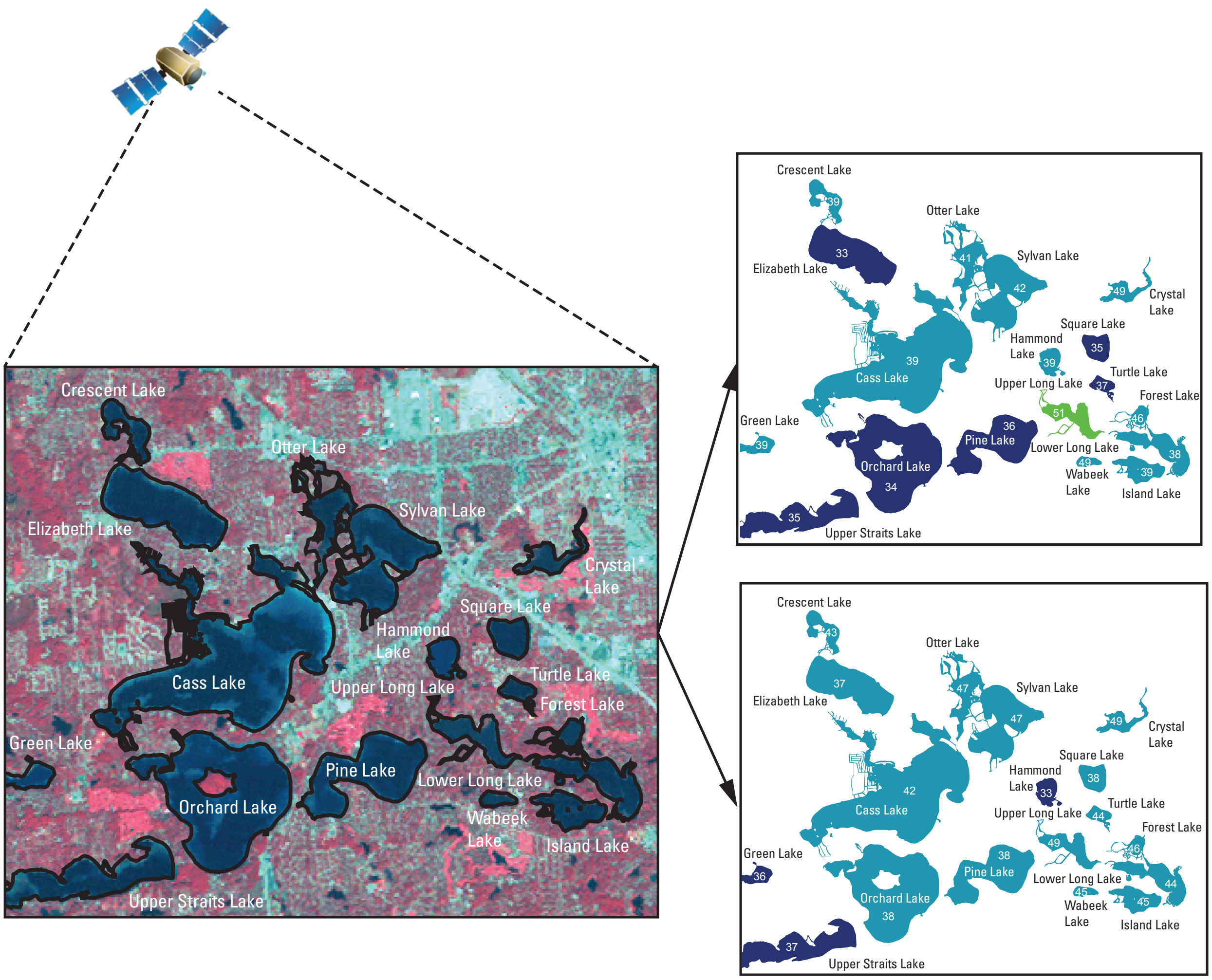
In cooperation with the Michigan Department of Natural Resources and Environment

Predicting Lake Trophic State by Relating Secchi-Disk Transparency Measurements to Landsat-Satellite Imagery for Michigan Inland Lakes, 2003–05 and 2007–08



Scientific Investigations Report 2011–5007

U.S. Department of the Interior
U.S. Geological Survey

Predicting Lake Trophic State by Relating Secchi-Disk Transparency Measurements to Landsat-Satellite Imagery for Michigan Inland Lakes, 2003–05 and 2007–08

By L.M. Fuller, R.S. Jodoin, and R.J. Minnerick

In cooperation with the Michigan Department of Natural Resources and Environment

Scientific Investigations Report 2011–5007

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Fuller, L.M., Jodoin, R.S., and Minnerick, R.J., 2011, Predicting lake trophic state by relating Secchi-disk transparency measurements to Landsat-satellite imagery for Michigan inland lakes, 2003–05 and 2007–08: U.S. Geological Survey Scientific Investigations Report 2011–5007, 36 p.

Acknowledgments

Mr. Ralph Bednarz of the Michigan Department of Natural Resources and Environment and the volunteers of the Cooperative Lake Monitoring Program (CLMP) were invaluable in providing much of the field data used in the project. Leif Olmanson of the Remote Sensing and Geospatial Analysis Laboratory, Department of Forest Resources, University of Minnesota provided the Gethist program for use in analyzing Michigan inland lakes.

U.S. Geological Survey (USGS) field technicians provided measurements for the Upper Peninsula of Michigan to supplement the measurements from volunteers of the CLMP. The following USGS Michigan Water Science Center employees were involved in the collection of data for this study: D. Burdett, J.M. Ellis, S.B. Horton, J. Knudsen, D.G. Wydra, and J.A. Wilkinson.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
meter (m)	3.281	foot (ft)
	Area	
acre	4,047	square meter (m^2)
square meter (m^2)	0.0002471	acre
acre	0.004047	square kilometer (km^2)
	Concentration	
micrograms per liter (µg/L)	0.001	milligrams per liter (mg/L)

Vertical coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviations used in this report

AOI	area of interest
Chl-*a*	chlorophyll *a*
CLMP	Cooperative Lakes Monitoring Program
GPS	global positioning system
LWQA	Lake Water Quality Assessment
MDNRE	Michigan Department of Natural Resources and Environment
R^2	coefficient of determination
SDT	Secchi-disk transparency
TM	Thematic Mapper
TP	total phosphorus
TSI	Trophic State Index
USGS	U.S. Geological Survey

Predicting Lake Trophic State by Relating Secchi-Disk Transparency Measurements to Landsat-Satellite Imagery for Michigan Inland Lakes, 2003–05 and 2007–08

By L.M. Fuller, R.S. Jodoin, and R.J. Minnerick

Abstract

Inland lakes are an important economic and environmental resource for Michigan. The U.S. Geological Survey and the Michigan Department of Natural Resources and Environment have been cooperatively monitoring the quality of selected lakes in Michigan through the Lake Water Quality Assessment program. Sampling for this program began in 2001; by 2010, 730 of Michigan's 11,000 inland lakes are expected to have been sampled once. Volunteers coordinated by the Michigan Department of Natural Resources and Environment began sampling lakes in 1974 and continue to sample (in 2010) approximately 250 inland lakes each year through the Michigan Cooperative Lakes Monitoring Program. Despite these sampling efforts, it still is impossible to physically collect measurements for all Michigan inland lakes; however, Landsat-satellite imagery has been used successfully in Minnesota, Wisconsin, Michigan, and elsewhere to predict the trophic state of unsampled inland lakes greater than 20 acres by producing regression equations relating in-place Secchi-disk measurements to Landsat bands. This study tested three alternatives to methods previously used in Michigan to improve results for predicted statewide Trophic State Index (TSI) computed from Secchi-disk transparency (TSI (SDT)). The alternative methods were used on 14 Landsat-satellite scenes with statewide TSI (SDT) for two time periods (2003–05 and 2007–08). Specifically, the methods were (1) satellite-data processing techniques to remove areas affected by clouds, cloud shadows, haze, shoreline, and dense vegetation for inland lakes greater than 20 acres in Michigan; (2) comparison of the previous method for producing a single open-water predicted TSI (SDT) value (which was based on an area of interest (AOI) and lake-average approach) to an alternative Gethist method for identifying open-water areas in inland lakes (which follows the initial satellite-data processing and targets the darkest pixels, representing the deepest water, before regression equations are created); and (3) checking to see whether the predicted TSI (SDT) values compared well between two regression equations, one previously used in Michigan and an alternative equation from the hydrologic literature.

The combination of improved satellite-data processing techniques and the Gethist method to identify open-water areas in inland lakes during 2003–05 and 2007–08 provided a stronger relation and statistical significance between predicted TSI (SDT) and measured TSI than did the AOI lake-average method; differences in results for the two methods were significant at the 99-percent confidence level. With regard to the comparison of the regression equations, there were no statistically significant differences at the 95-percent confidence level between results from the two equations. The previously used equation, in combination with the Gethist method, yielded coefficient of determination (R^2) values of 0.71 and 0.77 for the periods 2003–05 and 2007–08, respectively. The alternative equation, in combination with the Gethist method, yielded R^2 values of 0.74 and 0.75 for 2003–05 and 2007–08, respectively. Predicted TSI (SDT) and measured TSI (SDT) values for lakes used in the regression equations compared well, with R^2 values of 0.95 and 0.96 for predicted TSI (SDT) for 2003–05 and 2007–08, respectively. The R^2 values for statewide predicted TSI (SDT) for all inland lakes with available open-water areas for 2003–05 and 2007–08 were 0.91 and 0.93, respectively. Although the two equations predicted similar trophic-state classes, the alternative equation is planned to be used for future prediction of TSI (SDT) values for Michigan inland lakes, to promote consistency in comparing predicted values between States and for potential use in trend analysis.

Introduction

The State of Michigan has more than 11,000 inland lakes; approximately 4,000 of these lakes are greater than 20 acres in size. The public has access to launches or beaches at about 1,300 lakes in Michigan. Recreational, property, and ecological values all are closely related to the quality of water in these inland lakes (Krysel and others, 2003). Tourism in Michigan, much of which involves recreation at inland lakes, accounts for nearly $12 billion of economic activity each year

(Stynes, 2002). Thus, inland lakes are important economic and ecological resources to Michigan.

The U.S. Geological Survey (USGS) and the Michigan Department of Natural Resources and Environment (MDNRE) have been cooperatively monitoring the quality of inland lakes in Michigan through the Lake Water Quality Assessment (LWQA) monitoring program funded by the Clean Michigan Initiative. Through this program, the USGS has been sampling public-access lakes over 25 acres in size in both the spring and late summer. Sampling began in 2001; by 2010, 730 such lakes are expected to have been sampled. In addition, each year the MDNRE plans to provide data from their Cooperative Lakes Monitoring Program (CLMP), which is a volunteer network monitoring approximately 250 lakes weekly to monthly. Data from those two sampling networks are being used to characterize baseline water quality and compute trophic state of monitored inland lakes.

Measured water-quality characteristics of inland lakes are critical factors in determining the lakes' recreational use, habitat and species diversity, and economic return from the tourism industry. The USGS and the MDNRE monitor many inland lakes, but it is not economically feasible to monitor the quality of all 11,000 inland lakes in Michigan by use of conventional sampling techniques. Knowledge of the biological productivity of unsampled inland lakes is needed to assist resource managers in their efforts to protect and manage the quality in all of Michigan's inland lakes.

Landsat-satellite imagery has been used successfully in Minnesota (Olmanson and others, 2001; Kloiber and others, 2002), Wisconsin (Chipman and others, 2004; Peckham and Lillesand, 2006), and elsewhere (Baban, 1993; Dekker and Peters, 1993; Mayo and others, 1995; Giardino and others, 2001) to estimate Trophic State Index (TSI) Secchi-disk transparency (SDT) for unsampled inland lakes. During previous studies in Michigan (Nelson and others, 2003; Wiangwang, 2002), researchers attempted to use existing models for relating Landsat-satellite imagery to SDT; however, they were unable to obtain as high a coefficient of determination (R^2; an indicator of the strength of a statistical relation) as did researchers in previous studies in Minnesota and Wisconsin. Fuller and others (2004) estimated TSI (SDT) for Lower Michigan, using an alternative regression equation to that used by Olmanson and others (2001), with slightly higher R^2 values. Results from a study by Fuller and Minnerick (2007) documented a good fit between measured and statewide predicted TSI (SDT). Knowledge of improved satellite-data processing techniques, an alternative Gethist method to identify the open-water areas in satellite data, and two available regression equations used to predict trophic characteristics from Landsat-satellite imagery prompted a revisit of methods from Fuller and others (2004) to examine which methods would produce predictions more reflective of measured values for two sets of data from 2003–05 and 2007–08. Refining methods would improve and increase the knowledge about Michigan's inland lakes.

Previous Studies Relating Secchi-Disk Transparency to Inland Lakes

Carlson (1977) proposed to quantify the trophic state by its TSI, which can be classified into basic classes of oligotrophic, mesotrophic, eutrophic, and hypereutrophic. Carlson's TSI model was developed for use with lakes that have few rooted aquatic plants and little non-algal turbidity (U.S. Environmental Protection Agency, 2007). The natural progression of a lake from oligotrophic to eutrophic can be computed from measures of total phosphorus (TP), Secchi-disk transparency (SDT), and chlorophyll *a* (Chl-*a*). Table 1 shows the range of TSI values and how each measure is classified into oligotrophic, mesotrophic, eutrophic, and hypereutrophic.

The formulas for calculating TSI values are

$$TSI = 60 - 14.41 \ln (\text{SDT feet} * 0.3048)$$

$$TSI = 9.81 \ln \text{Chl-}a \text{ (micrograms per liter } (\mu g/L)) + 30.6$$

$$TSI = 14.41 \ln \text{TP } (\mu g/L) + 4.15$$

SDT is a commonly used, low-cost technique that measures water clarity; specifically, a black and white disk is lowered into the lake until it no longer can be seen. Water clarity is related to the quantity of phytoplankton in the water, although non-algal turbidity and tannic acids also can reduce water clarity. Chl-*a* measurements correlate with the concentration of phytoplankton within a given volume of lake water and are not affected by sediment or acids in the water. Typically, computing TSI values for a single lake using all three formulas should yield similar results. Increasing the concentration of phosphorus generally results in increased concentration of phytoplankton, which results in reduced water clarity. Yet at specific times of the year, or on specific lakes, results from the three formulas may not be congruous because of phosphorus-nutrient uptake by macrophytes. Therefore, substantial

Table 1. Lake Trophic State Index and classification ranges using Trophic State Index values, Secchi-disk transparency, chlorophyll-*a*, and total phosphorus for Michigan inland lakes, 2003–05 and 2007–08.

[TSI, Trophic State Index; SDT, Secchi–disk transparency; ft, feet; Chl-*a*; chlorophyll-*a*; µg/L, micrograms per liter; TP, ttal phosphorus; <, less than; >, greater than; data from Warbach (1990) and modified by the State of Michigan to account for regional characteristics]

Lake trophic condition	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

amounts of macrophytes in a lake may alter the relation of the three TSI values.

Of the three measures, SDT and concentration of Chl-*a* are quantifiable using remote-sensing techniques (Mayo and others, 1995; Zilioli and Brivio, 1997; Kloiber and others, 2000; Giardino and others, 2001; and Kloiber and others, 2002), though Kutser and others (2006) cautioned that Landsat-satellite imagery does not have adequate narrow spectral bands to distinguish the unique spectral signature of Chl-*a*, and regression equations actually may be predicting turbidity as it correlates to Chl-*a*.

A variety of equations relating SDT to Landsat-satellite imagery have been tested in different settings and with different sensors. Olmanson and others (2001) and Kloiber and others (2002) used the following equation for Minnesota lakes along with data from Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper plus (ETM+) satellites:

$$\ln(SDT) = a(band1/band3) + b(band1) + c \quad (1)$$

Fuller and others (2004), who also used Landsat satellite 5 TM, found an alternative equation for Michigan lakes that improved the relation, but the relation was not statistically significant at the 95-percent confidence level:

$$\ln(SDT) = a(band1) + b(band2) + c(band3) + d \quad (2)$$

The variables a, b, and c are empirically derived coefficients from the regression equation. Table 2 shows Landsat (TM) and Landsat (ETM+) bands and corresponding wavelength ranges.

In Fuller and others (2004), methods similar to those published in Olmanson and others (2001) were followed to produce predicted TSI (SDT) for Michigan inland lakes for the Lower Peninsula of Michigan. A statewide predicted TSI for 2003–06 from Fuller and Minnerick (2007) compared well to measurements, but the accuracy declined slightly owing to the method used to produce a predicted TSI (SDT) value reflective of the open-water area for each lake. Because we do not know the deep-basin location for all inland lakes in Michigan, the regression equation derived from using an Area of Interest (AOI) around the measurements was applied to all areas after satellite-data processing within each inland lake. All 30-m pixels within the area for each inland lake that remained after satellite-data processing were averaged to produce a single open-water predicted TSI value for each inland lake.

