Prepared in cooperation with the Michigan Department of Environmental Quality

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Scientific Investigations Report 2016–5023

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U.S. Geological Survey, Reston, Virginia: 2016

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Suggested citation:
Fuller, L.M., and Jodoin, R.S., 2016, Estimation of a Trophic State Index for selected inland lakes in Michigan, 1999–2013: U.S. Geological Survey Scientific Investigations Report 2016–5023, 16 p., http://dx.doi.org/10.3133/sir20165023.

ISSN 2328-0328 (online)

Acknowledgments

The Michigan Department of Environmental Quality and the volunteers of the Cooperative Lake Monitoring Program were invaluable in providing much of the field data used in this project. The Wisconsin Department of Natural Resources Surface Water Integrated Monitoring System Database was key to additional field data for the western half of the Upper Peninsula of Michigan. 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 field technicians provided measurements for the Upper Peninsula of Michigan to supplement the measurements from volunteers of the Cooperative Lake Monitoring Program. The following U.S. Geological Survey, 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, C. Taricska, D.G. Wydra, and J.A. Wilkinson.

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Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
	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).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

ANOVA	Analysis of Variance
CLMP	Cooperative Lakes Monitoring Program
MDEQ	Michigan Department of Environmental Quality
NLA	National Lakes Assessment
R^2	coefficient of determination
SDT	Secchi-disk transparency
eSDT	estimated Secchi-disk transparency
TSI	Trophic State Index
eTSI	estimated Trophic State Index
EPA	Environmental Protection Agency
USGS	U.S. Geological Survey

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Abstract

A 15-year estimated Trophic State Index (eTSI) for Michigan inland lakes is available, and it spans seven datasets, each representing 1 to 3 years of data from 1999 to 2013. On average, 3,000 inland lake eTSI values are represented in each of the datasets by a process that relates field-measured Secchi-disk transparency (SDT) to Landsat satellite imagery to provide eTSI values for unsampled inland lakes. The correlation between eTSI values and field-measured Trophic State Index (TSI) values from SDT was strong as shown by R^2 values from 0.71 to 0.83. Mean eTSI values ranged from 42.7 to 46.8 units, which when converted to estimated SDT (eSDT) ranged from 8.9 to 12.5 feet for the datasets. Most eTSI values for Michigan inland lakes are in the mesotrophic TSI class. The Environmental Protection Agency (EPA) Level III Ecoregions were used to illustrate and compare the spatial distribution of eTSI classes for Michigan inland lakes. Lakes in the Northern Lakes and Forests, North Central Hardwood Forests, and Southern Michigan/Northern Indiana Drift Plains ecoregions are predominantly in the mesotrophic TSI class. The Huron/Erie Lake Plains and Eastern Corn Belt Plains ecoregions, had predominantly eutrophic class lakes and also the highest percent of hypereutrophic lakes than other ecoregions in the State. Data from multiple sampling programs—including data collected by volunteers with the Cooperative Lakes Monitoring Program (CLMP) through the Michigan Department of Environmental Quality (MDEQ), and the 2007 National Lakes Assessment (NLA)—were compiled to compare the distribution of lake TSI classes between each program. The seven eTSI datasets are available for viewing and download with eSDT from the Michigan Lake Water Clarity Interactive Map Viewer at http://mi.water.usgs.gov/projects/RemoteSensing/index.html.

Introduction

The State of Michigan has over 11,000 inland lakes that are valuable ecological, aesthetic, and recreational resources. Approximately 4,000 of these lakes are larger than 20 acres in size, and about 1,300 of those lakes have public access to boat launches or beaches. Recreational, property, and ecological values are closely related to the quality of water in these inland lakes (Krysel and others, 2003). In 2014, tourism in Michigan accounted for $22.8 billion in economic activity, much of which was related to recreational activities at Michigan's lakes (Wichtner-Zoia and Nicholls, 2015). Thus, inland lakes are an important economic and ecological resource to Michigan.

The water-quality characteristics of inland lakes are critical factors in determining a lakes' recreational use and diversity of habitat and species. The U.S. Geological Survey (USGS) and the Michigan Department of Environmental Quality (MDEQ) monitor many of Michigan's lakes, but it is not economically feasible to monitor the quality of all 11,000 inland lakes 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 collect data for inland lakes, helping to protect and manage the quality of 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), Michigan (Fuller and others, 2011) and elsewhere (Baban, 1993; Dekker and Peters, 1993; Mayo and others, 1995; Giardino and others, 2001) to estimate a Trophic State Index (eTSI) from Secchi disk transparency (SDT) measurements for inland lakes. Carlson (1977) proposed to quantify the trophic state of a waterbody by its Trophic State Index (TSI) value, which can be classified into four basic classes: oligotrophic, mesotrophic, eutrophic, and hypereutrophic. Carlson's TSI model was developed for use with lakes that have few rooted aquatic plants and little nonalgal turbidity (Environmental Protection Agency, 2007). The progression of a lake from oligotrophic to eutrophic can be computed from measures of total phosphorus (TP), 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 from TP, SDT and Chl-*a* are.

$$TSI = 14.41 \ln \text{TP (micrograms per liter, (µg/L))} + 4.15 \quad (1)$$

$$TSI = 60 - 14.41 \ln (\text{SDT feet} * 0.3048) \quad (2)$$

$$TSI = 9.81 \ln \text{Chl-}a \text{ (µg/L)} + 30.6 \quad (3)$$

Previous studies to produce eTSI values from field-measurements of SDT in Michigan include Fuller and others (2004, 2011). To date, there are 15 years of eTSI values for Michigan's inland lakes larger than 20 acres, within 7 datasets grouped as either single or multiple years—due to cloud cover preventing full statewide coverage for a single year—including 1999–2000, 2002, 2003–05, 2007–08, 2009–10, 2011, and 2013. Landsat satellite imagery with 30-meter cells is cost effective and available throughout the late summer season, allowing for eTSI values for lakes larger than 20 acres. eTSI values for Michigan inland lakes provide additional information for lake managers by extending existing sampling programs. These datasets are available online for viewing and download from the (http://mi.water.usgs.gov/projects/RemoteSensing/index.html).

Purpose and Scope

The purpose of this report is to provide an overview of the process used to provide eTSI values for unsampled inland lakes in Michigan by correlation of Landsat satellite imagery to SDT measurements obtained in the field. Information about the eTSI datasets is summarized, and those available for viewing and downloading are described. Technical details on the process to produce the eTSI values can be found in the previous reports by Fuller and others (2004, 2011).

Methods

The process to produce eTSI values for inland lakes is described in Fuller and others (2011) and summarized here. First, Landsat satellite imagery with minimal cloud cover is selected from late-summer (July–September) and processed to mask out nonwater areas and isolate inland lakes larger than 20 acres by use of inland lake polygons (Breck, 2004). Second, field-measurements of SDT corresponding to the Landsat satellite imagery are obtained. Third, field-measurements of SDT, within plus or minus 10 days of the Landsat satellite imagery acquisition date, are correlated to the satellite imagery to produce a regression model specific to each date of Landsat satellite imagery. The end results are eTSI values for open-water areas of inland lakes larger than 20 acres within the Landsat satellite imagery.

