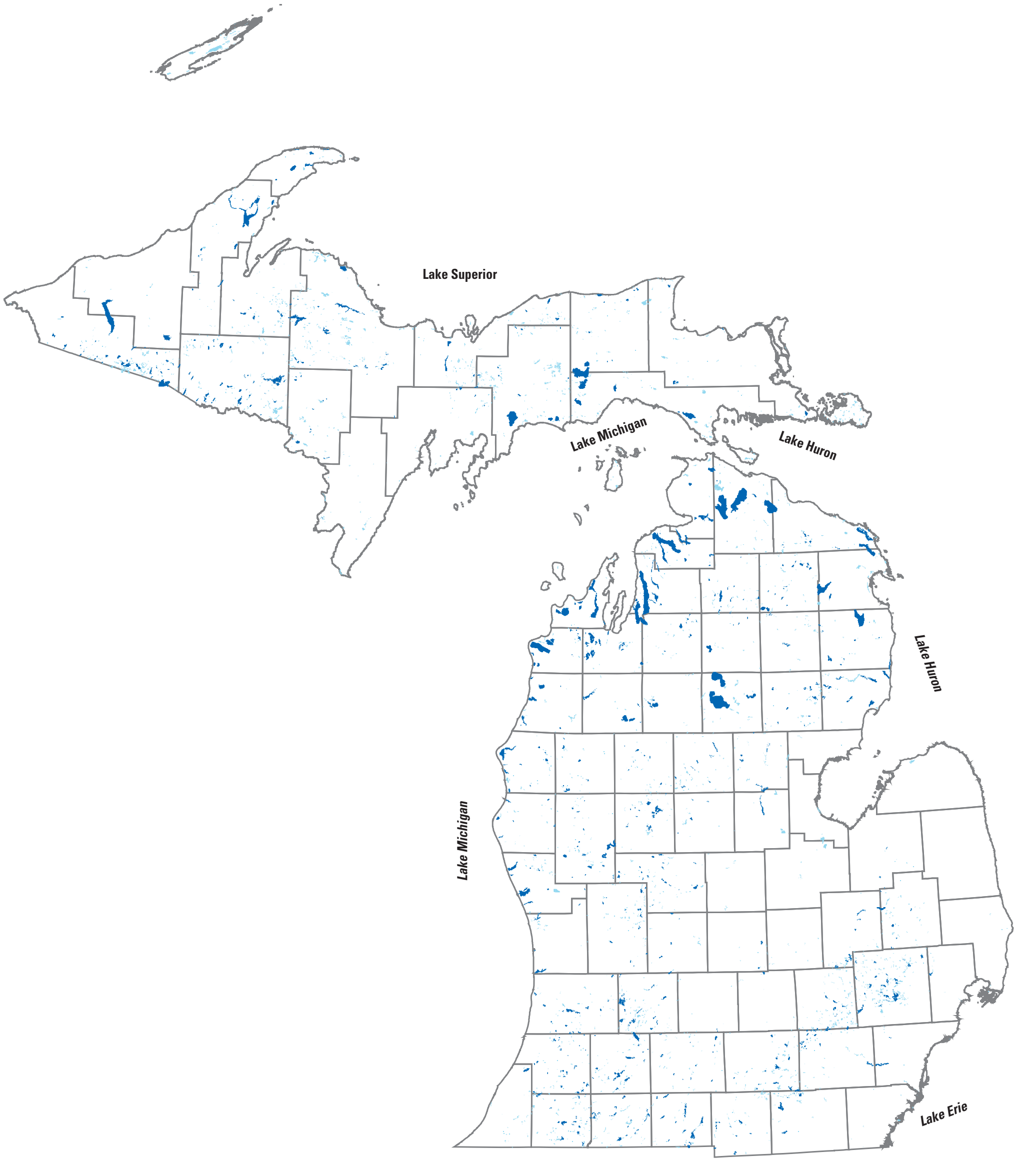
Prepared in cooperation with the Michigan Department of Natural Resources and Environment

Water-Quality Characteristics of Michigan's Inland Lakes, 2001–10



Scientific Investigations Report 2011–5233

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

Cover: Map showing inland lakes greater than 25 acres in Michigan.

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By L.M. Fuller and C.K. Taricska

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Conversion Factors and Abbreviations

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
meter (m)	3.281	foot (ft)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
	Volume	
milliliter (mL)	0.0338140227	ounce (oz)
	Concentration	
microgram per liter (µg/L)	0.001	milligram per liter (mg/L)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32

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). The pore sizes of filters used in processing water samples for chemical analysis are given in micrometers (µm); a micrometer is one-thousandth of a millimeter (mm).

Specific conductance is given in microsiemens per centimeter (µS/cm).

Abbreviations used in this report

AU/cm – Absorbance Units per centimeter
$CaCO_3$ – calcium carbonate
CLMP – Cooperative Lakes Monitoring Program
CMI – Clean Michigan Initiative
DO – dissolved oxygen
GPS – Global Positioning System
Lat-Long – latitude-longitude
LWQA – Lake Water Quality Assessment
MDEQ – Michigan Department of Environmental Quality
MDNRE – Michigan Department of Natural Resources and Environment
MRL – minimum reporting level
NLA – National Lakes Assessment
NPDES – National Pollutant Discharge Elimination System
NWIS – National Water Information System
R^2 –coefficient of determination
SDT – Secchi-disk transparency
SRS – Standard Reference Samples
STORET – Storage and Retrieval
TP – total phosphorus
TSI – Trophic State Index
USEPA – U.S. Environmental Protection Agency
USGS – U.S. Geological Survey

Water-Quality Characteristics of Michigan's Inland Lakes, 2001–10

By L.M. Fuller and C.K. Taricska

Abstract

The U.S. Geological Survey and the Michigan Department of Environmental Quality (MDEQ) jointly monitored for selected water-quality constituents and properties of inland lakes during 2001–10 as part of Michigan's Lake Water-Quality Assessment program. During 2001–10, 866 lake basins from 729 inland lakes greater than 25 acres were monitored for baseline water-quality conditions and trophic status. This report summarizes the water-quality characteristics and trophic conditions of the monitored lakes throughout the State; the data include vertical-profile measurements, nutrient measurements at three discrete depths, Secchi-disk transparency (SDT) measurements, and chlorophyll *a* measurements for the spring and summer, with major ions and other chemical indicators measured during the spring at mid-depth and color during the summer from near-surface samples.

In about 75 percent of inland lake deep basins (index stations), trophic characteristics were associated with oligotrophic or mesotrophic conditions; 5 percent or less were categorized as hypereutrophic, and 80 percent of hypereutrophic lakes had a maximum depth of 30 feet or less. Comparison of spring and summer measurements shows that water clarity based on SDT measurements were clearer in the spring than in the summer for 63 percent of lakes. For near-surface measurements made in spring, 97 percent of lakes can be considered phosphorus limited and less than half a percent nitrogen limited; for summer measurements, 96 percent of lakes can be considered phosphorus limited and less than half a percent nitrogen limited. Spatial patterns of major ions, alkalinity, and hardness measured in the spring at mid-depth all showed lower values in the Upper Peninsula of Michigan and a southward increase toward the southern areas of the Lower Peninsula, though the location of increase varied by constituent. A spatial analysis of the data based on U.S. Environmental Protection Agency Level III Ecoregions separated potassium, sulfate, and chloride concentrations fairly well, with a pattern of lower values in northern ecoregions trending toward higher values in southern ecoregions; lower and higher concentrations of magnesium, hardness, calcium, and alkalinity were well separated, but middle-range concentrations in central Michigan ecoregions were mixed. The highest concentrations of chloride and sodium were in the southeastern area of the Lower Peninsula.

Lakes with multiple basins showed few statistically significant differences in constituent concentrations at the 95-percent confidence level among combinations of depths between basins. The most statistically significant differences were found for water temperature, with significant differences in somewhat less than half the combinations in the spring and just a few combinations in the summer. The lack of significant differences between major basins of multibasin lakes indicates that monitoring of trophic characteristics in all major basins might not be necessary for the majority of constituents in future sampling programs.

Trophic characteristics based on the 2001–10 dataset were compared to trophic characteristics resulting from other Michigan sampling programs, including the volunteer Cooperative Lakes Monitoring Program coordinated by the MDEQ (measurements on 250 lakes in 2011), trophic-state predictions produced by relating existing measurements to remotely sensed data (measurements for about 3,000 lakes), and the National Lakes Assessment (NLA) statistically valid, probability-designed lakes program (measurements for 50 lakes in Michigan and about 1,100 lakes nationally). A higher percentage of oligotrophic lakes resulted when using SDT from the volunteer data and the 2001–10 dataset than when using the predicted measurements from remotely sensed data or the NLA. Comparing trophic characteristics from differently designed programs provides multiple interpretations of lake water-quality status in Michigan lakes.

No directional statistically significant difference was found at the 95-percent confidence level among historical nutrients and trophic characteristics when comparing 445 lakes with historical data for 1974–84 with the 2001–10 dataset, though SDT did show statistically significant differences at the 95-percent confidence level. Depending on the primary indicator, 50–66 percent of lakes did not change trophic-status class, 13–23 percent moved towards the oligotrophic end of the TSI scale, and 20–25 percent moved a class towards the eutrophic end of the TSI scale.

Increasing percentages of urban-dominant land cover in the drainage areas of lakes had a more positive correlation with chloride concentration than did increased percentages of other land-cover classes; there was also a slight correlation of urban-dominant land cover and calcium concentration. Removing data for lakes in southeastern Lower Michigan, known from previous reports to be higher in chloride, still resulted in a positive relation even though the coefficient of determination (R^2 value) decreased from 0.55 to 0.39. Dominant land-cover drainage areas were not strongly related to nutrients with respect to a linear relation, nor were lake drainage-area sizes.

Introduction

Michigan has more than 11,000 inland lakes. These resources provide numerous recreational opportunities for tourists and local residents, and they support a recreational industry in Michigan valued at $15 billion per year (Stynes, 2002). Knowledge of water-quality characteristics in these lakes is essential for the effective management of these resources.

Historically, the U.S. Geological Survey (USGS) and the Michigan Department of Environmental Quality (MDEQ) have jointly monitored water quality in Michigan's lakes and rivers. During the 1990s, however, funding for surface-water-quality monitoring was greatly reduced, and funds devoted to monitoring inland lakes through the Federal Clean Water Act Clean Lakes Program (Section 314) were eliminated. In 1998, citizens of Michigan passed the Clean Michigan Initiative (CMI) to clean up, protect, and enhance Michigan's environmental infrastructure. MDEQ and USGS jointly redesigned and implemented the Lake Water-Quality Assessment (LWQA) monitoring program because of expanding water-quality data needs, resulting in part from the new CMI program (Michigan Department of Environmental Quality, 2001).

Through the LWQA monitoring program, all Michigan lakes larger than 25 acres (with developed public boat-launch access) were monitored during 2001–10 (figs. 1*A* and 1*B*). The LWQA monitoring-program design incorporates the watershed-management units and 5-year rotational cycle currently being used by the MDEQ Ambient Surface Water Chemistry Monitoring Program (Michigan Department of Environmental Quality, 2000) to assess Michigan's rivers, Great Lakes connecting channels, and bays (fig. 2).

The 5-year basin-monitoring cycle identifies 45 watershed-management units on the basis of statewide drainage to the Great Lakes. Each year, 7 to 10 of the major watersheds in Michigan are monitored and assessed. This is done to ensure that specific watersheds are monitored in the 5-year cycle to assist in (1) statewide water-quality assessments, (2) the National Pollutant Discharge Elimination System (NPDES) permitting process, and (3) resource-management decisions. The monitoring emphasizes data collection to classify each lake by its primary biological productivity (trophic status) and document its general chemical characteristics.

History of Monitoring on Michigan's Inland Lakes

In 1973, the Michigan Department of Natural Resources (currently separate agencies: MDEQ and MDNR) began systematically monitoring the quality of Michigan inland lakes under Section 314 of the Clean Water Act. In previous years, few water-chemistry data had been collected on Michigan lakes, which hampered documentation of changes in lake water quality. Initially, it was expected that the "significant" lakes, defined as public lakes greater than or equal to 50 acres, could be sampled every 5 years. By 1979, however, more than half of the significant lakes had not been sampled. The U.S. Environmental Protection Agency (USEPA) increased funding under the Clean Water Act to assist states in assessing the quality of lakes. Also, a one-time grant from USEPA was awarded to the State of Michigan in June 1980 for the purpose of inventorying and classifying unsampled lakes.

Carlson's Trophic State Index (TSI) was chosen to classify lakes for five reasons: (1) the index works well over a broad range of trophic conditions; (2) lakes can be classified by total phosphorus (TP), transparency, and chlorophyll *a*; (3) the index is well suited for Michigan because it was developed by use of data from Michigan and Minnesota lakes; (4) the index is a continuum with divisions to distinguish general categories; and (5) TP, transparency, or chlorophyll *a* data previously collected could be evaluated. Because TSI may underestimate the trophic condition in lakes dominated by macrophytes, the relative abundance of submergent macrophytes was observed and noted in the lakes to assist with the TSI classification.

Purpose and Scope

This report summarizes the results of the 10-year data-collection project (2001–10) for the Michigan LWQA program. An explanation of sampled constituents is provided, and sample-collection methods used for the analysis are described. These constituents are summarized as a statewide deep-basin (index station) dataset and also as a comparison of multiple-basin lakes by season and sampling depth. Other Michigan sampling programs are compared with these data to determine whether all sampling programs provide the same results for Michigan inland lakes. Historical data are compared to current lake data to determine whether temporal changes have occurred, and the relation of land cover to lake water quality is discussed.

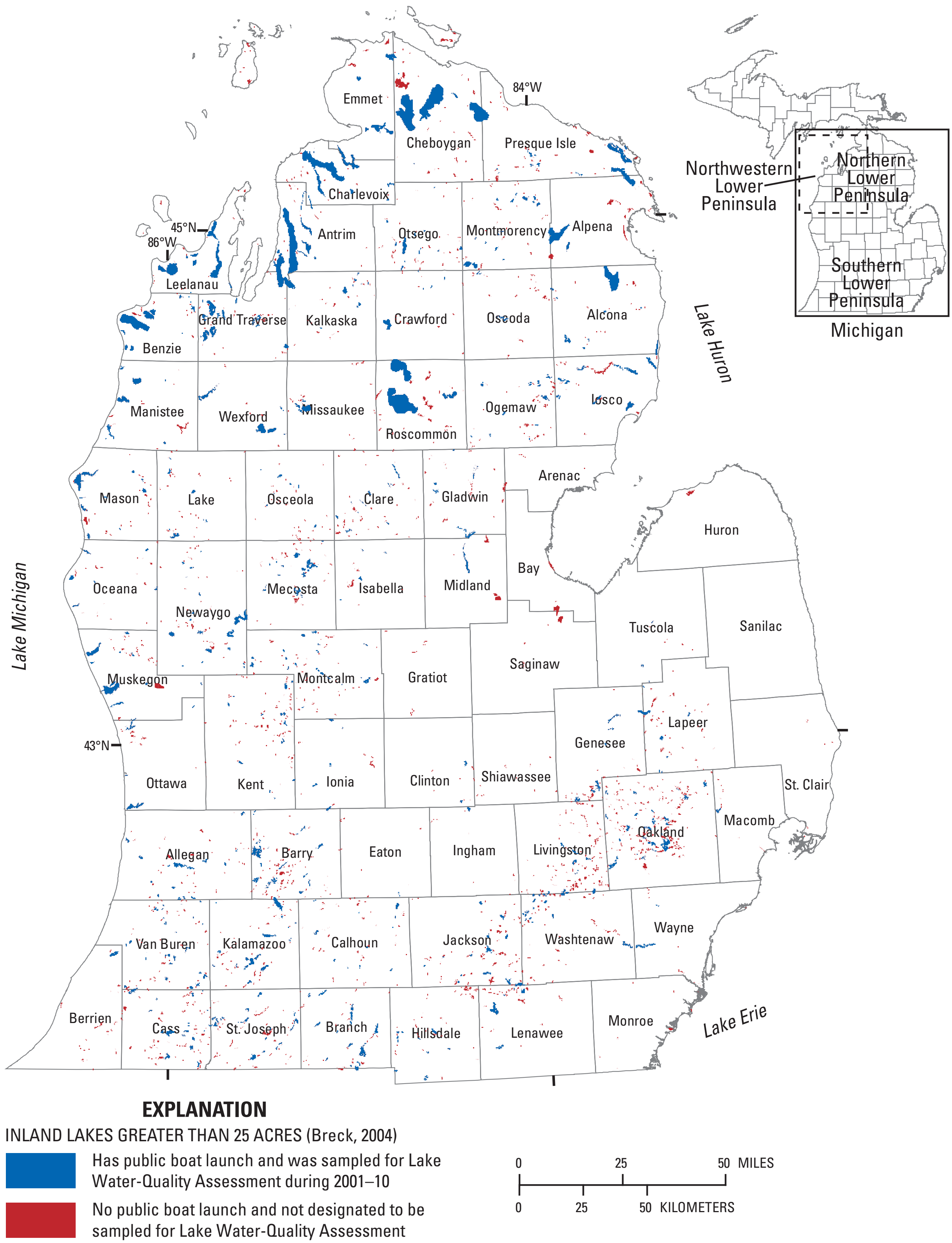

Figure 1*A*. Inland lakes greater than 25 acres in the Lower Peninsula of Michigan.

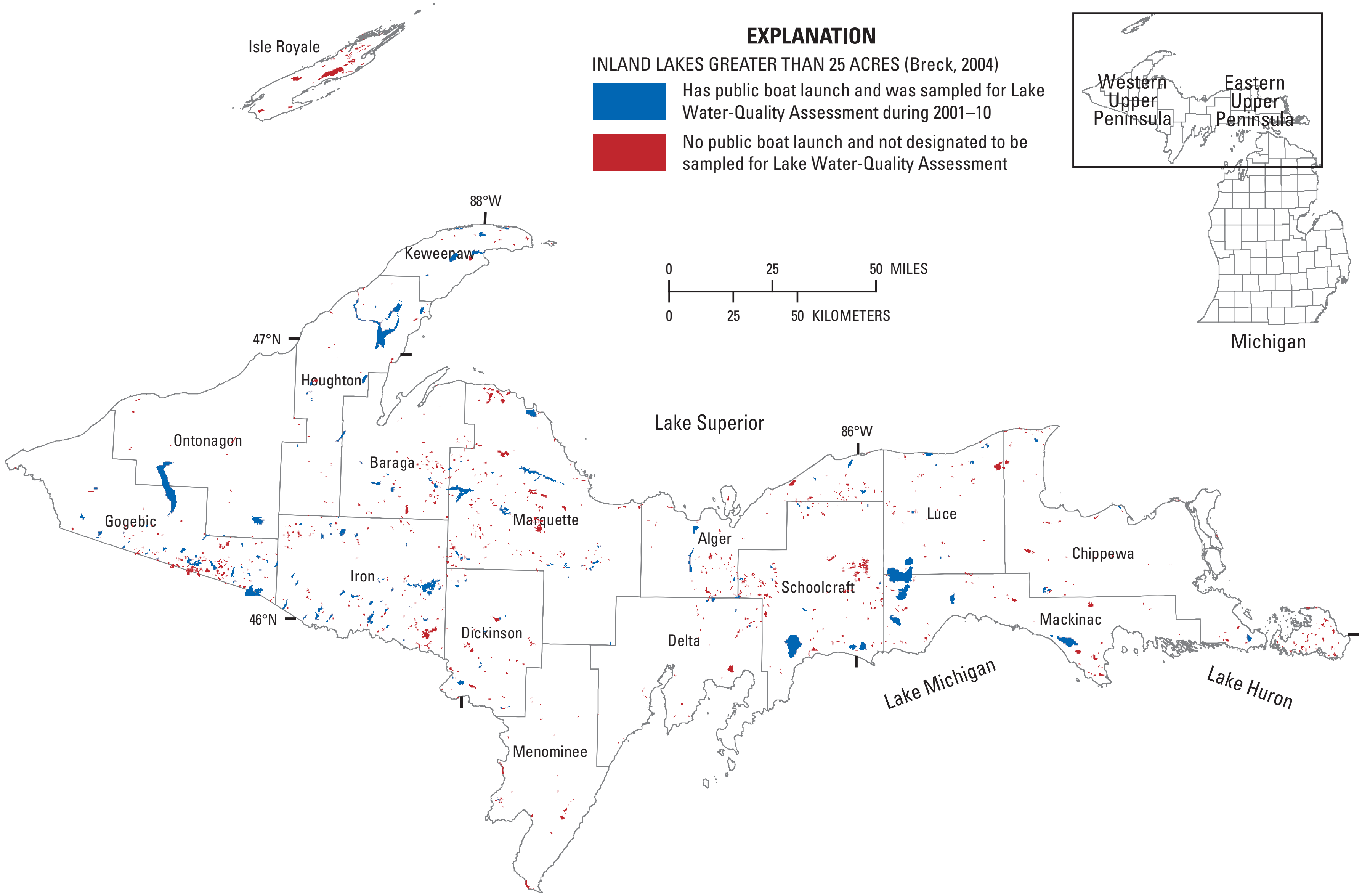

Figure 1*B*. Inland lakes greater than 25 acres in the Upper Peninsula of Michigan.

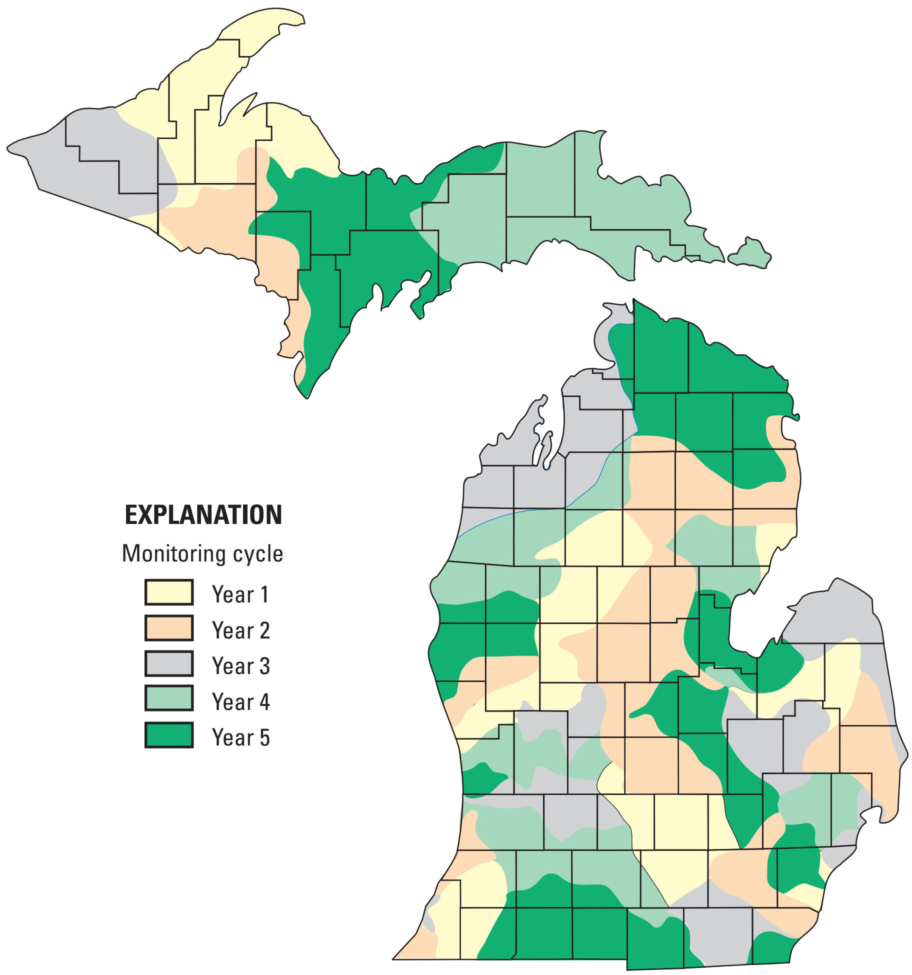

Figure 2. Watershed-management units and 5-year rotational cycle for Lake Water-Quality Assessment in Michigan.

Water-Quality Data-Collection Methods

The sampling methodology was designed to replicate the methods and techniques historically used by MDEQ to sample inland lakes. Care was taken to minimize deviation from past sampling methods, locations, or laboratory-analysis methods that could create variability in the data owing to changes in techniques or methods rather than actual changes in lake water quality.

Lake and Site Selection

Lakes sampled in a given year were selected randomly from 7 to 10 major watersheds throughout Michigan on the basis of watershed-management units and 5-year rotational cycle currently being used by MDEQ Ambient Surface Water Chemistry Monitoring Program (Michigan Department of Environmental Quality, 2000) to assess Michigan's rivers, Great Lakes connecting channels, and bays. Lakes targeted for monitoring under the LWQA monitoring program were 25 acres or larger with public boat-launch access. Each watershed is to be sampled on a 5-year rotation until all lakes meeting these criteria are sampled. After the first 5-year rotation (2001–05), a selection of lakes had been sampled in all 45 major watersheds in Michigan.

The sampling site in each major lake basin was as close as possible to the known historical sampling location (index station) in the deepest basin of each lake. Geographic coordinates for each sampling site were established with a handheld Global Positioning System (GPS) unit. Once the sample site was located with a GPS unit, the site was verified by comparing the depth measured with an electronic depth finder to measured depths from previous visits.