Minnesota and Wisconsin have used a Gethist program to reduce the areas remaining after satellite-data processing to identify the darkest pixels, which were then used to both produce regression equations and produce a single predicted TSI (SDT) value for each inland lake more representative of the open-water area. By use of this additional step, Minnesota and Wisconsin obtained statewide predicted TSI (SDT) for 20 and 30 years, respectively, and analyzed potential trends (Olmanson and others, 2008 Peckham and Lillesand, 2006). With improved methods, Michigan also could follow suit to produce predicted TSI (SDT) to monitor potential trends for inland lakes. Temporal statewide predictions would be useful for lake managers to monitor potential changes in Michigan inland lakes.

Purpose and Scope

This report was written to (1) document alternative methods for processing Landsat-satellite imagery that would remove areas affected by clouds, cloud shadows, haze, shoreline, and dense vegetation for inland lakes greater than 20 acres in Michigan; (2) compare the previous method of producing a single open water predicted TSI (SDT) value using an area of interest (AOI) and lake-average method to an alternative Gethist method; and (3) ascertain if the predicted TSI (SDT) and SDT values compared well between the regression equation in Fuller and others (2004) to the regression equation in Olmanson and others (2001) for statewide predictions for two time periods: 2003–05 and 2007–08. The methods used to produce the statewide predictions will be described, the field data-collection methods will be included only by reference.

Table 2. Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper Plus bands and corresponding wavelengths.

[µm, micrometers]

Landsat satellite	Visible spectrum			Near-infrared		Thermal	Mid-infrared	Panchromatic
	Band 1	**Band 2**	**Band 3**	**Band 4**	**Band 5**	**Band 6**	**Band 7**	**Band 8**
Landsat 5 Thematic Mapper	0.45–0.52 µm	0.52–0.60 µm	0.63–0.69 µm	0.76–0.90 µm	1.55–1.75 µm	10.40–12.50 µm	2.08–2.35 µm	Not available
Landsat 7 Enhanced Thematic Mapper plus	0.45–0.52 µm	0.52–0.60 µm	0.63–0.69 µm	0.77–0.90 µm	1.55–1.75 µm	10.40–12.50 µm	2.08–2.35 µm	0.52–0.90 µm

Methods

Relating remote-sensing Landsat-satellite imagery to Secchi-disk measurements involves several steps, which can be grouped into three categories. First, relatively cloud-free Landsat-satellite imagery is chosen during the late-summer period and processed to remove areas affected by clouds, cloud shadows, haze, shoreline, and dense vegetation for inland lakes greater than 20 acres in Michigan. Second, field data corresponding to the Landsat-satellite imagery are obtained. Third, the field data within plus or minus 7 days of the Landsat-satellite imagery acquisition date are related to produce a regression model specific to each date of Landsat-satellite imagery. The end results are predicted TSI (SDT) values for desirable open-water areas for inland lakes greater than 20 acres within the Landsat-satellite scenes.

Landsat-Satellite Imagery Acquisition and Processing

Seven paths of Landsat 5 Thematic Mapper (TM) satellite data (14 satellite scenes) were processed for 2003–05 and 2007–08. The 14 Landsat-satellite scenes encompassing Michigan are referenced by both a path number and a row number (fig. 1). The Landsat-satellite scenes were selected for one date from a 3-month period (July–September) with the least amount of cloud cover and haze (preferably less than 10 percent cloud cover). 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).

Only one date per Landsat-satellite scene is included each year. Although temporal coverage during the season would be interesting, Landsat has a 16-day repeat cycle only allowing 5 to 6 dates available per scene during the 3-month period from mid July to September. Usually only one date per scene is available with less than 10 percent cloud cover, the percentage necessary to produce reliable predictions. For the 2003–05 dataset, 3 years of data were used to complete the statewide predictions. In 2007, a sampling plan was implemented to produce a statewide predicted TSI (SDT) every other year. The sampling plan was to produce paths 20 to 23 with year 1 Landsat-satellite imagery and paths 24 and 25 with year 2 Landsat-satellite imagery; Landsat-satellite imagery for 2007–08 is shown on figure 1.

The images arrived in 1P format, which means they were systematically corrected (geometric and radiometric corrections) and provided an “end result [that] was a geometrically rectified product free from distortions related to the sensor (for example, jitter, view angle effects), satellite (for example, attitude deviations from nominal), and Earth (for example, rotation, curvature)” (National Aeronautics Space Administration, 2003), with ground-control points to improve spatial accuracy. The format chosen helped ensure that the image cells would correspond to the data-collection points as closely as possible.

Landsat-imagery processing was completed with ERDAS IMAGINE 9.3 and 10.0 software. The Landsat-satellite scenes were delivered in the Universal Transverse Mercator projection system by using the World Geodetic System 84 North American Datum zone 16 or 17, depending on the scene. Each scene was reprojected into Michigan Georef by using an Oblique Mercator projection, NAD83 datum, in meters. The Michigan Georef projection was used because it ensures one zone for all of Michigan, and it is used by most Federal, State, and local agencies in Michigan. When each image was compared with the Michigan transportation framework developed by the Michigan Center for Geographic Information, it was found to be accurate to within 1 to 2 cells or about 30 to 60 m. This accuracy was acceptable to place the measurements for each inland lake into the deep open-water area.

Landsat satellites record values for each 30- × 30-m (900-m^2) area (cell), in wavelength ranges (bands). Bands 1, 2, and 3 (visible spectrum of blue, green, and red, respectively) are used in this project. All bands have cell sizes of 30 m, so 900 m^2 of Earth are represented in one cell by one value for each band. TSI (SDT) predictions are made for lakes greater than 20 acres (approximately 81,000 m^2) to allow an adequate number of cells in the open-water area of the inland lakes to produce an accurate predictive model.

Water-Only Image

The water-only images are created to reduce file size and target analysis on the open-water area for inland lakes greater than 20 acres. Whereas Olmanson and others (2001) used an unsupervised classification to obtain open-water areas, we used a mask function was used to select pixels from the Landsat-satellite imagery that corresponded to a Michigan inland lakes polygon shapefile greater than 20 acres (from Breck, 2004). When the Landsat-satellite imagery was masked to match the inland lakes shapefile, some 30-m pixels were selected as water (inside the lakes-polygon shapefile), including vegetated areas of the shoreline, islands, or shallow water with vegetation.

A Normalized Difference Vegetation Index, which responds to the amount of green biomass (Jensen, 2007), was applied to remove the vegetated pixels within the inland lakes-polygon shapefile that corresponded to shoreline, islands, and shallow vegetated water. The resulting pixels had a negative value; thus, greenness presence was removed. An unsupervised classification was performed on the remaining pixels using 10 classes, 50 iterations, and a 0.99-confidence level. If necessary, the unsupervised classification was repeated. This step facilitated masking out more areas with clouds, shallow areas, or shoreline.

The final check was to input the remaining areas after the satellite-data processing into ArcMap 9.3 and display with a band 1,6,6 combination (mapping the blue band onto band 1, and bands 6 onto the green and red bands, respectively) to identify if any lakes were affected by haze or cloud shadows (a technique suggested by Olmanson and others, 2008). Lakes

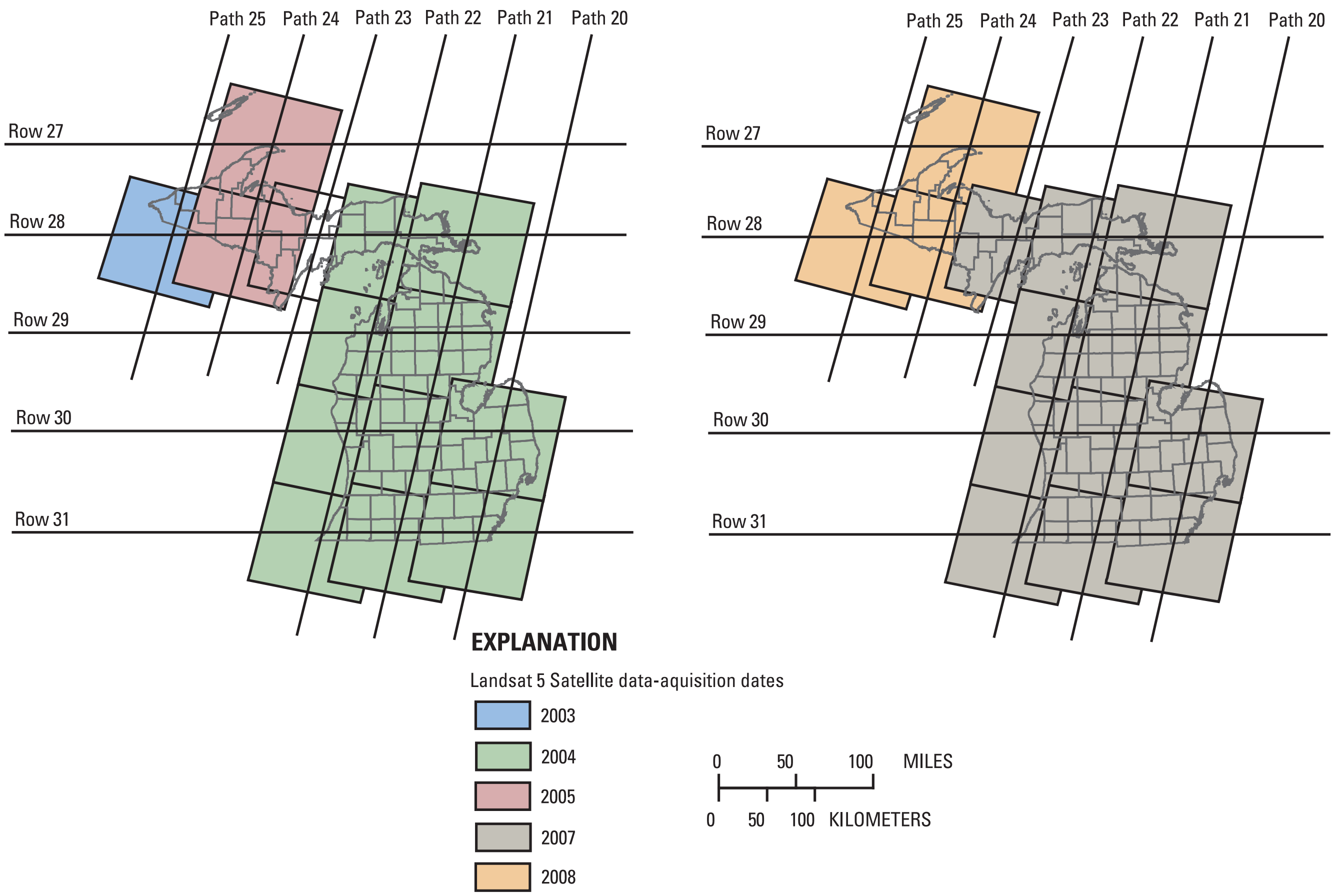


Figure 1. Landsat coverage for statewide predicted Trophic State Index and Secchi-disk transparency for 2003–05 and 2007–08.

were removed from the calculation if they were affected by haze, and affected areas were removed from large lakes that still had good representation in the open-water areas. See figure 2 for before-and-after Landsat-imagery processing to obtain open-water areas for use in regression equations for a portion of Oakland County, Michigan, inland lakes.

Field Data Collection and Processing

A Secchi disk is a common tool used to measure the overall clarity of water. The Secchi disk is an 8-in.-diameter circular disk painted black and white in alternating quadrants (fig. 3). The disk is lowered into the water, and the depth at which the disk is no longer visible is known as the SDT. Measurements of SDT were obtained from volunteers in the MDNRE CLMP who routinely measure SDT for various lakes in Michigan. SDT measurements done by volunteers have been studied and proven to be comparable with measurements done by professionals (Canfield and others, 2002; Obrecht and others, 1998). USGS field technicians collected samples in the Northern Lower Peninsula and the Upper Peninsula of Michigan immediately after Landsat-satellite scenes with low cloud cover to supplement measurements made by CLMP volunteers.

Shapefiles were created with measurements in the Michigan Georef projection that corresponded to a window of 7 days before or after satellite-acquisition dates, and this approach produced accurate predictive models. This window produced the best results in predictive SDT models (Kloiber and others, 2002). The number of measurements per path varied but a minimum of 20 measurements per Landsat-satellite scene in a path was desirable. Measurements were made at the deepest point in the lake so that reflectance from the bottom of the lake did not affect the measurements. The locations of the measurements used were noted during sampling, either by using a global positioning system (GPS) unit to record latitude and longitude coordinates or by clearly marking locations on a map during sampling and digitizing later to determine their coordinates.

All SDT measurements were reviewed; some were omitted owing to clouds, cloud shadows, or haze covering the open-water areas of the inland lake. Clouds and cloud shadows along with haze are limiting factors in producing accurate regression equations to predict water clarity and are why imagery should be chosen on clear satellite-overpass days (Olmanson and others, 2008). Measurements were omitted if information was available to determine that measured SDTs were more than two-thirds the lake depth (which occurs

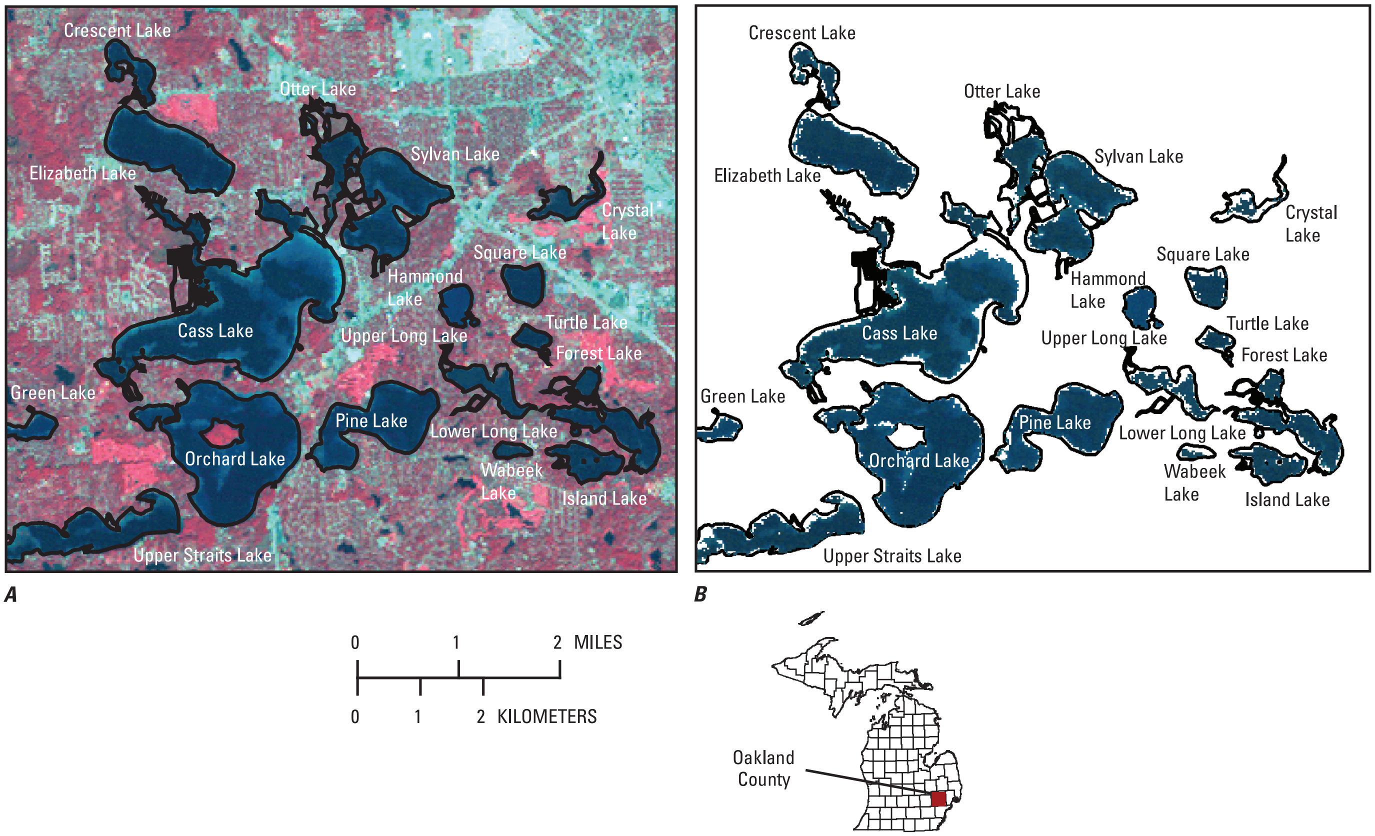


Figure 2. Landsat path 20 satellite image for September 22, 2004, in Oakland County, Michigan, for ***A***, before satellite-data processing and ***B***, after satellite-data processing.

