COMBINING SATELLITE REMOTE SENSING AND VOLUNTEER SECCHI DISK MEASUREMENT FOR LAKE TRANSPARENCY MONITORING

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Abstract
The Wisconsin Satellite Lake Observatory Initiative (SLOI) has brought together scientists and lake managers from multiple organizations with the goal of improving the use of satellite remote sensing for monitoring Wisconsin's numerous inland lakes. Efforts are now underway to test methods for lake assessment using multiple satellite platforms characterized by a range of spatial, temporal, and spectral resolutions. Lake water clarity has been mapped for over 7000 lakes statewide at a spatial resolution of 30 meters, based on 1999-2001 Landsat TM and ETM+ imagery, using a standardized regional image processing protocol developed under NASA sponsorship in coordination with the University of Minnesota. Daily Terra/MODIS data, received in real time via the University of Wisconsin's direct-reception X-band antenna, are also providing an unprecedented time series of images for the larger lakes in the region. Smaller lakes and ponds can be studied using such high resolution data sources as the 1 and 4m resolution IKONOS satellite. Central to "calibrating" these various satellite data sources empirically is acquisition of geographically extensive, well-timed ground truth in the form of Secchi disk measurements. Volunteer monitoring programs, such as the statewide Self-Help Lake Monitoring Program (SHP) coordinated by the Wisconsin Department of Natural Resources (WDNR), represent an ideal means for calibrating satellite-based models for estimating lake transparency at the individual lake, lake district, statewide, and regional scale. Combining the satellite and volunteer data permits substantial, cost-effective extension of the geographic reach of purely surface-based monitoring efforts.

Introduction

The Upper Midwest region of Wisconsin, Minnesota, and Michigan covers an area of 516,000 km^2, and includes tens of thousands of inland lakes, ranging in size from under 1 hectare to over 50,000 hectares. These lakes are of immense importance to the region, as a source of water for domestic consumption, and for industrial, and agricultural use. They are also valuable for recreation and tourism, fisheries, wildlife, and other environmental and social uses. Protection of the quality of the region's unique lake resources is of the highest importance, but resource management agencies are unable to directly monitor (*in situ*) more than a tiny fraction of the region's lakes, due to cost and logistics. In Wisconsin, the Department of Natural Resources (WDNR) monitors some 50-100 lakes in any given year, while a growing network of citizen volunteers collects a limited set of measurements on 500 or more additional lakes. This leaves the vast majority of the state's 15,000 lakes without any routine annual monitoring activity.

The Wisconsin Satellite Lake Observatory Initiative (SLOI) has the objective of extending our ability to monitor the state's lake resources through the use of satellite remote sensing (Lillesand et al., 2001; Chipman et al., 2002). SLOI is a collaborative effort of the University of Wisconsin's Environmental Remote Sensing Center (UW/ERSC) and Center for Limnology (UW/CFL), the WDNR, and the NASA Affiliated Research Center (ARC) program. In addition, through our involvement in the Upper Midwest Regional Earth Science Applications Center (RESAC), SLOI cooperates with scientists and resource managers in the neighboring states of Minnesota and Michigan. One of the major aspects of this cooperation has been the development and application of techniques for satellite-based monitoring of lake water clarity and trophic state (Olmanson et al., 2001; Bauer et al., 2001).

The use of satellite image data for lake water quality assessment in the Upper Midwest region has a relatively long history. For example, Scarpace et al. (1979) first measured the trophic status of Wisconsin's lakes on a statewide basis using Landsat Multispectral Scanner (MSS) data. Pilot projects employing MSS data for this purpose in Minnesota were also conducted by Brown et al. (1977 a, b) and Lillesand et al. (1983). Similarly, MSS data were central to the early trophic state assessment work of Boland (1976) and Witzig and Whitehurst (1981). Early efforts aimed at analyzing the next generation of Landsat data (from Landsat-4 and –5) for water quality monitoring in Wisconsin include Lathrop and Lillesand (1986) and Lathrop et al. (1991). Likewise, Olmanson (1997) used TM data to estimate the trophic state of lakes in the Minneapolis/St. Paul, Minnesota metropolitan area. These and similar early efforts have been summarized by Kloiber et al. (2000).

