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INFLUENCES OF WATERSHED PARAMETERS ON FISH POPULATIONS IN SELECTED MINNESOTA LAKES OF THE CENTRAL HARDWOOD FOREST ECOREGION[1]

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Abstract - We identified associations between watershed factors and catches of fish in lake survey nets from a selected class of physically similar southern Minnesota natural lakes. Data sets of environmental and natural resource characteristics and a geographic information system (GIS) developed by the State of Minnesota were used to obtain descriptive inventories of watershed characteristics. Principal Component Analysis was used to reduce the dimensionality of intercorrelated watershed landscape variables. Likewise, the dimensionality of fish catches in lake survey nets were reduced with separate principal component analyses. Interpretations of these analyses suggest that for ecological Lake Class 24 waters, smaller or less cultivated and more forested watersheds favored largemouth bass *Micropterus salmoides*, yellow bullhead *Ameiurus natalis*, sunfish *Lepomis spp.*, and northern pike *Esox lucius*. Conversely, lakes with larger or more cultivated and less forested watersheds favored black crappie *Pomoxis nigromaculatus*, black bullhead *Ameiurus melas*, and common carp *Cyprinus carpio*. GIS is potentially a powerful tool that could be used to formulate plans and foster public support for watershed management activities.

Introduction

Fisheries managers are focusing on holistic watershed and fish community levels (Platts 1980; Kerr 1982; Tonn et al. 1983; Bickford and Tisa 1992). Holistic management approaches are needed for Minnesota lakes because fish populations are significantly affected by watershed landscape factors such as post-glacial dispersal, connectiveness to other water bodies, and water quantity and quality. Differences in fish assemblages among many lakes in Minnesota and Ontario are the result of post-glacial dispersal of fishes in different drainages (Underhill 1989; Jackson and Harvey 1989; Hinch et al. 1991). Even within drainages, fish communities are affected by connections among water bodies that allow fish to

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exchange (Tonn and Magnuson 1982; Robinson and Tonn 1989; Osborne and Wiley 1992). Differences in fish communities and yield among Minnesota lakes have been attributed to regional variation in trophic status and chemical composition associated with the landscape (Moyle 1956; Schupp 1992). Schupp (1992) found water quality factors (Secchi transparency, total alkalinity, morphoedaphic index, and Carlson's trophic state index) were useful along with lake morphometry parameters in discriminating fish communities among Minnesota lakes.

The quantity and quality of water entering a lake is largely determined by watershed factors. The volume of surface runoff entering a lake is influenced by the size, slope, soil type, and land use within the watershed (Hjelmfelt and Cassidy 1975). This inflow carries organic matter, nutrients, sediments, and chemicals from human activities (Farnworth et al. 1979). Effects of these inputs to lakes can be modified by the watershed area:lake area ratio, hydraulic residence time, and source of inflow (i.e. seepage, surface runoff, tiling, ditching, urban storm sewers, streams, wetlands, and lakes) (Schindler 1971; Vollenweider 1976; Wischmeier and Smith 1978). Wilson and Walker (1989) were able to predict phosphorus, chlorophyll *a*, and water transparency in Minnesota lakes from watershed area, depth, and average runoff and stream phosphorus concentration characteristics of ecoregions.

Nutrient concentrations in lakes are closely associated with land-use practices within watersheds. According to the National Research Council, most of the nutrient input to the majority of U.S. lakes is contributed by urban and agricultural runoff (NRC 1992). Fandrei et al. (1988) reported higher epilimnetic total phosphorus concentrations in Minnesota lakes were associated with increased cultivated land and decreased water and forested land in their watersheds. Based on previous studies, Heiskary and Wilson (1990) reported that developed land-use can be expected to play a significant role in water quality based on rates of phosphorus export that are greater than or equal to that of cultivated land.

The quantity and quality of water draining into lakes from their watersheds can affect the abundance and species of fish found in lakes. Lakes with high flushing rates tend to provide less stable environments which are associated with decreased fish production (Carline 1986; Marshall and Ryan 1987; Regier and Henderson 1973). More direct effects on fish populations result from sediment loading and turbidity which result in physiological and reproductive impairments (Farnworth et al. 1979; Muncy et al. 1979). Changes in fish production and species composition have also occurred along gradients of lake productivity associated with nutrient loading (Leach et al. 1977; Downing et al. 1990; Bergman 1991; Persson et al. 1991). Chlorophyll concentrations, an indicator of lake productivity, have been linked to the harvest of sport fish and yields of *Stizostedion* spp. (Jones and Hoyer 1982; Oglesby et al. 1987).

Despite the potential influences of watersheds on fish communities, little information exists on interactions between fish populations in north-temperate natural lakes and watershed parameters. Oglesby (1982) suggests that hydraulic retention and edaphic watershed factors be analyzed to improve predictions of fish production. Watershed area and other abiotic variables were found useful for classifying fish communities in northern Wisconsin lakes (Tonn et al. 1983). In addition, Hill (1986) found that watershed size and basin slope explained differences in the standing stock of desirable sport fish in small Iowa impoundments.

In recent years, tools to analyze landscape characteristics have been developed that provide fisheries professionals with lake watershed information that was previously unavailable or difficult to obtain. Geographic information systems (GIS) have been developed to analyze descriptive inventories of geographic attributes (Berry 1993). GIS can be used to link land-use to lake and stream characteristics. As a result, single and cumulative effects of land-use on lakes and streams can be determined (Giles and Nielson 1992). In Minnesota metropolitan lakes, Detenbeck et al. (1993) used GIS to record and measure landscape variables that explained much of the variation in lake trophic status.

Presently, fisheries managers are moving toward more holistic approaches which necessitate evaluation of human disturbances on lake ecosystems. The MNDNR (1993) recommends that fish managers examine the effects of fish habitat (water quality) on both fish community and individual fish species. Information on watershed effects that can assist managers is presently lacking. The objective of this study was to identify relationships between watershed characteristics and fish populations in a selected Lake Class of central Minnesota lakes with similar morphometry.

Study Area

A set of 40 physically similar central Minnesota lakes from 10 counties (ecological Lake Class 24 - Schupp 1992) were selected for this study (Table 1). Class 24 lakes have a mean surface area of 147 ha with 40% littoral area, maximum depth of 19 m, total alkalinity

Table 1. Study lakes and associated MNDNR, Division of Waters (DOW) major and minor watersheds.