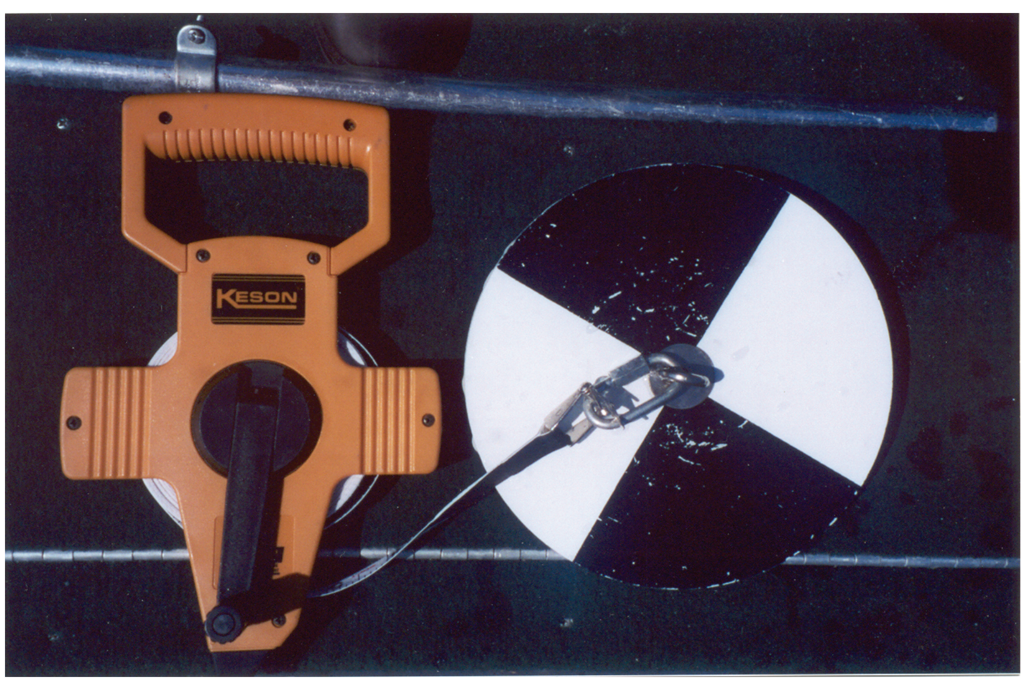


Figure 3. Example of Secchi disk used to measure water clarity in lakes.

mostly in shallow lakes), because of possible interference from the lake bottom.

Occasionally, latitude and longitude locations of measurements plotted outside the lake. In these circumstances, the coordinates were changed to correspond to the deepest location if a bathymetric map was available. If a bathymetric map could not be located, the measurement was omitted. Some lakes did not have latitude and longitude for measurements, nor could accurate bathymetric maps be located; these measurements were omitted. Table 3 summarizes measurements per Landsat-satellite scene.

Relating Field Data to Landsat-Satellite Imagery

The field SDT measurements were related to the Landsat-satellite imagery by using the AOI method documented in Fuller and others (2004) and an alternative Gethist method that selects a portion of the open-water areas remaining after satellite-data processing (as documented in Olmanson and others, 2001). Mean values for each band in the Landsat-satellite imagery then were used in two equations (differing in the bands used) to produce statewide TSI (SDT) predictions for 2003–05 and 2007–08.

AOI Method To Select Open-Water Areas

AOIs containing approximately nine cells were established around each measurement, and the average band values were recorded. Taking an average for each band in its AOI was found to smooth the radiometric noise and to produce more accurate predicted SDT 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 path or scene of Landsat-satellite data.

Gethist Method To Select Open-Water Areas

The open-water areas remaining after satellite-data processing for lakes greater than 20 acres were used in the Gethist program documented in Olmanson and others (2001). The Gethist program further reduced the remaining areas in each lake to identify the darkest pixels that should represent deeper open water. Specifications were set to ignore zeros, use 50 percent of the histogram, and use the bottom N percent pixels to represent the darkest pixels. The Gethist program returned mean values for each band of the Landsat-satellite imagery for each inland lake. The output was used in a statistical analysis program to produce regression equations specific to each path of satellite data.

Trophic State Index Calculation for SDT

Tibco Spotfire S+ 8.1 software was used for multiple regression calculations for each path. The equation documented in Fuller and others (2004) was applied to each path of satellite data for both the AOI and the Gethist method:

$$\ln(\mathrm{SDT}) = a(\mathrm{band1}) + b(\mathrm{band2}) + c(\mathrm{band3}) + d \quad (1)$$

The resulting equation used the natural log of SDT for the dependent variable, and the independent variables were bands 1, 2, and 3.

The equation used in Olmanson and others (2001) and Kloiber and others (2002) was applied to each path of satellite data for both the AOI and the Gethist method:

$$\ln(\mathrm{SDT}) = a(\mathrm{band1}/\mathrm{band3}) + b(\mathrm{band1}) + c \quad (2)$$

The natural log of SDT was the dependent variable, and the independent variables were a ratio of band 1 and 3, and band 1. The variables a, b, and c were derived coefficients from the regression equation.

TSI values then could be computed on the natural log of the SDT images derived previously using the equation from Carlson (1977).

The measured TSI (SDT) and SDT values were compared to the predicted TSI (SDT) and SDT values from equations 1 and 2. Results for both 2003–05 and 2007–08, by path, are listed in table 3. For the 2003–05 years, path 21, row 28 did not have an adequate number of measurements available during the Landsat-satellite imagery-acquisition date, so the regression equation from path 21, rows 29 to 31 was applied to that Landsat-satellite scene. A comparison (as percentages) for both sets of years of data using both methods and equations to measured TSI (SDT) and SDT is presented in table 4. Scatterplots with R^2 values are shown on figures 4*A* and 4*B* for 2003–05 and 2007–08, respectively, for all measured values of TSI (SDT) and SDT for the AOI lake-average method and the Gethist method generated by use of equations 1 and 2. Scatterplots comparing the predicted TSI (SDT) for all lakes with desirable pixels from 2003–05 and 2007–08 are shown for equations 1 and 2 on figure 5. The predicted paths were merged together to produce statewide 2003–05 and 2007–08 predictions on figures 6*A* and 6*B*, respectively. Appendixes 1 and 2 list the measurements used for the regression equations.

Table 3. Landsat-image and calibration-model data for Michigan inland lakes, 2003–05 and 2007–08.

[SDT, Secchi–disk transparency; AOI, area of interest; R^2, coefficient of determination; SEE, Standard Error of Estimate; TM, Thematic Mapper; <, less than]

Image date	Path	Rows	Number of images	Satellite	Percent cloud cover	Days prior	Days past	Number of measure-ments	SDT range (m)	SDT range (ft)	R^2	SEE	Number of lakes assessed	Equation 1	R^2	SEE	Equation 2
2003–05 SDT AOI																	
9/22/2004	20	30–31	2	Landsat TM 5	< 10	6	4	20	1.5–7.3	5.0–24.0	0.72	0.227	573	x = B1(0.0190) + B2(0.1355) + B3(–0.5709) + 4.6406	0.67	0.240	x = B1/B3(1.4334) + B1(–0.0339) + –3.2019
9/13/2004	21	*28–31	4	Landsat TM 5	< 10	8	6	72	0.8–8.5	2.5–28.0	0.70	0.244	1597	x = B1(0.0976) + B2(–0.0690) + B3(–0.2452) + 0.7801	0.66	0.258	x = B1/B3(1.1820) + B1(0.0035) + –3.4462
9/20/2004	22	28–31	4	Landsat TM 5	< 10	7	6	49	0.9–5.9	3.0–19.0	0.72	0.194	1368	x = B1(0.0210) + B2(0.0482) + B3(–0.3498) + 3.0269	0.69	0.202	x = B1/B3(0.7531) + B1(–0.0326) + –0.7185
9/21/2005	24	27	1	Landsat TM 5	< 10	0	5	10	2.0–5.3	6.5–17.5	0.67	0.227	72	x = B1(0.2464) + B2(–0.1678) + B3(–0.2477) + –4.7251	0.66	0.217	x = B1/B3(1.0829) + B1(0.1590) + –10.4585
7/19/2005	24	28	1	Landsat TM 5	< 10	0	6	15	2.1–6.7	7.0–22.0	0.72	0.188	463	x = B1(0.0343) + B2(–0.1110) + B3(–0.3256) + 5.3142	0.66	0.198	x = B1/B3(0.9666) + B1(–0.0910) + 1.7341
8/22/2003	25	28	1	Landsat TM 5	< 10	10	6	12	6.0–20.5	1.8–6.3	0.55	0.310	172	x = B1(0.0491) + B2(0.2245) + B3(–0.3501) + –0.5287	0.45	0.325	x = B1/B3(0.7459) + B1(0.0326) + –3.2937
2003–05 SDT Gethist																	
9/22/2004	20	30–31	2	Landsat TM 5	< 10	6	4	22	1.5–7.3	5.0–24.0	0.78	0.220	573	x = B1(0.0198) + B2(0.2138) + B3(–0.7569) + 5.2799	0.73	0.238	x = B1/B3(1.6413) + B1(–0.0196) + –4.8612
9/13/2004	21	*28–31	4	Landsat TM 5	< 10	8	6	75	0.8–8.5	2.5–28	0.72	0.233	1597	x = B1(0.1112) + B2(–0.0496) + B3(–0.3008) + 0.4164	0.69	0.243	x = B1/B3(1.3398) + B1(0.0104) + –4.4821
9/20/2004	22	28–31	4	Landsat TM 5	< 10	7	6	50	0.9–5.9	3–19.0	0.74	0.187	1368	x = B1(0.0159) + B2(0.0898) + B3(–0.4580) + 3.5664	0.72	0.192	x = B1/B3(0.8592) + B1(–0.0380) + –1.0662
1/11/1900	24	27	1	Landsat TM 5	< 10	0	5	10	2.0–5.3	6.5–17.5	0.73	0.207	72	x = B1(0.2417) + B2(–0.0502) + B3(–0.4146) + –4.4840	0.73	0.194	x = B1/B3(1.1798) + B1(0.1401) + –10.0580
7/19/2005	24	28	1	Landsat TM 5	< 10	0	6	15	2.1–6.7	7.0–22.0	0.77	0.205	463	x = B1(0.0883) + B2(0.2556) + B3(–0.5212) + –1.4099	0.73	0.214	x = B1/B3(0.7688) + B1(0.1562) + –9.6935
8/22/2003	25	28	1	Landsat TM 5	< 10	10	6	12	6.0–20.5	1.8–6.3	0.68	0.262	172	x = B1(0.1840) + B2(0.0937) + B3(–0.4114) + –4.0418	0.65	0.256	x = B1/B3(1.1529) + B1(0.0945) + –7.8513

Table 3. Landsat-image and calibration-model data for Michigan inland lakes, 2003–05 and 2007–08.—Continued

[SDT, Secchi–disk transparency; AOI, area of interest; R^2, coefficient of determination; SEE, Standard Error of Estimate; TM, Thematic Mapper; <, less than]

Image date	Path	Rows	Number of images	Satellite	Percent cloud cover	Days prior	Days past	Number of measure-ments	SDT range (m)	SDT range (ft)	R^2	SEE	Number of lakes assessed	Equation 1	R^2	SEE	Equation 2
2007–08 SDT AOI																	
8/30/2007	20	30–31	2	Landsat TM 5	< 10	6	3	18	1.8–4.9	6.0–16.0	0.75	0.155	506	x = B1(0.1320) + B2(–0.0021) + B3(–0.4418) + 0.2371	0.74	0.155	x = B1/B3(1.4583) + B1(0.0176) + –5.4392
9/22/2007	21	28–31	3	Landsat TM 5	< 10	7	0	68	0.8–6.7	2.5–22.0	0.69	0.205	1603	x = B1(0.0379) + B2(0.0366) + B3(–0.4568) + 4.0436	0.66	0.213	x = B1/B3(1.2140) + B1(–0.0544) + –1.2159
6/25/2007	22	28	1	Landsat TM 5	< 10	0	3	15	2.4–6.4	8.0–21.0	0.70	0.182	349	x = B1(0.0810) + B2(0.0499) + B3(–0.2736) + –0.2435	0.74	0.162	x = B1/B3(1.1476) + B1(0.0164) + –4.0149
9/13/2007	22	29–31	3	Landsat TM 5	< 10	5	7	56	2.5–23.0	0.8–7.0	0.73	0.205	892	x = B1(0.0844) + B2(–0.1191) + B3(–0.1500) + 1.0328	0.63	0.236	x = B1/B3(0.8629) + B1(0.0000) + –2.2677
8/3/2007	23	28	1	Landsat TM 5	< 10	0	5	15	2.9–6.1	9.5–20.0	0.74	0.121	464	x = B1(0.1313) + B2(–0.0065) + B3(–0.1344) + –3.5666	0.71	0.122	x = B1/B3(0.3908) + B1(0.0915) + –4.9307
7/27/2008	24	27–28	2	Landsat TM 5	< 10	0	4	17	2.1–5.0	6.8–16.4	0.67	0.154	432	x = B1(0.0694) + B2(0.0070) + B3(–0.0852) + –1.7354	0.73	0.134	x = B1/B3(0.4388) + B1(0.0485) +–3.3596
8/3/2008	25	28	1	Landsat TM 5	< 10	0	3	14	1.7–7.3	5.5–24.0	0.79	0.233	168	x = B1(–0.0992) + B2(–0.2703) + B3(0.1156) + 10.7408	0.65	0.290	x = B1/B3(0.0025) + B1(–0.1497) + 9.9124
2007–08 SDT Gethist																	
8/30/2007	20	30–31	2	Landsat TM 5	< 10	6	3	18	1.8–4.9	6.0–16.0	0.72	0.165	506	x = B1(0.1810) + B2(0.0617) + B3(–0.6804) + –0.5065	0.72	0.159	x = B1/B3(2.1944) + B1(0.0401) + –9.6437
9/22/2007	21	28–31	3	Landsat TM 5	< 10	7	0	72	0.8–7.0	2.5–23.0	0.76	0.182	1603	x = B1(0.0117) + B2(0.1001) + B3(–0.5401) + 5.0105	0.75	0.183	x = B1/B3(1.3083) + B1(–0.0631) + –1.2937
6/25/2007	22	28	1	Landsat TM 5	< 10	0	3	15	2.4–6.4	8.0–21.0	0.73	0.174	349	x = B1(0.0569) + B2(0.0919) + B3(–0.2803) + 0.4328	0.74	0.161	x = B1/B3(1.0580) + B1(0.0103) + –3.3394
9/13/2007	22	29–31	3	Landsat TM 5	< 10	5	7	56	2.5–23.0	0.8–7.0	0.72	0.207	892	x = B1(0.0811) + B2(–0.0860) + B3(–0.1948) + 1.1367	0.67	0.223	x = B1/B3(0.9800) + B1(–0.0046) + –2.5253
8/3/2007	23	28	1	Landsat TM 5	< 10	0	5	15	2.9–6.1	9.5–20.0	0.67	0.135	464	x = B1(0.1308) + B2(0.0088) + B3(–0.1204) + –3.8703	0.67	0.130	x = B1/B3(0.3153) + B1(0.1069) + –5.2894
7/27/2008	24	27–28	2	Landsat TM 5	< 10	0	4	18	2.1–5.6	6.8–18.3	0.68	0.173	432	x = B1(0.0289) + B2(0.1545) + B3(–0.1423) + –1.3854	0.68	0.166	x = B1/B3(0.4080) + B1(0.0512) + –3.3810
8/3/2008	25	28	1	Landsat TM 5	< 10	0	3	14	1.7–7.3	5.5–24.0	0.81	0.224	168	x = B1(0.1929) + B2(–0.3452) + B3(–0.2916) + 1.9305	0.73	0.256	x = B1/B3(1.6371) + B1(–0.0239) + –3.3531

[*] No in–situ measurements available in Path 22 Row 28.

Table 4. Results comparing methods using equations 1 and 2 for 2003–05 and 2007–08 in percent for measured Secchi-disk transparency values within 2, 5, and 10 feet of the predicted Secchi-disk transparency; and percent for measured Trophic State Index values within 2, 5, and 10 units of the predicted Trophic State Index values for Michigan inland lakes.

