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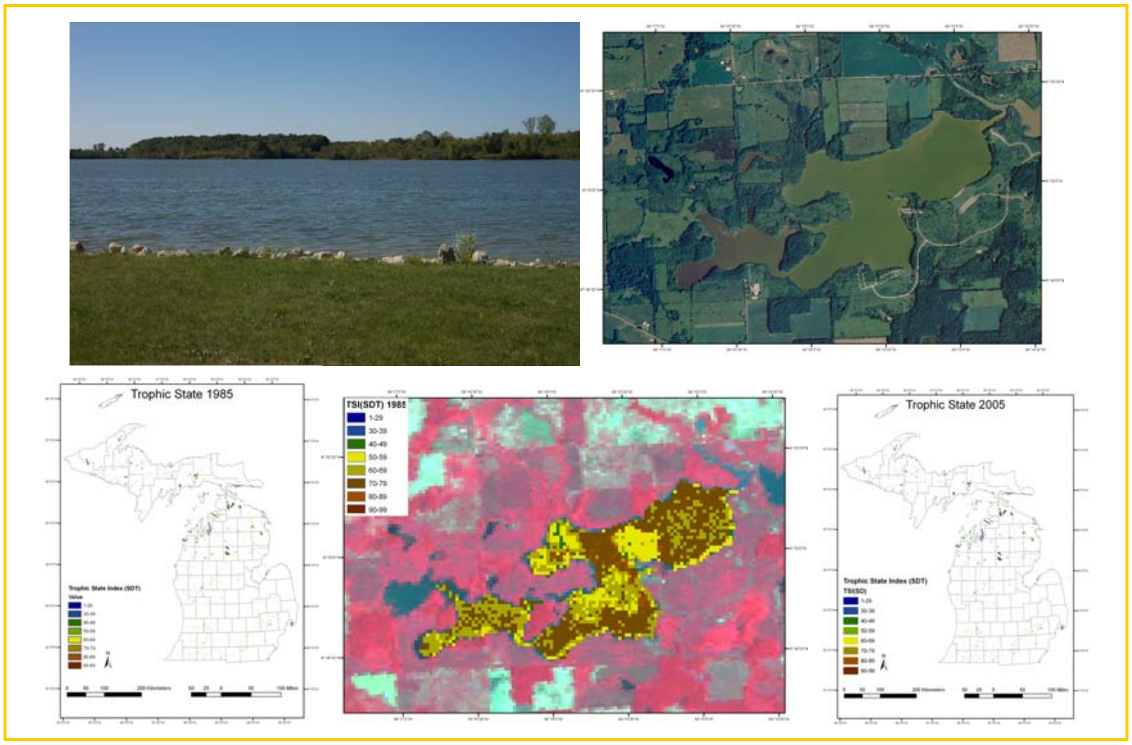

Remote Sensing of Lake Clarity

Richard Powell, Colin Brooks, Nancy French, and
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Executive Summary

We have demonstrated that satellite imagery can be used to track water quality changes over time for lakes across Michigan. Michigan Tech Research Institute (MTRI) researchers evaluated the water quality of large lakes in Michigan for the years of 1985 and 2005 by expanding upon traditional methods of water quality assessment using remote sensing imagery. MTRI researchers assessed water clarity from satellite imagery by modeling the relationship between in-situ Secchi disk transparency (SDT) data and lakes 20 acres or larger captured in moderate resolution Landsat satellite imagery. This relationship can be used to evaluate water quality by classifying the lakes according to their trophic state using a documented relationship between visible-light satellite imagery data and water clarity.

The US Geological Survey (USGS) has assessed Michigan lake water clarity using traditional remote sensing methods for the 2005 time period. Building upon these methods, we have developed and tested an algorithm to assess lake water clarity and trophic state for the 1985 period using historic Landsat satellite imagery. The approach classified the trophic state of large inland lakes in Michigan's Lower Peninsula with an accuracy of approximately 80% when compared to historic in-situ data. These data are now being used as inputs into the Environmental Quality Index (EQI) that has been developed by MTRI for the Michigan office of the Natural Resource Conservation Service (NRCS). The 1985 and 2005 Lake Clarity EQI inputs serve as examples of being able to use remote sensing to "go back in time" and assess how environmental quality has changed over a 20-year time period. These methods can also be used to track changes into the future as newer imagery becomes available.

A county-level comparison of the 1985 and 2005 water quality data revealed that 32 of Michigan's 83 counties indicated a change in trophic state index (TSI) values of 5% or greater, demonstrating that lake water clarity has generally improved across 39% of the state. Based on our sensitivity analysis, seven of these 32 counties have significant improvements in trophic state based on having a decrease in TSI of 5 TSI units or more. The results also indicate that six counties experienced significant improvement of 10% or more. Seven different counties showed a small amount (less than 5%) of worsening in TSI values, but are within the margin of error for the analysis. The remaining 44 counties indicated no change in TSI values during the study period.

This approach to remote sensing-based water quality assessment has identified several areas for future development. Using available in-situ turbidity data, the technique can be applied to more frequent, regional-scale evaluations using moderate resolution satellite imagery. Specifically, we anticipate that the impacts of NRCS programs on water quality could be evaluated at the watershed scale, focusing on watersheds with relatively high levels on NRCS activity. The approach is also suitable for high resolution imagery, such as color aerial photography, to assess local-scale areas of concern. At multiple scales, the water quality calculation methods developed and extended by MTRI provide a valuable way to analyze and track changes in water quality over time.

Background

Using Trophic State as an Water Quality Indicator

The trophic state of a lake is a concept which refers to the biological production that occurs in a lake. The level of production is determined by several factors such as phosphorus supply, volume, and age of the water in the lake. Several indicators have been identified to describe trophic state such as phosphorus concentration, water clarity, and chlorophyll concentration.

Water clarity, or transparency, is related to the quantity of phytoplankton, non-algal turbidity, and tannic acids in the water. Water clarity is commonly measured with a Secchi disk. A Secchi disk is a 20 centimeter (8 inch) diameter weighted disk colored black and white and attached to a measured line. The disk is lowered into a lake until it can no longer be seen. The depth at which the disk can no longer be seen is known as the Secchi Disk Transparency (SDT).

Carlson (1977) developed a trophic state indes (TSI) using algal biomass as the basis for trophic state classification (Table 1). The index uses any of three variables, chlorophyll, Secchi disk depth, and total phosphorus, to independently estimate algal biomass. Any of the three variables can be used to classify the trophic state of a waterbody.

Table 1: Trophic State Index (Carlson, 1977). *Lower TSI values indicate generally higher water quality.*

Trophic State Index	Secchi Depth (m)	Classification	Water Clarity
< 30	> 8	Oligotrophic	Clear water. Salmonid fisheries dominate.
30 -40	8 - 4		Salmonid fisheries in deep lakes only
40 -50	4 -2	Mesotrophic	Moderate clear water
50-60	2 -1	Eutrophic	Less clear water. Warm water fisheries dominate.
60-70	0.5 -1		Nuisance macrophytes, algal scums
70-80	0.25 – 0.5	Hypereutrophic	Dense algae and macrophytes
>80	< 0.25		Algal scums, few macrophytes. Rough fish.