Six paths of Landsat satellite data cover the State of Michigan; each path (except for path 23) is separated into multiple scenes that are referenced by path and row numbers (fig. 1). Each path of Landsat satellite data is acquired on the same date; thus multiple scenes from the same path can be grouped if all scenes are free of cloud cover and haze. The Landsat satellite scenes for each path were selected from 1 day over a 3-month period (July through September) with the least amount of cloud cover and haze (preferably less than

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

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

Lake trophic condition	TSI value	SDT (ft)	Chy-*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

Warbach, J.D., 1990, Protecting inland lakes: a watershed management guidebook, Lansing, MI, Planning & Zoning Center, Inc.,

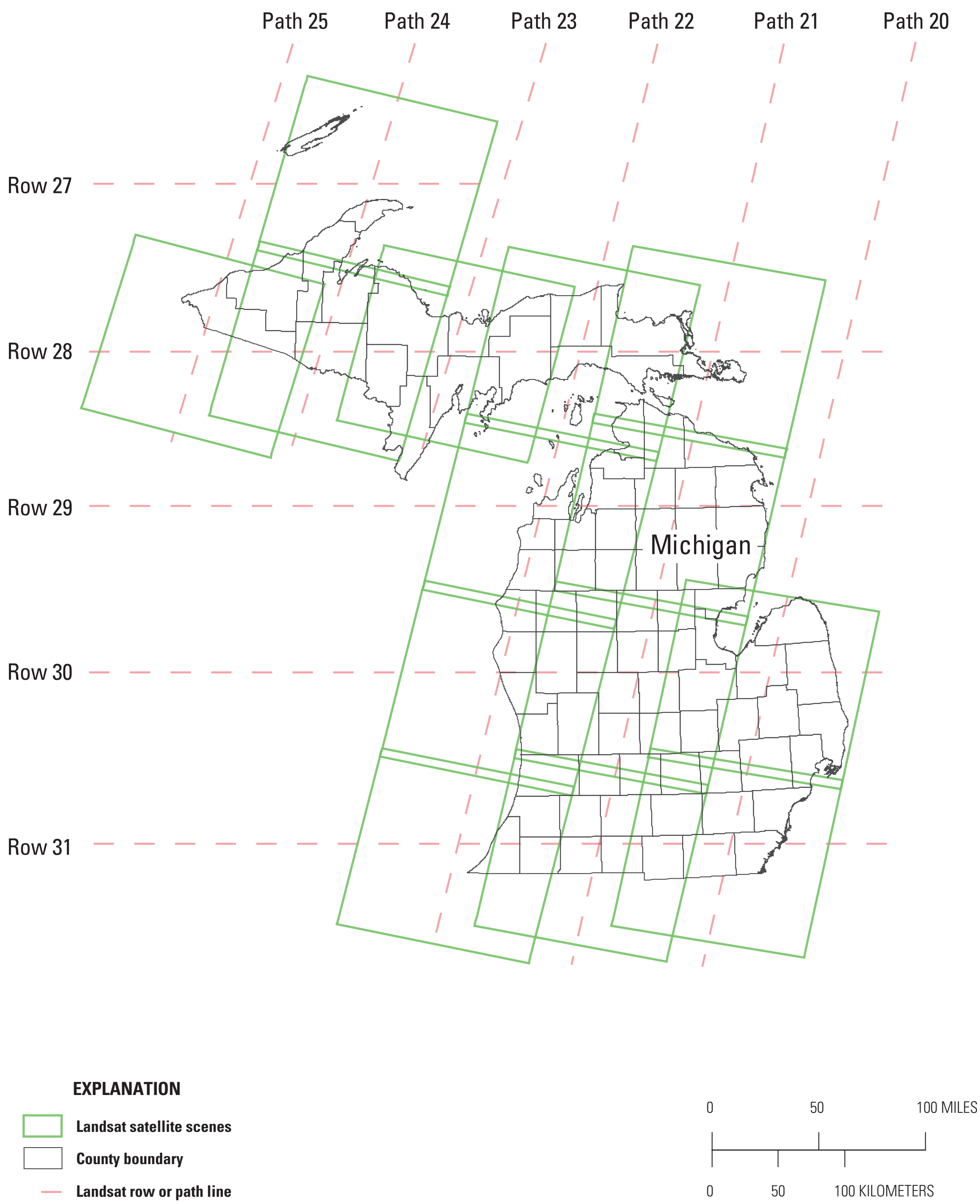

Figure 1. Landsat satellite scenes covering Michigan.

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, 2002). The satellite imagery was processed to remove areas affected by clouds, cloud shadows, haze, shoreline, and dense vegetation (Fuller and others, 2011). For some years, enough satellite imagery was available with minimal cloud coverage to provide eTSI values for a single year, such as 2002. Other years were combined, such as 1999–2000, when cloud cover prevented eTSI values for a single year.

SDT measurements are obtained using a Secchi disk, which is an 8-inch-diameter circular disk, painted black and white in alternating quadrants to measure water clarity. The Secchi disk is lowered into the lake, usually from a boat, and the depth at which the disk becomes no longer visible is known as the SDT. Field-measured SDT were obtained from the MDEQ Cooperative Lakes Monitoring Program (CLMP), which is a volunteer network monitoring approximately 250 lakes weekly during the months of April to October (http://www.mcgi.state.mi.us/miswims/). Other sources of data included the USGS and the Wisconsin Department of Natural Resources Surface Water Integrated Monitoring System Database; those data sources were used to supplement information in the western Upper Peninsula of Michigan where CLMP measurements were sparse (http://dnr.wi.gov/topic/surfacewater/swims/). Starting in 2002, the USGS, in cooperation with the MDEQ, provided a newsletter to the CLMP volunteers to educate them on the remote sensing initiative. The newsletter provided satellite overpass dates for each year, allowing CLMP volunteers to plan, when possible, to take their SDT measurements within plus or minus 3 days of the satellite imagery acquisition date. The 6-day window would allow for more useable measurements surrounding the satellite imagery date, although up to 10 days were found acceptable from Olmanson (2002). Since the newsletter was initiated in 2002, there was an increase in the number of SDT measurements more closely surrounding the satellite acquisition dates.

Field-measurements of SDT were correlated to the Landsat satellite imagery by using the GetHist program, which uses a portion of the open-water areas remaining after satellite data processing (as documented in Olmanson and others, 2001) to obtain mean reflectance values for each inland lake. The output values from the GetHist program were used to produce regression equations specific to each path of satellite data. In table 2, the bands with corresponding wavelengths are noted. The regression equation used to produce eTSI values for Landsat 5 and 7 was (Kloiber and others, 2002):

$$\ln(\mathrm{SDT}) = a(\mathrm{band1}/\mathrm{band3}) + b(\mathrm{band1}) + c \quad (4)$$

The regression equation used to produce eTSI values for Landsat 8, due to a different collection interval of bands, was

$$\ln(\mathrm{SDT}) = a(\mathrm{band2}/\mathrm{band4}) + b(\mathrm{band2}) + c \quad (5)$$

Table 2. Landsat 5–8 bands used in regression equations with corresponding wavelengths.

[µm, micrometers,]

Landsat satellite	Band 1	Band 2	Band 3	Band 4
Landsat 5 Thematic Mapper	0.45–0.52 µm	0.52–0.60 µm	0.63–0.69 µm	0.76–0.90 µm
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
Landsat 8 Operational Land Imager	0.43–0.45 µm	0.45–0.51 µm	0.53–0.59 µm	0.64–0.67 µm

Shaded bands used in regression equations

In both equations, the variables a, b, and c were derived coefficients from the regression equation.

The regression equation was then applied to the processed Landsat imagery for all unsampled lakes larger than 20 acres in the Landsat path for that date. Not all lakes had an eTSI value for every dataset, depending if field-measured SDT were available (path 23 in the Upper Peninsula had sparse coverage in some years), or if cloud cover, cloud shadows, or haze prevented an estimation.

The resulting eTSI and eSDT values for each path were combined for each dataset using highest to lowest R^2 values. An analysis of variance test (ANOVA) was used to determine if there was a statistically significant difference at the 95-percent confidence interval between the eTSI and eSDT means of the datasets. ANOVA determines if there was a difference between the means of the datasets, but not which datasets were different from each other. The ANOVA test was chosen due to the large number of lakes (approximately 3,000 per dataset), and because the TSI values reflect a normal distribution. To determine which datasets were statistically significant from each other, Tukey's honest significant difference (HSD) test was used (Coolidge, 2000).

Results

Seven datasets of eTSI values are available for Michigan inland lakes, spanning a 15-year period from 1999 to 2013. A total of 45 Landsat paths of satellite data were processed, and 5–8 paths with unique dates merged together to create eTSI values for each dataset. A summary of the image dates, with information on the field-measurements of SDT used and the regression equation information specific to each image date, is provided in table 3. The equations used to produce eTSI values are unique to each image date of Landsat data. The R^2 value

Table 3. Landsat-image and calibration-model data for estimated Trophic State Index (eTSI), Michigan inland lakes, 1999–2013.

