Measuring Water Clarity and Quality in Minnesota Lakes and Rivers: A Census-Based Approach Using Remote-Sensing Techniques

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The St. Croix River near Washington County, Minnesota.

Over the past few decades, satellite-derived information has become an integral part of our daily life. It is difficult to imagine how crude and inaccurate weather forecasts would be without the daily satellite feeds that drive the complex models on which weather forecasts are based, and of course the satellite images themselves have revolutionized how we view the movement (and scale) of weather patterns. Similarly, satellite technology has become such an essential and commonplace component of global telecommunications, television, and Internet systems that few give a second thought to the technology behind these marvels. Google Earth now provides detailed images on our television and computer screens of far-off places using high-resolution satellite images. In addition, GPS systems based on satellites now enable even "directionally challenged" drivers to head their cars to the desired destination and make it possible to locate and track people in the most remote and inaccessible locations.

Satellite technology also has had profound impacts on the Earth sciences and on science-based management of natural resources. For example, Landsat imagery has been used for several decades to analyze land-use and land-cover patterns, estimate crop production, and monitor forest health. More recently, the MODIS satellites have been used to estimate terrestrial primary production on a continental scale and to monitor oceanic levels of chlorophyll on a global scale. Satellites also provide essential hydrologic information (e.g., snow pack, rainfall, and evapotranspiration estimates) for water resources management.

Despite many efforts reported in the scientific literature during the past three decades, however, procedures using satellite imagery to measure surface water *quality* have not been adopted on a routine basis. For the past nine years, we have been working with colleagues and students to change this state of affairs and to develop workable procedures for routine use of satellite imagery and related technology to assess surface water-quality conditions by Minnesota's water management agencies. Most of our work has focused on lakes and water clarity as a simple measure related to users' perceptions of water quality. However, we also have explored the use of satellite imagery to measure other water-quality characteristics, such as chlorophyll (a measure of the abundance of algae in water) and humic matter (natural derivatives from plants that produce the brown stain in wetlands and water draining from forested areas), and evaluated the potential of remote-sensing techniques to identify and map aquatic vegetation in lakes and wetlands. We have explored the capabilities and limitations of several satellite sensor systems, as well as aircraft-mounted sensors with high spectral and spatial resolution that provide special capabilities for remote measurements of water quality in rivers and streams.

This article summarizes progress we have made in these areas with emphasis on water clarity and provides some perspectives on the likely future role of satellite- and aircraft-based remote-sensing techniques in water resource monitoring and management in Minnesota. The work described here has been supported by a variety of state and federal agencies, including the Metropolitan Council, Minnesota Pollution Control Agency, Department of Natural Resources, Legislative Commission on Minnesota Resources, NASA, and the U.S. EPA. The senior author was the 2003–2004 Fesler-Lampert Chair in Urban and Regional Affairs, and some of the work described in this paper was supported by that position.

Ground and Satellite Measurements of Lake Water Clarity

In essence, clarity measures the distance that light penetrates in a water body. In lakes, water clarity commonly is measured by a simple device called a Secchi disk—a 20-cm (8-inch) diameter white disk—that is lowered into the water column until it can no longer be seen. The depth of disappearance is called the Secchi depth. Three types of constituents affect water clarity: algae and algal-derived particles; natural, colored organic matter (humic matter); and soil-derived clay and silt particles. In Minnesota lakes, soil-derived turbidity usually is not important, and water clarity most commonly is related to algal abundance. Water clarity is useful in measuring water quality because it relates directly to both human-use perceptions of quality (clear water generally being preferred, especially for swimming) and to the abundance of algae. Thus, water clarity is an indirect measure of a lake's "trophic state"—its status in terms of nutrient concentrations and biological productivity. Because of its simplicity, Secchi depth is one of the most frequently measured properties of lakes, and many citizen monitoring programs have been developed over the past quarter century to supplement the monitoring by government agencies. Nonetheless, only about 10% of the lakes in the Twin Cities metropolitan area are monitored for water clarity in any given year, and in some parts of the state, the fraction monitored is much lower.

In our early studies on potential applications of satellite imagery to measure surface water quality, we found close correlations between water clarity, as measured by the Secchi disk, and light in the blue and red bands of the spectrum reflected from lake water surfaces and measured as "brightness" by satellite sensors. We used this information to develop procedures to estimate water clarity in terms of "inferred Secchi depth" using images gathered routinely (every 16 days, assuming no interference by cloud cover) by the Landsat satellites. With financial support from the Metropolitan Council, our initial studies focused on lakes in the Twin Cities metro area, but we later expanded our coverage across the entire state. Colleagues have applied our techniques for lake clarity monitoring in Wisconsin and Michigan, and recently we conducted pilot studies to evaluate the usefulness of the technique in Ohio, Indiana, and Illinois.

Because atmospheric conditions (e.g., haze and water vapor content) affect the light reflected by land and water surfaces as it travels back toward satellite sensors, no universal predictive relationship exists between water clarity and satellite sensor response. Instead, it is necessary to calibrate the general relationship applicable to Landsat and Secchi depth data for each Landsat image. We do this using standard regression procedures and Secchi depth measurements collected by existing monitoring programs on a few lakes (at least 20 and sometimes as many as 100 per image) near the time the satellite image was taken. The ground-based Secchi depth data do not need to be collected at exactly the same time that Landsat acquires an image; we found that measurements taken within a few days (±3 to 7 days) of image acquisition still provide strong relationships. This is because water clarity (Secchi depth) usually does not exhibit large and rapid fluctuations in a given lake (although there are strong seasonal patterns in clarity).

The general predictive equation that we found for water clarity estimation has the form:

$$\ln(SD) = a(TM1/TM3) + b(TM1) + c$$

where a, b, and c are coefficients fit to the calibration data by the regression analysis, $\ln(SD)$ is the natural logarithm of the Secchi depth for a given lake, and $TM1$ and $TM3$ are the brightness values measured by the Landsat sensor in the blue and red bands, respectively, for a pre-defined area of the lake surface. Once coefficients have been fitted to the equation, it can be used to infer Secchi depth values for all other lakes in the Landsat image. The images are approximately 110 miles on a side and may contain hundreds of lakes and ponds. The spatial resolution (so-called pixel size) of brightness data in the Landsat images is 30 meters (roughly 100 feet) on a side. Because we need to use data only from pixels for water surfaces not affected by land or aquatic vegetation, the net effect is that the procedure is capable of obtaining high-quality results on lakes larger than about 20 acres (8 hectares). For the seven-county Twin Cities metro area, which constitutes part of one Landsat image, this translates to approximately 550 lakes and open-water wetlands.[1]

