Remote Sensing: Does It Have a Role?

Assessing the Nation's Lakes

Steve Heiskary, Leif Olmanson, Anatoly Gitelson, & Jonathan Chipman

The United States Environmental Protection Agency (EPA) and the states have a responsibility to assess the water quality of the nation's lakes. According to EPA's *2000 Water Quality Report*, the overall percentage of assessed lakes has not increased in recent years and the report suggests the percentage may have decreased relative to previous assessments. Financial resources at the federal, state and local level are insufficient to assess lakes in a timely fashion using conventional methods.

EPA sees the need to survey the Nation's lakes in such a fashion that key questions about the quality of the Nation's lakes might be answered. Drawing from the agency's 2005 fact sheet on the "Survey of the Nation's Lakes":

- What percent of the nation's lakes are in good, fair, and poor condition for key indicators of ecological health and human activities?
- What is the relative importance of stressors such as nutrients and pathogens?

To address these questions, EPA is collaborating with the states, tribes, and USGS to develop a statistically based survey that will allow for national and regional estimates of the condition of lakes and reservoirs. The survey that is being planned will employ random sample sites and consistent procedures at all sites to ensure the results can be compared across the country. Given the goals of the national survey, remote sensing can complement the on-the-ground assessment of lakes and has the potential to allow for cost effective assessment of all lakes.

Remote sensing is an emerging technology, and new improvements in sensor design and advances in data analysis have increased its prospects for monitoring aquatic systems. The results from recent projects using remote sensing for assessment of lake water quality are promising and remote sensing is now being used routinely in some states (e.g., Minnesota, Nebraska, and Wisconsin) as part of their overall lake assessment efforts.

However, several questions remain concerning the most appropriate platforms and sensors for different applications; true costs associated with the various platforms; the availability of remotely sensed images; and the appropriateness of the various models for translating the images into usable estimates of water quality. The North American Lake Management Society (NALMS) has recognized the role remote sensing can play in the assessment of water quality and, in the project described here, is drawing on the expertise of several universities and states that have experience in remote sensing to answer these questions and make these techniques more widely available for states interested in using these technologies.

Remote Sensing

NALMS, EPA, and the Universities of Minnesota, Nebraska, and Wisconsin are collaborating on a project to conduct a retrospective assessment of several available remote sensing systems (Table 1) for monitoring lakes. These systems cover a broad range of spatial, spectral, and radiometric resolutions that will allow for direct comparison and assessment of the limitations and strengths of each and help determine the characteristics best suited for specified water quality monitoring goals, with an emphasis on developing remote sensing methods that can be used effectively for routine regional monitoring of lakes.

An overview of the platforms follows, with some recent applications that are a part of the NALMS project. The discussion covers: (1) moderate resolution Landsat imagery that is currently being used routinely to assess thousands of lakes in some states (e.g., Minnesota and Wisconsin); (2) low-resolution MODIS imagery that is being used to assess large lakes across broad regions; (3) high-resolution commercial IKONOS and QuickBird imagery that can assess smaller lakes and ponds at a local scale; (4) aircraft-based hyperspectral imagery that can be used for detailed water quality assessments of complex lake systems and is being used routinely (since 2004) to assess water quality in Nebraska lakes; and (5) boat-based sensors that can provide real-time water quality information.

Landsat

Although several satellite remote sensing systems have been used for water quality assessment, the relatively low cost, temporal coverage, spatial resolution, and data availability of the Landsat system make it particularly useful for assessment of inland lakes. The Landsat geographic coverage of 12,000 square miles per image allows for the simultaneous assessment of thousands of lakes in lake-rich areas. The spatial resolution of 30 meters is suitable for all lakes down to about 10 acres and can be used to map in-lake variability. Several studies have demonstrated a strong relationship between Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) data and in-situ observations of water clarity (e.g. Figure 1) and chlorophyll *a* (e.g., Lillesand et al. 1983; Mayo et al. 1995; Yacobi et al. 1995; Kloiber et al. 2002).

Table 1. Remote Sensing Sensor Characteristics.

Sensor	Pixel Size	Spatial Resolution	Spectral Resolution	Spatial Coverage	Notes
Boat-based sensing	*In-situ*	Very high	High	Low	Selected water bodies
Aircraft-based Hyperspectral / Multispectral	0.5 - 3 m	High	High	Low	Selected water bodies
Commercial High Resolution. Satellites: IKONOS & QuickBird	0.6 - 4 m	High	Low	Low	Small water bodies
Landsat TM & ETM+	30 m	Moderate	Moderate	Moderate	Archive: 1972 - present lakes ≥10 acres
MODIS	500 – 1000 m	Low	High	High	Large; daily coverage

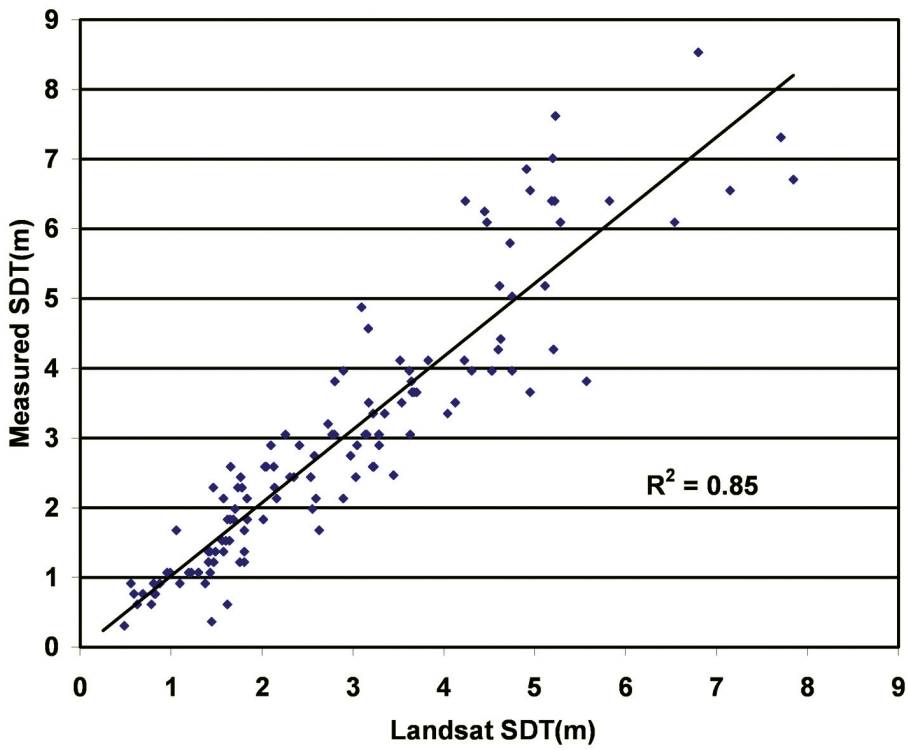


Figure 1. Relationship Landsat TM3/TM1 ratio to water clarity.