Assessing Trophic State with Remote Sensing

SDT and chlorophyll-a concentrations have been successfully predicted from satellite image data by quantifying the relationship between in-situ measurements of SDT and chlorophyll-a and the spectral response of the blue, green, red, and near-infrared bands in satellite image data (Mayo, *et al* 1995; Zilioli and Brivio, 1997). This approach has been successfully implemented in Minnesota (Olmanson *et al*, 2001), Wisconsin (Batzli, 2003), and Michigan (Fuller *et al*, 2004) to estimate water quality for inland lakes where in-situ data is limited.

In the Michigan study, the USGS used in-situ SDT data from a statewide lake monitoring program and developed a linear regression model that related the in-situ measurements to satellite imagery from the Landsat system. In-situ data sources and Landsat 5 Thematic Mapper (TM) data sources collected from 2003 to 2005 were used to develop the regression model and predict TSI values for various sections of the state. The sections were combined into a seamless data set of representing the entire state of Michigan and are nominally referred to as the Statewide TSI 2005 data set. Figure 1 provides an example of this data set.

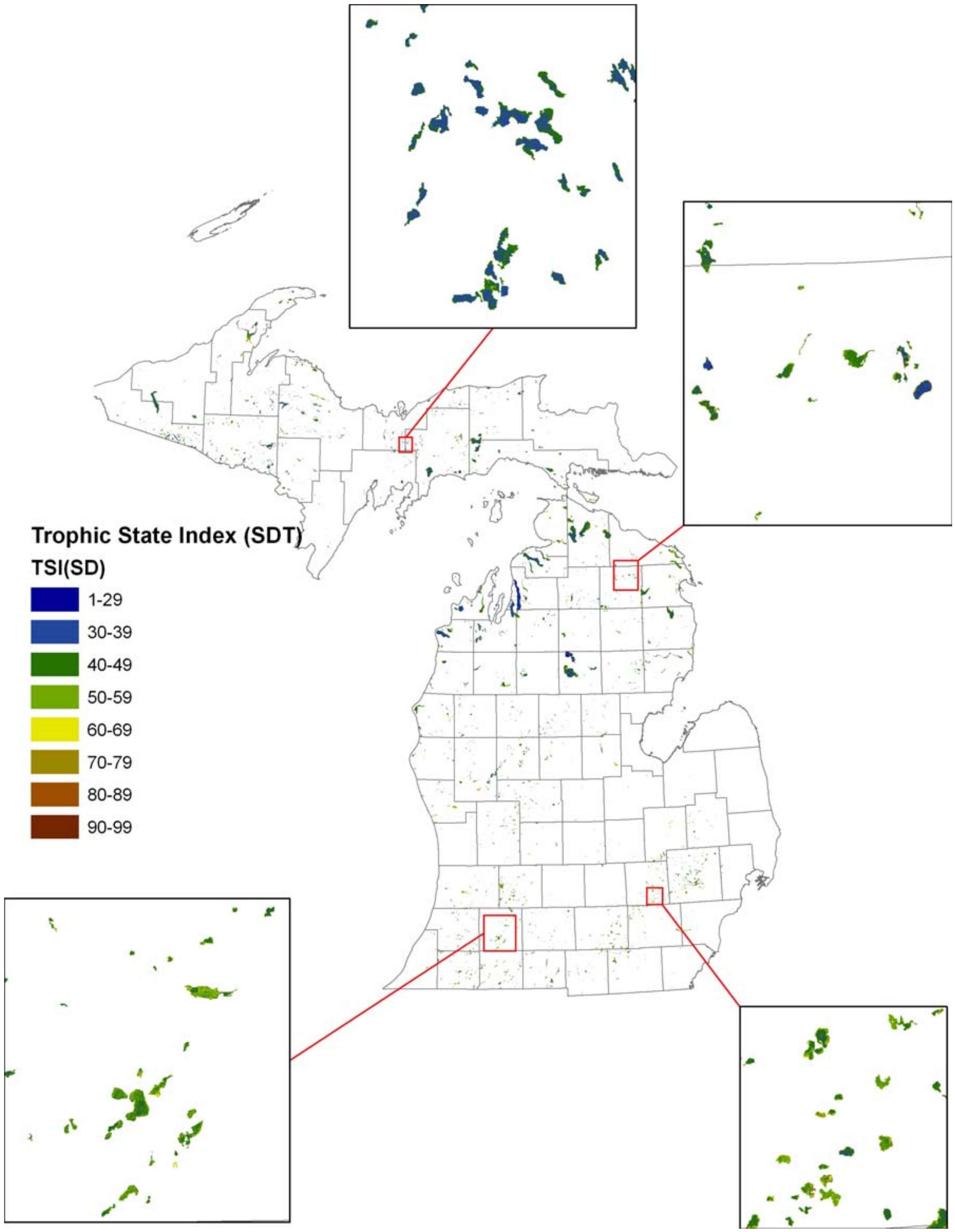


Figure 1: USGS TSI(SDT) values for the Lower Peninsula August 2005. *Note that most Michigan lakes are in this survey are classified as Mesotrophic in the Lower Peninsula and Oligotrophic (generally higher water quality) in the Upper Peninsula.*

The USGS Statewide TSI 2005 data serves as the contemporary water quality input for the EQI and serves as the basis for comparing the change in water quality for the time period prior to the implementation of conservation enhancement programs.

Extending Trophic State Assessment Methods

The USGS trophic state assessment project developed linear regression equations by relating in-situ SDT measurements collected in late summer with Landsat data acquired during the same time period. The coefficients are applied to the visible (Blue, Green, and Red) bands of the water-only pixels of the Landsat data. The resulting data values are then applied to Carlson's trophic state equation (1977) to produce a pixel-level map of trophic state values for lakes within the extent of the Landsat scene (185km by 185km). Figure 2 illustrates the individual Landsat scenes for the state of Michigan. All but scene 25-27 (far northwest of Michigan) were used to calculate lake clarity because of the small area covered and limited availability for that scene.