[SDT, Secchi-disk transparency; m, meter; ft, feet, R^2, coefficient of determination; SEE, Standard Error of Estimate; TM, Thematic Mapper; x, eTSI; B, Landsat satellite band number]

Image date	Path	Rows	Number of images used in path	Satellite	Days prior	Days past	Number of measurements	SDT range (m)	SDT range (ft)	R^2	SEE	Equation:
1999–2000 Estimated TSI												
7/17/2000	20	30–31	2	Landsat TM 5	4	6	22	1.7–6.4	5.5–21.0	0.75	0.098	x = B1/B3(2.4709) + B1(-0.0111) + -3.0607
7/30/1999	21	28–31	4	Landsat TM 5	7	7	54	0.9–10.0	3.0–33.0	0.69	0.2344	x = B1/B3(1.0250) + B1(-0.0040) + -2.6127
8/24/2000	22	28–31	4	Landsat TM 5	7	7	46	0.8–8.5	2.5–28.0	0.78	0.231	x = B1/B3(1.0489) + B1(-0.0314) + -1.1672
8/22/2000	24	27–28	2	Landsat TM 5	7	7	41	0.9–8.0	3.0–26.0	0.82	0.229	x = B1/B3(3.5069) + B1(0.1356) + -19.9172
8/29/2000	25	28	1	Landsat TM 5	7	7	90	0.6–6.9	2.0–22.5	0.81	0.239	x = B1/B3(1.6309) + B1(0.0468) + -7.6868
2002 Estimated TSI												
9/1/2002	20	30–31	2	Landsat TM 5	7	5	27	1.8–5.0	6.0–16.5	0.71	0.146	x = B1/B3(0.7484) + B1(-0.0264) + -0.3207
9/8/2002	21	28–31	4	Landsat TM 5	6	7	75	0.8–8.0	2.5–26.5	0.80	0.189	x = B1/B3(1.6781) + B1(0.0301) + -6.7672
7/13/2002	22	28–31	4	Landsat TM 5	6	7	59	0.9–8.2	3.0–27.0	0.80	0.202	x = B1/B3(1.2221) + B1(0.0236) + -4.8995
8/30/2002	22	29–31	4	Landsat TM 5	4	6	57	0.9–9.9	3.0–32.5	0.82	0.203	x = B1/B3(1.5958) + B1(0.0535) + -7.8518
7/11/2002	24	27–28	2	Landsat TM 5	7	7	69	1.1–2.0	3.5–25.0	0.85	0.173	x = B1/B3(1.5083) + B1(0.0492) + -7.7391
9/4/2002	25	28	1	Landsat TM 5	7	7	83	0.9–7.3	3.0–24.0	0.86	0.184	x = B1/B3(1.4881) + B1(-0.0335) + -3.5791
2003–05 Estimated TSI												
9/22/2004	20	30–31	2	Landsat TM 5	6	4	22	1.5–7.3	5.0–24.0	0.73	0.238	x = B1/B3(1.6413) + B1(-0.0196) + -4.8612
9/13/2004	21	28–31	4	Landsat TM 5	8	6	75	0.8–8.5	2.5–28	0.69	0.243	x = B1/B3(1.3398) + B1(0.0104) + -4.4821
9/20/2004	22	28–31	4	Landsat TM 5	7	6	50	0.9–5.9	3.0–19.0	0.72	0.192	x = B1/B3(0.8592) + B1(-0.0380) + -1.0662
9/21/2005	24	27	1	Landsat TM 5	0	5	10	2.0–5.3	6.5–17.5	0.73	0.194	x = B1/B3(1.1798) + B1(0.1401) + -10.0580
7/19/2005	24	28	1	Landsat TM 5	0	6	15	2.1–6.7	7.0–22.0	0.73	0.214	x = B1/B3(0.7688) + B1(0.1562) + -9.6935
8/22/2003	25	28	1	Landsat TM 5	10	6	12	6.0–20.5	1.8–6.3	0.65	0.256	x = B1/B3(1.1529) + B1(0.0945) + -7.8513
2007–08 Estimated TSI												
8/30/2007	20	30–31	2	Landsat TM 5	6	3	18	1.8–4.9	6.0–16.0	0.72	0.159	x = B1/B3(2.1944) + B1(0.0401) + -9.6437
9/22/2007	21	28–31	3	Landsat TM 5	7	0	72	0.8–7.0	2.5–23.0	0.75	0.183	x = B1/B3(1.3083) + B1(-0.0631) + -1.2937
6/25/2007	22	28	1	Landsat TM 5	0	3	15	2.4–6.4	8.0–21.0	0.74	0.161	x = B1/B3(1.0580) + B1(0.0103) + -3.3394
9/13/2007	22	29–31	3	Landsat TM 5	5	7	56	2.5–23.0	0.8–7.0	0.67	0.223	x = B1/B3(0.9800) + B1(-0.0046) + -2.5253
8/3/2007	23	28	1	Landsat TM 5	0	5	15	2.9–6.1	9.5–20.0	0.67	0.130	x = B1/B3(0.3153) + B1(0.1069) + -5.2894
7/27/2008	24	27–28	2	Landsat TM 5	0	4	18	2.1–5.6	6.8–18.3	0.68	0.166	x = B1/B3(0.4080) + B1(0.0512) + -3.3810
8/3/2008	25	28	1	Landsat TM 5	0	3	14	1.7–7.3	5.5–24.0	0.73	0.256	x = B1/B3(1.6371) + B1(-0.0239) + -3.3531

Table 3. Landsat-image and calibration-model data for estimated Trophic State Index (eTSI), Michigan inland lakes, 1999–2013.—Continued

[SDT, Secchi-disk transparency; m, meter; ft, feet, R^2, coefficient of determination; SEE, Standard Error of Estimate; TM, Thematic Mapper; x, eTSI; B, Landsat satellite band number]

Image date	Path	Rows	Number of images used in path	Satellite	Days prior	Days past	Number of measurements	SDT range (m)	SDT range (ft)	R^2	SEE	Equation:
2009–10 Estimated TSI												
9/4/2009	20	30–31	2	Landsat TM 5	5	4	12	0.8–6.4	2.5–21	0.76	0.304	x = B1/B3(2.5645) + B1(0.0870) + -13.1486
7/9/2009	21	28	1	Landsat TM 5	0	5	14	1.4–6.1	4.5–20	0.78	0.233	x = B1/B3(1.8087) + B1(-0.0106) + -5.8977
9/11/2009	21	29–31	3	Landsat TM 5	3	3	52	0.8–7	2.5–23	0.76	0.208	x = B1/B3(1.6664) + B1(0.0667) + -8.7592
9/2/2009	22	28	1	Landsat TM 5	8	2	21	1.5–5.3	5.0–17.5	0.73	0.210	x = B1/B3(2.1777) + B1(-0.1237) + -1.4833
9/2/2009	22	29–31	3	Landsat TM 5	3	4	69	0.8–8.2	2.5–27	0.78	0.211	x = B1/B3(1.0289) + B1(-0.0662) + 0.4062
8/31/2009	24	27–28	2	Landsat TM 5	7	7	88	0.8–10	2.8–33	0.73	0.297	x = B1/B3(1.8777) + B1(-0.0198) + -5.1770
7/8/2010	25	28	1	Landsat TM 5	3	8	36	1.2–7.3	4.0–24	0.81	0.191	x = B1/B3(1.5708) + B1(0.0421) + -6.9965
2011 Estimated TSI												
7/8/2011	20	30–31	2	Landsat TM 5	6	7	32	0.6–5.8	2.0–19.0	0.80	0.228	x = B1/B3(1.5391) + B1(0.0022) + -4.4871
7/15/2011	21	28	1	Landsat TM 5	0	4	12	1.4–4.3	4.5–14.0	0.70	0.210	x = B1/B3(1.1372) + B1(0.0948) + -8.6398
8/16/2011	21	29–31	3	Landsat TM 5	5	6	98	0.6–10.7	2.0–35.0	0.83	0.201	x = B1/B3(1.6740) + B1(-0.0161) + -4.6631
8/23/2011	22	28	1	Landsat TM 5	0	3	12	1.5–5.6	5.0–18.5	0.76	0.229	x = B1/B3(1.9254) + B1(0.0160) + -6.9818
7/6/2011	22	29–31	3	Landsat TM 5	4	7	41	1.7–7.2	5.5–23.5	0.70	0.160	x = B1/B3(0.5054) + B1(-0.0145) + 0.5187
8/14/2011	23	28	1	Landsat TM 5	2	3	12	2.6–5.2	8.5–17.0	0.69	0.125	x = B1/B3(-1.3926) + B1(0.0261) + 5.6555
8/6/2011	24	27–28	2	Landsat TM 5	7	7	47	1.5–5.5	4.8–18.0	0.80	0.124	x = B1/B3(0.9107) + B1(-0.0661) + 0.8236
7/11/2011	25	28	1	Landsat TM 5	7	6	113	0.9–8.2	3.0–27.0	0.81	0.213	x = B1/B3(1.4013) + B1(0.0571) + -7.1141
2013 Estimated TSI												
7/13/2013	20	30–31	2	Landsat 8	6	8	18	2.1–5.5	7.0–18.0	0.71	0.157	x = B2/B4(11.4066) + B2(-0.0005) + -9.6304
7/20/2013	21	28–29	2	Landsat 8	6	4	16	2.4–8.2	8.0–27.0	0.74	0.214	x = B2/B4(18.4695) + B2(-0.0002) + -21.6817
8/21/2013	21	29–31	3	Landsat 8	6	10	30	1.2–5.0	4.0–16.5	0.71	0.216	x = B2/B4(13.5427) + B2(-0.0005) + -12.1457
7/11/2013	22	28–31	4	Landsat 8	4	10	28	1.2–7.6	4.0–25.0	0.77	0.187	x = B2/B4(10.4659) + B2(-0.0004) + -8.7528
9/11/2013	24	27–28	2	Landsat 8	7	7	47	0.9–7.1	3.0–23.5	0.7414	0.224	x = B2/B4(17.0272) + B2(-0.0005) + -17.0226
9/26/2013	25	28	1	Landsat 7	7	8	37	1.2–5.9	4.0–19.5	0.81	0.201	x = B1/B3(3.0070) + B1(-0.0197) + -4.5451

