheries Society; American Institute of Fishery Research Biologists, Fellow; Sigma Xi

Select Publications:

Pereira, D.L., Y. Cohen, and G.R. Spangler. 1992. Dynamics and species interactions in the commercial fishery of the Red Lakes, Minnesota. Canadian Journal of Fisheries and Aquatic Sciences 49:293-302.

Pereira, D.L., C.S. Anderson, P. Radomski, T. Sak, and A. Stevens. 1995 Potential to index climate with growth and recruitment of temperate fishes. In R.J. Beamish [ed.] Climate change and northern fish populations. Canadian Special Publications of Fisheries and Aquatic Sciences 121:709-717.

Pereira, D.L., M.G. Halverson, R.E. Ramsell, and M.T. Drake. 2002. Changes in the largemouth bass fishery of Lake Minnetonka, Minnesota: evidence from tournament monitoring. Pages 513-524, in D.P. Philipp and M.S. Ridgway, editors. Black bass: ecology, conservation and management, American Fisheries Society, Symposium 31, Bethesda, Maryland.

Pereira, D.L. and Michael J. Hansen. 2003. A perspective on challenges to recreational fisheries management: summary of the symposium on active management of recreational fisheries. North American Journal of Fisheries Management 23:1276-1282.

Maceina, M.J. and D.L. Pereira. 2007. Recruitment. Pages 121 – 186 in C.S. Guy and M.L. Brown, editors. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

Ray D. Valley

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Education

M.S. Fisheries (Specialization in Ecology, Evolution, Behavioral Biology) 2000. Michigan State University, East Lansing MI.

B.S. Fisheries (High Distinction) 1998. University of Minnesota – St. Paul

Positions Held

2006-present – Senior Fisheries Research Biologist, Minnesota DNR, St. Paul, MN.

2001-2006 – Fisheries Research Biologist, Minnesota DNR, St. Paul, MN.

2000-2001 – District Fisheries Biologist, USDA Forest Service, Chippewa National Forest.

Professional Activities and Committees

2006-present – Member of the American Fisheries Society's Resource Policy subcommittee on Global Climate Change

2003-2007 – Co-chair of the Continuing Education Committee for the MN chapter of the American Fisheries Society

2001-present – peer-referee for 10 articles submitted to Ecological or Fisheries journals.

Peer-reviewed Publications

Valley, R.D. and M.T. Drake. 2007. What does resilience of a clear-water state in lakes mean for the spatial heterogeneity of macrophyte biovolume? Aquatic Botany 87:307-319.

Valley, R.D., W. Crowell, C. Welling, N. Proux. 2006. Effects of low dose applications of fluridone on submersed aquatic vegetation in a eutrophic Minnesota lake dominated by Eurasian watermilfoil and coontail. Journal of Aquatic Plant Management 44:19-25.

Bremigan, M.T., S.M. Hanson, P.A. Soranno, K.S. Cheruvelil, and R.D. Valley. 2006. Aquatic vegetation, largemouth bass and water quality responses to low-dose fluridone two years post treatment. Journal of Aquatic Plant Management 43:65-75

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.

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. Bremigan. 2002. Effects of selective removal of Eurasian watermilfoil on age-0 largemouth bass piscivory and growth in southern Michigan lakes. Journal of Aquatic Plant Management 40(2):79-87.

Valley, R.D. and M.T. Bremigan. 2002. Effects of macrophyte bed architecture on largemouth bass foraging: implications of exotic macrophyte invasions. Transactions of the American Fisheries Society 131(2):234-244.

Valley, R.D. and R.M. Newman. 1998. Competitive interactions between Eurasian watermilfoil and northern watermilfoil in experimental tanks. Journal of Aquatic Plant Management 36(2):121-126.

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University of Texas
Environmental Sciences Institute
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The University of Texas at Austin
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Research Interests:
Current research and interests include: modeling the effect of landuse and hydrologic modifications on nutrient fate and transport in watershed-reservoir systems; linking spatial analysis of watersheds with mechanistic, biological response models; developing of nutrient criteria through the use of predictive, developing and testing indicators of stream trophic status in response to watershed eutrophication

Education
1980 B.S. University of Minnesota, Minneapolis, MN
1990 Ph. D. University of Michigan, Ann Arbor, MI

Professional Experience:
US Geological Survey
- Research Scientist, 8/01 to present

University of Minnesota
- Research Associate. Dept. of Fisheries, Wildlife, and Conservation Biology

2/2006 to 2/2008

University of Texas
- Research Fellow, Environmental Science Institute, 1/2002 to present.

