In cooperation with the Michigan Department of Environmental Quality

# Predicting Water Quality by Relating Secchi-Disk Transparency and Chlorophyll *a* Measurements to Landsat Satellite Imagery for Michigan Inland Lakes, 2001–2006

## Introduction

The State of Michigan has more than 11,000 inland lakes; approximately 3,500 of these lakes are greater than 25 acres. The USGS, in cooperation with the Michigan Department of Environmental Quality (MDEQ), has been monitoring the quality of inland lakes in Michigan through the Lake Water Quality Assessment monitoring program. Approximately 100 inland lakes will be sampled per year from 2001 to 2015. Volunteers coordinated by MDEQ started sampling lakes in 1974, and continue to sample to date approximately 250 inland lakes each year through the Cooperative Lakes Monitoring Program (CLMP), Michigan's volunteer lakes monitoring program. Despite this sampling effort, it is still impossible to physically collect the necessary water-quality measurements for all 3,500 Michigan inland lakes. Therefore, a technique was used by USGS, modeled after Olmanson and others (2001), in cooperation with MDEQ that uses satellite remote sensing to predict water quality in unsampled inland lakes greater than 25 acres.

Water-quality characteristics that are associated with water clarity can be predicted for Michigan inland lakes by relating sampled measurements of secchi-disk transparency (SDT) and chlorophyll *a* concentrations (Chl-*a*), to satellite imagery. The trophic state index (TSI) which is an indicator of the biological productivity can be calculated based on SDT measurements, Chl-*a* concentrations, and total phosphorus (TP) concentrations measured near the lake's surface. Through this process, unsampled inland lakes within the fourteen Landsat satellite scenes encompassing Michigan can be translated into estimated TSI from either predicted SDT or Chl-*a* (fig. 1).