for each image date of eTSI ranged from 0.65 to 0.86, with a mean of 0.75, and an average standard of error of 0.20. These relationships between Landsat satellite-derived eTSI values and field-measured SDT converted to TSI values were strong, as shown in figure 2. The R^2 values ranged from 0.71 to 0.83.

eSDT and eTSI for Michigan inland lakes were compared to the field-measured SDT and TSI from SDT (table 4). The eSDT dataset values ranged from 67 to 70 percent within 2 SDT feet, 94 to 98 percent within 5 SDT feet, and all except one eSDT dataset had 100 percent within 10 SDT feet. For the eTSI, 48 to75 percent were within 2 TSI units, 84 to 98 percent within 5 TSI units, and all eTSI datasets were 100 percent within 10 TSI units. For all of the datasets, 74 to 86 percent of eTSI values were estimated to the correct TSI class.

Table 4. Results for datasets of measured Secchi-disk transparency values compared to estimated Secchi-disk transparency within 2, 5, and 10 feet; Trophic State Index values within 2, 5, and 10 units; and estimated to measured Trophic State Index class for Michigan inland lakes.

[SDT, Secchi-disk transparency; TSI, Trophic State Index]

Dateset	Percentage within 2 SDT feet	Percentage within 5 SDT feet	Percentage within 10 SDT feet	Percentage within 2 TSI units	Percentage within 5 TSI units	Percentage within 10 TSI units	Percentage within correct TSI class
1999–2000	68	94	100	49	84	100	77
2002	76	98	100	60	98	100	80
2003–05	68	96	100	48	95	100	78
2007–08	75	97	100	75	98	100	86
2009–10	67	94	99	51	91	100	79
2011	76	98	100	61	98	100	80
2013	70	96	100	52	93	100	74

On average, about 3,000 eTSI values are available for each of the 7 datasets. Summary statistics for eTSI units and eSDT (in feet) are shown in table 5. Mean eTSI ranged from 42.7 to 46.8 units and the mean eSDT ranged from 8.9 to 12.5 feet. When comparing the 1999–2000 and 2013 datasets, the eSDT mean increased from 8.9 to 12.5 feet and the median from 8.8 to 11.6 feet,, and the eTSI mean decreased from 46.8 to 42.7 TSI values and the median from 45.8 to 41.8 TSI values. If the 1999–2000 and 2013 datasets are removed, the eTSI and eSDT mean and median values remain relatively consistent among the middle year datasets (table 5). When comparing datasets, it is important to note that not all lakes have adequate representation in each dataset due to cloud cover, cloud shadow, haze, and dense vegetation. Additional factors affecting lakes not represented in each dataset could be due to the date and climate for that dataset, along with the Landsat platform used. Without eTSI and eSDT for missing lakes, it is difficult to determine how their inclusion might change the statistics.

To determine if there was a statistically significant difference at the 95-percent confidence interval, the ANOVA test was used to determine the significance between both the eTSI and the eSDT values for each dataset. The ANOVA F distribution for eTSI was 115.7, and for the eSDT was 171.1, both of which were larger than the F critical value of 2.1, which indicates that there was a statistical difference among the datasets (table 6). To determine which datasets were statistically significant, a Tukey's test value of 0.36 was used. Tukey's test values were greater for the eTSI between the 1999–2000 and 2013 datasets, and most of the 2011 dataset; values were greater for the eSDT between the 1999–2000, 2011 and 2013 datasets (table 7). In summary, eTSI values decreased, and eSDT values increased with time.

Most of Michigan's inland lakes are in the mesotrophic TSI class. Figure 3 shows the distribution of lakes by trophic class for each of the 1999–2013 datasets.

Five EPA level III ecoregions are in Michigan (fig. 4), and they differ by vegetation, soils, geology, climate, hydrology, and land use (Environmental Protection Agency, 2011). These ecoregions were used to determine and compare the spatial distribution of eTSI values for Michigan's inland lakes (fig. 4). The North Central Hardwood Forests ecoregion generally has more oligotrophic and mesotrophic, and fewer eutrophic classified lakes, and the mean eTSI values are generally lower and eSDT values are generally higher than in the other ecoregions of the State (table 8). The Northern Lakes and Forest ecoregion has the highest number of lakes with eTSI values in four out of the seven datasets (fig. 5), and is comparable