Lake Water Clarity in the Twin Cities Metropolitan Area

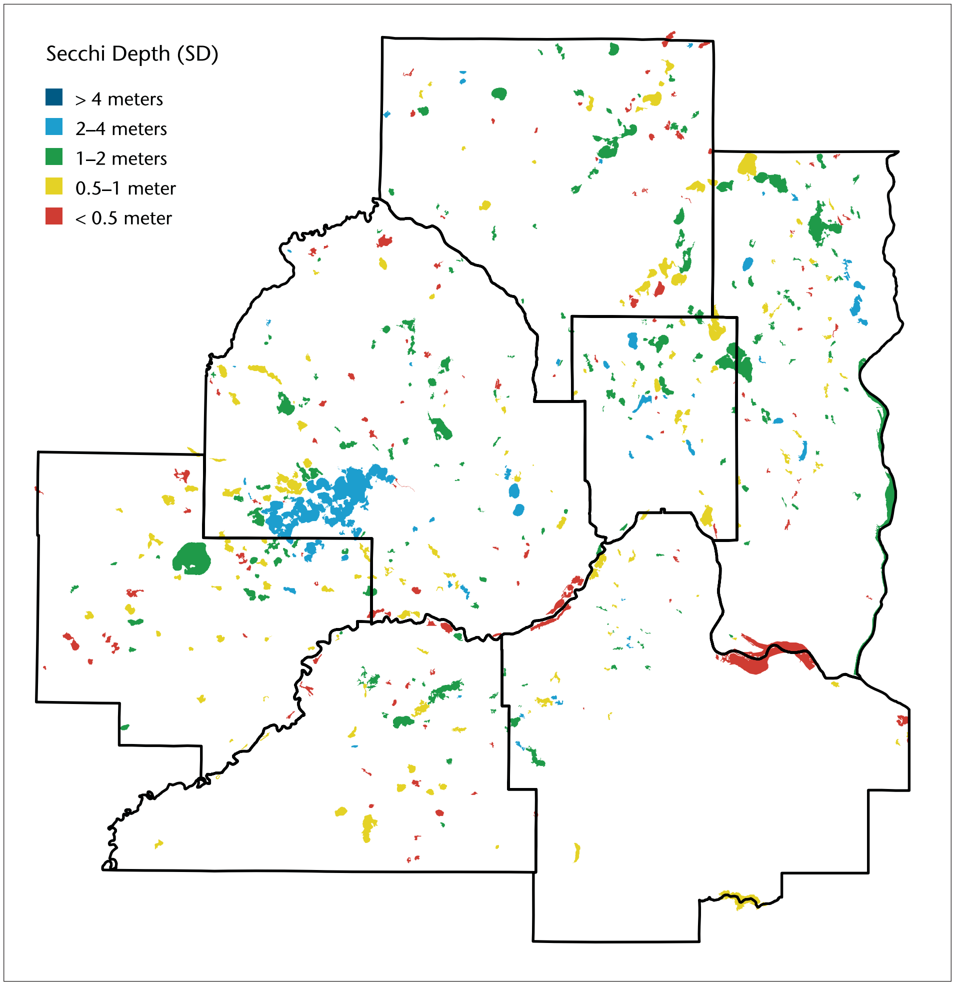
Our initial studies on the method established that it works in a practical sense and that it provides reliable data not otherwise available. Regarding practicality, historical Landsat images are available from the EROS Data Center in Sioux Falls, South Dakota, for relatively low cost (a few hundred dollars), and many images are available for free in existing local archives. Once the procedure is established for a given region, the processing time per image for an experienced analyst is less than a week, and the processing uses software that is

[1] The above description is a simplification of the procedures used to convert Landsat data into inferred lake clarity (Secchi depth) values. Details on the method are found in a manual available online at http://water.umn.edu.

readily available in remote-sensing laboratories. A search of historical archives showed that at least one cloud-free image is available for the Twin Cities metro area nearly every year for a late-summer index period (late July to early September), which we found to be the optimal time to assess water clarity in Minnesota lakes. Regarding data reliability, R^2 values (a measure of goodness of fit) for the regression relationships to establish the coefficients of the predictive equation normally are in the range of 0.8 to 0.9, meaning that they explain 80 to 90% of the variance in the relationship, and occasionally they are as high as 0.95 (95% of the variance). Given that ground-based measurements of Secchi depth are themselves subject to some imprecision, we consider this to be quite acceptable. In addition, excellent agreement between satellite-estimated and ground-observed Secchi depth trends can be achieved. For example, Secchi depth temporal trends during the 25-year record were found to be virtually identical in several metro-area lakes for which long-term ground-based data were available to compare with Landsat-inferred results. For Coon Lake (Anoka County), Secchi depth was found to increase at a rate of 0.062 m per year during the period 1973–1998 based on in-lake measurements, and a best-fit regression equation of the satellite-inferred Secchi depth yielded an increase of 0.067 m per year during the same time period.

In subsequent studies on water clarity in metro-area lakes, we were interested in evaluating spatial and temporal patterns in lake clarity. Specifically, we wanted to answer the following questions: (1) Does lake water clarity in the metro area vary depending on climatic conditions, such as extended periods of drought or above-average precipitation?; (2) Can long-term trends in water clarity of metro area lakes be related to well-documented changes in land-use/cover within the region?; and (3) How strong are the relationships between lake clarity and land-use/land-cover conditions in the landscape around lakes? To address these questions, we first analyzed a series of 10 images from the late-summer index period covering a 25-year interval (1973–1998). Ground-based calibration data were obtained for each image, primarily from the Metropolitan Council's citizen monitoring program, and Landsat-inferred Secchi-depth values were obtained by the procedures described above for approximately 575 lakes and open-water wetlands in the Twin Cities metro area.

Figure 1. Water Clarity (SD) for Twin Cities Metropolitan Area Lakes (inferred from Landsat TM image), September 1998



Note: One (1) meter equals 3.3 feet.

Results for 1998, the last year in this initial analysis (Figure 1), demonstrate that at any given time lakes in the metro area exhibit a wide range of water clarity. Analysis of the temporal trend results shown in Table 1 indicates that climatic conditions have an important influence on water clarity in the region's lakes. For example, 1988, which was one of the hottest and driest summers on record in the region, had the highest fraction of lakes in the lowest clarity class and one of the lowest fractions of lakes in the highest clarity class among all the study years. Hot sunny weather, combined with low rainfall that produced little flushing of water through the lakes, yielded heavy algal blooms and low water clarity in many lakes. In contrast, 1993 and 1996, which were wet and relatively cool summers, had low fractions of lakes in the lowest clarity class and high fractions in the highest clarity class. The combination of cooler temperatures, less sun, and greater flushing of water through the lakes resulted in lower amounts of algae and higher clarity in many lakes. The 1996 image was acquired in mid-July, just outside the late-summer window that we found best represents the period of lowest water clarity in Minnesota lakes, and this also may explain the higher water clarity values in that year.

Several statistical tests were used to examine temporal differences and trends across years in lake water clarity. A Kruskal-Wallis test showed no significant differences in metro-area regional lake water clarity between the years 1983, 1986, 1991, 1995, and 1998, but water clarity was below normal in 1973 and 1988 and above normal in 1975, 1993, and 1996.