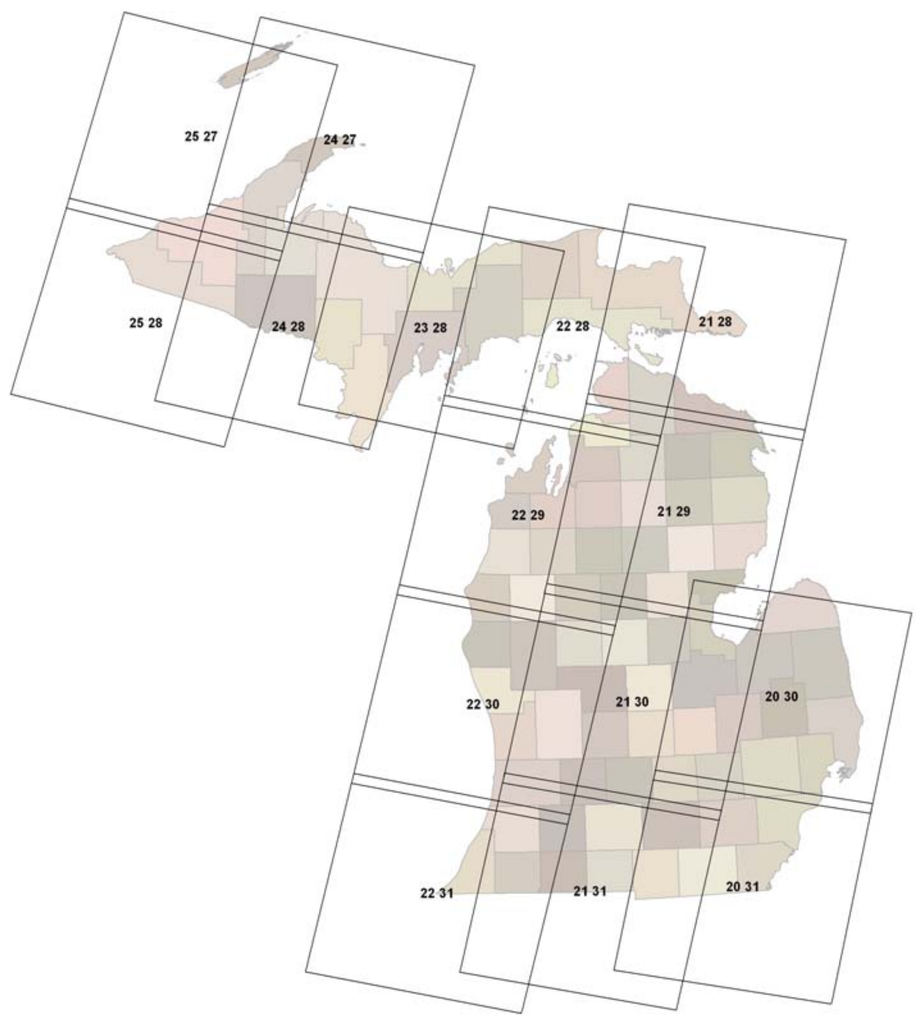


Figure 2: Landsat scenes covering Michigan. Numbers indicate Worldwide Reference System2 (WRS2) Path and Row. *15 Landsat satellite imagery scenes are needed to cover all of Michigan.*

Although a considerable amount of Landsat earth observation data dating back to 1972 is available for the assessment of past environmental conditions, in-situ water quality data, such as SDT, is relatively limited. Therefore, MTRI analysts have developed an alternative approach to assessing trophic state by processing satellite imagery into formats that are comparable over time. The approach expands upon the methods employed by the USGS by applying the study's regression coefficients to Landsat scenes from the mid-1980's that have been radiometrically calibrated to the same 2003 to 2006 Landsat scenes used by the USGS study. This step normalizes the imagery for effects outside of real surface change. Several factors independent of surface change can affect spectral reflectance measured at the sensor. These include sensor calibration, solar elevation, atmospheric conditions, and topography. Of these, sensor calibration, solar angle and atmospheric conditions change through time. Normalizing imagery to account for these influences reduces the non-land cover induced radiometric variation between temporally separate images. The result is a set of images that appear to have been acquired under the same conditions, allowing for more reliable detection of surface changes in water quality.

There are two primary approaches to radiometric standardization: absolute correction and relative normalization. Absolute correction uses measured atmospheric conditions and sensor characteristics to account for the effect of atmospheric, illumination, and sensor differences. These methods tend to be more accurate than relative standardization methods, but have the disadvantage of being dependent on in situ atmospheric data that is rarely collected.

Relative normalization is an alternative to absolute radiometric correction, and was the method chosen by MTRI analysts, after careful consideration, to make the satellite images comparable over time. This method is used to normalize an image relative to a reference image (Jensen, 1996). The method is based on identification of features that are assumed to have the same spectral reflectance through the series of images (Schott et al., 1988). The ideal invariant targets are those that are at approximately the same elevation as the rest of the scene (for a better representation of the atmospheric conditions across the scene), are located in a relatively flat area (to minimize the effects of solar azimuth differences) and have a minimal amount of vegetation (as vegetation readily changes in response to seasonal changes and environmental stresses).

In this method, statistical adjustments are based on the assumption that the differences in gray-level distributions of invariant objects are assumed to be a linear function (Schott et al., 1988). Invariant targets tend to be urban features (roads, buildings) because the spectral response is assumed to change very little over time. After normalization targets are chosen, the target brightness values from the scene to be normalized are regressed against the target brightness of the reference image. This is a linear regression model relating each band of each pairing of images, consisting of an additive component (intercept) which accounts for the difference in path radiance, and a multiplicative component (slope) which corrects for differences in detector calibration, sun angle, Earth-sun distance, atmospheric influences and sun-target-sensor geometry between dates.

We applied the relative normalization method to Landsat TM scenes from the mid-1980's that are spatially coincident, yet temporally separate from the Landsat data used in the USGS Michigan study. The resulting data is relatively free of the effects of atmospheric, illumination, and sensor differences and is used to assess the trophic state of large inland lakes using the same in-situ based regression coefficients as the USGS study.

Data

To assess trophic state in the pre-program implementation time period for the EQI, 14 Landsat 5 TM scenes were selected from the archive of the USGS Center for Earth Resources Observation & Science (EROS) data center. The selected scenes had the least amount of cloud cover, haze, or distortions compared to other scenes in the EROS archive and are spatially and seasonally coincident with scenes used by the USGS for the Michigan lake clarity assessment. Due to the data quality requirements, the majority of scenes are from late summer 1985. Two scenes are from later time periods, 1986 and 1989. Table 2 describes the selected scenes as the Target Image, their location, and their corresponding reference image used in the USGS study. Figure 1 illustrates the locations of the Worldwide Reference System 2 (WRS2) paths and rows covering Michigan.

The USGS Michigan Water Science Center in Lansing, Michigan provided the Landsat TM scenes used in the 2005 water quality assessment as well as the regression equations relating the in-situ SDT measurements to the imagery. Table 3 lists the regression equations used to model the relation between the relevant bands in the historical Landsat imagery and SDT. Bands 1, 2, and 3 in the table correspond to the blue, green, and red bandwidths in the Landsat data. The coefficient of determination, R^2, of the regression equation ranges from .69 to .84, with the value .74 occurring most frequently, indicating that approximately 74% of the change in in-situ SDT data is explained by a change in the Blue, Green, and Red bands across the entire state.

Table 2: Landsat TM Data Sources and Dates of Acquisition. *All but one of the scenes are from the optimal summer (July to September) time period for analyzing water clarity.*

WRS2-Path	WRS2-Row	Reference Image Date	Target Image Date
20	30	8/19/2003	07/13/1984
20	31	8/19/2003	07/13/1984
21	28	7/18/2004	08/08/1985
21	29	9/11/2003	08/08/1985
21	30	9/11/2003	08/08/1985
21	31	9/11/2003	08/08/1985
22	28	7/18/2004	07/11/1984
22	29	9/2/2003	08/31/1985
22	30	9/2/2003	08/31/1985
22	31	9/11/2003	08/31/1985
23	28	7/15/2005	08/09/1986
24	27	9/21/2005	08/13/1985
24	28	7/19/2005	08/16/1986
25	28	8/22/2003	05/27/1989

Table 3: Coefficients relating SDT to Landsat TM data. *These were used to calculate the historical water clarity from satellite imagery, with Band 1 = Landsat blue band, Band 2 = Landsat green band, and Band 3 = Landsat red band.*

WRS2-Path	WRS2-Row	R^2	Samples	Band1	Band2	Band3	Intercept
20	30	0.84	27	0.108	-0.082	-0.2551	0.2112
20	31	0.84	27	0.108	-0.082	-0.2551	0.2112
21	28	0.74	15	0.1874	-0.182	-0.2689	-2.1249
21	29	0.70	19	0.1402	-0.0588	-0.3061	-0.8009
21	30	0.72	40	0.0912	0.0277	-0.3018	0.2859
21	31	0.72	40	0.0912	0.0277	-0.3018	0.2859
22	28	0.74	15	0.1874	-0.182	-0.2689	-2.1249
22	29	0.74	34	0.0042	0.0964	-0.3181	3.2467
22	30	0.74	34	0.0042	0.0964	-0.3181	3.2467
22	31	0.80	20	0.1291	-0.2275	0.0026	-1.9591
23	28	0.75	13	0.5371	0.0364	-0.7258	-16.3462
24	27	0.75	13	0.5371	0.0364	-0.7258	-16.3462
24	28	0.69	17	0.1079	-0.0727	-0.3955	1.7542
25	28	0.73	16	0.227	0.1797	-0.5299	-6.1487

Methods

Several steps were performed to transform the “pre-program” Landsat imagery into estimates of lake water clarity for the EQI. As illustrated in Figure 3, these steps are: performing relative normalization of the Landsat scenes, extracting water-only pixels from the normalized images, applying the USGS coefficients to calculate TSI values, and calculating zonal statistics of the TSI values for each county in Michigan. Each step is comprised of several other tasks which are explained in detail in this section.