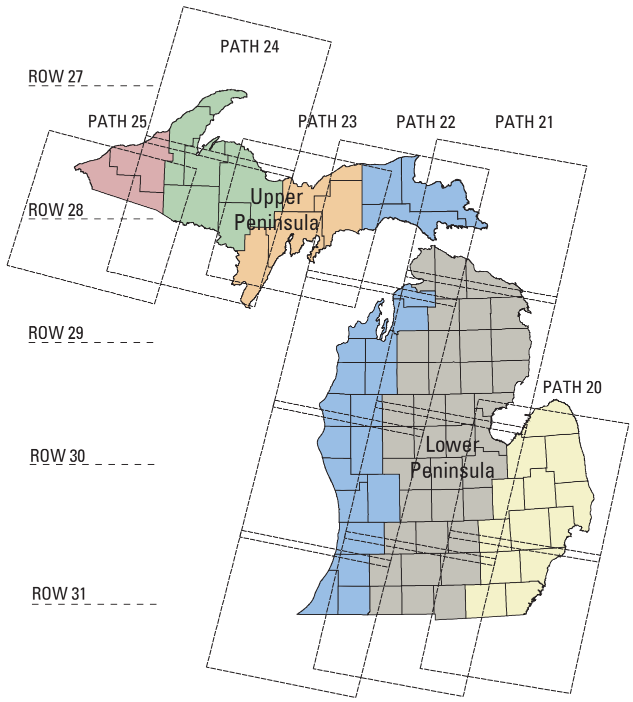


**Figure 1.** Landsat satellite-scene coverage identified by flight path and row number for Michigan.

## What is the Trophic State Index?

Carlson (1977) developed a numerical trophic state index (TSI) for lakes which can be related to the traditional trophic status classification scheme that groups lakes into basic classes of oligotrophic (TSI value < 38), mesotrophic (TSI value 38-48), eutrophic (TSI value 49-61), and hypereutrophic (TSI value > 61). Carlson's TSI was developed for use with lakes that have few rooted aquatic plants and only small amounts of inorganic suspended matter. Carlson's TSI can be calculataed from SDT, Chl-a, and phosphorus. Water bodies that are oligotrophic have high SDT values (high water clarity), and those that are eutrophic have low SDT values (low water clarity) (Bukata and others, 1995). Eutrophic lakes have higher Chl-*a* concentrations than oligotrophic lakes. Of the three measures to compute TSI, SDT and Chl-*a* concentration are quantifiable by means of remote sensing techniques; and more specifically, with satellite imagery (Mayo and others, 1995; Zilioli and Brivio, 1997; Kloiber and others, 2000; Giardino and others, 2001; Kloiber and others, 2002; Fuller and others, 2004). Even though table 1 is arranged into distinct categories, TSI is a continuum classification scheme with boundaries that overlap.

## What is Secchi-Disk Transparency?

Water clarity, or transparency, is commonly measured with a Secchi disk. The clarity of lake water is reduced by the presence of suspended sediment and Marl (CaCO3), bits of organic matter, free-floating algae, and zooplankton. Algae are often the dominant influence on transparency of lake water. Therefore, SDT is related to the free-floating algae concentration or the primary biological productivity of a lake and is used as a trophic state indicator.

SDT is a low-cost and effective measurement of water clarity. A Secchi disk, a 20 centimeter (8 inch) diameter metal or weighted plastic disk normally black and white, is attached to a measured line and lowered into a lake until it can no longer be seen. The depth at which it disappears is known as the SDT. The appearance of Secchi disks in three lakes with differing water quality is shown in figure 2.

## What is Chlorophyll *a*?

Chlorophyll *a* is a photosynthetic pigment that is found in all plants, including algae (Wetzel, 2001). Its concentration is commonly used to represent the density of the algal population in a lake. Free-floating algae (phytoplankton) are the primary food producers in the food chain. Moderate concentration of algae is necessary for a biologically productive, healthy lake; however, excessive concentrations (algal blooms) are undesirable and can have profound effects on the water quality. The accelerated production of algae in a lake is generally the result of excess nutrients– in particular, phosphorus. The depth at which light can penetrate a lake diminishes with more algae in a lake. Thus the greater the value of chl-*a* and phosphorus, the lower the value of SDT. This is how water clarity (SDT), algal productivity (estimated from Chl-*a*), and nutrients (mainly phosphorus) are interrelated in determining water quality and estimating trophic state conditions.

**Table 1.** Lake trophic states and classification ranges for trophic state index, total phosphorus, Secchi-disk transparency, and cholorophyll *a*.

[Based on Michigan Department of Natural Resources (1982) and modified by the State of Michigan to account for regional characteristics. TSI, trophic state index; SDT, Secchi-disk transparency; Chl-*a*, chlorophyll *a*; TP, total phosphorus; ft, feet; mg/L, micrograms per liter]

| Lake Trophic State | Carlson TSI | SDT (ft) | Chl-*a* (μg/L) | TP (μg/L) |
|---|---|---|---|---|
| Oligotrophic | < 38 | > 15 | < 2.2 | < 10 |
| Mesotrophic | 38–48 | 7.5–15 | 2.2–6 | 10–20 |
| Eutrophic | 49–61 | 3–7.4 | 6.1–22 | 20.1–50 |
| Hypereutrophic | > 61 | < 3 | > 22 | > 50 |

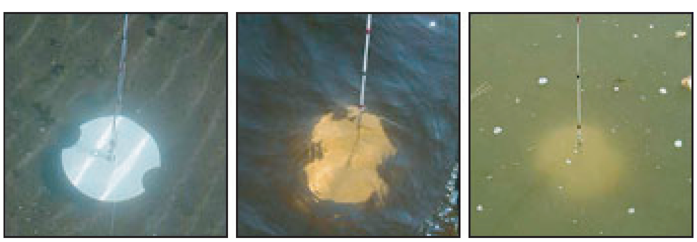

**Figure 2.** Examples of Secchi disks and their appearance in water of decreasing transparency, from left to right, within various lakes in Minnesota. Photographs courtesy of Minnesota Pollution Control Agency.