For effective environmental planning and management, it is vital to have long-term water quality information on a broad regional scale. Although it is not possible to go back in time and collect additional water quality information using conventional field methods to fill gaps from previous efforts, Landsat data have been collected regularly since the early 1970s, enabling historical water quality information to be extracted from the Landsat images. The extraction of historic and current water quality data from satellite images, coupled with existing data collection efforts, may facilitate the development of comprehensive regional databases that can be used to evaluate regional differences and water quality trends over time. If used along with land-use data, this information can help determine the impacts different land-use practices have on lake conditions. Results of such analyses will aid local and state agencies to make informed decisions about development policy and improve the management of lake resources. Figure 2 shows an ecoregion-scale land cover and water clarity statistical comparison.

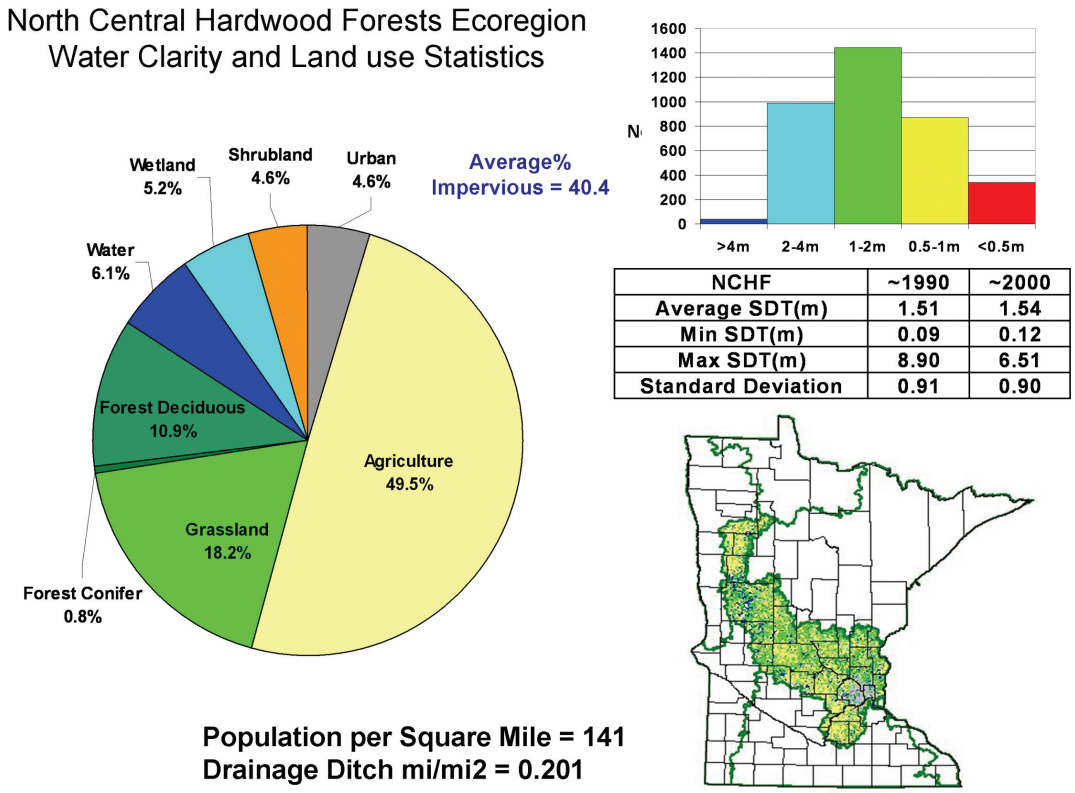
Development of comprehensive water quality databases are well underway in Minnesota, Wisconsin, and Michigan, which have all completed Landsat state-wide water clarity assessments (Figure 3). In Minnesota, the University of Minnesota is completing a historical water clarity database of over 10,000 lakes that cover the entire state for the ~1975, ~1985, ~1990, ~1995, ~2000 and ~2005 time periods (www.water.umn.edu). These water clarity atlases are currently being used to assess spatial and temporal patterns in lake water clarity based on surrounding land use and cover by using a geographical information system (GIS) to link the lake clarity data with land use features.

As part of the NALMS EPA remote sensing project, Landsat assessment of lakes will be applied to paths of Landsat imagery in Illinois, Indiana, and Ohio. Each participating state will receive a prototype water clarity assessment for their state.

MODIS

Complementing the regional-scale imagery of sensors such as Landsat, global monitoring systems such as MODIS can be used to monitor large lakes, on a daily to weekly timescale, across entire regions. The MODIS instrument is carried on NASA's Terra and Aqua satellites; taken together, the two systems provide daily coverage over the entire world, except for the north and south poles. Another advantage of MODIS is that the images are available for free, in near-real time, via the Internet. There is a tradeoff, however – MODIS's coarse spatial resolution (250 to 1000 meters) means that only relatively large lakes can be studied.

The same procedures used for mapping water clarity from Landsat have also been tested on MODIS images of the upper Midwest. Scientists at the University of Wisconsin used field samples collected by citizen volunteers to calibrate four dates of MODIS imagery from September 2001. Despite



NCHF	~1990	~2000
Average SDT(m)	1.51	1.54
Min SDT(m)	0.09	0.12
Max SDT(m)	8.90	6.51
Standard Deviation	0.91	0.90

Figure 2. Land cover and water clarity statistics for North Central Hardwood Forest ecoregion of Minnesota.

intermittent cloud cover, some 243 satellite-derived measurements of Secchi disk transparency depth were made, on 90 lakes across Wisconsin. As part of the NALMS EPA project, archival MODIS imagery from 2000-2005 is now being analyzed to determine its usefulness for estimating both water clarity and chlorophyll *a* concentrations in a wide range of lake types.

In late July and early August of 2005, a group of scientists and citizen volunteers made 115 field surveys of lakes across Minnesota and western Ontario, collecting data on chlorophyll concentrations, water clarity, and other measurements (Figure 4). The data from this field sampling campaign are an ideal source for calibrating satellite-based water quality models, because they include a wide range of types of lakes, with very different levels of chlorophyll, colored dissolved organic carbon, suspended solids, and water clarity.