Relative Normalization of Landsat Imagery

Each of the pre-program Landsat scenes dating from the mid-1980’s were normalized to a spatially coincident Landsat scene from the early-2000’s used by the USGS study with the method described in detail in the Background section of this document. The process involves selecting features from the imagery which are assumed to be invariant between the temporally separate scenes, such as roads and buildings. As illustrated in Figure 4, features such as roads and building change little over time and can be used to extract spectral signatures for use in normalization.

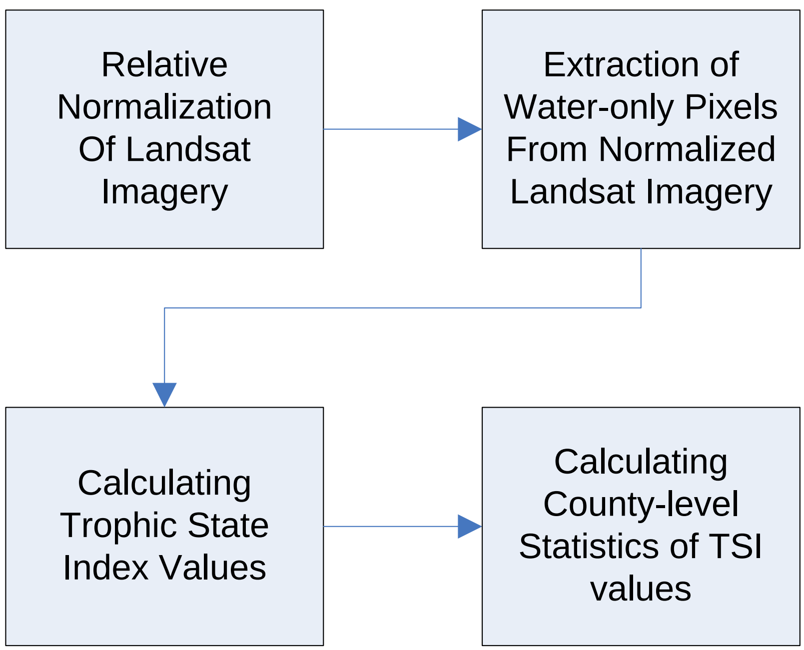


Figure 3: Processing steps to assess lake water clarity for the EQI.

Landsat TM July 1984

Landsat TM August 2003

Figure 4: Example of multi-temporal Landsat imagery used in the study at Ford and Belleville Lakes. *Note how some features such as the airport runway, buildings, and roadways maintain the same relative spectral response despite the 19 year difference.*

ERDAS Imagine software was used to define an Area of Interest over invariant targets in locations suitable to both the target and reference scene. ERDAS Imagine was used to extract the spectral values from each band for both the target and reference scenes and export them as a text file. Using the text file output, brightness values from the target scene (to be normalized) were regressed against the brightness of the reference image for each pairing of bands. The slope and intercept values for each band were applied to the target image using the Spatial Modeler tool within ERDAS Imagine. The resulting output provides a Landsat data set capturing the current surface conditions of the pre-program time period that is normalized to the differences in path radiance, detector calibration, sun angle, Earth-sun distance, atmospheric influences and sun-target-sensor geometry between the target and reference scenes. Figure 5 illustrates the result of the relative normalization process. In the graph, the blue line indicates mean band values of the reference scene. The green line indicates the mean band values of the target scene. The yellow line indicates band values of the normalized scene that is used for water quality assessment. The error bars indicate the potential error of the calibrated scene relative to target and reference scenes using the Standard Error computed from the regression model used for normalization.

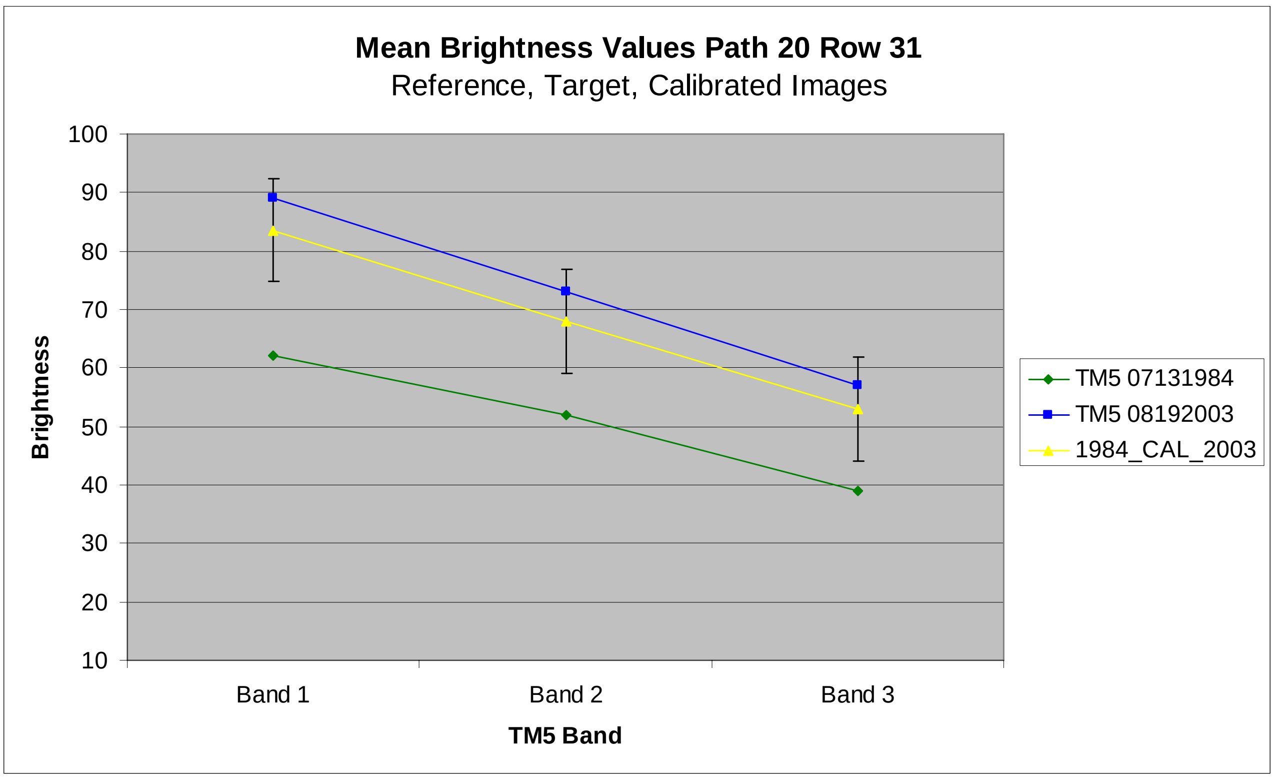


Figure 5: Example of mean brightness values of the blue, green, and red bandwidths of the target, reference, and normalized Landsat data. *Error bars represent Standard Error of the normalized scene.*

