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GEOSPATIAL AND TEMPORAL ANALYSIS OF A 20-YEAR RECORD OF LANDSAT-BASED WATER CLARITY IN MINNESOTA'S 10,000 LAKES[1]

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ABSTRACT: A large 20-year database on water clarity for all Minnesota lakes ≥8 ha was analyzed statistically for spatial distributions, temporal trends, and relationships with in-lake and watershed factors that potentially affect lake clarity. The database includes Landsat-based water clarity estimates expressed in terms of Secchi depth ($SD_{Landsat}$), an integrative measure of water quality, for more than 10,500 lakes for time periods centered around 1985, 1990, 1995, 2000, and 2005. Minnesota lake clarity is lower (more turbid) in the south and southwest and clearer in the north and northeast; this pattern is evident at the levels of individual lakes and ecoregions. Temporal trends in clarity were detected in ~11% of the lakes: 4.6% had improving clarity and 6.2% had decreasing clarity. Ecoregions in southern and western Minnesota, where agriculture is the predominant land use, had higher percentages of lakes with decreasing clarity than the rest of the state, and small and shallow lakes had higher percentages of decreasing clarity trends than large and deep lakes. The mean $SD_{Landsat}$ statewide remained stable from 1985 to 2005 but decreased in ecoregions dominated by agricultural land use. Deep lakes had higher clarity than shallow lakes statewide and for lakes grouped by land cover. $SD_{Landsat}$ decreased as the percentage of agriculture and/or urban area increased at county and catchment levels and it increased with increasing forested land.

(KEY TERMS: water clarity; Secchi depth; lakes; remote sensing; statistics; Landsat.)

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INTRODUCTION

The state of Minnesota, United States (U.S.), whose motto is "land of 10,000 lakes," actually has ~12,000 lakes 4 ha or larger in area (http://www.dnr.state.mn.us/faq/mnfacts/water.html). They vary greatly at local, regional, and statewide scales by size, depth, ecology, and water quality. The wide diversity of lakes allows for many recreational and tourism opportunities but makes their management challenging.

In addition to natural landscape variations that affect watershed hydrology, urban and agricultural land cover in watersheds affects the spatial and temporal patterns of runoff and thus affects lake water quality. Numerous studies have evaluated the effects of land use on water quality. These studies often

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have been conducted at the watershed scale and have measured or modeled the effects of land uses (Tong and Chen, 2002) or land-use change (e.g., Mattikalli and Richards, 1996; Choi *et al.*, 2003; Wilson and Weng, 2010) on water quality. Other studies conducted at local to regional scales have compared lake conditions and land use in different watersheds and linked land use with water quality differences (e.g., Shannon and Brezonik, 1972; Baker *et al.*, 1985; Gove *et al.*, 2001). Heiskary and Wilson (1989) used the ecoregion framework of Omernik (1987), which recognizes distinct regional patterns of geology, vegetation, hydrology, and land use, to characterize water quality differences in four of Minnesota's ecoregions. These findings were used to help define water quality goals for each ecoregion and led to the development of lake water quality standards (Minnesota Rule Ch. 7050; https://www.revisor.mn.gov/rules/?id=7050&view=chapter). Data used to develop lake standards were derived from targeted studies by state and local governments, a distribution of minimally impacted (reference) lakes, and a statewide volunteer network. These sources provided good statewide coverage, but the lake selection was not random and favored larger, publicly accessible lakes. Biases may occur when results from nonrandom samples are extrapolated to the larger population of Minnesota lakes (Peterson *et al.*, 1999; Wagner *et al.*, 2008; Soranno *et al.*, 2011).

Water clarity, commonly expressed as Secchi depth (SD), is a primary indicator of water quality, its suitability for human use, and general ecological conditions in lakes. It integrates the influence of three major in-lake constituents: autochthonous organic particles resulting from algal activity (algal turbidity, AT), clay minerals (inorganic suspended solids, ISS), and humic color, all of which are sensitive to human disturbance and environmental conditions.

Landsat imagery is a cost-effective source to assemble spatially comprehensive SD information for regional lake assessments (e.g., Kloiber *et al.*, 2002a, b; Chipman *et al.*, 2009). Sensors on Landsat and similar satellites measure solar energy reflected from the Earth's surface within various wavelength regions (or bands). The fraction of solar radiation reflected from water varies with wavelength and depends on concentrations of light-scattering particles and light-absorbing substances (e.g., phytoplankton pigments and aquatic humic material) in the water body. Complicated semi-analytical algorithms have been developed to relate wavelength-dependent reflectance to concentrations of some light-absorbing or light-scattering substances in water. More commonly, however, predictive relationships are developed by empirical (regression) techniques. For example, strong empirical relationships (typical R^2 of 0.75-0.90) have been found between field-measured SD and reflectance in Landsat bands 1 (blue region) and 3 (red region) (e.g., Kloiber *et al.*, 2002b). Such relationships (or calibration equations) have been used to estimate SD values in other lakes of a given Landsat image, for which field data are not available. The spatial resolution of the Landsat sensors (pixel size = 30 m) enables the extraction of water quality information on lakes with surface areas as small as ~8 ha.

We used the above approach to develop a water clarity database for all lakes (both natural water bodies and man-made reservoirs) in Minnesota ≥8 ha (20 ac) covering a 20-year time frame. The database (Olmanson *et al.*, 2008) includes nearly 100,000 Landsat-based estimates of water clarity reported in terms of Secchi depth ($SD_{Landsat}$) on more than 10,500 lakes made at ~5-year intervals from 1985 to 2005.

This article builds on our earlier work (Olmanson *et al.*, 2008), which focused on development and validation of the database and presented initial findings on statewide temporal trends and spatial patterns of lake clarity ($SD_{Landsat}$) in Minnesota. Here we describe the results of statistical analyses of the database for geospatial and temporal trends of water clarity over the 20-year period, as well as relationships with surrounding land cover/use and in-lake conditions. As part of the analyses we grouped the lakes by general physical and chemical characteristics (area, depth, and alkalinity) and linked their water clarity ($SD_{Landsat}$) values to land cover variables at the ecoregion, county, minor watershed, and catchment levels. The database is unique not only in terms of its size but also because it effectively is a census of the entire population of lakes >8 ha in area rather than just a sample of Minnesota lakes.

METHODS

Landsat Water Clarity Data

The water clarity database was developed using more than 100 Landsat images from the Landsat 4 Multispectral Scanner, Landsat 5 Thematic Mapper (TM), and Landsat 7 Enhanced Thematic Mapper plus (ETM+). Near-contemporaneous field SD measurements were obtained for calibration purposes from the volunteer Citizen Lake Monitoring Program, coordinated by the Minnesota Pollution Control Agency (MPCA). Field SD data available for image calibration ranged from 13 in isolated areas to 278 for full paths of imagery for some populated areas.

Previous studies showed that field SD data collected within ±7 days of a Landsat image provided strong statistical relationships (Kloiber *et al.*, 2002b). Using log-transformed SD data as the dependent variable and bands TM1 and TM3 as independent variables, we performed multiple regressions using the general form:

$$\ln(\mathrm{SD}_{\mathrm{Landsat}}) = a(\mathrm{TM1}/\mathrm{TM3}) + b(\mathrm{TM1}) + c$$

where coefficients a, b, and c were fit to the calibration data by regression analysis, $\ln(\mathrm{SD}_{\mathrm{Landsat}})$ is the natural logarithm of Landsat-derived SD for a given lake, and TM1 and TM3 are Landsat brightness values for selected lake pixels in the blue and red bands, respectively. Typical R^2 values for calibration equations averaged 0.83 (range 0.71-0.96), and standard errors averaged 0.29 (range 0.14-0.41) for the log-transformed data. Further details on image processing, extraction of $\mathrm{SD}_{\mathrm{Landsat}}$ from the imagery, and data accuracy were described by Olmanson *et al.* (2008). The database includes assessments of late-summer water clarity for >10,500 lakes for five time periods centered around 1985, 1990, 1995, 2000, and 2005 (Olmanson *et al.*, 2008), and the data can be accessed at http://water.umn.edu. Because clear images for the late-summer index period were not available over the entire state in most years, the nominal time periods generally include results from multiple years (e.g., 1994, 1995, and 1996 for the "1995" time period).