Figure 5 shows a map of predicted chlorophyll *a* concentrations in lakes in northern Minnesota and western Ontario, based on the analysis of Terra MODIS imagery and field data from the 2005 survey. The correlation between the satellite predictions and actual field measurements is quite good (Figure 6). This type of analysis can show spatial variations in water quality across a single large lake (e.g., Lake of the Woods on the U.S./Canada boundary), or among groups of lakes. Thanks to the daily coverage of MODIS, it can also provide an unparalleled view of temporal changes in water quality, subject to the limitation of cloud cover.

Raw MODIS data can be obtained from NASA archives, or from a network of regional

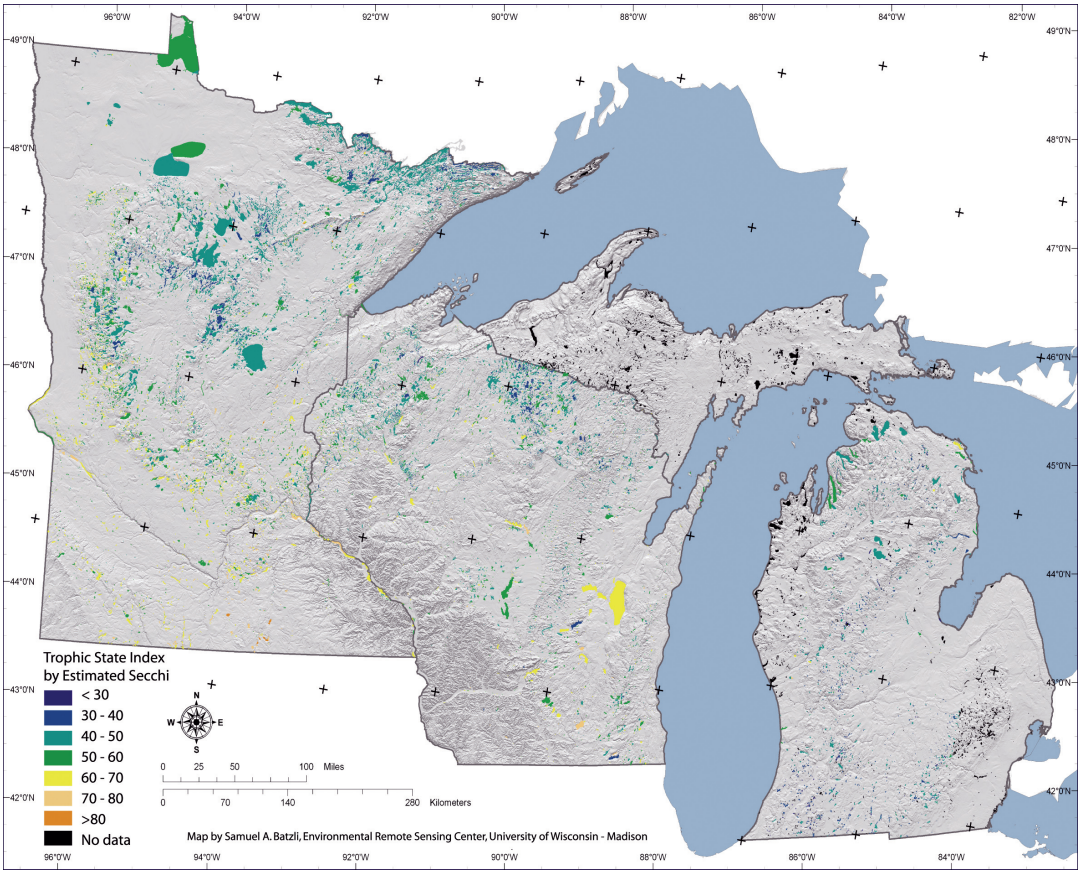


Figure 3. Three-state Landsat-based water clarity map.

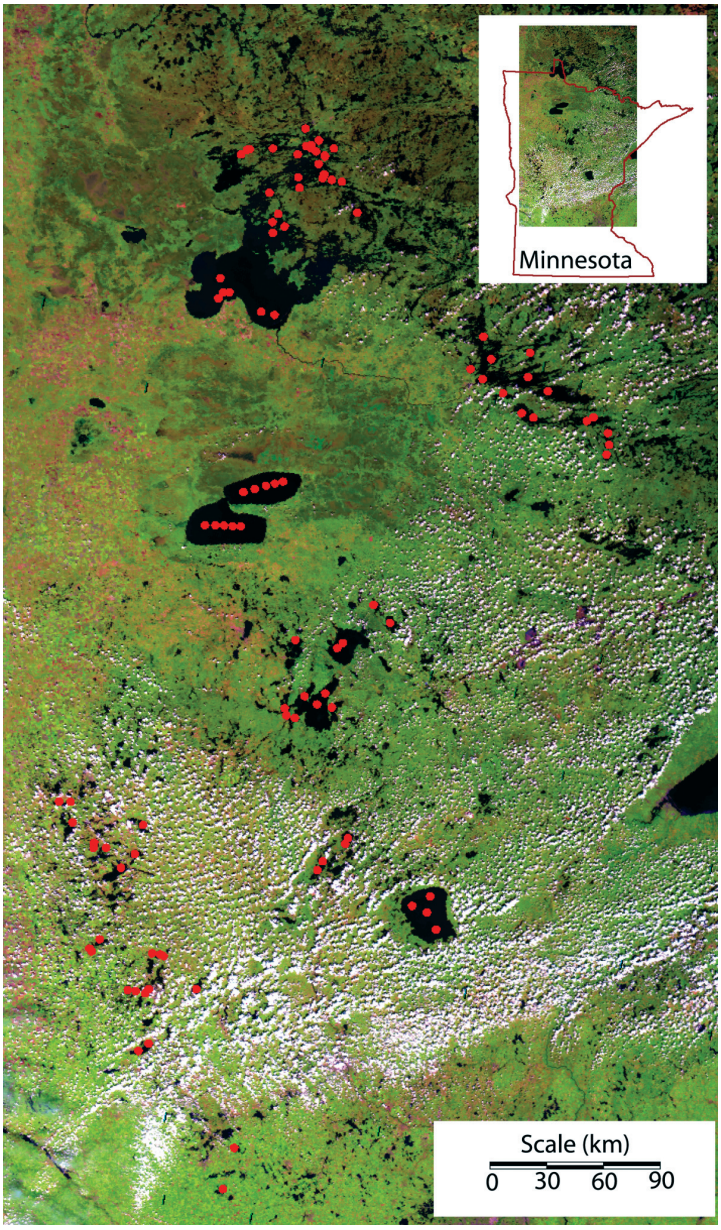


Figure 4. Map of lake sampling sites superimposed on Terra MODIS image, August 1, 2005.

ground receiving stations, known as EOS Direct Broadcast sites. MODIS images of the western Great Lakes region are collected in real time via the University of Wisconsin's EOS Direct Broadcast facility, and are automatically posted on the Web at http://www.lakesat.org/ each day.