Extraction of Water-only Pixels from Normalized Landsat Imagery

The calculation of TSI values based on SDT requires Landsat pixels representing water only areas that are free from the effects of overhanging vegetation, shoreline, shallow water areas and reflectance from the lake bottom. We integrated Geographic Information System (GIS) and remote sensing image processing techniques to extract water-only pixels from the data. A hybrid unsupervised/supervised image classification approach, similar to the protocol described by Olmanson *et al.* (2002), using ERDAS Imagine was employed. The approach leveraged the characteristic of water to absorb the Near-Infrared and Mid-Infrared bandwidths. The resulting data set was used within a GIS overlay analysis of using the Michigan Geographic Framework Version 6 (MGFv6) lake polygon coverage to identify areas of class confusion and lakes greater than twenty (20) acres in size. Water-only pixels meeting this criterion were used as an analysis mask within ERDAS Imagine to subset the blue, green, and red Landsat TM bands into an open water image which is used for further processing.

Calculating Trophic State Index Values

TSI values based on SDT were calculated by applying the coefficients calculated by the USGS (Table 3) for each scene to the open water only pixels extracted from the normalized Landsat data. Each scene was processed using a Spatial Model developed in ERDAS Imagine (Figure 6). The result was a pixel-level lake map. Each pixel was classified with a TSI value based on SDT which was compared to the small amount of pre-program data for an accuracy assessment and then compared to the USGS Statewide TSI 2005 data set to evaluate changes in lake water clarity over time.

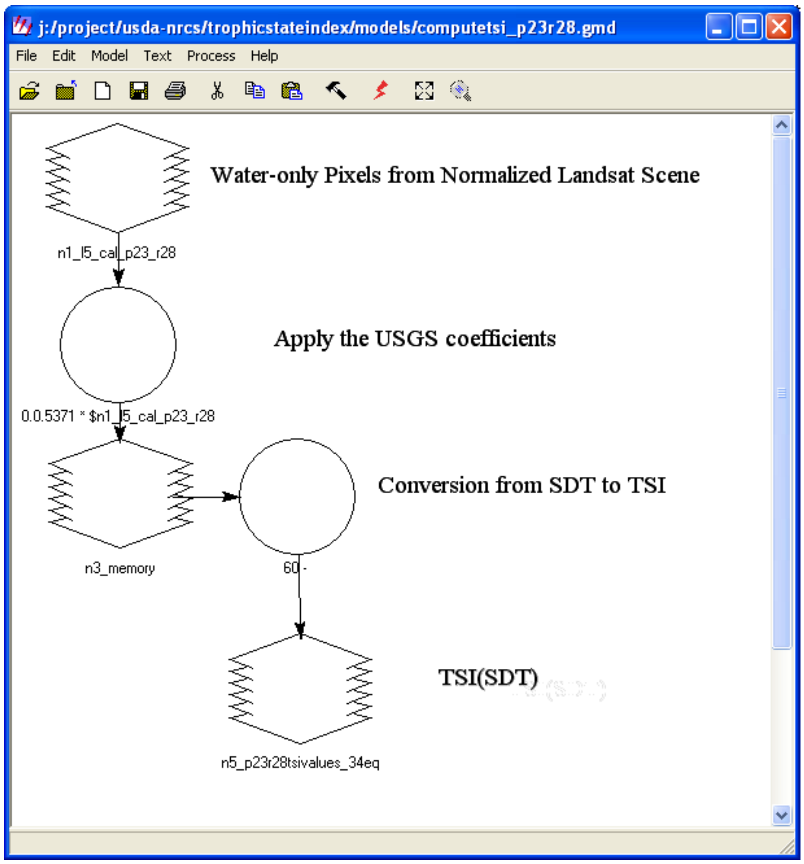


Figure 6: Spatial Model developed by MTRI to calculate TSI(SDT) by applying ERDAS Imagine image analysis software.

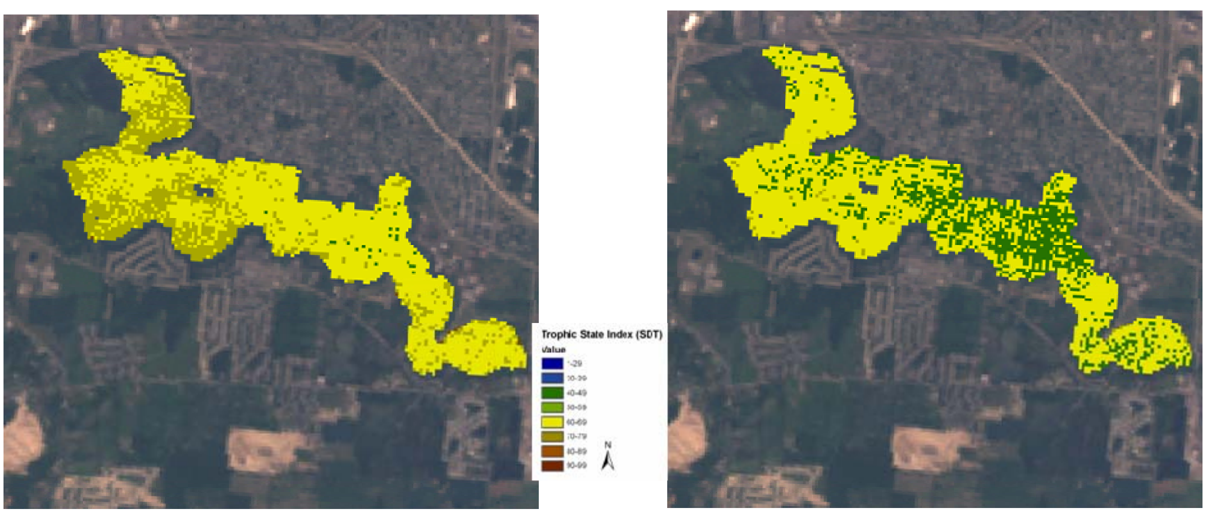
Calculating County-level Statistics of TSI values

The EQI requires assessment data to be evaluated at the county level to compliment the administration and reporting of conservation programs. The Zonal Statistics function in the ESRI Spatial Analyst extension was used to calculate the area weighted mean of TSI(SDT) for each Michigan county using the MGFv6 county polygon layer as the zone. The result was a table of descriptive statistics that is used to link the mean TSI(SDT) values to the county that there pixels are completely within. The same process was repeated using the USGS Statewide TSI 2005 data set to develop a county-level TSI(SDT) map for a comparison of the changes in lake water clarity, by county, between the 1985 and 2005.

Results and Discussion

As described in the Methods section, TSI values were calculated from water only pixels from the collection of nominally 1985 Landsat scenes (Figure 7). This data set was also used to calculate mean index values for each Michigan County. County-level average index values were also calculated from the USGS Statewide TSI 2005 data to summarize and compare lake water clarity across the entire state with the 1985 data set. Detailed examples of the pixel-level results between the 1985 and 2005 study periods are found in Figure 7. The results of the state-wide analysis are illustrated in Figure 8.