Site Identification

All previously sampled lake basins were identified with a USEPA Storage and Retrieval (STORET) number. Data stored in the USGS National Water Information System (NWIS) are referenced with a USGS station number, which is the latitude-longitude (Lat-Long) of the location where the sample was collected. A sequence number indicating the depth at which a sample was collected was then incorporated into the station number as the last two digits. The lake-station numbering system is summarized below:

Lat-Long-01	Vertical profile data
Lat-Long-02	Sample collected 3 ft above lake bottom
Lat-Long-03	Depth-integrated sample through the photic zone
Lat-Long-05	Sample collected 3 ft below lake surface
Lat-Long-06	Sample collected at mid-depth or metalimnion

Sampling Strategy

All lakes selected for monitoring within a given year were sampled once during spring turnover (usually April) and again in late summer (August or September), when they are typically thermally stratified. Samples collected during spring turnover, when water is well mixed, represent average water quality in the lake as a whole. Samples collected in late summer, when water is warmest and algae and aquatic macrophyte growth is at its peak, represent water-quality characteristics when biological productivity is the greatest specific to each zone of the lake.

Discrete lake-water samples were collected at several depths representing each zone of the lake water column (epilimnion, metalimnion, hypolimnion) at the index station (deepest basin) of each lake. Additional sample locations were used for those lakes that had multiple deep basins where complete interbasin mixing was unlikely.

Before sample collection, vertical profiles of dissolved oxygen (DO) concentration, water temperature, specific conductance, and pH were measured to determine thermal stratification. Water clarity was measured with a Secchi disk, and the photic zone was determined as twice the Secchi disk depth. During late-summer sampling, a qualitative macrophyte evaluation was made in the littoral zone of each lake to refine the trophic-state evaluation, and a measure of color was added during 2007–10.

Field and Laboratory Methods

Water Sampling

Standard MDEQ and USGS field methods were used to collect and preserve samples. During spring sampling, three discrete samples were collected. One sample was collected 3 ft below the surface, another 3 ft above the bottom, and the third at mid-depth. Summer sampling used the same sample depths except in stratified lakes, where the mid-depth sample was collected from the center of the metalimnion (thermocline). During spring sampling, only mid-depth samples were collected on shallow lakes when depth prohibited collection of three discrete samples. Samples were recorded in the database as the "3 ft below lake surface" samples when depth prohibited collection of three discrete samples during the summer. The depths at which the samples were recorded for these shallow lakes were noted for both spring and summer.

Water samples collected near bottom, near surface, and at mid-depth were analyzed for nutrients; samples for analyses of all other water-quality characteristics were collected only in the spring from mid-depth. All water samples except for chlorophyll *a* samples were collected as discrete samples with a Van Dorn-style sampler. Water samples for chlorophyll *a* analysis were depth-integrated composite samples collected by lowering a bottle sampler through the photic zone. On those lakes where the photic zone extended to the lake bottom, the bottle sampler was lowered to within 1 ft of the lake bottom with care taken not to disturb bottom sediments.

Water samples for nutrients were preserved with sulfuric acid (H_2SO_4) to a pH of less than 2, and water samples for selected ions (calcium, magnesium, sodium, and potassium) were preserved with nitric acid (HNO_3) to a pH of less than 2. Chlorophyll *a* samples were filtered onsite through a 0.45 µm combination acetate, nitrate cellulose filter (filter type HAWP 047 00). The filter then was placed in a vial containing 10 milliliters (mL) of 90 percent acetone. All samples then were overnight shipped in coolers with ice to the MDEQ laboratory for analysis of chlorophyll *a* and ions. Nutrient analyses were completed either by the MDEQ or its contract laboratory. Standard analytical methods approved by the USEPA were used for sample analyses (table 1).

Table 1. Properties and constituents, laboratory analytical methods, and reporting levels of water-quality data samples collected from Michigan lakes during 2001–10.

[MRL, minimum reporting level; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; µg/L, microgams per liter; AU/cm, Absorbance Units per centimeter; USEPA, U.S. Environmental Protection Agency]

Property or constituent	Units	MRL[1]	Method	Reference
Alkalinity, water unfiltered (acid neutralizing capacity)	mg/L as $CaCO_3$	20	310.1	USEPA, 1983
Calcium, total recoverable	mg/L	1	7140/215.1	USEPA, 1983
Chloride, dissolved	mg/L	1	325	USEPA, 1983
Hardness, total	mg/L as $CaCO_3$	5	Calculated SM 2340 B	Clesceri and others, 1998
Magnesium, total recoverable	mg/L	1	7450/242.1	USEPA, 1983
Sodium, total recoverable	mg/L	1	7770/273.1	USEPA, 1983
Sulfate	mg/L	2	375.1	USEPA, 1983
Potassium, total recoverable	mg/L	.1	7610/258.1	USEPA, 1983
Nitrogen, ammonia plus organic, total	mg/L	.1	351.2	USEPA, 1983
Nitrogen, ammonia, total	mg/L	.01	350.1	USEPA, 1983
Nitrogen, nitrate plus nitrite, total	mg/L	.01	353.2	USEPA, 1983
Phosphorus, total	mg/L	.005	365.4	USEPA, 1983
Chlorophyll *a*	µg/L	1	SM 10200 H	Clesceri and others, 1998
Absorbance at 400 nanometers (color)	AU/cm	.007	SM 2004B	Clesceri and others, 1998

[1]Established reporting levels for various analytical procedures (Oblinger-Childress and others, 1999).

Trophic-Status Evaluation

A biologically productive lake is desirable for many activities such as fishing and maintaining a healthy wildlife population; however, a lake can be overly productive. Eventually, if excessive plant and algal growth goes unchecked, the lake may become impaired. The MDEQ classifies lakes on their level of primary biological productivity or trophic status. A lake with low productivity is classified as oligotrophic, and a lake with moderate productivity is classified as mesotrophic. A biologically productive lake is classified as eutrophic, and an excessively biologically productive lake is classified as hypereutrophic. The trophic status of lakes can be compared and tracked over time to help evaluate eutrophication resulting from nutrient enrichment, which may reflect changes in land-use practices.

The primary biological productivity in each lake basin was evaluated by MDEQ with Carlson's TSI (Carlson, 1977). Carlson's TSI was developed for use with lakes that have few rooted aquatic plants and little non-algal turbidity (U.S. Environmental Protection Agency, 2007). Late-summer sample data are used in this evaluation because primary biological productivity is at its peak and lakes are typically at maximum thermal stratification. Carlson's TSI was computed from TP concentrations (collected near the surface), chlorophyll *a* concentrations (collected in the photic zone; fig. 3), and Secchi-disk measurements (fig. 4).

Carlson's TSI is a numerical scale ranging from 0 to 100. The low end of the scale represents low primary biological productivity (oligotrophy), the middle of the scale represents moderate biological productivity (mesotrophy), the high end of the scale represents a very biologically active lake (eutrophy), and the highest end of the scale represents excessive biological productivity (hypereutrophy). Carlson and Simpson (1996) suggest TSI ranges for northern temperate lakes whereby a TSI value less than 40 represents oligotrophic conditions; 40–50, mesotrophic; 50–70, eutrophic; and greater than 70, hypereutrophic.

Although the concept of TSI ranges is simple, the interpretation can be complex because of their interdependency. The TSI values computed from any of the three indicators (chlorophyll *a*, TP, and Secchi-disk transparency (SDT)) will not necessarily be the same. There is a chemical and physical environment that can influence particular indicators and the interrelation with one another (Wetzel, 2001).

The MDEQ has adopted a modified scale and interpretation of the three indicators to account for regional characteristics (Michigan Department of Natural Resources, 1982). TSI values less than 38 represent oligotrophic conditions; 38–48, mesotrophic; 49–61, eutrophic; and greater than 61, hypereutrophic.

Figure 3. U.S. Geological Survey technician preparing to collect a chlorophyll *a* measurement.

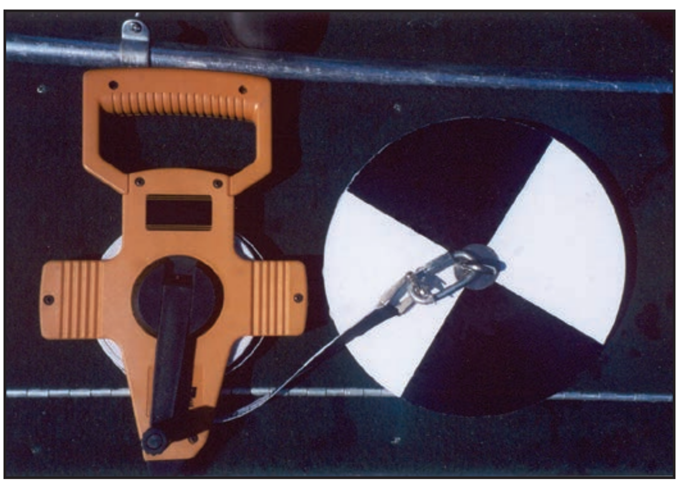

Figure 4. Secchi disk, which is lowered into the water attached to a measuring tape to determine the Secchi-disk transparency (depth at which the Secchi disk disappears).

Walker (1979) proposed that averaging the TSI values from all three indicators would provide a means of reducing the effects of individual sampling and measurement errors, thus developing a robust estimate of the index. Carlson's TSI may underestimate the trophic state of lakes dominated by macrophytes. The relative abundance of submergent macrophytes was used to indicate more productive conditions than indicated by TSI values. Walker assumed that "moderate" and "dense" growths of macrophytes were indicative of mesotrophic and eutrophic conditions, respectively. Therefore, if the TSI indicated mesotrophic conditions but "dense" growths of aquatic macrophytes were present, the lake would then be classified as eutrophic. For lakes with multiple basins, the TSI values from the index station (deepest basin) were used to determine the trophic state of these lakes.

The following equations were used to calculate the TSI values for each indicator, and were then averaged for lakes presented in appendix 1 and are summarized in table 2 for determining the trophic-status classification:

$$\text{TSI Secchi disk} = 60 - 14.41 * \ln(\text{Secchi-disk transparency, in meters}) \quad (1)$$

$$\text{TSI chlorophyll } a = 9.81 * \ln(\text{chlorophyll } a\text{, in micrograms per liter}) + 30.6 \quad (2)$$

$$\text{TSI total phosphorus} = 14.42 * \ln(\text{total phosphorus, in micrograms per liter}) + 4.15 \quad (3)$$

Table 2. Lake trophic state and classification ranges of Trophic State Index for total phosphorus, Secchi-disk transparency, and chlorophyll *a*.

[Based on Michigan Department of Natural Resources (1982) and modified by the State of Michigan to account for regional characteristics; TSI, Trophic State Index; SDT, Secchi-disk transparency; Chl-*a*, chlorophyll *a*; TP, total phosphorus; m, meter; µg/L, micrograms per liter; mg/L, milligrams per liter; <, less than; >, greater than]

Lake trophic state	Carlson's TSI	SDT (m)	Chl-*a* (µg/L)	TP (mg/L)
Oligotrophic	< 38	> 4.6	< 2.2	< 0.010
Mesotrophic	38–48	2.3–4.6	2.2–6	.010–.020
Eutrophic	49–61	.9–2.2	6.1–22	.021–.050
Hypereutrophic	> 61	< .9	> 22	> .050

Quality Assurance of Data, Treatment of Censored Data, and Access to Data

In accordance with USGS policy, analytical laboratories that provide chemical, radiochemical, and biological analyses are regularly reviewed and evaluated to ensure that data quality is appropriately maintained (U.S. Geological Survey, 1998). During the review process for the Michigan lake-sample analyses, any samples that did not follow prescribed processing protocol were excluded from the database. In a few instances, sample bottles leaked and were not processed. For these reasons, some samples of various constituents were removed. The tables in this report note the number of samples analyzed for the respective constituents.

The MDEQ laboratory and their private contract laboratory provided analytical results with associated data-qualifier descriptions. All analytical methods used were matched with the appropriate USGS constituent codes and methods, in addition to the remarks codes for less-than and estimated data, before the data were stored in the USGS National Water Information System (NWIS) database. Both laboratories participated in the USGS Standard Reference Sample (SRS) program, and the laboratories were evaluated by using performance evaluation samples called SRS. The SRS were submitted to the laboratories semiannually for performance-comparison purposes. Statistical evaluation of the results provided information to compare the analytical performance between laboratories and to determine possible analytical deficiencies and problems. Although the SRS project is not a certification program, participation is required for all laboratories that provide water-quality data for the USGS. Any analyte measured by an individual laboratory that did not receive marginal or higher ratings during the evaluation period was not used in the data analysis for this report. Laboratory-evaluation results for the Michigan Department of Environmental Quality lab number 341 can be found under the results tab at *http://bqs.usgs.gov/srs/*.

In addition to the actual measurement done by the laboratories for each constituent, some data also were censored—that is, reported as “nondetect” or “less than (<)”—or estimated (E). Nondetects result when analysis for a specific constituent yields no evidence of the constituent being present in the sample. Less-than data result when a constituent is detected but the concentration is less than the minimum reporting level (MRL) for that constituent; for example, < 0.01 mg/L. This occurs when an exact value cannot be assigned to a constituent but can be assigned various ranges less than applicable reporting limits. Estimated values are assigned for a variety of reasons where the analysis deviates from strict protocol or ideal analytical conditions, such as extrapolation or minor loss of sample during preparation.

A conservative approach to the treatment of censored data was used from Data Interpretation Example number 1 from Bonn (2008). Half the reporting limit was used for all nondetect and less-than data values, except when more than 5 percent of the data values were nondetect and less-than values, in which case the Helsel and Cohn (1988) adjusted maximum likelihood method was used to assist in the creation of summary statistics. All LWQA monitoring data were archived in the USEPA data-management system (STORET), as well as in the USGS NWIS database. These data are available to the public on the Internet at *http://mi.waterdata.usgs.gov/nwis/qw*, *http://www.epa.gov/storet*, and *http://www.michigan.gov/miswims*.

Statewide Water Quality of Inland Lakes

During 2001–10, lakes greater than 25 acres (with developed public boat-launch access) were sampled in all 45 of Michigan’s watershed-management units. Of the 729 lakes sampled, 109 were lakes with more than 1 major basin. In all, 866 lake basins were assessed and used in the analysis for this report. All lake basins included vertical-profile measurements, nutrient measurements at three discrete depths, SDT measurements (unless the Secchi disk hit the bottom of the lake, in which case no SDT depth was recorded), and depth-integrated chlorophyll *a* measurements all for spring and summer, with major ions and physical properties measured only for spring mid-depth and color only for summer during 2007–10.

In the spring, 52 lakes were deemed too shallow for the collection of near-lake-surface and near-lake-bottom measurements, thus only mid-depth samples were collected for all lake basins in the spring. In the summer, 58 lakes were deemed too shallow; thus, measurements were recorded in the near lake surface and not for mid-depth or lake bottom. Measurements for shallow lakes were made in the spring from 1 to 6 ft and in the summer from 1 to 5 ft. These measurements could be reflective of the near surface or mid-depth or metalimnion measurement depths.

For summary statistics, the spring measurements deemed too shallow for three discrete measurements were moved from near surface to mid-depth to allow comparison between the two seasons. For other analyses where a near-surface sample was required (such as phosphorus for TSI calculation), the single measurement noted in the mid-depth or metalimnionin the spring, or near surface for the summer was used. Of the shallow lakes, 48 were determined to be too shallow in the spring and summer, 4 lakes were determined to be too shallow only in the spring, and 10 lakes were determined to be too shallow only in the summer.

A few properties and constituents measured are reported as missing data values owing to leaking, improperly preserved samples, field meters not functioning correctly or losing battery power, and other similar circumstances. Four lakes, one with multiple basins, were resampled and are noted in appendix 1. The resampled data were used in this analysis, though available measurements for the original sample date are stored in NWIS.

Index Station (Deepest-Basin) Data Comparison

During 2001–10, the 729 lakes sampled had measurements from the index station (deepest basin). A statistical summary of the index station (deepest-basin) water-quality data collected at various depths are listed in table 3. The data are summarized below by physical and chemical category.

Table 3. Statistical summary, by physical property or consitutent, of Michigan lakes sampled in the index station (deepest basin) during 2001–10. (The Helsel and Cohn (1988) adjusted maximum liklihood method was used to create summary statistics for constituents with greater than 5 percent of the data as nondetects or less-than values; otherwise, half the reporting limit was used for all nondetect and less-than data values.

[Min, minimum; 25 Per, 25 Percentile; Med, median; 75 Per, 75 Percentile; Max, Maximum; St. Dev, standard deviation; µg/L, micrograms per liter; mg/L, milligrams per liter; deg C, degrees Celsius; µS/cm, microsiemens per centimeter; std units, standard units; AU/cm, absorbance units per centimeter; $CaCO_3$, calcium carbonate; <, less-than sign noting greater than 5 percent of data were nondetects or less-than values and adjusted maximum liklihood method was used]

Spring									
Constituent	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Secchi-disk transparency	meters	697	0.30	2.10	3.20	3.64	4.70	14.80	2.01
Chlorophyll *a*	µg/L	724	<1.0	1.10	2.70	4.42	5.63	52.00	5.68
Dissolved oxygen	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	mg/L	729	5.3	7.8	8.30	8.76	9.50	14.20	1.53
Mid-depth or metalimnion	mg/L	728	0	2.2	6.75	5.88	8.50	15.60	3.71
Near bottom	mg/L	727	0	1	7.70	6.36	10.40	14.10	4.44
Water temperature	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	deg C	729	1.5	20	23.00	20.72	25.00	29.00	6.58
Mid-depth or metalimnion	deg C	728	2.5	9.5	16.75	15.84	22.00	28.50	6.98
Near bottom	deg C	728	2.5	5	6.50	8.31	10.00	27.00	4.82
Specific conductance	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	µS/cm	728	12	164	276.50	274.01	359.00	1,230.00	158.20
Mid-depth or metalimnion	µS/cm	729	12	161	285.00	290.58	388.00	1,380.00	175.04
Near bottom	µS/cm	729	13	172	312.00	309.74	419.00	1,390.00	182.72
pH	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	std units	727	5.1	7.9	8.20	8.12	8.40	9.60	0.55
Mid-depth or metalimnion	std units	724	4.8	7.3	7.70	7.65	8.10	9.50	0.66
Near bottom	std units	723	4.5	7.1	7.50	7.49	8.00	9.90	0.66
Ammonia plus organic nitrogen	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	mg/L	683	0.050	0.35	0.49	0.53	0.64	2.19	0.26
Mid-depth or metalimnion	mg/L	729	0.050	0.35	0.49	0.52	0.65	2.89	0.26
Near bottom	mg/L	682	0.050	0.38	0.52	0.58	0.71	4.70	0.35
Ammonia	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	mg/L	682	0.001	0.01	0.03	0.06	0.07	0.68	0.10
Mid-depth or metalimnion	mg/L	728	0.001	0.01	0.03	0.07	0.08	0.67	0.10
Near bottom	mg/L	682	0.001	0.02	0.05	0.12	0.15	4.00	0.23

Table 3. Statistical summary, by physical property or consitutent, of Michigan lakes sampled in the index station (deepest basin) during 2001–10. (The Helsel and Cohn (1988) adjusted maximum liklihood method was used to create summary statistics for constituents with greater than 5 percent of the data as nondetects or less-than values; otherwise, half the reporting limit was used for all nondetect and less-than data values.)—Continued

[Min, minimum; 25 Per, 25 Percentile; Med, median; 75 Per, 75 Percentile; Max, Maximum; St. Dev, standard deviation; µg/L, micrograms per liter; mg/L, milligrams per liter; deg C, degrees Celsius; µS/cm, microsiemens per centimeter; std units, standard units; AU/cm, absorbance units per centimeter; $CaCO_3$, calcium carbonate; <, less-than sign noting greater than 5 percent of data were nondetects or less-than values and adjusted maximum liklihood method was used]

Summer									
Constituent	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Secchi-disk transparency	meters	693	0.3	2.1000	3.00	3.14	4.00	11.30	1.48
Chlorophyll *a*	µg/L	727	0.5	2.0000	3.60	6.10	6.00	120.00	9.98
**Color	AU/cm	285	<0.007	<0.007	0.01	0.01	0.01	0.15	0.01
Dissolved oxygen	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	mg/L	729	5.3	7.6	8.10	8.12	8.50	15.80	1.01
Mid-depth or metalimnion	mg/L	729	0.1	2.2	6.20	5.49	7.90	15.50	3.44
Near bottom	mg/L	728	0	0.3	0.50	2.22	3.40	13.10	2.96
Water temperature	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	deg C	729	16.5	22.5	24.00	23.91	25.50	29.00	2.21
Mid-depth or metalimnion	deg C	729	6.5	15	20.00	18.74	22.50	28.00	4.99
Near bottom	deg C	727	3.5	7	11.00	13.05	19.50	28.00	6.62
Specific conductance	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	µS/cm	728	12	162.75	273.00	271.13	358.00	1,310.00	157.79
Mid-depth or metalimnion	µS/cm	729	12	167	288.00	288.59	382.00	1,380.00	171.93
Near bottom	µS/cm	729	12	187	320.00	323.65	438.00	1,390.00	186.13
pH	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	std units	728	5.1	8	8.26	8.19	8.50	9.60	0.54
Mid-depth or metalimnion	std units	729	4.8	7.3	7.70	7.66	8.10	9.50	0.67
Near bottom	std units	728	5.2	6.9	7.30	7.29	7.60	9.50	0.65
Ammonia plus organic nitrogen	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	mg/L	678	0.05	0.38	0.52	0.58	0.69	2.64	0.32
Mid-depth or metalimnion	mg/L	729	0.05	0.39	0.54	0.61	0.73	3.10	0.34
Near bottom	mg/L	678	0.05	0.53	0.86	1.07	1.36	7.58	0.82
Ammonia	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	mg/L	678	0.0010	0.0050	0.01	0.02	0.03	0.82	0.05
Mid-depth or metalimnion	mg/L	729	0.0010	0.0060	0.02	0.05	0.04	4.00	0.18
Near bottom	mg/L	678	0.0010	0.0343	0.22	0.48	0.68	6.79	0.68

Table 3. Statistical summary, by physical property or consitutent, of Michigan lakes sampled in the index station (deepest basin) during 2001–10. (The Helsel and Cohn (1988) adjusted maximum liklihood method was used to create summary statistics for constituents with greater than 5 percent of the data as nondetects or less-than values; otherwise, half the reporting limit was used for all nondetect and less-than data values.)—Continued

[Min, minimum; 25 Per, 25 Percentile; Med, median; 75 Per, 75 Percentile; Max, Maximum; St. Dev, standard deviation; µg/L, micrograms per liter; mg/L, milligrams per liter; deg C, degrees Celsius; µS/cm, microsiemens per centimeter; std units, standard units; AU/cm, absorbance units per centimeter; $CaCO_3$, calcium carbonate; <, less-than sign noting greater than 5 percent of data were nondetects or less-than values and adjusted maximum liklihood method was used]

Spring—continued									
Total phosphorus	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	mg/L	683	0.003	0.009	0.013	0.018	0.021	0.234	0.018
Mid-depth or metalimnion	mg/L	729	0.003	0.009	0.014	0.018	0.020	0.203	0.017
Near bottom	mg/L	683	0.003	0.010	0.014	0.024	0.022	1.880	0.081
Nitrate plus nitrite	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	mg/L	683	0.001	0.05	0.09	0.26	0.21	6.70	0.56
Mid-depth or metalimnion	mg/L	728	0.001	0.05	0.10	0.26	0.21	6.70	0.55
Near bottom	mg/L	683	0.001	0.05	0.10	0.27	0.21	5.90	0.55
Total nitrogen (sum of ammonia + organic nitrogen and nitrate + nitrite)	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	mg/L	683	0.116	0.46	0.60	0.79	0.86	7.72	0.66
Mid-depth or metalimnion	mg/L	729	0.107	0.46	0.62	0.78	0.86	7.75	0.65
Near bottom	mg/L	683	0.059	0.47	0.66	0.85	0.95	6.85	0.69
Mid-depth or metalimnion	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
*Alkalinity (as $CaCO_3$)	mg/L	729	<20	64.00	116.00	109.53	150.00	323.00	58.20
*Calcium - total	mg/L	729	1.100	20.50	35.00	34.17	45.50	98.60	19.03
*Chloride	mg/L	726	0.500	4.00	9.00	16.72	19.00	278.00	25.14
*Hardness - calculated	mg/L	729	2.500	76.00	136.00	130.70	178.00	337.00	72.62
*Potassium - total	mg/L	729	0.050	0.60	1.00	1.20	1.60	5.40	0.82
*Magnesium - total	mg/L	729	0.500	5.40	11.30	11.08	16.00	28.20	6.57
*Sodium - total	mg/L	728	<1.0	2.20	4.95	8.28	8.60	154.00	13.00
*Sulfate	mg/L	727	1.000	3.00	6.00	10.50	14.00	142.00	12.58

Table 3. Statistical summary, by physical property or consitutent, of Michigan lakes sampled in the index station (deepest basin) during 2001–10. (The Helsel and Cohn (1988) adjusted maximum liklihood method was used to create summary statistics for constituents with greater than 5 percent of the data as nondetects or less-than values; otherwise, half the reporting limit was used for all nondetect and less-than data values.)—Continued

[Min, minimum; 25 Per, 25 Percentile; Med, median; 75 Per, 75 Percentile; Max, Maximum; St. Dev, standard deviation; µg/L, micrograms per liter; mg/L, milligrams per liter; deg C, degrees Celsius; µS/cm, microsiemens per centimeter; std units, standard units; AU/cm, absorbance units per centimeter; $CaCO_3$, calcium carbonate; <, less-than sign noting greater than 5 percent of data were nondetects or less-than values and adjusted maximum liklihood method was used]

Summer—continued									
Total phosphorus	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	mg/L	678	0.00250	0.008	0.012	0.016	0.017	0.172	0.016
Mid-depth or metalimnion	mg/L	729	0.00250	0.011	0.015	0.021	0.022	0.420	0.024
Near bottom	mg/L	678	0.00250	0.015	0.029	0.075	0.066	2.160	0.152
Nitrate plus nitrite	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	mg/L	678	<0.01	0.0020	0.00	0.05	0.01	3.10	0.22
Mid-depth or metalimnion	mg/L	728	<0.01	0.0020	0.00	0.07	0.01	3.60	0.26
Near bottom	mg/L	678	<0.01	0.0020	0.00	0.06	0.02	3.60	0.20
Total nitrogen (sum of ammonia + organic nitrogen and nitrate + nitrite)	**Units**	**Count**	**Min**	**25 Per**	**Med**	**Mean**	**75 Per**	**Max**	**St. Dev**
Near surface	mg/L	678	<0.01	0.396	0.54	0.63	0.73	4.11	0.40
Mid-depth or metalimnion	mg/L	728	<0.01	0.425	0.59	0.68	0.79	4.44	0.44
Near bottom	mg/L	678	<0.01	0.56	0.89	1.13	1.42	7.59	0.83

*Spring only.