IKONOS and QuickBird High-Resolution Imagery

Although high-resolution imagery in the form of aerial photography has been available for many years, the launch of the IKONOS-2 by Space Imaging, Inc. in 1999 signaled a new era in satellite remote sensing. IKONOS and QuickBird imagery have four multispectral bands similar to Landsat TM bands 1-4 and higher spatial resolution, making them good candidates for applying previously developed methods to the assessment of smaller lakes and ponds.

In a previous research project (Sawaya et al. 2003) the 4-meter resolution of the IKONOS imagery allowed the assessment of smaller water bodies than is possible with Landsat 30-meter resolution imagery. With an Eagan, Minnesota IKONOS image we were able to easily assess water clarity of water bodies smaller than 0.5 acres when open water conditions existed. We were able to assess the water clarity of 236 lakes and ponds using the IKONOS image. In contrast, we could only assess the water clarity of 48 lakes and ponds in Eagan when using Landsat imagery, as the minimum lake size assessed with Landsat 30-meter resolution imagery was around 4 acres.

High-resolution satellite data were also useful for general analysis of city land use and land cover features (Figure 7). Visual assessment of how land use/cover affects water clarity can be investigated by overlaying the classified lakes on the original IKONOS imagery. For example, in the southeastern corner of Eagan, the Lebanon Hills Regional Park is an area with an abundance of forest and wetland areas and limited development in the form of parking lots and pavilions for park visitors. This area has relatively high lake water clarity with Secchi disk transparency (SDT) of ~2 meters. In many of the residential and commercially developed areas, stormwater is directed into many of the water bodies using them as convenient reservoirs. The increase in impervious surface and direct connection to the stormwater system has dramatically changed the hydrology of many water bodies in Eagan. These changes of increased watershed size, amount of runoff, and quality of runoff water have impacted many of Eagan's water bodies. These impacts can be seen in Figure 7 where water clarity of lakes and ponds in many of the developed areas is generally more eutrophic with SDT of ~0.5 meters.

The high-resolution commercial imagery is relatively expensive and would be cost prohibitive for regional assessments. However, it could be utilized in a statistically based survey when smaller (<10 acres) lakes are of interest. As part of the NALMS EPA remote sensing project, lakes assessed with IKONOS imagery will be statistically compared with lakes assessed for the same area using Landsat imagery. This comparison should help determine the importance of smaller lakes for a national assessment strategy.

Aircraft-based High Resolution Hyperspectral Imagery

Scientists with the Center for Advanced Land Management Information Technologies (CALMIT) at the University of Nebraska-Lincoln are researching aircraft-based high-resolution hyperspectral imagery that can be used for more comprehensive water quality assessments of complex lake systems than is possible with any of the other platforms discussed. Data collection using the AISA-Eagle (AE) imaging spectrometer installed in a Piper Saratoga aircraft (Figure 8) allows collection of up to 512, very narrow, contiguous spectral bands throughout the visible and near-IR portions of the electromagnetic spectrum at spatial resolution down to less than one meter. Hyperspectral imagery allows for discrimination of water quality variables that are not distinguishable within the relatively coarse bandwidths of conventional multispectral platforms. Figure 9 shows reflectance spectra of

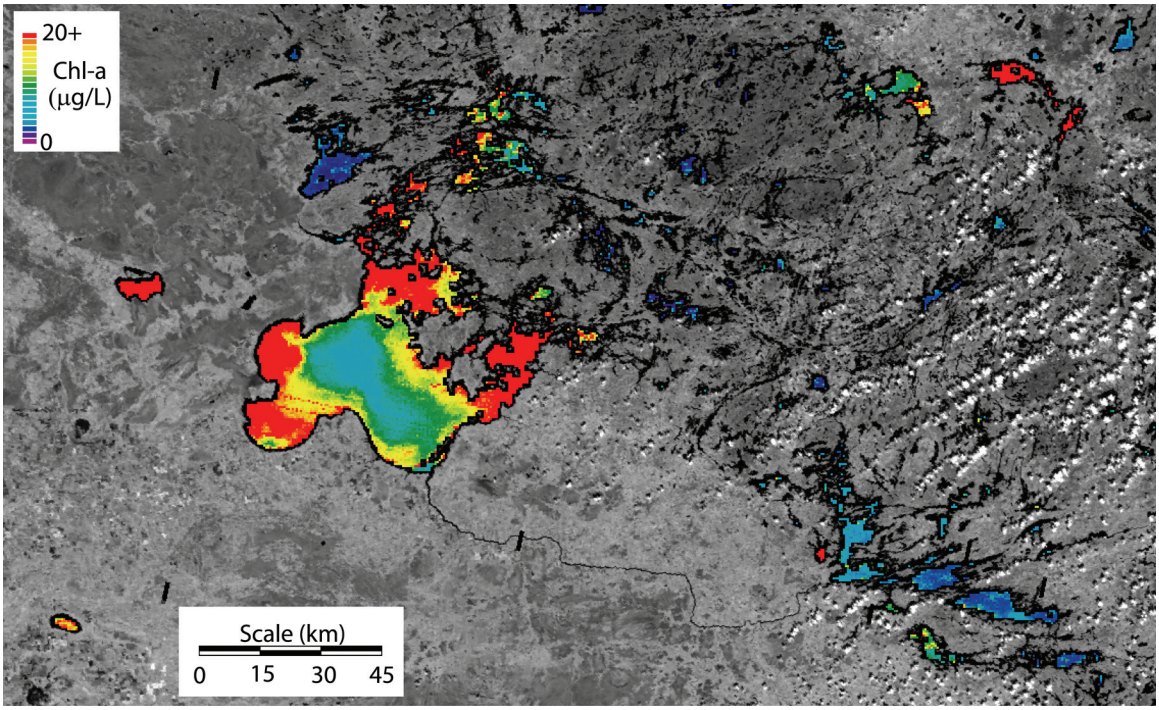


*Figure 5. Chlorophyll-*a *map based on MODIS imagery.*

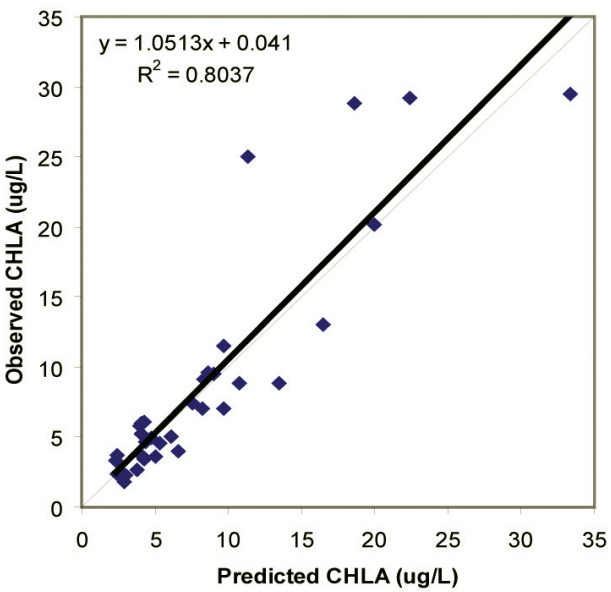


*Figure 6. Predicted chlorophyll-*a *concentrations (from MODIS imagery) and observed concentrations from field sampling.*

Lake Minnetonka as scanned by Ocean Optics USB2000 radiometers in August 2005.