## How Does Landsat Satellite Imagery Fit In?

Availability of satellite imagery, seasonality, day of month, atmospheric conditions, and the size of the inland lakes are all factors that are taken into consideration, and effect the ability to translate satellite imagery into estimated TSI from either predicted SDT or Chl-*a*.

Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced TM plus (data from both satellites were used in the project) record data by paths (National Aeronautics and Space Administration, 2007). Each path has a 16-day repeat cycle, and adjacent paths are taken every 7 days. For example, path 22 is taken 7 days after path 21, and path 20 is taken 7 days before path 21.

The fourteen satellite scenes encompassing Michigan are referenced by both a path number and a row number (fig. 1). Since satellite data is translated into estimated TSI from predicted SDT or Chl-*a* by satellite scene, and all the paths for Michigan are not available for the same day, statewide water-quality predictions are available over a 3-month period July through September. These months have been shown to produce the most accurate predictive models, because the lakes are at their maximum biological productivity (Kloiber and others, 2000).

Landsat satellites record a value of 0-255 for each 30 x 30 meter (900 square meters) area, termed a cell, in wavelength ranges called bands. Bands 1, 2, 3 (visible spectrum of blue, green, and red, respectively), and 7 (middle infrared) are used in the project. All four bands have cell sizes of 30 meters, so 900 square meters of earth are represented in one cell by one value for each band. Water-quality predictions can be made only for lakes greater than 25 acres (approximately 101,200 square meters) because of the cell size, so that the number of cells is adequate to produce an accurate predictive model.

Cloud cover is a factor in the quality of Landsat data, and satellite scenes are selected for model development only if cloud cover is less than 10 percent. Also, because of model requirements, water-quality predictions can not be made for an individual inland lake if less than 25 acres is visible because of cloud cover.

## Relating Field Measurements of Water Quality to Satellite Imagery

Measurements of SDT or Chl-*a* from approximately 20 inland lakes are needed for each of the fourteen satellite scenes encompassing Michigan. These measurements are then related to a satellite scene to determine a regression equation specific to that satellite scene. Each year, the model is recalibrated by satellite scene with corresponding water-quality measurements. The regression equation can then be used to predict water-quality characteristics for unsampled inland lakes within each satellite scene.

## Making Field Measurements for Secchi-Disk Transparency and Chlorophyll *a*

Measurements of SDT and Chl-*a* were used in the project that were within a range of 7 days before or after the satellite acquisition dates to produce an accurate predictive model, with best results obtained from measurements made within a range of 3 days. Approximately 20 measurements were used per satellite scene, and were made at the deepest point in the lake so that reflectance from the bottom of the lake did not affect the measurements. The exact locations of the measurements used were noted during sampling, either by using a GPS unit to record latitude and longitude coordinates or by clearly marking locations on a map during sampling and digitized later to determine their coordinates. SDT values were omitted if they were more than two-thirds the lake depth (which occurs mostly in shallow lakes), because the satellite could also be sensing the lake bottom.

## Relating Field Measurements to Satellite Imagery

Areas of interest (AOIs) containing approximately nine cells were established around each measurement, and the average value (ranging from 0-255) for each band from the satellite scene was recorded. Taking an average for each band in its AOI was found to produce more accurate predicted SDT and Chl-*a* values (Olmanson and others, 2001). Average band values for each measurement were used in a statistical analysis program to determine the regression equation specific to each satellite scene. Regression equations are what translate the Landsat satellite scenes into predicted SDT and Chl-*a* values.