Given the above success stories, which date back to the 1970s, it is reasonable to ask why there has not been widespread adoption of satellite-based methods for lake water quality assessment by either resource managers or policy makers. In our view, there are three primary institutional reasons why this has been the historical case:

- The geospatial infrastructure and desktop capabilities of today's world did not exist in the above era.
- The sources of satellite data were limited and the costs were high such that it was not practical to acquire time series of data needed for meaningful water quality trend analysis on a regional basis.
- There was a general lack of understanding of the "big picture" of land use and water quality interaction at regional scales.

In short, there was no clear aggregated market of end users requiring such information to meet their day-to-day needs.

In our view, the above institutional barriers to application have been broken. Managers and policymakers are evolving from being spatially literate to being spatially dependant in their day-to-day activities. At the same time, land use and its impact on water quality and quantity have taken center stage. With multiple, affordable sources of satellite data, cost and availability considerations no longer preclude adoption of the technology.

Having said the above, there are still several technical and methodological impediments that must be addressed before regional lake water quality assessment via remote sensing becomes applied on a widespread operational basis. In Wisconsin, these include, but are not limited to:

- The need to extend the knowledge base on the inherent spectral reflectance properties of the range of lake waters found throughout the state.

- The need to develop an explicit, replicative, and user accepted field sampling and image processing protocol for "calibrating" satellite image data as a water quality monitoring tool.

- The need to develop software toolkits for exploiting a variety of current and future satellite systems; and, to demonstrate the synergism among these systems in the context of water quality management in general and water quality monitoring in particular.

These three impediments are the focus of a series of projects being undertaken by UW/ERSC through the NASA ARC and Upper Midwest RESAC programs. The first impediment is now being addressed through the development of a library of lake reflectance spectra, obtained using a hand-held field spectroradiometer, and collected simultaneously with biological, chemical, and physical limnological data on a diverse set of lakes around the state. The second and third are being addressed by programs for statewide and regional lake monitoring with multiple satellite remote sensing systems, including the Landsat-5 Thematic Mapper (TM), the Landsat-7 Enhanced Thematic Mapper Plus (ETM+), Terra/MODIS, and others. These programs are discussed in this paper, based in part on previous work reported in Lillesand et al. (2001), Chipman et al. (2002), and Chipman et al. (in review).

The Self-Help Lake Monitoring Program

Satellite image analysis may best be viewed as a means for extending a limited set of field observations to areas and/or times where field data are not available, rather than as a replacement for existing field monitoring programs. It is generally necessary, or at least helpful, to have access to a robust set of field data for calibrating satellite-based models and for accuracy assessment and validation of the results. In Wisconsin, one of the best sources of field data is the WDNR's Self-Help Lake Monitoring Program (SHP), which coordinates the acquisition of field observations of lake water quality by citizen volunteers statewide. The SHP provides data on hundreds of lakes, with the earliest observations dating to 1986. All volunteers provide data on a limited set of factors including Secchi disk transparency (SDT) and apparent color, while a subset also sample for chlorophyll *a* and total phosphorus. Many also provide additional information on meteorological and other conditions on the lake at the time of sampling.

One of the first opportunities for cooperation between the SHP volunteers and the remote sensing community has focused on the timing of field data collection. Since three of the major satellite systems being investigated for lake monitoring (Landsat-7, Terra, and EO-1) are all in the same orbit, only minutes apart, it is especially desirable to have the field observations coincide with the orbital schedule of these satellites. Starting with the summer 2000 field season, the satellite orbital schedule has been mailed to all volunteers, who have been encouraged to time their data collections accordingly. As shown in Figure 1, this has been highly successful, with approximately 25% of field data being collected on the exact overpass dates and 75% being collected within plus or minus three days of the overpass. Collaboration between SLOI and the SHP has also had the unexpected side effect of boosting interest and participation in the program – the number of field observations increased by 50% in the summer following the start of the collaboration.

Statewide Lake Water Clarity Mapping with Landsat

The first satellite in the Landsat series was launched in 1972. Since 1982, the Landsat satellites have included the TM or ETM+ sensors with 30m spatial resolution and spectral bands in the blue, green, red, near-infrared, and mid-infrared regions of the electromagnetic spectrum, in addition to coarser-resolution thermal bands. The most recent system, Landsat-7, was launched in 1999. These systems provide an excellent source for lake monitoring, for a variety of reasons, including the following:

- The data are available at relatively low cost (the cost of filling user requests) from the US Geological Survey and other providers, and can be shared cooperatively among users.
- The moderate resolution (30m) and area of coverage (185km swath width) represent a compromise between the extremes of coarse-resolution systems, which cover large areas but miss many small lakes, and high-resolution commercial satellites, which capture small lakes but only in very limited areas.
- There is a legacy of 20 years of archival imagery at the above-described 30m spatial resolution, plus an additional previous decade of coarser-resolution imagery.