The study area selected for this project is Lake Minnetonka which is a relatively large (14,500 acres), complex (16 interconnecting lakes) lake that is an important natural and recreational resource for the Twin Cities metropolitan area. Thirty-six well-positioned spectral bands (water quality band-set) were selected for the overflights of Lake Minnetonka and the imagery was collected at 3-meter spatial resolution on August 23, 2005.

Previously developed algorithms (Gitelson et al. 2000; Dall'Olmo and Gitelson 2005) were applied to the imagery. The spectral analysis and modeling techniques enable, among other things, concentrations of phytoplankton pigments such as chlorophyll-*a* (Chl-*a*) and phycocyanin (indicator of blue-green algae presence) and total suspended matter in water bodies to be quantified and mapped. Quantification of these characteristics makes it possible to detect harmful algal blooms from their early stages of development. The algorithms have been validated in a wide range of optical conditions and chlorophyll concentrations in turbid and productive waters in several parts of the world.

Chl-*a* distribution in Lake Minnetonka is depicted in Figure 10 based on data retrieved from an airborne image acquired using CALMIT's AE imaging spectrometer. Concurrent water sampling and laboratory analysis provided a basis for evaluating the performance of algorithms for water quality retrieval from the imaging spectrometer data. The comparison of the model calculated with reflectance retrieved from the AE image and analytically measured Chl-*a* concentrations showed very high correlation between predicted and measured values (Figure 11). The model explains more than 94 percent of Chl-*a* variability.

We also attempted to characterize remotely phycocyanin (a pigment associated with blue-green algae) concentration for Lake Minnetonka using a specific spectral feature of phycocyanin trough, around 625 nm in reflectance spectra (see Figure 9). This yields a qualitative map of blue-green algal dominance (Figure 12) and, together with Chl-*a* concentrations (Figure 10) could allow for an assessment of the risk of encountering nuisance blue-green algal blooms. Notice that the imagery (Figures 10 and 12) allows comparison of Chl-*a* and phycocyanin concentrations from one portion of the lake to the next, plus comparison of differences from place to place within one segment of the lake.

Boat-Based Real-Time Sensor

The University of Nebraska-Lincoln is also pioneering techniques for the assessment of water quality by means of real-time boat-based sensing. Using the configuration shown in Figure 13, one can travel at a relatively rapid rate across a water body and characterize water quality from place to place – yielding real-time measurements. In doing so, it is possible to discern quickly and easily locations that are anomalous and need water sampling. Additionally, the sensor could be attached to a fixed platform (or buoy), and used to document changing water-quality conditions over time.

Previously developed algorithms (Gitelson et al. 2000; Dall'Olmo and Gitelson 2005) were tested in experiments in Lake Minnetonka on August 22,

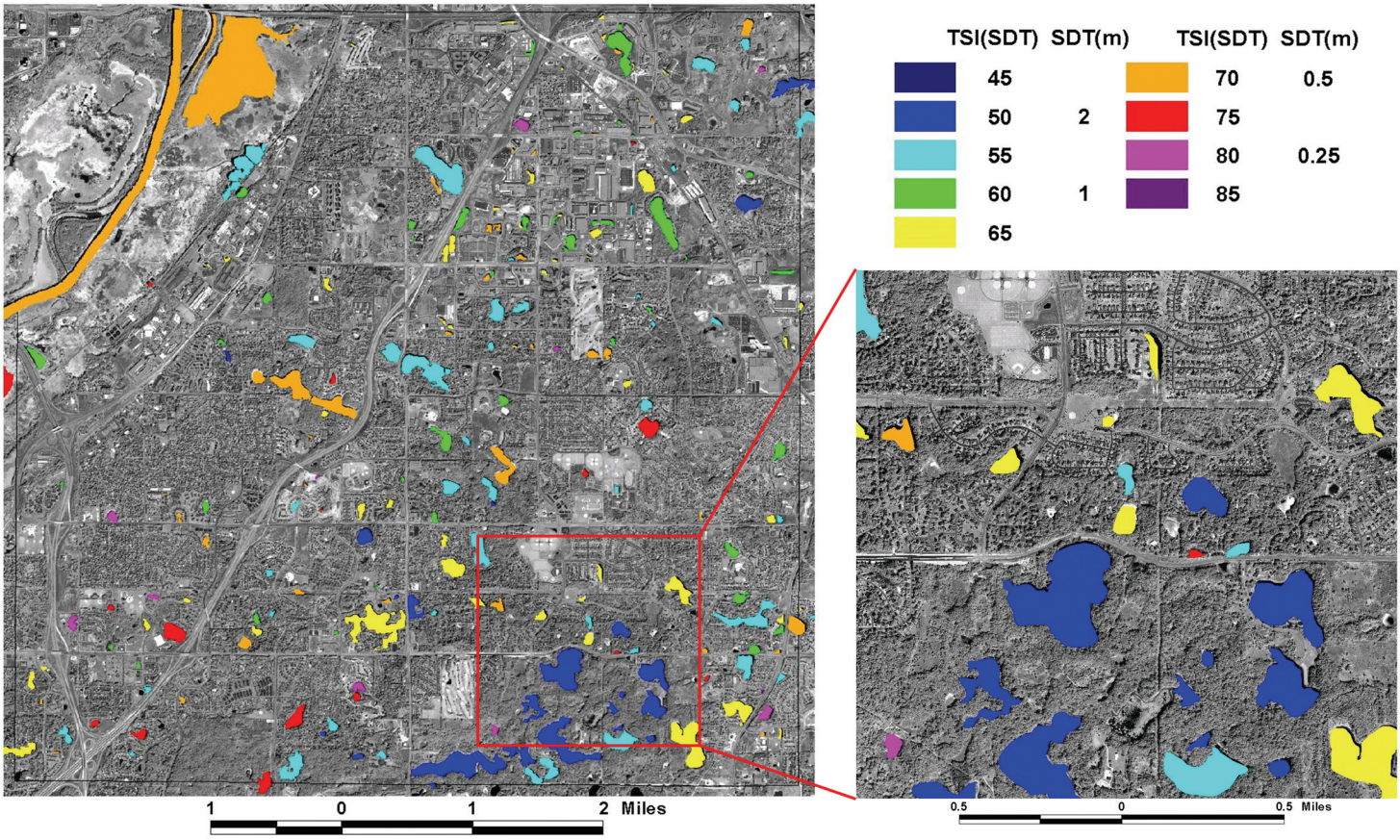


Figure 7. IKONOS water clarity map of Eagan, Minnesota.