As illustrated in Table 4, the LKM2 attribute indicates the number of water-only pixels (in square kilometers) available for assessment. Many counties contain a limited number of water-only pixels. In fact, Sanilac County did not contain any lakes large enough (greater than 20 acres) for assessment. Six counties (Shiawassee, Arenac, Saginaw, St. Clair, Huron, and Sanilac) contained less than one square kilometer (100 hectares) of lake pixels for assessment. The majority of these counties are located in Michigan's Thumb and Saginaw Valley. The average area of water only pixels by county is approximately 30 square kilometers (3,000 hectares), however the number of lake-only pixels is highly variable with a standard deviation of 34.77. Therefore, it is noted that several of the counties indicating the greatest improvement in lake clarity, such as Wayne, Isabella, Clinton, and Eaton, have a relatively small amount of water-only pixels compared to the other counties.



1984 **2003**

Figure 7: Example of local scale TSI (SDT) values for Ford Lake during the two study periods. *Note the improvement from Hypereutrophic to Eutrophic values in the western basins and the improvement from Eutrophic to Mesotrophic in the central and eastern basin.*

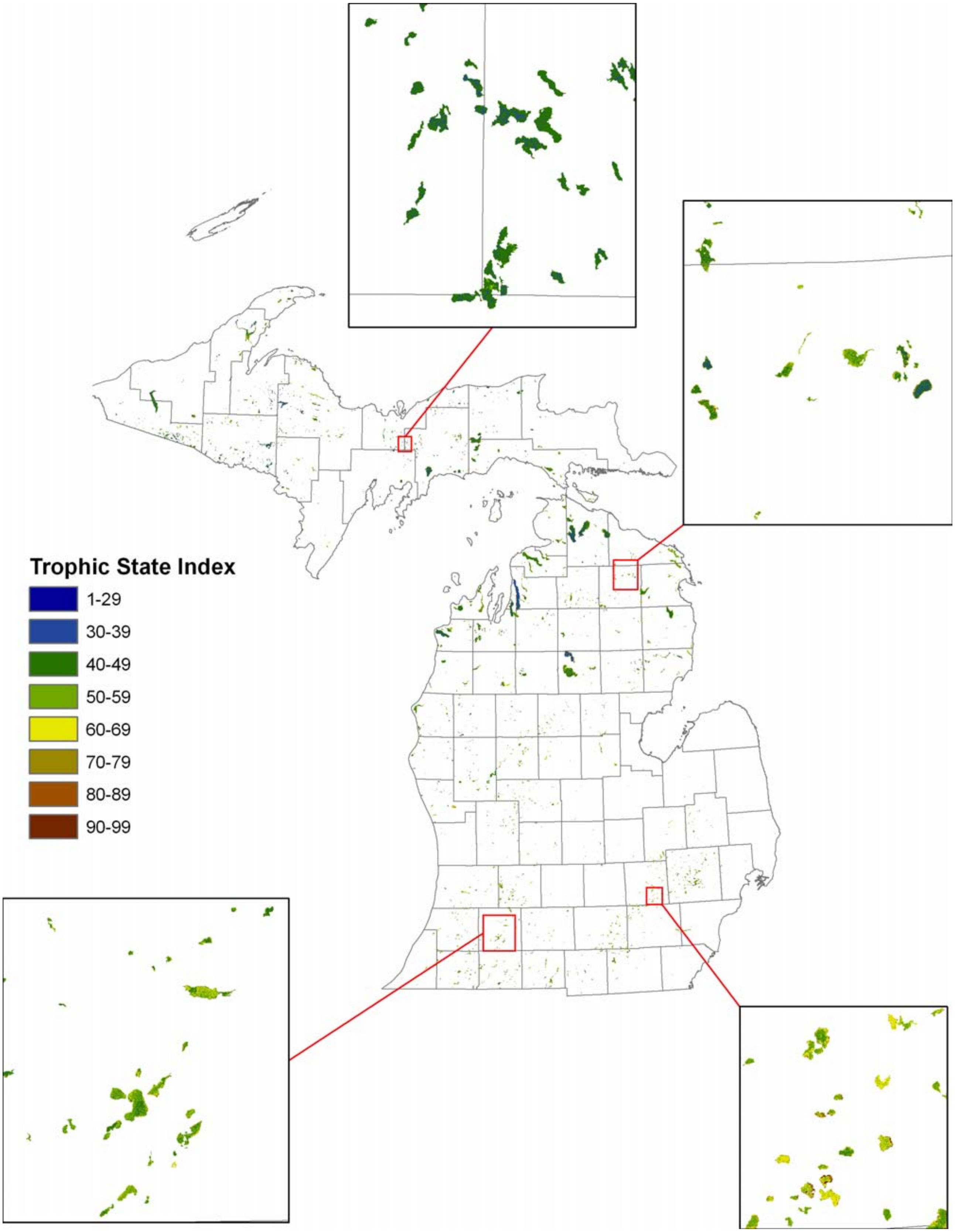


Figure 8: TSI(SDT) values for Michigan lakes 1985. *Note that many southeast Michigan lakes are classified as Eutrophic with some lakes containing local areas classified as Hypereutrophic.*

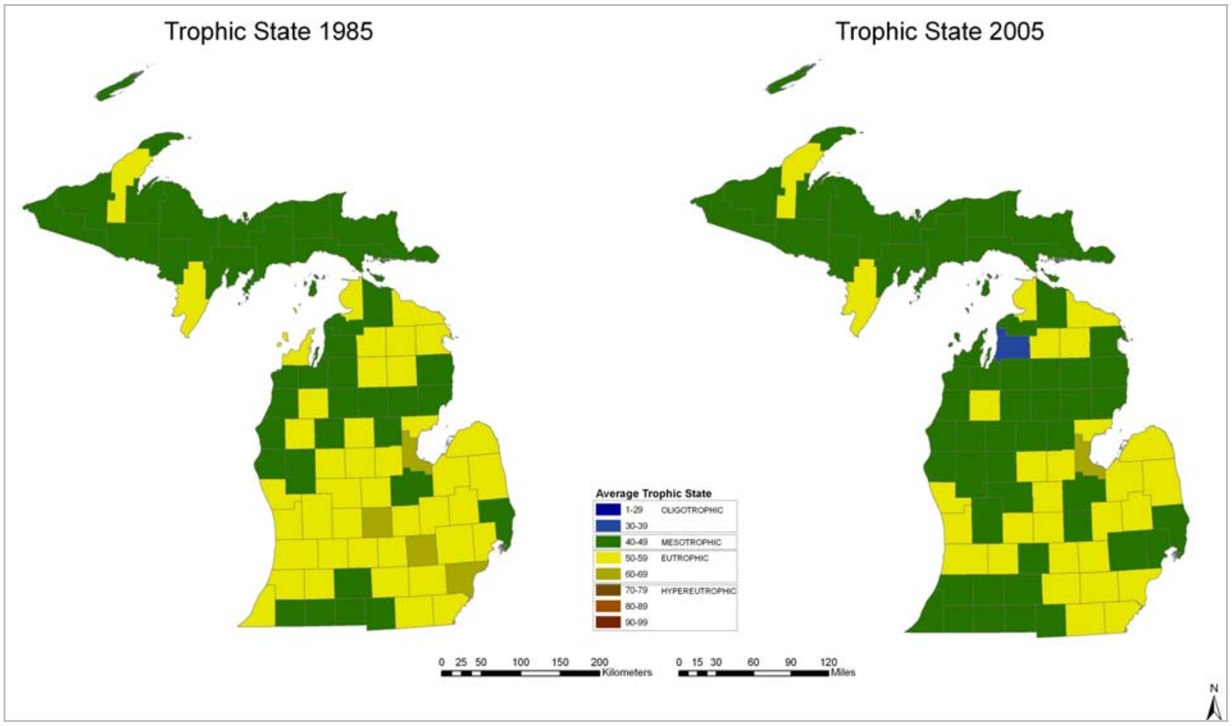


Figure 9: Comparison of TSI(SDT) values, 1985 vs. 2005, by county. *21 counties have changed trophic state, of which six counties have changed by more than 10% (all improvements in water clarity) and 7 counties have changed by 5 or more TSI units (also all improvements).*