An Example of an AOI around a Secchi-disk measurement for Lake Lansing in Ingham County, Mich. (path 21 row 30), is shown in figure 3, and table 2 is the corresponding AOI information that would be used to produce the regression equation for that satellite scene. Approximately 20 measurements are used to produce the regression equation per satellite scene. The following equations were used to predict SDT and Chl-*a*:

$$\ln(SDT) = a(band1) + b(band2) + c(band3) + d \qquad (1)$$

$$\ln(Chl\text{-}a) = a(band2) + b(band3) + c(band7) + d \qquad (2)$$

In the equations, the natural log (ln) of SDT was calculated in units of meters, the ln of Chl-*a* was calculated in units of milligrams per liter, and band values ranged from 0 through 255. The letters a–d are parameters that are specific to the equations for each satellite scene.

**Figure 3.** Landsat 5 TM satellite scene of Lake Lansing, Ingham County, Mich. (path 21 row 30). Yellow dot indicates location of a 2003 Secchi-disk transparency (SDT) measurement, and ring of black dots surrounding area of interest (AOI) consisting of nine cells.

**Table 2.** Area-of -interest (AOI) information averaged from nine cells surrounding a 2002 Secchi-disk transparency (SDT) measurement from a 2002 Landsat 5 TM satellite image of Lake Lansing, Mich.

[SDT, Secchi-disk transparency; m, meters; ln, natural log]

| Lake Name | Band 1 | Band 2 | Band 3 | SDT m | ln(SDTm) |
|---|---|---|---|---|---|
| Lansing | 64.77 | 41.38 | 30.46 | 3.05 | 1.11 |

## Predicting Trophic State Index for Unsampled Lakes From Field Measurements

Figure 4 is a graphical depiction of equation (1) where approximately 20 SDT measurements from 2003 are related to a 2003 Landsat satellite scene path 21 row 29 located in the northern Lower Peninsula of Michigan (fig. 1). Figure 4 is showing the relation or best fit between 2003 SDT values and the corresponding satellite scene for that year.

Predicted TSI values computed from predicted SDT or Chl-*a* are available from 2001 through 2006. All predicted TSI values were based on SDT measurements except for 2004, when Chl-*a* measurements were used for the TSI predictions in the Lower Peninsula (fig. 1). TSI predictions are available in a grid format that shows intra-lake variability (variability of 30-meter grid cell values within a lake) and by an average predicted TSI value by lake (fig. 5). Intralake variability can be useful for identifying areas within a lake that might need further examination. Predicted TSI values available by satellite scene from 2001 through 2006 are shown in figure 6. Future plans are to have complete coverage for Michigan of predicted TSI values, available on a 2-year rotation. The TSI predictions are viewable on an Internet Map Server site (IMS) at: http://mi.water.usgs.gov/splan1/sp00301/remotesensing.php under "IMS sites".

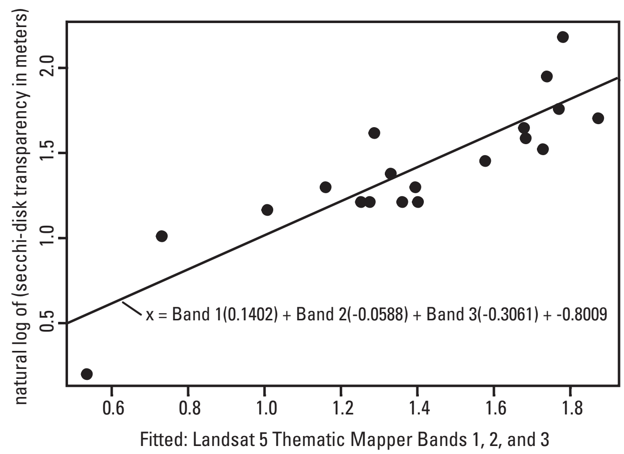


**Figure 4.** Graph of the relation between 2003 Secchi-disk measurements and a 2003 Landsat 5 TM satellite scene path 21, row 29; northern Lower Peninsula of Michigan.