[SDT, Secchi-disk transparency; TSI, Trophic State Index; AOI, area of interest; Eq, equation; LakeAve, Lake average; all data are in percent]

	2 SDT feet	**5 SDT feet**	**10 SDT feet**	**2 TSI units**	**5 TSI units**	**10 TSI units**	**Correct TSI Class**
2003–05							
AOIEq1	63	93	100	50	94	100	77
LakeAveAOIEq1	51	81	97	39	72	96	64
GethistEq1	68	97	100	54	98	100	79
AOIEq2	69	95	100	45	89	100	76
LakeAveAOIEq2	56	85	99	37	73	97	68
GethistEq2	68	96	100	48	95	100	78
2007–08							
	2 SDT feet	**5 SDT feet**	**10 SDT feet**	**2 TSI units**	**5 TSI units**	**10 TSI units**	**Correct TSI Class**
AOIEq1	77	97	100	61	100	100	81
LakeAveAOIEq1	55	88	99	43	79	97	73
GethistEq1	76	97	100	65	97	100	85
AOIEq2	74	97	100	59	94	100	79
LakeAveAOIEq2	67	90	100	51	83	99	77
GethistEq2	75	97	100	75	98	100	86

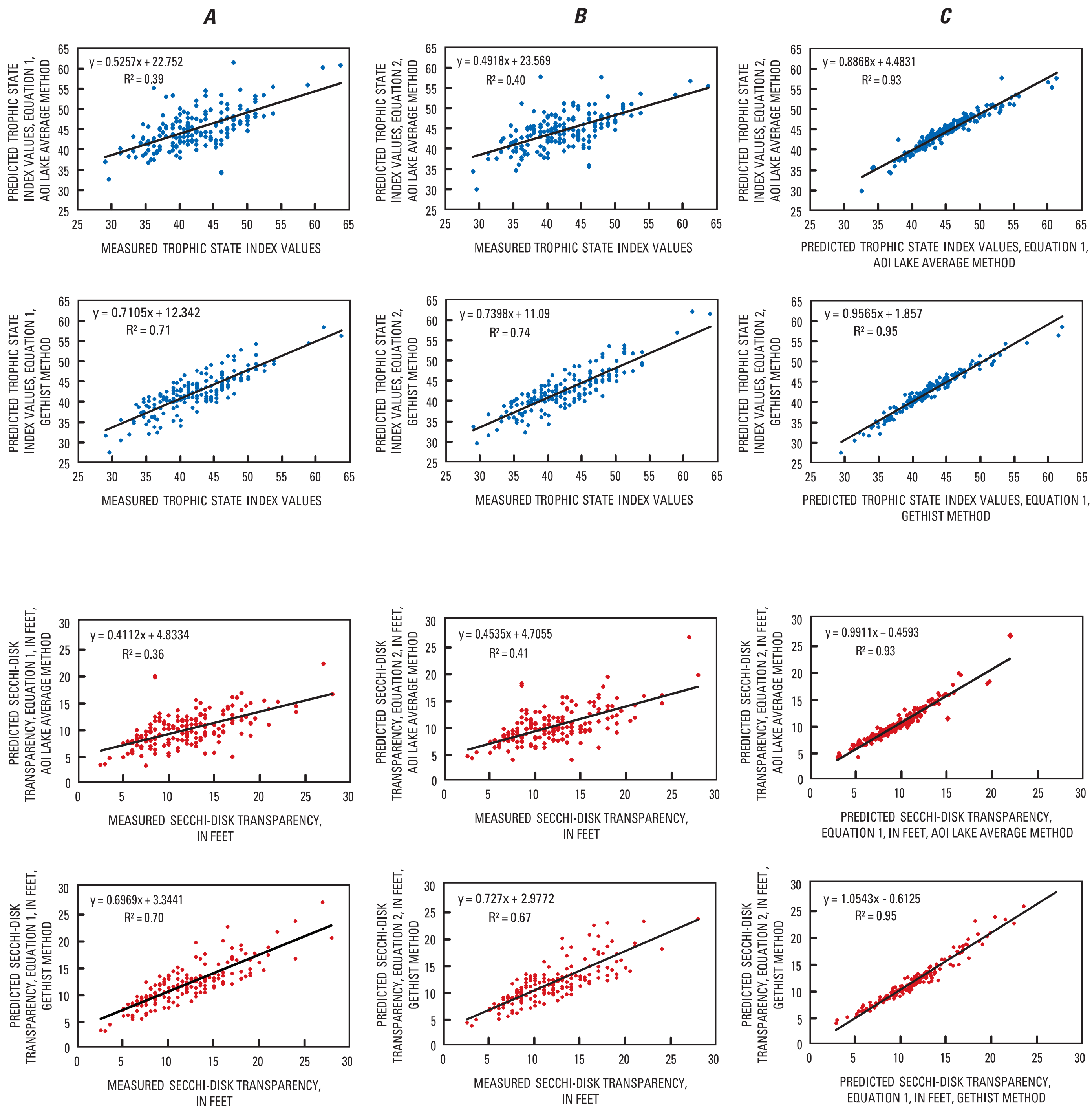


Figure 4*A*. Scatterplots for 2003–05 of *A,* Michigan measured Trophic State Index (TSI) values and Secchi-disk transparency (SDT) values, in feet, to predicted TSI and SDT values using equation 1 for both the area of interest (AOI) lake-average method and the Gethist method; *B,* measured TSI values and SDT values, in feet, to predicted TSI and SDT values using equation 2 for both the AOI lake-average method and the Gethist method; and *C,* predicted TSI and SDT values using equation 1 to predicted TSI and SDT values using equation 2.

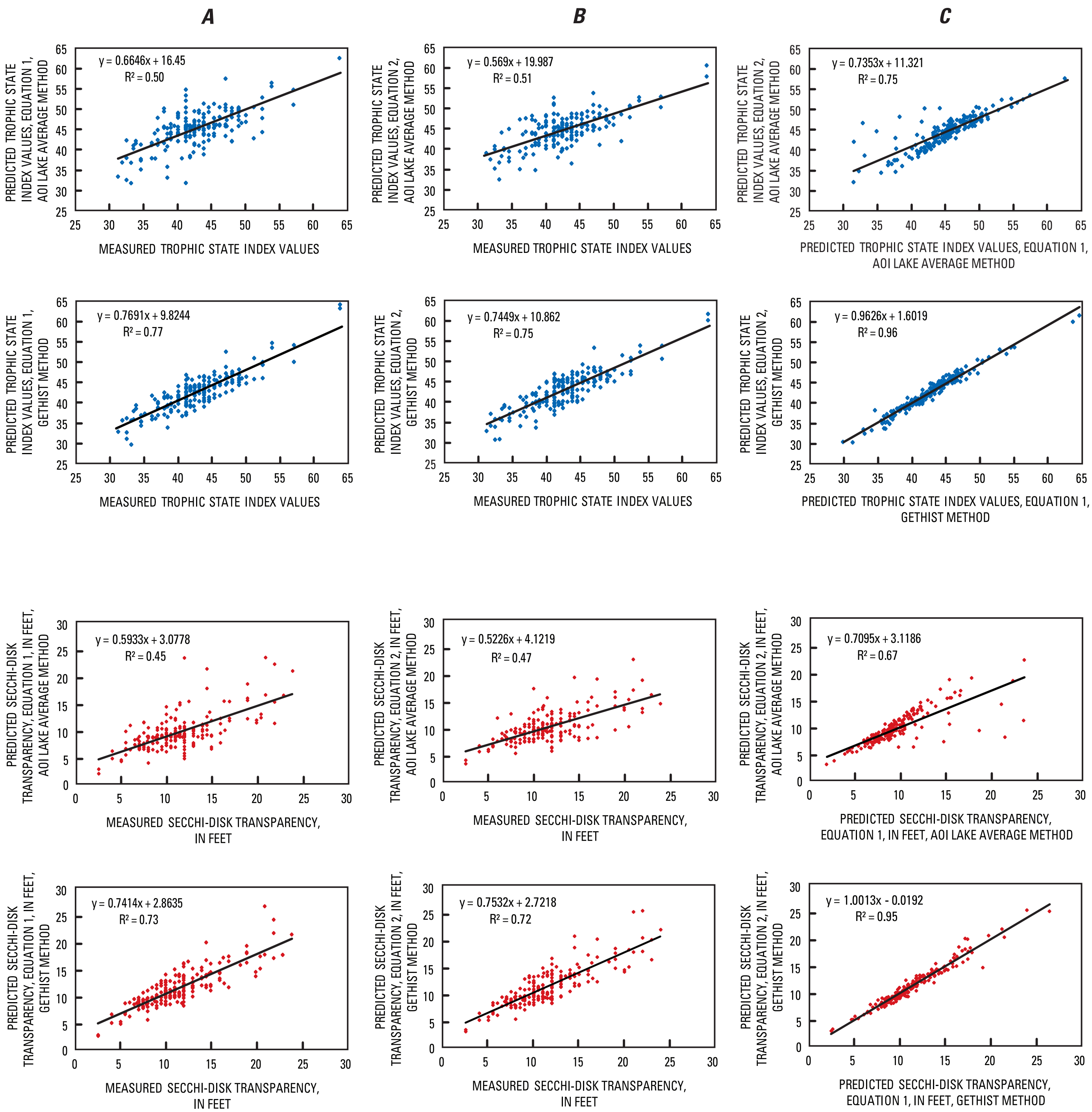


Figure 4*B*. Scatterplots for 2007–08 of *A,* Michigan measured Trophic State Index (TSI) values and Secchi-disk transparency (SDT) values, in feet, to predicted TSI and SDT values using equation 1 for both the area of interest (AOI) lake-average method and the Gethist method; *B,* measured TSI values and SDT values, in feet, to predicted TSI and SDT values using equation 2 for both the AOI lake-average method and the Gethist method; and *C,* predicted TSI and SDT values using equation 1 to predicted TSI and SDT values using equation 2.

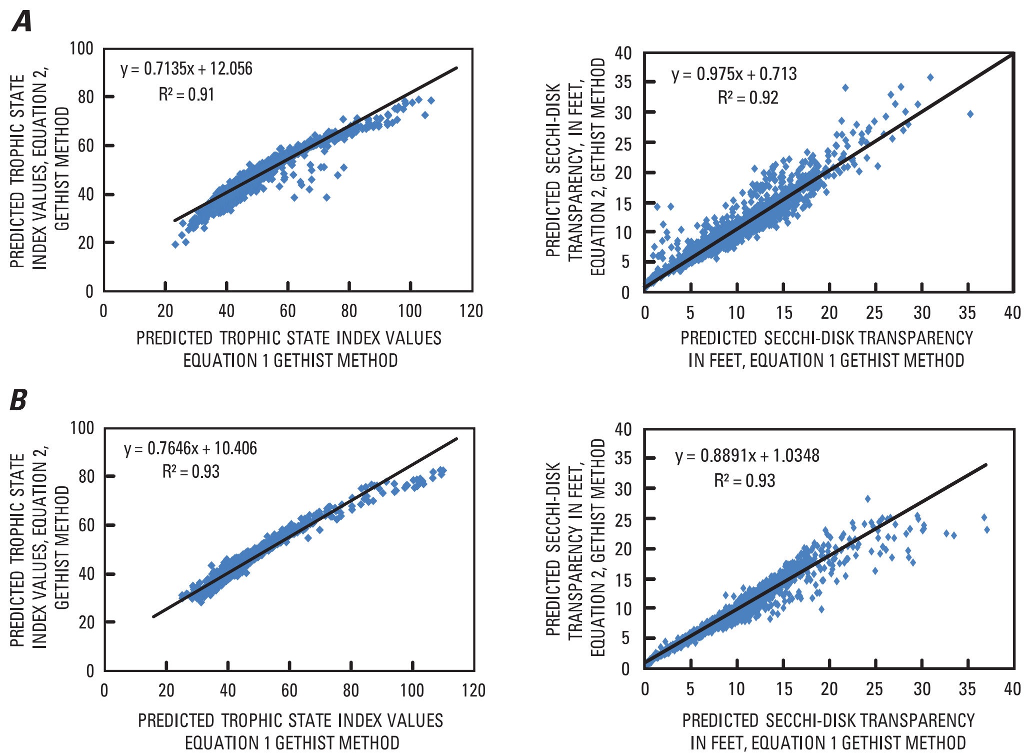


Figure 5. Scatterplots of ***A***, 2003–05 and ***B***, 2007–08 for Michigan inland lakes greater than 20 acres with available open-water areas for statewide predicted Trophic State Index values and Secchi-disk transparency, in feet, using the Gethist method for equations 1 and 2.

Regression Equations and Tests of Significance

Fisher's Transformation (Yamane, 1973) was used to test the difference of two correlation coefficients to determine whether there was a statistically significant difference between the AOI lake-average method and the Gethist method, and also between equations 1 and 2. The square root of the R^2 values was used for Fisher's Transformation of R. Results of Fisher's Transformation (tables 5 and 6) higher than 2.579 mean that differences were statistically significant at the 99-percent confidence level, whereas those lower than 1.96 mean that differences were not statistically significant even at the 95-percent confidence level.

Results

Fourteen Landsat 5 satellite scenes were processed to produce two statewide predicted TSI (SDT) and SDT layers for Michigan inland lakes. One scene—path 23, row 28 in the 2003–05 period—did not have an adequate number of field measurements remaining after removing lakes effected by clouds, cloud shadows, and haze to produce a regression equation. Although approximately 20 field measurements within each Landsat-satellite scene are desirable, fewer measurements were available for a few scenes, especially in the Upper Peninsula. Even so, the R^2 values from the resulting regression equations were still comparable to those for other satellite paths. All 14 Landsat-satellite scenes had coverage for 2007–08. Whereas Landsat-satellite scenes are selected on the basis of their low cloud cover, predictions could not be made for all lakes greater than 20 acres for every statewide time period because some lakes lacked a large enough remaining open-water area after the satellite-data processing.

Landsat-Satellite Imagery Data-Processing Improvements

Improvements to the satellite-data processing included how lakes are selected and how selected areas are determined. First, lakes were selected by masking known lake-polygon locations, as per the approach of Breck (2004); this ensured that all lakes greater than 20 acres had representation. Previous methods in Fuller and others (2004) did not ensure that all lakes would be selected. Second, a Normalized Difference Vegetation Index was used to remove vegetated areas, which assisted in the removal of shoreline, islands, and shallow vegetated areas within the lake-polygon locations. Third, an unsupervised classification was run to further remove shallow, vegetated, and cloud areas. Finally, the image was viewed in a band 1, 6, 6 (mapping the blue band onto band 1, and bands 6 onto the green and red bands, respectively) combination to identify haze and remove affected lakes or portions of lakes.

Comparison of the AOI Lake-Average Method and the Gethist Method

The measured and predicted TSI (SDT) and SDT compared well between the AOI lake average and Gethist methods; however, the R^2 values and also the percent of lakes predicting close to the measured values were lower for the AOI lake-average method. To allow application of the regression equation, a method from Fuller and others (2004) averaged all areas remaining in each lake after satellite-data processing, because all deep-basin locations or open-water areas are not known for all inland lakes greater than 20 acres. The AOI lake-average method lowered the percentage of lakes within 2 and 5 TSI (SDT) units or 2 and 5 SDT, in feet (table 4). This difference also can be seen in figures 4*A* and 4*B* with scatterplots and R^2 values showing the strength of the relation between the AOI lake-average and Gethist methods. For 2003–05, the measured to predicted TSI (SDT) AOI lake-average method returned R^2 values of 0.39 and 0.40 using equations 1 and 2, respectively (0.50 and 0.51 R^2 for 2007–08), and the Gethist method returned R^2 values of 0.71 and 0.74 using equations 1 and 2, respectively (0.77 and 0.75 R^2 for 2007–08). Similar comparisons were found for the measured and predicted SDT.

Fisher's Transformation was used to determine whether there was a statistically significant difference between the AOI lake-average and Gethist methods. Table 5 illustrates that for both 2003–05 and 2007–08, using either equation 1 or 2, there was a statistically significant difference at the 99-percent confidence level.