Although no simple long-term trend in lake water clarity was detected at the scale of the entire Twin Cities metro area, a Kendall Tau-b analysis for each of the approximately 500 metro-area lakes with sufficient data to conduct a trend analysis indicates that 49 lakes (10% of the total) had significant temporal trends. Water clarity improved in 34 lakes since 1973 and declined in only

Table 1. Water Clarity Trends for Twin Cities Metropolitan Area Lakes, 1973–1998

Secchi Depth (SD)	Number of lakes, by month and year									
	July 1973	Aug 1975	Sept 1983	Aug 1986	Aug 1988	Sept 1991	Aug 1993	July 1995	July 1996	Sept 1998
> 4 meters	7 (1.6%)	4 (1.0%)	14 (3.2%)	0 (0.0%)	3 (0.6%)	0 (0.0%)	0 (0.0%)	1 (0.2%)	4 (0.8%)	0 (0.0%)
2–4 meters	94 (21.1%)	79 (18.9%)	61 (14.0%)	94 (19.5%)	77 (16.4%)	75 (15.5%)	68 (14.0%)	86 (17.7%)	118 (23.9%)	96 (19.7%)
1–2 meters	192 (43.2%)	165 (39.6%)	182 (41.7%)	160 (33.3%)	120 (25.5%)	187 (38.6%)	218 (45.0%)	192 (39.6%)	245 (49.6%)	184 (37.8%)
0.5–1 meter	122 (27.4%)	137 (32.9%)	114 (26.1%)	168 (34.9%)	168 (35.7%)	173 (35.7%)	144 (29.8%)	151 (31.1%)	104 (21.1%)	149 (30.6%)
< 0.5 meter	30 (6.7%)	32 (7.7%)	65 (14.9%)	59 (12.3%)	102 (21.7%)	49 (10.1%)	54 (11.2%)	55 (11.3%)	23 (4.7%)	58 (11.9%)
Total	**445**	**417**	**436**	**481**	**470**	**484**	**484**	**485**	**494**	**487**

Note: One (1) meter equals 3.3 feet. Column percentages may not total 100% due to rounding.

15 lakes. The most common trend (43% of lakes with trends) was an increase in clarity of 4 to 8% per year. Lakes with decreasing clarity generally were small or quite shallow, suggesting that morphometry (the physical shape and size characteristics of a lake) may predispose a lake to respond more strongly to changes in natural or human-induced stresses. The finding that more lakes had improving rather than worsening clarity during the 25-year record at first was surprising, given the major geographic expansion of the Twin Cities footprint that occurred during that time period. However, suburban sprawl has occurred largely at the expense of agricultural lands rather than more pristine forested areas, and croplands often produce higher levels of nutrients in storm-water runoff than do suburban residential areas. Moreover, the salutary effects of efforts to manage the quality of urban and suburban storm-water runoff, and also to directly manage water-quality conditions in lakes, should not be discounted.

Since the studies described above were completed, we have continued to assess lake water clarity across the Twin Cities metro area. Additional information for 2000, 2003, and 2005 is available on the "Twin Cities Lake Browser" (see http://water.umn.edu), through which one can locate individual lakes of interest and obtain data for the entire period of record. Perhaps more significant is the fact that the Metropolitan Council Environmental Services (MCES) has adopted the procedure and is conducting annual assessments of water clarity in metro-area lakes. Results for 2003, 2004, and 2005 are available from MCES.

Water Clarity in Ponds and Small Lakes

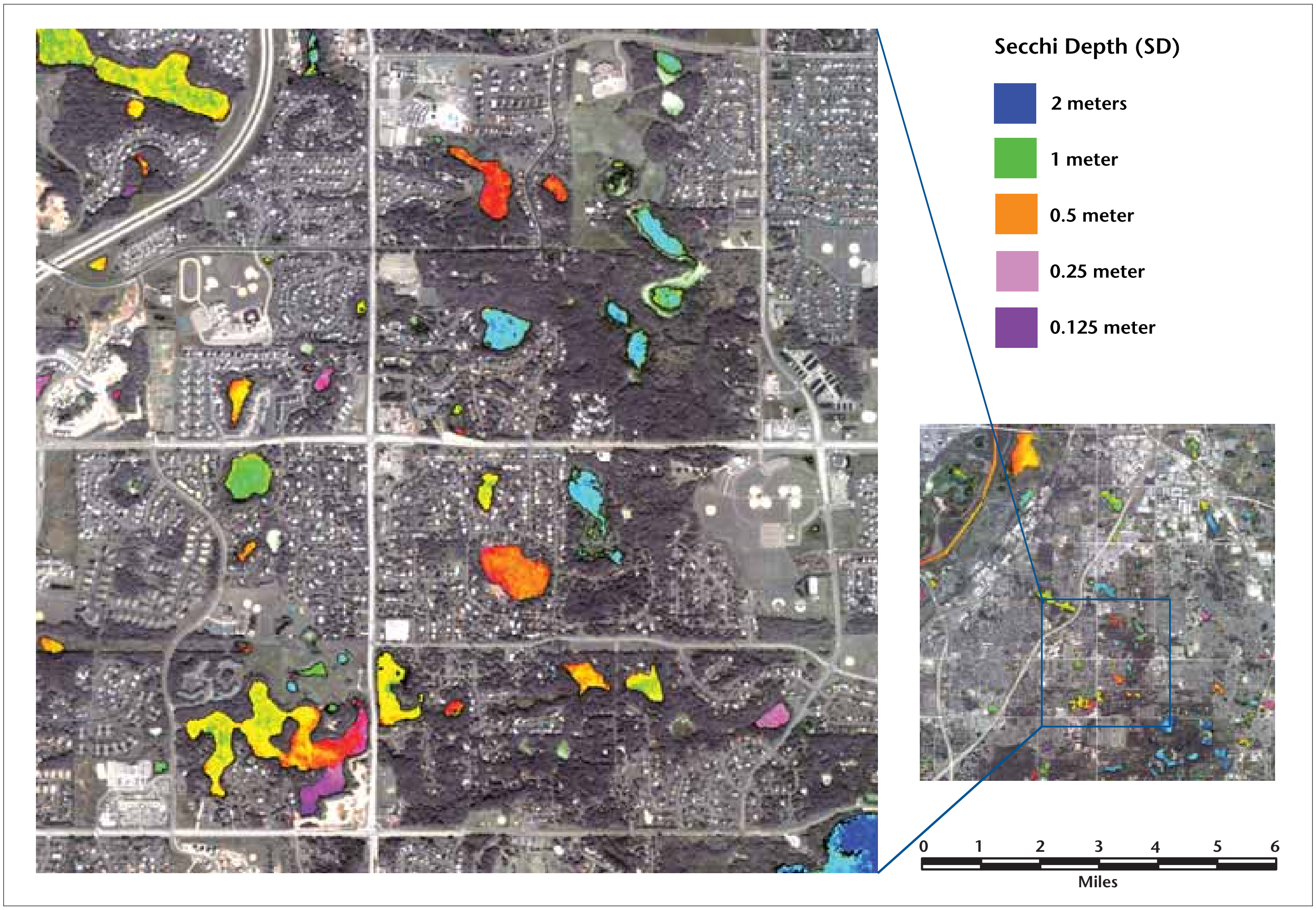
The relatively modest spatial resolution of the Landsat sensor (30 m) limits the usefulness of Landsat imagery to assess water clarity conditions in small lakes and ponds. Newer commercial satellites with spatial resolution (pixel sizes) of 1 to 4 meters overcome this limitation and allow assessment of water clarity in neighborhood ponds much smaller than an acre in area. Two such commercial satellites, IKONOS and Quickbird, are the primary sources of the amazing aerial images shown increasingly in television news broadcasts and the imagery that provides the basis for Google Earth. Both satellites have sensors similar to the Landsat TM sensors in spectral characteristics (e.g., three broad bands in the visible spectrum and one in the near infrared).