County	Lake abbv.	Lake name	DOW lake number	DOW major watershed	DOW watershed number
Carver	MN	Minnewashta	10-009	Mississippi R.	20055
	AN	Ann	10-012	Minnesota R. (Shakopee)	33117
	SH	Schutz	10-018	Mississippi R.	20054
	BA	Bavaria	10-019	Minnesota R. (Shakopee)	33115
	ZU	Zumbra	10-041	Mississippi R.	20054
	PI	Pierson	10-053	Mississippi R.	20054
Douglas	GR	Grants	21-150	Long Prairie R.	14023
	SP	Spring	21-130	Long Prairie R.	14008
Hennepin	CA	Calhoun	27-031	Mississippi R.	20094
	CE	Cedar	27-039	Mississippi R.	20094
	BR	Bryant	27-067	Minnesota R. (Shakopee)	33141
	ME	Medicine	27-104	Mississippi R.	20096,20097
	FI	Fish	27-118	Mississippi R.	20098
	CM	Christmas	27-137	Mississippi R.	20055
	SA	Sarah	27-191	North Fork Crow R.	18084
Lesueur	VO	Volney	40-033	Cannon R.	39103
	GE	German	40-063	Cannon R.	39106,39107
Meeker	MI	Minniebelle	47-119	North Fork Crow R.	18049
Rice	DU	Dudley	66-014	Cannon R.	39100
	FO	Fox	66-029	Cannon R.	39083
	FR	French	66-038	Cannon R.	39100
	MZ	Mazaska	66-039	Cannon R.	39083
Stearns	BF	Big Fish	73-106	Sauk R.	16014
	PI	Pine	73-136	Mississippi R.(Sartell)	15017
	ED	Eden	73-150	Sauk R.	16059,16006,16007
	KI	Kings	73-233	Sauk R.	16028
Todd	LO	Long	77-027	Mississippi R.(Brainerd)	10133
	LA	Lady	77-032	Mississippi R.(Brainerd)	10133
Washington	BC	Big Carnelian	82-049	St. Croix R.	37068
Wright	CH	Charlotte	86-011	North Fork Crow R.	18087
	PU	Pulaski	86-053	North Fork Crow R.	18073
	MA	Maple	86-134	North Fork Crow R.	18014
	ID	Ida	86-146	Mississippi R.(St. Cloud)	17003
	MR	Mary	86-156	Mississippi R.(St. Cloud)	17004
	MA	Mary	86-193	North Fork Crow R.	18076
	HO	Howard	86-199	North Fork Crow R.	18078
	CP	Camp	86-221	North Fork Crow R.	18079
	CD	Cedar	86-227	Mississippi R.(St. Cloud)	17009
	SU	Sugar	86-233	Mississippi R.(St. Cloud)	17072
	PL	Pleasant	86-251	Mississippi R.(St. Cloud)	17073

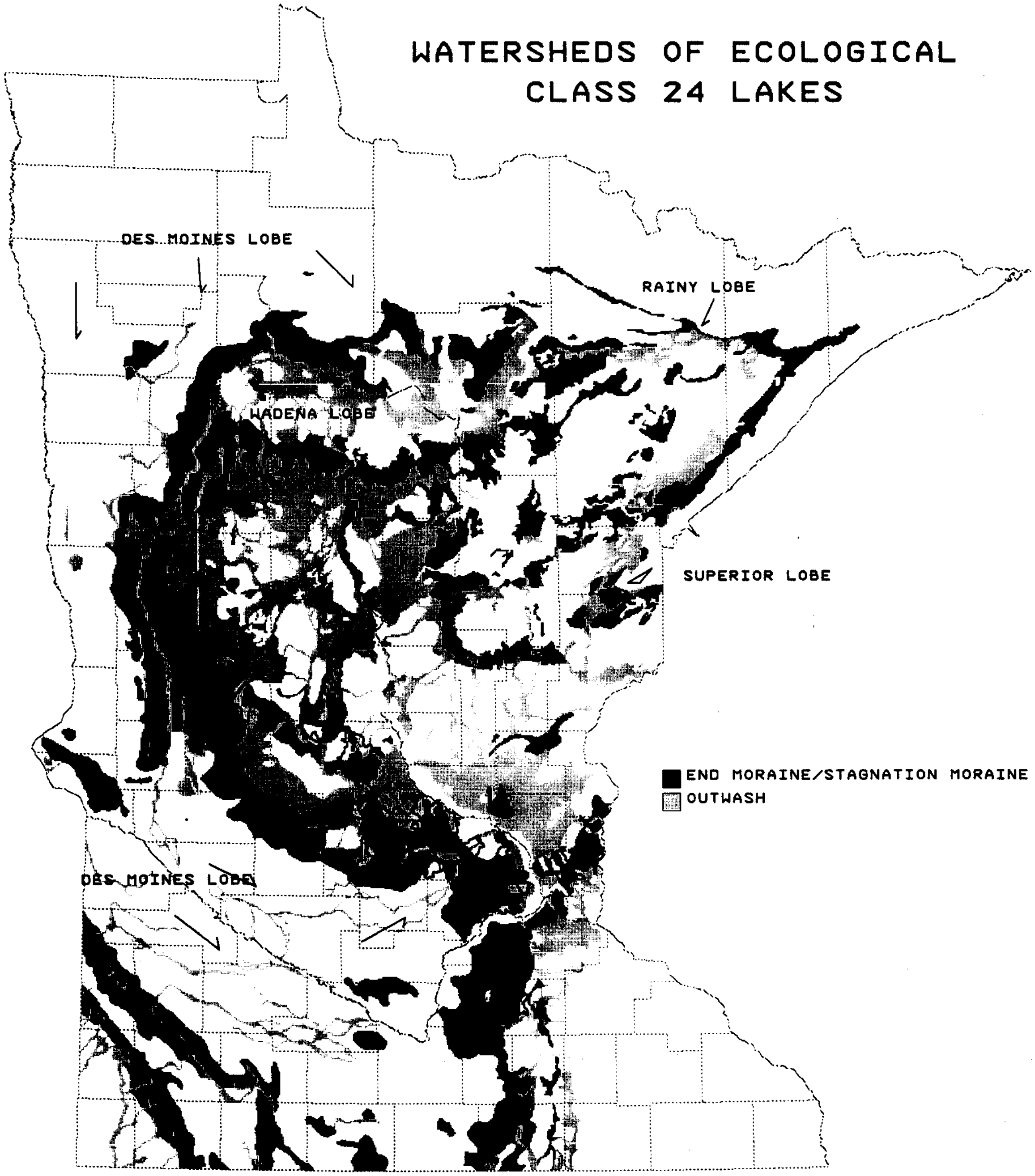

Figure 1. Location of the study lake watersheds relative to glacial moraines and outwash.

of 143 mg/l, and Secchi transparency of 2 m (Schupp 1992). The lakes were formed by glaciers and their watersheds were located mostly within areas of stagnation and end moraines of the Des Moines lobe of Wisconsin age glaciation (Figure 1). All watersheds were located in an area of diverse land-use including agriculture, urban, and wetland and other undeveloped land-use within the North Central Hardwood Forest (NCHF) Ecoregion. All the study lake watersheds are within the Mississippi River drainage with lakes in the Cannon River and St. Croix River watersheds entering the Mississippi River below St. Anthony Falls. St. Anthony Falls is a major barrier to fish migration and limits the distribution of some fish species (Underhill 1989). Lakes that have experienced winterkill, were reclaimed, had significant artificial water diversion, or were closely connected with a larger water body were excluded from this study.

Walleye *Stizostedion vitreum* and northern pike *Esox lucius* have been stocked in most of the study lakes. Other species that have been stocked include bluegill *Lepomis macrochirus*, largemouth bass *Micropterus salmoides*, smallmouth bass *Micropterus dolomieu*, black crappie *Pomoxis nigromaculatus*, muskellunge *Esox masquinongy*, channel catfish *Ictalurus punctatus*, rainbow trout *Oncorhynchus mykiss*, and brown trout *Salmo trutta* (Table 2).

Methods

Lake and watershed data -- Lake watersheds were delineated and matched with data describing geologic, edaphic, and land-use characteristics using GIS. Height-of-land lake watershed boundaries were determined from U.S. Geological Survey 7.5 minute topographic maps and mylar overlays of existing

Table 2. Fish species captured during MNDNR lake survey and assessment netting (1980-1990).