**Summer only 2007–10.

Vertical Profile

Dissolved oxygen, water temperature, specific conductance, and pH were measured throughout the water column. Boxplots for comparison of individual constituents measured in the spring and summer at specific depths are shown in figures 5–8. (In these figures and similar figures later in the report, "adjacent" values represent up to one step above the 75th percentile for upper adjacent, or one step below the 25th percentile for lower adjacent, "outside" values if present represent values between 1 and 2 steps above the 75th and below the 25th, and "detached" values if present represent values more than 2 steps above the 75th or below the 25th. One step is equal to 1.5 times the height of the box, or interquartile range. (Helsel and Hirsch, 2002); the other statistics should be self-explanatory.)

Dissolved oxygen concentration is a critical factor in lake ecosystems; DO is a component of many chemical and biological processes and is important in determining the productivity of a lake. It is critical to many organisms for respiration and is an important controlling factor regarding the diversity of fish and other living organisms that lakes support. Dissolved oxygen is fairly consistent between spring and summer for the near surface and mid-depth or metalimnion but is lower in the summer than in the spring for the majority of measurements (fig. 5). This could be the result of incomplete lake turnover in the spring. If a lake does not mix completely, anoxic conditions develop in the hypolimnion during the summer months (Denys, 2009).

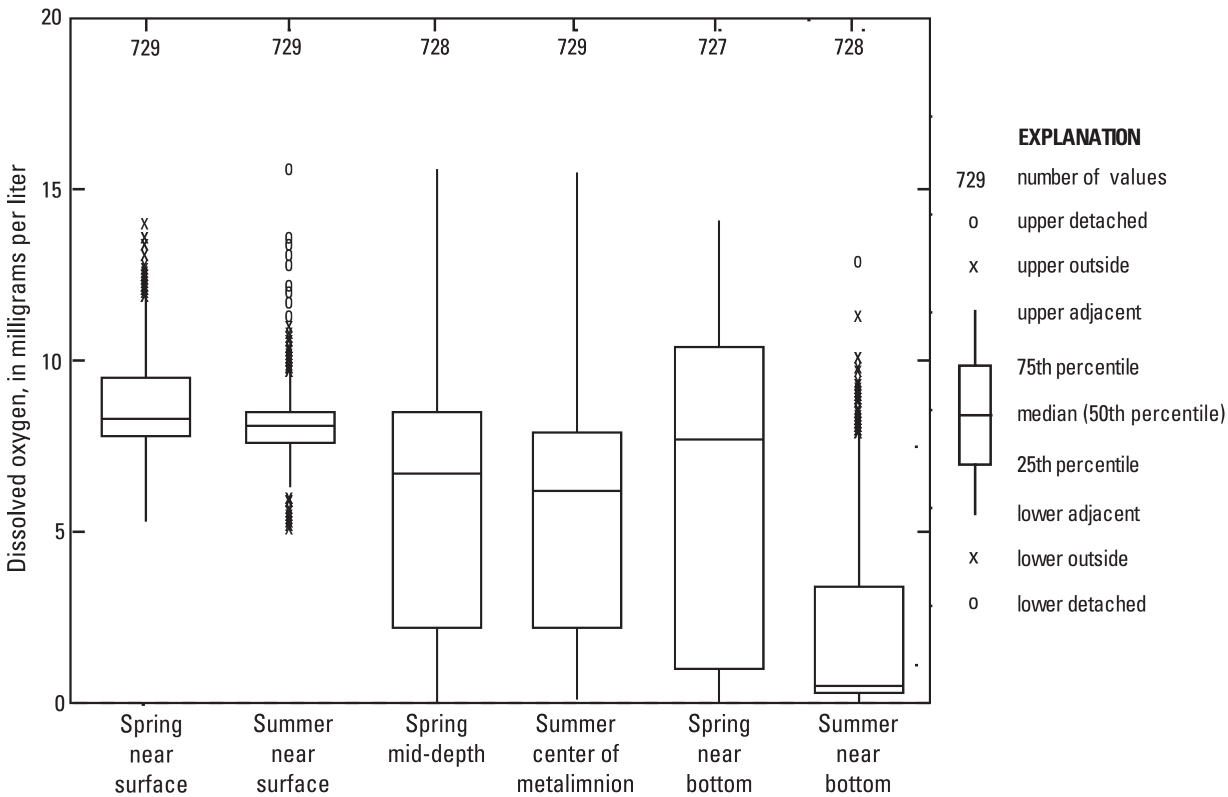

Figure 5. Statistical distribution of dissolved oxygen for spring and summer for near surface, mid-depth or metalimnion, and near bottom for the index stations (deepest basins) in Michigan lakes measured during 2001–10.

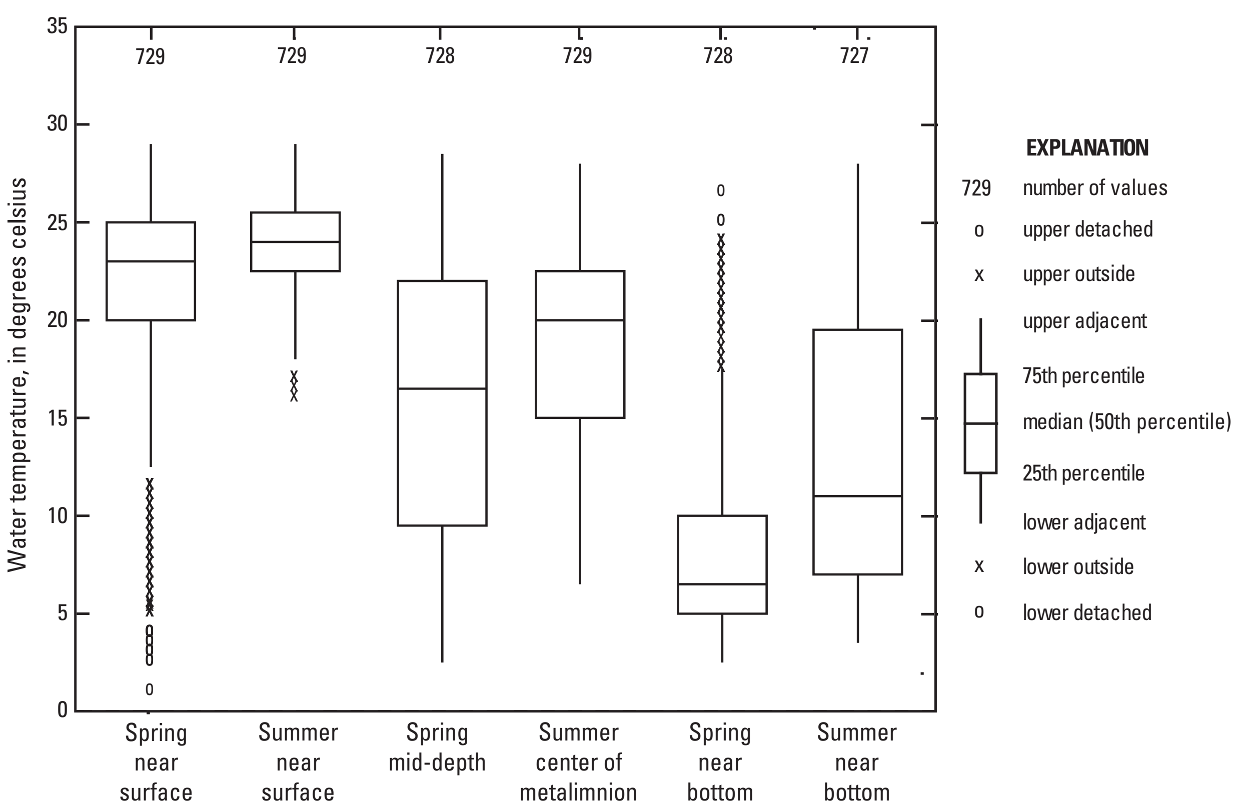

Figure 6. Statistical distribution of water temperature for spring and summer for near surface, mid-depth or metalimnion, and near bottom for the index stations (deepest basins) in Michigan lakes measured during 2001–10.

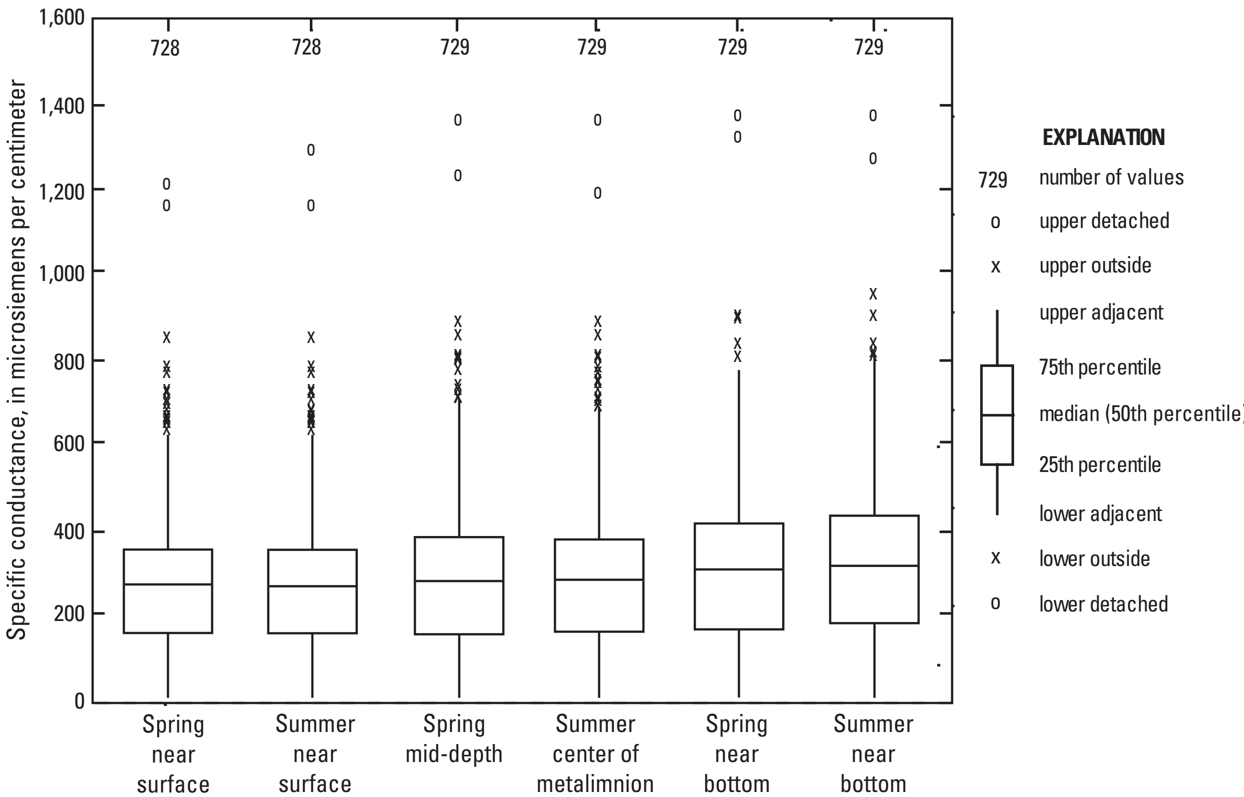

Figure 7. Statistical distribution of specific conductance for spring and summer for near surface, mid-depth or metalimnion, and near bottom for the index stations (deepest basins) in Michigan lakes measured during 2001–10.

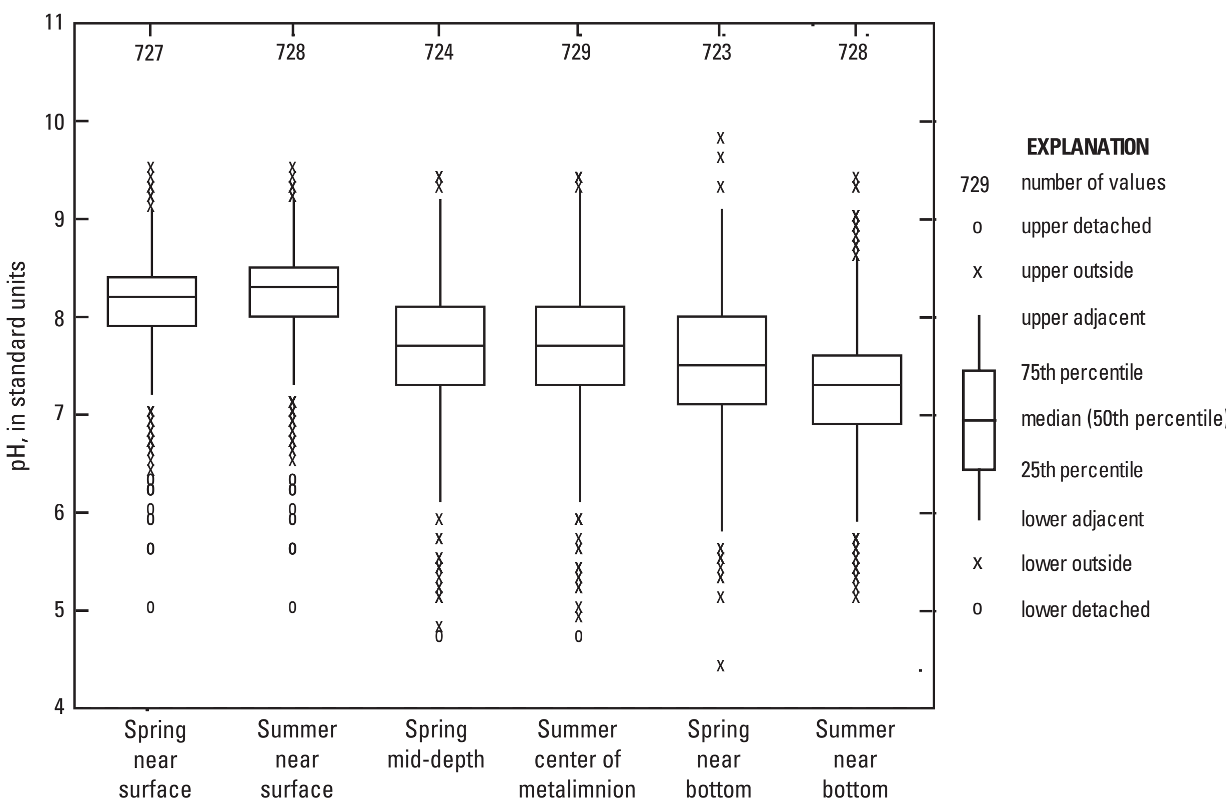

Figure 8. Statistical distribution of pH for spring and summer for near surface, mid-depth or metalimnion, and near bottom for the index stations (deepest basins) in Michigan lakes measured during 2001–10.

Water temperature in lakes is important because of the role it plays in lake stratification and its relation to chemical and biological processes. Thermal stratification is a phenomenon found in most Michigan lakes, whereby a layer of less dense, warm water is isolated from mixing with a denser, colder layer as the thermocline is established in the summer. The extent of thermal stratification in lakes depends on the interaction between the size and depth of the lake basin, solar heating, and local wind characteristics. Water temperature for the majority of lakes undergoes the greatest change between seasons for near-bottom measurements, where temperature is greater in the summer than in the spring (fig. 6). Water temperature was the most different for the majority of lake's near bottom measurements, where the temperature difference is greatest between the top and bottom measurements in the summer than in the spring. The smaller difference between top and bottom measurements in the spring is most likely because the lakes were close to complete turnover, and the greater difference in the summer was most likely owing to surface warming, which can result in lake stratification (though not all lakes stratified).

Specific conductance is a measure of the ability of water to conduct an electrical current and is an indicator of the concentration of dissolved solids in water. As the concentration of dissolved minerals increases, specific conductance also increases. While a lake is stratified, specific conductance generally is higher near the bottom because of the release of dissolved materials (such as iron, manganese, and phosphorus) from the bottom sediments under anoxic conditions. Specific conductance is fairly similar between the spring and summer depth comparisons, though the mean does show a slight overall increase with depth (fig. 7).

The pH of a lake is a measure of the hydrogen ion activity in the lake water; it is defined as the negative logarithm of the hydrogen ion concentration and varies over a 14-unit log scale. A pH of 7.0 is neutral, values less than 7.0 indicate acidic conditions, and values greater than 7.0 indicate alkaline conditions. The pH in most natural surface water ranges from 6.5 to 8.5, but pH values outside this range do occur. Overall, the pH in measured lakes is slightly lower as the measurement depth increases (fig. 8). Many chemical and biological processes, including photosynthesis, nitrification, and calcium-carbonate dissolution, control pH in lake water. Algae and aquatic plants produce oxygen and consume carbon dioxide by the photosynthesis process during the day and produce carbon dioxide when they respire at night. Carbon dioxide then combines with water to form carbonic acid, thereby creating a diurnal fluctuation of pH. This fluctuation is important because it affects the solubility of many chemical constituents and because aquatic organisms have limited pH tolerances. It has been shown that pH values greater than 8.5 will accelerate the release of phosphorus from lake-bottom sediment (James and Barko, 1991). At 6 to 7 percent of lakes (the majority less than 30 ft deep), measured pH was greater than 8.5 at mid-depth or metalimnion for spring or summer. Less than 2 percent of lakes had a pH greater than 8.5 for all three discrete sampling depths. Four percent of lakes had a pH value less than 6.5, with less than 2 percent of lakes with a pH less than 6.5 for all three discrete sampling depths; these latter lakes are solely in the Upper Peninsula.

The spatial distribution of the percentage of DO in the water column below two critical levels is shown in figure 9. Available data indicate that a healthy warmwater fish population requires DO concentrations of at least 2–5 mg/L (Kalff, 2002). Dissolved oxygen concentrations below 0.5 mg/L were categorized as anoxic for Michigan lakes according to Wehrly and others (2011). While some species have evolved to survive weeks to months with low DO, there can still be negative effects with longer periods of low DO such as inefficient food conversion for fish species. The portion of the water column with low DO can become unavailable to species, such as those requiring refuge during the day in deeper water from predators. Effects and stressors from low DO are dependent on the length of time of the low DO period and the lake system (Kalff, 2002).

Although there were a greater percentage of lakes in the summer than in the spring with DO below 2 and 0.5 mg/L, the lakes seem to be somewhat evenly distributed spatially among the Michigan lakes measured. In the spring, 34 percent of lakes had 25–69 percent of the water column (25–69 percent of the total lake depth) below 2.0 mg/L and 12 percent had 25–50 percent of the water column below 0.5 mg/L. In the summer, 58 percent of lakes had 25–86 percent of the water column below 2.0 mg/L and 30 percent had 25–83 percent of the water column below 0.5 mg/L.

The spatial distribution of mid-depth or metalimnion specific conductance and pH measurements is shown in figure 10. While specific conductance is similar among the spring and summer measurements, it varies noticeably by lower values in the Upper Peninsula of Michigan (hereinafter, "Upper Peninsula") compared to increasingly higher from the north to south of the Lower Peninsula of Michigan (hereinafter, "Lower Peninsula"). The highest values have been noted in the southeastern part of the Lower Peninsula. Lake-water pH does not vary noticeably among the spring and summer measurements, or spatially throughout Michigan, though most of the measurements below 6.5 seem to be solely in the Upper Peninsula. Lillie and Mason (1983) also found for Wisconsin that the majority of lakes with lower pH values were located in the northeast region of Wisconsin, and was "probably indicative of the large number of brown-stained lakes" in that region.

To determine whether differences among the vertical-profile measurements at different depth measurements in the deepest basin were statistically significant, and also whether differences between same depth measurements in the deepest basin between spring and summer were statistically significant, the Wilcoxon signed-rank test (Helsel and Hirsch, 2002) was used; results are listed in tables 4 and 5, respectively. The Wilcoxon signed-rank test is used for paired data to determine whether the median difference equals zero. There was a statistically significant difference at the 95-percent confidence level between spring and summer for all measurements except DO at mid-depth or metalimnion. There was also a statistically significant difference at the 95-percent confidence level among DO, water temperature, specific conductance, and pH between all measurement depths.

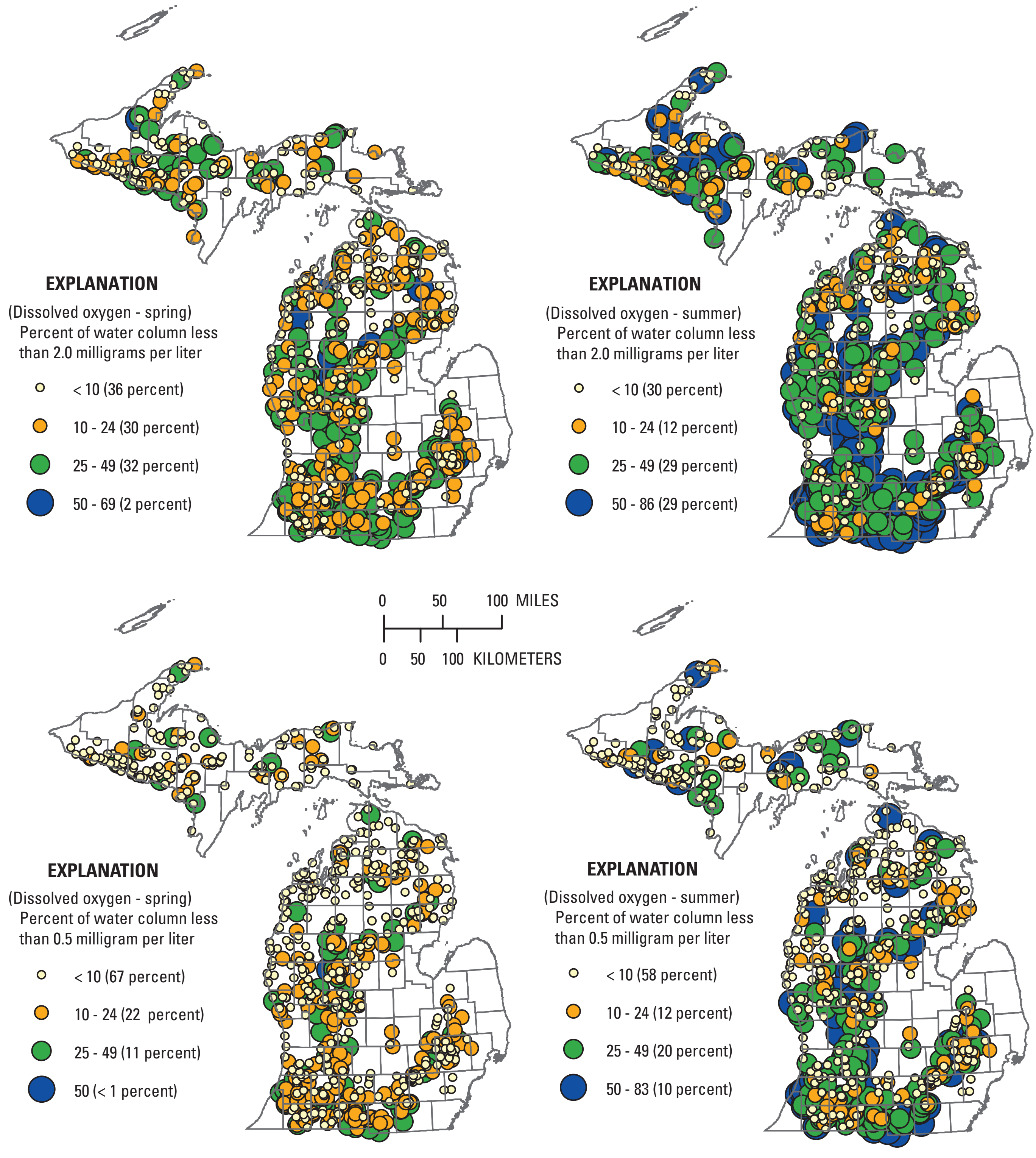

Figure 9. Spatial distribution of dissolved oxygen and the percentage of the water column below 0.5 and 2.0 milligrams per liter in spring and summer measurements for Michigan inland lakes during 2001–10.