As described in Chipman et al. (in review), Landsat TM and ETM+ data are being used by SLOI to monitor lake characteristics, including water clarity and trophic state, following concepts embodied in the Upper Midwest RESAC lake water clarity image processing protocol (Olmanson et al., 2001). Spectral data for all lakes in a given satellite image are extracted using the WDNR 1:24,000-scale Hydrography GIS layer. Mixed pixels along lakeshores, areas of aquatic vegetation, and optically shallow portions of the littoral zone are masked out using an unsupervised clustering and classification process. To ensure that the spectral data for a given lake are representative of the deepest, darkest portion of the lake, a histogram analysis procedure is used to further reduce the pixels included in each lake's spectral signature.

To establish a relationship between lake transparency and observed spectral radiance, the SHP-sampled lakes within the Landsat scene are used to develop a regression model. This multiple regression model predicts the natural logarithm of SDT, in meters, as a function of observed spectral radiance from a combination of multispectral bands on the TM or ETM+ sensor, and has the following structure:

$$\ln(\mathrm{SDT}) = b_0 + \left(b_1 \frac{TM1}{TM3}\right) + \left(b_2\ TM1\right)$$

where the independent variables TM1 and TM3 are the observed spectral radiance values from the blue and red bands (respectively) of the Landsat TM or ETM+; and b_0, b_1, and b_2 are regression model coefficients.

This approach requires carefully timed and spatially distributed field measurements, but has the advantage of compensating for atmospheric effects, changes in solar illumination, and other peripheral effects between multiple image dates. Typically, two or three consecutive scenes along a single orbital path may be used in combination, when atmospheric conditions permit. The resulting regression model is then applied to the image data for all lakes in each scene, either on a whole-lake level (using the spectral signatures extracted previously) or on an individual pixel level.

In some cases, sufficient numbers of field data may not be available to develop scene-specific regression models. For these scenes, it may be possible to use a reduced version of the model, based only on the TM1/TM3 spectral radiance ratio:

$$\ln(\mathrm{SDT}) = b_0 + \left(b_1 \frac{TM1}{TM3}\right)$$

This reduced model has the advantage of being relatively stable (i.e., b_0 and b_1 change very little among scenes), so that within certain limits it can be applied directly to the imagery without being re-calibrated for every scene (Figure 2). This approach works best for clear-sky scenes with no perceptible haze. In addition, due to sensor calibration differences it may be necessary to use slightly different models for images processed by different data providers.

To assess the importance of timing the field data collection to match the satellite image acquisition dates, we subdivided the field observations into three categories, and evaluated the relationship between the TM1/TM3 ratio and ln(SDT) within each category. As expected, field data collected on the exact satellite overpass date have the closest correlation with the TM1/TM3 ratio (R^2 = 0.85). Field data collected 1-3 days and 4-7 days off of the overpass date have increasingly lower correlations (R^2 = 0.82 and 0.75, respectively). However, the model parameter values changed relatively little among the three groups, which suggests that field observations collected up to a week from the image acquisition date may still be used without introducing a major bias in the model.

The Statewide Lake Transparency Database

Seventeen Landsat TM and ETM+ scenes have been analyzed for the 1999-2001 summer seasons. Within each Landsat path, the multiple regression model was applied to predict SDT for all lakes whose spectral data were extracted from the imagery. The lake databases from all Landsat paths were then combined into a single unified database. This database has a total of 15,615 predictions of SDT for 7,590 unique lakes, with the additional 8,025 predictions representing lakes that fall within the area of overlap of two adjacent Landsat paths as well as some Landsat scenes for which two dates of imagery were analyzed. The SDT predictions in this database range from 0-14 m.

Some of the Landsat scenes included more field-sampled lakes than were needed for development of the regression models. In this case, the field data were randomly divided into two groups, one for model development and one for accuracy assessment. Statewide, a total of 152 lakes were set aside for accuracy assessment. Figure 3 provides a comparison of the observed SDT versus the predicted SDT for these 152 independent validation lakes. The RMSE of the predictions is 0.7 m, over a range of 0-8 m SDT.