			Number of lakes fish present	
Common name	Abbreviation	Taxonomic name	Trap nets	Gill nets
Longnose gar	LNG	*Lepisosteus osseus*	2	3
Bowfin	BOF	*Amia calva*	29	20
Cisco	TLC	*Coregonus artedi*	1	4
Northern pike	NOP	*Esox lucius*	39	39
Muskellunge	MUE	*Esox masquinongy*	2	2
Common carp	CAP	*Cyprinus carpio*	29	25
Golden shiner	GOS	*Notemigonus crysoleucas*	17	14
Shiner	SHI	*Notropis spp.*	1	0
White sucker	WTS	*Catostomus commersoni*	25	36
Bigmouth buffalo	BIB	*Ictiobus cyprinellus*	5	2
Smallmouth buffalo	SAB	*Ictiobus bubalus*	1	0
Black bullhead	BLB	*Ameiurus melas*	37	39
Yellow bullhead	YEB	*Ameiurus natalis*	40	37
Brown bullhead	BRB	*Ameiurus nebulosus*	22	27
Channel catfish	CCF	*Ictalurus punctatus*	0	1
White bass	WHB	*Morone chrysops*	4	4
Rock bass	RKB	*Ambloplites rupestris*	6	5
Green sunfish	GSF	*Lepomis cyanellus*	29	9
Pumpkinseed	PKS	*Lepomis gibbosus*	39	31
Bluegill	BLG	*Lepomis macrochirus*	40	36
Hybrid sunfish	HSF	*Lepomis X Lepomis*	35	25
Smallmouth bass	SMB	*Micropterus dolomieu*	1	1
Largemouth bass	LMB	*Micropterus salmoides*	34	33
White crappie	WHC	*Pomoxis annularis*	11	13
Black crappie	BLC	*Pomoxis nigromaculatus*	40	39
Yellow perch	YEP	*Perca flavescens*	32	37
Walleye	WAE	*Stizostedion vitreum*	22	31
Freshwater drum	FRD	*Aplodinotus grunniens*	5	5

MNDNR minor watershed delineations (watersheds >5 mi^2 of any stream, river, or ditch) (MNDNR 1979). Basins without outlets within height-of-land lake watershed boundaries were also delineated and excluded from lake watersheds. Watershed boundaries and lake contours from MNDNR maps were digitized as vector files using a large-scale computer drawing board with Environmental Planning and Programming Language software (EPPL7) (LMIC 1991).

Watershed area, lake contour area, and areas associated with various types of land-use, slope, geology, and soil were calculated with EPPL7. Vector files of watershed boundaries were converted to 100 m^2 raster (rectangular grid) cells and lake contours were converted to either 2 m^2 or 5 m^2 raster cells. For each lake, the areas of raster cells describing watershed are (WAR), lake area (LAR), and lake contour area (A) were summed. Lake volumes (VOL) were estimated by summing the volume (V) of each isobath estimated from the equation: $V_{z_0}-V_{z_1}=\frac{1}{3}(A_{z_0}+A_{z_1}+\sqrt{A_{z_0}\times A_{z_1}})(z_0-z_1)$, where z_0 is the upper contour depth (m) and z_1 is the lower contour depth (m) (Cole 1979). Mean depths (DEP) were calculated by dividing the lake volume (m^3) by lake surface area (m^2).

Areal water load (WAL), and hydraulic residence time (RET) were calculated using the Minnesota Lake Eutrophication Analysis Procedure (MINLEAP) computer model calibrated for the NCHF ecoregion (Wilson and Walker 1989). Watershed area, lake surface area, and mean depth were input variables. This model was also used to predict total phosphorous concentrations, chlorophyll *a*, and Secchi disk transparency in the study lakes. Significant *($P<0.05$)* differences between model predictions of these parameters and MNDNR lake survey measurements were determined using t-tests in MINLEAP (Wilson and Walker 1989).

Watershed raster files for each lake were also used as base files to extract topographic, edaphic, and land-use information from Minnesota Land Management Information System 100 m^2 raster data (MLMIS100) described by LMIC (1989). All MLMIS100 variables except percent slope were originally assigned by 16.2 ha (40 acre) cell resolution (Table 3). Land-use in the MLMIS100 data set

Table 3. Descriptive statistics for 18 watershed-lake variables from the study lakes data set (N=40) and Pearson correlation coefficients between these variables and the first three principal components (PC1-3) calculated from the data set.

Variable	Mean	Coefficient of Variation (%)	Median	Minimum	Maximum	Correlation Coefficents PC1	PC2	PC3
Average percent slope SL P (%)	1.04	7	0.99	0.18	2.08	-.12	.48	.45
Soil erodibility factor KFT	0.29	13	0.29	0.20	0.35	-.21	.23	-.26
Available soil phosporus PO4 (1-4)	2.58	24	2.80	1.00	3.46	-.13	.27	.64
Soil drainage DRN (1-13)	12.5	17	13.0	9.4	13.6	-.37	-.35	.21
Watershed area WAR (ha)	1486	143	769	146	9883	.96	-.22	-.01
Lake surface area LAK (ha)	147	143	161	40	2382	.82	-.25	.31
River surface area R IV (ha)	42	281	0	0	630	.69	-.25	.17
Stream surface area STM (ha)	198	258	27	0	2978	.74	.16	-.18
Lake area LAR (ha)	161	71	109	41	421	.36	-.74	.07
Lake volume VOL ($m*10^3$)	712	78	501	141	2240	.30	-.83	.16
Mean depth DEP (m)	4.4	30	4.0	2.7	7.6	-.14	-.38	.31
Areal water load WAL (m/y)	-1.49	145	0.69	0.25	11.94	.80	.36	-.07
Hydraulic residence time RET (y)	7.2	85	5.5	0.3	26.5	-.81	-.45	.15
Forested FOR (%)	9.1	91	7.1	0	30.4	.11	.29	.65
Open water and marsh WAT (%)	10.3	80	8.6	0	38.7	.07	.41	.24
Developed DEV (%)	17.4	128	9.1	0	92.6	-.23	-.48	.38
Pasture and open PAS (%)	17.5	56	16.4	0	40.2	.26	.50	.38
Cultivated CUL (%)	45.6	51	49.2	0	90.4	.03	.02	-.86

was derived from 1969 aerial photographs, but Fandrei et al. (1988) states only minor changes in agricultural land-use occurred in this region from 1970 through the mid-1980s. We verified the accuracy of our watershed area and land-use measurements with data in published reports and found good agreement with data for Lake Minniebelle (MPCA 1987), Lake Pulaski (Barr Engineering 1991), and Volney, Long, and Sugar lakes (Heiskary and Wilson 1990). Watershed area for Lady Lake reported by Heiskary and Wilson (1990) differed from the watershed area we measured resulting in different land-use percentages.

Fish data -- Catches of fish in standardized trap nets and experimental gill nets set in the study lakes before 1991 were extracted from a statewide database of all MNDNR lake surveys and assessments. Most study lakes have had at least 3 fish population surveys since 1970. Netting was conducted according to standardized procedures (Scidmore 1970; MNDNR 1993). Because of selectivity associated with the sampling techniques, we analyzed both mean number per lift (CPUE) and mean weight per lift (biomass) calculated for each gear and lake as indices of species abundance. We also analyzed median length of each species calculated for each gear and lake.

Data analysis -- Fish survey data was analyzed to detect patterns in species occurrence in gill nets and trap nets across a watershed size gradient. A matrix of species occurrences by lakes ordinated by watershed area was constructed for trap and gill net data. These matrices were inspected for patterns of species addition related to watershed size and drainage above and below St. Anthony Falls. Relationships between watershed size and species addition were summarized by regressing the total number of species captured in lakes against $\log_{10}$ WAR.