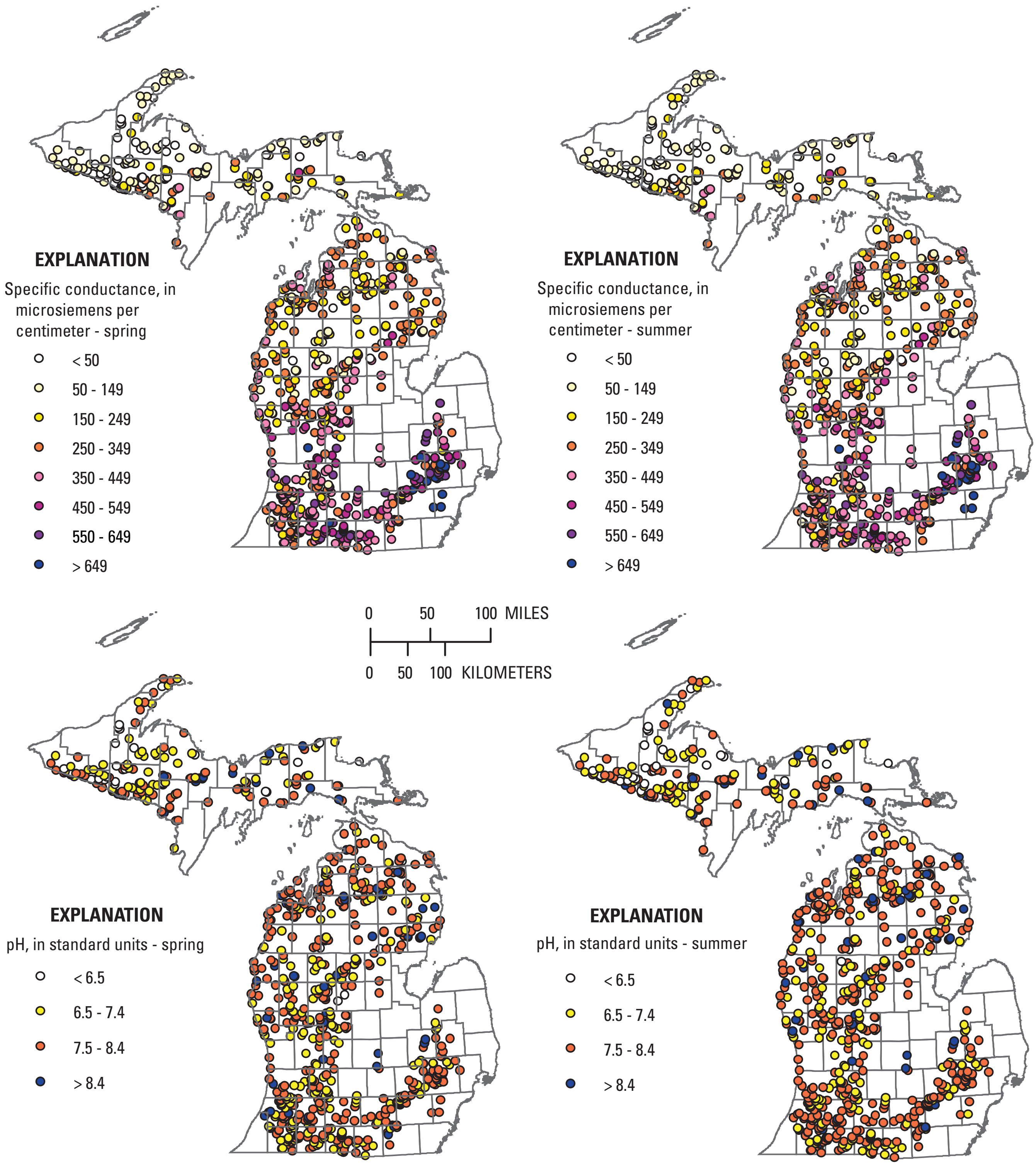

Figure 10. Spatial distribution of specific conductance and pH in spring and summer mid-depth or metalimnion measurements for Michigan inland lakes during 2001–10.

Table 4. Results of Wilcoxon signed-rank test to determine statistical significance among Michigan lakes spring and summer measurements throughout the vertical profile at measured depths for 2001–10.

[Significant at 95-percent confidence level if p-value result is less than 0.05]

Constituent	Sample size	Spring and summer
Dissolved oxygen		p-value
Near surface	729	0.00
Mid-depth or metalimnion	728	.49
Near bottom	727	.00
Water temperature		p-value
Near surface	729	0.00
Mid-depth or metalimnion	728	.00
Near bottom	727	.00
Specific conductance		p-value
Near surface	728	0.00
Mid-depth or metalimnion	729	.00
Near bottom	729	.00
pH		p-value
Near surface	727	0.00
Mid-depth or metalimnion	724	.01
Near bottom	723	.00

Table 5. Results of Wilcoxon signed-rank test to determine statistical significance among Michigan lakes in the vertical profile between measured depths for 2001–10.

[Significant at 95-percent confidence level if p-value result is less than 0.05]

	Sample size	Near surface and mid-depth	Sample size	Near surface and near bottom	Sample size	Mid-depth and near bottom
Spring		p-value		p-value		p-value
Dissolved oxygen	728	0.00	727	0.00	727	0.02
Water temperature	728	.00	728	.00	728	.00
Specific conductance	728	.00	728	.00	729	.00
pH	724	.00	723	.00	723	.00
Summer		p-value		p-value		p-value
Dissolved oxygen	729	0.00	729	0.00	729	0.00
Water temperature	729	.00	727	.00	727	.00
Specific conductance	728	.00	728	.00	729	.00
pH	728	.00	728	.00	728	.00

Trophic Status: Secchi-Disk Transparency, Chlorophyll *a*, and Total Phosphorus

At about 75 percent of inland lake index stations (deep basins) measured, trophic characteristics were associated with oligotrophic or mesotrophic conditions—74 percent if SDT was used as the sole indicator, 78 percent if chlorophyll *a* was used, and 84 percent if TP was used to determine the TSI values and trophic classifications. Differences in the percentages separating the oligotrophic and mesotrophic classes were greater when the three indicators were compared (fig. 11). Five percent of the lakes or fewer were categorized as hypereutrophic when using any of the three indicators. Land-cover data (Homer, 2004) show that the dominant land-cover type for lakes in northern Lower Michigan is mostly forested, with urban and agriculture as the dominant land cover for southern Lower Michigan; these land-cover differences could play a role in the trophic-classification spatial difference in Lower Michigan.

Fewer lakes were available for using SDT as the sole indicator because the Secchi disk hit the bottom of some lakes. In these instances, recording the depth of the lake would give a false sense of the TSI class. For example, if a lake has a maximum depth of about 6 to 9 ft (2 to 3 m) and the Secchi disk hit bottom, recording the lake depth for the SDT would be misleading because it would be associated with a mesotrophic to eutrophic TSI category. If a Secchi disk hit bottom, it might be indicative of a clear oligotrophic lake. Of the 36 lakes where the Secchi disk hit bottom, all but one lake might be considered shallow: 28 of the lakes were considered too shallow to allow for three discrete-depth measurements; in 7 lakes, maximum depth ranged from 7.5 to 20 ft; the last lake had a depth of 48 ft. For the lakes too shallow for three discrete-depth measurements, the single TP measurement from summer was used to compute the TSI and trophic status. Statistical distributions of individual measurements made in the spring and summer for SDT and chlorophyll *a* in the summer total for phosphorus used to compute TSI are shown in figure 12.

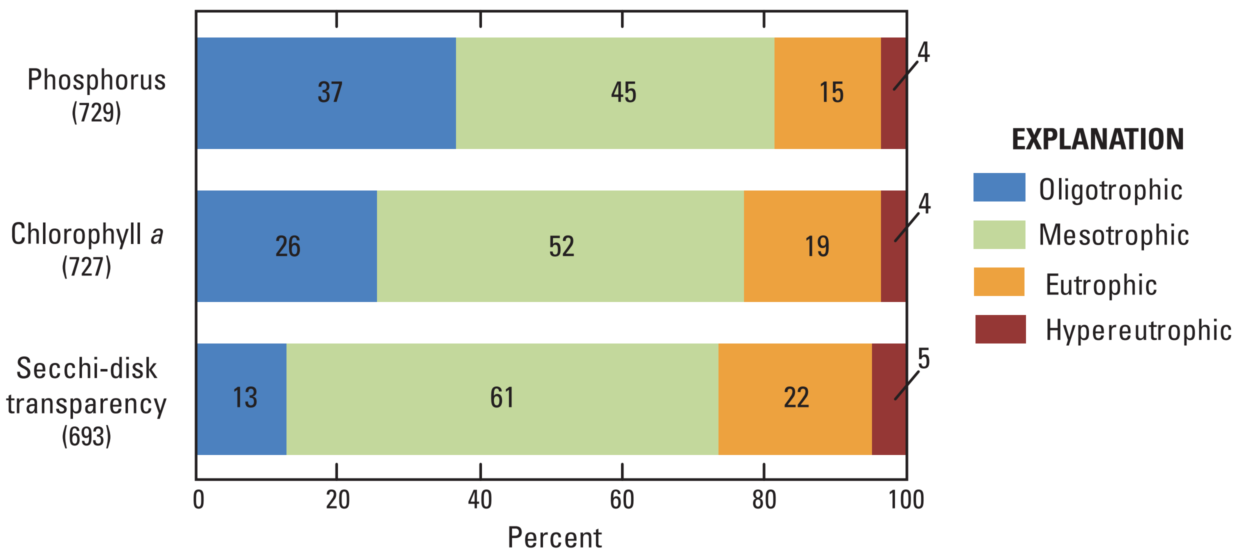

Figure 11. Trophic-status distribution using Secchi-disk transparency, chlorophyll *a*, or total phosphorus as the indicator.

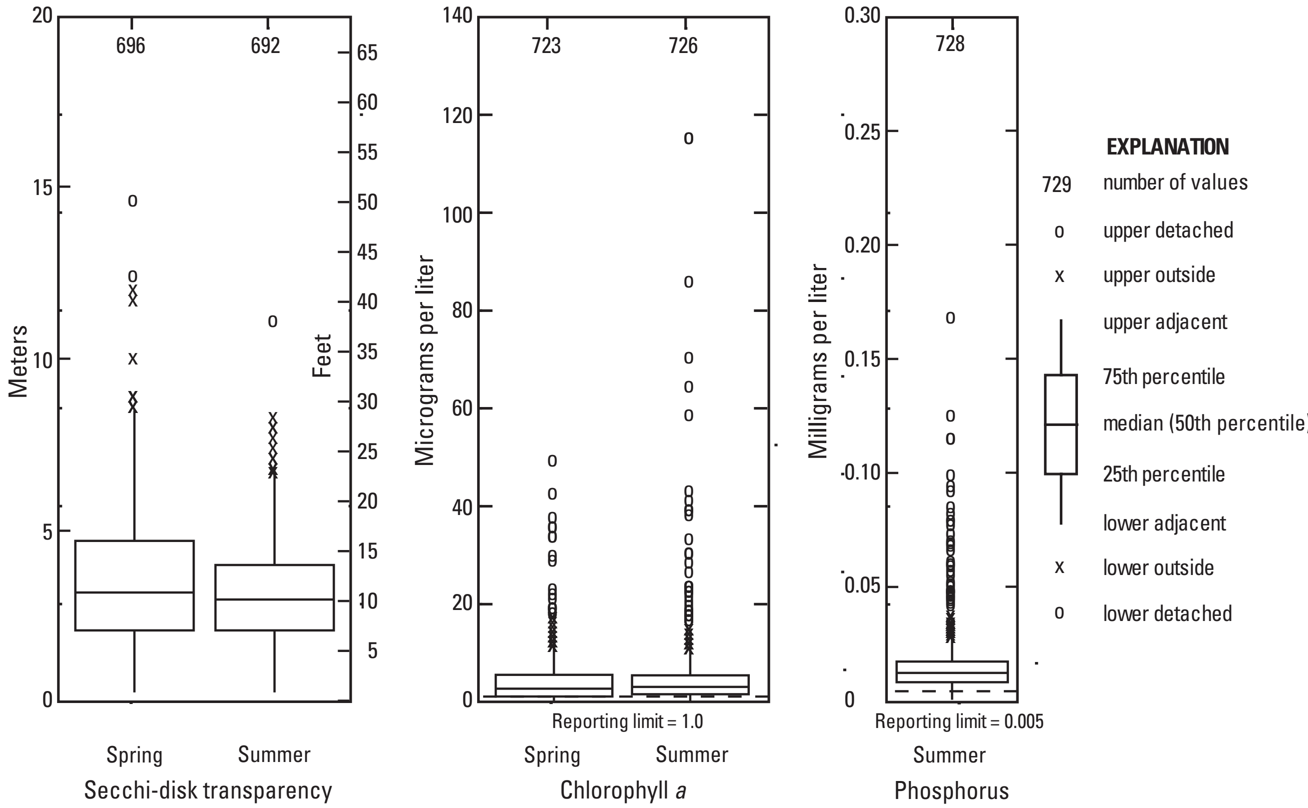

Figure 12. Statistical distribution of Secchi-disk transparency and chlorophyll *a* in spring and summer measurements and near-surface phosphorus in summer measurements at the index stations (deepest basins) in Michigan lakes during 2001–10.

The spatial distribution of mesotrophic and eutrophic lakes in Michigan is fairly even around the State. Oligotrophic lakes are more numerous and dense in the northern part of the Lower Peninsula, and hypereutrophic lakes are more numerous in the southern part of the Lower Peninsula, as is evident in figure 13. As lake depth decreases, the TSI values increase, as can be seen in figure 14. More than 80 percent of hypereutrophic lakes, regardless of the sole indicator used to compute the TSI, were 30 ft deep or less, with the deepest hypereutrophic lake measured at 52 ft. Bottom sediments in shallow lakes can play a major role in nutrient releases throughout the water column during wind-induced sediment resuspension and/or biological processes. The resuspension of sediment results in high levels of turbidity and nutrients in the lake. These conditions affect light penetration and influence algal productivity (Søndergaard and others, 2003).

There was a statistically significant difference at the 95-percent confidence level among spring and summer SDT and chlorophyll *a* measurements for individual lakes (table 6). However, there were fairly even counts of lakes with increases and decreases in the SDT and Chlorophyll *a* measurements among spring and summer in comparing all lakes; thus, an overall positive or negative relation between seasons was not found. For SDT measurements, there were slightly more clearer lakes in the spring than summer for 63 percent of lakes measured. Water clarity can be reduced by the presence of suspended sediment, dissolved organic substances, free-floating algae, and zooplankton, but algae commonly are the dominant affect on the clarity of lake water. Therefore, as a lake becomes more productive during summer months, it generally is expected that water clarity would decrease.

Color

True color, as by the spectrophotometric method, was added to the LWQA monitoring program during summer 2007–10 (fig. 15), and it provides a standardized means to assess lake-water color. Although color is a measure of the appearance of water, true color measures of water result when dissolved substances have been removed. Suspended matter, which includes algae and non-algal matter, can affect water color, as can climatic events such as increased rainfall (and thus runoff) and drought conditions. High levels of color in water can have a negative effect on lake biota if they prevent light from reaching necessary depths (Florida LAKEWATCH, 2004). A study by Webster and others (2008) showed both color and TP had a strong positive effect on chlorophyll *a* and a negative effect on Secchi transparency. Webster and others (2008) suggest misinterpretation of these widely used trophic-status indicators could occur without corresponding color measurements.

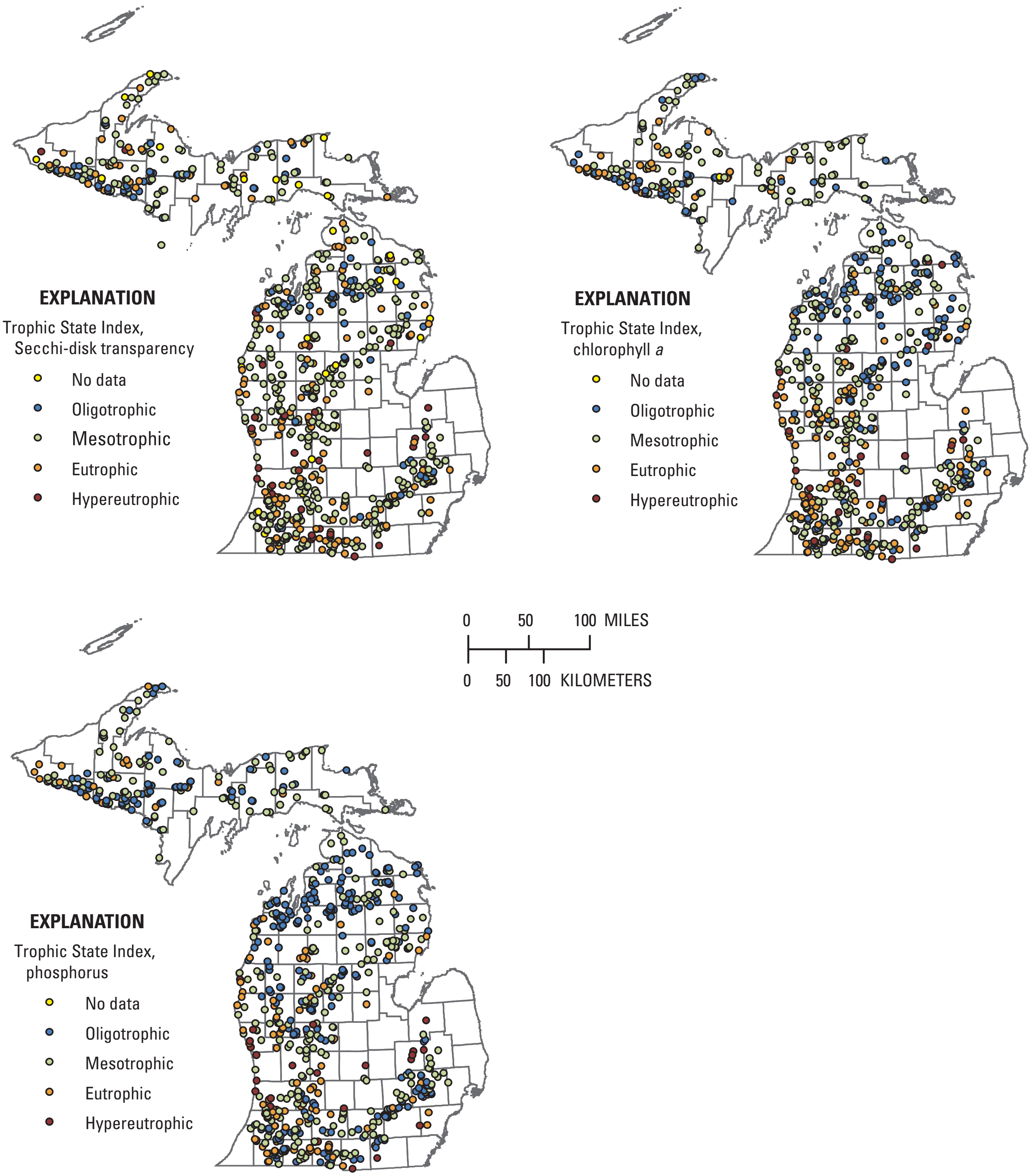

Figure 13. Spatial distribution of trophic status for Michigan inland lakes during 2001–10.

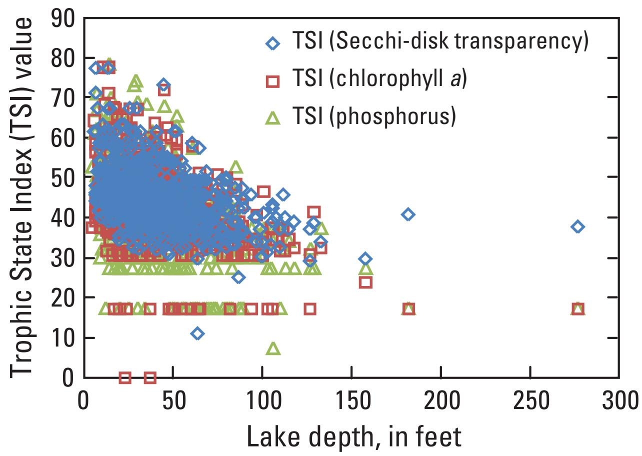

Figure 14. Trophic State Index (TSI) values compared to lake depth for Michigan inland lakes during 2001–10.

Table 6. Results of Wilcoxon signed-rank test to determine statistical significance between Michigan lakes spring and summer measurements of Secchi-disk transparency and chlorophyll *a* for 2001–10.

[Significant at 95-percent confidence level if p-value result is less than 0.05]

Measurement	Sample size	p-value
Secchi-disk transparency	693	0.00
Chlorophyll *a*	724	.00

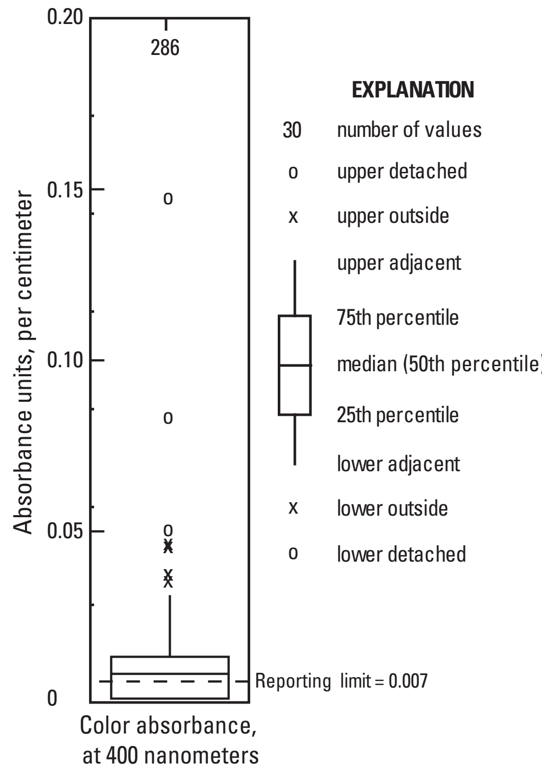

Figure 15. Statistical distribution of true color in the summer near-surface measurements at the index stations (deepest basins) in Michigan lakes during 2007–10.

Nutrients

Total phosphorus, Kjeldahl nitrogen (ammonia plus organic nitrogen), ammonia, and nitrate plus nitrite all were sampled near surface, at mid-depth or metalimnion, and near bottom during spring and summer. Total nitrogen was calculated by summing Kjeldahl nitrogen and nitrate plus nitrite. For those lakes considered too shallow to allow for three discrete-depth measurements, the available measurements were used in this analysis. Individual lake measurements for spring and summer at the three discrete depths are shown in figures 16–19. Nitrate plus nitrite values were higher in the spring than summer for the majority of lakes, whereas ammonia and ammonia plus organic nitrogen were higher in the summer near-bottom measurements. This pattern, along with the DO being lower in the summer near bottom (fig. 5), suggests that nutrient cycling and conversion was occurring in the summer at near-bottom depths.

Phosphorus and nitrogen are required for algae and aquatic macrophyte growth. The concentration of these nutrients will determine the quantity of plants that a lake can support. The quantity and diversity of the algae and aquatic macrophyte communities in turn plays an important role in the quantity and diversity of fish and other living organisms in the environment. However, if excessive amounts of nutrients are present, algal blooms and excessive growth of aquatic macrophytes can occur. Commonly, it requires only small additional quantities of nutrients above those that are naturally present to increase the primary productivity of a lake to the point where eutrophication becomes a concern. The nutrient in shortest supply tends to be the limiting control on production (Kalff, 2002). The spatial distribution of total nitrogen and TP for near-surface measurements in the spring and summer are shown in figure 20.

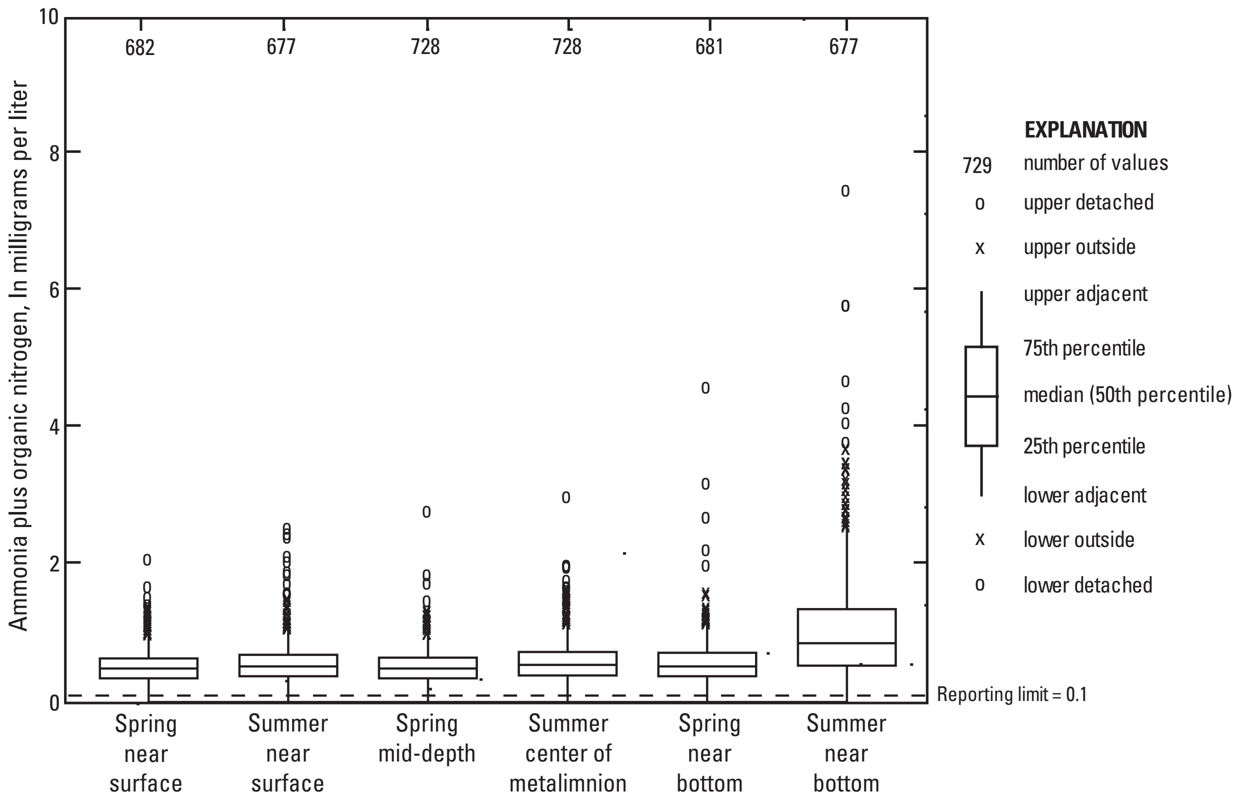

Figure 16. Statistical distribution of Kjeldahl nitrogen (ammonia plus organic nitrogen) in spring and summer near-surface, mid-depth or metalimnion, and near-bottom measurements at the index stations (deepest basins) in Michigan lakes during 2001–10.