For some applications it may be preferable to have a single SDT value associated with each lake, and to have some measure of the reliability of the SDT estimates. This is the case for the statewide lake transparency map (Figure 4). For this map, direct field observations of SDT were used for the 596 lakes where such data were available. For all other lakes, Landsat-based estimates of SDT were used. If a given lake was present in two or more Landsat scenes, the scene with the highest model R^2 value was used. In addition, shallow lakes (and lakes of unknown depth) were excluded from the classification system, because their Landsat-based SDT predictions may be unreliable. In most cases these are very small lakes (the median area of these lakes is 4.3 hectares).

Other database elements can provide the end-user with more detailed information about the SDT data. The total number of Landsat pixels extracted, and the number actually used (following the masking and histogram analysis procedures) can be examined to flag lakes whose SDT estimates are based on a small number (or proportion) of pixels. As the database is populated from additional images, the increasing number of SDT estimates per lake will provide a more robust view of lake transparency.

Lake Monitoring with Terra/MODIS Images

One disadvantage of Landsat for lake monitoring is that its 16-day orbital repeat cycle limits the frequency of coverage over any given location. This limitation is particularly significant when combined with the effects of cloud cover; lake districts in moderately cloudy regions such as the US Upper Midwest may go for several months without a single cloud-free Landsat image being acquired. This gap can be filled, at least for large lakes, by sensors such as MODIS, which provide more frequent coverage (at a cost of coarser spatial resolution).

Data from the MODIS instrument on the Terra satellite are received in real-time at the University of Wisconsin's X-band direct broadcast reception facility, located on the roof of the Atmospheric, Oceanic, and Space Sciences building. The most appropriate bands for water quality monitoring on MODIS have nominal spatial resolutions of 500m and 1km. This limits the minimum observable lake size, but the 2300km field of view permits daily (or near-daily, depending on cloud cover) images to be acquired at Wisconsin's latitude.

The methods described previously for estimating lake water clarity with Landsat images can be adapted to MODIS data using the 500m bands. At this spatial resolution, for practical purposes only lakes over approximately 400 hectares in area can be reliably monitored. Beginning in July of 2001, we have produced weekly to biweekly estimates of SDT for eleven lakes plus Green Bay, Lake Michigan. These estimates were produced using the MODIS blue/red spectral radiance ratio (the spectral sensitivities of the blue and red bands on MODIS differ slightly from those of Landsat). The model was derived based on MODIS imagery acquired on September 8 and 17, 2000. Eventually, this approach can probably be extended to some 100 lakes statewide, plus similar numbers in Minnesota and Michigan.

Figure 5 shows a series of MODIS images of Green Bay, covering the period from July 3 to September 30, 2001, along with pixel-level maps of the estimated water clarity derived from these images. A total of 50 field measurements collected at 12 stations in Green Bay by the Green Bay Metropolitan Sewerage District were used to assess the accuracy of these estimates. As shown in Figure 6a, the RMS error for the MODIS transparency estimates for the 50 field observations was 33cm. Considering that the field observations were made from a boat at individual points, while the satellite's instantaneous field of view covers 25 hectares or more, this level of accuracy is considered quite good.

Because individual Secchi disk observations include a certain level of error, it is often helpful to average multiple observations. Figure 6b shows the accuracy of the MODIS-derived seasonal mean transparency estimates for the 12 stations in Green Bay. While the sample size is small, the fit between the satellite and field observations is almost exactly 1:1, and the RMS error is only 17cm. Figure 7 shows a similar accuracy assessment using field data collected on 10 inland lakes around Wisconsin by UW/CFL researchers and SHP volunteers. These lakes cover a wider range of water clarity than the Green Bay stations (0-5.5m), and represent lakes with very different biological, chemical, and physical characteristics. The RMS error for the MODIS seasonal mean transparency estimates for these lakes is 51cm.

The next step in the MODIS component of SLOI is to apply the lake transparency protocol to the approximately 100 lakes statewide that are large enough to be reliably monitored at the spatial resolution of 500m. Efforts will also be made to further refine and automate the data processing, with the ultimate goal of uploading statewide lake water clarity predictions in near-real time, perhaps within 6 hours of the reception of data from the satellite at the UW direct broadcast reception facility.