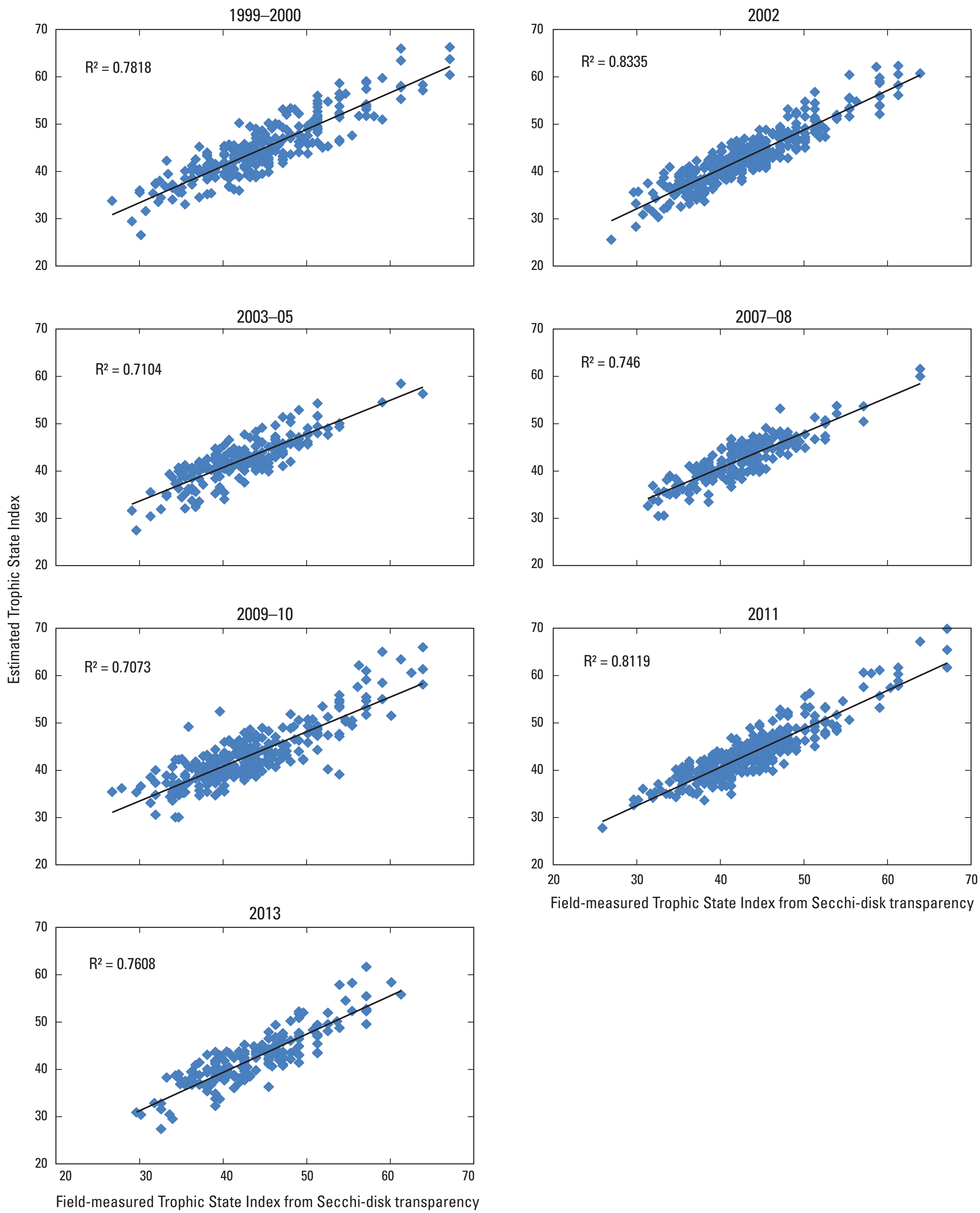

Figure 2. Landsat estimated Trophic State Index (eTSI) vs field-measured TSI, Michigan inland lakes, 1999–2013.

Table 5. Statistical summary of statewide estimated Trophic State Index (eTSI) and estimated Secchi-disk transparency (eSDT) for Michigan inland lakes by dataset.

Statewide estimated Trophic State Index (eSTI)							
	1999–2000	**2002**	**2003–05**	**2007–08**	**2009–10**	**2011**	**2013**
count	3,265	3,278	2,955	2,876	2,465	3,071	3,171
minimum	20.4	10.7	19.5	28.9	25.6	5.2	18.2
25th percentile	42.7	41.2	40.7	41.1	40.4	40.1	37.9
median	45.8	44.4	44.2	44.1	44.1	43.7	41.8
mean	46.8	45.3	45.3	44.9	45.1	44.7	42.7
75th percentile	50.6	48.8	48.9	47.3	48.1	47.4	45.9
maximum	82.6	80.3	79.2	83.2	84.1	87.8	99.3
standard deviation	6.2	6.6	6.9	6.3	6.9	7.3	8.3
Statewide estimated Secchi-disk transparency (eSDT) (in feet)							
	1999–2000	**2002**	**2003–05**	**2007–08**	**2009–10**	**2011**	**2013**
count	3,265	3,278	2,955	2,876	2,465	3,071	3,171
minimum	0.7	0.8	0.9	0.7	0.6	0.5	0.2
25th percentile	6.3	7.2	7.1	7.9	7.5	7.9	8.7
median	8.8	9.7	9.9	9.9	9.9	10.2	11.6
mean	8.9	10.1	10.1	10.1	10.1	10.6	12.5
75th percentile	10.9	12.1	12.5	12.2	12.8	13.0	15.2
maximum	51.3	100.2	54.5	28.4	35.8	146.8	59.7
standard deviation	3.8	5.0	4.4	3.7	4.0	5.3	6.1

Table 6. Analysis of variance for estimated Trophic State Index (eTSI) and Secchi-disk transparency (SDT) for Michigan inland lakes from 7 datasets from 1999–2013.

ANOVA - estimated Trophic State Index (eTSI)						
Source of variation	**Sum of square**	**Degrees of freedom**	**Mean squares**	**F distribution**	**P-value**	**F critical value**
Between Groups	32,599	6	5,433	116	0.0	2.1
Within Groups	988,524	21,055	47			
Total	1,021,123	21,061				
ANOVA - Secchi-disk transparency (SDT)						
Source of variation	**Sum of square**	**Degrees of freedom**	**Mean squares**	**F distribution**	**P-value**	**F critical value**
Between Groups	22,809	6	3,802	171	0.0	2.1
Within Groups	467,796	21,055	22			
Total	490,605	21,061				

Table 7. Tukey's test for estimated Trophic State Index (eTSI) and Secchi-disk transparency (SDT) for Michigan inland lakes from 7 datasets from 1999–2013.

Tukey's - Difference of means for estimated Trophic State Index (eTSI)

	1999–2000	2002	2003–05	2007–08	2009–10	2011	2013
1999–2000	0						
2002	* 1.53	0					
2003–05	* 1.53	0.00	0				
2007–08	* 1.93	* 0.40	* 0.39	0			
2009–10	* 1.66	0.13	0.13	0.27	0		
2011	* 2.07	* 0.54	* 0.53	0.14	* 0.41	0	
2013	* 4.40	* 2.87	* 2.87	* 2.48	* 2.74	* 2.34	0

Tukey's - Difference of means for Secchi-disk transparency (SDT)

	1999–2000	2002	2003–05	2007–08	2009–10	2011	2013
1999–2000	0						
2002	* 1.13	0					
2003–05	* 1.15	0.02	0				
2007–08	* 1.20	0.07	0.05	0			
2009–10	* 1.19	0.05	0.04	0.01	0		
2011	* 1.63	* 0.50	* 0.48	* 0.43	* 0.44	0	
2013	* 3.63	* 2.49	* 2.48	* 2.43	* 2.44	* 2.00	0

*Tukey's HSD test values greater than 0.36 are statistically significant at the 95-percent confidence interval.