Figure 2 shows an image for Eagan, Minnesota, acquired on August 23, 2000, by the IKONOS satellite. The city of Eagan, located in the southeastern metro area (just southeast of the Minneapolis–St. Paul Airport) and roughly 6 by 6 miles (about the size of an IKONOS image), has about 375 small lakes, ponds, and open-water wetlands greater than one acre in area. The image was processed using the basic procedures we developed for Landsat imagery. Multiple regression analysis of the brightness signatures from 19 lakes with Secchi depth measured within three days of the image date yielded a strong fit to the equation model described earlier ($R^2 = 0.82$, meaning that the relationship explains more than 80% of the variation in the data). We created a pixel-level map of water clarity of small lakes and ponds in Eagan, as shown in Figure 2. Only 14 of Eagan's 375 lakes, ponds, and wetlands were large enough to be included in our previous metro-area assessments and 22 were included in our statewide assessments (see below), but the IKONOS image assessed 236 water bodies. The wide range of water clarity in small ponds within a small geographic area is striking and likely reflects both natural factors (pond depth and watershed area) and effects of landscape use and management practices. We found similar results for images obtained in 2001 and 2002. The cost of IKONOS data ($2,500 to $4,000 per image) probably would be too large for many cities just for lake-clarity assessments, but should be justifiable if the images also are used to monitor changes in land use, land cover, and wetland status.

Statewide Census-Level Assessment of Lake Water Clarity

Starting in 2000, we expanded our analysis of lake water clarity in Minnesota from the metro region to the entire state. Since that time, we have completed five censuses at approximately five-year intervals for the 20-year period 1985–2005. Each census

Figure 2. IKONOS Image Showing Water Clarity for Lakes and Ponds in Eagan, Minnesota, August 23, 2000



comprises information on more than 10,000 lakes and open-water wetlands across the entire state of Minnesota. The techniques used to produce these results are similar to those we developed for the metro-area assessments. For the statewide assessments, we generally sought Landsat images where ideally each entire path across the state yielded useable information (clear skies). Landsat orbits Earth such that it traverses Minnesota in southwest-to-northeast paths that are approximately 110 miles wide, and the trajectory is such that successive paths partially overlap. By using entire paths across the state rather than single images, we were able to extend the geographic range with available ground data for calibration purposes; some remote areas in northern Minnesota, for example, have very limited ground-based measurements. The overlapping nature of the Landsat paths also meant that multiple satellite-inferred Secchi depth measurements were obtained for approximately 60% of the state's lakes in each census. Because clouds sometimes obscure Landsat images for parts of the state during the late-summer measurement period, the statewide censuses usually are composites of analyzed images acquired within plus or minus one year of the nominal year for a census.

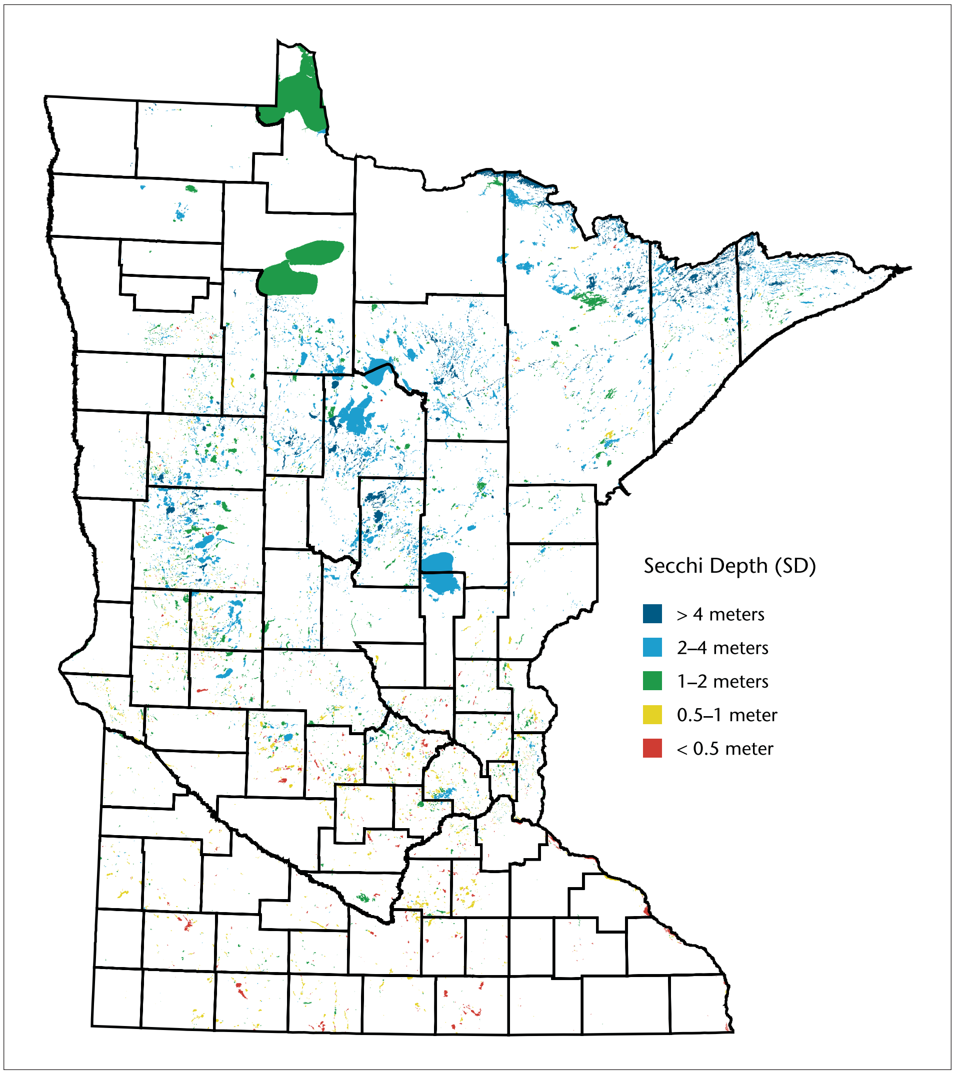
We currently are in the process of analyzing this data set, which we believe is unprecedented in size and scope, for spatial and temporal trends. Figure 3 illustrates the distribution of lake water clarity across the state for the year 2005 (a similar image for 2000 is available from the authors as a large poster suitable for framing and classroom use), and Table 2 summarizes temporal trends in the numbers of Minnesota lakes in different water-clarity classes for the

Table 2. Water Clarity in Minnesota Lakes Based on Landsat-Inferred Secchi Depth (SD), 1985–2005

Secchi Depth (SD)	Number of lakes, by year				
	1985	1990	1995	2000	2005
> 4 meters	1,043	1,213	1,059	909	1,254
2–4 meters	4,917	3,981	4,649	4,641	4,363
1–2 meters	3,080	3,150	3,356	2,637	3,091
0.5–1 meter	1,627	1,898	1,670	1,729	1,902
< 0.5 meter	469	490	254	600	631
Total	**11,136**	**10,732**	**10,988**	**10,516**	**11,241**

Note: One (1) meter equals 3.3 feet.