Land Cover Data

We used land cover data from the 2000 Minnesota land cover classification by the University of Minnesota Remote Sensing and Geospatial Analysis Laboratory. The classification used a K-nearest neighbor classifier to classify multi-temporal tasseled cap features of greenness, brightness, and wetness of Landsat TM and ETM+ imagery with a combination of spring, summer, and fall dates. The classification scheme was modeled after the image processing protocol of the Upper Midwest Gap Analysis Program (Lillesand *et al.*, 1998) and included seven level 1 land cover classes: urban, agriculture, grassland, forest, water, wetland, and shrub land. The average overall statewide classification accuracy was 84.5%. Impervious surface area was classified as a continuous variable (0-100%) using regression models relating imperviousness to tasseled cap greenness of the summer Landsat images (applied only to developed and urban areas in the land cover classification). The coefficient of determination (r^2) between measured values and Landsat estimates of percent impervious cover was 0.86 (standard error = 11.7). For further information and data access, see http://land.umn.edu/ and Bauer *et al.* (2007).

Lake Classification by Morphometric and Chemical Characteristics

Although every lake is unique in the totality of its biological, chemical, and morphometric characteristics, a few key variables such as depth and watershed/lake area serve as important influences on lake responses to watershed activities. To differentiate in-lake characteristics from watershed influences we grouped the lakes by general physical and chemical characteristics using a tripartite classification system (area, depth, and alkalinity; Table 1) described by Osgood *et al.* (2002). Surface area was calculated using lake polygons created by the Minnesota Department of Natural Resources (MDNR) from aerial photography, but measured data were needed for lake depth and alkalinity. These characteristics are available for only a subset of Minnesota lakes. We extracted these data from a set of 4,265 "survey lakes" sampled by the MDNR. The MDNR has measured maximum depth for 4,167 lakes and calculated mean depth for 1,139 lakes. We estimated mean depth (when not available) from maximum depth data using a regression relationship we developed between the two variables (r^2 = 0.82). This method was used by Osgood *et al.* (2002) and Osgood (1988).

Alkalinity data were available for 1,390 lakes. We developed a map of alkalinity in lakes across the state using the kriging algorithm in ArcMap (Oliver, 1990) and the available alkalinity data. Alkalinity has a distinct pattern in Minnesota: low in the northeast and high in the southwest. Alkalinity values for lakes without measured values were estimated from the alkalinity map.

The above operations yielded 4,167 (MDNR) survey lakes with surface area, mean depth, and alkalinity data. For statistical analyses the survey lakes were screened to eliminate complex, multi-basin lakes, for which depth data may not adequately represent each basin. This left 3,357 single basin lakes that were used for further analysis. The lakes were grouped into 27 classes with the ranges presented in Table 1.

TABLE 1. Lake Classification Criteria.

Number	Size (ha)	Mean Depth (m)	Alkalinity (mg/l as $CaCO_3$)
1	Small <40	Shallow <2	Low <50
2	Medium 40-200	Medium 2-5	Medium 50-100
3	Large >200	Deep >5	High >100

Note: For example, Lake Class 111 would be a small shallow lake with low alkalinity.

Geographic Delineations

We used the U.S. Environmental Protection Agency (USEPA) Level-III ecoregions of the conterminous U.S. (LMIC/MPCA version, Omernik, 1987) as one basis for our geospatial and temporal analyses. Minnesota has seven ecoregions (Figure 1), each of which is different in terms of aggregate land use, geology, soils, vegetation, climate, wildlife, and hydrologic characteristics. We also used county, minor watershed, catchment delineations, and individual lakes at the statewide level and within ecoregions, to investigate geospatial and temporal trends. The smallest delineated drainage areas mapped by the MDNR, called "catchments," have been delineated topographically within major and minor watershed boundaries. The watersheds for some lakes contain many catchments (and may include additional lakes). Therefore, we selected only the 1,018 lake watersheds that are headwater catchments, and we linked land cover information to each of these lakes. Additional information about the MDNR catchments is found at http://deli.dnr.state.mn.us/metadata/wshd_lev08py3.html.

Statistical Analysis

To compile the data needed for analysis, we used Esri ArcMap 10 to calculate lake areas from the lake polygons, tabulate land cover area for each catchment and ecoregion and link each lake to its catchment, minor watershed, and ecoregion. Microsoft Excel was used to calculate land cover percentages for each catchment and categorize catchments by statewide land cover quintiles. To investigate water clarity trends of individual lakes we used Excel's LINEST function to calculate the least squares linear regression statistics for the 9,647 lakes with $SD_{Landsat}$ data for all five time periods (1985-2005). To determine how trends varied by lake type, we linked each lake to the "wetland type" from Bulletin 25 (MDNR, 1968), which classifies lakes according to U.S. Fish and Wildlife Service Circular 39 (USFWS, 1971). JMP 9.0 was used for analysis of variance (ANOVA) of the classes and to summarize the data statistically.

RESULTS AND DISCUSSION

Geospatial and temporal analyses were conducted on three datasets: (1) the full water clarity ($SD_{Landsat}$) database of Minnesota lakes for five time periods (9,647 lakes with data in all five periods, hereafter termed "coincident lakes"; range of 10,516-11,241 lakes in a given period), (2) single basin survey lakes with known morphometric and chemical characteristics (N = 3,357), and (3) headwater catchment lakes (a subset of the single basin survey lakes; N = 1,018)

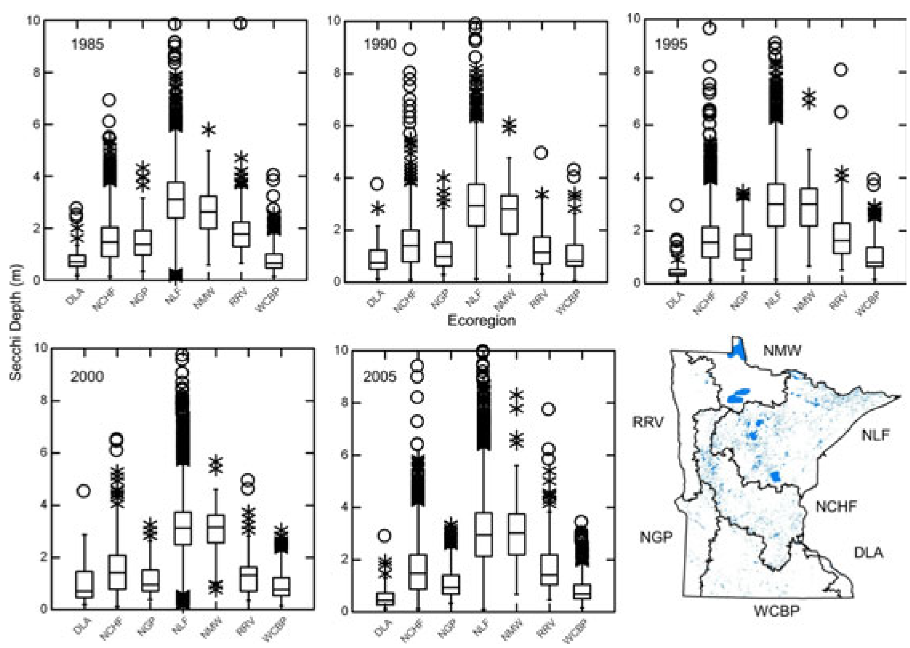

FIGURE 1. Boxplots of Landsat-Based Lake Water Clarity ($SD_{Landsat}$) for 1985-2005 by Minnesota Ecoregion (RRV, Red River Valley; NMW, Northern Minnesota Wetlands; NLF, Northern Lakes and Forest; NCHF, North Central Hardwood Forest; DLA, Driftless Area; WCBP, Western Corn Belt Plains; NGP, Northern Glaciated Plains; SD, Secchi depth).

in conjunction with land cover data for the 2000 time period. The latter dataset, although only a fraction of the entire database, is still large and has the advantage of allowing comparisons of responses of different lake types to the extent of development and differences in land cover.

Spatial and Temporal Analyses: All Lakes

Spatial and Temporal Trends: General Statewide. At the statewide level, we found four major spatial and temporal trends for water clarity ($SD_{Landsat}$) in Minnesota lakes (Tables 2 and 3 and Figure 1). First, lake clarity consistently was lower in the south and southwest and higher in the north and northeast. Second, statewide average values for $SD_{Landsat}$ varied only slightly between 1985 and 2005 (range of 2.21-2.27 m for all lakes and 2.28-2.40 m for the 9,647 coincident lakes). Third, many of the clearest lakes are abandoned iron mine pits in the Northern Lakes and Forest (NLF) ecoregion that have filled with water. Fourth, mean $SD_{Landsat}$ in the NLF and North Central Hardwood Forest (NCHF) ecoregions in central and northern Minnesota remained stable from 1985 to 2005, but decreasing trends were detected in the Western Corn Belt Plains (WCBP) and Northern Glaciated Plains (NGP) ecoregions in southern Minnesota, where agriculture is the predominant land use. These findings are the same as reported by Olmanson *et al.* (2008) in a preliminary analysis of the database.