Tarleton State University:
- Adjunct Professor, Environmental Sciences, Tarleton State University, 1/99 to 8/07
- Research Scientist, Environmental Sciences Program, Texas Institute for Applied Environmental Research; Tarleton State University, 1/98 to 8/01

Water Quality Consultant, Environmental Policies and Institutions for Central Asia, US Agency for International Development, Almaty, Republic of Kazakstan, 4/99 to 8/99

Visiting Assistant Professor, Wildlife and Fisheries Department, Texas A&M University 6/93-12/93

Texas Natural Resource Conservation Commission:
- Research Scientist and Team Leader, Ecosystem Research and Assessment Team, Research and Environmental Assessments Division 1993 to 1997
- Research Scientist, Science Policy and Research Section, Standards and Assessment Division, Texas Water Commission, 1992 to 1993
- Aquatic Ecologist, Water Quality Standards Team, Standards and Assessment Division, Texas Water Commission, 1990 to 1992

Professional Affiliations:

American Society of Limnology and Oceanography

Phycological Society of America

Soil and Water Conservation Society

Refereed Publications:

Baker, J.W., J.P. Grover, B.W. Brooks, F. Ureña-Boeck, D.L. Roelke, R.M. Errera, R. Kiesling. 2007. Growth and toxicity of Prymnesium parvum (Haptophyta) as a function of salinity, light and temperature. Journal of Phycology. 43:219-227.

Grover, J.P., J.W. Baker, F. Ureña-Boeck, B.W. Brooks, R. Errera, D.L. Roelke, R.L. Kiesling. 2007. Laboratory tests of ammonium and barley straw extract as agents to suppress abundance of the harmful alga Prymnesium parvum and its toxicity to fish. Water Research. 41: 2503-2512.

Roelke D.L., R. Errera, R. Kiesling, B.W. Brooks, J.P. Grover, L. Schwierzke, F. Ureña-Boeck, J. Baker, J.L. Pinckney. 2007. Effects of nutrient enrichment on Prymnesium parvum population dynamics and toxicity: Results from field experiments, Lake Possum Kingdom, USA. Aquatic Microbial Ecology. 46:125-140.

McNaught, A. S., R. L. Kiesling, and A. Ghadouani. 2004. Changes to zooplankton community structure following colonization of a small lake by Leptodora kindti. Limnology and Oceanography 49: 1239-1249.

Kiesling, R.L. 2003. Applying Indicators of Hydrologic Alteration to Texas Streams- overview of methods with examples from the Trinity River basin. U.S. Geological Survey Publication FS 128-03.

Kiesling, R.L., A. M. McFarland, and L. M. Hauck. 2001. Stream community responses to eutrophication from nonpoint source nutrient loading. In J. J. Warwick, ed., Water Quality Monitoring and Modeling. American Water Resources Association, Middleburg, Virginia, TPS-01-1, 284 pp.

Kiesling, R.L. and L. M. Hauck. 1999. The use of nutrient bioassays in TMDL target development. In R. Sakrison and P. Strurtevant, eds., Watershed Management to Protect Declining Species. American Water Resources Association, Middleburg, Virginia, TPS-99-4, 561 pp.

Kiesling, R.L. with R.J. Garono, E.Wold, S. Schooler, and D. Bradsby. 1998. Adult Insect Assemblages as a Conservation Planning Tool. . Verh. Internat. Verein. Limnol. In press. (Proceedings of the 27th Congress of the International Association of Theoretical and Applied Limnology, Dublin, Ireland)

Kilham, S. S., and R. L. Kiesling. 1991. Algal-consumer interactions in two-stage continuous culture: the role of species-specific algal mortality rates during competition. Verh. Internat. Verein. Limnol. 24: 1277-1280.

Tilman, D., R.L. Kiesling, R. Sterner, S.S. Kilham, and F. A. Johnson. 1986. Green, bluegreen and diatom algae: Taxonomic differences in competitive ability for phosphorus, silicon and nitrogen. Arch. Hydrobiol. 106: 473-485.