Principal components analysis (PCA) was used to summarize data sets of trap net catches, gill net catches, and watershed variables. This analysis is a multivariate technique used to reduce the number of variables (Johnson and Richards 1992; Ludwig and Reynolds 1988). Principal components analysis with varimax rotation was done separately on data sets of watershed variables, trap net CPUE, trap net biomass, gill net CPUE, and gill net biomass using SYSTAT (Wilkinson 1990).

Some data transformations were necessary prior to analyses. Percent land-use variables were normalized using arc-sine transformation as suggested by Detenbeck et al. (1993), all area and volume measurements were transformed into natural logs, and CPUE and biomass data were transformed using $\log_e(x+1)$. Only fish species captured in at least 70% of the lakes were used in the analyses. Also, *Lepomis* spp. and their hybrids (except bluegill) were grouped as sunfish because of inconsistent species identification on the surveys.

Correlation matrices were the input to PCA as suggested by Rexstad et al. (1988) for data sets containing variables with large differences in units of measure. After PCA we used detrended correspondence analysis and non-metric multidimensional scaling programs to detect possible nonlinear relationships in the data sets (Ludwig and Reynolds 1988). Results from these procedures differed little from the results obtained from PCA and only results of PCA are reported.

Correlation and simple and multiple linear regression analyses were used to interpret principal component ordinations. Pearson correlation coefficients were used to identify associations between watershed principal components and mean total phosphorus, chlorophyll *a*, and Secchi depth measured in MNDNR lake surveys. Effects of key watershed variables on principal component ordinations of fish assemblages were identified with multiple regression analyses (Ludwig and Reynolds 1988). We used agreement of forward and backward selection procedures implemented in SYSTAT to obtain multiple regression models (Wilkinson 1990). Independent variables were added and removed from these analyses using *0.15* probability criteria. Because of uncontrolled variation in both dependent and independent variables, models with correlations coefficients ($P < 0.10$) were accepted as valid models. Modeling procedures were also repeated for catch indices of individual species targeted by trap nets (black bullhead *Ameiurus melas*, yellow bullhead *Ameiurus natalis*, bluegill, sunfish *Lepomis* spp., and black crappie) and gill nets (northern pike, white sucker *Catostomus commersoni*, walleye, and yellow perch *Perca flavescens*). Selection of these species was based on target species listed for each gear in the MNDNR Lake Survey Manual (MNDNR 1993).

Partial correlations were used to discern between the effects of Secchi depth and the effects of other watershed factors influencing fish populations. Secchi depth was forced into the previously defined models as an independent variable. Partial correlations were then calculated for each variable. Correlation coefficients with $P<0.05$ were considered statistically significant.

Results

Watershed Factors and Water Quality

Watershed size variables were more variable than slope, edaphic, and land-use characteristics. Watershed area and water retention times differed among lakes by factors of 67X and 88X, respectively (Table 3). Coefficients of variation (CV) describing watershed size variables (WAR, LAK, RIV, STM) were much higher than CV of other variables, especially CV of slope and edaphic variables (SLP, KFT, PO4, and DRN) (Table 3). Approximately one-third of the watersheds of some lakes were covered by either wetlands, forest (oak, elm-ash-cottonwood, and maple-basswood), or open-pasture. In other lakes, nearly all the watershed was described as either cultivated or developed. Land use in the study lake watersheds was similar to land use summarized for the Minnesota NCHF Ecoregion (Heiskary and Wilson 1990).

The first three watershed principal components accounted for 56.4% of the variation in the data set. None of the other principal components accounted for more than 10% of additional variation. The first component (PC1) accounted for 25% of the variation, and was most strongly correlated with watershed area (Table 3). The second principal component (PC2) accounted for 17% of the variation in the data set, and was inversely correlated with variables describing lake size, most notably lake volume (Table 3). The third principal component (PC3) accounted for 14% of the variation in the data set, and was positively correlated with percent forest cover and negatively correlated with percent cultivation (Table 3).

Watershed principal components were associated with water quality in the study lakes. Total phosphorus concentrations measured in lake surveys were positively correlated with PC1 scores (watershed size) and negatively correlated with PC3 scores (forested land-use without cultivation) (Table 4). Corresponding to these correlations, we found Secchi depth measured in lake surveys was negatively correlated with PC1 scores and positively correlated with PC3 scores (Table 4). Lakes with total phosphorus concentrations significantly higher than concentrations predicted from the MINLEAP model (Lake Sarah, Hennepin County; Volney and German lakes, Lesueur County; and Eden Lake, Stearns County) are characterized by low PC3 scores and moderate to high PC1 scores (Figure 2).

Fish Species Richness and Watershed Area

A large number of fish species were sampled from the study lakes despite limitations of the gear for catching small species. A total of 26 species, excluding hybrid sunfish, were captured in trap nets

Table 4. Pearson correlation coefficients between the first three watershed-lake principal components (PC1, watershed size; PC2, lake size; and PC3, land-use) and mean surface phosphorus concentration (TP) and Secchi disk transparency (SDT).

Variable	N	PC1	PC2	PC3	TP
TP	40	0.49**	-0.06	-0.44**	
SDT	37	-0.42**	-0.20	0.41*	-0.34*

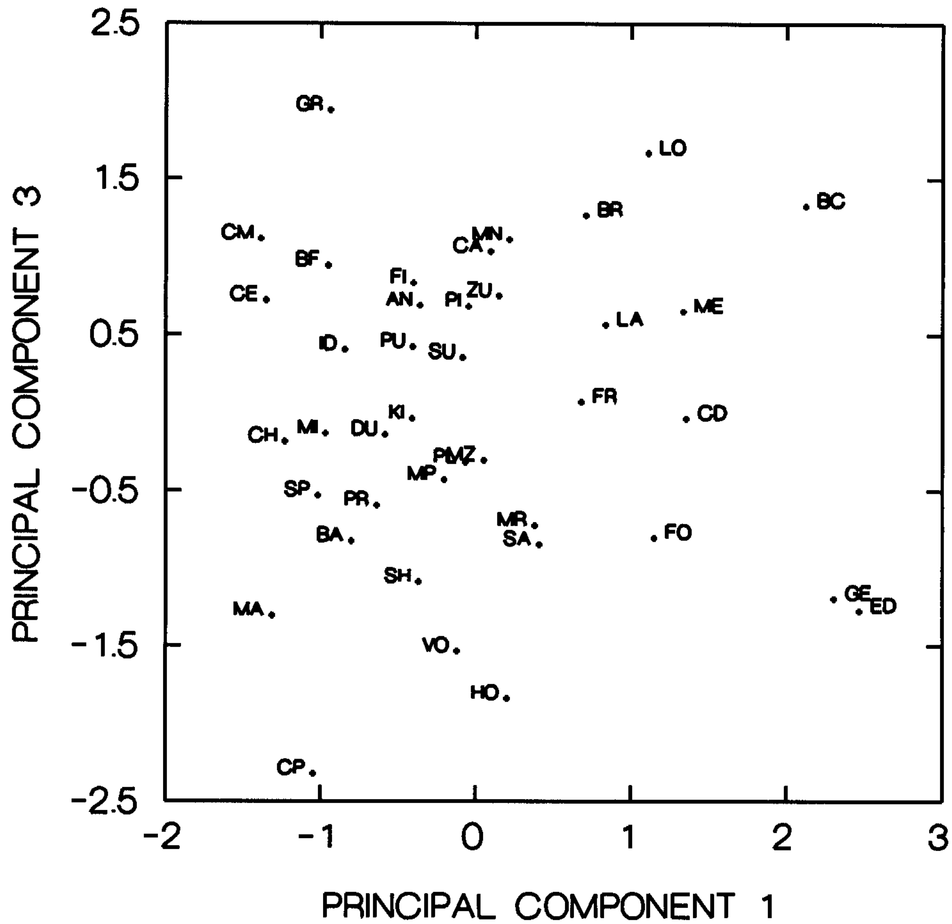

Figure 2. Rotated component scores of the first and third principal components calculated from variables descriptive of watersheds and lake size.