Spatial and Temporal Trends: Within Ecoregions. Minnesota's seven ecoregions differ in terms of their geological, ecological, climatic, hydrologic, and land-use characteristics, and significant differences also occur in lake clarity among the ecoregions (Tables 2 and 3 and Figure 1). The observed patterns are fairly consistent for the five time periods (1985-2005). The NLF and Northern Minnesota Wetlands (NMW), which have land cover dominated by forest, lakes, and wetlands (Figure 2), generally had the largest $SD_{Landsat}$ values in the state. The Driftless Area (DLA), NGP, and WCBP generally had the smallest $SD_{Landsat}$ values; the last two are dominated by agricultural land cover (Figure 2).

The 25th-75th percentile values for $SD_{Landsat}$ means in individual NLF lakes from all time periods, hereafter referred to as the "typical range," are 2.27-3.77 m, and the grand average for all lakes over the five measurement periods is 3.09 m. In addition, average $SD_{Landsat}$ remained fairly stable from 1985 to 2005 (range = 0.10 m and standard deviation [SD] = 0.04 m). Using all available field measurements of SD,

TABLE 2. Minnesota Landsat Water Clarity Database Summary (values in m): Results for Entire State, 9,647 (1985-2005) Coincident Lakes and the State's Seven Ecoregions.

	Year				
Geographic Area	**1985**	**1990**	**1995**	**2000**	**2005**
Minnesota					
Minimum	0.08	0.07	0.08	0.12	0.09
25th percentile	1.24	1.15	1.28	1.15	1.09
Median	2.13	2.00	2.07	2.15	2.00
Mean	2.26	2.21	2.27	2.25	2.25
75th percentile	3.13	3.04	3.13	3.23	3.10
Maximum	12.88	14.44	11.18	13.10	17.56
Number (*n*)	11,136	10,732	10,988	10,516	11,241
Standard deviation	1.26	1.36	1.27	1.29	1.51
Minnesota coincident lakes					
Minimum	0.11	0.14	0.11	0.13	0.11
25th percentile	1.36	1.23	1.34	1.24	1.24
Median	2.26	2.00	2.20	2.30	2.22
Mean	2.37	2.28	2.36	2.32	2.40
75th percentile	3.29	3.25	3.29	3.37	3.31
Maximum	12.88	14.49	11.18	13.10	17.56
Number (*n*)	9,647	9,647	9,647	9,647	9,647
Standard deviation	1.29	1.39	1.30	1.31	1.56
Northern Lakes and Forest Ecoregion (NLF)					
Minimum	0.08	0.14	0.15	0.15	0.09
25th percentile	2.39	2.15	2.17	2.49	2.13
Median	3.11	2.94	3.00	3.14	2.95
Mean	3.13	3.05	3.03	3.12	3.10
75th percentile	3.77	3.75	3.77	3.74	3.82
Maximum	12.88	14.49	11.16	13.10	17.56
Number (*n*)	5,243	5,149	5,123	4,980	5,151
Standard deviation	1.10	1.29	1.20	1.09	1.52
North Central Hardwood Forest Ecoregion (NCHF)					
Minimum	0.14	0.09	0.14	0.12	0.11
25th percentile	0.90	0.79	0.99	0.78	0.86
Median	1.46	1.41	1.55	1.42	1.47
Mean	1.54	1.51	1.68	1.54	1.64
75th percentile	2.03	2.00	2.14	2.08	2.19
Maximum	6.90	8.90	9.62	6.51	9.39
Number (*n*)	4,147	3,920	4,075	3,790	4,226
Standard deviation	0.80	0.91	0.91	0.90	1.01
Western Corn Belt Plains Ecoregion (WCBP)					
Minimum	0.14	0.07	0.15	0.15	0.15
25th percentile	0.48	0.62	0.64	0.54	0.50
Median	0.66	0.82	0.81	0.76	0.69
Mean	0.81	1.07	1.04	0.96	0.85
75th percentile	1.01	1.43	1.37	1.23	1.04
Maximum	4.02	4.29	3.92	3.04	3.42
Number (*n*)	658	673	695	685	746
Standard deviation	0.50	0.61	0.56	0.58	0.53
Northern Glaciated Plains Ecoregion (NGP)					
Minimum	0.34	0.29	0.51	0.38	0.33
25th percentile	0.98	0.62	0.92	0.71	0.68
Median	1.34	0.98	1.29	0.95	0.93
Mean	1.50	1.13	1.45	1.15	1.12
75th percentile	1.92	1.52	1.84	1.52	1.41
Maximum	4.32	4.01	3.49	3.25	3.35
Number (*n*)	639	565	650	631	656
Standard deviation	0.63	0.60	0.64	0.54	0.59

(continued)

TABLE 2. (Continued)

	Year				
Geographic Area	**1985**	**1990**	**1995**	**2000**	**2005**
Red River Valley Ecoregion (RRV)					
Minimum	0.65	0.32	0.52	0.35	0.45
25th percentile	1.29	0.71	1.15	0.71	1.03
Median	1.77	1.15	1.63	1.32	1.43
Mean	1.88	1.29	1.88	1.37	1.91
75th percentile	2.24	1.74	2.28	1.63	2.20
Maximum	9.85	4.93	11.18	4.93	17.40
Number (n)	212	198	207	196	211
Standard deviation	0.92	0.68	1.17	0.83	1.85
Northern Minnesota Wetlands Ecoregion (NMW)					
Minimum	0.58	0.60	0.66	0.76	0.67
25th percentile	1.99	1.82	2.18	2.56	2.18
Median	2.63	2.81	3.10	3.16	3.02
Mean	2.63	2.61	2.90	3.05	3.09
75th percentile	3.25	3.34	3.60	3.62	3.75
Maximum	5.79	6.09	7.12	5.67	8.31
Number (n)	180	182	187	179	196
Standard deviation	0.88	1.05	1.01	0.88	1.22
Driftless Area Ecoregion (DLA)					
Minimum	0.19	0.14	0.08	0.20	0.11
25th percentile	0.54	0.50	0.30	0.44	0.25
Median	0.71	0.75	0.39	0.71	0.43
Mean	0.85	1.02	0.53	1.03	0.60
75th percentile	0.97	1.24	0.57	1.47	0.72
Maximum	2.74	3.74	2.93	4.51	2.88
Number	57	45	51	55	55
Standard deviation	0.63	0.60	0.64	0.54	0.59

TABLE 3. Landsat-Based Water Clarity Statistics (values in m) for Minnesota Lakes, from 1985 to 2005, by Ecoregion.[1]

Ecoregion	% of State Lakes	No. of Lakes	Typical Range	Mean	Range	SD
NLF	47	5,671	2.27-3.77	3.09	0.1	0.04
NCHF	37	4,466	0.86-2.09	1.58	0.17	0.07
WCBP	5.9	835	0.56-1.22	0.95	0.26	0.11
NGP	5.7	690	0.78-1.64	1.27	0.38	0.19
RRV	1.9	215	0.98-2.02	1.67	0.62	0.31
NMW	1.6	215	2.15-3.51	2.86	0.48	0.23
DLA	0.5	101	0.41-0.99	0.81	0.5	0.23

[1]See Table 2 for key to ecoregion acronyms.

Heiskary and Wilson (1989) found similar results with a typical range of 1.8-3.9 m, but Heiskary and Wilson (2008) found a higher typical range (2.4-4.6 m) using field data only from reference lakes (lakes that are minimally impacted and considered representative for their ecoregion). The lake-rich NLF, which includes the Boundary Waters Canoe Wilderness Area, contains 47% of Minnesota's lakes and is characterized by hilly land interspersed with wetlands, bogs, lakes, and ponds and a land cover that is 66% forest. Its lakes are used mainly for recreation, and water clarity thus is an important quality.