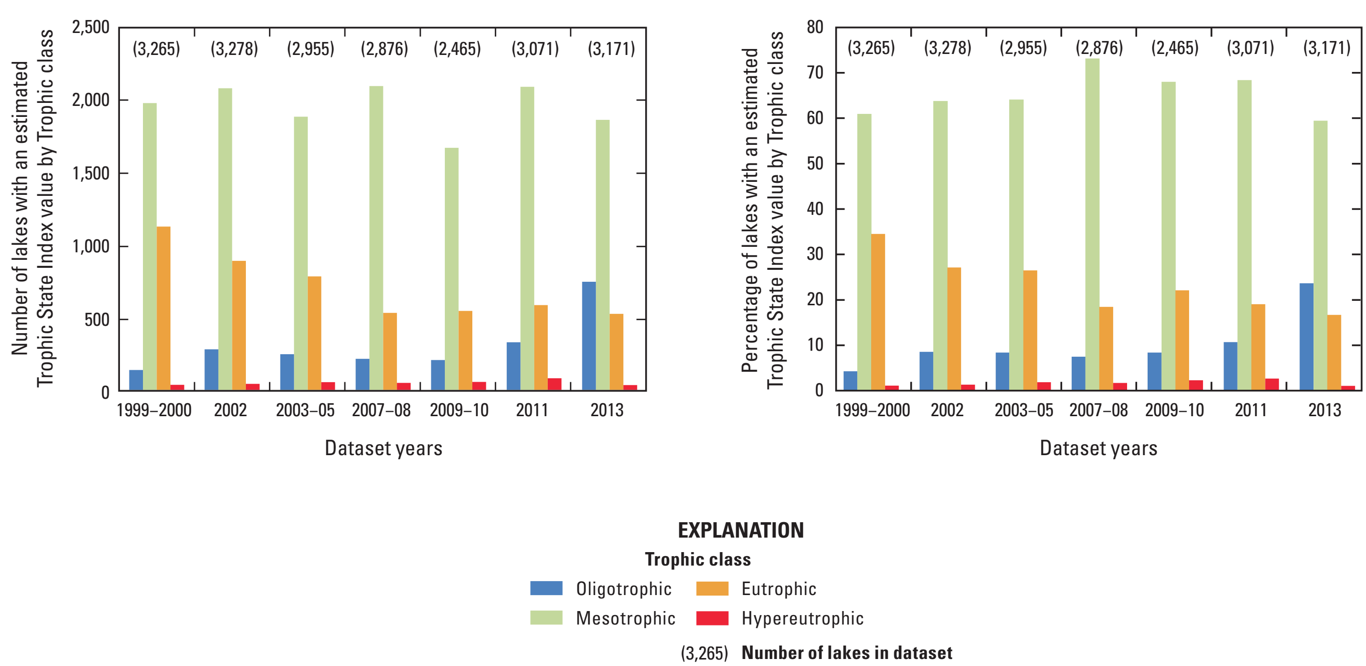

Figure 3. Distribution of lakes by trophic class for the 1999–2013 datasets.

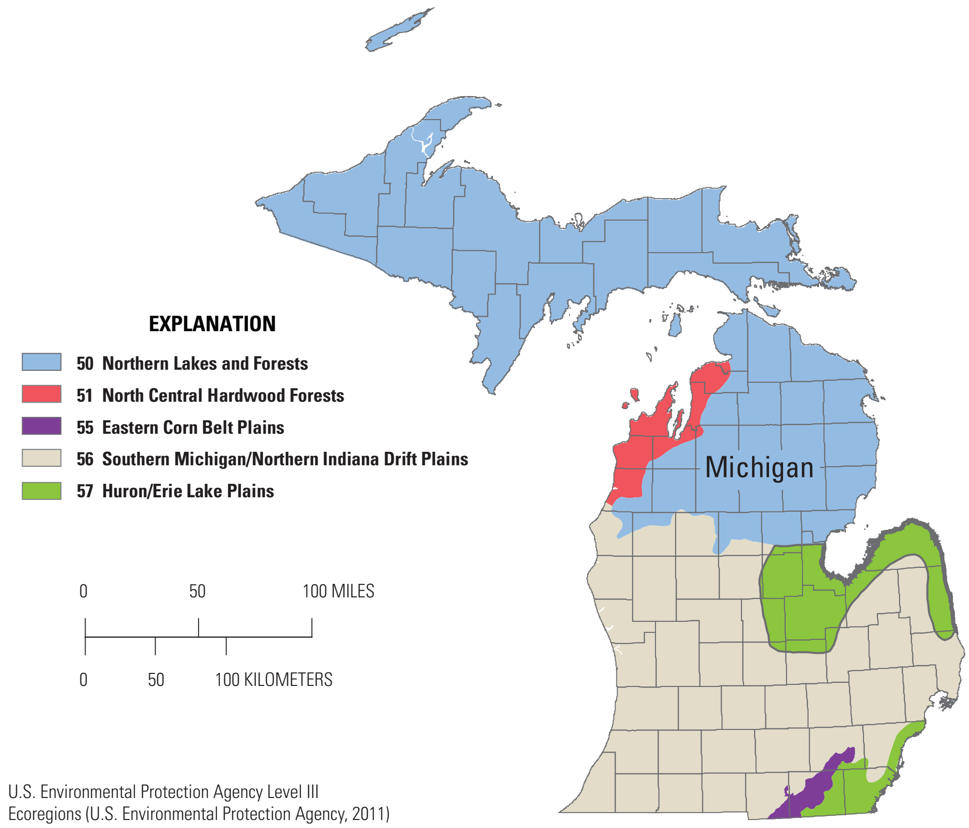

Figure 4. Environmental Protection Agency Level III Ecoregions for Michigan.

Table 8. Mean estimated Trophic State Index (eTSI) and Secchi-disk transparency (SDT) by U.S. Environmental Protection Agency Level III Ecoregions for Michigan inland lakes by dataset.

Mean estimated Trophic State Index (eTSI) value							
Level III Ecoregion	**1999–2000**	**2002**	**2003–05**	**2007–08**	**2009–10**	**2011**	**2013**
Northern Lakes and Forests	46.4	45.2	44.4	43.7	45.6	44.0	43.3
North Central Hardwood Forests	43.8	40.5	45.6	44.9	43.0	41.2	38.1
Eastern Corn Belt Plains	55.2	54.6	57.7	59.5	47.2	62.5	47.5
Southern Michigan/Northern Indiana Drift Plains	47.2	45.6	45.8	45.7	44.7	45.6	41.5
Huron/Erie Lake Plains	50.8	51.1	54.9	60.3	56.1	53.1	48.0
Mean estimated Secchi-disk transparency (eSDT) (in feet)							
Level III Ecoregion	**1999–2000**	**2002**	**2003–05**	**2007–08**	**2009–10**	**2011**	**2013**
Northern Lakes and Forests	9.4	10.3	10.9	10.9	10.0	11.2	12.2
North Central Hardwood Forests	11.5	15.9	9.7	9.8	11.6	14.0	17.1
Eastern Corn Belt Plains	5.2	5.2	4.7	5.0	9.8	4.1	9.8
Southern Michigan/Northern Indiana Drift Plains	8.4	9.5	9.5	9.5	10.1	9.7	12.7
Huron/Erie Lake Plains	7.3	7.6	6.5	4.3	5.0	7.8	9.7