Figure 3. Landsat-TM–Based Census of Water Clarity in Minnesota Lakes, 2005



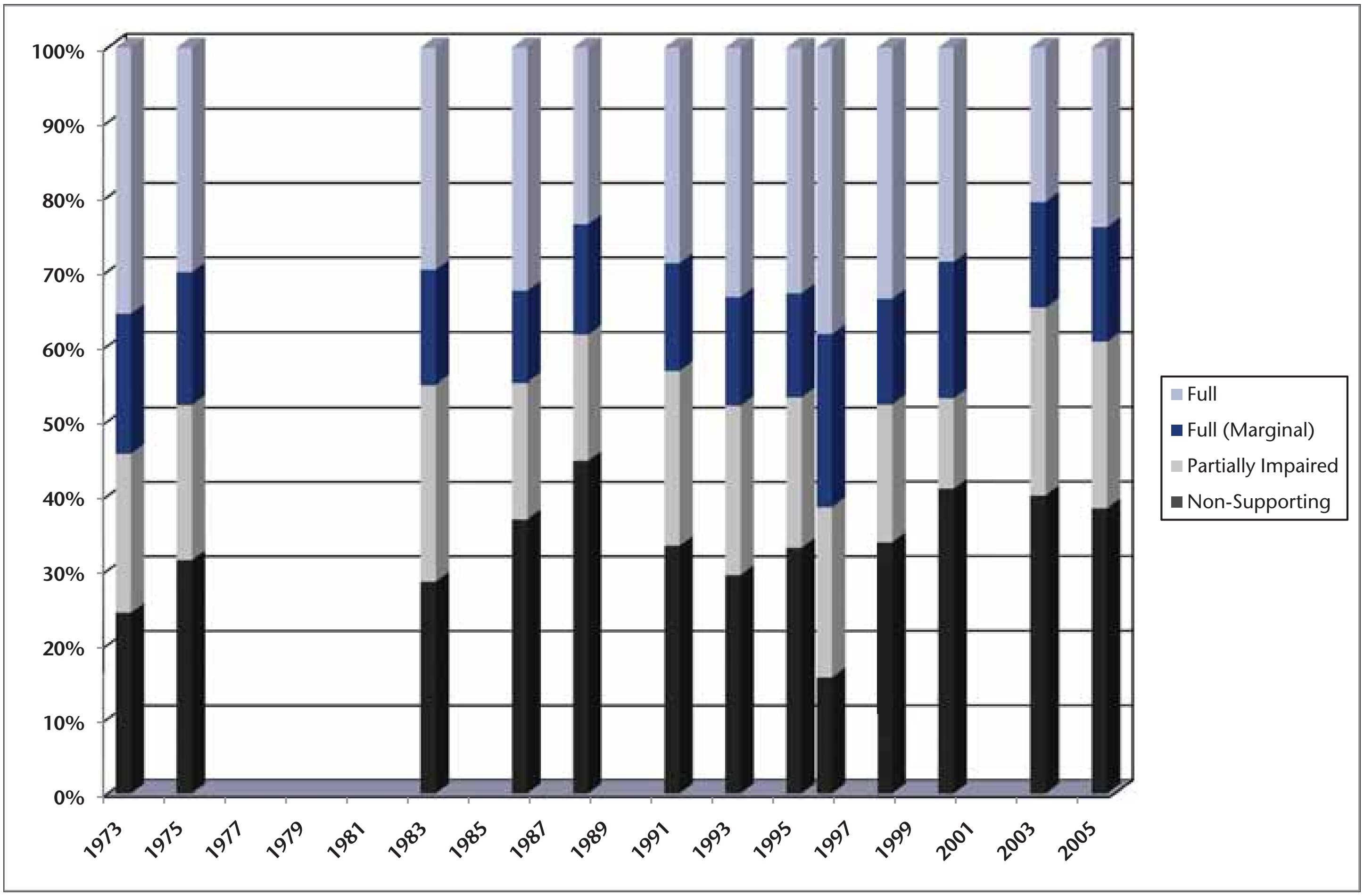
period of record. Overall, the distribution of lakes across the water-clarity classes is fairly stable throughout the 20-year period 1985–2005, but a few differences stand out. For example, substantially fewer lakes were found in the lowest water clarity class (< 0.5 m) in 1995 than in all other years, and in 2000 there were fewer lakes with water clarity values in the 1 to 2 m range but more lakes with values in the 3 to 4 m range than in other years. Information on trends in lake clarity for individual counties and across Minnesota's ecoregions can be found at http://water.umn.edu, and the "Lake Browser" on this site allows users to locate individual lakes across the state and obtain water clarity and other information.

Of interest regarding the statewide census information is how it extends the earlier information on lake clarity within the Twin Cities metro area. Figure 4 shows the distribution of TCMA lakes in four "swimming use-support" classes based on water clarity over the extended period of record, 1973–2005. The Minnesota Pollution Control Agency developed criteria for these use-support classes based on algal bloom problems associated with various concentrations of total phosphorus (TP) in lakes. Based on established relationships between TP and Secchi depth, we converted the criteria into equivalent Secchi depth values. For example, a TP concentration of about 80 micrograms per liter (µg/L) corresponds to a Secchi depth of 0.62 m (or 2.0 ft) in lakes where phosphorus controls the growth of algae. Lakes with higher TP concentrations (hence, lower Secchi depth values) than that are considered to be "non-supporting" (that is, unfit) for swimming because they have a high frequency of nuisance algal blooms. The results in Figure 4 suggest a gradual trend in the fraction of metro-area lakes in the non-supporting category during the first half of this decade, compared with results for the end of the earlier record (through 1998). However, when the entire 32-year study period is examined, no simple linear trend is apparent regarding the extent to which metro-area lakes support swimming. Instead, a cyclic pattern is evident that may be related to climatic conditions. For example, the fraction of lakes in the non-supporting category reached a maximum in the late 1980s, corresponding to the end of a long-term drought, and a minimum in the mid-1990s, corresponding to a period of above-average rainfall in the region. The fraction of lakes in the fully supporting category showed the opposite trend (minimum in the late 1980s and maximum in the mid-1990s). Thus, it appears that climatic conditions play an important role in the temporal pattern of lake water clarity at the region scale.