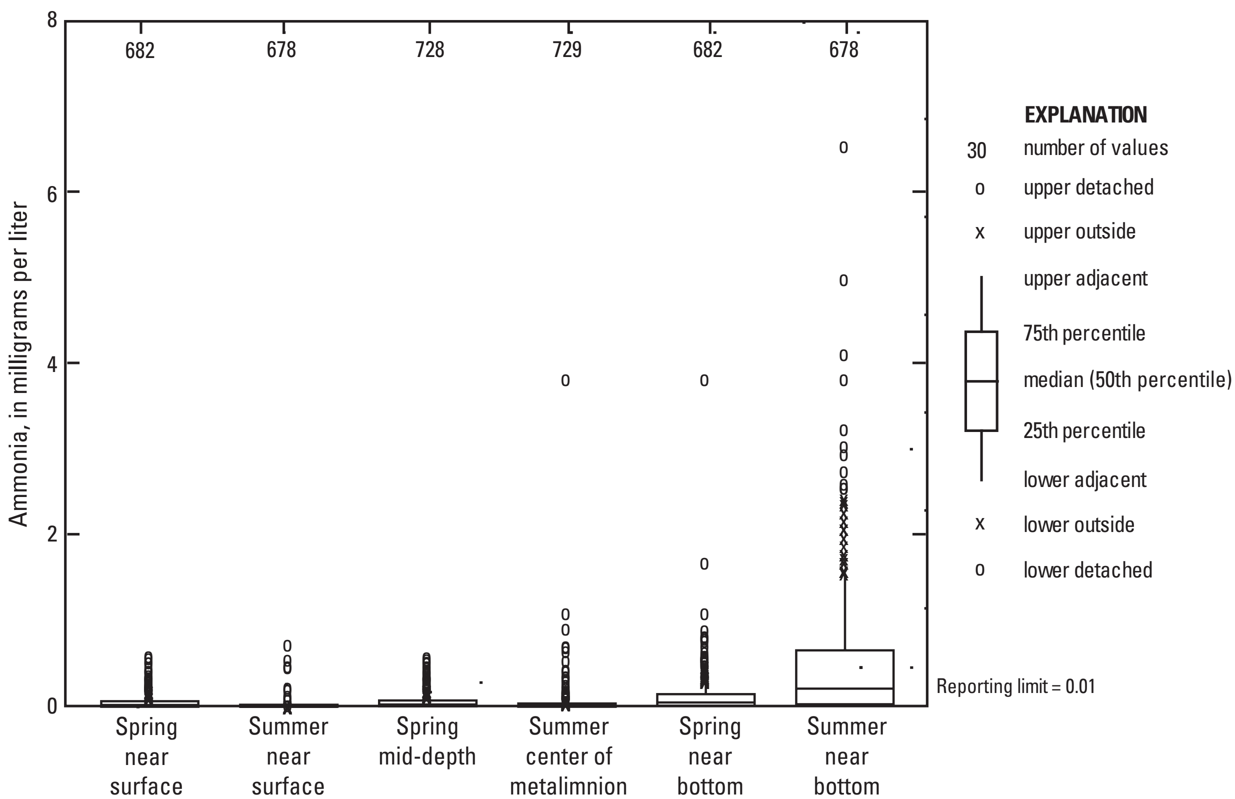

Figure 17. Statistical distribution of ammonia in spring and summer near-surface, mid-depth or metalimnion, and near-bottom measurements at the index stations (deepest basins) in Michigan lakes during 2001–10.

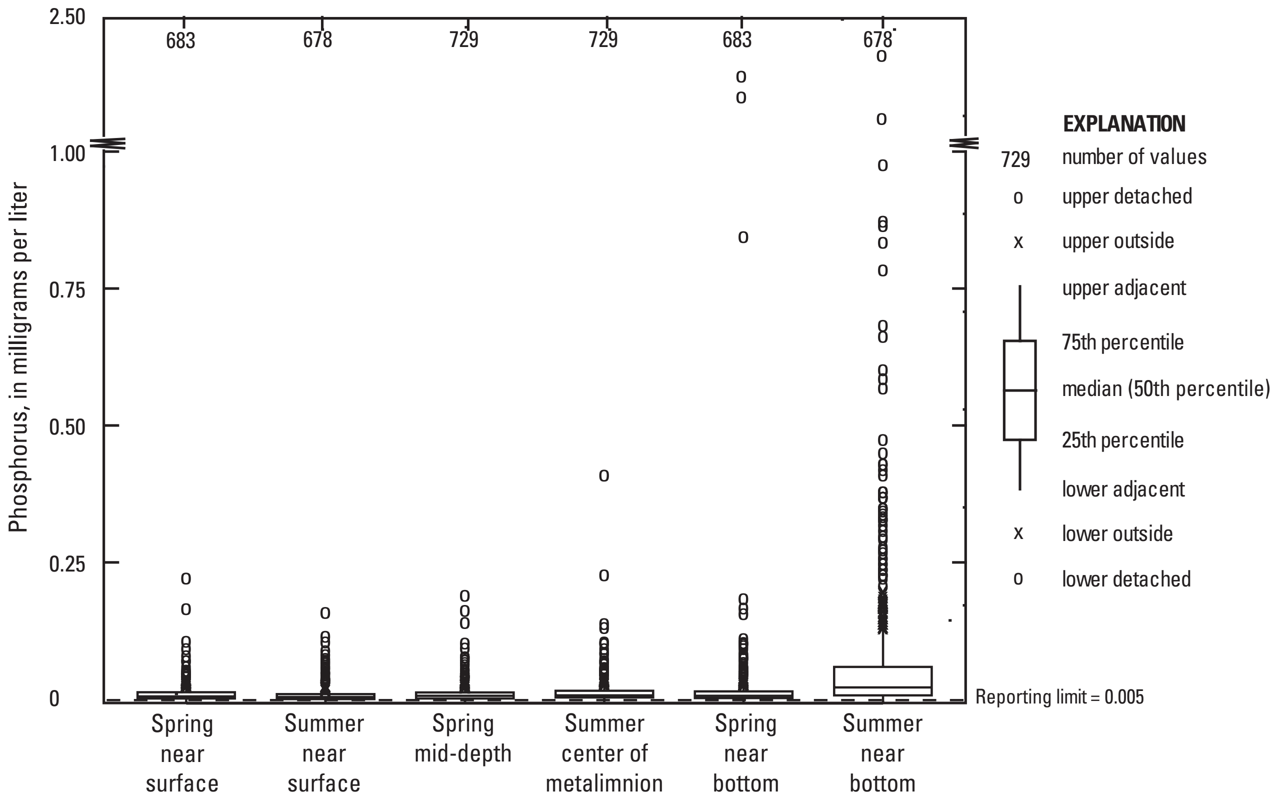

Figure 18. Statistical distribution of total phosphorus in spring and summer for near-surface, mid-depth or metalimnion, and near-bottom measurements at the index stations (deepest basins) in Michigan lakes during 2001–10.

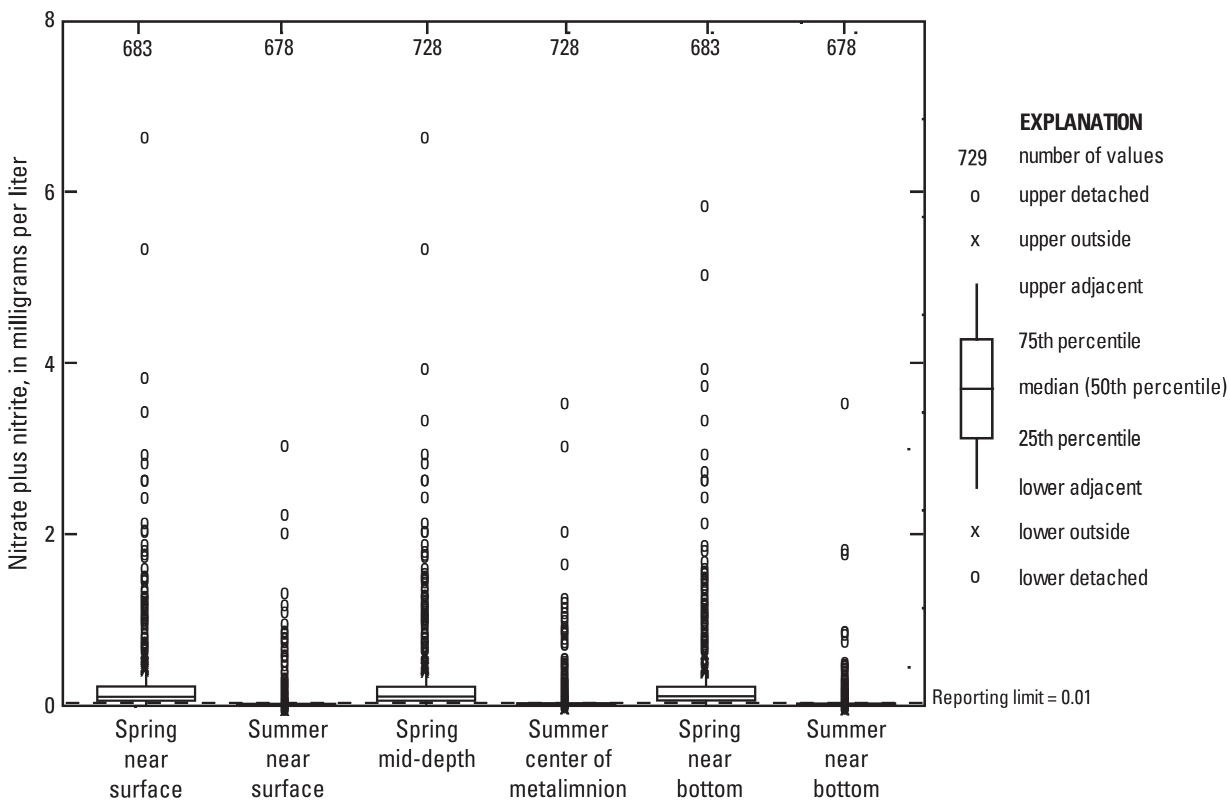

Figure 19. Statistical distribution of nitrate plus nitrite in spring and summer for near-surface, mid-depth or metalimnion, and near-bottom measurements at the index stations (deepest basins) in Michigan lakes during 2001–10.

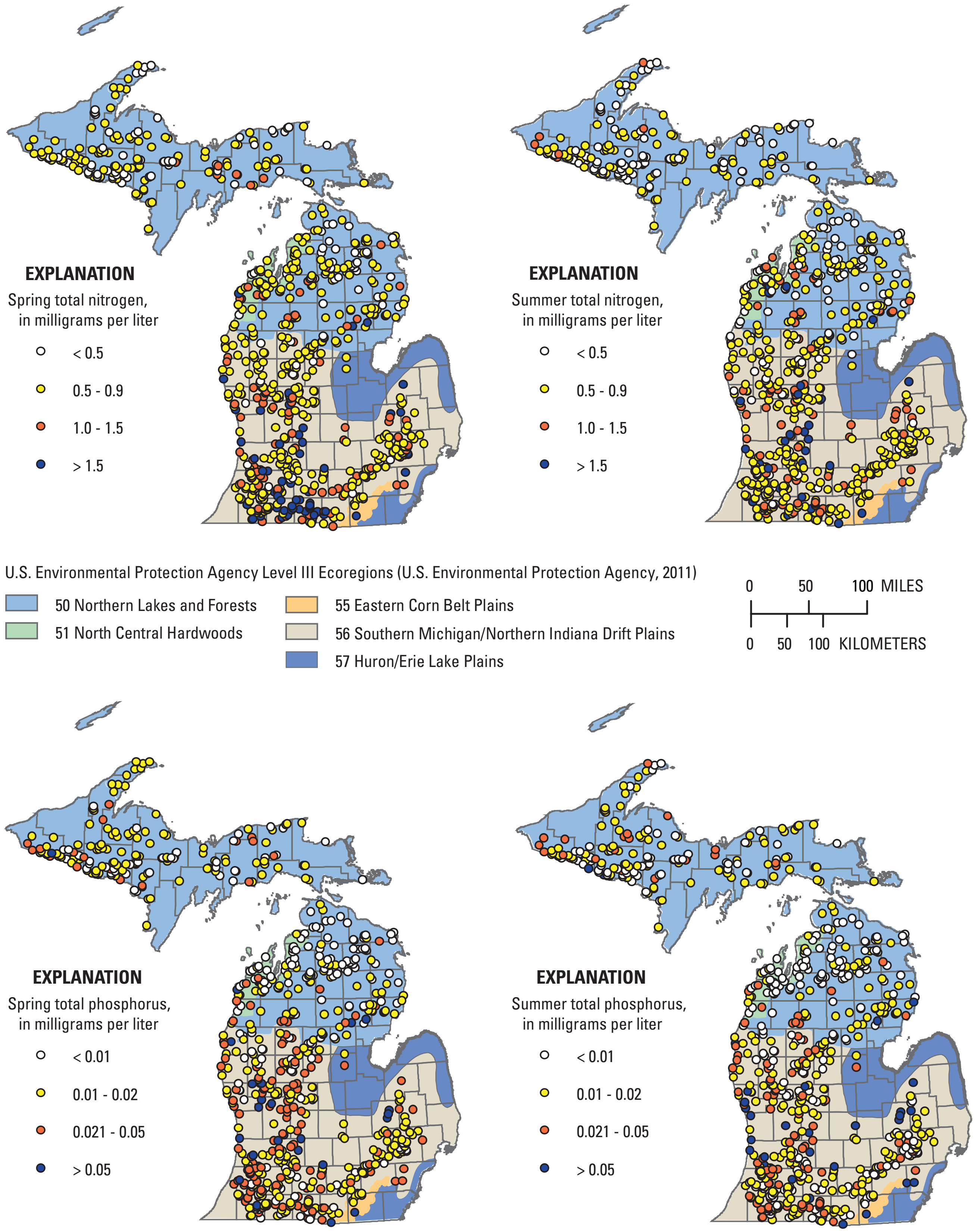

Figure 20. Spatial distribution of total nitrogen and total phosphorus for both spring and summer near surface measurements for Michigan inland lakes during 2001–10.

Lakes with total nitrogen to TP ratios greater than 15:1 near surface generally are considered phosphorus limited; ratios ranging from 10:1 to 15:1 indicate a transition situation; and a ratio less than 10 to 1 indicates nitrogen limitation (Vollenweider, 1968, 1969, 1976). On the basis of near-surface measurements from Michigan lakes during 2001–10 in the spring, 97 percent of the lakes can be considered phosphorus limited and less than a half percent nitrogen limited; for summer measurements, 96 percent would be phosphorus limited, and less than a half percent nitrogen limited. Following these same guidelines for the mid-depth or metalimnion measurements, similar percentages of phosphorus-limited lakes (around mid-90 percents) and nitrogen-limited lakes (less than 1 percent) occurred during both seasons, as well as for the spring near bottom; on the basis of summer near-bottom measurements, 75 percent of the lakes were phosphorus limited and 14 percent nitrogen limited.

To determine whether differences among the nutrient measurements at different depths and also between spring and summer were statistically significant, the Wilcoxon signed-rank test was used. Results are listed in tables 7 and 8, respectively. For the spring, all nutrients measured were statistically significant at the 95-percent confidence level among all depths except for ammonia plus organic nitrogen and TP between the near surface and mid-depth measurements. For summer, differences among all nutrients measured were statistically significant at the 95-percent confidence level among all depths except for nitrate plus nitrite between mid-depth or metalimnion and near bottom. On a lake-by-lake basis, there were more differences in nutrients among depths in the spring than in the summer between the near surface and mid-depth. All differences in nutrient concentrations were determined to be statistically significant at the 95-percent confidence level among spring and summer measurements at the discrete depths.

Table 8. Results of Wilcoxon signed-rank test to determine statistical significance among Michigan lakes spring and summer nutrients at measured depths for 2001–10.

[Significant at 95-percent confidence level if p-value result is less than 0.05]

Constituent	Sample size	Spring and summer
Ammonia plus organic nitrogen		p-value
Near surface	678	0.00
Mid-depth or metalimnion	729	.00
Near bottom	678	.00
Ammonia		p-value
Near surface	678	0.00
Mid-depth or metalimnion	728	.00
Near bottom	678	.00
Total phosphorus		p-value
Near surface	678	0.01
Mid-depth or metalimnion	729	.00
Near bottom	678	.00
Nitrate plus nitrite		p-value
Near surface	678	0.00
Mid-depth or metalimnion	728	.00
Near bottom	678	.00

Table 7. Results of Wilcoxon signed-rank test to determine statistical significance among Michigan lakes nutrients at measured depths for 2001–10.

[Significant at 95-percent confidence level if p-value result is less than 0.05]

	Sample size	Near surface and mid-depth	Sample size	Near surface and near bottom	Sample size	Mid-depth and near bottom
Spring		p-value		p-value		p-value
Ammonia plus organic nitrogen	683	0.96	682	0.00	682	0.00
Ammonia	682	.00	682	.00	682	.00
Total phosphorus	683	.95	683	.00	683	.00
Nitrate plus nitrite	683	.00	683	.00	683	.03
Summer		p-value		p-value		p-value
Ammonia plus organic nitrogen	678	0.00	678	0.00	678	0.00
Ammonia	678	.00	678	.00	678	.00
Total phosphorus	678	.01	678	.00	678	.00
Nitrate plus nitrite	678	.00	678	.00	678	.47

Major Ions and Physical Properties

In the spring, major ions and various physical properties of water were measured at mid-depth to establish “whole lake” baseline water-quality conditions after mixing and before potential summer stratification. Catchment runoff contributes to the concentration of major ions, along with those naturally present that together yield the salinity in inland lakes. Sources of major ions can include local geology, human activities, and climatic variation, and the concentration and mix of major ions influence lake biota (Kalff, 2002); statistical distributions of measurements of major ions and associated properties are shown in figures 21 and 22. There were spatial patterns of lower values in the Upper Peninsula, with increasing values towards the southern part of Michigan, for all major ions and physical properties, although the location of increase and intensity varied by constituent and property.

U.S. Environmental Protection Agency level III ecoregions (U.S. Environmental Protection Agency, 2011), which were created on the basis of land cover, geology, physiography, vegetation, climate, soils, wildlife, and hydrology, are shown in figures 23*A* and 23*B* along with constituent values. Potassium, sulfate, and chloride concentrations fairly closely followed the level III ecoregion boundaries. Magnesium, hardness, calcium, and alkalinity middle-range values were spatially diverse, though low to middle values were found in the Northern Lakes and Forest ecoregion covering the Upper Peninsula and the northern Lower Peninsula, and middle to higher values were found in the southern Michigan/Northern Indiana Drift Plains ecoregion. Alkalinity and magnesium concentrations were the lowest in the Upper Peninsula, but the higher concentrations started in the eastern end of the Upper Peninsula and continued to increase southward, with the highest measurements in the southern Lower Peninsula. Sodium and chloride concentrations were lower in the Upper Peninsula and in most of the Lower Peninsula, but higher concentrations were clustered in the southeastern Lower Peninsula, especially for lakes in Genesee, Livingston, and Oakland Counties. Higher concentrations of sodium and chloride observed in the southeastern Lower Peninsula are most likely a result from the use of road salt for deicing roads, parking lots, and other impervious surfaces during the winter months. Elevated concentrations of chlorides can inhibit plant growth, impair reproduction, and reduce the diversity of organisms in streams (Mullaney and others, 2009).

Examination of Multibasin Lakes

Of the 729 Michigan lakes measured, 109 have at least two deep basins, 26 have three deep basins, and 2 have four deep basins where thermal stratification is likely to occur during the summer. All these secondary basins were measured, replicating the same water-quality parameters measured at the index stations (deepest basins). The basins were ranked 1 through 4 by their maximum depth; examples of multiple-basin lakes are shown in figure 24.

The Wilcoxon signed-rank test was used to determine statistical significance of differences in measurements among multiple basins. When basins 1 and 2 were compared for the spring, differences in SDT, water temperature for mid-depth and near bottom, pH for near surface, and nitrate plus nitrite for near surface and mid-depth were determined to be statistically significant at the 95-percent confidence level. Differences in chlorophyll *a*, water temperature, potassium, and magnesium were also statistically significant at the 95-percent confidence level between other basin combinations. In the summer, differences in water temperature near-bottom measurements, pH for near-surface measurements, and nitrate plus nitrite for near-bottom measurements were statistically significant at the 95-percent confidence level between basins 1 and 2. Differences in DO and water temperature were statistically significant at the 95-percent confidence level between other basin combinations. There were not enough lakes with four basins to test for significant difference between the fourth basins. The resulting p-values are listed in table 9. Owing to the lack of statistical significance overall for differences between constituents in lakes with multiple basins, one basin measurement per lake would be sufficient, perhaps with some exceptions depending on desired constituents.

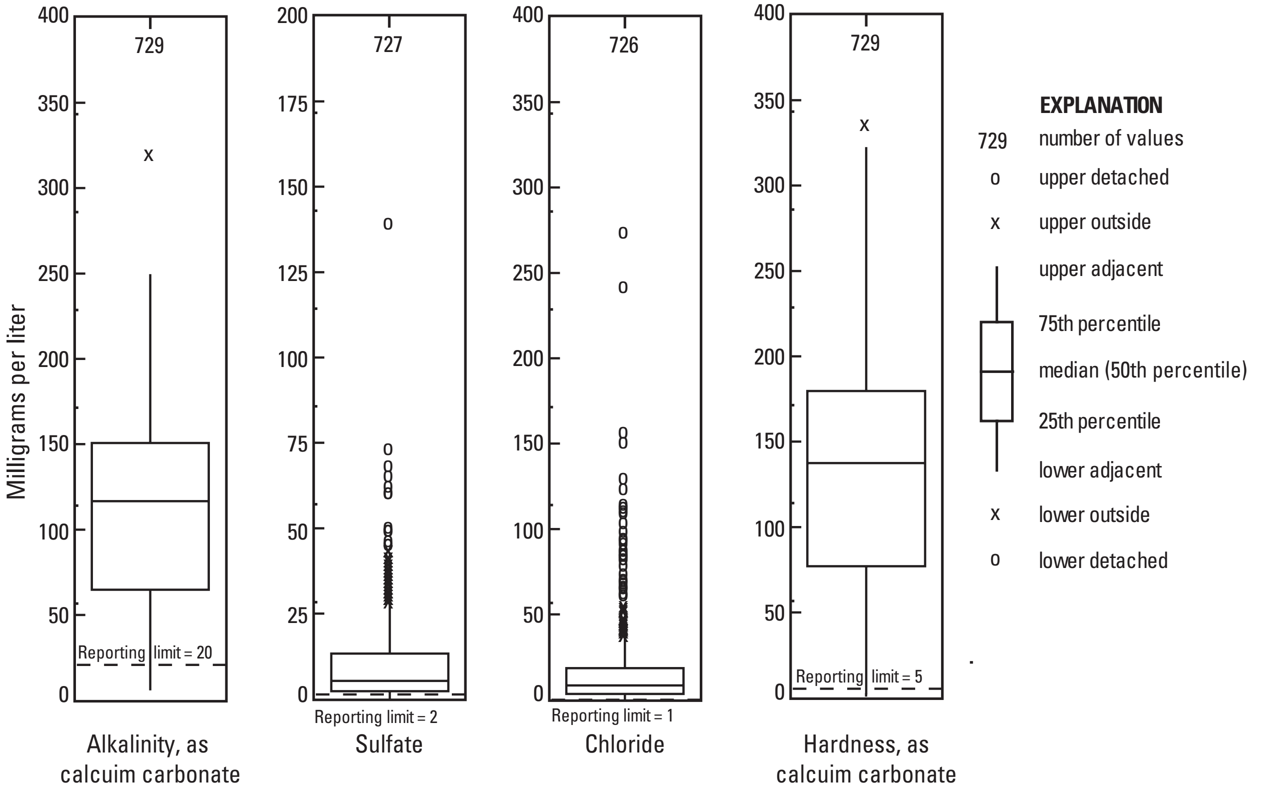

Figure 21. Statistical distribution of alkalinity, sulfate, chloride, and hardness in spring measurements at the index stations (deepest basins) in Michigan lakes during 2001–10.