Tilman, D. and R.L. Kiesling. 1984. Freshwater algal ecology: taxonomic tradeoffs in the temperature dependence of nutrient competitive abilities. In: M.J. Klug and C.A. Reddy, eds., Current Perspectives in Microbial Ecology. Amer. Soc. Microbiology, Washington, D.C.

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Technical Publications:

Kiesling, R. L. A.M. S. McFarland, and L. M. Hauck. 2001. Analysis of PL-566 reservoir production responses along a nutrient loading gradient. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR108.

Kiesling, R. L., L. M. Hauck, and A.M. S. McFarland,. 2001. Nutrient targets in the Bosque River watershed: developing ecosystem restoration criteria for a eutrophic watershed. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR0107.

Kiesling, R. L. with A.M. S. McFarland, and C Pearson. 2001. Lake Waco – Characterization of a central Texas reservoir. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, RR0104.

Kiesling, R. L. with A.M. S. McFarland, and L. Hauck. 2001. Fate and transport of soluble reactive phosphorus in the North Bosque River of central Texas. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, RR0101.

Kiesling, R. L. with J. F. Flowers, and L. M. Hauck. 2001. Water Quality Modeling of Lake Waco Using CE-QUAL-W2 for Assessment of Phophorus Control Strategies. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR0114.

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Education

1993 Master of Science in Geology (Ground-water Geology), University of Minnesota, Minor in Civil Engineering, Advisor: H. O. Pfannkuch

1985 Bachelor of Science in Geology, State University of New York, Cortland, Minor in Music, Advisor: J. Bugh

Professional Experience

1995 – present **Hydrologist, U. S. Geological Survey, Minnesota Water Science Center.**

1989 - 1995 **Hydrogeologist/Geologist, U. S. Bureau of Mines, Twin Cities Research Center.**

1987 - 1989 **Hydrologist/Research Assistant, Minnesota Board of Soil and Water Resources.**

1985 - 1987 **Teaching and Research Assistant, University of Minnesota, Department of Geology/Geophysics.**

PUBLICATIONS

Jones, P. M., 2006, Ground-water/surface-water interaction in nearshore areas of three lake on the Grand Portage Reservation, northeastern Minnesota, 2003-04, U.S. Geological Survey, Scientific Investigations Report, 2006-5034, 49 p.

Jones, P.M., 2005, Simulated effects of water-level changes in the Mississippi River and Pokegama Reservoir on ground-water levels, Grand Rapids area, Minnesota: U.S. Geological Survey Scientific Investigation Report, 2005-5139, 18p.

Jones, P.M., 2004, Simulation of ground-water flow in glaciofluvial aquifers in the Grand Rapids area, Minnesota: U.S. Geological Survey Scientific Investigation Report, 2004-5159, 23 p.

Lannoo M.J., Sutherland D.R., Jones P., Rosenberry D., Klaver R.W., Hoppe D.M., Johnson P.T.J., Lunde K.B., Facemire C., and Kapfer J.M., 2003, Multiple causes for the malformed frog phenomenon, *in* Linder, G., Little, E., Krest, S., and Sparling, D., eds., Symposium on Multiple Stressor Effects in Relation to Declining Amphibian Populations: American Society for Testing and Materials, West Conshoshocken, Pennsylvania, ASTM STP 1443.

Jones, P.M., 2002, Characterization of ground-water flow between the Canisteo mine pit and surrounding aquifers, Mesabi Iron Range, Minnesota, U.S. Geological Survey, Water-Resources Investigations Report, 02-4198, 30 p.

Jones, P.M., 2002, Chemical sampling at malformation sites: People, Land & Water (news magazine of the U.S. Department of the Interior), v. 9, no. 1, p. 31.

Jones, P.M. and Menheer, M.A., 2002, Surface-Water Microlayer Sampler Used at Frog-Malformation Sites, WRD Instrument News, March, 2002, p. 1-6.

Jones, P.M. and Winterstein, T.A., 2000, Characterization of rainfall-runoff response estimation of the effect of wetland restoration on runoff, Heron Lake Basin, southwestern Minnesota, 1991-97, U.S. Geological Survey, Water-Resources Investigations Report, 00-4095, 48 p., I CD Rom.

Jones, P.M. and J. Oswald, 1994. Hydrologic Assessment of Wellhead Protection in Mining Regions. In the Proceedings of the 1994 American Water Works Association Annual Conference, New York, June 19-22, p. 219-229.