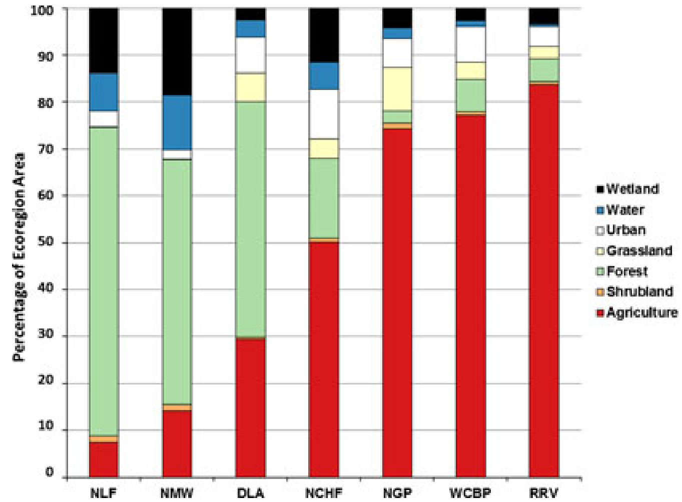

FIGURE 2. Minnesota Land Cover Distribution in 2000 by Ecoregion. For a definition of abbreviations, see Figure 1.

Lakes in the NCHF exhibited a wide range of $SD_{Landsat}$ (typical range of 0.86-2.09 m), but the overall average clarity remained stable between 1985 and 2005 (grand mean = 1.58 m; range = 0.17 m; SD = 0.07 m). Heiskary and Wilson (1989) found a similar wide range of SD based on field data (typical range of 0.8-2.2 m) and Heiskary and Wilson (2008) found a higher typical range of field SD (1.5-3.2 m) based on the ecoregion's reference lakes. This ecoregion also is "lake-rich" (37% of the state's lakes) and broadly represents the original transition between prairie and forested land and a terrain that varies from rolling hills to plains. Today its largest land cover is agriculture (50%), but there also are large areas of forest (17%) and wetlands (12%). The NCHF includes the Twin Cities metropolitan area and has the highest proportion (11%) of urban and suburban land among the state's ecoregions. Many NCHF lakes have been developed for residential and recreational purposes, and water clarity is important to home owners and a factor in property values (Krysel *et al.*, 2003).

Water clarity in the WCBP generally is low — typical range for $SD_{Landsat}$ = 0.56-1.22 m; overall average = 0.95 m. Using all available field data on SD, Heiskary and Wilson (1989) found an even lower typical range (0.3-0.9 m), but based on field data from reference lakes, Heiskary and Wilson (2008) found results closer to our results (typical range of 0.5-1.0 m). The average $SD_{Landsat}$ in WCBP lakes showed some variability between 1985 and 2005 (range of 0.26 m and SD of 0.11 m), and for 1990-2005 there was a trend of declining clarity (slope = –0.044; r^2 = 0.91). The highest mean $SD_{Landsat}$ was 1.07 m in 1990 and the lowest was 0.85 m in 2005. This ecoregion has 5.9% of the state's lakes and is characterized by nearly level to gently rolling terrain dominated by agriculture (77% of the total land area).

Water clarity in the NGP also is low (typical range of $SD_{Landsat}$ = 0.78-1.64 m and grand average = 1.27 m). Using all available field data on SD, Heiskary and Wilson (1989) found a lower typical range (0.3-1.2 m), and using only reference lakes, Heiskary and Wilson (2008) also found a low typical range (0.4-0.8 m). The latter result may reflect difficulties in finding minimally impacted reference lakes in this ecoregion. The average $SD_{Landsat}$ of NGP lakes was more variable temporally than in other ecoregions (range = 0.38 m; SD = 0.19 m), and there was a strong trend of declining clarity (slope = -0.085; $r^2 = 0.45$). The highest mean $SD_{Landsat}$ (1.5 m) occurred in 1985 and the lowest (1.12 m) in 2005. This ecoregion has 5.7% of the state's lakes and is similar to the WCBP in its flat to gently rolling terrain dominated by agriculture (74%), but it has more wetland (4%) and grassland (9%) than the WCBP.

In aggregate, Minnesota's other three ecoregions account for only 4% of the state's lakes. The Red River Valley (RRV) ecoregion, a flat plain left by glacial Lake Agassiz, has <2% of the state's lakes. It is called the Lake Agassiz Plain ecoregion and has somewhat different boundaries in a more recent (2007) delineation of ecoregions by the USEPA (http://www.epa.gov/wed/pages/ecoregions/mn_eco.htm), but we used the RRV version to be consistent with previous studies. The average $SD_{Landsat}$ was more variable in the RRV than in other ecoregions; means were ~1.9 m in 1985, 1995, and 2005 and ~1.3 m in 1990 and 2000 (Table 2). The overall average $SD_{Landsat}$ for the 20-year record was 1.67 m, with a typical range of 0.98-2.02 m. The NMW has fewer than 1.6% of the state's lakes but includes some of the state's largest lakes: Lower and Upper Red Lake and Lake of the Woods. The latter lake is plagued by excessive algal blooms (Binding *et al.*, 2011), but more typically, this ecoregion has high water clarity with a trend of increasing $SD_{Landsat}$ (Tables 2 and 3 and Figure 1). The DLA has only 0.5% of the state's lakes, and most of them are man-made reservoirs or backwater areas of the Mississippi River and its tributaries. This ecoregion is characterized by steep slopes that drain to the Mississippi River and is named for its lack of recent glacial activity. The mean water clarity ($SD_{Landsat}$) of the lakes is fairly low and variable (Tables 2 and 3 and Figure 1).

Spatial and Temporal Trends: Individual Lakes. Although there is a general pattern of lakes being more eutrophic and thus low in clarity in southern Minnesota and clearer in the north, at the local level the lakes are quite variable (Figure 3; also see Olmanson *et al.*, 2008). The range and variability

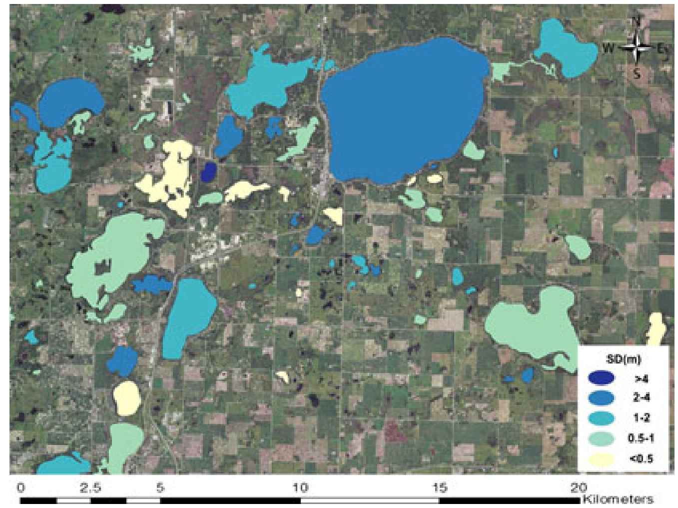

FIGURE 3. Water Clarity ($SD_{Landsat}$) in 2005 for Green Lake Area (Spicer, Minnesota) Showing the Variability in Water Clarity at the Local Level.

in $SD_{Landsat}$ throughout the state and at the ecoregion and even local level is striking and likely reflects both natural characteristics (e.g., depth and watershed size) and anthropogenic effects (e.g., land use and management practices).

We analyzed for temporal trends in individual lakes and investigated morphometric and spatial patterns in these trends at statewide and ecoregion levels. Many criteria can be used to identify whether temporal trends exist in a dataset. We used a simple and conservative approach: a temporal trend was said to occur for a given lake if water clarity increased or decreased by a factor of two (i.e., a doubling or halving of Landsat-based SD) over the 20-year record. The water clarity data were log transformed to normalize the values. Using these criteria, we found that 1,039 (10.8%) of Minnesota's lakes had trends in $SD_{Landsat}$. Of this total, 440 lakes (4.6%) had increasing trends, and 599 lakes (6.2%) had decreasing trends (Figure 4). Lakes with increasing and decreasing $SD_{Landsat}$ trends are spread throughout the state (Figure 4a), but some clusters of lakes with increasing or decreasing water clarity also are apparent. For example, abandoned iron mine pits in the NLF were dominated by increasing $SD_{Landsat}$, and shallow lakes along Lake Superior's north shore were dominated by decreasing $SD_{Landsat}$.