and 25 species, excluding hybrid sunfish, were captured in gill nets (Table 2). The most common species observed were sunfish spp., crappie spp., largemouth bass, bullhead spp., northern pike, white sucker, common carp, yellow perch, and walleye. Freshwater drum *Aplodinotus grunniens*, white bass *Morone chrysops*, and longnose gar *Lepisosteus osseus* were sampled only from lakes connected to the Mississippi River below St. Anthony Falls, a barrier to upstream migration.

The number of fish species caught from lakes increased with watershed area. Trap net catch increased from 12 to 16 fish species over the range of study lake watershed sizes and gill net catches increased from 12 to 15 species (Figure 3). The number of species sampled in trap nets was significantly correlated with $\log_{10}$ watershed area (r=0.46; P<0.003). A similar relationship was observed between the number of species in gill net catch and $\log_{10}$ watershed area; however, r was not statistically significant (r=0.27; P=0.102). Black bullhead, yellow bullhead, walleye, white sucker, white crappie *Pomoxis annularis*, rock bass *Ambloplites rupestris*, freshwater drum, bigmouth buffalo *Ictiobus cyprinellus*, white bass, and longnose gar were mostly caught from lakes with larger watersheds, while only golden shiner *Notemigonus crysoleucas* was more frequently caught from lakes with smaller watersheds.

PCA Ordinations of Fish Catch

The first three PCA ordinations of the CPUE and biomass of fish in trap nets

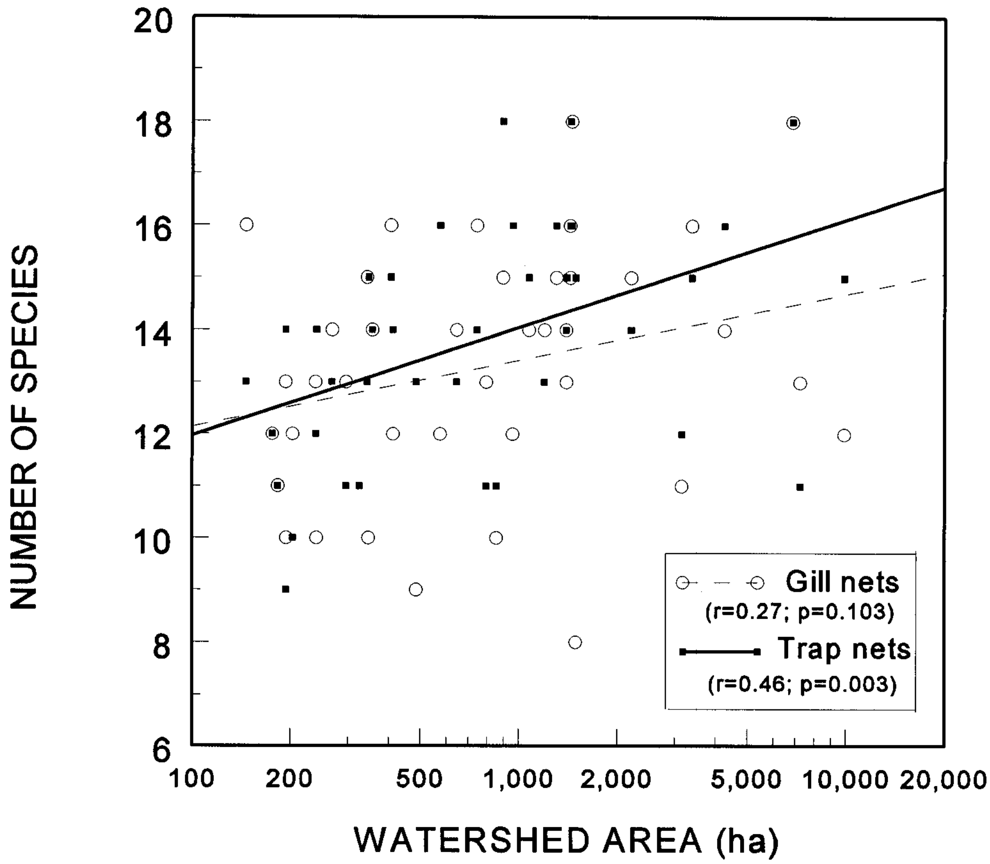

Figure 3. Relationship between the number of fish species captured in MNDNR survey nets set in 40 ecological Class 24 lakes and $\log_e$ lake watershed area.

accounted for 62 and 67% of the variation in the respective data sets. Lakes with higher trap net CPUE and biomass PC1 scores tended to have higher catches of common carp, black bullhead, and black crappie suggesting that these fish are behaviorally compatible and have similar habitat preferences (Table 5). Principal components analysis also indicated a yellow bullhead-sunfish-largemouth bass assemblage in lakes with low trap net CPUE PC1 scores and high trap net biomass PC2 scores (Table 5).

Fish species assemblages identified with PCA of gill net catch were similar to those found with PCA of trap net catches. Scores of gill net CPUE PC1 and biomass PC1 were highly correlated with a yellow bullhead-sunfish-largemouth bass assemblage (Table 5). We also found highly significant correlations between gill net principal components (CPUE PC1 and biomass PC2) and a black crappie-black bullhead assemblage (Table 5). Other principal components of gill net catch were correlated with a walleye-yellow perch-white sucker assemblage (CPUE-PC2) and northern pike biomass (biomass PC3). PCA ordinations of the CPUE and biomass of fish in gill nets accounted for 69 and 61% of the variation in the respective data sets.

Associations Between Fish Catch and Watershed Factors

Our analyses of associations between catches of fish in survey nets and key watershed variables identified by PCA ordinations

Table 5. Percent variation explained by principal components (PC1, PC2, PC3) calculated on data sets of number/lift (CPUE) and weight/lift (biomass) from trap net and gill net catches and Pearson correlation coefficients between catch statistics of individual species and PC1-3 calculated for that statistic. Significant (*P* < 0.001) correlation coefficients shown in bold type.