Jones, P.M. and J.L. Ellenberger, 1994. Hydrologic Assessment of Wellhead Protection in the Vicinity of a Room-and-Pillar Coal Mine. In the Proceedings of the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, April 24-29, v. 2, p. 281-288.

Ellenberger, J. L. and P. M. Jones, 1994. Rock Quality Alteration Surrounding Drifts and an In Situ Leaching Design Using Underground Workings. Proceedings of the 1994 Society for Mining, Metallurgy, and Exploration, Inc., Annual Meeting, Albuquerque, NM, Print No. 94-244.

Jones, P. M., 1992. Factors Affecting Solution Balance During In Situ Leaching of an Unsaturated Ore Body. Minerals and Metallurgical Processing, August, 1992, p. 110-114.

Earley, D. III and P. M. Jones., 1992. Geochemical Effects on the Hydrology of In Situ Leach Mining of Copper Oxide Ore at the Cyprus Casa Grande Mine, Arizona. Proceedings of the 1992 Society for Mining, Metallurgy, and Exploration, Inc. Annual Meeting, Phoenix, AZ., Print No. 92-242.

Friedel, M. J., R. D. Schmidt, P. M. Jones, and Y. C. Kim., 1992. Geostatistical Analysis of Dynamic Transmissivity Conditions During In Situ Copper Leaching. In 23rd Application of Computers and Operations Research in the Mineral Industry, Port City Press, Baltimore, MD, p. 49-61.

Jones, P. M., 1991. Factors Affecting Solution Balance During In Situ Leaching of an Unsaturated Copper Ore Body. Proceedings of the 1991 Society for Mining, Metallurgy, and Exploration, Inc., Annual Meeting, Denver, CO, Print No. 91-633.

Jones, P. M., 1991. Nitrate Transport Through a Portion of the Anoka Sand Plain Aquifer, Central Minnesota. M.S. Thesis, University of Minnesota, Department of Geology and Geophysics.

Pfannkuch, H. O., P. M. Jones, and L. Guo, 1987. Groundwater Systems Analysis and Modeling. In File Structure Design and Data Specifications for Water Resources Geographic Information Systems, Water Resources Research Center, University of Minnesota, Special Report no. 10, Pages 13-1 - 13-67.

DR. MARK B. EDLUND

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Professional Preparation

University of Minnesota, Twin Cities Campus, Biochemistry, B.S. (1987)
University of Michigan, Ann Arbor, Natural Resources, M.S. (1992)
University of Michigan, Ann Arbor, Natural Resources, Ph.D. (1998)
University of Michigan, Science Museum of Minnesota, Post-doc (1998-2001)

Appointments

2007-present, Senior Scientist, Science Museum of Minnesota, St. Croix Watershed Research Station
2002-2006, Associate Scientist, Science Museum of Minnesota, St. Croix Watershed Research Station
2001-present, Adjunct Faculty, Univerisity of Minnesota, Geology and Geophysics, Water Resources Science
2000-2002, Assistant Scientist, St. Croix Watershed Research Station, Science Museum of Minnesota
1998-2001, Postdoctoral Research Fellow, Center for Great Lakes and Aquatic Sciences, University of Michigan
1998-1999, International Research Fellow, National Science Foundation, Mongolian State University and University of Michigan
1997-1998, Rackham Predoctoral Fellow, University of Michigan
1987-1997, Research Assistant I, Ctr for Great Lakes & Aquatic Sciences, Univ of Michigan

Publications Relevant to Proposed Activity

Edlund, M. B., Engstrom, D. R., Triplett, L., Lafrancois, B. M. and Leavitt, P. R. 2009. Twentieth-century eutrophication of the St. Croix River (Minnesota-Wisconsin, USA) reconstructed from the sediments of its natural impoundment. Journal of Paleolimnology. DOI:10.1007/s10933-008-9296-1

Triplett, L. D., Engstrom, D. R. and **Edlund, M. B.** 2009. A whole-basin stratigraphic record of sediment and phosphorus loading to the St. Croix River, USA. Journal of Paleolimnology DOI:10.1007/s10933-008-9290-7

Shinneman, A. L. C., **Edlund, M. B.**, Almendinger, J. E. and Soninkhishig, N. 2009. Diatoms as indicators of water quality in Western Mongolian lakes: a 54-site calibration set. Journal of Paleolimnology DOI:10.1007/s10933-008-9282-7