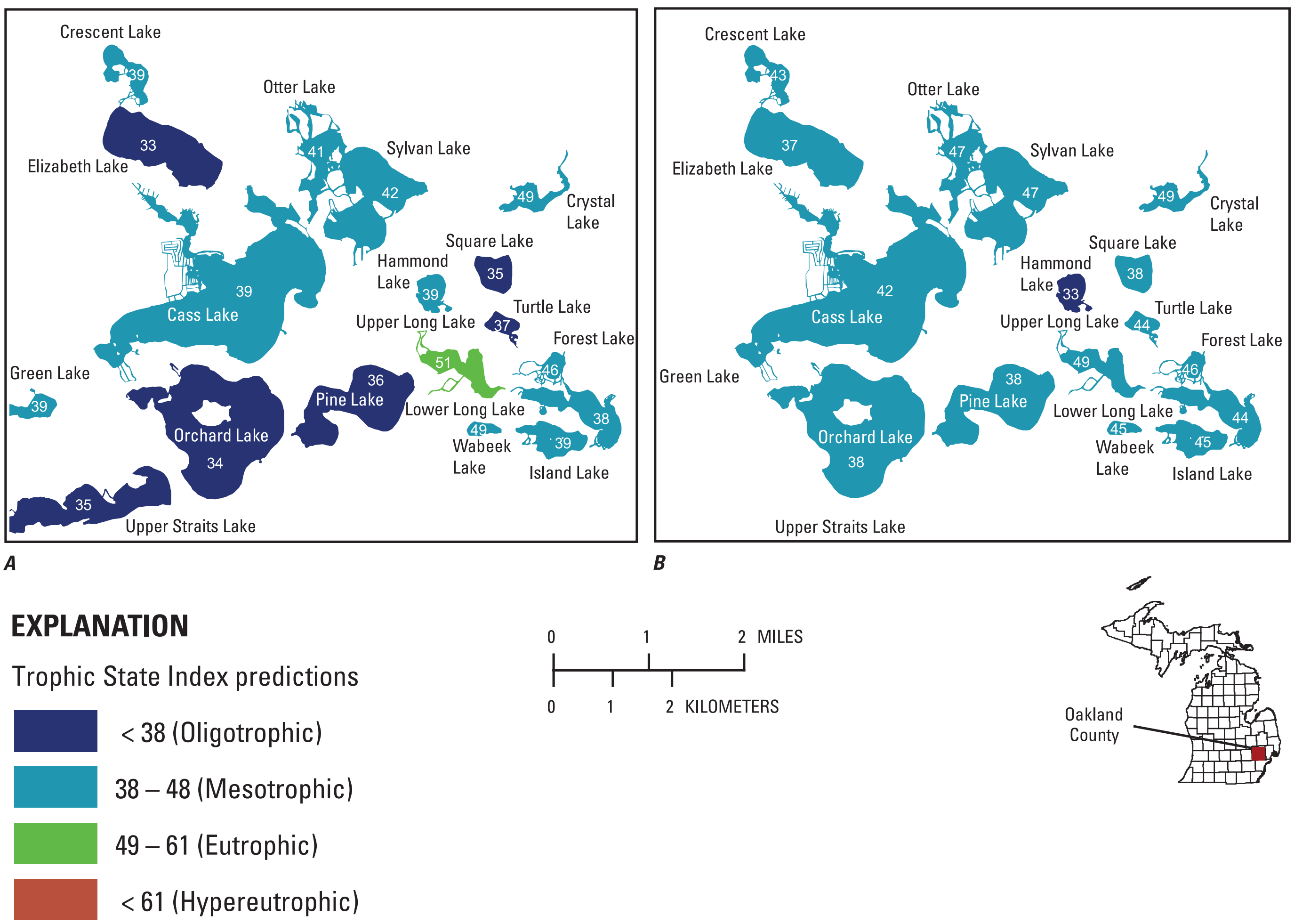


Figure 6. Landsat path 20, in Oakland County, Michigan, for ***A***, Predicted Trophic State Index values for Michigan inland lakes 2003–05 and ***B***, Predicted Trophic State Index values for Michigan inland lakes 2007–08

Comparison of Equations 1 and 2

The R^2 values for the regression equations to predict TSI (SDT) and SDT for 2003–05 and 2007–08 using the Gethist method were similar for equations 1 and 2. Fisher's Transformation was used to determine whether there was a statistically significant differences between equations 1 and 2 using the Gethist method. Table 6 illustrates that there was no statistically significant difference at the 95-percent confidence level between equations 1 and 2 using the Gethist method.

When the predicted TSI (SDT) and SDT values for the subset of lakes with measurements were plotted in a scatterplot for equations 1 and 2, the R^2 value for 2003–05 was 0.95 and for 2007–08 was 0.96. When the regression predictions were extended to all lakes greater than 20 acres with open-water areas, the R^2 values decreased slightly to 0.91 for 2003–05 and 0.93 for 2007–08. Although the relation is still strong, the scatterplots in figure 5 show that equation 1 can predict higher TSI values. This discrepancy between the two predicted datasets starts around a TSI of 60, which corresponds to the hypereutrophic category. Although the majority of lakes do not change trophic-state categories between the equations, the TSI values are different. Similarly, when comparing the predicted SDT between equations 1 and 2, equation 2 predicts higher SDT (lower TSI), starting around 20 ft and greater, than equation 1. Whereas inland lakes with an SDT greater than 15 ft all would be classified in the oligotrophic category, the actual TSI values from the two equations can differ.

Unfortunately, there are only 10 out of 184 measurements for 2003–05 and 12 out of 208 measurements for 2007–08 with SDT values greater than 20 ft (TSI < 34) and greater than 60 TSI units (SDT < 3.5 ft) for 2003–05. Measurements that do fall within these ranges show no pattern for overpredicting in either range of values. The difference between the equations is beyond the range of lakes with available data.

The relation between equations 1 and 2 is strong for measured and predicted TSI (SDT) and SDT; however, for ease of comparison for predicted TSI (SDT) or SDT values between Minnesota and Wisconsin, and also for future trend analysis that might focus solely on the predicted TSI (SDT) or SDT values, equation 2 will be used for 2003–05, 2007–08, and future statewide predictions. The count and percentage for measured and predicted TSI (SDT) for equations 1 and 2 by Trophic State class can be found in table 7.

Table 5. Predicted Trophic State Index and Secchi-disk transparency results for Fisher's Transformation Significance Tests for Michigan inland lakes, 2003–05 and 2007–08.

[TSI, Trophic State index; AOI, areas of interest; R^2, coefficient of determination; SDT, Secchi-disk transparency]

	AOI lake average R^2	Gethist R^2	Fisher's Transformation*
TSI			
2003–05, Equation 1	0.39	0.71	4.70
2003–05, Equation 2	0.40	0.74	5.18
2007–08, Equation 1	0.50	0.77	4.56
2007–08, Equation 2	0.51	0.75	3.97
SDT			
2003–05, Equation 1	0.36	0.70	4.87
2003–05, Equation 2	0.41	0.67	3.71
2007–08, Equation 1	0.45	0.73	4.34
2007–08, Equation 2	0.47	0.72	3.88

* Fisher's Transformation values greater than 2.576 are statistically significant at the 99-percent confidence interval.

Table 6. Comparison of Predicted Trophic State Index and Secchi-disk transparency results for equations 1 and 2 using Fisher's Transformation Significance Tests for Michigan inland lakes, 2003–05 and 2007–08.

[TSI, Trophic State index; R^2, coefficient of determination; SDT, Secchi-disk transparency]

	Equation 1 R^2	Equation 2 R^2	Fisher's Transformation*
2003–05 Gethist TSI	0.71	0.74	0.60
2003–05 Gethist SDT	0.77	0.75	0.45
	Equation 1 R^2	**Equation 2 R^2**	**Fisher's Transformation***
2007–08 Gethist TSI	0.70	0.67	0.53
2007–08 Gethist SDT	0.73	0.72	0.20

* Fisher's Transformation values greater than 1.96 are statistically significant at the 95-percent confidence interval.

Summary and Conclusions

Michigan has more than 11,000 inland lakes, and their sheer number poses a physical and economical problem for collection of data needed to compute a statewide Trophic State Index (TSI). Volunteers with the Michigan Department of Natural Resources and Environment (MDNRE) Cooperative Lake Monitoring Program (CLMP) and field technicians of the U.S. Geological Survey (USGS) monitor selected lakes each year. An economical and feasible tool to expand the use of the sampling data is to relate Secchi-disk transparency (SDT) measurements to Landsat-satellite imagery with regression equations. These regression equations then can be applied to Landsat-satellite imagery to produce predicted statewide TSI (SDT) values for unmeasured open-water areas of inland lakes.

The purpose of this publication is to describe a refinement of methods originally published in Fuller and others (2004); the goal of the refinement was to produce a statewide predicted TSI for Michigan inland lakes that is more representative of the open-water area than was possible previously. The methods used in the refinement are (1) techniques used for processing Landsat-satellite imagery to identify open-water areas in lakes, (2) comparison of two methods— the area of interest (AOI) lake-average method and the Gethist method (Olmanson and others, 2001)—to return a single predicted TSI representing the open-water area of lakes, and (3) comparison of two equations from Fuller and others (2004) to equations from Olmanson and others (2001) and Kloiber and others (2002) to ascertain which equation produces predictions most reflective of measured values.

The satellite-data processing technique used to select inland lakes ensures that all inland lakes greater than 20 acres from the Michigan lake polygons shapefile (Breck, 2004) will be included unless intentionally removed during further data evaluation and processing. Running a Normalized Difference Vegetated Index on the pixels within the inland lake shapefile aided in the removal of vegetated pixels associated with shoreline, islands, or shallow water. An unsupervised classification then was run to further remove clouds and shallow water. Together, these satellite-data processing techniques did a better job than previous techniques to remove lake areas that would confound regression analysis and to better confine the dataset to unobscured open-water areas suitable for analysis.

Incorporating the Gethist image-processing method provided R^2 values more comparable to the R^2 values from the AOI areas used to produce the regression equations from Fuller and others (2004). Even though the Gethist areas were,

Table 7. Count and percent of measured and statewide predicted Trophic State classes for Michigan inland lakes, 2003–05 and 2007–08.

[TSI, Trophic State Index]

	Oligotrophic	Mesotrophic	Eutrophic	Hypereutrophic
2003–05				
Measured TSI count	36	122	25	1
Statewide predicted equation 1 count	184	1,979	759	199
Statewide predicted equation 2 count	245	2,014	757	105
Measured TSI percent	19.6	66.3	13.6	0.5
Statewide predicted equation 1 percent	5.9	63.4	24.3	6.4
Statewide predicted equation 2 percent	7.9	64.5	24.3	3.4
2007–08				
	Oligotrophic	**Mesotrophic**	**Eutrophic**	**Hypereutrophic**
Measured TSI count	30	155	21	2
Statewide predicted equation 1 count	208	2,247	474	95
Statewide predicted equation 2 count	213	2,242	499	70
Measured TSI percent	14.4	74.5	10.1	1.0
Statewide predicted equation 1 percent	6.9	74.3	15.7	3.1
Statewide predicted equation 2 percent	7.0	74.1	16.5	2.3

on average, larger than the AOI areas used previously to produce the regression equations, the Gethist method provided higher R^2 values than the AOI lake-average method, which was used to apply the regression equations previously created using the AOI areas from Fuller and others (2004). The larger benefit is that the Gethist method can be applied to all lakes and does not require knowledge of the deep open-water areas, thus providing a predicted TSI (SDT) result more reflective of the deep open-water areas for unsampled inland lakes in Michigan.

Another benefit of the Gethist method is that it does not require the analyst to know the lake-measurement location. Unlike with the AOI method, measurements do not need to be removed from the analytical dataset if they do not have a corresponding latitude and longitude or if a bathymetric map is unavailable to estimate the measurement location. The Gethist method outputs the average band values for each lake in the Landsat-satellite imagery. The average band values reflect a reduced area representing the darkest values from the areas identified after satellite-data processing. The resulting average band values from the Gethist method then are related to available SDT measurements in the Landsat-satellite scenes. Predicted TSI (SDT) for inland lakes with field measurements using the Gethist method and equation 1 from Fuller and others (2004) compared well with equation 2 found in Olmanson and others (2001) and Kloiber and others (2002). There was no statistically significant difference at the 95-percent confidence level between results from the two equations for either dataset.

Comparison of predicted TSI (SDTs) for the subset of lakes with field measurements in 2003–05 and 2007–08 resulted in R^2 values of 0.95 and 0.96, respectively. When the statewide predicted TSI (SDTs) were applied to all lakes greater than 20 acres without interference from clouds, cloud shadows, haze, or dense vegetation using equations 1 and 2, the R^2 values were 0.91 for 2003–05 and 0.93 for 2007–08. Although this is still a strong relation indicating minimal differences in results, equation 1 nevertheless predicts higher than equation 2 for TSI values greater than 60 (SDT $<$ 3.5 ft) and lower for SDT values greater than 20 ft (TSI $<$ 34). The few measurements available in these high and low ranges did not reflect the pattern for overpredicting and underpredicting, and measurements were not available at the far extremes on either side to provide insight. Although the lakes still predicted to the correct trophic state category, the predicted TSI (SDT) and SDT values were different at the extreme ends of the TSI scale. For ease of comparison between Minnesota and Wisconsin statewide predictions, and also for future trend analysis that might focus solely on the predicted TSI (SDT) or SDT values, equation 2 is planned to be used for 2003–05 and 2007–08 and future statewide predictions.

References Cited

Baban, S.M.J., 1993, Detecting water quality parameters in the Norfolk Broads, UK, using Landsat imagery: International Journal of Remote Sensing, v. 14, no. 7, p. 1,247–1,267.

Breck, James, 2004, Michigan lake polygons: Michigan Department of Natural Resources and Environment, Fisheries Division, Institute for Fisheries Research, accessed December 2008 at *http://www.mcgi.state.mi.us/mgdl/?rel=thext&action=thmname&cid=3&cat=Lake+Polygons*.

Canfield, D.E., Jr., Brown, C.D., Bachmann, R.W., and Hoyer, M.V., 2002, Volunteer lake monitoring—Testing the reliability of data collected by the Florida LAKEWATCH Program: Lake and Reservoir Management, v. 18, no. 1, p. 1–9.

Carlson, R.E., 1977, A trophic state index for lakes: Limnology and Oceanography, v. 22, p. 361–369.

Chipman, J.W., Lillesand, T.M., Schmaltz, J.E., Leale, J.E., and Nordheim, M.J., 2004, Mapping lake water clarity with Landsat images in Wisconsin, USA: Canada Journal of Remote Sensing, v. 30, p. 1–7.

Dekker, A.G., and Peters, S.W.M., 1993, The use of the Thematic Mapper for the analysis of eutrophic lakes—A case study in the Netherlands: International Journal of Remote Sensing, v. 4, no. 5, p. 799–821.

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 Survey Scientific Investigations Report 2004–5086, 44 p. (also available at *http://pubs.usgs.gov/sir/2004/5086/*).

Fuller, L.M., and Minnerick, R.J., 2007, Predicting water quality by relating Secchi-disk transparency and chlorophyll *a* measurements to Landsat satellite imagery for Michigan inland lakes, 2001–06: U.S. Geological Survey Fact Sheet 2007–3022, 4 p., available online at *http://pubs.usgs.gov/fs/2007/3022/*.

Fuller, L.M., and Minnerick, R.J., 2008, State and regional water-quality characteristics and trophic conditions of Michigan's inland lakes, 2001–2005: U.S. Geological Survey Scientific Investigations Report 2008–5188, 58 p. (also available at *http://pubs.water.usgs.gov/sir20085188/)*.

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.

Jensen, J.R., 2007, Remote sensing of the environment—An earth resource perspective (2d ed.): Upper Saddle River, N.J., Prentice Hall, p. 383–386.

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: Archive 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, no. 1, p. 38–47.

Krysel, Charles; Boyer, E.M.; Parson, Charles; and Welle, Patrick, 2003, Lakeshore property values and water quality—Evidence from property sales in the Mississippi Headwaters Region [abs.]: Accessed June 2010 at *http://www.uwsp.edu/cnr/uwexlakes/economicsOfWater/documents/76_mSPropertySales_krysel_abstr.pdf*.

Kutser, Tiit; Metsamaa, Liisa; Strömbeck, Niklas; and Vahtmäe, Ele, 2006, Monitoring cyanobacterial blooms by satellite remote sensing: Estuarine, Coastal and Shelf Science, v. 67, p. 303–312.

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.

National Aeronautics Space Administration, 2003, Landsat 7 science data user's handbook—Chapter 11, Data products: Accessed June 2010 at *http://landsathandbook.gsfc.nasa.gov/handbook/handbook_htmls/chapter11/chapter11.html*.

Nelson, S.A.C., Soranno, P.A., Cheruvelil, K.S., Batzli, S.A., and Skole, D.L., 2003, Regional assessment of lake water clarity using satellite remote sensing: Journal of Limnology, v. 62, supp. 1, p. 27–32.

Obrecht, D.V.; Milanick, Margaret; Perkins, B.D., Ready, Diana; and Jones, J.R., 1998, Evaluation of data generated from lake samples collected by volunteers: Lake and Reservoir Management, v. 14, no. 1, p. 21–27.

Olmanson, L.G., Bauer, M.E., and Brezonik, P.L., 2008, A 20-year Landsat water clarity census of Minnesota's 10,000 lakes: Remote Sensing of Environment, v. 112, no. 11, p. 4,086–4,097.

Olmanson, L.G., Kloiber, S.M., Bauer, M.E., and Brezonik, P.L., 2001, Image processing protocol for regional assessments of lake water quality: St. Paul, Minn., University of Minnesota, Water Resources Center and Remote Sensing Laboratory, p. 1–13.

Peckham, S.D., and Lillesand, T.M., 2006, Detection of spatial and temporal trends in Wisconsin lake water clarity using Landsat-derived estimates of Secchi depth: Lake and Reservoir Management, v. 22, no. 4, p. 331–341.

Stynes, D.J., 2002, Michigan statewide tourism spending and economic impact estimates 1998–2000: Accessed November 2003 at *http://web4.canr.msu.edu/mgm2/econ/miteim/MichiganSatExec.pdf*.