Conclusions and Future Directions

A set of image processing protocols for estimating lake water clarity based on satellite imagery has been developed and tested with numerous Landsat and MODIS images. This procedure produces reliable estimates of lake transparency at least over the range of 0-8m in the upper Great Lakes region. The model used is based on the blue/red spectral radiance ratio, which is linearly related to the natural logarithm of Secchi disk transparency. Field data collected contemporaneously with the satellite overpass will produce the best model fit, but in many cases data can be used if collected within a period of plus or minus seven days from the image acquisition date. While its coarse spatial resolution limits its use to the largest water bodies in the region (generally 400 hectares and larger), MODIS has the advantage of providing imagery on a daily or near-daily basis, depending on cloud cover. This permits more frequent monitoring of large lakes.

As next steps, we will be updating our 1999-2001 statewide assessment of lake water clarity, developing a statewide historical database of lake water clarity based on archival Landsat imagery, refining and automating procedures for near real-time lake clarity assessment using MODIS, and investigating newly acquired imaging spectrometer data from EO-1/Hyperion. We will also be examining potential applications of high-resolution satellite imagery, not only for lake transparency estimation, but also for such activities as mapping aquatic macrophyte beds, riparian-zone vegetation, and watershed land use and land cover.

Other potential future directions include improvements in field data collection and calibration techniques. The UW/CFL has recently begun testing automated buoys for real-time monitoring on several lakes, and has proposed the deployment of a network of 50-100 buoys on inland lakes across Wisconsin. These would provide a reliable source for model calibration and validation efforts. The availability of more advanced ground-based and satellite sensors should also lead to improvements in atmospheric correction techniques, which in turn should contribute to further improvements in the extraction of lake characteristics from satellite imagery.

Acknowledgments

This work was supported, in part, by the Upper Midwest Regional Earth Science Applications Center under NASA grant NAG 13-99002, by the NASA Affiliated Research Center Program, and by the NSF-funded North Temperate Lakes Long-Term Ecological Research Site. Field data and other assistance were provided by a wide range of groups and organizations, including the Wisconsin Department of Natural Resources, the UW-Madison Center for Limnology, the Green Bay Metropolitan Sewerage District, and the hundreds of citizen volunteers of the Wisconsin Self-Help Lake Monitoring Program. We also wish to acknowledge the cooperation of our RESAC-related colleagues at the University of Minnesota in the development of the initial form of the TM and ETM+ empirical modeling protocol. We acknowledge Leif G. Olmanson in particular for his collaboration in this area. Many researchers at UW/ERSC have made major contributions to the SLOI activities reported herein. These include, among others: Dr. Jonathan Chipman, Jeffery Schmaltz, Jill Leale, Kelly Lewelling, Mark Nordheim, Robert Goldmann, and Timothy Olsen.

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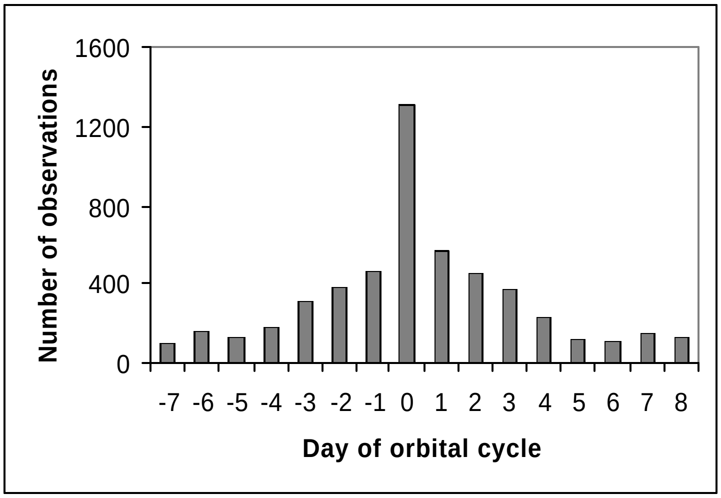

Figure 1: Distribution of field data collected by volunteers during the entire 2000 field season, in relation to the repeated 16-day Landsat-7 orbital cycle. Peak on day 0 corresponds to satellite overpass.