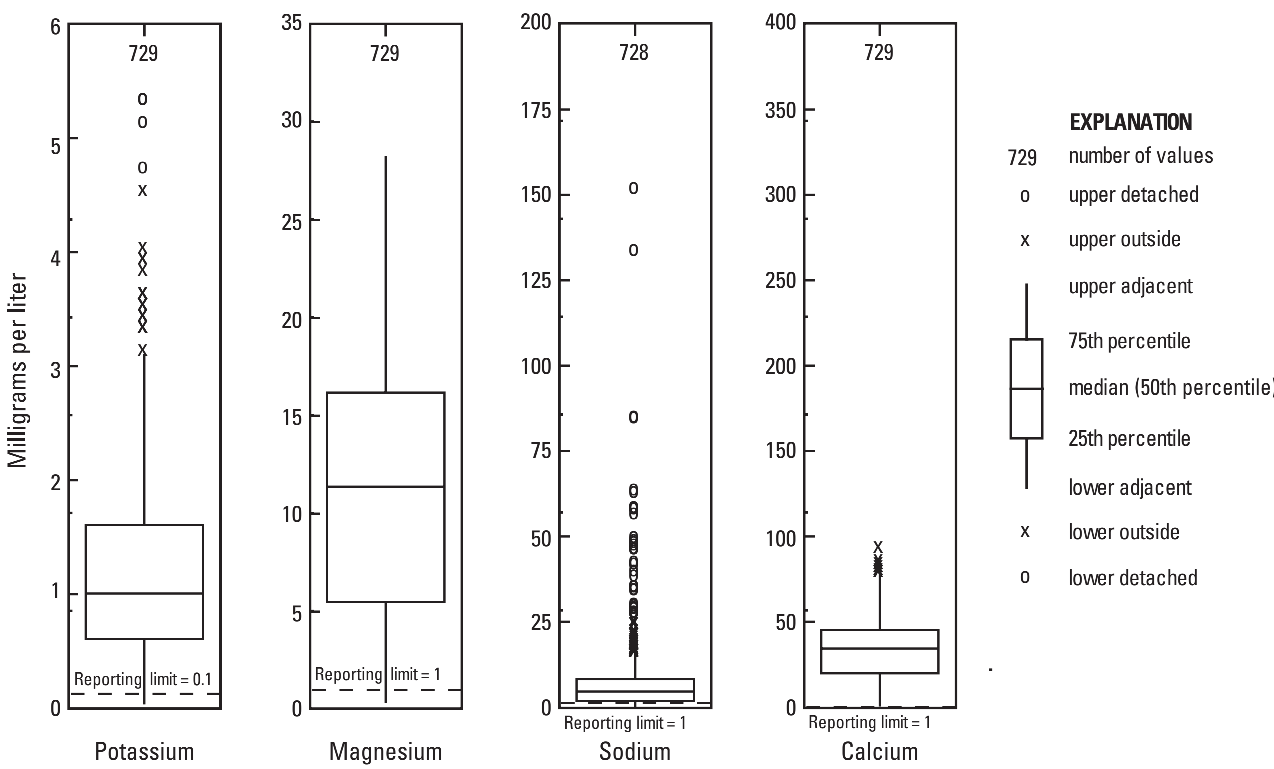

Figure 22. Statistical distribution of potassium, magnesium, sodium, and calcium in spring measurements at the index stations (deepest basins) in Michigan lakes during 2001–10.

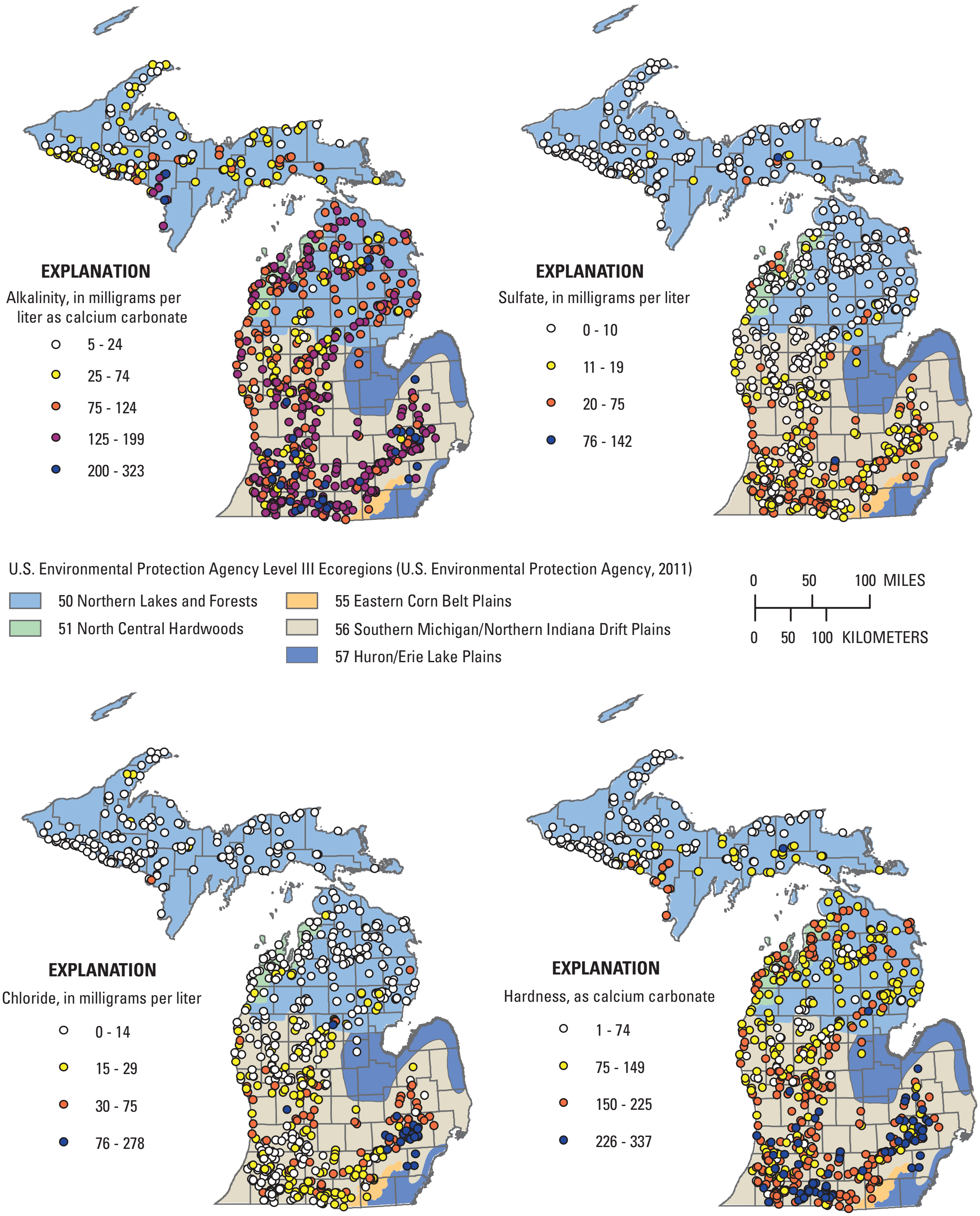

Figure 23*A*. Spatial distribution of alkalinity, sulfate, chloride, and hardness measured at Michigan inland lakes during 2001–10 in relation to U.S. Environmental Protection Agency Level III ecoregions.

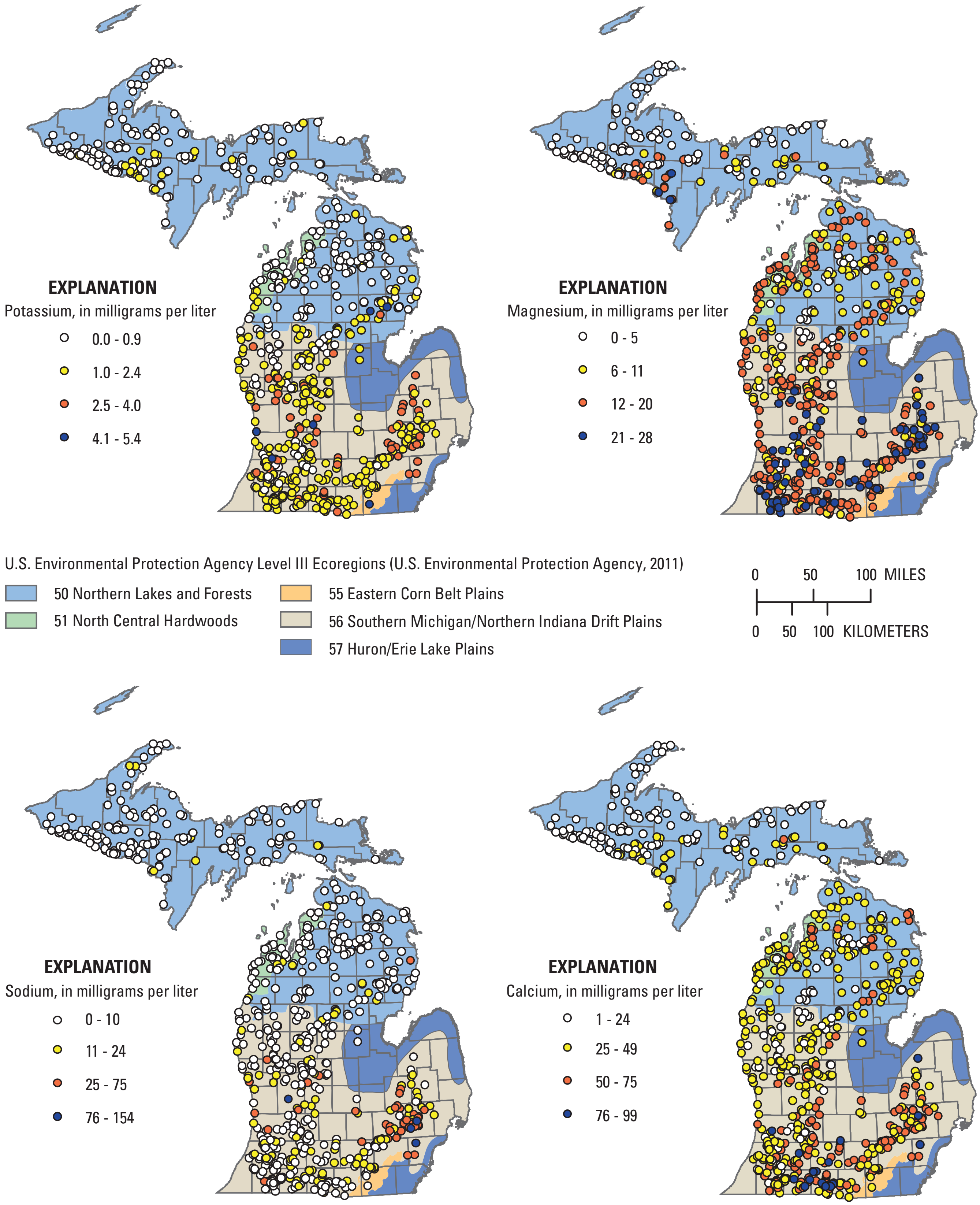

Figure 23*B*. Spatial distribution of potassium, magnesium, sodium, and calcium measured at Michigan inland lakes during 2001–10 in relation to U.S. Environmental Protection Agency Level III ecoregions.

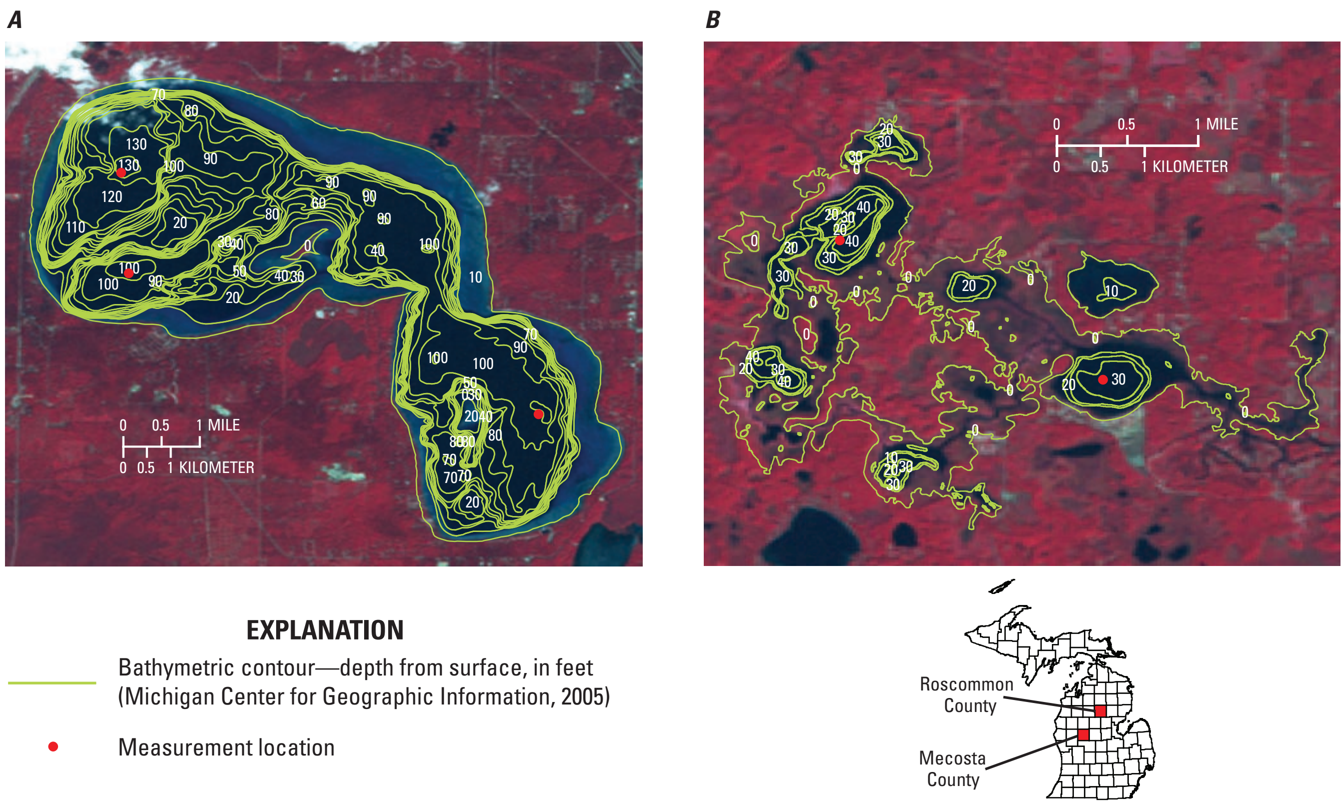

Figure 24. Multiple-basin lake examples in Michigan shown over Landsat satellite imagery for September 11, 2009. *A*, Higgins Lake in Roscommon County. *B*, Martiny Lake in Mecosta County.

Table 9. Results of Wilcoxon signed-rank test to determine statistical significance among Michigan lakes with multiple basins, by constituent, for 2001–10.

[$CaCO_3$, calcium carbonate; ~, not enough measurements to produce p-value; significant at 95-percent confidence level if p-value result is less than 0.05]

Spring	Basin 1 and 2		Basin 1 and 3		Basin 2 and 3	
Constituent	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Secchi-disk transparency	109	0.70	26	0.20	26	0.71
Chlorophyll *a*	108	0.88	26	0.03	26	0.07
Dissolved oxygen	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	109	0.25	26	0.78	26	0.51
Mid-depth or metalimnion	109	0.70	26	0.48	26	0.98
Near bottom	108	0.88	26	0.65	26	0.56
Water temperature	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	109	0.68	26	0.22	26	0.57
Mid-depth or metalimnion	109	0.00	26	0.03	26	0.05
Near bottom	108	0.00	26	0.07	26	0.38
Specific conductance	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	109	0.51	26	0.88	26	0.32
Mid-depth or metalimnion	109	0.67	26	0.95	26	0.47
Near bottom	109	0.53	26	0.57	26	0.57
pH	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	109	0.04	26	0.17	26	0.95
Mid-depth or metalimnion	108	0.26	26	0.19	26	0.17
Near bottom	108	0.79	26	0.72	26	0.81
Ammonia plus organic nitrogen	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	106	0.79	23	0.81	23	0.88
Mid-depth or metalimnion	109	0.13	26	0.66	26	0.06
Near bottom	106	0.81	23	0.48	23	0.84
Ammonia	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	105	0.98	23	0.66	23	0.65
Mid-depth or metalimnion	108	0.10	26	0.90	26	0.50
Near bottom	105	0.06	23	0.47	23	0.64
Total phosphorus	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	104	0.27	23	0.74	23	0.34
Mid-depth or metalimnion	109	0.79	26	0.64	26	0.29
Near bottom	106	0.32	23	0.93	23	0.84
Nitrate plus nitrite	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	106	0.03	23	0.58	23	0.60
Mid-depth or metalimnion	109	0.04	26	0.74	26	0.39
Near bottom	106	0.25	23	0.70	23	0.41

Table 9. Results of Wilcoxon signed-rank test to determine statistical significance among Michigan lakes with multiple basins, by constituent, for 2001–10.—Continued

[$CaCO_3$, calcium carbonate; ~, not enough measurements to produce p-value; significant at 95-percent confidence level if p-value result is less than 0.05]

	Basin					
Summer	**1 and 2**		**1 and 3**		**2 and 3**	
Constituent	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Secchi-disk transparency	107	0.58	25	0.17	25	0.29
Chlorophyll *a*	109	0.18	26	0.37	26	0.84
**Color	45	0.13	8	~	8	~
Dissolved oxygen	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	109	0.70	26	0.28	26	0.16
Mid-depth or metalimnion	109	0.41	26	0.28	26	0.03
Near bottom	108	0.81	26	0.67	26	0.57
Water temperature	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	109	0.41	26	0.30	26	0.79
Mid-depth or metalimnion	109	0.19	26	0.13	26	0.14
Near bottom	107	0.00	26	0.03	26	0.24
Specific conductance	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	109	0.30	26	0.40	26	0.77
Mid-depth or metalimnion	109	0.10	26	0.43	26	0.94
Near bottom	109	0.42	26	0.12	26	0.29
pH	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	109	0.01	26	0.24	26	0.63
Mid-depth or metalimnion	109	0.25	26	0.42	26	0.95
Near bottom	109	0.63	26	0.25	26	0.51
Ammonia plus organic nitrogen	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	105	0.54	23	0.56	23	0.92
Mid-depth or metalimnion	109	0.45	26	0.40	26	0.37
Near bottom	105	0.45	23	0.47	23	0.41
Ammonia	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	105	0.60	23	0.14	23	0.96
Mid-depth or metalimnion	109	0.54	26	0.22	26	0.84
Near bottom	105	0.17	23	0.76	23	0.85
Total phosphorus	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	105	0.76	23	0.33	23	0.15
Mid-depth or metalimnion	109	0.33	26	0.40	26	0.77
Near bottom	105	0.08	23	0.55	23	0.27
Nitrate plus nitrite	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
Near surface	105	0.28	23	0.49	23	0.66
Mid-depth or metalimnion	109	0.47	26	0.40	26	0.55
Near bottom	105	0.03	23	0.36	23	0.31

Table 9. Results of Wilcoxon signed-rank test to determine statistical significance among Michigan lakes with multiple basins, by constituent, for 2001–10.—Continued

[$CaCO_3$, calcium carbonate; ~, not enough measurements to produce p-value; significant at 95-percent confidence level if p-value result is less than 0.05]

	Basin					
Spring—continued	**1 and 2**		**1 and 3**		**2 and 3**	
Mid-depth or metalimnion	**Sample size**	**p-value**	**Sample size**	**p-value**	**Sample size**	**p-value**
*Alkalinity (as CaCO3)	109	0.59	26	0.26	26	0.33
*Calcium - total	109	0.95	26	0.10	26	0.30
*Chloride	108	0.82	25	0.35	25	0.86
*Hardness - calculated	109	0.98	26	0.24	26	0.16
*Potassium - total	109	0.97	26	0.05	26	0.30
*Magnesium - total	109	0.63	26	0.69	26	0.01
*Sodium - total	109	0.58	26	0.85	26	0.29
*Sulfate	108	0.07	25	1.00	26	0.11

*Spring only.

**Summer only 2007–10.

Comparisons With Other Lake-Monitoring Data for Michigan

Volunteers coordinated by the original MDNR (now the MDEQ) began sampling lakes in 1974 and continue to sample (in 2010) approximately 250 inland lakes each year through the Michigan Cooperative Lakes Monitoring Program (CLMP). The objectives of the CLMP are to help citizen volunteers monitor indicators of water quality in their lakes such as SDT, chlorophyll *a*, phosphorus, DO, and temperature; to perform aquatic-plant surveys along with identifying whether exotic species are present; and to document changes in lake quality over time (*http://www.micorps.net/lakeoverview.html*).

Chlorophyll *a* and SDT data were used from the CLMP to determine trophic-status conditions from those lakes monitored for 2001–10. Lake data were chosen for the month of August of each year, and only one measurement for that month in the primary sampling station (deepest basin) was used to determine trophic-status conditions. The month of August corresponded to when measurements were made for the summer sampling season, which allowed a comparable time period between the two datasets. The majority of lakes have been sampled for multiple years, but some lakes are or are not measured each year for various reasons, which is why the number of measurements per year has varied. The resulting trophic-status conditions by percent for each year are shown in figure 25.

Data from the CLMP in addition to supplemental data specific to the Upper Peninsula, which was jointly measured by USGS and MDEQ, were used to extend the existing SDT measurements to produce TSI predictions for Michigan lakes greater than 20 acres based on satellite imagery. The remote sensing processes to produce the predicted TSI values are summarized in Fuller and others (2011). The statewide predictions for Michigan inland lakes greater than 20 acres without interference from clouds, cloud shadows, haze, dense vegetation, or shoreline for the periods 2003–05, 2007–08, and 2009–10 are shown in figure 26.

The National Lakes Assessment (NLA)—based on chemical, physical, and biological data—measured lakes nationwide during 2007 to provide a statistically valid, probability-designed estimate of the condition of lakes on a national and regional scale (U.S. Environmental Protection Agency, 2009). Michigan was one of the States that opted to increase the number of measurements collected to provide State-specific estimates. The calculated TSI values were weighted on the basis of lake size and ecological region by use of a mapping and analysis tool (NLA Data Viewer) developed by USEPA (Kiddon, 2009). The tool was used to obtain the data and produce the percentages of trophic-status categories for Michigan data and also for the Nation for comparison to those produced using trophic-status criteria specific to Michigan (from table 2) using SDT, chlorophyll *a*, and phosphorus; results are shown in figure 27.

When SDT was compared for the current (2001–10) 729 deepest basin in lakes greater than 25 acres with public boat launch (fig. 11) to the CLMP from Michigan's volunteer monitoring network for years 2001 through 2010 (fig. 25), similar percentages for trophic-status categories emerged; on average, however, the CLMP percentage for the oligotrophic class was slightly higher and for the hypereutrophic class was slightly lower. It makes sense that more volunteers might be living on or having access to clearer lakes than impaired lakes. When the SDT data for 2001–10 were compared to the remote sensing statewide predicted layer with predictions for all lakes greater than 20 acres (fig. 26) regardless of public or volunteer access, the percentage for the oligotrophic class was lower.

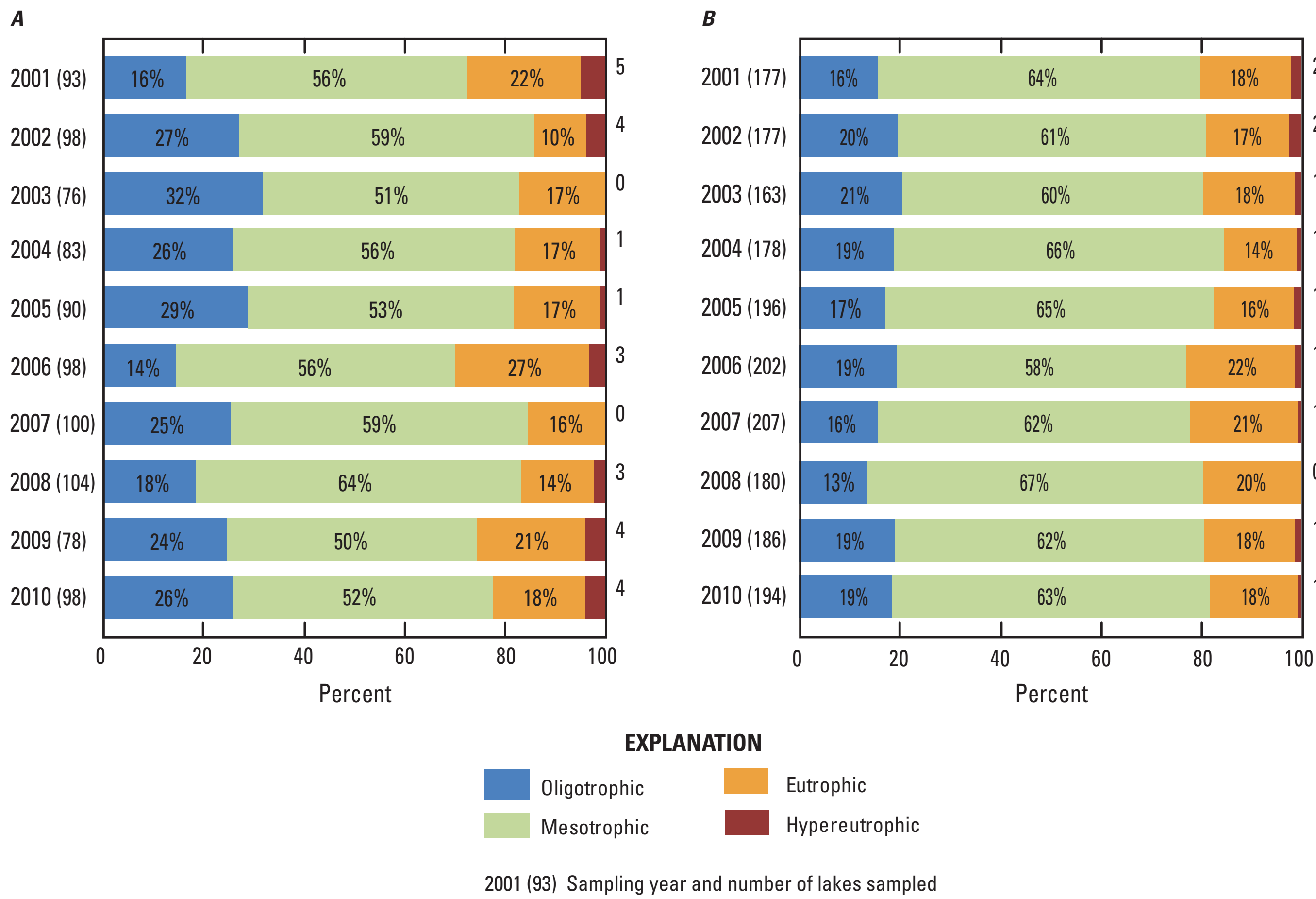

Figure 25. Trophic status based on data from the Cooperative Lakes Monitoring Program for one date per lake during the month of August for 2001–10 calculated from *A,* chlorophyll *a* and *B*, Secchi-disk transparency.