Figure 8. Piper Saratoga aircraft (left panel) serves as the platform for the AISA-Eagle sensor. Right panel: sensor equipment deployed in the fuselage of the aircraft.

2005, the day before the aircraft-based hyperspectral imagery was collected. Hyperspectral reflectance measurements were taken from a boat using two inter-calibrated Ocean Optics USB2000 radiometers. Data were collected in the wavelength range of 400-900 nm with a sampling interval of 0.3 nm and a spectral resolution of about 1.5 nm. Radiometer #1, equipped with a 25° field-of-view optical fiber was pointed downward to measure the below-surface upward radiance. Radiometer #2 was equipped with an optical fiber and a hemispherical optic that was pointed upward to measure the downward irradiance. The dual-fiber approach results in fast measurements (Figure 9) and minimal error due to variation in illumination conditions.

Water samples were collected simultaneously with the radiometric measurements for laboratory analysis of Chl-*a* and total suspended solids concentrations. Chl-*a* concentrations ranged from 7 to 97.1 mg/m^3 with average value of 31.3 mg/m^3. Secchi depth ranged

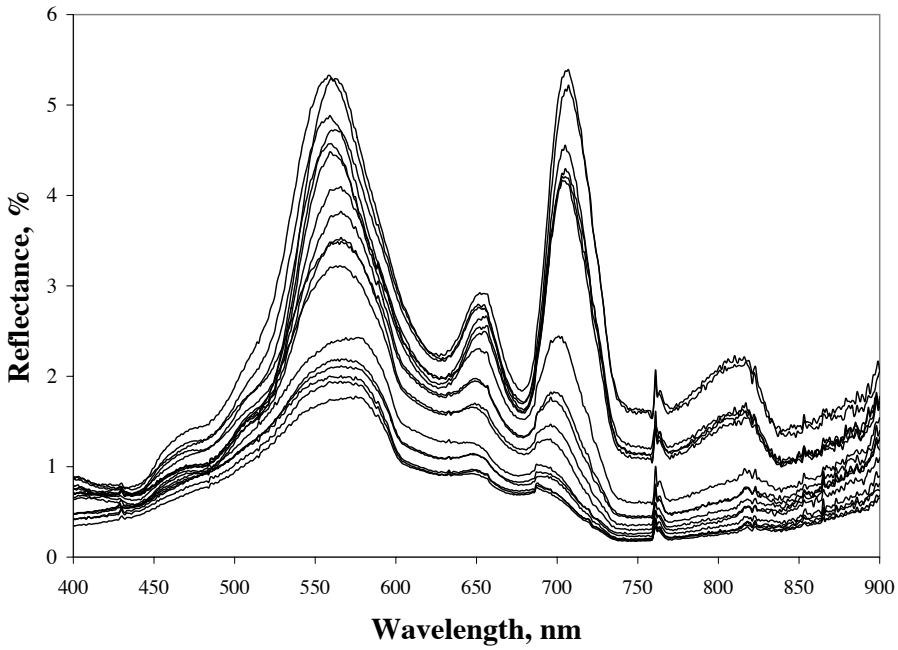


Figure 9. Reflectance spectra of Lake Minnetonka scanned by Ocean Optics USB2000 radiometers in August 2005.

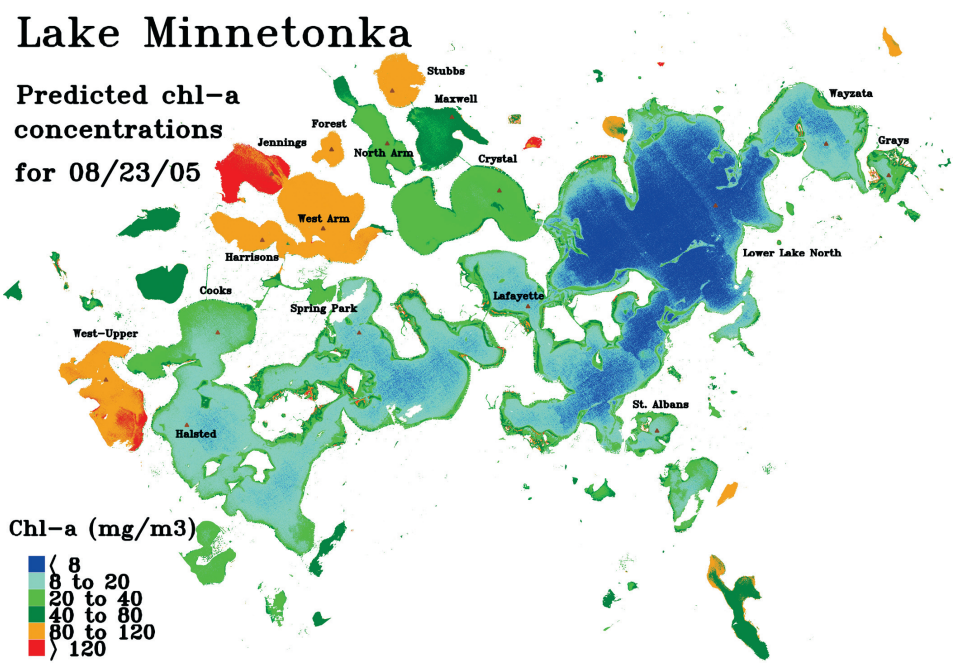


Figure 10. Chlorophyll distribution in Lake Minnetonka on August 23 retrieved from AISA imagery using two-band model (Gitelson et al., 2000).

from 0.4 to 3.1 m, total suspended solids from 2.8 to 19 mg/l. The developed models accounted for more than 98% of Chl-*a* variability (Figure 14).

The three-band model (Dall'Olmo and Gitelson 2005) was initially calibrated based on data collected in turbid Nebraska and Iowa lakes. It was encouraging to see that the model could be applied to a very different lake system like Minnetonka (low suspended sediment but highly variable Chl-*a*) without any further calibration (Figure 15).