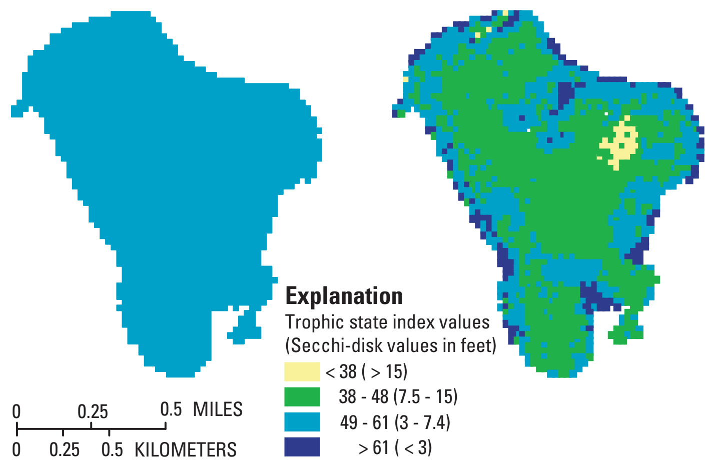


**Figure 5.** Predicted trophic state index and corresponding Secchi-disk values for Lake Lansing in Ingham County, Mich. (lakewide average on the left, and intralake variability on the right).

## Measured and Predicted Values of TSI Compare Well

Comparisons of data show that the predicted TSI values correlate well to the measured TSI values. An average from 2001 through 2006 shows that 71 percent of the predicted TSI values were in the correct measured TSI classes of oligotrophic, mesotrophic, eutrophic, and hypereutrophic (as defined in table 1). Another examination of the results shows that 42 percent of the predicted TSI values were within 2 TSI units of the measured TSI, 80 percent were within 5 TSI units, and 98 percent were within 10 TSI units of the field measurements. The majority of the data is predicting to the correct class, and is also predicting close to the measured TSI value.

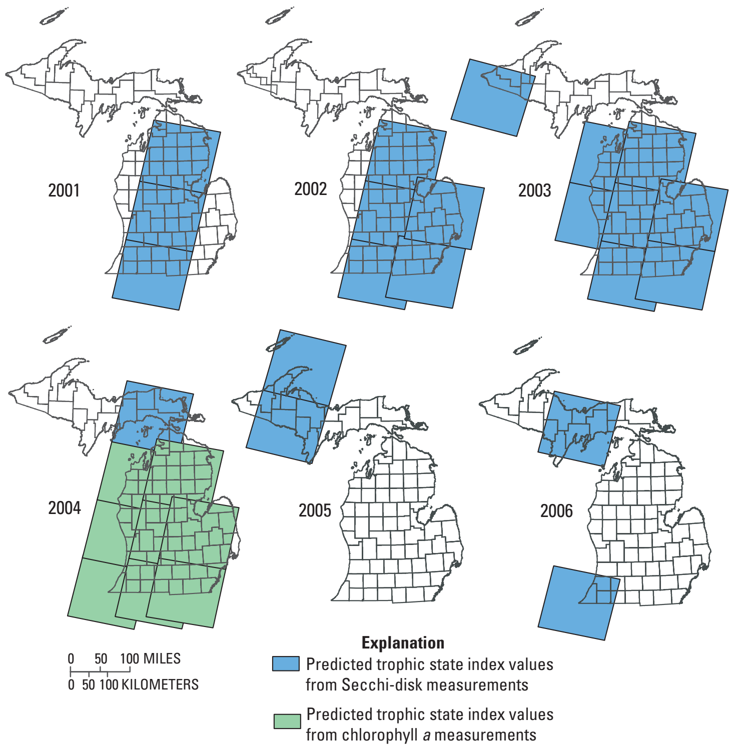


**Figure 6.** Availability of predicted trophic state index values for Michigan, 2001–2006, based on relations of Secchi-disk transparency or chlorophyll a values to satellite data. Boxed boundaries are approximations of Landsat satellite scene locations by which trophic state index predictions were made.