With the larger database available from the statewide censuses, we also have been able to examine relationships between lake clarity and land-use/land-cover conditions in the surrounding terrestrial landscape, a goal we were not able to achieve in our earlier studies focused only on the Twin Cities metro area. For example, contrasts in land use/land cover among the three largest ecoregions in the state (Figure 5) are obvious, and patterns of lake clarity appear to reflect these differences. The Northern Lakes and Forests (NLF) ecoregion in northeastern Minnesota is more than 60% forested and only roughly 6% agricultural; the Western Cornbelt Plains (WCP) ecoregion in southern Minnesota is only 4% forested, and agricultural land occupies more than 80% of the region; and the North Central Hardwood Forest (NCHF) ecoregion in the center of the state has intermediate land-use/land-cover conditions (12% forested and 50% agricultural land). Reflecting these ecoregion differences, water clarity in NLF lakes averages slightly more than 3 m, and about 70% of the lakes have values in the 2 to 4 m range. In contrast, water clarity in WCP lakes averages just less than 1.0 m, and only about 8% of the lakes in this region have clarity values in the 2 to 4 m range (and very few have values greater than 4 m). Lakes in the NCHF exhibit a wide range of clarity, but the average value is about 1.5 m, and roughly 40% of the lakes have clarity values in the 1 to 2 m range.

Of course, other factors aside from land use/land cover affect lake clarity—water column depth, underlying geology, and population density in lake catchments also play important

Figure 4. Swimming Use Support for Twin Cities Metropolitan Area Lakes, 1973–2005



Note: Swimming use support based on water clarity (Secchi depth, SD). SD values defining the use-support classes are as follows: *full,* > 1.60 meter; *full (marginal),* 1.21–1.60 meter; *partially impaired,* 0.80–1.20 meter; *non-supporting,* < 0.80 meter. One (1) meter equals 3.3 feet.

roles. In general, lakes in the NLF tend to be deeper than lakes in the WCP, and geology and climate are important factors that predispose the NLF to be much more forested than the WCF.

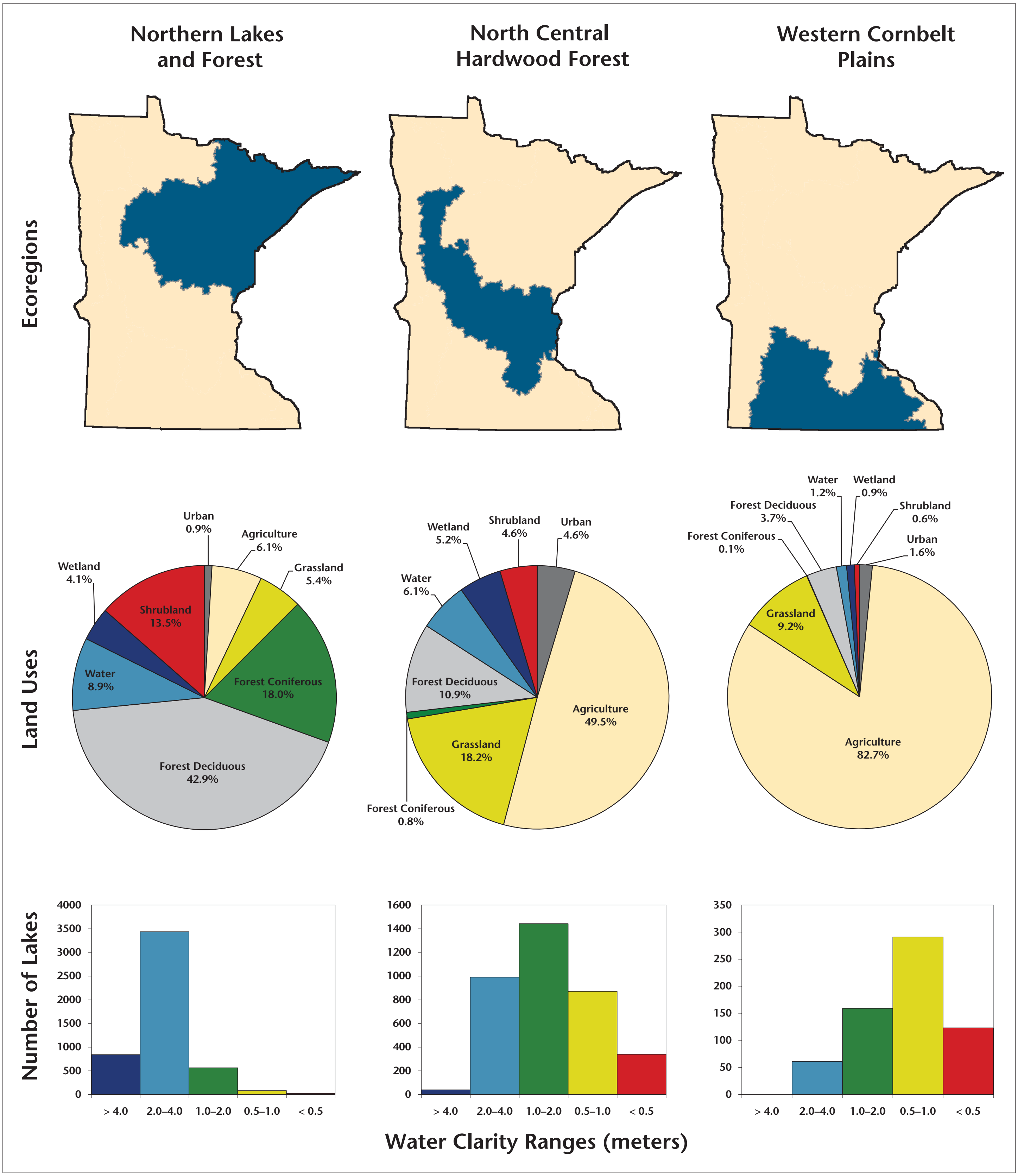
Striking relationships between lake water clarity and land use/cover also were found when the data were examined at the county level (Figure 6). Across Minnesota counties, average lake clarity increases with increasing percentages of forested land and decreases with increasing percentages of agricultural and urban land. The rate of decrease with degree of urban land is especially dramatic; average lake clarity declines to only about 1.0 m (3.3 ft) at 10% urban land in a county. Others have reported similar effects of urbanization and extent of impervious area on the biotic integrity of streams. Digital map layers delineating individual lake catchments are becoming available for Minnesota, and it will be interesting to see whether relationships with lake clarity improve when land-use analyses are conducted at the scale of individual lake catchment areas.

Aircraft-Based Remote Sensing of Water Quality in Rivers and Streams

Satellite imagery works well to assess water clarity and related optical properties of lakes (such as chlorophyll and humic color), but geometric considerations make satellite imagery a poor choice for remote sensing of rivers and streams. As they pass through the Twin Cities metro area, only large rivers like the Minnesota and Mississippi Rivers are wide enough to have pixels representing water surfaces that are not affected by shoreline and land surfaces. High-resolution satellites like IKONOS do have the required spatial resolution, but acquisition of such images for a particular date and time is not a straightforward proposition, and the relatively small areas these images cover lead to impractically large costs per river mile monitored.