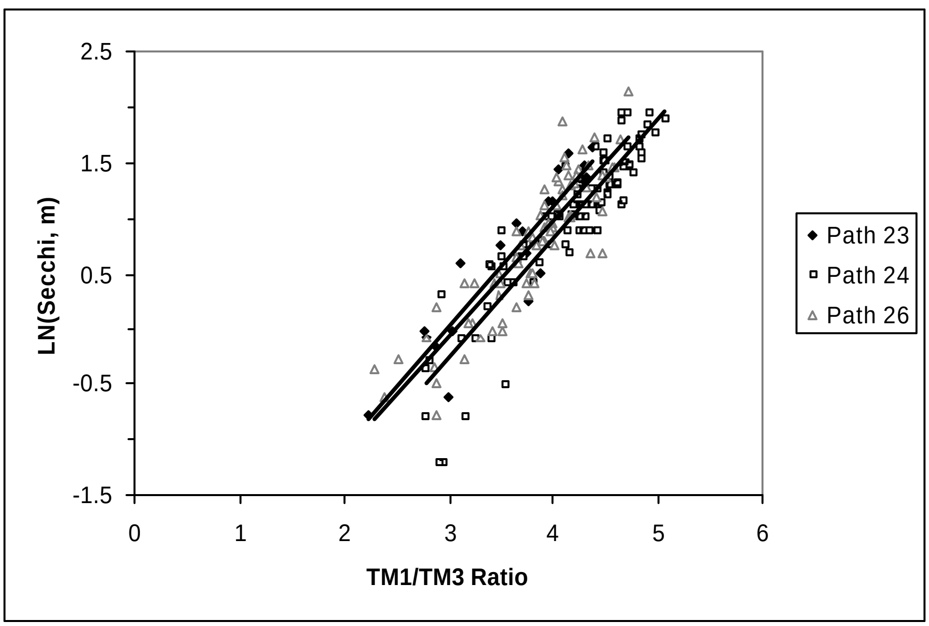

Figure 2: Relationship between TM1/TM3 spectral radiance ratio and the natural logarithm of SDT, for field-observed lakes in three Landsat paths: Path 23 (8 Sept. 2000, three Landsat-7 ETM+ scenes, n=21 lakes, R^2=0.85); Path 24 (27 July 1999, three Landsat-7 ETM+ scenes, n=94 lakes, R^2=0.83); and Path 26 (5 Sept. 2000, one Landsat-5 TM scene, n=76 lakes, R^2=0.79).

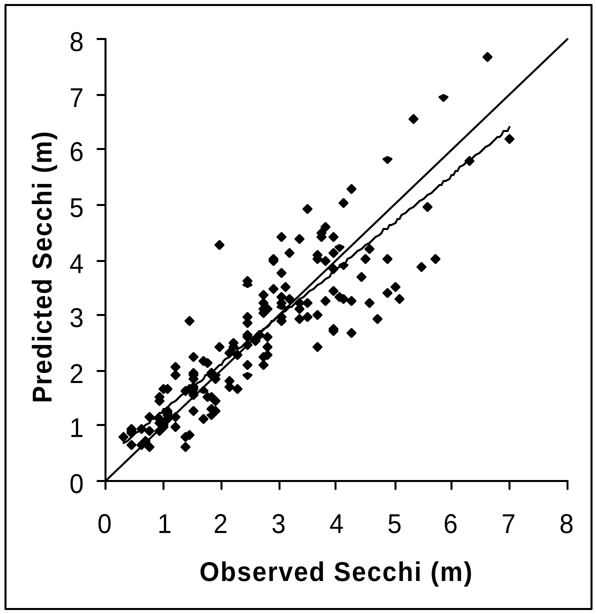

Figure 3: Accuracy assessment based on comparison of observed and predicted SDT for 152 independent validation lakes. RMSE = 0.7 m.