For all lakes with trends, there were 41% more lakes with decreasing rather than increasing $SD_{Landsat}$ among the smaller lakes (<150 ha), but only 12.5% more lakes with decreasing rather than increasing $SD_{Landsat}$ among larger lakes (>150 ha) (Figure 4b). The MDNR (1968) classification of lakes into broad "wetland" categories provided "lake type" information for 88% of the lakes we identified as hav-

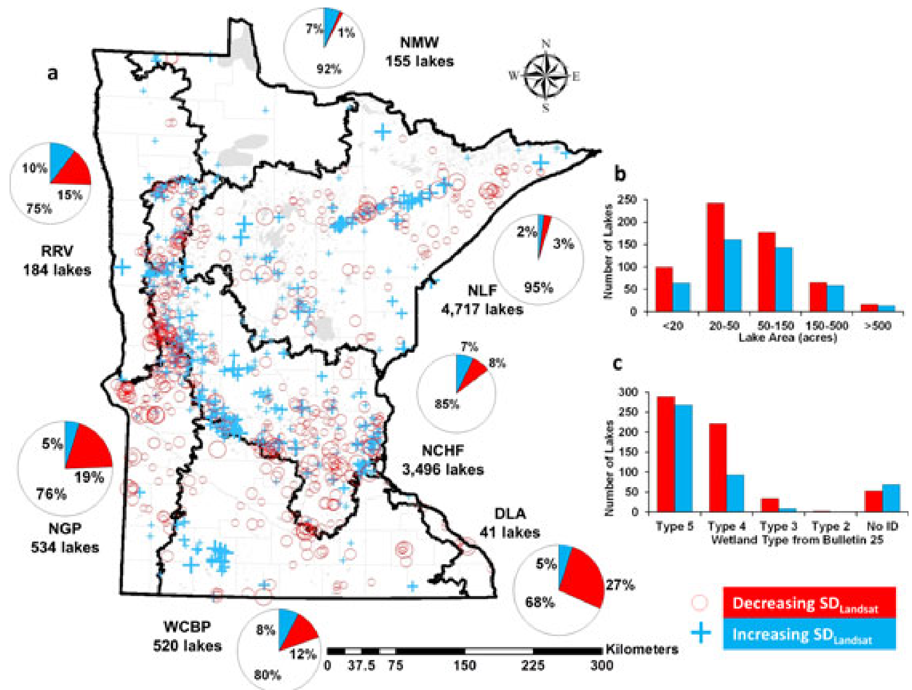

FIGURE 4. (a) Map of Lake Water Clarity Trends. Symbol size indicates magnitude of trend and pie charts show percentages of lakes in each ecoregion with increasing and decreasing water clarity trends. (b) Trends by lake area. (c) Trends by lake type. For a definition of abbreviations, see Figure 1.

ing trends. Among the lakes identified as "type 2, 3, or 4" wetlands, which are generally shallow water bodies, 151% more lakes had decreasing $SD_{Landsat}$ than increasing $SD_{Landsat}$, but among those classified as "type 5" wetlands, which are generally deeper water bodies, only 8% more lakes had decreasing $SD_{Landsat}$ than increasing $SD_{Landsat}$ (Figure 4c). These trends suggest that smaller and shallower lakes are more susceptible to decreasing water clarity — potentially due to changes in land use — than larger and deeper lakes; this has long been a well-accepted principle in limnology (e.g., Vollenweider, 1968).

At the ecoregion level, 20-32% of the lakes in four ecoregions (RRV, NGP, WCBP, and DLA) had trends as defined by our criteria, and decreasing $SD_{Landsat}$ was much more common than increasing $SD_{Landsat}$ (Figure 4a). These ecoregions are dominated by agricultural land, and the trends may indicate changes in agricultural activity over the study period. The two ecoregions with the largest numbers of lakes had fewer with detectable clarity trends. The NCHF had trends in ~15% of its lakes and nearly equal portions of increasing and decreasing $SD_{Landsat}$; <5% of the NLF lakes had trends (2.7% decreasing and 2% increasing). The NMW had increasing water $SD_{Landsat}$ in 6.5% of its lakes and decreasing values in 1.3%. The NLF and NMW have lower percentages of agricultural and urban land use than the other ecoregions, which may account for their relative stability, and the relatively large fraction of NMW lakes with increased $SD_{Landsat}$ may reflect the relatively small dataset or climatic changes over the study period.

Spatial and Temporal Analyses: Survey Lakes

To determine whether the survey lakes are representative of Minnesota lakes we compared the size class distributions of all lakes in the state and the survey lakes. Small lakes, which constitute ~70% of Minnesota lakes, are underrepresented in the survey lakes, for which only 40% are small. Also, NLF lakes are more highly represented in the survey than lakes of other ecoregions (Table 4). The survey lakes thus are not a representative sample of all Minnesota lakes. Because the NLF lakes generally have higher clarity than lakes in other ecoregions and because large and small lakes have different temporal trends in water clarity, use of the survey lakes to extrapolate to the entire population of Minnesota lakes could yield biased results. Consequently, we only compare different types of lakes within this dataset and do not extrapolate to all lakes in the state. For this more limited purpose, the survey dataset actually is better because the lake area and depth classes (Figure 5) are fairly equally represented. Regarding

TABLE 4. Comparison of Total Numbers of Lakes in Minnesota and the Minnesota Department of Natural Resources Survey Lakes by Ecoregion.[1]

Lakes	Minnesota	DLA	NCHF	NGP	NLF	NMW	RRV	WCBP
No. of Minnesota lakes	12,193	101	4,466	690	5,671	215	215	835
No. of survey lakes	3,357	4	900	70	2,209	22	29	123
% of lakes surveyed	27.5	4.0	20.2	10.1	39.0	10.2	13.5	14.7

[1]See Table 2 for key to ecoregion acronyms.

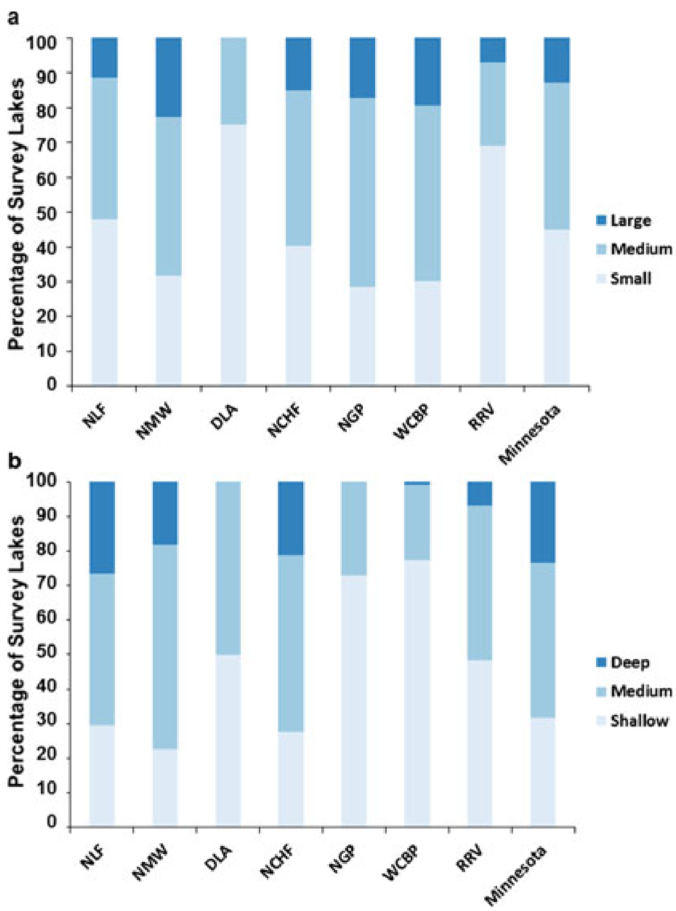

FIGURE 5. Distribution of (a) Area and (b) Depth for Minnesota Survey Lakes by Ecoregion. For a definition of abbreviations, see Figure 1.

lake class distributions, all size classes and shallow lakes are well distributed throughout the state but medium and deep lakes occur more in central and northern Minnesota.

We examined the tripartite (area, depth, and alkalinity) classification system at the state and ecoregion levels to determine whether the variables contribute to differences in water clarity. To distinguish general patterns we focused on values in the typical range (25th-75th percentile). At the statewide level, some significant differences in water clarity are associated with the depth, size, and alkalinity classes (Figure 6a). Clarity ($SD_{Landsat}$) generally was lower in shallow lakes than deep lakes. To a smaller degree, clarity was lower in large lakes than in small lakes and higher in low alkalinity lakes than in high alkalinity lakes. At the ecoregion level, the patterns hold for depth and size but not for alkalinity. For example, box plots of $SD_{Landsat}$ for the NLF (Figure 6b) show similar distributions for all alkalinity classes, and the highest alkalinity class had slightly higher water clarity. The clarity differences in alkalinity at the statewide level thus appear to be an artifact of geographic trends in alkalinity. Most low alkalinity lakes occur in the NLF, which also has the highest water clarity. Alkalinity (and probably other chemical factors related to it) thus can be ignored as a factor related to water clarity, reducing the number of classes to nine. Because depth has a much stronger influence than area, we further simplified our analysis to the three depth classes. At the ecoregion level, the lowest $SD_{Landsat}$ values occur in the shallowest lakes and highest occur in the deepest lakes (Figure 6b). Depth has long been recognized as a factor contributing to differences in trophic conditions in Minnesota lakes (Heiskary and Wilson, 1988) and was used as a factor in developing nutrient criteria for Minnesota lakes; Heiskary and Wilson (2008) recommended that the MPCA use separate nutrient criteria for shallow lake management.