Multispectral sensors similar to those in satellites like Landsat and IKONOS (or with higher spectral resolution) that are deployable in small aircraft are commercially available. Because aircraft can be flown precisely on flight paths along river reaches, they offer an attractive possibility for monitoring river water quality and obtaining more complete spatial coverage than is possible with ground-based sampling. To explore the usefulness of this technique, we conducted a series of studies in the summers of 2004 and 2005 on rivers in the Twin Cities metro area and nearby areas using a small plane and sensor system operated by the University of Nebraska. In contrast to the Landsat TM and IKONOS sensors, which have only a few, broad spectral bands, the sensors we used in the aircraft studies collected reflected light in many (narrow) spectral bands, and this provided much better opportunities to develop stronger predictive relationships for various optically related water-quality characteristics. Support for this work was provided by the Legislative Commission on Minnesota Resources through the Minnesota Pollution Control Agency (MPCA), and collection of ground-based calibration data was achieved by a collaborative effort of the MPCA and the Metropolitan Council Environmental Services.

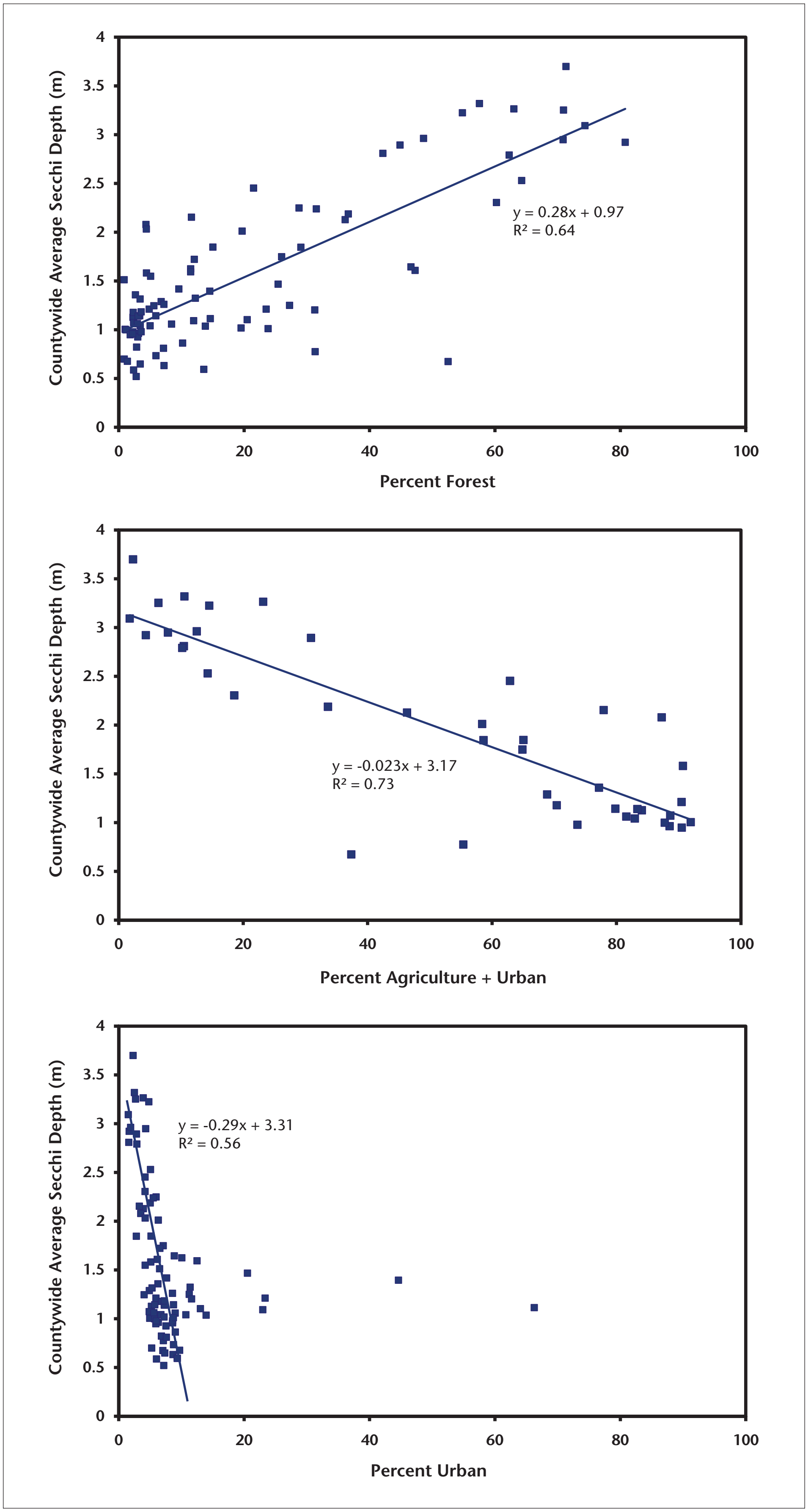
Figure 5. Land-Use/Land-Cover Distribution and Water Clarity in Three Minnesota Ecoregions



Source: Land-cover data are from 1990 Minnesota Land Cover GAP. Secchi depth data are from 2000.

Note: One (1) meter equals 3.3 feet.

Figure 6. Relationship between Average Secchi Depth (SD) for Lakes in each Minnesota County and Percentage of Forested, Agricultural, or Urban Land



Note: One (1) meter equals 3.3 feet. Trend line for urban area is based only on counties with urban area < 11%.