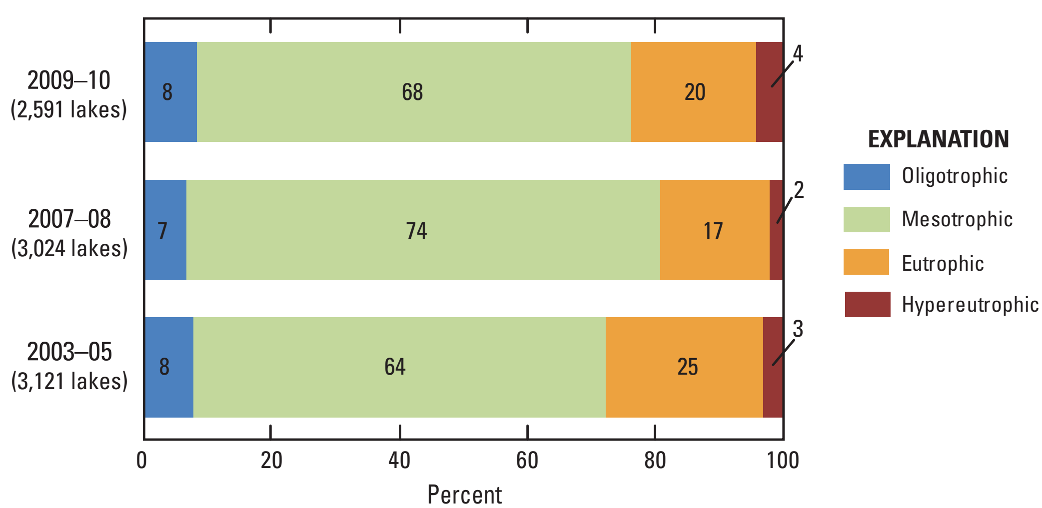

Figure 26. Statewide predictions of trophic status, by time period, produced by relating existing Secchi-disk transparency measurements to satellite imagery to produce predictions for all Michigan lakes greater than 20 acres.

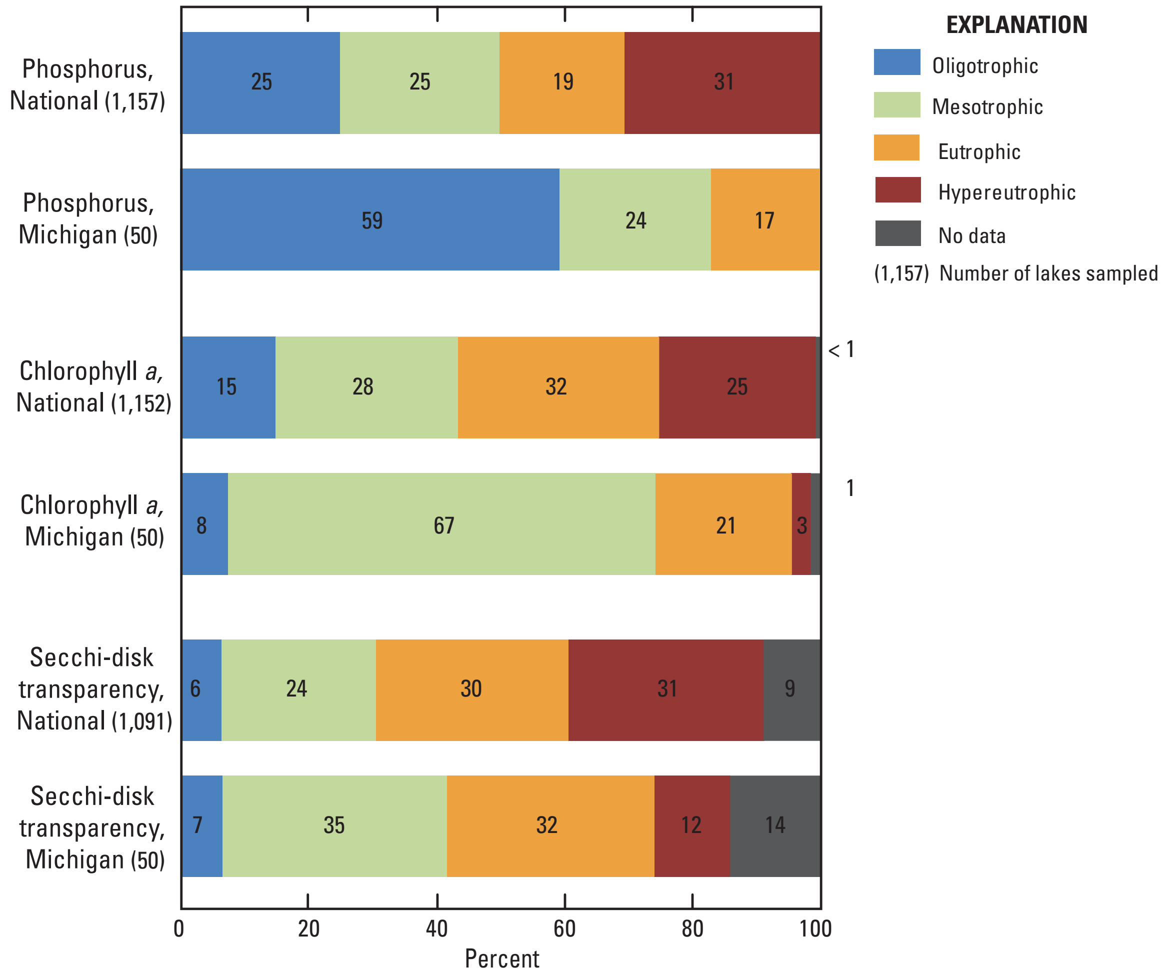

Figure 27. National Lakes Assessment trophic status (statistically valid, probability-weighted design) comparing Michigan and National data using total phosphorus, chlorophyll *a*, and Secchi-disk transparency.

This finding might suggest that Michigan lakes with public boat launch access and volunteer access might be clearer than Michigan lakes overall, regardless of public or volunteer access. The percentages for NLA (fig. 27) SDT Michigan-specific trophic classes and National classes are lower than those for the current 2001–10 dataset but more consistent with the remote sensing statewide predicted layer. The percentage for the mesotrophic class is much lower than for any of the other three datasets and higher for the eutrophic and hypereutrophic classes than for any of the other three datasets. Also, there was a substantial amount of unavailable data in the NLA set, which might be the cause of the difference between classes.

When chlorophyll *a* was compared for the current (2001–10) 729 deepest basin in lakes greater than 25 acres with public boat launch (fig. 11) to the CLMP from Michigan's volunteer monitoring network for years 2001 through 2010 (fig. 25) similar percentages for trophic-status categories emerged. Chlorophyll *a* data were not available from remote sensing statewide predicted layer. The NLA (fig. 27) chlorophyll *a* data resulted in a lower percentage of oligotrophic lakes and a slightly higher percentage for mesotrophic lakes, but results were more comparable for the eutrophic and hypereutrophic classes. The trophic category percentages for the National lakes are not as comparable for any of the trophic classes, which could suggest lake differences nationally are not as comparable for chlorophyll *a*.

Comparison with Historical Measurements

Historical near-surface summer measurements made during 1974–84 for 445 lakes using standard protocols of the MDRNE were compared to their current (2001–10) lake measurements. Selection of the subset of 445 historical lake measurements was based on comparable sampling methods. The constituents compared were total nitrogen, TP, chlorophyll *a*, and SDT; increases and decreases for each constituent are shown in figure 28.

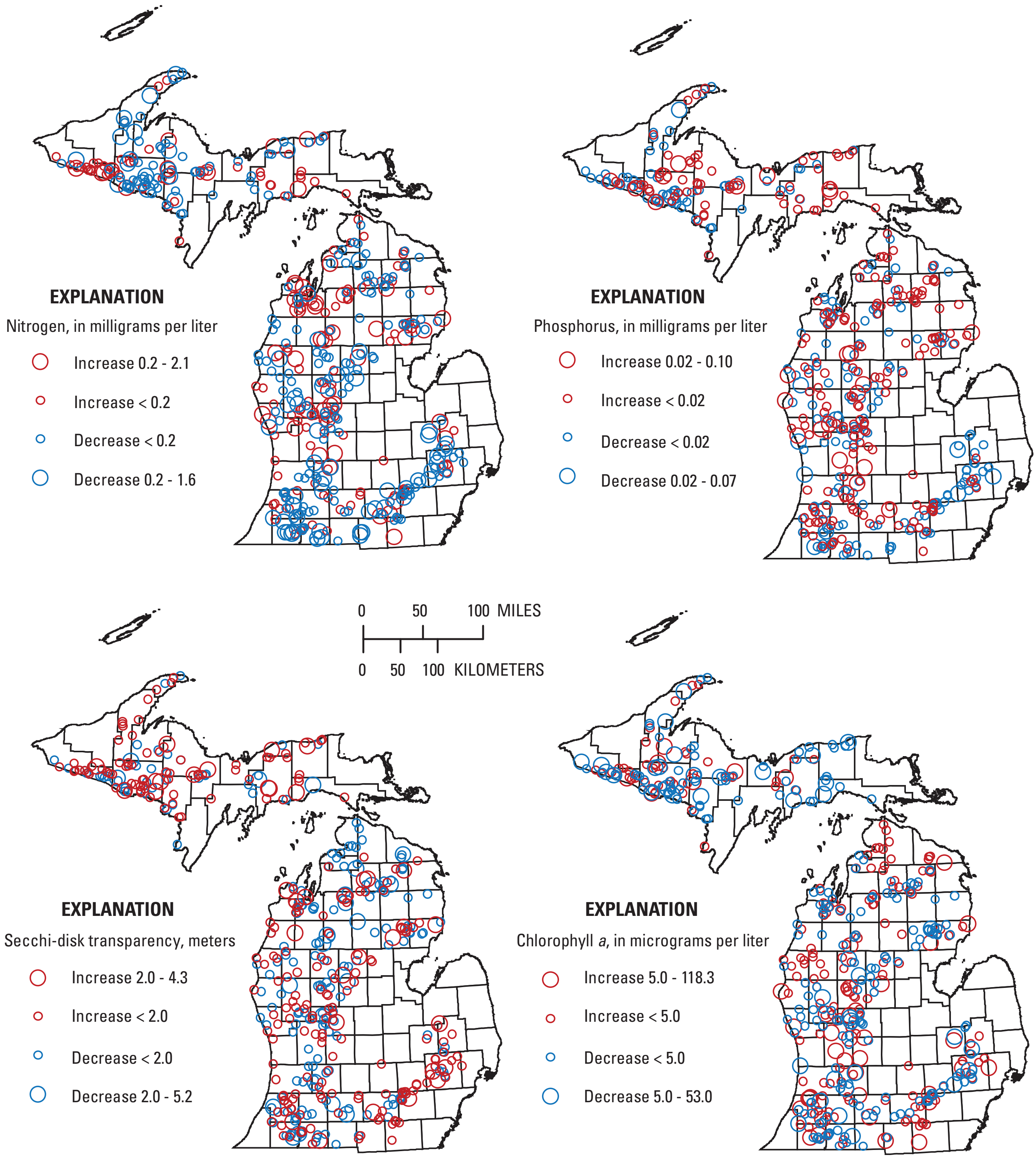

Figure 28. Increase (higher values) or decrease (smaller values) in property and constituent values from historical to current measurements for Michigan inland lakes.

The Wilcoxon signed-rank test was used to determine statistical significance of differences among the historical and current measurements, as listed in table 10. SDT showed statistically significant differences among historical and current measurements at the 95-percent confidence level; however, as is evident in figure 28, the number and distribution around the State is fairly even between the increasing and decreasing values. Even though comparison of historical to current values showed statistically significant differences at the 95-percent confidence level, these difference did not indicate an overall trend towards clearer lakes or impaired lakes.

Table 10. Results of Wilcoxon signed-rank test to determine statistical significance of differences among historical and current Michigan lakes property and constituent values for 2001–10.

[Significant at 95-percent confidence level if p-value result is less than 0.05]

Property or constituent	Sample size	p-value
Secchi-disk transparency	434	0.02
Chlorophyll *a*	444	.60
Total nitrogen	445	.55
Total phosphorus	445	.30

The trophic-status conditions are fairly comparable among current and historical measured lakes, with 87 percent of current lakes and 84 percent of historical lakes classified as oligotrophic or mesotrophic, using TP as the primary indicator; 80 percent of current lakes and 76 percent of historical lakes classified as oligotrophic or mesotrophic, using chlorophyll *a* as the primary indicator; and 78 percent of both current and historical lakes classified as oligotrophic or mesotrophic using SDT as the primary indicator (fig. 29). Although the percentage of lakes classified as oligotrophic and mesotrophic are comparable between historical and current measurements using any of the three primary indicators, this result does not necessarily mean that the same lakes were in these categories between historical and current measurements. Depending on the primary indicator, 50–66 percent of lakes did not change trophic-status conditions between the historical and current measurements, 13–23 percent moved towards the oligotrophic end of the TSI scale, and 20–25 percent moved towards the eutrophic end of the TSI scale (table 11). Further spatial analysis might help to identify patterns, hotspots, or certain lake characteristics (such as lake depth or land cover) where potential positive or negative trends for nutrients or trophic classes could be identified, but the current analysis comparing the 445 lakes did not seem to show patterns spatially, nor does it indicate overall increases or decreases.

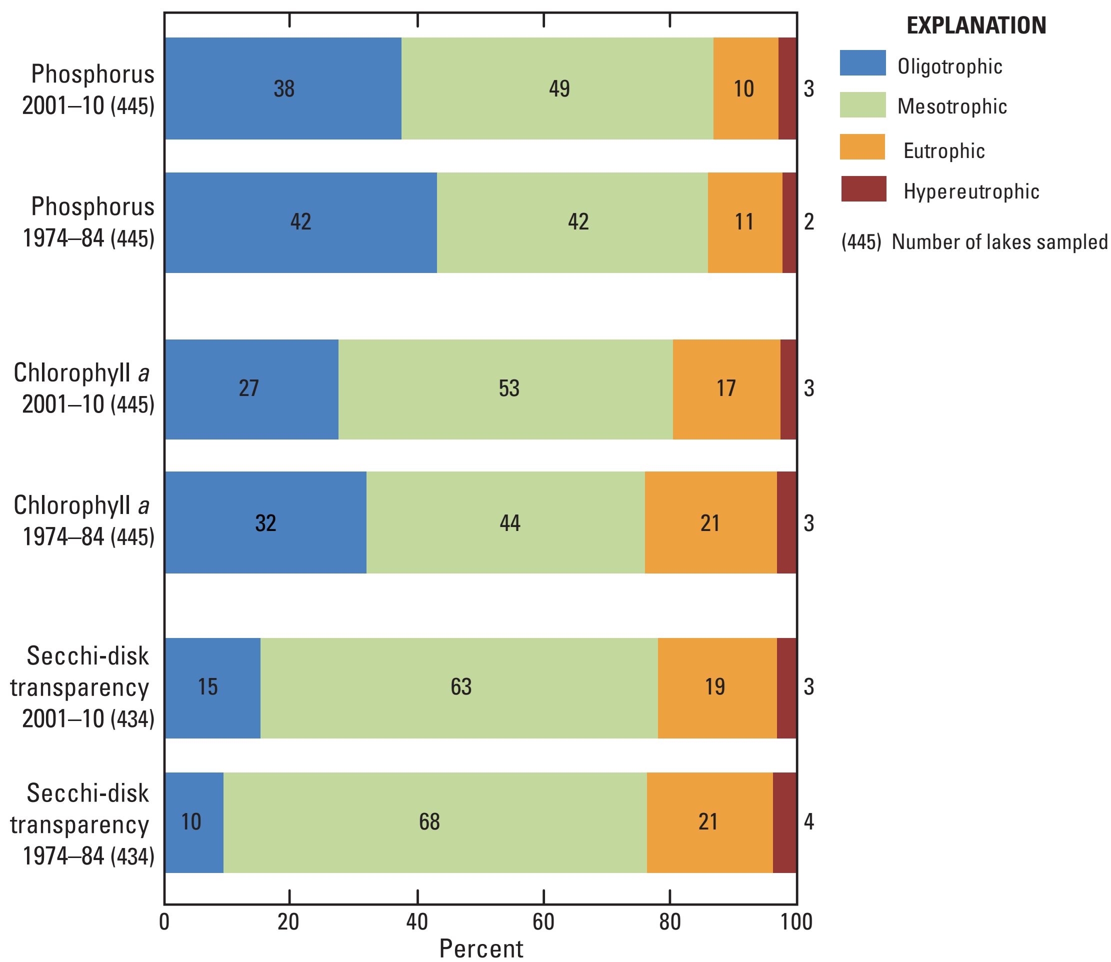

Figure 29. Historical and current trophic status for comparable lakes based on total phosphorus, chlorophyll *a*, and Secchi-disk transparency.

Table 11. Comparison of historical and current trophic status and percentage of lakes decreasing, not changing, or increasing classes for 2001–10.

[TSI, trophic state index]

	Towards oligotrophic ←	Same	→ Towards eutrophic
	Percent		
	Down class	Same class	Up class
TSI (Secchi-disk transparency)	13	66	20
TSI (Chlorophyll *a*)	24	50	25
TSI (Phosphorus)	23	57	20

Relation of Lake Water Quality to Land Cover

The dominant land cover for each lake was found by first selecting catchments from the National Hydrography Dataset Plus, using version 1 for lakes in hydrologic region 7 and version 2 for lakes in hydrologic region 4 (Horizon Systems Corporation, 2011). Catchments that touched or intersected each lake were selected as the lake drainage basin, and the dominant National Land Cover Database 2001 class was chosen for each lake drainage basin (Homer and others, 2004). The five dominant land-cover classes that resulted for the 729 lakes were agriculture (185 lakes), forest (433 lakes), urban (59 lakes), wetlands (51 lakes), and barren (1 lake).

The forest- and wetland-dominant land-cover drainage areas are the only two in the Upper Peninsula. The majority of agriculture-dominated drainage areas are in the southwest area of the Lower Peninsula. Although most of the urban-dominated drainage areas are in the southeast area of the Lower Peninsula, some are in larger city areas on the west side of the Lower Peninsula, especially along Lake Michigan. The spatial distribution of dominant land-cover drainage areas is shown in figure 30.

Water type for the 729 measured lakes was color coded by dominant land cover on a trilinear (Piper) diagram analysis (fig. 31). For lake-drainage areas where the dominant land-cover class was less than 40 percent, the next dominant land-cover class was added to the figure. Although the patterns for agriculture- and forest-dominated lake-drainage areas are somewhat similar, patterns for urban- and potentially wetland-dominated lake-drainage areas had some differences. Urban lakes differ with respect to chloride and nitrate plus nitrite, which are higher than for the other dominant land-cover classes. Calcium also is somewhat lower than for the other classes. If wetland-dominated classes are representative of more natural waters, then lakes in urban-dominated land-cover classes could have lower calcium and higher chloride and nitrate plus nitrite than lakes with more natural water and wetland drainage areas.

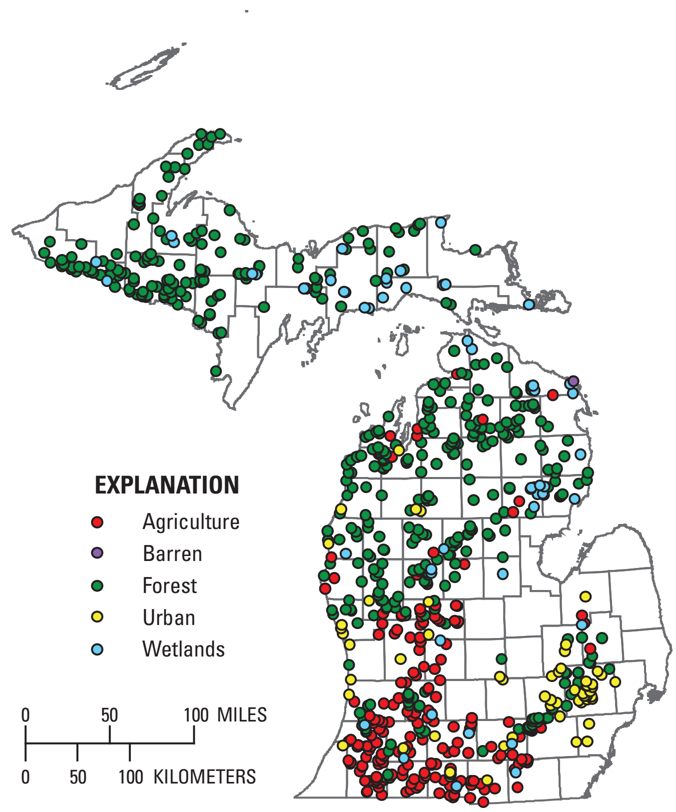

Figure 30. Spatial distribution of dominant National Land Cover Data 2001 class for Michigan inland lakes drainage areas for 2001–10.

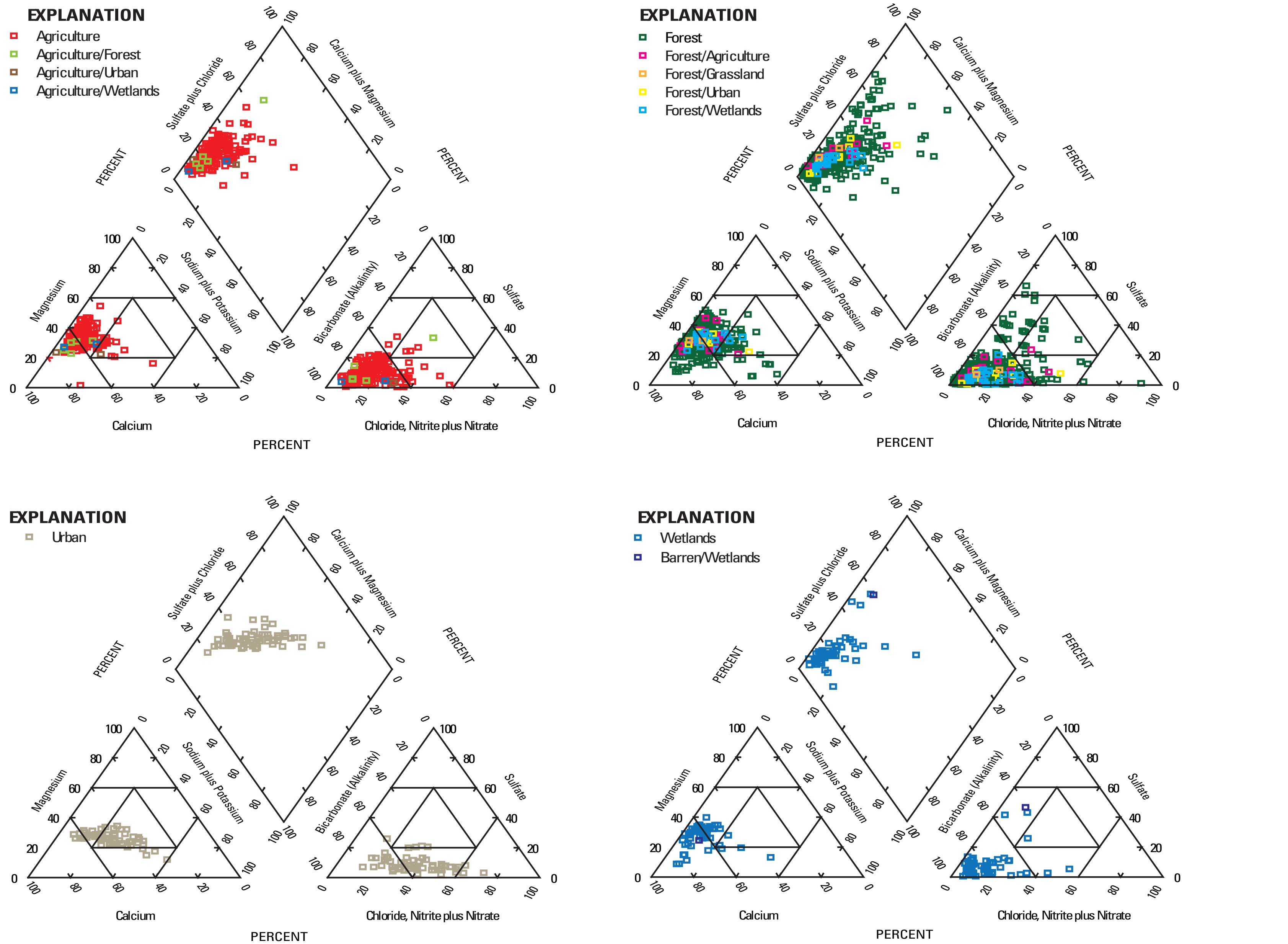

Figure 31. Trilinear (Piper) diagram analysis, color coded by National Land Cover Data 2001 majority class for lake-drainage areas.

Water type also was color coded by USEPA level III ecoregions (U.S. Environmental Protection Agency, 2011); Michigan glacial landsystems (Michigan Department of Environmental Quality and others, 2005); 6-digit hydrologic unit code boundaries (Steeves and Nebert, 1994); ecological drainage units (Higgins and others, 2005); and trophic status calculated from lake measurements using SDT, chlorophyll *a*, and TP as the primary indicators. These classification systems were used to test whether any noticeable driving factors were separating lake-water type. Although some properties and constituents individually showed separation between groups, these classification systems did not result in the degree of separation that is seen in the land-cover data between all constituents used to determine water type. These additional trilinear (Piper) diagram analyses are presented in appendix 2.