Edlund, M. B., Triplett, L. D., Tomasek, M. and Bartilson, K. 2009. From paleo to policy: partitioning of historical point and nonpoint phosphorus loads to the St. Croix River, Minnesota-Wisconsin, USA. Journal of Paleolimnology DOI: 10.1007/s10933-008-9288-1

Serieyssol, C. A., **Edlund, M. B.** and Kallemeyn, L.W. 2009. Impact of logging, damming, and hydromanagement on two boreal lakes: a paleolimnological before—after, control—impact study. Journal of Paleolimnology DOI:10.1007/s10933-008-9300-9

Edlund, M. B. and Stoermer, E. F. 2000. A 200,000-year, high-resolution record of diatom productivity and community makeup from Lake Baikal shows high correspondence to the marine oxygen-isotope record of climate change. Limnology and Oceanography 45:948-962.

Heiskary, S. A., Swain, E. M. and **Edlund, M. B.** 2004. Reconstructing Historical Water Quality in Minnesota Lakes from Fossil Diatoms. Environmental Bulletin No. 4: 1-8.

Edlund, M. B., Stoermer, E. F. and Pilskaln, C. H. 1995. Siliceous microfossil succession in the recent history of two basins in Lake Baikal Siberia. J. Paleolimnol. 14:165-184.

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Education
B.S. Fisheries – 1982 University of Minnesota – St. Paul.

Current Position
1991-present Natural Resource Specialist-Aquatic Biologist (Division of Ecological Resources)

Other Positions Held
Natural Resource Specialist-Section of Fisheries
Natural Resource Specialist-Section of Ecological Services

Current projects:
- Uses and influences of rotenone on walleye rearing ponds in southern Minnesota. (Report is currently in the review process).
- Mississippi River Long Term Monitoring Program- Lake Pepin zooplankton community analysis.
- Zooplankton community analysis of the Upper Mississippi River prior to Asian carp invasion.
- Zooplankton community analysis of Voyagers National Park lakes- before and after Bythotrephes longimanus invasion.
- Zooplankton community analysis of Lake of the Woods- before and after *Bythotrephes longimanus* invasion.
- Zooplankton community analysis of Mille Lacs Lake before and after *Dreissena polymorpha* invasion.
- Development of aquatic macroinvertebrate indices of biotic integrity for Minnesota lakes.

Reports and Publications
Burdis, R.M. and J.K. Hirsch. 2005. Establishment of a viable population of Daphnia lumholtzi in Lake Pepin, Upper Mississippi River. Journal of Freshwater Ecology 20:205-207.
Parsons, B.G., J.R. Reed, H.G. 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, Fisheries Investigational Report 514, St. Paul.
Hirsch, J.K., and M.T. Negus. 2000. Fall stocking of rainbow trout in Bad Medicine Lake: A bioenergetics assessment of impacts on the Daphnia pulex population. Minnesota Department of Natural Resources, Fisheries Special Publication No. 155, St. Paul.
Montz, G.R. and J.K. Hirsch. 2000. The Odonata of Camp Ripley military reservation. Minnesota Department of Natural Resources, Ecological Services Section, St. Paul.
Westerlund, J.E., P.C. Jacobson, H.K. Van Offelen, 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, Fisheries Investigational Report 467, St. Paul.

Hirsch, J.K. 1998. Nonindigenous fish in inland waters: Response plan to new introductions. Minnesota Department of Natural Resources, Fisheries Special Publication No. 152, St. Paul.

Montz, G.R. and J.K Hirsch. 1996. An assessment of the aquatic invertebrate community in impact and non-impact zones of Camp Ripley military reservation. Minnesota Department of Natural Resources, Ecological Services Section, St. Paul.

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Education:

M.S. Fisheries Biology 1990 Auburn University.
B.S. Biology (Zoology Emphasis) 1986, University of Wisconsin – Oshkosh.