Water Clarity-Watershed Land-Use Relationships

A limnological paradigm of long standing is that lakes are reflections of their watersheds (Brezonik, 1996); that is, water quality in lakes depends not only on in-lake factors like depth but also on the loadings of nutrients and other materials they receive from their watersheds or catchments. We investigated relationships between land use and water clarity for the 2000 time period at several geographic scales (county, minor watershed, and catchment). At the county level, strong relationships were found between mean $SD_{Landsat}$ and land cover classes. For relationships between $SD_{Landsat}$ and percent developed (urban and agriculture) land (Figure 7) and forested land, we found r^2 values of 0.75 and 0.78, respec-

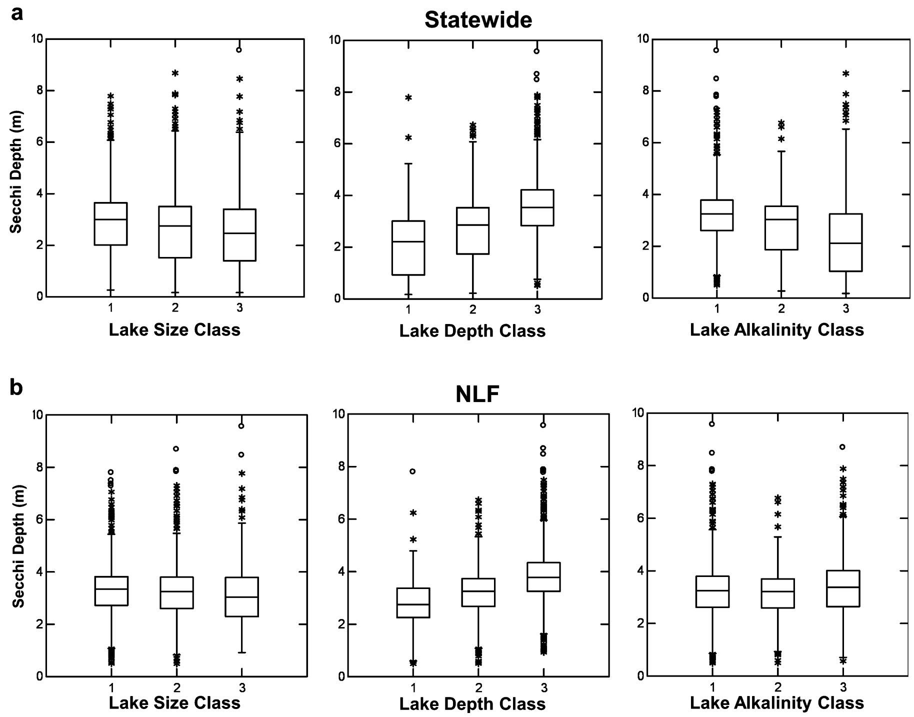

FIGURE 6. Boxplots of Landsat-Based Water Clarity ($SD_{Landsat}$) for 2000 by Lake Class for (a) All of Minnesota and (b) Northern Lakes and Forest Ecoregion (NLF).

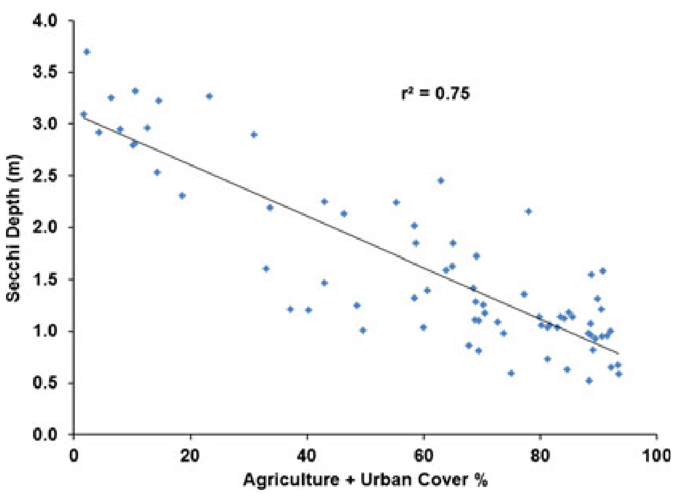

FIGURE 7. Developed Land Cover (urban plus agricultural) *vs*. Water Clarity at the County Level for the 2000 Time Period.

tively. Mean values of $SD_{Landsat}$ decreased with increasing urban and agricultural lands but increased with increasing forest lands. As the geographic scale decreased to minor watershed and catchment levels, the variability increased and strengths of the relationships decreased (e.g., $r^2 = 0.53$ and 0.43, respectively, for percent forest land cover) (Figure 8). This can be attributed to the "law of large numbers" where the average water clarity of a larger number of lakes (with many contributing factors) at the county level reduces the variability. As the geographic scale of the delineations decreased in size, the number of lakes also decreased (to only one at the catchment level). Because this analysis accounted only for land cover, other unaccounted for factors, such as variations in pollutant export within agricultural and urban lands and variations in depth and watershed size, increased the variability.

To decrease the variability we focused on survey lakes with known morphometric characteristics at the catchment level. Headwater catchments (lake watersheds) linked with land cover were examined, and results are presented in boxplots representing the "typical range" within lake depth classes. Using one-way ANOVA we found significant differences in $SD_{Landsat}$ for classes of lakes with different fractions (quintiles) of land cover in their catchments. Lakes with watersheds having more urban (Figure 9a) and agricultural (Figure 9b) land tend to have lower $SD_{Landsat}$ values. This pattern also was found to hold within ecoregions (Figure 10). The NLF and NCHF, the ecoregions with the largest numbers of lakes in Minnesota, had sufficient ranges of land cover conditions within catchments to examine land cover trends. In both cases, a trend of decreasing $SD_{Landsat}$ was found with increasing percentage of agricultural plus urban land within a lake's catchment. The other five ecoregions are more homogeneous in land cover distribution within individual catchments and lacked

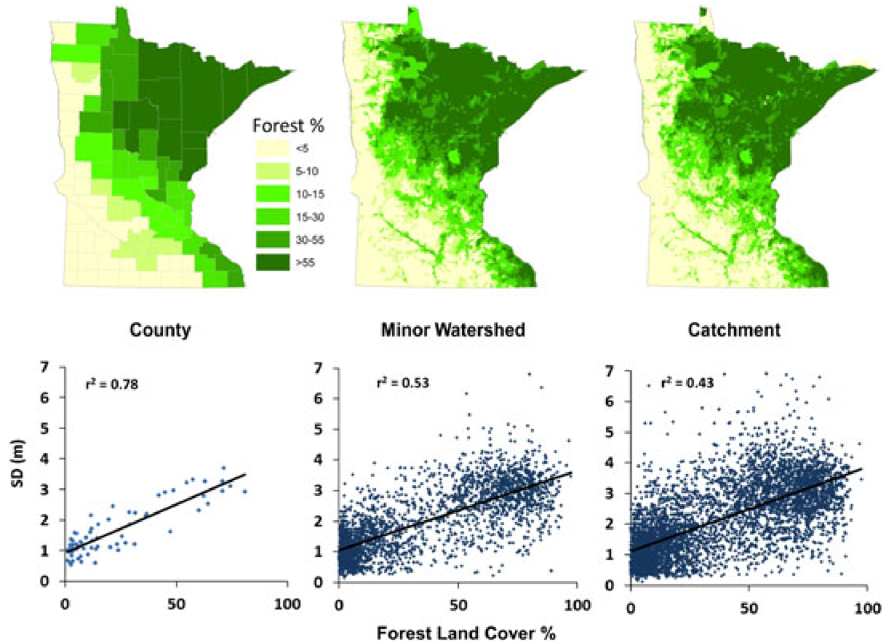

FIGURE 8. Distribution of Forest Land Cover in Minnesota at County, Minor Watershed, and Catchment Scales and Corresponding Plots of Lake Clarity ($SD_{Landsat}$) *vs*. Percent Forest Cover for the 2000 Time Period.

sufficient ranges in percentage of agricultural plus urban land cover to evaluate trends.