A comparison of county-level TSI values is described in Figure 9. To assist with the comparison of the change in TSI values over time, the difference of the 1985 TSI values and 2005 TSI values was computed and mapped. Figure 10 illustrates these differences with counties that experienced a decline in lake clarity indicated in orange and counties showing improvement represented in green.

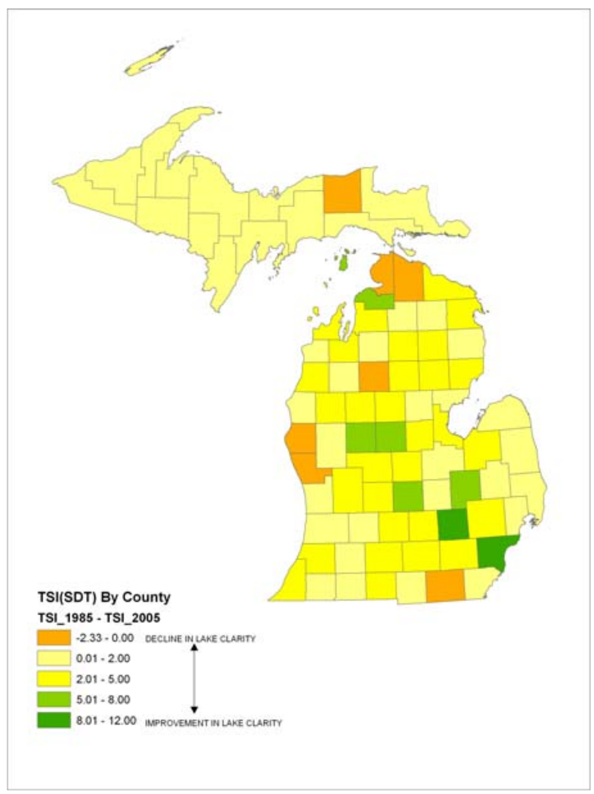


Figure 10: Differences in TSI(SDT) values between 1985 and 2005 by county. *MTRI analysis shows that a change of five or more TSI units appears to be significant; these are the seven green & dark green counties and were all improvements in lake clarity. The orange counties had decreases in lake clarity, but none reach the significant threshold of 5 units of change in TSI.*

Table 4: County-level comparison of TSI(SDT) values over time. *The values with 5 or more TSI units are emphasized in dark green and the values with 10% or more change in TSI are emphasized in purple. These are the seven counties (highlighted with regular bold) where change in TSI is notable. Using a 5% threshold, there are 32 total counties with notable change in TSI; all are improvements in lake clarity.*

NAME	AREAKM2	LKM2	TSI_1985	TSI_2005	DIFF8505	PERCHG
LIVINGSTON	1515	25.59	60.17	50.10	**10.07**	**16.74%**
WAYNE	1664	4.83	63.23	53.52	**9.71**	**15.36%**
ISABELLA	1495	6.42	57.66	51.03	**6.63**	**11.50%**
CHARLEVOIX	1175	90.37	48.64	43.21	**5.43**	**11.16%**
MECOSTA	1478	25.05	51.24	45.91	**5.33**	**10.40%**
CLINTON	1487	3.12	62.81	56.29	**6.52**	**10.37%**
GENESEE	1681	15.06	56.51	51.30	**5.21**	**9.22%**
MONTCALM	1865	21.83	52.56	47.73	4.84	**9.20%**
EATON	1500	1.84	50.90	46.28	4.62	**9.08%**
CALHOUN	1859	10.20	48.92	44.80	4.13	**8.44%**
BERRIEN	1503	4.67	49.65	45.66	3.99	**8.03%**
JACKSON	1872	31.57	54.83	50.49	4.34	**7.91%**
BRANCH	1345	24.49	48.98	45.29	3.69	**7.53%**
TUSCOLA	2108	1.22	56.96	52.68	4.28	**7.52%**
MIDLAND	1367	10.12	56.63	52.38	4.25	**7.50%**
ROSCOMMON	1501	134.46	45.15	41.83	3.32	**7.35%**
IONIA	1501	6.53	52.86	49.07	3.79	**7.17%**
LEELANAU	973	68.02	49.19	45.75	3.44	**7.00%**
VAN BUREN	1613	19.09	50.40	47.01	3.39	**6.73%**
LAKE	1486	11.15	49.31	46.05	3.26	**6.62%**
ANTRIM	1359	121.30	40.44	37.79	2.65	**6.55%**
INGHAM	1451	2.27	52.88	49.43	3.44	**6.51%**
CLARE	1489	14.69	49.42	46.21	3.21	**6.50%**
GRAND TRAVERSE	1269	58.79	46.74	43.76	2.98	**6.39%**
GRATIOT	1479	1.45	57.59	54.05	3.54	**6.14%**
ALPENA	1539	43.57	50.74	47.67	3.07	**6.06%**
OAKLAND	2348	60.87	50.41	47.45	2.96	**5.87%**
IOSCO	1466	34.41	47.90	45.11	2.79	**5.83%**
CRAWFORD	1458	10.88	51.07	48.16	2.90	**5.68%**
KENT	2257	21.83	51.14	48.38	2.76	**5.40%**
OGEMAW	1488	16.63	48.80	46.21	2.59	**5.30%**
OSCEOLA	1483	8.42	48.93	46.41	2.52	**5.16%**
PRESQUE ISLE	1774	49.39	53.55	50.97	2.58	4.82%
WASHTENAW	1870	21.00	52.78	50.37	2.41	4.56%
MANISTEE	1443	18.51	48.36	46.18	2.18	4.50%
BAY	1163	1.48	62.95	60.13	2.81	4.47%
OSCODA	1480	7.23	49.66	47.65	2.01	4.05%
MONTMORENCY	1457	28.84	50.95	49.01	1.94	3.81%
WEXFORD	1489	24.98	51.97	50.08	1.88	3.62%
SAGINAW	2112	0.47	47.15	45.60	1.56	3.31%
BENZIE	900	63.72	44.56	43.10	1.46	3.27%
GLADWIN	1335	10.22	48.95	47.36	1.60	3.26%

Table 4 (continued): County-level comparison of TSI(SDT) values over time. *The values with 5 or more TSI units are emphasized in dark green and the values with 10% or more change in TSI are emphasized in purple. These are the seven counties (highlighted with regular bold) where change in TSI is notable. Using a 5% threshold, there are 32 total counties with notable change in TSI; all are improvements in lake clarity.*