Experience:

Fisheries Research Biologist – Senior, Minnesota Department of Natural Resources (September 2000 Present).
Fisheries Research Biologist – Intermediate, Minnesota Department of Natural Resources (May 1991 - September 2000)
Fisheries Management Specialist, Minnesota Department of Natural Resources (September 1990 – May 1991)
Research Associate, Auburn University, Department of Fisheries and Allied Aquacultures (January 1990 – September 1990)

Professional Service

2005 Chair, NCD Walleye Technical Committee (Elected)
2004 Chair, NCD Walleye Technical Committee (Elected)
2003 Chair-Elect, NCD Walleye Technical Committee
2003 North Central Division Walleye Tech Committee Rep. for MN
2000 Certified Fishery Professional
1999-2000 Minnesota Chapter Executive Committee (Elected)
1998-2000 AFS Resource Policy Committee
1994-1998 Minnesota Chapter Membership Committee Chair
1996-1998 AFS Most Active Chapter Award Committee
1994-1996 AFS Meritorious Achievement Award Committee
1992-1993 North Central Division Esocid Tech. Committee Chair (Elected)
1989-1990 Auburn University Chapter, Vice President (Elected)

Select Publications

Reed, J.R., and W.D. Davies. 1991. Population Dynamics of Black Crappies and White Crappies in Weiss Reservoir, Alabama: Implications for the Implementation of Harvest Restrictions. North American Journal of Fisheries Management 11:598-603.

Reed, J.R., and B.G. Parsons. 1996. Observations on Predation of Small Bluegill in a Minnesota Centrarchid Lake. Minnesota Department of Natural Resources Fisheries Investigational Report No. 452, St. Paul.

Reed, J.R., and B.G. Parsons. 1999. Influence of Walleye Fingerling Production on Wetland Communities. Minnesota Department of Natural Resources Fisheries Investigational Report No. 477, St. Paul.

Reed, J.R., and B.G. Parsons. 1999. Angler Opinions of Bluegill Management and Related Hypothetical Effects on Bluegill Fisheries in Four Minnesota Lakes. North American Journal of Fisheries Management 19:515-519.

Reed, J.R. 2006. Effects of landscape-scale factors on wetland biomanipulations. Minnesota Department of Natural Resources Fisheries Investigational Report No. 533, St. Paul.

Reed, J.R., M. L. McInerny and L. Erickson-Eastwood. 2009. Development of standardized, state-wide regulations for Minnesota lakes – using crappie as an example. North American Journal of Fisheries Management, Reservoir Symposium Special Edition.

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.

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Education

Ph.D. (Oceanography and Limnology) University of Wisconsin-Madison 1999
M.S. (Oceanography and Limnology) University of Wisconsin-Madison 1995
B.S. (Biology) University of Wisconsin-Stevens Point 1993

Positions Held

2006- present Associate Professor, Department of Biology, University of Minnesota-Duluth, Graduate Facutly: Water Resources Science, Department of Biology

2001- 2006 Assistant Professor, Department of Biology, University of Minnesota-Duluth, Graduate Facutly: Water Resources Science, Department of Biology

2002-Present Senior Research Associate, Center for Water and the Environment, Natural Resources Research Institute, University of Minnesota

2002-Present Adjunct Assistant Professor, Large Lakes Observatory, University of Minnesota

1999-2000 Research Associate, NTL-LTER, University of Wisconsin-Madison

1998 Project Assistant, NTL-LTER, University of Wisconsin-Madison

1993-1998 Research Assistant, NTL-LTER, University of Wisconsin-Madison

Professional Activities

1999-present -- Participated as reviewer for over 40 articles submitted to: Aquatic Ecosystem Health and Management, Canadian Journal of Fisheries and Aquatic Science, Ecology, Journal of Plankton Research, Hydrobiologia, Journal of Great Lakes Research, Fisheries, Transactions of the American Fisheries Society, Landscape Ecology, Ecological Modeling and the Marine Ecology Progress Series. Have also reviewed research proposals for the National Science Foundation, Michigan Sea Grant, New York Sea Grant, National Sea Grant and the National Marine Fisheries Service.

2003-present -- Associate Editor for: the Journal of Great Lakes Research

Peer Reviewed Publications

Yule, D.L., J.D. Stockwell, D.R. Schreiner, L.M. Evrard, M. Balge, and T.R. Hrabik. In Press. 2008. Seasonal Abundance of Pelagic Forage Fishes and Spawning-Size Cisco in the Western Arm of Lake Superior. Fisheries Research.