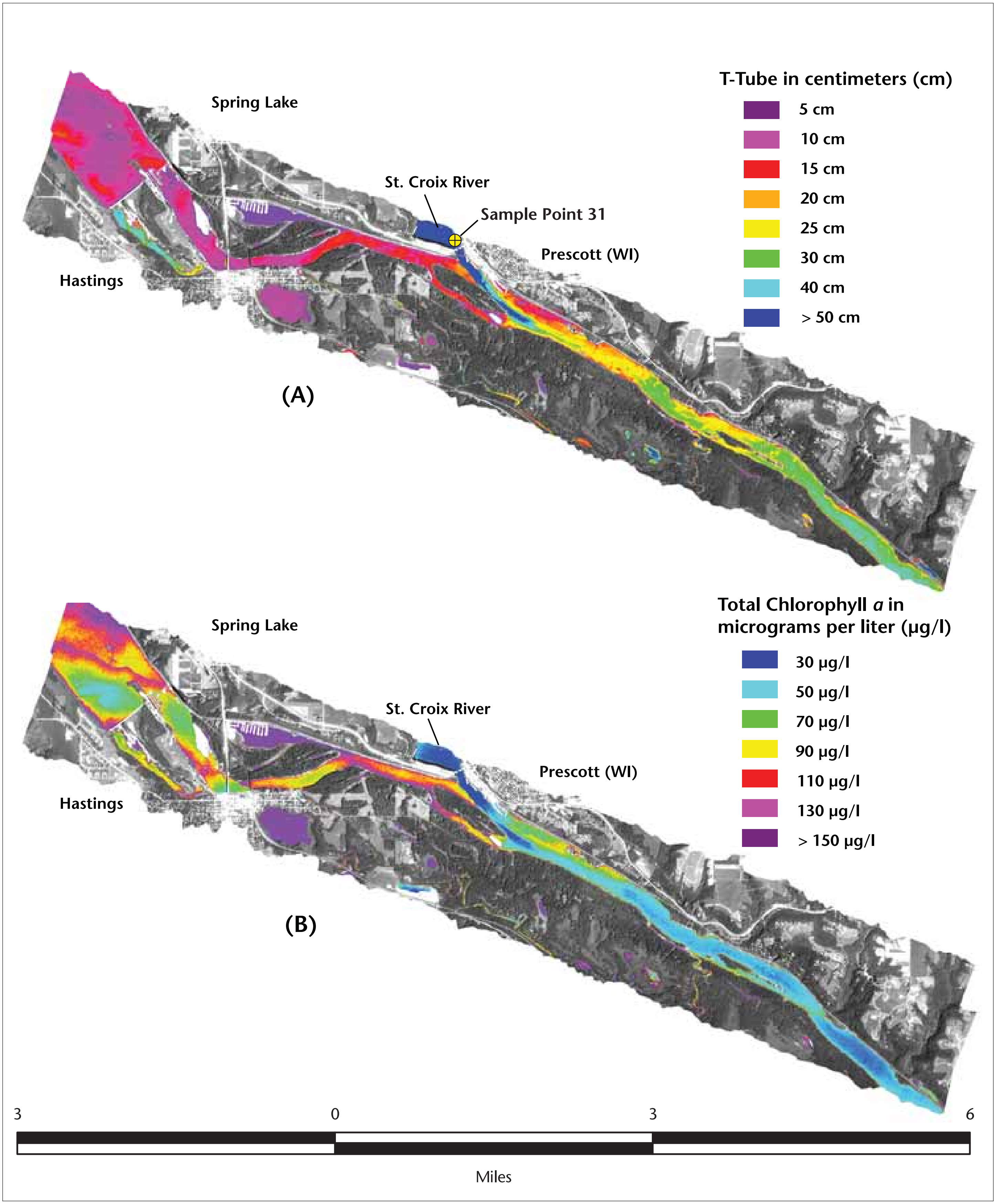
Procedures used to obtain and analyze data from the aircraft-mounted sensor were generally similar to those we have been using for satellite data. Because of the high degree of spatial and temporal variability in optical properties (such as turbidity, water clarity, and chlorophyll concentrations) of flowing waters, collection of water samples from the rivers was coordinated to occur near the same time as the aircraft overpass. Water clarity was measured on river samples using a Transparency Tube (T-tube) that provides data analogous to Secchi depth but is easier to use in flowing waters. Statistically strong relationships were found between ground-based measurements of water-quality characteristics and the brightness of light at specific wavelengths collected by the aircraft-mounted sensor ($R^2 = 0.94$ for T-tube water clarity and 0.72 for chlorophyll *a*).

The exploratory studies were successful and yielded maps for several optically related water-quality characteristics, including turbidity, water clarity, suspended solids, and chlorophyll, along several major river reaches in the region. Typical results are shown in Figure 7, which illustrates the distribution of water clarity (a) and chlorophyll (b) along a stretch of the Mississippi River starting at highly turbid Spring Lake (above Lock and Dam No. 2) near Hastings, Minnesota. The influence of water low in suspended matter from the St. Croix River on clarity in the Mississippi River is apparent, and the figure shows that water clarity improved further as suspended matter settled out over a distance of about 3 to 4 miles from the confluence of the St. Croix. Chlorophyll levels were very high in parts of Spring Lake (but spatially highly variable) and the Mississippi River downstream of the lake, but concentrations decreased markedly after confluence with the cleaner waters of the St. Croix River. As illustrated in Figure 7, in typical ground-based routine monitoring programs on rivers, one or perhaps a few sampling locations along the river would be sampled and the high spatial variability of water quality would be missed.

Concluding Comments: Prospects for the Future

Effective management of natural resources depends on accurate and complete information, as well as an informed public. We view the remote-sensing techniques for information

Figure 7. Spatial Distribution of (a) Water Clarity Measured by a T-tube and (b) Total Chlorophyll a in the Mississippi River from Spring Lake to Downstream of the Confluence with the St. Croix River



Note: Based on aircraft-based imagery collected August 19, 2004.

Photo courtesy of the Minnesota Pollution Control Agency

This photo shows the dramatic difference in water clarity at the confluence of the St. Croix River (blue water) and the highly turbid Mississippi River.

gathering on surface water described in this article as tools that will help achieve both of these goals. Satellite imagery provides a cost-effective means to obtain comprehensive spatial coverage on the status and trends in key characteristics of surface-water quality, and the results can be made readily available to the public in easily understood formats. Of course, these methods cannot tell us everything we would like to know about water quality; satellite sensors cannot detect the presence of potentially harmful metal pollutants, organic pollutants, or bacterial pathogens in water. However, the sensors do provide accurate information about water clarity and the occurrence of algal blooms in water, and these are common issues affecting the usability as well as the economic value of Minnesota lakes.

Scientists in other states have adopted the methods we developed to study Minnesota lakes, and resource management agencies in Minnesota and elsewhere are starting to adopt these same methods as routine. Prospects for future improvements of the techniques are bright, because satellite sensors likely to be developed during the next decade should provide better spectral, spatial, and temporal resolution. Development of techniques for automated correction of satellite data to account for atmospheric effects should be possible, and this would eliminate the need to gather ground-based calibration data for every image.

Our recent work with aircraft-mounted sensors is especially promising in that it provides a means of gathering spatially comprehensive information on water quality in rivers and streams heretofore not practical with ground-based sampling programs. Such comprehensive information, as shown for the Mississippi River in Figure 7, could be used to provide much more robust validation of models used to forecast water-quality conditions than current ground-based methods allow. Moreover, the compelling nature of the visual images themselves should help both scientists and the public to gain a deeper appreciation and better understanding of our aquatic resources.

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The research upon which this article is based was supported in part through funds provided by the Fesler-Lampert Chair in Urban and Regional Affairs, one of four endowed chairs and two named professorships made possible through a generous contribution to the University of Minnesota by David and Elizabeth Fesler. The Fesler-Lampert Endowment in Interdisciplinary and Graduate Studies was initially established in 1985 to stimulate interdisciplinary research and teaching through the appointment of distinguished, broadly learned scholars to endowed faculty positions at the University of Minnesota. Additional support was provided by the Metropolitan Council, Minnesota Pollution Control Agency, Department of Natural Resources, Legislative Commission on Minnesota Resources, National Aeronautics and Space Administration (NASA), and the U.S. Environmental Protection Agency (EPA).