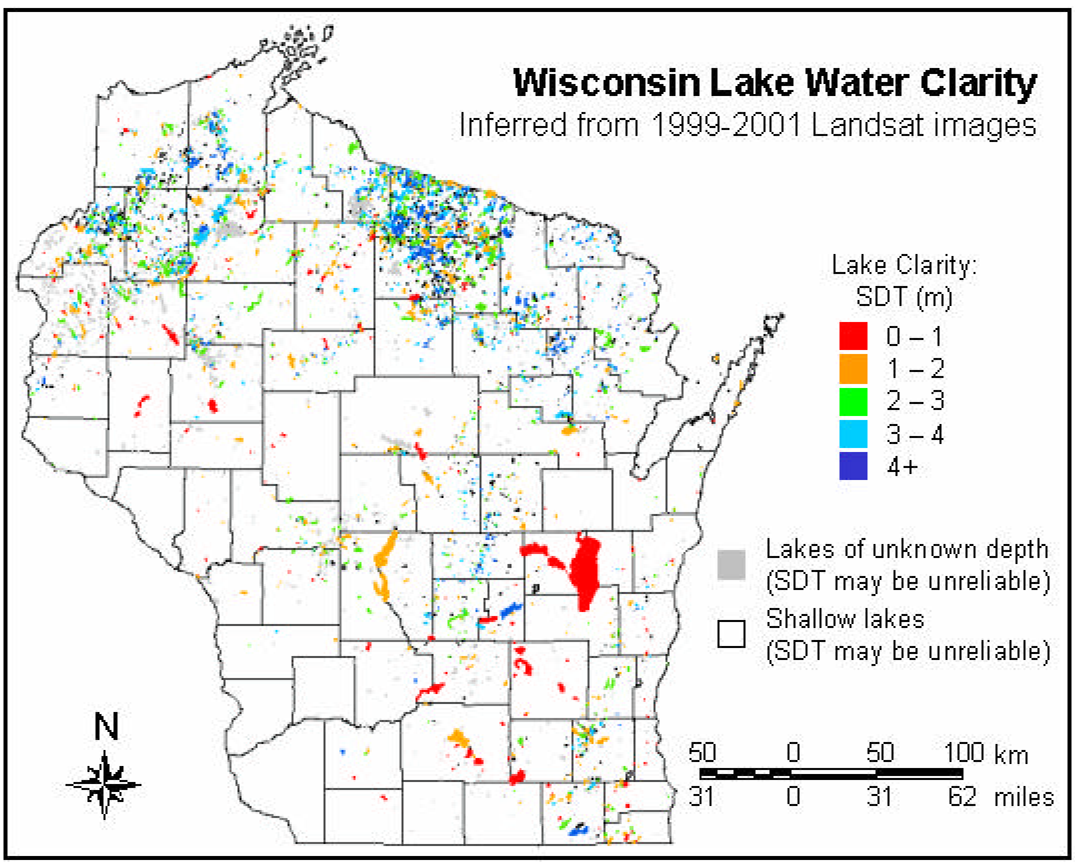

Figure 4: Wisconsin 1999-2001 statewide lake water clarity assessment.

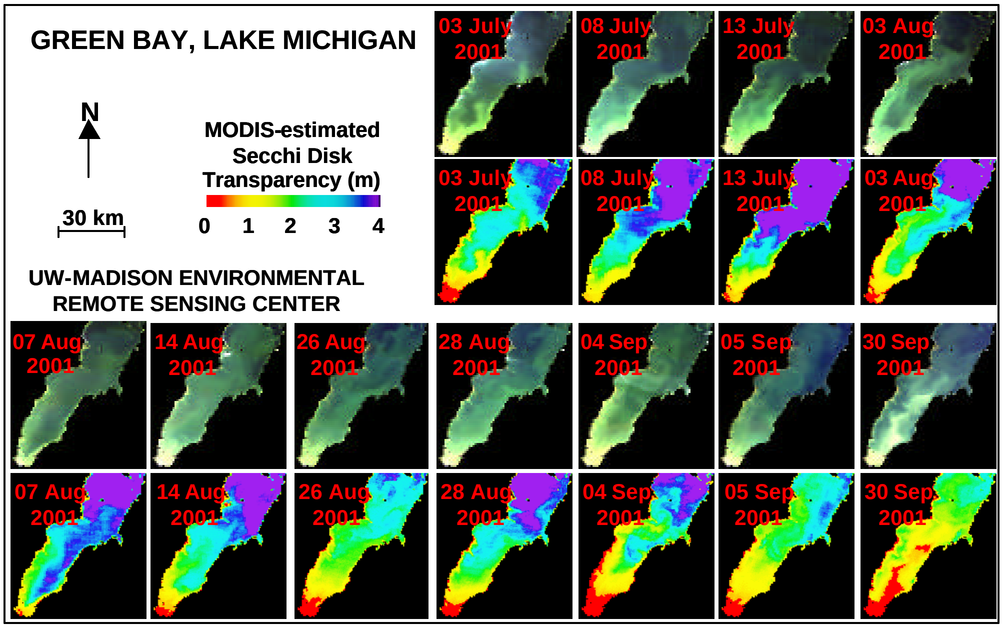

Figure 5. Terra/MODIS images and predicted SDT maps of Green Bay, Lake Michigan for summer 2001.