U.S. Environmental Protection Agency, 2007, Aquatic biodiversity—Carlson's Trophic State Index: Accessed June 2010 at *http://www.epa.gov/bioindicators/aquatic/carlson.html*.

Wiangwang, Narumon, 2002, Water clarity/trophic condition monitoring by using satellite remote sensing data: East Lansing, Mich., Michigan State University, Department of Geography Graduate Program, Master's thesis, 152 p.

Yamane, Taro, 1973, Statistics—An introductory analysis (3d ed): New York, Harper & Row, p. 493–498.

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.

Appendixes 1 and 2

Appendix 1. Results and computations by Landsat-satellite path for Michigan inland lakes, 2003–05, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake average TSI		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
20	30–31	Round Lake	Clinton	87	2004–09–25	5.5	1.7	53	51	48	53	51	52	49
20	30–31	Byram Lake	Genesee	134	2004–09–19	12.0	3.7	41	42	44	48	48	43	44
20	30–31	Fenton Lake	Genesee	866	2004–09–19	15.5	4.7	38	34	32	44	43	38	37
20	30–31	Ponemah Lake	Genesee	410	2004–09–25	12.5	3.8	41	41	41	45	44	42	41
20	30–31	Silver Lake	Genesee	339	2004–09–26	15.0	4.6	38	40	40	43	44	39	40
20	30–31	Clear Lake	Jackson	129	2004–09–21	11.5	3.5	42	44	44	48	47	41	42
20	30–31	Gilletts Lake	Jackson	334	2004–09–16	7.5	2.3	48	43	43	61	58	52	51
20	30–31	Grass Lake	Jackson	353	2004–09–18	5.0	1.5	54	*	*	*	*	49	50
20	30–31	Vineyard Lake	Jackson	541	2004–09–21	14.0	4.3	39	37	38	46	45	38	38
20	30–31	Nepessing Lake	Lapeer	427	2004–09–23	17.0	5.2	36	38	38	43	43	39	39
20	30–31	Evans Lake	Lenawee	215	2004–09–22	24.0	7.3	31	37	36	39	37	32	30
20	30–31	East Crooked Lake	Livingston	248	2004–09–20	19.0	5.8	35	41	42	46	46	39	40
20	30–31	Gut Lake	Livingston	32	2004–09–20	13.0	4.0	40	40	40	38	38	34	34
20	30–31	Hamburg Lake	Livingston	99	2004–09–21	17.0	5.2	36	36	37	41	40	36	36
20	30–31	Oneida Lake	Livingston	46	2004–09–19	10.0	3.0	44	43	43	49	47	43	41
20	30–31	Strawberry Lake	Livingston	261	2004–09–24	9.0	2.7	45	44	43	46	45	42	41
20	30–31	West Crooked Lake	Livingston	191	2004–09–19	8.5	2.6	46	41	43	47	47	42	43
20	30–31	Buckhorn Lake	Oakland	43	2004–09–25	13.0	4.0	40	44	42	50	48	44	43
20	30–31	Taylor Lake	Oakland	39	2004–09–25	20.0	6.1	34	*	*	*	*	37	39
20	30–31	Leisure Lake	Shiawassee	45	2004–09–22	5.0	1.5	54	55	54	55	53	52	50
20	30–31	Pleasant Lake	Washtenaw	193	2004–09–22	10.0	3.0	44	43	45	47	48	44	45
20	30–31	Portage Lake	Washtenaw	641	2004–09–19	10.0	3.0	44	41	42	52	51	46	47
21	28–31	Hubbard Lake	Alcona	8768	2004–09–13	14.0	4.3	39	37	36	40	38	36	35

Appendix 1. Results and computations by Landsat-satellite path for Michigan inland lakes, 2003–05, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake average TSI		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
21	28–31	Jewell Lake	Alcona	184	2004–09–12	8.5	2.6	46	43	43	53	51	47	47
21	28–31	Bellaire Lake	Antrim	1789	2004–09–14	16.0	4.9	37	34	34	40	39	34	34
21	28–31	Clam Lake	Antrim	438	2004–09–15	21.0	6.4	33	33	32	40	39	35	35
21	28–31	Barlow Lake	Barry	181	2004–09–15	7.5	2.3	48	42	42	46	45	41	42
21	28–31	Randall N Cemetary L	Branch	511	2004–09–16	7.5	2.3	48	47	47	48	48	47	48
21	28–31	Birch Lake	Cass	282	2004–09–13	12.0	3.7	41	45	44	46	45	44	43
21	28–31	Christiana	Cass	560	2004–09–14	6.5	2.0	50	47	47	48	48	47	48
21	28–31	Diamond Lake	Cass	1041	2004–09–14	12.0	3.7	41	43	43	47	45	44	43
21	28–31	Juno	Cass	560	2004–09–14	6.5	2.0	50	48	48	48	48	47	48
21	28–31	Magician Lake	Cass	522	2004–09–15	7.0	2.1	49	45	45	50	48	48	47
21	28–31	Painter	Cass	560	2004–09–14	5.5	1.7	53	48	48	48	48	47	48
21	28–31	Shavehead Lake	Cass	299	2004–09–19	8.0	2.4	47	45	43	48	45	45	44
21	28–31	Twin Lake (north)	Cass	61	2004–09–11	12.5	3.8	41	46	46	49	48	46	47
21	28–31	Twin Lake (south)	Cass	43	2004–09–12	7.0	2.1	49	45	45	51	48	47	46
21	28–31	Shingle Lake	Clare	30	2004–09–14	11.0	3.4	43	40	40	40	39	38	38
21	28–31	Windover Lake	Clare	68	2004–09–13	21.0	6.4	33	35	34	43	42	36	35
21	28–31	Round Lake	Clinton	87	2004–09–12	6.0	1.8	51	46	47	48	49	47	48
21	28–31	Byram Lake	Genesee	134	2004–09–19	12.0	3.7	41	46	46	46	45	44	44
21	28–31	Fenton Lake	Genesee	866	2004–09–11	16.0	4.9	37	37	37	43	43	40	40
21	28–31	Ponemah Lake	Genesee	410	2004–09–10	11.5	3.5	42	42	42	42	42	41	41
21	28–31	Silver Lake	Genesee	339	2004–09–12	12.5	3.8	41	42	41	44	43	40	40
21	28–31	Lake Twenty	Gladwin	124	2004–09–08	9.5	2.9	45	38	37	43	43	41	41
21	28–31	Crystal Lake	Hillsdale	130	2004–09–15	14.0	4.3	39	44	45	44	44	43	43

Appendix 1. Results and computations by Landsat-satellite path for Michigan inland lakes, 2003–05, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake average TSI		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
21	28–31	Perch Lake	Hillsdale	46	2004–09–16	8.0	2.4	47	46	46	45	46	45	45
21	28–31	Cedar Lake	Iosco	142	2004–09–13	8.5	2.6	46	*	*	*	*	50	50
21	28–31	Van Etten Lake	Iosco	1409	2004–09–10	7.5	2.3	48	48	48	45	46	45	46
21	28–31	Gilletts Lake	Jackson	334	2004–09–16	7.5	2.3	48	*	*	*	*	51	50
21	28–31	Grass Lake	Jackson	353	2004–09–18	5.0	1.5	54	49	50	49	49	49	49
21	28–31	Portage Lake	Jackson	398	2004–09–18	11.0	3.4	43	45	45	51	49	48	48
21	28–31	Vineyard Lake	Jackson	541	2004–09–09	10.0	3.0	44	46	46	53	51	49	48
21	28–31	Indian Lake	Kalamazoo	788	2004–09–13	6.0	1.8	51	51	49	53	50	52	49
21	28–31	Bear Lake	Kalkaska	313	2004–09–16	28.0	8.5	29	32	29	37	34	34	32
21	28–31	Cub Lake	Kalkaska	57	2004–09–10	24.0	7.3	31	36	35	40	39	37	36
21	28–31	Bostwick Lake	Kent	213	2004–09–17	6.5	2.0	50	43	44	46	47	45	46
21	28–31	Freska Lake	Kent	59	2004–09–16	8.0	2.4	47	*	*	*	*	45	46
21	28–31	Murray Lake	Kent	312	2004–09–16	11.0	3.4	43	44	44	45	45	43	44
21	28–31	East Crooked Lake	Livingston	248	2004–09–13	16.0	4.9	37	40	40	45	45	42	42
21	28–31	Gut Lake	Livingston	32	2004–09–11	13.0	4.0	40	40	41	42	42	40	41
21	28–31	Oneida Lake	Livingston	46	2004–09–12	10.5	3.2	43	42	43	44	45	42	43
21	28–31	Strawberry Lake	Livingston	261	2004–09–11	8.0	2.4	47	45	46	45	45	43	44
21	28–31	West Crooked Lake	Livingston	191	2004–09–12	7.5	2.3	48	46	47	47	47	45	46
21	28–31	Horsehead Lake	Mecosta	443	2004–09–15	12.0	3.7	41	43	44	46	45	40	41
21	28–31	Mecosta Lake	Mecosta	312	2004–09–07	9.0	2.7	45	43	43	46	46	45	45
21	28–31	Pretty Lake	Mecosta	116	2004–09–19	11.0	3.4	43	40	40	41	42	39	40
21	28–31	Round Lake	Mecosta	157	2004–09–18	14.0	4.3	39	43	45	42	43	41	42
21	28–31	West Canadian Lake	Mescoda	133	2004–09–10	12.0	3.7	41	39	40	43	44	41	42

Appendix 1. Results and computations by Landsat-satellite path for Michigan inland lakes, 2003–05, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake average TSI		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
21	28–31	Sanford Lake	Midland	1402	2004–09–11	9.0	2.7	45	39	39	42	42	40	40
21	28–31	Baldwin Lake	Montcalm	62	2004–09–18	9.5	2.9	45	41	42	43	44	42	43
21	28–31	Clifford Lake	Montcalm	195	2004–09–15	11.0	3.4	43	44	45	44	45	43	44
21	28–31	Derby Lake	Montcalm	114	2004–09–15	19.0	5.8	35	40	41	43	43	40	41
21	28–31	Muskellunge Lake	Montcalm	137	2004–09–10	11.0	3.4	43	42	43	44	45	42	43
21	28–31	Picnic Lake	Montcalm	23	2004–09–07	2.5	0.8	64	60	55	61	55	61	56
21	28–31	Avalon Lake	Montmorency	386	2004–09–15	27.0	8.2	30	31	29	33	30	30	27
21	28–31	Bills Lake	Newaygo	200	2004–09–16	10.0	3.0	44	41	42	44	43	40	40
21	28–31	Sylvan Lake	Newaygo	102	2004–09–16	10.0	3.0	44	40	42	43	43	40	41
21	28–31	Island Lake	Ogemaw	60	2004–09–13	15.0	4.6	38	43	44	45	45	42	43
21	28–31	Center Lake	Osceola	41	2004–09–12	17.0	5.2	36	37	38	37	37	36	36
21	28–31	Hicks Lake	Osceola	160	2004–09–09	3.5	1.1	59	59	55	56	53	57	55
21	28–31	Wells Lake	Osceola	48	2004–09–15	18.0	5.5	35	39	40	41	42	40	41
21	28–31	Big Bradford Lake	Otsego	256	2004–09–06	17.0	5.2	36	39	38	39	38	35	34
21	28–31	Big Lake	Otsego	124	2004–09–10	19.0	5.8	35	36	36	38	38	37	36
21	28–31	Viking Lake	Otsego	36	2004–09–12	6.0	1.8	51	53	51	52	50	53	52
21	28–31	Corey Lake	St. Joseph	599	2004–09–16	8.0	2.4	47	43	44	48	46	45	44
21	28–31	Fishers Lake	St. Joseph	330	2004–09–11	10.0	3.0	44	48	47	49	47	45	45
21	28–31	Fishers Lake	St. Joseph	330	2004–09–11	10.0	3.0	44	47	47	49	47	45	45
21	28–31	Klinger Lake	St. Joseph	835	2004–09–15	11.0	3.4	43	46	45	47	46	45	45
21	28–31	Pleasant Lake	St. Joseph	256	2004–09–15	13.0	4.0	40	44	45	49	48	45	45
21	28–31	Cedar Lake	Van Buren	275	2004–09–10	13.5	4.1	40	43	44	47	47	44	45
21	28–31	Crooked Lake	Van Buren	117	2004–09–05	12.0	3.7	41	46	47	46	46	44	45

Appendix 1. Results and computations by Landsat-satellite path for Michigan inland lakes, 2003–05, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake average TSI		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
21	28–31	Crooked Lake Little	Van Buren	114	2004–09–14	14.0	4.3	39	45	46	45	46	44	45
21	28–31	Silver Lake	Van Buren	50	2004–09–13	12.5	3.8	41	41	43	43	45	42	44
21	28–31	Pleasant Lake	Washtenaw	193	2004–09–16	10.5	3.2	43	48	48	47	47	47	47
21	28–31	Portage Lake	Washtenaw	641	2004–09–12	9.5	2.9	45	48	48	50	50	49	49
21	28–31	Stone Ledge Lake	Wexford	83	2004–09–18	13.0	4.0	40	38	37	39	39	36	35
22	28–31	Goshorn Lake	Allegan	28	2004–09–18	6.5	2.0	50	48	47	48	47	48	46
22	28–31	Hutchins Lake	Allegan	379	2004–09–17	8.0	2.4	47	42	43	50	49	45	45
22	28–31	Torch Lake	Antrim	18722	2004–09–23	16.5	5.0	37	38	38	39	39	37	36
22	28–31	Ann Lake	Benzie	501	2004–09–17	13.0	4.0	40	42	43	47	46	43	43
22	28–31	Crystal Lake	Benzie	9869	2004–09–26	18.0	5.5	35	36	33	37	35	35	32
22	28–31	Christiana	Cass	560	2004–09–22	7.5	2.3	48	48	47	48	47	46	46
22	28–31	Diamond Lake	Cass	1041	2004–09–23	12.0	3.7	41	40	41	49	48	43	45
22	28–31	Juno	Cass	560	2004–09–22	7.0	2.1	49	44	44	47	46	46	46
22	28–31	Painter	Cass	560	2004–09–22	6.5	2.0	50	47	47	47	46	46	46
22	28–31	Shavehead Lake	Cass	299	2004–09–19	8.0	2.4	47	49	50	51	51	50	51
22	28–31	Twin Lake (north)	Cass	61	2004–09–19	18.0	5.5	35	41	41	46	44	41	40
22	28–31	Twin Lake (south)	Cass	43	2004–09–23	10.0	3.0	44	41	41	54	51	43	44
22	28–31	Lily Lake	Clare	190	2004–09–24	9.5	2.9	45	42	42	42	42	41	41
22	28–31	Shingle Lake	Clare	30	2004–09–22	13.0	4.0	40	40	40	42	42	41	40
22	28–31	Arbutus Lake	Grand Trave	378	2004–09–15	14.0	4.3	39	42	42	45	44	40	40
22	28–31	Long Lake	Grand Trave	2911	2004–09–18	19.0	5.8	35	40	39	43	41	39	38
22	28–31	Indian Lake	Kalamazoo	788	2004–09–25	7.0	2.1	49	53	52	55	53	53	53
22	28–31	Freska Lake	Kent	59	2004–09–23	9.5	2.9	45	42	42	42	42	41	41

Appendix 1. Results and computations by Landsat-satellite path for Michigan inland lakes, 2003–05, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake average TSI		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
22	28–31	Murray Lake	Kent	312	2004–09–16	11.0	3.4	43	46	46	45	44	43	43
22	28–31	Big Star Lake	Lake	890	2004–09–18	11.5	3.5	42	38	38	42	41	39	39
22	28–31	Glen Lake Little	Leelanau	1415	2004–09–22	7.0	2.1	49	47	47	46	47	45	47
22	28–31	Hamlin Lake	Mason	4622	2004–09–19	13.5	4.1	40	42	41	42	43	41	40
22	28–31	Hamlin Lake	Mason	4622	2004–09–23	9.5	2.9	45	41	40	43	44	41	40
22	28–31	Horsehead Lake	Mecosta	443	2004–09–20	15.5	4.7	38	41	41	46	45	40	41
22	28–31	Mecosta Lake	Mecosta	312	2004–09–18	15.0	4.6	38	41	41	45	45	42	43
22	28–31	Pretty Lake	Mecosta	116	2004–09–19	11.0	3.4	43	41	42	42	42	40	41
22	28–31	Round Lake	Mecosta	157	2004–09–18	14.0	4.3	39	39	38	41	41	40	40
22	28–31	West Canadian Lake	Mescoda	133	2004–09–17	11.5	3.5	42	40	40	43	43	42	42
22	28–31	Sapphire Lake	Missaukee	246	2004–09–13	7.5	2.3	48	47	47	48	47	46	46
22	28–31	Baldwin Lake	Montcalm	62	2004–09–18	9.5	2.9	45	43	44	44	44	44	44
22	28–31	Clifford Lake	Montcalm	195	2004–09–23	12.0	3.7	41	43	43	44	44	43	43
22	28–31	Bills Lake	Newaygo	200	2004–09–18	12.0	3.7	41	40	41	46	46	40	42
22	28–31	Kimball Lake	Newaygo	147	2004–09–19	6.0	1.8	51	52	52	52	51	52	52
22	28–31	Pickerel Lake	Newaygo	308	2004–09–19	12.0	3.7	41	39	39	45	44	42	42
22	28–31	Sylvan Lake	Newaygo	102	2004–09–16	10.0	3.0	44	42	43	44	45	40	42
22	28–31	Crystal Lake	Oceana	121	2004–09–20	8.0	2.4	47	44	45	44	44	43	44
22	28–31	Robinson Lake	Oceana	134	2004–09–14	10.0	3.0	44	41	40	41	40	40	40
22	28–31	Stony Lake	Oceana	287	2004–09–15	12.0	3.7	41	41	41	42	42	41	41
22	28–31	Center Lake	Osceola	41	2004–09–19	18.0	5.5	35	40	40	40	39	39	39
22	28–31	Hicks Lake	Osceola	160	2004–09–25	3.0	0.9	61	60	57	60	57	62	58
22	28–31	Corey Lake	St. Joseph	599	2004–09–24	8.5	2.6	46	47	48	49	48	44	46