The pattern described earlier with regard to depth also holds: shallow lakes had lower water clarity than deep lakes with similar land cover. Urban and agricultural land uses have long been recognized as significant contributors to water quality degradation. Many studies have used empirical relationships or models to quantify these effects (e.g., Shannon and Brezonik, 1972; Baker *et al.*, 1985; Mattikalli and Richards, 1996; Brezonik and Stadelmann, 2002; Tong and Chen, 2002; Leone *et al.*, 2008). In contrast, increasing forest cover was associated with increasing $SD_{Landsat}$ (Figure 9c).

The above findings are generally consistent with others in the literature. Detenbeck *et al.* (1993) used a geographic information system to link water quality and land cover variables for 33 lake watersheds in Minnesota and found that forest was associated with higher water quality while agriculture was associated with lower water quality. Ramstack *et al.* (2004) used the distribution of diatom indicator species in sediment cores from 55 Minnesota lakes to compare inferred water quality of pre-settlement (~1750 and 1800) with post-settlement (1800 to present) conditions and found changes were significantly correlated with the percentage of watershed area that was developed (urban or agriculture). For the forested areas of northeastern Minnesota inferred water quality has changed little since 1800.

Landsat data enabled us to produce comprehensive water clarity assessments of lakes in Minnesota. The fundamentally integrative nature of SD (whether field measured or satellite derived) as a measure of water clarity, which is often considered a beneficial attribute, nonetheless imposes limitations on efforts to relate differences among lakes or over time to specific causes. For example, detailed information is not available on the extent to which humic color (CDOM) or inorganic suspended solids influence SD values (whether from satellite or field measurement), and both factors are influenced by different watershed conditions than algal growths are. In addition, the Landsat-derived SD values used in our analysis are based on late-summer imagery and field calibration data that more closely represent annual minimum values rather than annual means. In general, it is easier to develop predictive relationships for mean conditions than for extreme values. Overall, water clarity (or SD) does not lend itself to quantitative input-output analysis (loading models) like estimates of nutrient concentrations do.

Although lake depth and land use are major contributing factors for water clarity, many other factors, including climatic conditions, could be considered. Kloiber (2006) found that soil factors, such as percent organic matter or clay, contributed over half of the explanatory power of the regression models to estimate nonpoint source pollution. Other hydrologic factors, such as watershed to lake area ratio, also may provide insight in contributing factors to water clarity. Another potentially important factor is the density of agriculture animals in pastures and feedlot operations (Arbuckle and Downing, 2001; Berka

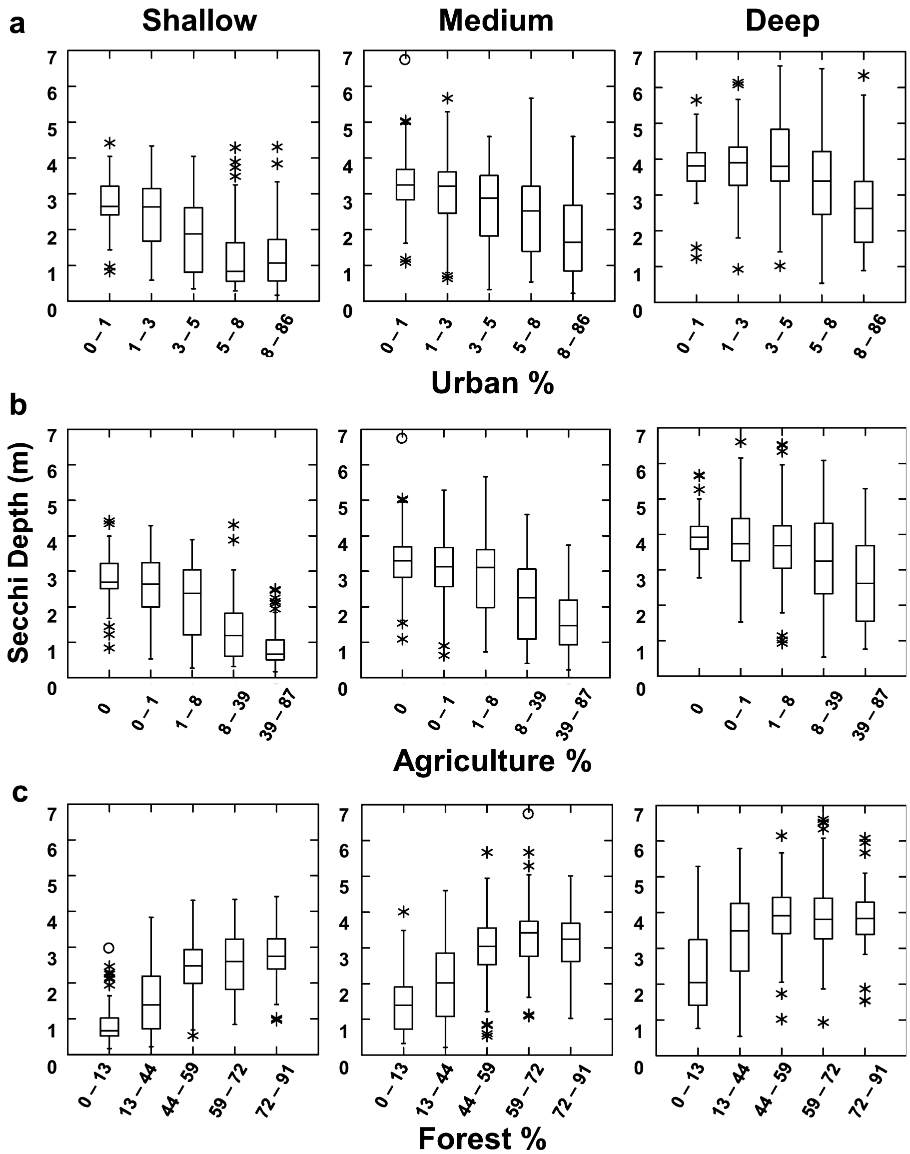

FIGURE 9. Boxplots of Landsat Lake Water Clarity in 2000 by Depth Class for Quintiles of Land Cover Percent (a) Urban, (b) Agriculture, and (c) Forest within Catchment.

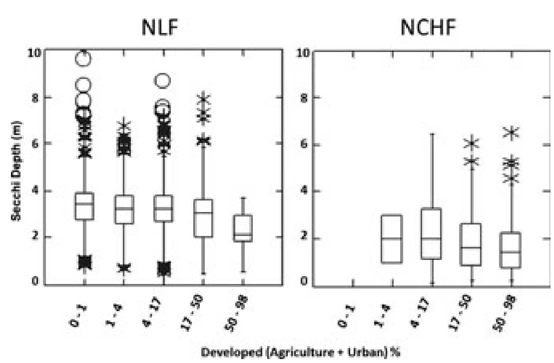

FIGURE 10. Boxplots of Landsat Lake Water Clarity in 2000 for Quintiles of Developed (agriculture + urban) Land Cover Percent for Northern Lakes and Forest (NLF) and North Central Hardwood Forest Ecoregions (NCHF).

et al., 2001). Another factor that could have a large impact on lake clarity but would be difficult to quantify is the presence or absence of rough fish such as carp.

CONCLUSIONS

Satellite imagery provides an accurate method to obtain comprehensive spatial and temporal coverage of a key water quality characteristic, water clarity. Traditional ground-based monitoring programs generally target lakes of specific interest (i.e., lakes are not randomly selected), and use of such data to extrapolate to regional assessments can lead to biased conclusions. However, use of such data to calibrate Landsat imagery enables reliable assessments of the entire population. Here we used a 20-year database of Landsat-derived water clarity expressed as $SD_{Landsat}$ for more than 10,000 Minnesota lakes to conduct statistical analyses of the spatial distributions and temporal trends of water clarity in the state. Statewide patterns — lakes generally are more turbid in the south and southwest and clearer in the north and northeast — can be attributed largely to differences in land cover and use. As the percentage of developed (agriculture and urban) land uses increased in a lake's watershed or other delineation of surrounding land, water clarity was found to decrease, but the opposite trend was found for forested land. The mean $SD_{Landsat}$ statewide remained stable from 1985 to 2005, but trends of decreasing clarity were detected in ecoregions dominated by agricultural land use. Temporal trends were detected in ~11% of Minnesota's lakes: 4.6% had improving clarity and 6.2% had decreasing clarity. Ecoregions in southern and western Minnesota, where agriculture is the predominant land use, had higher percentages of lakes with decreasing $SD_{Landsat}$ than the rest of the state. When lakes were grouped into depth classes, the deepest group of lakes was found to have higher clarity than the shallowest group with comparable catchment land cover. Small and shallow lakes appeared to be more susceptible to degradation and had a higher percentage of decreasing $SD_{Landsat}$ trends than large and deep lakes. Finally, because lake water clarity as measured by SD depends on three independent optical properties of water (algal turbidity, humic color, and suspended inorganic solids), the relationships between clarity and catchment conditions such as land cover are very complicated and not readily amenable to quantitative input-output modeling.