Species	CPUE PC1	CPUE PC2	CPUE PC3		Biomass PC1	Biomass PC2	Biomass PC3
				Trap net			
	(28.2)	(20.8)	(13.0)		(34.0)	(19.6)	(13.4)
Bowfin	.20	.32	-.25		**.63**	**.50**	.34
Northern pike	-.21	**.66**	-.06		**.46**	**.51**	.16
Common carp	**.66**	**.40**	**-.48**		**.81**	-.12	.29
Black bullhead	**.60**	**.49**	.19		**.76**	-.28	-.09
Yellow bullhead	**-.76**	.24	.06		.21	**.73**	-.12
Bluegill	**-.41**	**.69**	-.25		-.17	.34	**.71**
Sunfish	**-.83**	.17	.11		**-.46**	**.65**	-.29
Largemouth bass	**-.42**	**.52**	.02		.37	**.50**	**-.54**
Black crappie	**.58**	**.53**	.32		**.84**	-.13	.07
Yellow perch	.11	.20	**.88**		**.66**	-.15	**-.46**
				Gill net			
	(37.5)	(20.1)	(11.8)		(29.6)	(18.2)	(13.1)
Northern pike	**.64**	.01	**-.49**		-.10	-.39	**.67**
White sucker	.03	**.73**	-.21		-.31	**.47**	.20
Black bullhead	**-.57**	.33	**-.47**		**-.50**	**.65**	.38
Yellow bullhead	**.84**	-.08	.17		**.69**	.16	**.40**
Bluegill	**.62**	.17	**.50**		**.82**	-.02	.01
Sunfish	**.80**	.35	.21		**.79**	.13	.02
Largemouth bass	**.65**	**.44**	-.07		**.59**	.07	-.23
Black crappie	**-.65**	.28	**.49**		.23	**.86**	.21
Walleye	.17	**.76**	**-.49**		**-.66**	.02	-.20
Yellow perch	**-.65**	**.60**	.29		.02	**.50**	**-.61**

(watershed area, lake volume, cultivated area:forested area) suggested that watershed factors were associated with fish community gradients. Higher catch of the black bullhead-black crappie-common carp assemblage and lower catches of the yellow bullhead-sunfish-largemouth bass assemblage tended to occur in smaller volume lakes with larger watersheds and higher ratios of cultivation to forest cover (Tables 6 and 7). Partial correlations between watershed area and principal components of fish catch after Secchi depth effects were removed from multiple regression models were not significant except for principal components describing variation in black bullhead and black crappie biomass (trap net biomass PC1; gill net biomass PC2) (Tables 6 and 7).

The walleye-yellow perch-white sucker assemblage was also affected by watershed factors. This assemblage, represented in gill net catches by CPUE-PC2 and in trap net catches by CPUE-PC3, was significantly correlated with watershed area. The association was still significant after lake volume and Secchi depth effects in multiple regression models were removed using partial correlations.

Trap net catch indices of black crappie and black bullhead were related to watershed size. Watershed area accounted for 11-21% of the variation in black crappie CPUE and biomass, respectively (Table 6). Although Secchi depth could explain some of the variability in the biomass of black crappie in trap nets, watershed area was still significantly correlated with black crappie biomass in trap nets after Secchi depth effects were removed. Lakes with larger watersheds had higher CPUE and biomass of black bullhead in trap nets. Significant partial correlations were

Table 6. Regression coefficients of multiple regression models for trap-net catch per unit effort (CPUE) and biomass per lift PCA scores and for $\log_e$+1(trap-net CPUE) and $\log_e$+1 (trap-net biomass per lift) of selected species. Independent variables evaluated in stepwise multiple regression were $\log_e$ (watershed area-ha*100), $\log_e$ (lake volume-m^3), and $\log_e$ (cultivated area:forested area). Partial correlation coefficients given in parentheses are those calculated with Secchi depth (m) added to the models. Significant *($P < 0.05$)* partial correlation coefficients are shown in bold type.

Parameter	Intercept	Model Variables: Watershed area	Model Variables: Lake volume	Model Variables: Cultivated area: forested area	Secchi depth	r	Adjusted r^2
CPUE							
PC-1	-0.128	.063 *(.16)*			*(-.26)*	.26	.04
PC-3	0.868	.066 ***(.31)***	-.065 *(-.25)*		*(-.01)*	.36	.09
Black bullhead	7.064	.392 ***(.31)***	-.413 *(-.26)*		*(.07)*	.33	.06
Sunfish	-1.914		.294 ***(.32)***		***(.41)***	.34	.09
Black crappie	1.099	.311*(.29)*			*(-.20)*	.37	.11
Biomass per lift							
PC-1	1.036	.167 ***(.43)***	-.089 *(-.16)*		*(-.24)*	.55	.27
Bowfin	-0.074	.193 ***(.49)***			*(-.11)*	.54	.28
Black bullhead	5.905	.373 ***(.33)***	-.384 *(-.28)*		*(-.04)*	.40	.12
Yellow bullhead	0.623			.088 ***(.34)***	*(.07)*	.34	.09
Sunfish	-0.989		.207 ***(.47)***		*(.21)*	.48	.21
Black crappie	.298	.378 ***(.37)***			***(-.36)***	.48	.21
Median length							
Sunfish	-1.082		.311 ***(.42)***		*(-.09)*	.41	.13
Yellow bullhead	9.128	.451 ***(.43)***			*(.01)*	.47	.20

found between black bullhead catch and watershed area after lake volume and Secchi depth effects were removed.

Sunfish catch in trap nets were related to lake volume more than to watershed area and land use. Lake volume was significantly correlated with sunfish CPUE, biomass, and median length. Partial correlations between lake volume and sunfish catch indices were significant after Secchi depth effects were removed. Conversely, Secchi depth was still a factor explaining a significant portion of the variation in the trap net CPUE of sunfish after lake volume effects were removed.

Catches of northern pike, white sucker, and yellow perch in gill nets were associated with watershed factors, but catches of walleye in gill nets were more associated with lake volume than watershed factors (Table 7).

Table 7. Regression coefficients of multiple regression models for gill-net catch per unit effort (CPUE) and biomass per lift PCA scores and for $\log_e$+1(gill-net CPUE) and log +1 (gill-net biomass per lift) of selected species. Independent variables evaluated in stepwise multiple regression were $\log_e$ (watershed area-ha*100), $\log_e$ (lake volume-m^3), and $\log_e$ (cultivated area:forested area). Partial correlation coefficients given in parentheses are those calculated with Secchi depth (m) added to the models. Significant *($P < 0.05$)* partial correlation coefficients are shown in bold type.

		Model Variables					
Parameter	Intercept	Watershed area	Lake volume	Cultivated area: forested area	Secchi depth	r	Adjusted r^2
			CPUE (no./lift)				
PC-1	-1.794	-.142 *(-.25)*	.135 *(.18)*		***(.41)***	.46	.17
PC-2	-0.179	.087 ***(.43)***			*(.11)*	.43	.16
PC-3	-0.055			.031 *(.19)*	***(-.48)***	.28	.05
Northern pike	2.397			-.137 *(-.24)*	***(.52)***	.33	.09
White sucker	0.410	.121 ***(.37)***		-.081 *(-.23)*	*(.23)*	.42	.13
Walleye	-6.350		.475 ***(.46)***		*(-.04)*	.46	.19
Yellow perch	0.283	.663 ***(.48)***		.192 *(.17)*	***(-.42)***	.60	.32
			Biomass (wt./lift)				
PC-2	1.333	.065 *(-.28)*	-.091 *(-.24)*	-.033 *(.19)*	*(-.16)*	.42	.10
PC-3	0.170	.046 *(-.19)*		-.043 ***(-.31)***	*(.25)*	.44	.15
Northern pike	0.541	-.036 *(-.26)*		-.025 *(-.28)*	*(.23)*	.45	.16
White sucker	0.520			-.037 *(-.28)*	*(-.13)*	.25	.04
			Median length				
Northern pike	18.070	.872 ***(.31)***			*(-.18)*	.42	.14
Walleye	58.877		-2.559 ***(-.55)***		*(.12)*	.54	.25

Significant correlations were found for models of gill net catches of northern pike, white sucker, and yellow perch with watershed size and the ratio of cultivated area:forested area. Partial correlations of these gill net catches with the cultivated land-use ratio were not significant after watershed area and Secchi effects were removed. Biomass and median length of northern pike caught in gill nets decreased with increased watershed size. Catch-per-unit-effort of white sucker and yellow perch in gill nets also increased with larger watersheds, but white sucker catches were negatively related to the ratio of cultivated area:forested area while yellow perch were positively related to the cultivated area:forested area. Walleye gill net CPUE increased and the median walleye length caught in gill nets decreased with increases in lake volume after Secchi depth effects were removed.