Summary

Remote sensing holds great promise for lake assessment and monitoring. There are numerous platforms available that can be applied to answer a variety of questions routinely encountered in the course of lake and watershed studies. The selection of the appropriate platform will be dependent on several factors, including the size and number of lakes to be assessed, degree of resolution, and cost of the various applications. NALMS, along with the Universities of Minnesota, Nebraska, and Wisconsin, and the U.S. EPA, are collaborating on a project that will yield detailed evaluations of the various platforms currently in use, preferred applications, limitations, costs and other factors that should help those considering the use of remote sensing select the platform that best suits their data needs.

While remote sensing cannot replace all lake sampling, it can complement existing sampling programs and often allow for broader extrapolation of information. And so in answer to the question we first posed – Yes – remote sensing does have a place in the National Lake Assessment!

References

Dall'Olmo, G., Gitelson, A.A., Rundquist, D.C., Leavitt, B., Barrow, T., and J.C. Holz. 2005. Assessing the potential of SeaWiFS and MODIS for estimating chlorophyll concentration in turbid productive waters using red and near-infrared bands. Remote *Sensing of Environment* 96:176-187.

Dall'Olmo, G., and A. A. Gitelson. 2005. Effect of bio-optical parameter variability on the remote estimation of chlorophyll-a concentration in turbid productive waters: experimental results. *Applied Optics* 44(3):412-422.

Gitelson, A., Y. Yacobi, J. Schalles, D. Rundquist, L. Han, R. Stark, and D. Etzion, 2000. Remote estimation of phytoplankton density in productive waters. *Archives of Hydrobiology: Advances in Limnology* 55:121-136.

Kloiber, S. M., P.L. Brezonik, L.G. Olmanson, and M.E. Bauer. 2002. A procedure for regional lake water clarity assessment using Landsat and multispectral data. *Remote Sensing of Environment* 82:38-47.

Lillesand, T. M., W.L. Johnson, R.L. Deuell, O.M. Lindstrom, and D.E. Meisner. 1983. Use of Landsat data to predict the trophic state of Minnesota

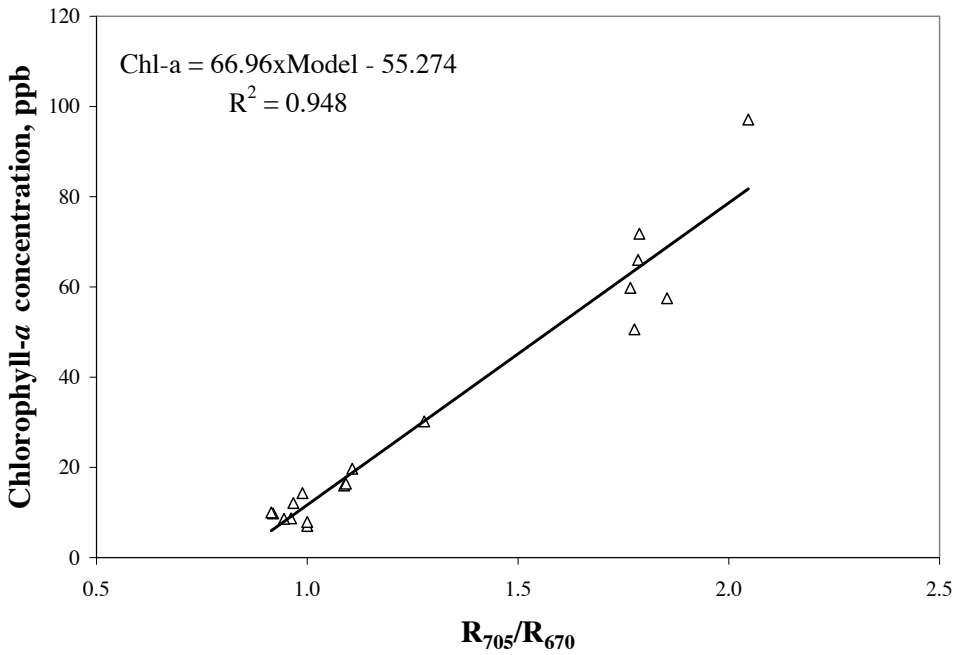


Figure 11. Remote estimate of Chl-a concentration retrieved from AISA-Eagle image plotted versus analytical Chl-a concentrations measured in Lake Minnetonka on August 23.

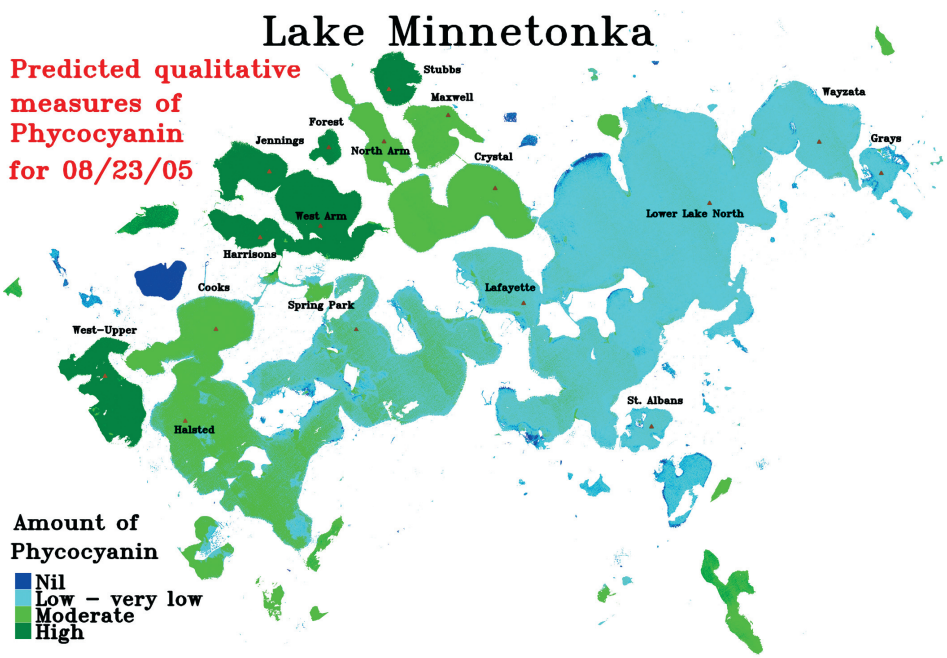


Figure 12. Phycocyanin distributions in Lake Minnetonka on August 23 2005 using data acquired by the AISA-Eagle hyperspectral system. Areas with the high phycocyanin concentrations are at the highest risk of toxin being present in water.

lakes. *Photogrammetric Engineering and Remote Sensing* 49:219-229.