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LITERATURE CITED

Arbuckle, K.E. and J.A. Downing, 2001. The Influence of Watershed Land Use on Lake N:P in a Predominantly Agricultural Landscape. Limnology and Oceanography 46:970-975.

Baker, L.A., P.L. Brezonik, and C. Kratzer, 1985. Nutrient Loading Models for Florida Lakes. Lake and Reservoir Management 1:253-258.

Bauer, M.E., B.C. Loeffelholz, and B. Wilson, 2007. Estimating and Mapping Impervious Surface Area by Regression Analysis of Landsat Imagery. *In*: Remote Sensing of Impervious Surfaces, Q. Weng (Editor). CRC Press, Boca Raton, Florida, pp. 3-20.

Berka, C., H. Schreier, and K. Hall, 2001. Linking Water Quality with Agricultural Intensification in a Rural Watershed. Water, Air, and Soil Pollution 127:389-401.

Binding, C.E., T.A. Greenberg, and R.P. Bukata, 2011. Time Series of Algal Blooms in Lake of the Woods Using the MERIS Maximum Chlorophyll Index. Journal of Plankton Research 33:1847-1852.

Brezonik, P.L., 1996. Organizing Paradigms for the Study of Inland Aquatic Ecosystems. *In*: Freshwater Ecosystems. Revitalizing Educational Programs in Limnology, Committee on Inland Aquatic Ecosystems. Water Science & Technology Board, National Research Council, National Academy Press, Washington, D.C., pp. 181-202.

Brezonik, P.L. and T.H. Stadelmann, 2002. Analysis and Predictive Models of Stormwater Runoff Volumes, Loads, and Pollutant Concentrations from Watersheds in the Twin Cities Metropolitan Area, Minnesota, USA. Water Research 36:1743-1757.

Chipman, J.W., L.G. Olmanson, and A.A. Gitelson, 2009. Remote Sensing Methods for Lake Management: A Guide for Resource Managers and Decision-Makers. Developed by North American Lake Management Society, Madison, Wisconsin in collaboration with Dartmouth College, University of Minnesota, University of Nebraska, and University of Wisconsin for the United States Environmental Protection Agency.

Choi, J., B. Engel, S. Muthukrishnan, and J. Harbor, 2003. GIS Based Long Term Hydrologic Impact Evaluation for Watershed Urbanization. Journal of the American Water Resources Association 39:623-635.

Detenbeck, N.E., C.A. Johnston, and G.J. Niemi, 1993. Wetland Effects on Lake Water Quality in the Minneapolis/St. Paul Metropolitan Area. Landscape Ecology 8:39-61.

Gove, N.E., R.T. Edwards, and L.L. Conquest, 2001. Effects of Scale on Land Use and Water Quality Relationships. Journal of the American Water Resources Association 37:1721-1734.

Heiskary, S.A. and C.B. Wilson, 1988. Minnesota Lake Water Quality Assessment Report. Minnesota Pollution Control Agency, St. Paul, Minnesota, 95 pp.

Heiskary, S.A. and C.B. Wilson, 1989. The Regional Nature of Lake Water Quality Across Minnesota: An Analysis for Improving Resource Management. Journal of the Minnesota Academy of Science 55:71-77.

Heiskary, S.A. and C.B. Wilson, 2008. Minnesota's Approach to Lake Nutrient Criteria Development. Lake and Reservoir Management 24(3):282-297.

Kloiber, S.M., 2006. Estimating Nonpoint Source Pollution for the Twin Cities Metropolitan Area Using Landscape Variables. Water, Air, and Soil Pollution 172:313-335.

Kloiber, S.M., P.L. Brezonik, and M.E. Bauer, 2002a. Application of Landsat Imagery to Regional-Scale Assessments of Lake Clarity. Water Research 36:4330-4340.

Kloiber, S.M., P.L. Brezonik, L.G. Olmanson, and M.E. Bauer, 2002b. A Procedure for Regional Lake Water Clarity Assessment Using Landsat Multispectral Data. Remote Sensing of Environment 82:38-47.

Krysel, C., E. Boyer, C. Parson, and P. Welle, 2003. Lakeshore Property Values and Water Quality: Evidence from Property Sales in the Mississippi Headwaters Region. Mississippi Headwaters Board and Bemidji State University.

Leone, A., M.N. Ripa, L. Boccia, and A.L. Porto, 2008. Phosphorus Export from Agricultural Land: A Simple Approach. Biosystems Engineering 101:270-280.

Lillesand, T.M., J.W. Chipman, D.E. Nagel, H.M. Reese, M.R. Bobo, and R.A. Goldmann, 1998. Upper Midwest Gap Analysis Program Image Processing Protocol. U.S. Geological Survey, Environmental Management Technical Center, Onalaska, Wisconsin. EMTC98-G001, 25 pp.

Mattikalli, N.M. and K.S. Richards, 1996. Estimation of Surface Water Quality Changes in Response to Land Use Change: Application of the Export Coefficient Model Using Remote Sensing and Geographic Information System. Journal of Environmental Management 48:263-282.

MDNR (Minnesota Department of Natural Resources), 1968. An Inventory of Minnesota Lakes. Bulletin 25, Minnesota Department of Natural Resources, St. Paul, Minnesota.

Oliver, M.A., 1990. Kriging: A Method of Interpolation for Geographical Information Systems. International Journal of Geographic Information Systems 4:313-332.

Olmanson, L.G., M.E. Bauer, and P.L. Brezonik, 2008. A 20-Year Landsat Water Clarity Census of Minnesota's 10,000 Lakes. Remote Sensing of Environment 112:4086-4097.

Omernik, J.M., 1987. Ecoregions of the Conterminous United States, Map. Annals of the Association of American Geographers 77:118-125.

Osgood, R.A., 1988. Lake Mixis and Internal Phosphorus Dynamics. Archiv fur Hydrobiologie 113:629-638.

Osgood, R.A., P.L. Brezonik, and L. Hatch, 2002. Methods for Classifying Lakes Based on Measures of Development, Technical Report 143, Water Resources Center, University of Minnesota, St. Paul, Minnesota.

Peterson, S.A., N.S. Urquhart, and E.B. Welch, 1999. Sample Representativeness: A Must for Reliable Regional Lake Condition Estimates. Environmental Science and Technology 33:1559-1565.

Ramstack, J.M., S.C. Fritz, and D.R. Engstrom, 2004. Twentieth Century Water Quality Trends in Minnesota Lakes Compared with Presettlement Variability. Canadian Journal of Fisheries and Aquatic Sciences 61:561-576.

Shannon, E.E. and P.L. Brezonik, 1972. Relationships between Lake Trophic State and Nitrogen and Phosphorus Loading. Environmental Science and Technology 6:719-725.

Soranno, P.A., T. Wagner, S.L. Martin, C. McLean, L.N. Novitski, C.D. Provence, and A.R. Rober, 2011. Quantifying Regional Reference Conditions for Freshwater Ecosystem Management: A Comparison of Approaches and Future Research Needs. Lake Reservoir Management 27:138-148.

Tong, S. and W. Chen, 2002. Modeling the Relationship between Land Use and Surface Water Quality. Journal of Environmental Management 66:377-393.

USFWS (U.S. Fish and Wildlife Service), 1971. Wetlands of the United States. U.S. Fish and Wildlife Service, Circular 39, Washington, D.C.

Vollenweider, R.A., 1968. Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication. Organization for Economic Cooperation and Development (OECD), DAS/CSI/68.27, Paris, 199 pp.

Wagner, T., P.A. Soranno, K.S. Cheruvelil, W.H. Renwick, K.E. Webster, P. Vaux, and R.J. Abbitt, 2008. Quantifying Sample Biases of Inland Lake Sampling Programs in Relation to Lake Surface Area and Land Use/Cover. Environmental Monitoring and Assessment 141:131-147.

Wilson, C.O. and Q. Weng, 2010. Assessing Surface Water Quality and Its Relations with Urban Land Cover Changes in the Lake Calumet Area, Greater Chicago. Environmental Management 45:1096-1111.