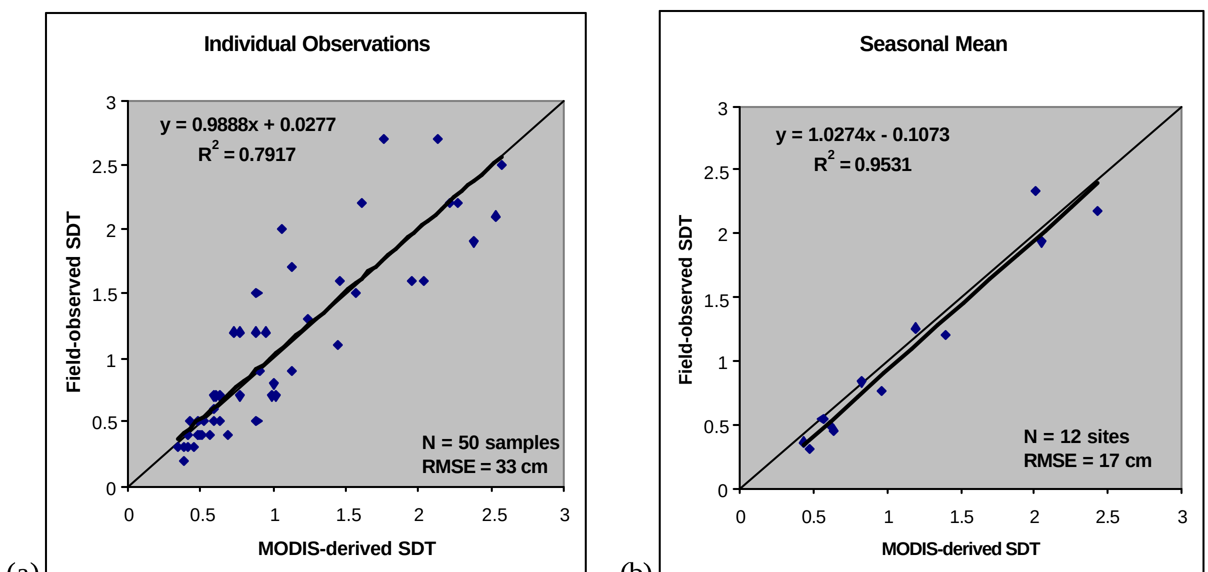

Figure 6. Comparison of MODIS-derived lake clarity estimates and field observations, for 12 sites in Green Bay, Lake Michigan. (a) Individual observations of SDT. (b) Seasonal mean of SDT, based on 4-5 observations per site between July and September, 2001.

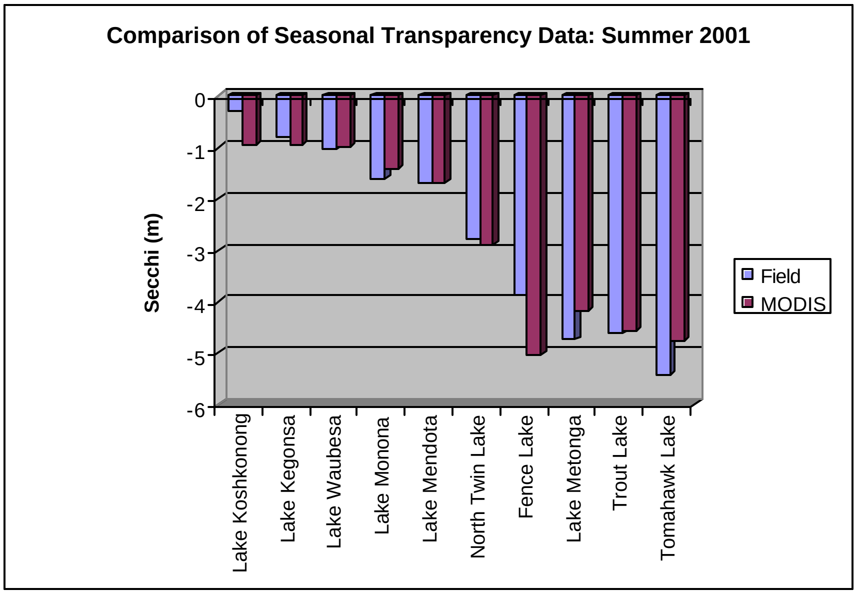

Figure 7. Comparison of MODIS-derived seasonal mean lake clarity estimates and field observations, for 10 inland lakes ranging from highly eutrophic to oligotrophic, summer 2001.