Linear regression graphs for chloride and calcium for spring mid-depth measurements (fig. 32) show a positive relation with lakes that have urban land cover as the dominant class, though the relation is stronger for chloride than calcium. Positive chloride trends were found by Syed and Fogarty (2005) for the Clinton River at Mount Clemens, which drains four southeastern Michigan counties, with the southern part of the watershed being composed of more than 50 percent urban land cover in 2001. Chloride has been found in elevated levels in groundwater in southeastern Michigan, including Oakland County (Aichele, 2004; Myers and others, 2000). Also in Oakland County, a strong positive relation was found between chloride in stream water and degree of urban development in the watershed (Aichele, 2005). By removing chloride measurements for Oakland, Livingston, and Genesee Counties in southeastern Michigan, there still was a positive relation between chloride and percent land cover (fig. 33), though the coefficient of determination (R^2) value decreased from 0.55 to 0.39. The relations are weak between lake-drainage area size and nutrients when using linear relations. These results can be viewed in appendix 3. Further spatial analysis might help to identify patterns, hotspots, or certain lake characteristics (such as lake depth or landcover) where overall potential positive or negative relations could be identified.

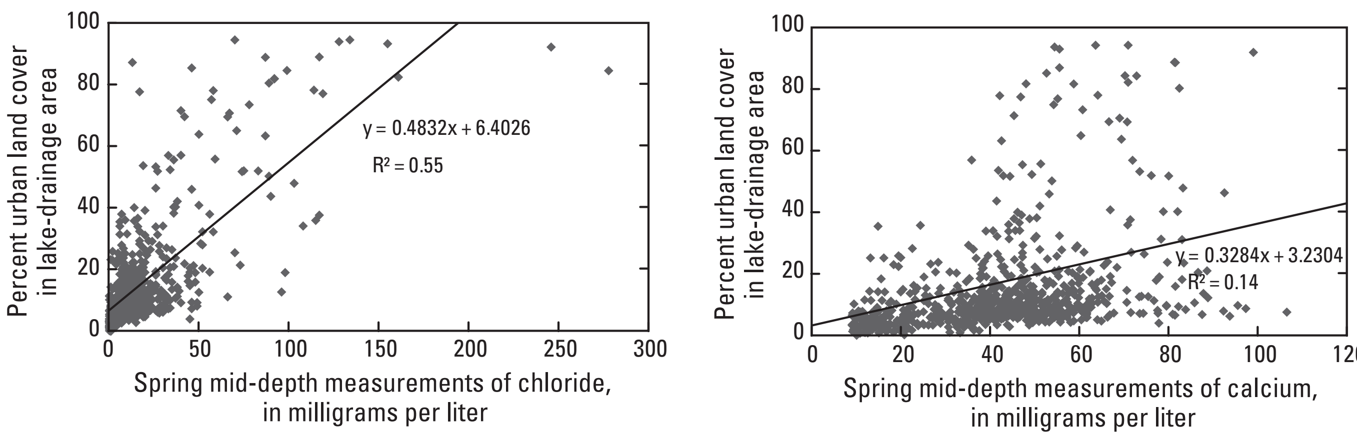

Figure 32. Chloride and calcium mid-depth measurements made in spring compared to percent urban National Land Cover Data 2001 for lake-drainage areas.

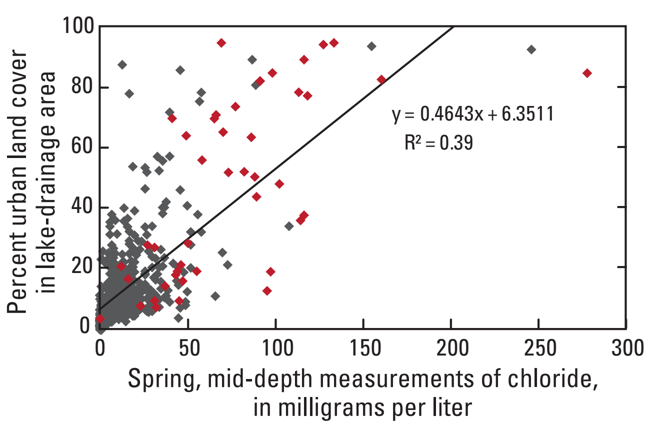

Figure 33. Chloride mid-depth measurements made in spring compared to percent urban National Land Cover Data 2001 for lake-drainage areas, excluding Oakland, Livingston, or Genesee County data (shown in red) from the regression analysis.

Summary and Conclusions

During 2001–10, 729 lakes greater than 25 acres (with public boat-launch access) were jointly monitored by the U.S. Geological Survey (USGS) and the Michigan Department of Environmental Quality (MDEQ) as part of Michigan's Lake Water-Quality Assessment program. Of the 729 lakes sampled, 109 have more than one major basin, 26 had three, and 2 have four major basins, for a total of 866 basins that were assessed and used in the analyses for this report. All lake basins included vertical-profile measurements; nutrient measurements at three discrete depths; Secchi-disk transparency (SDT) measurements (unless the Secchi disk hit the bottom of the lake in which case no SDT depth was recorded); and depth-integrated chlorophyll *a* measurements for the spring and summer, with major ions and physical properties measured for spring mid-depth and true color for summer for 2007–10. In the spring, 52 lakes were deemed too shallow for the collection of 3 discrete-depth measurements, with 58 lakes being too shallow in the summer.

Deep-basin measurements in the vertical profile for dissolved oxygen (DO) showed that in the spring, 12 percent of lakes had 25-50 percent of the water column (25–50 percent of the total lake depth) below below 0.5 mg/L. In the summer, 30 percent of lakes had 25–83 percent of the water column below 0.5 mg/L Specific conductance showed a spatial pattern of lower values in the Upper Peninsula and increasingly higher values from the north to south in the Lower Peninsula. Lake-water pH did not vary as noticeably throughout the State, but measurements below 6.5 were mostly in the Upper Peninsula. Comparisons of the vertical profile at discrete depths corresponding to near surface, mid-depth or metalimnion, and near bottom show statistically significant differences at the 95-percent level among all depths and constituents except DO for mid-depth between spring and summer.

In about 75 percent of inland lake deep basins measured, depending whether SDT, chlorophyll *a*, or TP was used as the primary indicator, trophic characteristics were associated with oligotrophic or mesotrophic conditions. Five percent or fewer were categorized as hypereutrophic when using any of the three indicators, with more than 80 percent of hypereutrophic lakes having a maximum depth of 30 ft or less. Deeper lakes were correlated with lower Trophic State Index (TSI) values reflecting towards the oligotrophic end of the scale. There was a statistically significant difference at the 95percent confidence level between spring and summer SDT and chlorophyll *a* measurements. There were somewhat even increases and decreases in the SDT measurements among spring and summer when comparing all lakes; an overall statistical increase or decrease was not found. SDT measurements were clearer in the spring than in the summer in 63 percent of lakes.

During 2001–10, on the basis of near-surface measurements made in the spring, 97 percent can be considered phosphorus limited and less than half a percent nitrogen limited; for the summer measurements, 96 percent can be considered phosphorus limited and less than half a percent nitrogen limited. Differences in concentrations of the majority of nutrients were statistically significant at the 95-percent confidence level between discrete sampling depths, and differences in concentrations of all nutrients were statistically significant at the 95-percent confidence level between spring and summer measurements.

All major ions and physical properties measured in the spring at mid-depth showed spatial patterns of lower values in the Upper Peninsula that increased southward to the southern areas in the Lower Peninsula, though the location of increase varied by constituent. U.S. Environmental Protection Agency Level III Ecoregions separated potassium, sulfate, and chloride values fairly well; separated lower and higher values for magnesium, hardness, calcium, and alkalinity; and were mixed spatially for middle-range values. The highest concentrations of chloride and sodium were in the southeastern part of the Lower Peninsula.

For the majority of constituents measured, differences in concentrations for lakes with more than one major basin did not prove to be overall statistically significant at the 95-percent confidence level between basins. There were more statistically significant differences in the spring than in the summer. However, it is notable that the most statistically significant differences at the 95-percent confidence level were found for water temperature at various depth and basin combinations; this finding indicates that water temperature could be a useful single measure of a multiple-basin lake for gaining an understanding of the lake as a whole.

Comparison of other Michigan lake-sampling programs producing trophic-status determinations for Michigan inland lakes revealed a few interesting relations to the current (20001–10) dataset. For example, volunteers coordinated by the MDEQ (former MDNR) started sampling in 1974 and continue to sample to date (2010) approximately 250 inland lakes each year through the Cooperative Lakes Monitoring Program (CLMP). When the primary sampling station (deepest-basin) measurement per lake for TSI from SDT in the month of August during 2001–10 is compared, the percentage of lakes in the oligotrophic class is higher than in the 2001–10 dataset. The hypereutrophic class has a lower percentage of lakes than the 2001–10dataset, whereas the mesotrophic and eutrophic classes are fairly comparable. This difference might result from more CLMP volunteers living near or otherwise having access to clearer lakes. Results from comparing TSI from chlorophyll *a*, the are more varied by year for the CLMP data.

Data from the CLMP, in addition to supplemental data specific to the Upper Peninsula (jointly collected by USGS and MDEQ), were used to extend the existing SDT measurements to produce TSI predictions using remotely sensed data for Michigan lakes greater than 20 acres. The three time periods of available TSI predictions from SDT include 3,121 lakes for 2003–05; 3,024 lakes for 2007–08; and 2,591 lakes for 2009–10. The predictions on average for the three periods result in a lower percentage of lakes in the oligotrophic category, a higher percentage in the mesotrophic category, about the same percentage in the eutrophic category, and a slightly lower percentage in the hypereutrophic category compared to the 2001–10 dataset. The predictions are an interesting comparison and extension to program monitoring based on public boat-launch access or volunteer residence or access, with some noticeable differences in percentages for trophic classes.

The National Lakes Assessment (NLA) is a statistically valid, probability-designed estimate of the condition of lakes on a national and regional scale, and it includes 50 lakes measured in Michigan during 2007. Percentages Michigan NLA lakes in the oligotrophic and mesotrophic trophic classes were larger than those in the 2001–10 lake data, though combining the two classes produced similar results. Of the Michigan lakes from the 2001–10 data that were greater than 25 acres (with public boat-launch access), a higher percentage of lakes were in the oligotrophic class (except when using phosphorus as the sole indicator) than the Michigan NLA lakes. When trophic status was determined by using SDT was the sole indicator for lakes for 2001–10, 74 percent of lakes were classified as oligotrophic or mesotrophic, compared to only 42 percent from the NLA Michigan lakes (though SDT depth was not recorded for 14 percent of the NLA Michigan lakes); 5 percent were classified as hypereutrophic, compared to 12 percent of the NLA Michigan lakes.

Data for 445 lakes measured historically by the MDNRE during 1974–84 were compared to 2001–10 lake measurements. Four constituents were comparable between the two time periods: total nitrogen, TP, chlorophyll *a*, and SDT. Of the four, only SDT was found to have statistically significant differences between datasets at the 95-percent confidence level, though no overall historical increasing or decreasing trend in SDT is evident. Depending on the primary indicator, 50–66 percent of lakes did not change trophic-status class, 13–23 percent moved down a class towards the oligotrophic end of the TSI scale, and 20–25 percent moved up a class towards the eutrophic end of the TSI scale.

Dominant land cover was calculated for each lake drainage area, resulting in five dominant land-cover classes of agriculture, forest, urban, wetlands, and barren. Lake water types were shown on a tri-linear (Piper) diagram analysis that assisted in the identification of higher chloride concentrations in urban-dominant drainage areas and somewhat lower calcium than in other land-cover classes. Although previous reports document high chloride concentrations in southeastern Lower Michigan, removing data from lakes in this area still resulted in a positive relation between percent urban land cover and chloride, though the coefficient of determination (R^2) value decreased from 0.55 to 0.39.

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Appendix 2

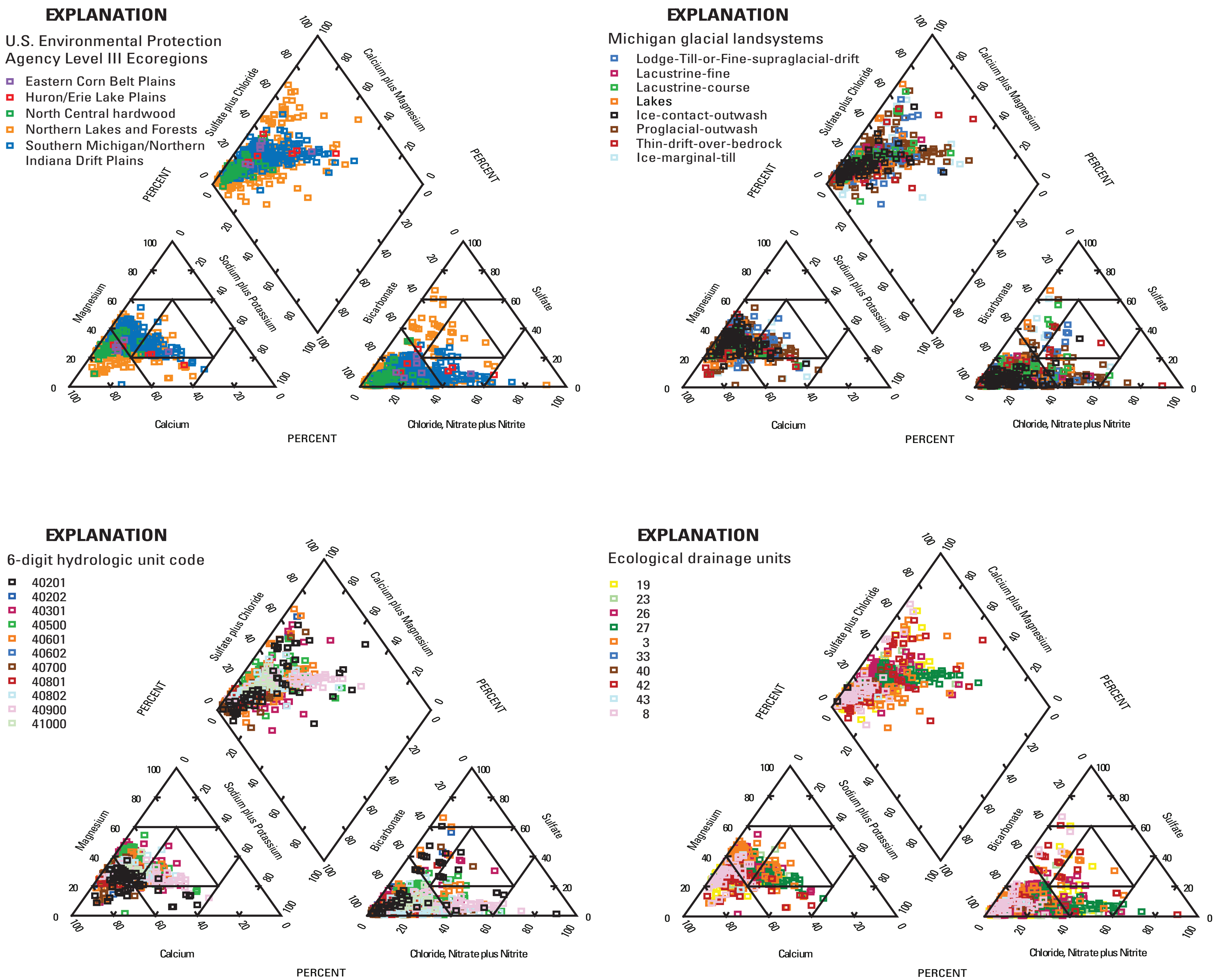

Figure 2–1. Trilinear (Piper) diagram analysis, color coded by U.S. Environmental Protection Agency Level III Ecoregions, Michigan glacial landsystems, 6-digit hydrologic unit codes, and ecological drainage units.

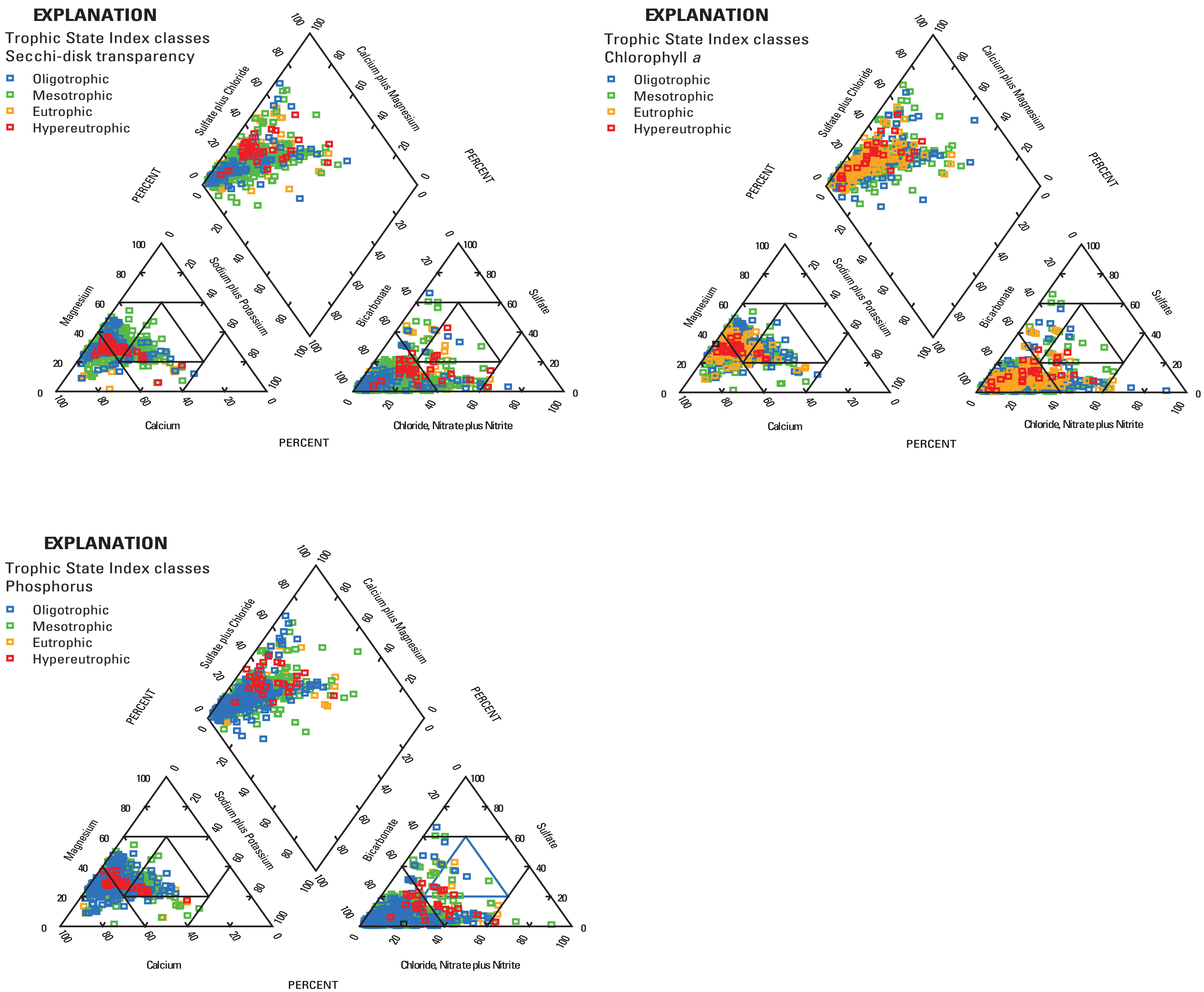

Figure 2–2. Trilinear (Piper)diagram analysis, color coded by Trophic State Index classes using Secchi-disk transparency, chlorophyll *a*, or total phosphorus as the primary indicator.

Appendix 3

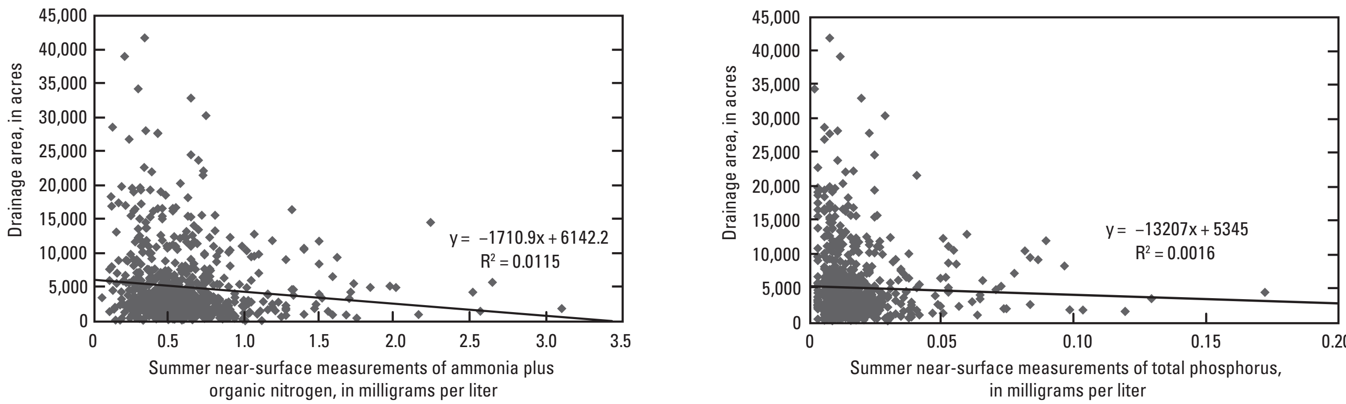

Figure 3–1. Ammonia plus organic nitrogen and total phosphorus near-surface measurements made in summer compared to lake drainage-area size.

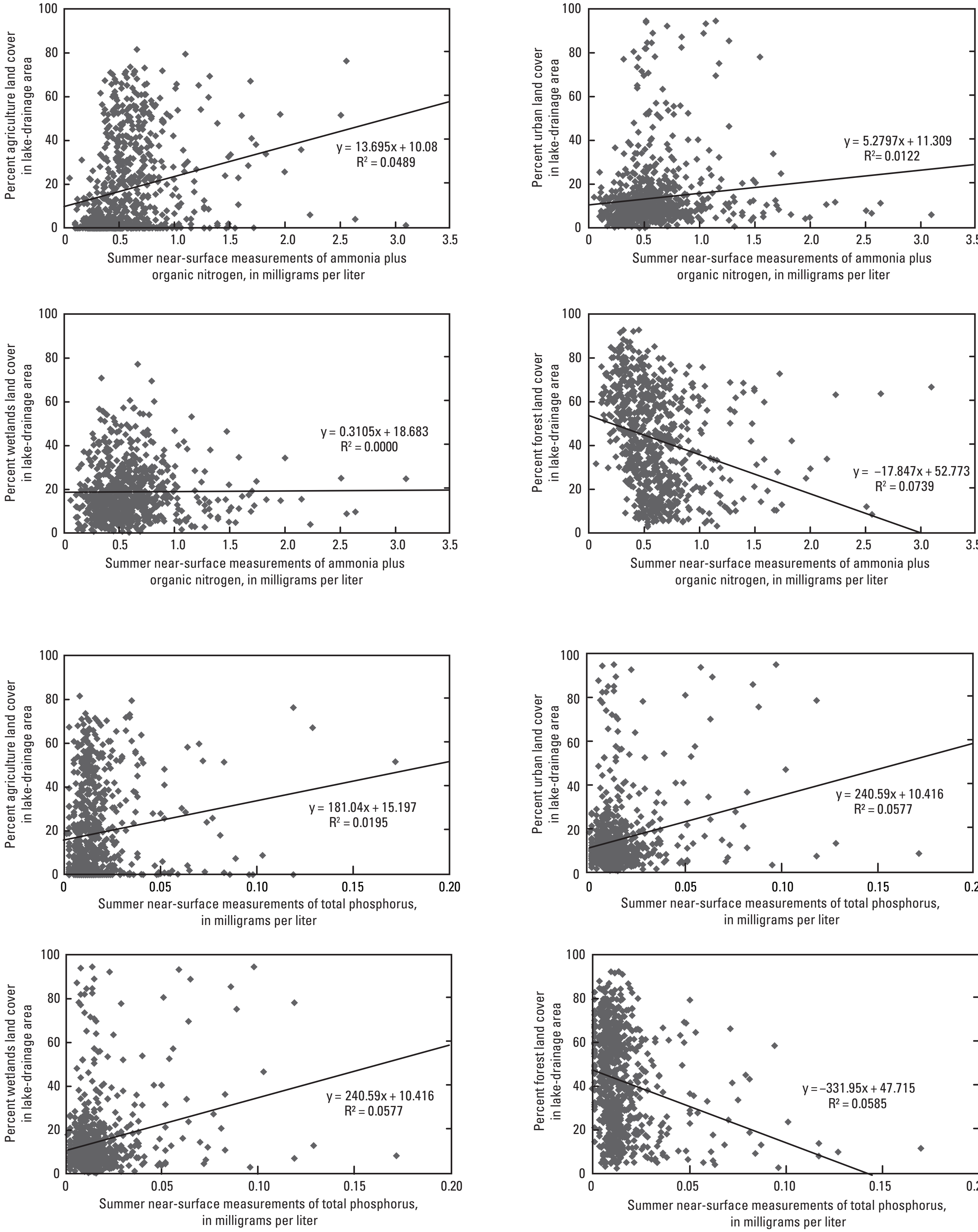

Figure 3–2. Ammonia plus organic nitrogen and total phosphorus near-surface measurements made in summer compared to dominant percent National Land Cover Data 2001 (Homer, 2004) for lake drainage areas.

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