Appendix 1. Results and computations by Landsat-satellite path for Michigan inland lakes, 2003–05, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake average TSI		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
22	28–31	Fishers Lake	St. Joseph	330	2004–09–25	13.5	4.1	40	43	43	48	49	42	43
22	28–31	Fishers Lake	St. Joseph	330	2004–09–18	14.0	4.3	39	42	43	53	58	42	43
22	28–31	Pleasant Lake	St. Joseph	256	2004–09–22	15.0	4.6	38	41	41	46	44	40	41
22	28–31	Wahbememe	St. Joseph	22	2004–09–19	16.0	4.9	37	*	*	*	*	42	42
22	28–31	Cedar Lake	Van Buren	275	2004–09–18	13.0	4.0	40	42	42	45	44	41	41
22	28–31	Crooked Lake	Van Buren	117	2004–09–19	11.0	3.4	43	39	38	44	44	42	42
22	28–31	Crooked Lake Little	Van Buren	114	2004–09–14	14.0	4.3	39	41	41	43	43	41	41
22	28–31	Silver Lake	Van Buren	50	2004–09–19	13.5	4.1	40	40	39	41	40	40	39
22	28–31	Stone Ledge Lake	Wexford	83	2004–09–18	13.0	4.0	40	43	43	43	43	41	41
24	27	Clear Lake	Houghton	23	2005–09–26	17.5	5.3	36	38	37	37	36	37	36
24	27	Gerald Lake	Houghton	356	2005–09–24	13.5	4.1	40	36	37	41	40	42	42
24	27	Pike Lake	Houghton	83	2005–09–26	8.5	2.6	46	42	42	42	43	44	44
24	27	Portage Lake	Houghton	10808	2005–09–24	8.5	2.6	46	43	41	47	47	47	47
24	27	Roland Lake	Houghton	258	2005–09–24	16.0	4.9	37	39	39	41	41	41	41
24	27	Torch Lake	Houghton	2400	2005–09–24	13.5	4.1	40	33	33	38	38	37	37
24	27	Fanny Hooe Lake	Keweenaw	230	2005–09–23	14.5	4.4	39	38	38	39	39	40	40
24	27	Manganese Lake	Keweenaw	56	2005–09–23	12.0	3.7	41	41	42	41	42	42	42
24	27	Medora Lake	Keweenaw	690	2005–09–23	9.0	2.7	45	42	43	41	41	42	42
24	27	Lake Independence	Marquette	2041	2005–09–26	6.5	2.0	50	51	48	50	47	50	49
24	28	Bass Lake	Dickinson	60	2005–07–21	22.0	6.7	33	33	33	38	37	33	32
24	28	Carney Lake	Dickinson	115	2005–07–25	17.0	5.2	36	39	39	42	41	37	38
24	28	Hanbury Lake	Dickinson	78	2005–07–25	19.5	5.9	34	38	37	42	40	36	37
24	28	Mary Lake	Dickinson	85	2005–07–25	15.0	4.6	38	34	35	53	49	41	41

Appendix 1. Results and computations by Landsat-satellite path for Michigan inland lakes, 2003–05, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake average TSI		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
24	28	Pickerel Lake	Dickinson	68	2005–07–25	15.5	4.7	38	36	36	48	45	40	41
24	28	Bass Lake	Marquette	76	2005–07–25	16.5	5.0	37	37	37	39	39	32	32
24	28	Bass Lake	Marquette	273	2005–07–21	8.5	2.6	46	43	43	51	49	44	44
24	28	Deer Lake	Marquette	906	2005–07–22	7.0	2.1	49	46	45	47	46	45	45
24	28	Engman Lake	Marquette	48	2005–07–21	11.5	3.5	42	44	45	45	46	44	44
24	28	Fish Lake	Marquette	151	2005–07–22	8.5	2.6	46	36	38	34	36	46	45
24	28	Greenwood Reservoir	Marquette	1073	2005–07–22	8.5	2.6	46	36	38	34	35	45	44
24	28	Horseshoe Lake	Marquette	126	2005–07–22	9.0	2.7	45	40	40	46	44	43	43
24	28	Johnson Lake	Marquette	78	2005–07–21	18.0	5.5	35	36	35	42	40	35	35
24	28	Little Lake	Marquette	460	2005–07–21	17.0	5.2	36	39	38	55	51	42	41
24	28	Squaw Lake	Marquette	247	2005–07–22	18.5	5.6	35	35	36	39	39	36	34
25	28	Allen Lake	Gogebic	78	2003–08–28	8.5	2.6	46	45	43	44	42	45	43
25	28	Bass Lake	Gogebic	200	2003–08–25	8.5	2.6	46	43	43	41	40	46	47
25	28	Beatons Lake	Gogebic	324	2003–08–27	18.5	5.6	35	38	38	41	42	40	39
25	28	Clark Lake	Gogebic	836	2003–08–26	20.5	6.2	34	39	41	38	42	39	39
25	28	Dinner Lake	Gogebic	108	2003–08–12	10.5	3.2	43	40	43	43	40	39	42
25	28	Duck Lake	Gogebic	612	2003–08–12	9.5	2.9	45	42	44	50	50	45	46
25	28	Lac Vieux Desert	Gogebic	4370	2003–08–12	6.5	2.0	50	49	48	45	45	50	48
25	28	Oxbow Lake	Gogebic	98	2003–08–13	8.0	2.4	47	42	40	43	43	43	41
25	28	Pomeroy Lake	Gogebic	314	2003–08–13	6.0	1.8	51	53	53	49	49	54	54
25	28	Thousand Island Lake	Gogebic	1009	2003–08–27	12.5	3.8	41	43	44	42	42	41	41
25	28	Bond Falls Flowage	Ontonagon	2127	2003–08–26	9.0	2.7	45	42	42	41	40	42	42
25	28	County Line Lake	Ontonagon	67	2003–08–27	16.0	4.9	37	45	43	45	45	39	38

Appendix 2. Results and computations by Landsat-satellite path for Michigan inland lakes, 2007–08, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
20	3031	Byram Lake	Genesee	134	2007–09–02	15.0	4.6	38	39	39	50	48	39	39
20	3031	Clear Lake	Jackson	129	2007–08–31	12.0	3.7	41	39	39	53	52	37	38
20	3031	Vineyard Lake	Jackson	541	2007–08–31	12.0	3.7	41	43	44	49	47	43	42
20	3031	Base Line Lake	Livingston	244	2007–08–24	11.5	3.5	42	40	40	38	38	41	40
20	3031	Chemung Lake	Livingston	313	2007–08–27	15.0	4.6	38	38	38	49	47	42	42
20	3031	Earl Lake	Livingston	53	2007–08–29	6.0	1.8	51	48	48	43	42	51	51
20	3031	Gallagher Lake	Livingston	189	2007–09–02	10.5	3.2	43	42	42	41	40	43	42
20	3031	Green Oak Lake	Livingston	152	2007–08–24	13.5	4.1	40	41	41	46	45	39	40
20	3031	Gut Lake	Livingston	32	2007–08–30	13.0	4.0	40	41	41	48	48	42	42
20	3031	Hamburg Lake	Livingston	99	2007–08–29	16.0	4.9	37	41	41	48	47	39	39
20	3031	Oneida Lake	Livingston	46	2007–08–25	7.0	2.1	49	48	48	49	50	45	45
20	3031	Ore Lake	Livingston	231	2007–09–01	11.0	3.4	43	42	42	41	39	43	43
20	3031	Round Lake	Livingston	74	2007–08–25	7.5	2.3	48	47	47	42	41	45	46
20	3031	Strawberry Lake	Livingston	261	2007–09–01	8.0	2.4	47	45	46	46	45	45	45
20	3031	Buckhorn Lake	Oakland	43	2007–09–02	13.0	4.0	40	42	42	48	48	41	41
20	3031	Long Lake	Oakland	104	2007–08–30	13.0	4.0	40	43	43	45	45	42	42
20	3031	Middle Straits Lake	Oakland	178	2007–08–26	14.0	4.3	39	37	37	46	46	38	39
20	3031	Portage Lake	Washtenaw	641	2007–08–31	10.0	3.0	44	47	47	46	45	47	47
21	2831	Cedar Lake	Alcona	912	2007–09–20	8.0	2.4	47	48	49	57	54	53	53
21	2831	Hubbard Lake	Alcona	8768	2007–09–16	12.0	3.7	41	41	42	44	43	40	41
21	2831	Vaughn Lake	Alcona	112	2007–09–20	15.0	4.6	38	37	37	41	41	37	38
21	2831	Osterhout Lake	Allegan	172	2007–09–18	10.0	3.0	44	45	45	48	45	44	43
21	2831	Bellaire Lake	Antrim	1789	2007–09–20	16.0	4.9	37	*	*	*	*	39	39
21	2831	Barlow Lake	Barry	181	2007–09–17	10.0	3.0	44	45	43	47	45	41	41

Appendix 2. Results and computations by Landsat-satellite path for Michigan inland lakes, 2007–08, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
21	2831	Cobb Lake	Barry	92	2007–09–21	13.0	4.0	40	42	41	45	44	40	40
21	2831	Payne Lake	Barry	113	2007–09–22	11.0	3.4	43	41	41	49	46	44	44
21	2831	Stuart Lake	Calhoun	115	2007–09–21	13.0	4.0	40	45	45	49	46	42	42
21	2831	Upper Brace Lake	Calhoun	71	2007–09–21	12.0	3.7	41	41	41	46	44	42	42
21	2831	Birch Lake	Cass	282	2007–09–20	20.0	6.1	34	38	38	41	40	39	39
21	2831	Diamond Lake	Cass	1041	2007–09–19	13.0	4.0	40	41	42	42	41	38	39
21	2831	Eagle Lake	Cass	400	2007–09–19	10.5	3.2	43	*	*	*	*	45	45
21	2831	Magician Lake	Cass	522	2007–09–15	10.0	3.0	44	44	44	47	44	44	44
21	2831	Puterbaugh Lake	Cass	44	2007–09–20	9.5	2.9	45	47	47	50	47	46	46
21	2831	Twin Lake (north)	Cass	61	2007–09–19	10.0	3.0	44	*	*	*	*	43	42
21	2831	Twin Lake (south)	Cass	43	2007–09–19	11.5	3.5	42	44	44	44	43	43	44
21	2831	Arnold Lake	Clare	121	2007–09–19	17.0	5.2	36	36	36	41	39	37	36
21	2831	George Lake	Clare	129	2007–09–18	11.5	3.5	42	41	41	43	41	40	40
21	2831	Lily Lake	Clare	190	2007–09–22	11.0	3.4	43	39	39	41	40	38	38
21	2831	Shingle Lake	Clare	30	2007–09–18	14.0	4.3	39	41	41	43	41	40	40
21	2831	Round Lake	Clinton	87	2007–09–16	7.5	2.3	48	44	44	50	48	45	45
21	2831	Margrethe Lake	Crawford	1922	2007–09–16	12.0	3.7	41	37	37	45	43	39	40
21	2831	Ponemah Lake	Genesee	410	2007–09–21	14.0	4.3	39	40	40	42	41	38	39
21	2831	Lake Twenty	Gladwin	124	2007–09–20	12.0	3.7	41	43	43	45	43	42	42
21	2831	Smallwood Lake	Gladwin	371	2007–09–18	9.0	2.7	45	43	43	51	48	46	46
21	2831	Lake Diane	Hillsdale	266	2007–09–22	2.5	0.8	64	60	58	68	60	65	62
21	2831	Rebeck Lake	Hillsdale	50	2007–09–15	6.5	2.0	50	46	45	48	46	45	45
21	2831	Lansing Lake	Ingham	456	2007–09–20	6.0	1.8	51	46	46	50	48	46	47
21	2831	Chain Lakes (west)	Iosco	84	2007–09–22	12.0	3.7	41	41	42	55	51	44	45

Appendix 2. Results and computations by Landsat-satellite path for Michigan inland lakes, 2007–08, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
21	2831	Clark Lake	Jackson	576	2007–09–20	14.0	4.3	39	44	45	45	45	42	43
21	2831	Clear Lake	Jackson	129	2007–09–18	11.0	3.4	43	44	44	47	46	42	43
21	2831	Vineyard Lake	Jackson	541	2007–09–21	13.0	4.0	40	42	42	52	51	44	45
21	2831	Wamplers Lake	Jackson	797	2007–09–19	7.0	2.1	49	45	45	50	48	45	45
21	2831	Sherman Lake	Kalamazoo	148	2007–09–16	20.5	6.2	34	39	38	40	38	36	35
21	2831	Cub Lake	Kalkaska	57	2007–09–20	16.0	4.9	37	41	41	45	44	40	41
21	2831	Eagle Lake	Kalkaska	25	2007–09–16	16.0	4.9	37	41	40	42	40	40	40
21	2831	North Blue Lake	Kalkaska	56	2007–09–22	17.0	5.2	36	35	34	38	35	36	34
21	2831	Starvation Lake	Kalkaska	99	2007–09–20	16.0	4.9	37	41	41	41	38	37	36
21	2831	Twin Lake	Kalkaska	209	2007–09–22	23.0	7.0	32	46	46	39	36	36	34
21	2831	Evans Lake	Lenawee	215	2007–09–19	15.0	4.6	38	41	41	46	44	41	42
21	2831	Round Lake	Lenawee	512	2007–09–16	12.0	3.7	41	46	47	48	47	44	45
21	2831	Chemung Lake	Livingston	313	2007–09–17	14.0	4.3	39	40	40	44	42	40	40
21	2831	Earl Lake	Livingston	53	2007–09–20	5.0	1.5	54	54	52	56	53	55	54
21	2831	Blue Lake	Mecosta	229	2007–09–18	12.0	3.7	41	37	37	43	42	40	39
21	2831	Canadian Lakes	Mecosta	321	2007–09–20	11.0	3.4	43	41	42	46	43	42	42
21	2831	Horsehead Lake	Mecosta	443	2007–09–20	10.0	3.0	44	43	44	47	45	43	44
21	2831	Mecosta Lake	Mecosta	312	2007–09–22	12.0	3.7	41	37	37	47	45	41	41
21	2831	Pretty Lake	Mecosta	116	2007–09–22	12.0	3.7	41	38	38	45	43	41	41
21	2831	Round Lake	Mecosta	157	2007–09–22	14.0	4.3	39	42	42	44	42	40	40
21	2831	West Canadian Lake	Mescoda	133	2007–09–20	12.0	3.7	41	44	44	44	42	40	40
21	2831	Baldwin Lake	Montcalm	62	2007–09–18	10.0	3.0	44	40	41	45	43	41	41
21	2831	Clifford Lake	Montcalm	195	2007–09–22	13.0	4.0	40	40	40	45	43	42	42
21	2831	East Twin Lake	Montmorency	820	2007–09–22	8.5	2.6	46	44	45	46	45	42	43