Discussion

Fish populations in Minnesota Class 24 lakes appear to be affected by watershed characteristics. Watershed factors associated with fish community differences include watershed size and a land use factor described by differences between cultivation (disturbed) and forest cover (undisturbed). These associations correspond to known linkages between fish populations and effects related to nutrient loading and connections with other water bodies.

Species additions with increased watershed size were expected due to increased connections with other water bodies. Larger streams with good linkages to downstream systems generally contain more fish species than smaller streams (Osborne and Wiley 1992), and we would expect this relationship extends to lakes. Eadie et al. (1986) stated that "fish colonize lakes and rivers almost exclusively through corridors or bridges of aquatic habitat connected to the source species pool". In Michigan, Schneider (1981) found that large lakes connected to large rivers had the highest fish species diversity and small seepage lakes had the lowest diversity. We also observed species additions reflecting obvious downstream connections in lakes with larger watersheds. For example, longnose gar, white bass, and freshwater drum are riverine species that do not occur in the Mississippi River above St. Anthony Falls (Underhill 1989), and were found only in lakes with larger watersheds that drained to the Mississippi River below St. Anthony Falls. Bigmouth buffalo and rock bass are other species frequently associated with riverine habitats that occurred only in study lakes with larger watersheds.

Increased watershed size and cultivated land use were associated with increased phosphorus loading in the study lakes. Correlations between phosphorus concentrations and watershed size, and land use factors in the study lakes were consistent with nutrient loading relationships described in Minnesota lakes by Fandrei et al. (1988) and Wilson and Walker (1989). Taylor et al. (1971) found phosphorus exports from farmland were significantly higher than exports from forested land. Concentrations of phosphorus in runoff from farmland are higher than from forested land, and water yield from unforested land is also generally less than water yield from forested land (Hill 1981; Brooks et al. 1991).

Differences in fish assemblages among lakes corresponded to trophic state differences associated with watershed size and land use. Assemblages consisting primarily of yellow bullhead, sunfish, northern pike, and largemouth bass were associated with smaller, less cultivated and more forested watersheds; whereas, fish assemblages consisting primarily of black bullhead, black crappie, and common carp were associated with larger watersheds. In a statewide analysis of Minnesota lakes, Schupp (1992) reported higher black crappie and black bullhead CPUE and lower yellow bullhead CPUE in trap nets as lake trophic status increased. Case histories of Sallie (Becker County), Volney (LeSueur County), and Richardson (Meeker County) lakes in Minnesota have indicated that fish communities became more dominated by black bullhead and black crappie following excessive phosphorus loadings due to human disturbance (Olson and Koopman 1976; MNDNR file data). Similar gradients of fish community change with eutrophication in lakes have been described by Leach et al. (1977) and Persson et al. (1991).

Our findings support the hypothesis that watershed factors are associated with fish community differences among lakes. Results we obtained do not prove direct cause and effect relationships between watershed variables and fish populations, nor do they eliminate the role of other influential variables. Yet, most of the watershed-fish community associations we found are intuitively sound and supported by other studies. Furthermore, catch from trap nets and gill nets described similar gradients of change with respect to watershed influences despite differences in set locations and modes of capture. In the future, more accurate models of watershed effects on fish populations could be developed due to improvements in GIS technology and the availability of more precise data, as well as more accurate and precise lake survey information.

Management Implications

Our study supports the hypothesis that sport fish populations in many Minnesota lakes are intrinsically linked to watershed factors. Consequently, the bounds for successful fisheries management are partially decided by watershed factors. Management strategies aimed at protecting and improving fish populations should include consideration of watershed influences. Descriptions of watershed size, connectivity, and phosphorus loading, when combined with knowledge of ecological gradients of fish community change, should enable managers to educate clientele and set appropriate management objectives based on existing the ecological lake classification (Schupp 1992). For example, our black crappie CPUE model suggests that catches above the ecological Lake Class 24 third quartile are likely in lakes with watersheds exceeding 1,600 ha (4,000 acres). High catches of black bullhead and common carp would also be expected in these lakes because they are associated with high black crappie catches. This type of information should be useful to managers who evaluate lake survey results and develop management plans based on questions posed by Schupp (1992).

GIS should be developed for Minnesota fisheries professionals to use for managing lakes and watersheds. GIS provides the necessary tools to analyze landscape variables and interrelationships affecting fisheries. Also, maps and other visuals created by GIS are useful in communicating with clients.

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Appendix Table 1. Summary statistics of trap net and gill net catches in data sets used for principal components analysis.

Species	Gill net CPUE			
	Mean	C.V.	Median	Max.
Northern pike	9.4	64	8.3	23.0
White sucker	0.9	153	0.5	7.9
Black bullhead	9.6	148	4.2	72.2
Yellow bullhead	9.0	118	6.0	40.3
Bluegill	9.5	82	7.5	29.6
Sunfish	6.5	74	5.2	20.4
Largemouth bass	1.3	138	0.8	9.5
Black crappie	10.7	132	5.9	80.6
Walleye	3.0	143	1.6	23.4
Yellow perch	15.1	152	6.3	117.6

Species	Gill net biomass			
	Mean	C.V.	Median	Max.
Northern pike	5.4	36	4.7	10.3
White sucker	0.6	62	0.5	1.7
Black bullhead	2.4	59	2.1	7.5
Yellow bullhead	2.1	78	1.8	10.0
Bluegill	0.7	47	0.7	1.4
Sunfish	1.9	33	2.0	3.1
Largemouth bass	2.9	74	2.4	8.7
Black crappie	5.7	42	5.5	11.8
Walleye	0.6	99	0.5	2.4
Yellow perch	0.9	41	0.9	1.5

Species	Trap net CPUE			
	Mean	C.V.	Median	Max.
Bowfin	1.5	108	1.2	7.3
Northern pike	4.7	107	3.5	25.2
Common carp	1.7	108	1.1	7.9
Black bullhead	10.6	277	1.7	181.3
Yellow bullhead	11.2	71	9.2	29.4
Bluegill	39.5	108	26.0	188.5
Sunfish	17.7	98	12.4	83.5
Largemouth bass	1.7	128	1.0	9.4
Black crappie	8.8	182	3.7	93.6
Yellow perch	0.5	121	0.2	2.3

Species	Trap net biomass			
	Mean	C.V.	Median	Max.
Bowfin	0.5	203	0.3	6.3
Northern pike	0.2	76	0.1	0.5
Common carp	1.0	296	0.1	16.9
Black bullhead	2.9	251	0.2	42.0
Yellow bullhead	1.4	77	1.1	5.4
Bluegill	14.2	73	11.3	50.1
Sunfish	8.7	41	8.7	18.7
Largemouth bass	0.2	128	0.1	1.7
Black crappie	3.5	144	1.1	20.0
Yellow perch	0.3	159	0.1	2.5

Appendix Table 2. Number of MNDNR trap net surveys in which each of the listed fish species were captured in the study lakes.