## Predictions are Reliable and Economical

Michigan has more than 11,000 inland lakes with approximately 3,500 over 25 acres. It is economically and logistically impossible to physically collect the necessary water-quality measurements for all 3,500 inland lakes greater than 25 acres through volunteers with the CLMP or through the USGS. Remote sensing is an effective and economical tool to enhance the value of conventional sampling data by producing regression equations that translate satellite imagery into predicted TSI values from SDT or Chl-*a* for Michigan inland lakes greater than 25 acres (approximately 101,200 square meters) in size.

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## References Cited

Bukata, R.P., Jerome, J.H., Kondratyev, K.Y., and Pozdnyakov, D.V., 1995, Optical properties and remote sensing of inland and coastal waters: Boca Raton, Fla., CRC Press, p. 214–216.

Carlson, R.E., 1977, A trophic state index for lakes: Limnology and Oceanography: v. 22, no. 2, p. 361–369.

Fuller, L.M., Aichele, S.S., and Minnerick, R.J., 2004, Predicting water quality by relating Secchi-disk transparency and chlorophyll *a* measurements to satellite imagery for Michigan inland lakes, August 2002: U.S. Geological Survery Scientific Investigations Report 2004–5086, 25 p.

Giardino, Claudia; Pepe, Monica; Brivio, P.A.; Ghezzi, Paolo; and Zilioli, Eugenio, 2001, Detecting chlorophyll, Secchi disk depth and surface temperature in a sub-alpine lake using Landsat imagery: Science of the Total Environment: v. 268, p. 19–29.

Kloiber, S.M., Anderle, T.H., Brezonik, P.L., Olmanson, L., Bauer, M.E. and Brown, D.A., 2000, Trophic state assessment of lakes in the Twin Cities (Minnesota, USA) region by satellite imagery: Archiv für Hydrobiologie, Special Issues, Advances in Limnology, v. 55, p. 137–151.

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

Mayo, M., Gitelson A., Yacobi Y.Z., and Ben-Avraham Z., 1995, Chlorophyll distribution in Lake Kinneret determined from Landsat Thematic Mapper data: International Journal of Remote Sensing: v. 16, no. 1, p. 175–182.

Michigan Department of Natural Resources, 1982, Michigan Inland Lake Project: Identification, Survey and Classification: U.S. Environmental Protection Agency Clean Lakes Agreement No. S 005511-01 Final Project Report, September 1982.

National Aeronautics and Space Administration, 2007, The Landsat program: Accessed January 30, 2007, at http://landsat.gsfc.nasa.gov/

Olmanson, L.G., Kloiber, S.M., Bauer, M.E., and Brezonik, P.L., 2001, Image processing protocol for regional assessments of lake water quality: University of Minnesota,Water Resources Center and Remote Sensing Laboratory, Public Report Series no. 14, 19 p.

Wetzel, R.G., 2001, Limnology—Lake and river ecosystems (3rd ed.): San Diego, Calif., Academic Press, 1,006 p.

Zilioli, E., and Brivio, P.A., 1997, The satellite derived optical information for the comparative assessment of lacustrine water quality: Science of the Total Environment, v. 196, p. 229–245.

## For More Information

For more information on the remote sensing project, a report describing the process used for 2002 data is listed at http://pubs.usgs.gov/sir/2004/5086/ and the Web site for the project, with a link to a website with the viewable Secchi-disk transparency and Chl-*a* predictions, can be found at http://mi.water.usgs.gov/splan1/sp00301/remotesensing.php

Minnesota and Wisconsin have similar websites with viewable predictions accessible at: http://resac.gis.umn.edu/water/regional_water_clarity/regional_water_clarity.htm

Additional information on the MDEQ and USGS inland lake water-quality sampling program can be found at http://pubs.usgs.gov/fs/2004/3048/

Additional information on the Cooperative Lakes Monitoring Program can be found at http://www.michigan.gov/deq/0,1607,7-135-3313_3686_3731---,00.html