Mayo, M., A. Gitelson, Y. Yacobi, and Z. Ben-Avraham, 1995. Chlorophyll distribution in Lake Kinneret determined from Landsat Thematic Mapper data. *Int. J. Remote Sensing* 16:175-182.

Menken, K., P.L. Brezonik, and M.E. Bauer. 2006. Influence of chlorophyll and humic color on reflectance spectra of lakes: implications for measurement of lake-water properties by remote sensing. *Lake and Reservoir Management*. In press.

Sawaya, K., L. Olmanson, N. Heinert, P. Brezonik, and M. Bauer. 2003. Extending satellite remote sensing to local scales: Land and water resource monitoring using high-resolution imagery. *Remote Sensing of Environment* 88:144-156.

Yacobi, Y., A. Gitelson, and M. Mayo. 1995. Remote sensing of chlorophyll in Lake Kinneret using high spectral resolution radiometer and Landsat Thematic Mapper: Spectral features of reflectance and algorithm development. *J. Plankton Research* 17:1-19.

Acknowledgements

Collaborators on this study include Dr. Marvin Bauer and Dr. Patrick Brezonik, University of Minnesota; Dr. Thomas Lillesand, University of Wisconsin; and Dr. Donald Rundquist, Dr. Giorgio Dall'Olmo and Wesley Moses, University of Nebraska.

Steve Heiskary is a research scientist with the Minnesota Pollution Control Agency. Steve has served as a Regional Director for NALMS and most recently served as President of NALMS in 2004. Steve is currently overseeing this joint NALMS, EPA, and University project for NALMS.

Leif Olmanson is a remote sensing and GIS specialist working as a Research Scientist at the University of Minnesota Water Resources Center and Remote Sensing and Geospatial Analysis Laboratory, where he conducts research and develops remote sensing applications for water resource management.

Anatoly Gitelson is professor of remote sensing at the University of Nebraska in the Center for Advanced Land Management Information Technologies (CALMIT), School of Natural Resources. He has been involved with research and development of remote sensing for monitoring aquatic and terrestrial environments since 1981.

Dr. Jonathan W. Chipman is an assistant scientist at the University of Wisconsin-Madison Environmental Remote Sensing Center. His research interests cover a wide range of environmental applications of remote sensing. You may reach Jonathan at: jchipman@wisc.edu.

Figure 13. Boat-based sensor configuration.

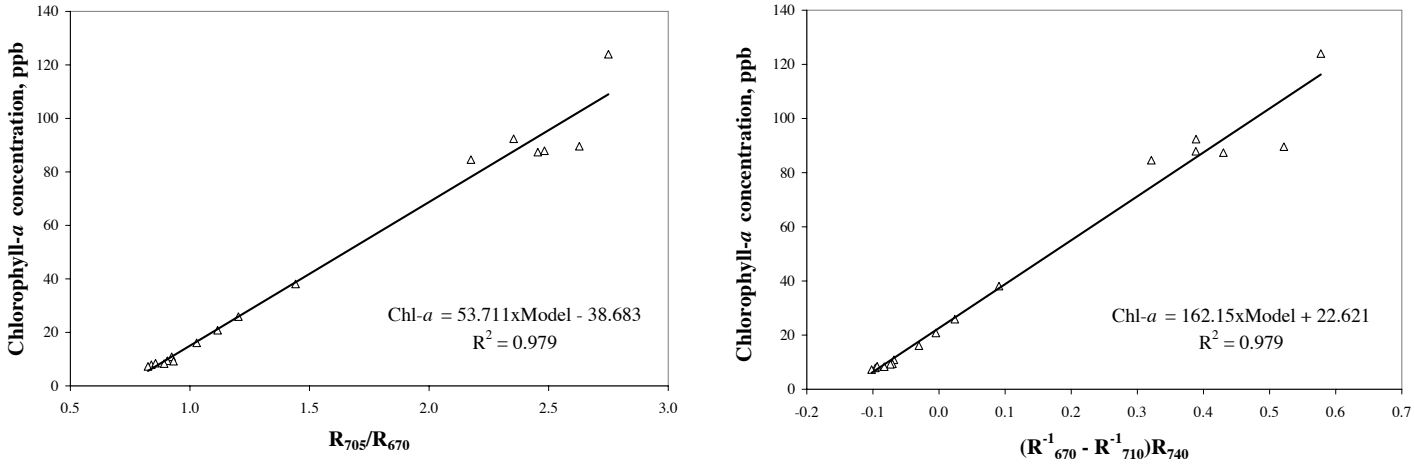


*Figure 14. Models for chlorophyll-*a *retrieval plotted vs. analytically measured chlorophyll-*a *concentration. Left, two-band model (670 nm and 705 nm); right, three-band model (670, 710 , and 740 nm).*

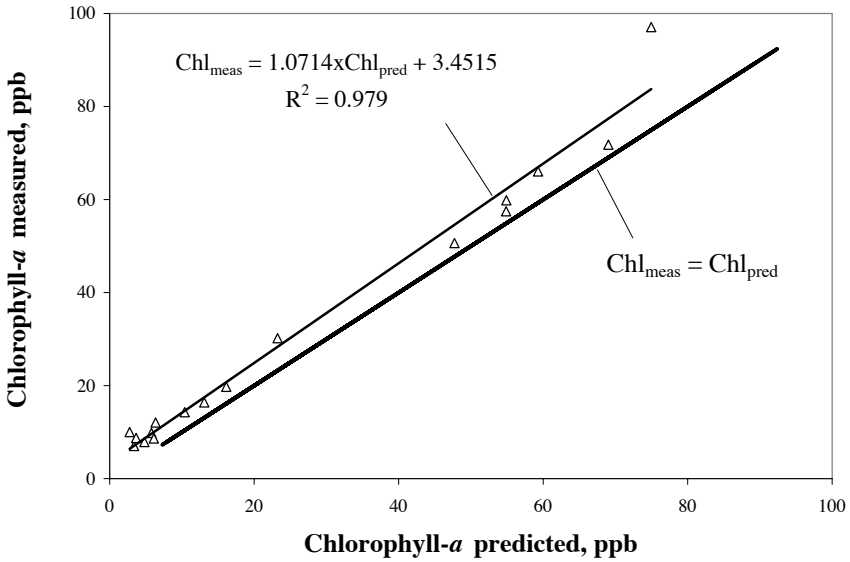


*Figure 15. Chlorophyll-*a *concentration, predicted in Lake Minnetonka on August 22, 2005 by the three-band model calibrated over Nebraska and Iowa lakes, plotted versus analytically measured chlorophyll-*a.

Did you know?

Tomato juice was first served at a French Lick, Indiana, hotel in 1925.