	ma	cm	sp	ce	du[1]	ch	cp	gr	ba	id	an	pr	sh	bf	ki	mi	pi	fi	zu	pu	vo[1]	mn	mz	mp[1]	pl	br	ho	la	ca	sa	fr[1]	su	mr	lo	fo[1]	cd	me	ge[1]	bc	ed	total
BLG	4	3	1	3	3	3	2	3	3	2	3	3	3	3	3	3	2	3	3	2	3	3	5	3	3	3	3	3	3	2	4	2	2	3	2	3	3	3	3	3	40
YEB	4	3	1	3	3	3	2	3	3	2	3	3	3	3	3	3	2	2	3	2	3	3	5	3	3	3	3	3	2	2	4	2	2	3	1	3	3	3	3	3	40
BLC	4	3	1	2	3	3	2	3	3	1	3	2	3	3	3	3	2	2	3	2	4	3	5	3	3	3	3	3	3	2	3	2	2	3	1	3	2	3	3	3	40
PMK	4	3	1	3	2	3	2	2	3	2	3	2	2	3	3	3	1	3	3	2	2	3	3	3	3	3	3	3	3	2	4	2	2	3		3	3	2	3	3	39
NOP	3	3	1	1	3	3	1	3	3	2	2	3	2	2	1	2		2	1	2	2	3	3	3	2	2	2	2	2	2	2	2	1	2	1	1	3	3	2	3	39
BLB		3		1	1	3	1	3	3		3	3	3	2	2	1	2	3	3	1	4	3	4	1	2	3	3	1	3	1	4	2	2	1	1	3	2	3	2	3	37
HSF	4	3	1	2		3	2	1	2	1	2	3	2	3	3	2	1	3	2	2		3		3	3	3	2	2	3	2		2	1	2		3	3	1	3	2	35
LMB	2	2	1	1		3	2	3		1	3	2	2	2	2	1	1	2		2			1	2	3	1	2	1	2	2	1	2	2	3		3	2	1	2	3	34
YEP	3	2	1					1	3		1		1	1	3	2	2	2	3	1	2		4	1	2	3	2	2	3	2	4	1	1	2	2	3	3		3	3	32
BOF		1	1	2	3			2		1		3	1	3	3		1	2	3		2	3	5	2			3	3	1	2	3	2	2	3		3	3	3		3	29
CAP		2		3	1	1		3	3	1	1	1	1	1	1	2	2	1	1	1	1	1	4	2	1	3	3		1	2	4	2	2		2	2	3	3		2	29
GSF	2	3	1			1	2			2		1	3	3	3	3	1	3	1	2		2		2	3	2		1	1	1	2	2	1	1		2	1		1		29
WAE	3			2			2	1						2	3	3				1	3		5	1	2		2	1			3	2	1	1	2	3		3		3	22
BRB			1					2	1	2		3	1	1	3			1	2			2		1	2		1	2	2	1		2				3	3		1	3	22
WTS	1			2			1	2	1				1			2	1	2	2	2			5	2		1	3		2	2	1	1	1	1	2		3	1		3	25
GOS	1			1	1		2		2		2		1		1			1					2	1		3	1		1	1								1		3	17
WHC	1								1			1					1	1					5				3			2	2						2	2			11
RKB																	2					3				1			2		3		1					6			
FRD																					4		5								4				2			3			5
BIB																							2								1		1		1			2			5
WHB																							1								3				1			2			4
LNG																							4															1			2
MUE				1																										4											2
SMB																1																									1
SAB																																						1			1
SHI																					1																				1
TLC																									1																1
	13	12	11	14	9	10	12	14	13	11	11	13	15	14	15	14	13	16	13	14	11	11	18	16	15	13	16	14	15	16	18	16	15	14	22	15	16	18	11	15	

[1] Denotes lakes that are directly connected to the Mississippi River below St. Anthony Falls by the Cannon River.

Appendix Table 3. Number of MNDNR gill net surveys in which each of the listed fish species were captured in the study lakes.

	ma	cm	sp	ce	du[1]	ch	cp	gr	ba	id	an	pr	sh	bf	ki	mi	pi	fi	zu	pu	vo[1]	mn	mz	mp[1]	pl	br	ho	la	ca	sa	fr[1]	su	mr	lo	fo[1]	cd	me	ge[1]	bc	ed	total
NOP	4	3	1	3	3	3	2	3	3	2		3	3	3	3	3	2	3	3	2	4	3	5	3	3	3	3	3	3	2	4	2	2	3	2	3	3	3	3	3	39
BLC	4	3	1	3	3	2	2	2	3	2		3	3	2	2	2	1	2	3	2	4	3	5	3	3	3	3	3	3	2	4	2	2	3	1	2	3	3	3	3	39
BLB	3	2	1	3	2	3	2	4	3	2		3	3	3	3	1	2	3	3	1	4	3	4	2	3	3	3	2	2	2	4	2	2	2	1	3	3	3	2	3	39
YEB	4	3	1	3	2	3	2	2	3	2		3	3	3	3	3	1	2	3	2	2	3	3	3	3	3	3	3	1	1	2	2		3		3	3	2	3	2	37
YEP	4	2	1	3		1	2	2	3			2	3	3	3	3	2	2	2	2	4		5	2	3	3	3	3	3	2	4	1	1	2	2	3	3	3	3	3	37
BLG	4	3	1	3	3	3	2		3	2		3	3	2	3	3		2	3	2	2	3	5	3	3	3	3	3	3	2	3	2	2	2		3	3	3	3	3	36
WTS	3	3		2		1	2	2	3	1		3		3	2	2	2	2	3	2	1	2	5	1	3	2	3	3	3	1	2	2	1	3	2	3	3	1	2	3	36
LMB	3	2		2	2	2	2	1	1	2		2	3	3	2	2			1	2		1	1	1	2	1	3	3	2	1		2	1	3		3	3	1	3	1	33
WAE	4		1	2	1	2	2	1		2				3	3	3	1	1		2	4		5	2	3		3	2	2	1	4	2	2	3	2	3		3	1	2	31
PMK	3	3	1	2		3	2		2	2		2	2	2	3	3		2	2	2	1	2		1	3	2	2	3	2	1	3	2		2		2		3	3		31
BRB	2	2	1			1	1	2	1	2		3		2	3	2			1	1		1			2	2	1	2	1	2		2		2		1	3		2	2	27
HSF	3	2	1	2		3	2		2	1		2		3	3			1	1	2					3	2	2	1	1	1		2		2		2	3		3		25
CAP	1			1	1			3	3			1	1		1	1		1	1	1	3		4	2		1	3			1	4	2			2	1	3	3		1	25
BOF				1	3					1		3		2	1		1		2		2	1	3					3		1	3	2		2		3	1	3		2	20
GOS	1	1					2		1	1					1				1					1		2	2			2							2	2	1		14
WHC	2		1						1			1					1	1					5				3			2	4				1		2	3			13
GSF	1											2	1	2	3					1	1				2	1						2									9
FRD																					4		5								4				2			3			5
RKB																				2								2				2		3		3					5
WHB																							3								4				2			1			4
TLC																									2							2		2		3					4
LNG					1																		3															3			3
BIB																																			1			3			2
MUE																															3	1									2
SMB																				1																					1
CCF																													1												1
	16	12	11	13	10	12	13	10	14	13	0	15	10	14	15	12	9	12	14	16	13	10	15	12	14	14	15	14	13	16	15	18	8	15	11	16	14	18	13	12	

[1] Denotes lakes that are directly connected to the Mississippi River below St. Anthonys Falls by the Cannon River.