Appendix 2. Results and computations by Landsat-satellite path for Michigan inland lakes, 2007–08, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
21	2831	West Twin Lake	Montmorency	1306	2007–09–20	8.5	2.6	46	48	48	50	49	47	48
21	2831	Bills Lake	Newaygo	200	2007–09–22	12.0	3.7	41	36	36	42	41	38	39
21	2831	Pickerel Lake	Newaygo	308	2007–09–15	12.0	3.7	41	41	41	43	40	40	39
21	2831	Center Lake	Osceola	41	2007–09–16	20.0	6.1	34	39	39	42	40	40	39
21	2831	Hicks Lake	Osceola	160	2007–09–17	5.5	1.7	53	52	51	53	50	50	50
21	2831	Big Bradford Lake	Otsego	256	2007–09–21	22.0	6.7	33	35	35	42	40	36	36
21	2831	Big Lake	Otsego	124	2007–09–17	19.0	5.8	35	39	39	41	39	37	37
21	2831	Crockery Lake	Ottawa	104	2007–09–17	7.0	2.1	49	48	48	50	47	46	47
21	2831	Corey Lake	St. Joseph	599	2007–09–18	14.5	4.4	39	40	40	43	41	40	39
21	2831	Fishers Lake	St. Joseph	330	2007–09–22	12.0	3.7	41	42	43	45	43	43	44
21	2831	Klinger Lake	St. Joseph	835	2007–09–20	11.0	3.4	43	45	45	46	45	43	45
21	2831	Perrin Lake	St. Joseph	109	2007–09–21	10.0	3.0	44	42	42	51	48	47	46
21	2831	Cedar Lake	Van Buren	275	2007–09–17	13.0	4.0	40	40	40	44	43	41	40
21	2831	Crooked Lake	Van Buren	117	2007–09–21	10.5	3.2	43	40	39	43	43	41	40
21	2831	Crooked Lake Little	Van Buren	114	2007–09–21	11.5	3.5	42	41	39	43	43	39	39
21	2831	Gravel Lake	Van Buren	297	2007–09–20	9.5	2.9	45	*	*	*	*	41	40
21	2831	Maple Lake	Van Buren	193	2007–09–18	7.0	2.1	49	45	45	50	47	46	45
21	2831	Stone Ledge Lake	Wexford	83	2007–09–18	8.5	2.6	46	46	47	48	49	45	45
22	28	Frenchman Lake	Chippewa	185	2007–06–26	12.0	3.7	41	43	43	45	45	43	43
22	28	Trout Lake	Chippewa	568	2007–06–26	11.5	3.5	42	41	41	46	45	44	44
22	28	Wegwaas Lake	Chippewa	148	2007–06–26	10.0	3.0	44	43	43	44	44	42	43
22	28	Bass Lake	Luce	144	2007–06–28	21.0	6.4	33	36	35	37	36	36	36
22	28	Bodi Lake	Luce	275	2007–06–27	10.0	3.0	44	48	48	49	48	46	46
22	28	Culhane Lake	Luce	100	2007–06–27	11.0	3.4	43	45	45	44	44	43	43

Appendix 2. Results and computations by Landsat-satellite path for Michigan inland lakes, 2007–08, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
22	28	East Lake	Luce	125	2007–06–28	10.0	3.0	44	39	40	40	41	39	40
22	28	Kaks Lake	Luce	59	2007–06–28	9.5	2.9	45	43	43	43	43	43	43
22	28	Muskallonge Lake	Luce	762	2007–06–27	9.0	2.7	45	42	43	43	44	42	43
22	28	Perch Lake	Luce	91	2007–06–27	19.0	5.8	35	36	36	37	37	36	35
22	28	Pike Lake	Luce	286	2007–06–27	9.5	2.9	45	43	43	42	42	42	41
22	28	Brevoort Lake	Mackinac	4315	2007–06–26	13.0	4.0	40	41	42	44	44	42	42
22	28	East Lake	Mackinac	927	2007–06–26	10.5	3.2	43	44	44	46	46	44	45
22	28	Millecoquins Lake	Mackinac	1123	2007–06–26	8.0	2.4	47	45	45	50	49	48	47
22	28	Dutch Fred Lake	Schoolcraft	34	2007–06–28	19.0	5.8	35	36	36	37	38	36	36
22	2931	Osterhout Lake	Allegan	172	2007–09–14	7.0	2.1	49	46	45	47	47	45	45
22	2931	Wetmore Lake	Allegan	46	2007–09–20	7.5	2.3	48	43	45	45	45	43	43
22	2931	Torch Lake	Antrim	18722	2007–09–08	21.0	6.4	33	29	31	32	32	30	31
22	2931	Woods Lake of the	Antrim	172	2007–09–13	5.0	1.5	54	54	51	55	52	54	52
22	2931	Barlow Lake	Barry	181	2007–09–15	10.5	3.2	43	41	42	43	42	44	43
22	2931	Cobb Lake	Barry	92	2007–09–13	15.0	4.6	38	42	42	42	40	43	42
22	2931	Crooked Lake	Barry	644	2007–09–09	7.5	2.3	48	48	48	49	49	48	47
22	2931	Payne Lake	Barry	113	2007–09–08	7.5	2.3	48	47	47	49	48	46	46
22	2931	Ann Lake	Benzie	501	2007–09–08	14.5	4.4	39	42	43	44	44	42	42
22	2931	Crystal Lake	Benzie	9869	2007–09–08	23.0	7.0	32	36	38	37	37	36	37
22	2931	Platte Lake	Benzie	2532	2007–09–09	11.0	3.4	43	46	45	47	45	44	44
22	2931	Sanford Lake	Benzie	53	2007–09–10	11.0	3.4	43	42	43	44	45	43	44
22	2931	Diamond Lake	Cass	1041	2007–09–11	10.0	3.0	44	43	39	47	43	43	41
22	2931	Eagle Lake	Cass	400	2007–09–19	10.5	3.2	43	46	44	49	47	47	46
22	2931	Magician Lake	Cass	522	2007–09–15	10.0	3.0	44	44	43	48	46	45	44

Appendix 2. Results and computations by Landsat-satellite path for Michigan inland lakes, 2007–08, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
22	2931	Puterbaugh Lake	Cass	44	2007–09–12	7.0	2.1	49	50	47	50	48	48	47
22	2931	Twin Lake (north)	Cass	61	2007–09–14	9.5	2.9	45	41	40	45	44	41	40
22	2931	Twin Lake (south)	Cass	43	2007–09–08	10.5	3.2	43	44	41	49	46	44	43
22	2931	George Lake	Clare	129	2007–09–09	11.0	3.4	43	46	47	45	46	44	45
22	2931	Windover Lake	Clare	68	2007–09–08	12.0	3.7	41	47	46	50	48	47	47
22	2931	Margrethe Lake	Crawford	1922	2007–09–16	12.0	3.7	41	46	47	49	48	46	47
22	2931	Bostwick Lake	Kent	213	2007–09–13	5.5	1.7	53	48	49	48	48	46	47
22	2931	Freska Lake	Kent	59	2007–09–11	10.0	3.0	44	43	44	44	45	43	44
22	2931	Reeds Lake	Kent	270	2007–09–19	4.0	1.2	57	54	53	55	53	55	54
22	2931	Big Star Lake	Lake	890	2007–09–11	11.0	3.4	43	44	46	43	46	43	45
22	2931	Glen Lake	Leelanau	4871	2007–09–12	14.5	4.4	39	34	34	36	35	34	33
22	2931	Hamlin Lake	Mason	4622	2007–09–14	13.0	4.0	40	43	46	44	46	43	45
22	2931	Blue Lake	Mecosta	229	2007–09–15	11.0	3.4	43	42	43	46	46	44	45
22	2931	Canadian Lakes	Mecosta	321	2007–09–20	11.0	3.4	43	43	45	45	47	45	46
22	2931	Horsehead Lake	Mecosta	443	2007–09–13	9.5	2.9	45	46	48	49	48	46	47
22	2931	Mecosta Lake	Mecosta	312	2007–09–13	10.0	3.0	44	46	47	49	49	46	47
22	2931	West Canadian Lake	Mescoda	133	2007–09–20	12.0	3.7	41	45	47	46	47	45	46
22	2931	Sapphire Lake	Missaukee	246	2007–09–10	7.5	2.3	48	46	47	48	48	47	48
22	2931	Baldwin Lake	Montcalm	62	2007–09–13	9.0	2.7	45	44	45	45	46	44	44
22	2931	Clifford Lake	Montcalm	195	2007–09–15	9.0	2.7	45	45	46	46	47	44	46
22	2931	Bills Lake	Newaygo	200	2007–09–14	10.5	3.2	43	43	42	46	44	43	42
22	2931	Emerald Lake	Newaygo	77	2007–09–13	11.5	3.5	42	44	44	45	44	44	44
22	2931	Fremont Lake	Newaygo	825	2007–09–12	8.0	2.4	47	51	50	51	49	49	48
22	2931	Hess Lake	Newaygo	765	2007–09–11	2.5	0.8	64	62	57	62	58	64	60

Appendix 2. Results and computations by Landsat-satellite path for Michigan inland lakes, 2007–08, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
22	2931	Kimball Lake	Newaygo	147	2007–09–15	6.5	2.0	50	48	48	47	48	47	48
22	2931	Pickerel Lake	Newaygo	308	2007–09–15	12.0	3.7	41	44	45	46	46	44	45
22	2931	Sylvan Lake	Newaygo	102	2007–09–13	11.0	3.4	43	43	42	45	43	43	42
22	2931	Robinson Lake	Oceana	134	2007–09–16	9.5	2.9	45	45	47	46	47	45	47
22	2931	Stony Lake	Oceana	287	2007–09–14	8.0	2.4	47	42	43	43	44	43	44
22	2931	Hicks Lake	Osceola	160	2007–09–09	5.5	1.7	53	50	51	50	50	50	51
22	2931	Viking Lake	Otsego	36	2007–09–20	4.0	1.2	57	51	49	51	50	50	50
22	2931	Crockery Lake	Ottawa	104	2007–09–11	7.0	2.1	49	46	45	48	47	47	47
22	2931	Corey Lake	St. Joseph	599	2007–09–11	14.5	4.4	39	43	42	45	43	42	40
22	2931	Cedar Lake	Van Buren	275	2007–09–15	16.5	5.0	37	40	40	44	42	41	40
22	2931	Crooked Lake	Van Buren	117	2007–09–09	11.0	3.4	43	41	40	45	42	41	40
22	2931	Crooked Lake Little	Van Buren	114	2007–09–12	13.0	4.0	40	37	37	43	41	42	40
22	2931	Gravel Lake	Van Buren	297	2007–09–13	9.0	2.7	45	43	43	44	43	41	40
22	2931	School Section Lake	Van Buren	79	2007–09–13	9.0	2.7	45	48	47	48	47	47	47
22	2931	Silver Lake	Van Buren	50	2007–09–13	10.0	3.0	44	41	41	42	43	41	41
22	2931	Pleasant Lake	Wexford	130	2007–09–13	8.5	2.6	46	46	48	46	48	45	47
22	2931	Stone Ledge Lake	Wexford	83	2007–09–14	9.0	2.7	45	45	45	48	46	48	49
23	28	Deer Lake	Alger	266	2007–08–07	11.0	3.4	43	44	44	41	41	42	42
23	28	Fish Lake	Alger	134	2007–08–07	14.5	4.4	39	38	37	41	41	42	42
23	28	Dana Lake	Delta	85	2007–08–07	9.5	2.9	45	45	45	43	43	43	43
23	28	Deep Lake	Delta	39	2007–08–07	14.5	4.4	39	40	40	41	40	40	40
23	28	Round Lake	Delta	482	2007–08–07	15.5	4.7	38	39	39	42	41	41	41
23	28	Bass Lake	Marquette	76	2007–08–06	20.0	6.1	34	37	37	36	36	35	35
23	28	Engman Lake	Marquette	48	2007–08–06	10.0	3.0	44	41	41	42	41	41	41

Appendix 2. Results and computations by Landsat-satellite path for Michigan inland lakes, 2007–08, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
23	28	Johnson Lake	Marquette	78	2007–08–06	18.0	5.5	35	36	36	38	37	36	36
23	28	Little Shag Lake	Marquette	107	2007–08–06	14.0	4.3	39	37	37	38	38	38	38
23	28	Pike Lake	Marquette	90	2007–08–06	14.0	4.3	39	39	40	41	40	39	39
23	28	Shag Lake	Marquette	195	2007–08–06	13.5	4.1	40	39	39	41	40	40	40
23	28	Sporley Lake	Marquette	77	2007–08–06	14.0	4.3	39	38	38	39	38	38	38
23	28	Grassy Lake	Schoolcraft	188	2007–08–08	11.0	3.4	43	41	42	43	42	42	41
23	28	McKeever Lake	Schoolcraft	147	2007–08–08	13.0	4.0	40	40	39	42	41	41	41
23	28	Petes Lake	Schoolcraft	194	2007–08–08	17.0	5.2	36	37	37	36	36	35	35
24	2728	Bass Lake	Dickinson	60	2008–07–31	16.4	5.0	37	38	38	38	38	36	37
24	2728	Carney Lake	Dickinson	115	2008–07–31	11.1	3.4	42	39	39	39	39	39	39
24	2728	Hanbury Lake	Dickinson	78	2008–07–31	18.3	5.6	35	*	*	*	*	38	37
24	2728	Mary Lake	Dickinson	85	2008–07–31	14.8	4.5	38	40	39	40	38	39	38
24	2728	Gerald Lake	Houghton	356	2008–07–29	11.8	3.6	42	45	44	46	45	46	45
24	2728	Otter Lake	Houghton	863	2008–07–30	11.5	3.5	42	44	45	45	45	44	45
24	2728	Pike Lake	Houghton	83	2008–07–29	7.9	2.4	47	48	48	46	45	45	45
24	2728	Roland Lake	Houghton	258	2008–07–29	11.3	3.4	42	44	44	45	45	46	45
24	2728	Sandy Lake	Houghton	101	2008–07–29	7.0	2.1	49	47	47	46	45	47	45
24	2728	Torch Lake	Houghton	2400	2008–07–30	10.0	3.0	44	43	43	45	45	44	45
24	2728	La Belle Lac	Keweenaw	1205	2008–07–30	8.0	2.4	47	46	46	46	46	45	45
24	2728	Manganese Lake	Keweenaw	56	2008–07–30	9.5	2.9	45	44	43	46	45	45	45
24	2728	Medora Lake	Keweenaw	690	2008–07–30	9.0	2.7	45	45	45	45	45	44	45
24	2728	Engman Lake	Marquette	48	2008–07–30	10.0	3.0	44	45	45	45	45	43	45
24	2728	Fish Lake	Marquette	151	2008–07–28	7.9	2.4	47	47	47	47	47	47	47
24	2728	Greenwood Reservoir	Marquette	1073	2008–07–28	6.8	2.1	49	46	46	46	46	46	46

Appendix 2. Results and computations by Landsat-satellite path for Michigan inland lakes, 2007–08, of measured and predicted Secchi-disk transparency and Trophic State Index values for the area of interest, area of interest lake-average method, and the Gethist method.—Continued

[SDT, Secchi-disk transparency; AOI, area of interest; TSI, Trophic State Index; Eq, equation; *, measurement not used owing to issue with placement]

Landsat satellite					Measured SDT				AOI TSI		AOI lake		Gethist TSI	
Path	Row	Lake Name	County	Acres	Sampled	SDT ft	SDT m	TSI	Eq1	Eq2	Eq1	Eq2	Eq1	Eq2
24	2728	Lake Independence	Marquette	2041	2008–07–28	10.5	3.2	43	44	44	45	45	45	45
24	2728	Lake Michigamme	Marquette	4292	2008–07–29	8.8	2.7	46	46	46	46	46	46	46
25	28	Allen Lake	Gogebic	78	2008–08–06	14.5	4.4	39	35	39	33	47	39	41
25	28	Beatons Lake	Gogebic	324	2008–08–05	22.0	6.7	33	33	34	32	35	31	30
25	28	Cisco Lake	Gogebic	567	2008–08–05	5.5	1.7	53	49	47	44	50	50	47
25	28	Duck Lake	Gogebic	612	2008–08–06	11.5	3.5	42	44	46	38	48	43	44
25	28	Imp Lake	Gogebic	91	2008–08–06	24.0	7.3	31	28	28	33	39	33	33
25	28	Lac Vieux Desert	Gogebic	4370	2008–08–06	7.5	2.3	48	47	42	42	50	48	46
25	28	Little Duck Lake	Gogebic	44	2008–08–06	19.0	5.8	35	39	40	35	45	35	38
25	28	Marion Lake	Gogebic	297	2008–08–06	12.0	3.7	41	41	39	32	42	37	37
25	28	Thousand Island Lake	Gogebic	1009	2008–08–06	12.5	3.8	41	39	40	38	43	37	38
25	28	Golden Lake	Iron	274	2008–08–04	22.0	6.7	33	33	33	38	40	33	34
25	28	Hagerman Lake	Iron	565	2008–08–04	17.0	5.2	36	38	40	42	47	42	41
25	28	Ottawa Lake	Iron	532	2008–08–04	20.5	6.2	34	39	40	41	44	38	38
25	28	Smoky Lake	Iron	596	2008–08–04	14.5	4.4	39	41	37	41	41	37	35
25	28	Lake Gogebic	Ontonagon	13127	2008–08–05	8.0	2.4	47	43	46	50	51	46	48

Fuller and others—**Predicting Lake Trophic State for Michigan Inland Lakes, 2003–05 and 2007–08**—Scientific Investigations Report 2011–5007

Printed on recycled paper