Stockwell, J.S., M.P. Ebener, J.A.Black, T.R. Hrabik, R.A. Kinnunen, W.P. Mattes, J.K. Oyadamari, S.T. Schram, D.R. Schreiner, M.J. Seider, S.P. Sitar, and D.P. Yule. In Press. A synthesis of cisco (Coregonus artedi) in Lake Superior: implications for native fish recovery in the Great Lakes. North American Journal of Fisheries Management.

Jensen, O.P., P.M. Yurista, T.R. Hrabik, J.D. Stockwell. 2008. Densities and diel vertical migration of /Mysis relicta/ in Lake Superior: a comparison of optical plankton counter and net-based approaches. Verh. Internat. Verein. Limnol.

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Jensen, O.P. T. R. Hrabik, S.J.D. Martell, C.J. Walters and J. F. Kitchell. 2006. Diel vertical migration in a Lake Superior pelagic community: modeling trade-offs at three trophic levels. Canadian Journal of Fisheries and Aquatic Sciences 63: 2296-2307.

Sass, G.G, J. F. Kitchell, S. R. Carpenter, T. R. Hrabik, A. Sugden-Newberry, T. K. Kratz and M. G. Turner. 2006. Fish community and food web responses to a whole-lake removal of coarse woody habitat. Fisheries 31: 321-330

Danz, N.P., G.J. Niemi, R.R. Regal, T. Hollenhorst, L. Johnson, J. Hanowski, R. Axler, J. Ciborowski, T.R. Hrabik, V. J. Brady, J.R. Kelly, J.C. Brazner, and R. W. Howe. 2006. Integrated measures of anthropogenic stress in the U.S. waters of the Laurentian Great Lakes. Environmental Management.

Mercado – Silva, N., J. D. Olden, J. T. Maxted, T. R. Hrabik, M. J. Vander Zanden. 2006. Invasion potential of rainbow smelt (*Osmerus mordax*; Pisces: Osmeridae) in the Great Lakes region: predictions from distribution in their native range. Conservation Biology 20: 1740-1749.

Mason, D.M., T.B. Johnson, C.J. Harvey, J.F. Kitchell, S.T. Schram, C.R. Bronte, M.H. Hoff, S. J. Lozano, A. S. Trebitz, D. R. Schreiner, E. C. Lamon, and T.R. Hrabik. 2005. Hydroacoustic estimates of abundance and spatial distribution of pelagic fishes in western Lake Superior. Journal of Great Lakes Research 31:426-438.

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Hrabik, T.R., B.K. Greenfield, D. B. Lewis, A. I. Pollard, K. A. Wilson and T. K. Kratz 2005. Landscape scale variation in taxonomic diversity in four groups of aquatic organisms: the Influence of physical, chemical and biological properties. Ecosystems 8:301-317

Wilson, K.A. and T. R. Hrabik. 2005. The impacts and spread of invading exotic species in north-temperate lakes. In Long-Term Dynamics of Lakes in the Landscape. Edited by Magnuson, J. J., T. K. Kratz and B. Benson. Oxford University Press.

Richmond, H.E., T. R. Hrabik and A. F.Mensinger. 2004. Foraging mechanisms of age-0 yellow perch (*Perca flavescens*). J. Fish. Biol. 65 (1): 195-205

Hrabik, T. R. and C. J. Watras. 2002 Recent declines in mercury concentration in a freshwater fishery: the effects of de-acidification and decreased atmospheric mercury deposition. The Science of the Total Environment 297:229-237

Lathrop, R.C., B. M. Johnson, T. B. Johnson, M. T. Vogelsang, S. R. Carpenter, T. R. Hrabik, J. F. Kitchell, J. J. Magnuson, L. G. Rudstam, and R.S. Stewart. 2002. Stocking piscivores to improve fishing and water clarity: a synthesis of the Lake Mendota biomanipulation project. Freshwater Biology: 47:2410-2424

Greenfield, B.K., T.R. Hrabik, C.J. Harvey, S.R. Carpenter and T. K. Kratz. 2001. Predicting mercury levels in fish: use of water chemistry, trophic ecology, and spatial traits. Canadian Journal of Fisheries and Aquatic Sciences 58: 1419-1429

Hrabik, T. R., M. P. Carey and M. S. Webster. 2001. Interactions between young-of-year exotic rainbow smelt and native yellow perch in a northern temperate lake. Transactions of the American Fisheries Society 130:568-582.

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