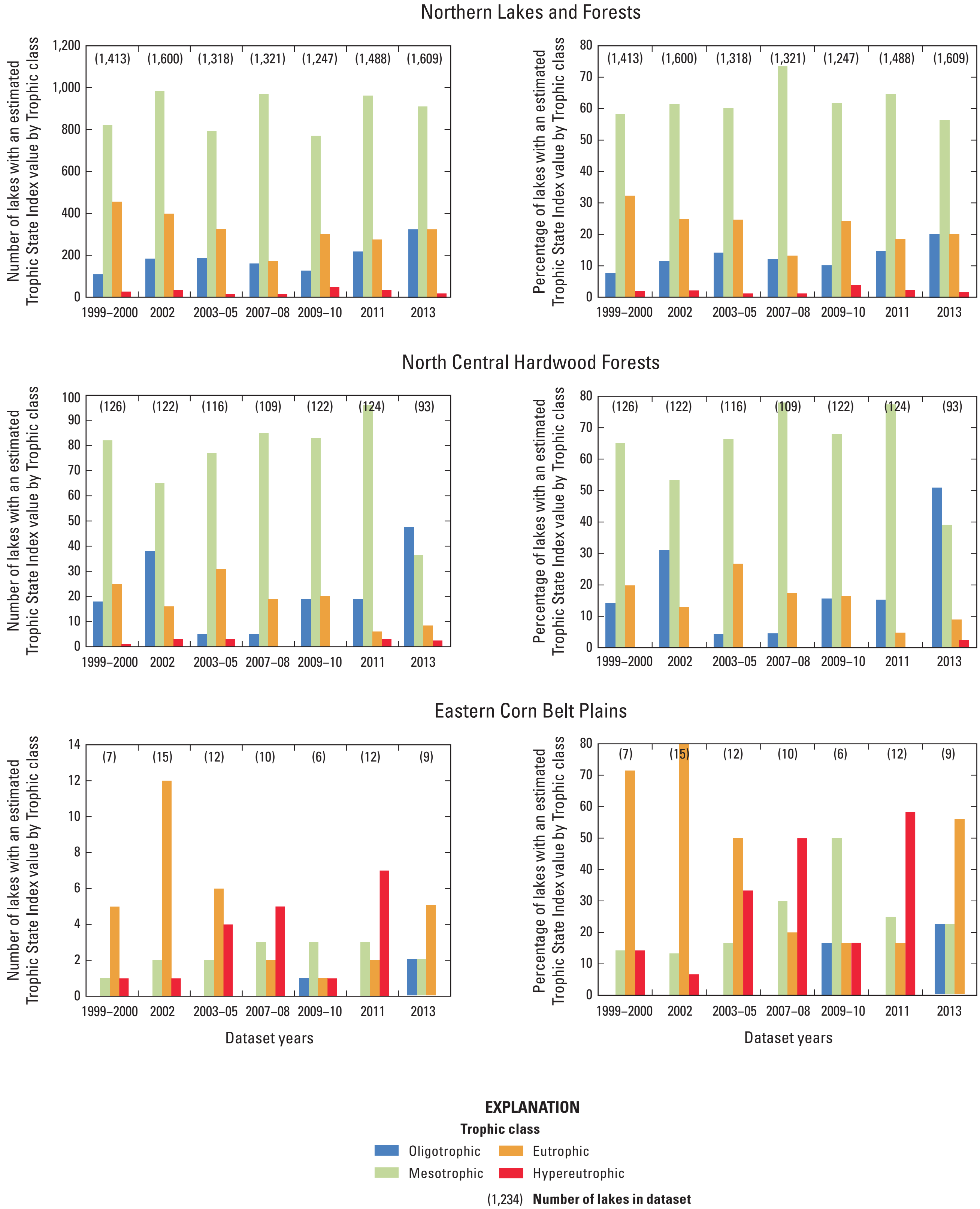

Figure 5. Estimated Trophic State Index (eTSI) by TSI class and Environmental Protection Agency Level III Ecoregions for the 1999–2013 datasets.

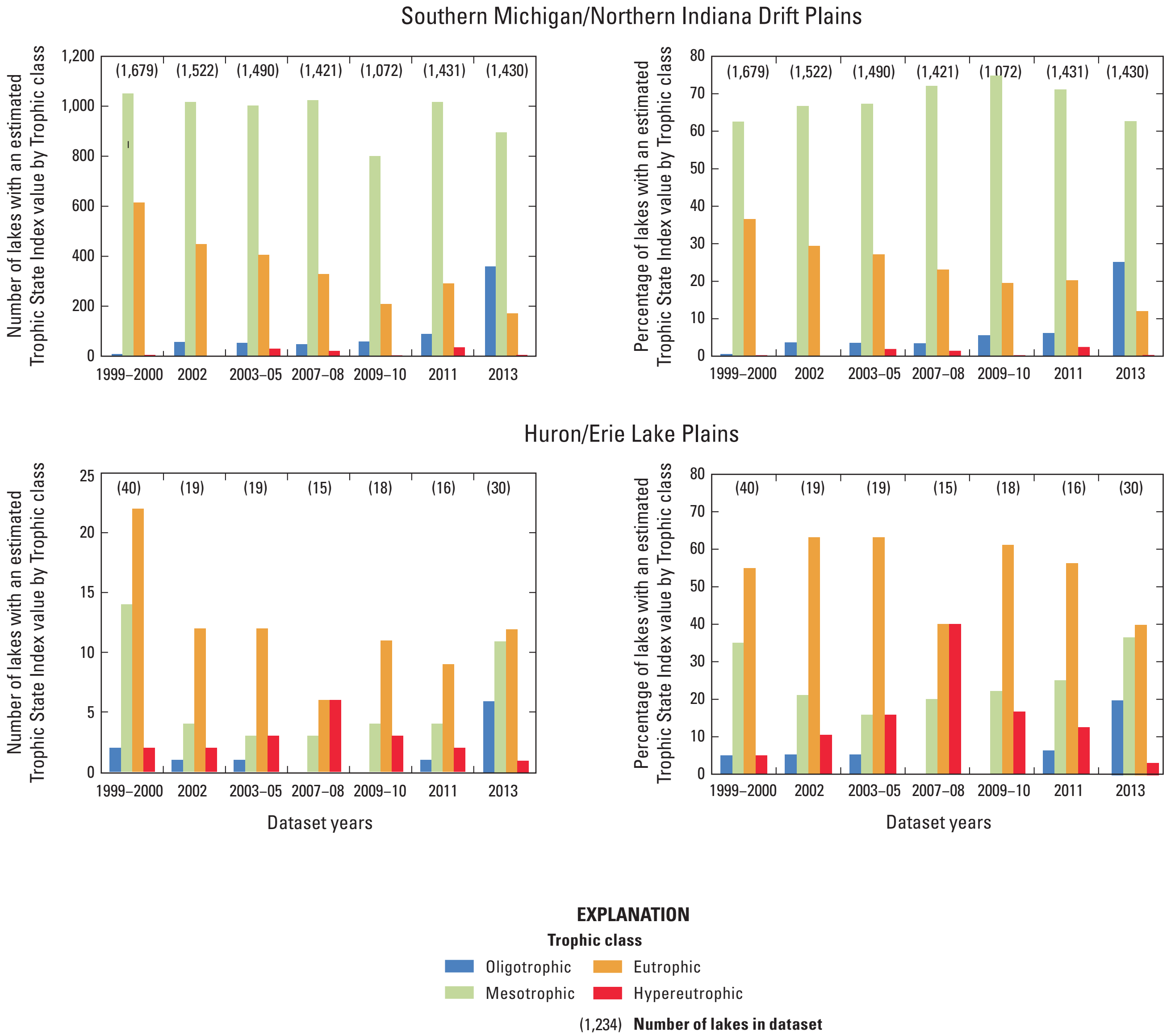

Figure 5. Estimated Trophic State Index (eTSI) by TSI class and Environmental Protection Agency Level III Ecoregions for the 1999–2013 datasets.—Continued

in TSI class distribution to the North Central Hardwood Forests ecoregion. The Southern Michigan/Northern Indiana Drift Plains ecoregion had the largest number of lakes with eTSI values in three out of the seven datasets, though had the highest number of lakes with eTSI values when all datasets were combined. It also had comparable representation to the Northern Lakes and Forest ecoregion, though there are fewer oligotrophic and more eutrophic lakes. The smallest ecoregions, located in the southern Lower Peninsula of Michigan, had mostly eutrophic lakes and more hypereutrophic lakes than the other ecoregions.

Although most eTSI datasets vary somewhat in the distribution of lakes in the TSI classes, it is noticeable that the 2013 dataset has the highest mean eSDT and lowest mean eTSI values among the ecoregions (table 8). Although this dataset has one of the highest numbers of lakes, and possibly more oligotrophic lakes were included in the output, 2013 is the only year Landsat 8 satellite imagery was used. Factors that could contribute to the shift for an increase in eSDT and a decrease in eTSI values include the TSI class, types of cloud and haze free lakes in the dataset, the date of the imagery, climate conditions for that year, and the different Landsat 8 satellite data used.

Comparison of the programs that provide TSI for Michigan inland lakes shows interesting results. Volunteers with the CLMP measure approximately 250 inland lakes each year. These measurements, plus supplemental measurements, are used to produce eTSI by use of remotely sensed Landsat satellite imagery. The National Lakes Assessment (NLA) randomly selected—based on chemical, physical, and biological data—and measured lakes nationwide during 2007 to provide a statistically valid, probability-designed estimate of the condition of lakes on a national and regional scale (Environmental Protection Agency, 2009). When the TSI determined from the SDT was compared for the CLMP from 2007 to the eTSI for the 2007–08 dataset, similar percentages for trophic-status categories emerged; on average, however, the CLMP percentage of lakes for the oligotrophic class was slightly higher, and for the hypereutrophic class was slightly lower (fig. 6). This may be due to more volunteers living on or having access to clearer lakes than those with access to impaired lakes. The percentages for NLA TSI from SDT, when comparing the National 2007 data and the Michigan-specific 2007 TSI from SDT, showed a difference for the mesotrophic, eutrophic, and hypereutrophic classes. The percentage for the mesotrophic class is much lower than the other datasets and higher for the eutrophic and hypereutrophic classes. Also, data in the NLA set were not available, mainly because an SDT value was not recorded if the Secchi-disk hit lake bottom, and this could contribute to the difference between classes.

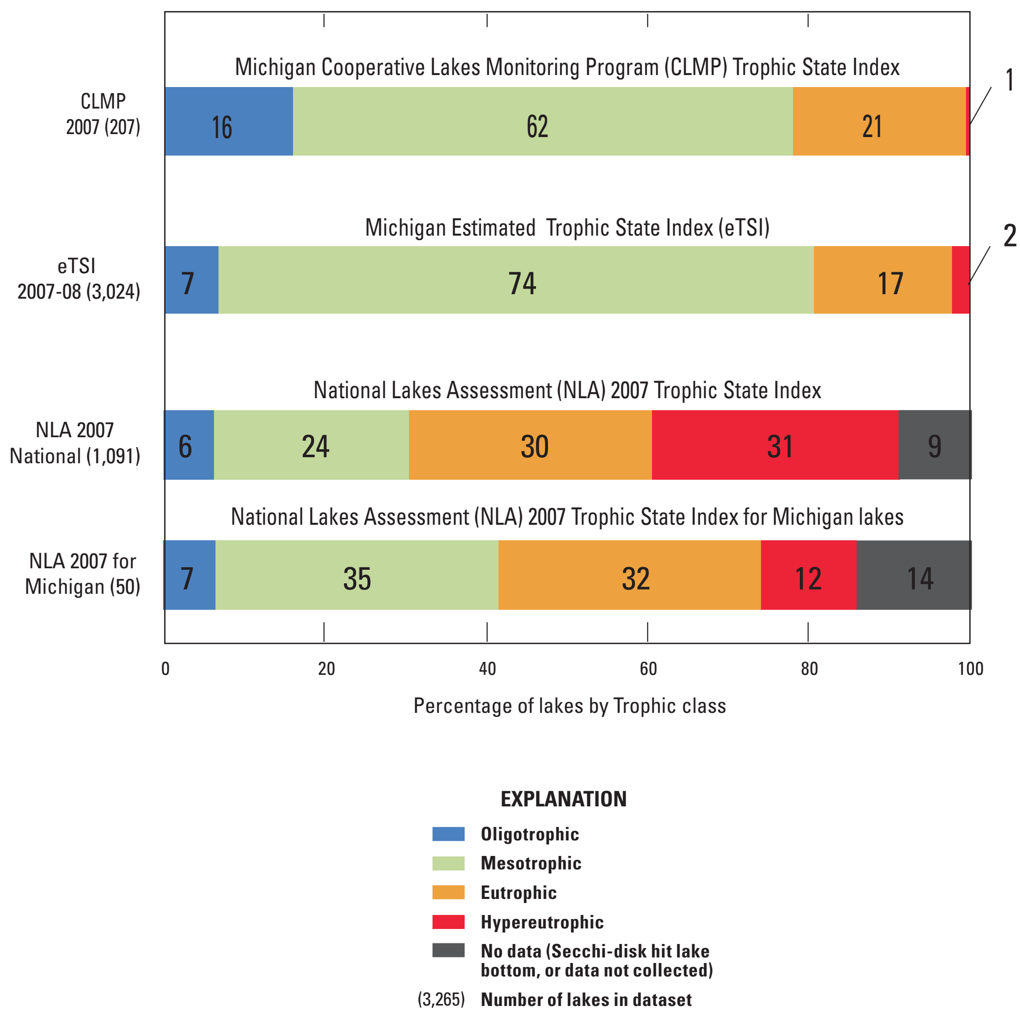

Figure 6. Comparison of program results based on Secchi-disk transparency to determine Trophic State Indexes (TSIs) for 2007.

Summary

Long-term data are required to effectively manage the more than 11,000 Michigan inland lakes, 4,000 of which are larger than 20 acres. Lake sampling programs provide data to determine lake condition; that information can be extended by use of Landsat satellite data to produce estimated Trophic State Index (eTSI) for lakes larger than 20 acres. Seven datasets of eTSI from 1999 to 2013 are available for an average of about 3,000 lakes of that size and clear of cloud interference, cloud shadows, haze, and dense vegetation. These datasets provide long-term regional and spatial eTSI to monitor lakes.

The method used to produce eTSI for inland lakes involves choosing Landsat satellite imagery with minimal cloud cover from the late-summer period and then process that imagery to mask out nonwater areas for the inland lakes larger than 20 acres in size. Field measurements of Secchi-disk transparency (SDT) corresponding to the Landsat satellite imagery obtained within 10 days of the Landsat satellite imagery acquisition date are then correlated to the satellite imagery to produce a regression equation specific to each date of Landsat satellite imagery. The result is an eTSI for open-water areas of inland lakes larger than 20 acres.

Each of the seven datasets from 1999 to 2013 showed strong relationships between Landsat satellite derived eTSI and field-measured Trophic State Index (TSI) by use of SDT measurements with R^2 values that ranged from 0.65 to 0.86. Mean eTSI ranged from 42.7 to 46.8 units, and mean estimated Secchi-disk transparency (eSDT) ranged from 8.9 to 12.5 feet. eTSI units decreased and eSDT increased when the 1999–2000 estimated mean and median values were compared to the 2013 values. However, if the 1999–2000 and 2013 datasets are removed, the mean and median values are relatively consistent between the 2002, 2003–05, 2007–08, 2009–10, and 2011 datasets. An ANOVA test determined that there was a statistically significant difference at the 95-percent confidence interval among the datasets, and Tukey's test results showed a significant difference at the 95-percent confidence interval between the 1999–2000, 2013, and between most datasets and the 2011 dataset for eTSI, and between the 1999–2000, 2011 and 2013 datasets for eSDT. In summary, eTSI values decreased, and eSDT increased.

Many factors could affect the eTSI among datasets, such as the lakes included or not available for estimated values in a dataset, the date and climate for a particular dataset, or a difference among Landsat satellite platforms. Not all lakes have representation in each dataset due to cloud cover, cloud shadow, haze, and dense vegetation preventing an estimated value, and without the estimated values for missing lakes, it is difficult to determine how their inclusion might change the statistics.

The Environmental Protection Agency (EPA) Level III Ecoregions in Michigan were used to determine and compare the spatial distribution of eTSI for inland lakes. The Northern Lakes and Forests and North Central Hardwood Forests ecoregion lakes were predominantly in the mesotrophic TSI class. The Southern Michigan/Northern Indiana Drift Plains ecoregion also had predominantly mesotrophic class lakes, but had a higher percentage of eutrophic lakes and fewer oligotrophic lakes than the Northern Lakes and Forests and North Central Hardwood Forests ecoregions. The Huron/Erie Lake Plains and Eastern Corn Belt Plains ecoregions, were the smallest ecoregions and had the fewest number of lakes having eTSI values; those regions had lakes that were predominantly in the eutrophic class, and had the highest percentage of hypereutrophic lakes relative to the other ecoregions.

Two sampling programs—the Cooperative Lakes Monitoring Program (CLMP) and the National Lakes Assessment (NLA)—were compared to the eTSI dataset for comparable years. The CLMP data collected by volunteers through the Michigan Department of Environmental Quality (MDEQ) for 2007 are similar to the NLA data, though the percent of oligotrophic lakes was greater in the CLMP data, which could result from more volunteers living and having access on the oligotrophic lakes. The NLA data specifically from Michigan for 2007 show a difference for the mesotrophic, eutrophic, and hypereutrophic classes. The percentage of lakes in the mesotrophic class is much lower than in the other datasets and higher for the eutrophic and hypereutrophic classes. These sampling programs can provide different pictures for Michigan inland lakes.

A long-term regional and spatial picture for lake managers can be created using different monitoring programs for Michigan inland lakes. Although in-situ data are a valuable resource, it is not physically and economically feasible to measure all 11,000 Michigan inland lakes. Extending measurements from existing lake monitoring programs has helped to provide additional lake eTSI values. The 15 years with seven datasets are available for viewing and download at (http://mi.water.usgs.gov/projects/RemoteSensing/index.html).

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Publishing support provided by the
U.S. Geological Survey Science Publishing Network,
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Director, Michigan Water Science Center
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Fuller and Jodoin—**Estimation of a Trophic State Index for Selected Inland Lakes in Michigan, 1999–2013**—Scientific Investigations Report 2016–5023

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20165023