NAME	AREAKM2	LKM2	TSI_1985	TSI_2005	DIFF8505	PERCHG
NEWAYGO	2230	36.95	48.53	46.96	1.57	3.23%
ALLEGAN	2181	21.20	54.00	52.31	1.69	3.12%
MACKINAC	2754	97.22	47.45	46.04	1.41	2.97%
ARENAC	953	0.56	56.88	55.21	1.67	2.94%
** SANILAC*	*2497*	*0.00*	*52.25*	*50.75*	*1.50*	*2.88%*
BARRY	1493	37.04	50.86	49.44	1.42	2.79%
HURON	2170	0.04	53.38	51.90	1.48	2.77%
KALKASKA	1477	18.14	48.19	46.86	1.33	2.76%
MASON	1320	32.32	47.60	46.32	1.28	2.69%
MACOMB	1253	2.64	49.13	47.84	1.30	2.64%
ALCONA	1799	46.48	46.25	45.04	1.21	2.62%
MONROE	1444	1.36	52.83	51.55	1.28	2.42%
LAPEER	1716	9.18	51.67	50.43	1.24	2.40%
CHIPPEWA	4685	16.21	45.53	44.55	0.98	2.16%
OTSEGO	1362	22.48	50.37	49.31	1.06	2.11%
MARQUETTE	4840	107.21	47.17	46.20	0.97	2.05%
SHIAWASSEE	1400	0.82	49.47	48.52	0.94	1.91%
GOGEBIC	2965	92.26	45.14	44.33	0.80	1.78%
HILLSDALE	1571	12.43	48.54	47.76	0.79	1.62%
ONTONAGON	3439	34.00	43.89	43.24	0.65	1.49%
MENOMINEE	2722	9.89	53.54	52.82	0.73	1.36%
SCHOOLCRAFT	3162	86.22	44.01	43.44	0.57	1.29%
HOUGHTON	2697	69.20	50.12	49.56	0.56	1.12%
OTTAWA	1494	2.99	55.40	54.82	0.58	1.06%
KALAMAZOO	1502	28.89	49.24	48.74	0.50	1.01%
ST JOSEPH	1349	25.62	46.99	46.51	0.47	1.01%
DELTA	3055	13.34	41.26	40.86	0.39	0.96%
IRON	3136	88.71	43.12	42.72	0.39	0.91%
CASS	1316	28.48	47.79	47.37	0.42	0.88%
ST CLAIR	1903	0.11	48.25	47.85	0.41	0.84%
KEWEENAW	1458	19.52	48.94	48.53	0.41	0.83%
BARAGA	2374	27.04	42.21	41.96	0.25	0.59%
DICKINSON	2010	24.53	48.24	48.16	0.08	0.16%
ALGER	2425	34.14	41.31	41.25	0.06	0.15%
OCEANA	1414	10.60	48.86	48.95	-0.09	-0.18%
EMMET	1253	35.88	54.16	54.61	-0.44	-0.82%
MISSAUKEE	1485	14.07	46.01	46.63	-0.61	-1.33%
LUCE	2399	42.75	44.94	46.14	-1.20	-2.67%
LENAWEE	1970	21.04	51.67	53.48	-1.81	-3.51%
MUSKEGON	1366	18.04	55.11	57.44	-2.33	-4.23%
CHEBOYGAN	2061	192.74	43.92	45.99	-2.07	-4.71%

** Sanilac County estimated from averaging neighboring counties*

Table 4 lists the mean TSI values for the two time periods by county along with several other attributes. The AREAKM2 field describes the area of the county in square kilometers. LAKEKM2 lists the area of lake pixels processed by square kilometers. TSI_1985 and TSI_2005 represent the TSI(SDT) values for the county for their respective time period. The DIFF8505 field represents the raw difference (TSI_1985 – TSI_2005) of the two time periods. CHANGE represents the percent change between 1985 and 2005 values and is computed as (((TSI_1985 – TSI_2005) / TSI_1985) * 100). The table is sorted by the CHANGE attribute in descending order.

Sensitivity Analysis

To evaluate the precision at which the change in TSI values can be accurately interpreted, MTRI analysts performed an analysis of the variability of TSI values calculated from in-situ data. Previous Secchi Disk field data collection projects for other water quality assessment projects indicate that SDT measurements of a given water body may vary from approximately 1 to 6 inches based on field conditions, collection procedure, and personnel. For example, Davies-Colley (1993), defined a Secchi Disk collection protocol which includes: using a disk of the appropriate size for the clarity range, collecting from the sunny side of the boat, collecting as near to mid-day as possible and allowing at least 2 minutes for looking the disk at the point of appearance, among others parameters. Thus, variations in these procedures may result in different transparency measurements for the same location.

An analysis of the sensitivity of the TSI(SDT) calculation to the variation in SDT measurements was performed by modeling the change in TSI(SDT) values calculated from in-situ data. The variation, 1 and 6 inches, (3.1cm and 15cm) was both added and subtracted to in-situ SDT measurements from 12 Lower Peninsula lakes in 2003-2005. TSI(SDT) was calculated for the additive and subtractive SDT values and compared to the TSI(SDT) value calculated from the in-situ data. Figure 11 illustrates that adding or subtracting approximately one-tenth of a foot (3.1cm) to the SDT has no effect on the calculated TSI value.

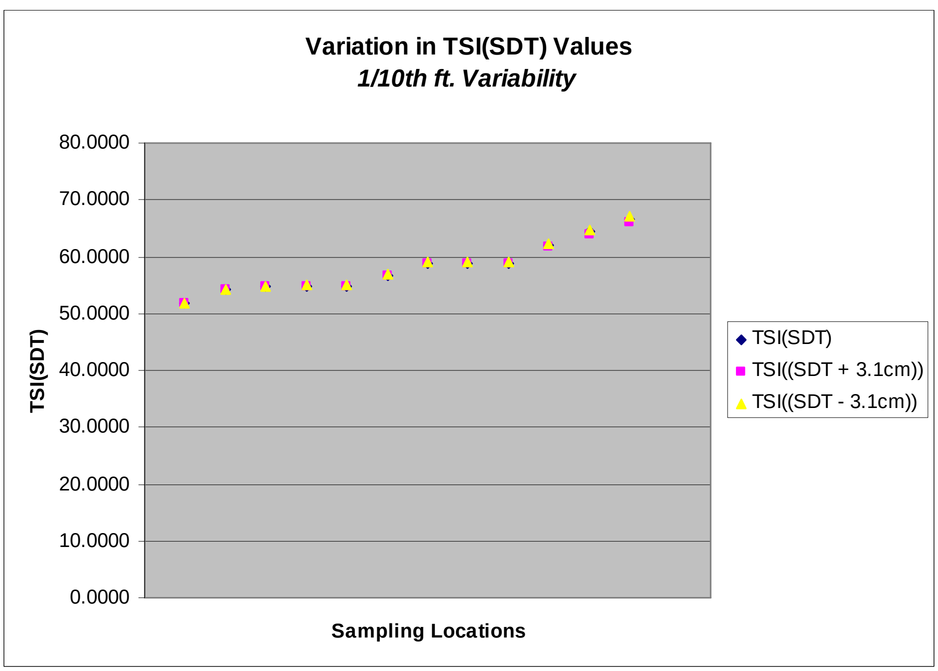


Figure 11. Effect of 1/10th foot variability in SDT measurement on TSI(SDT)

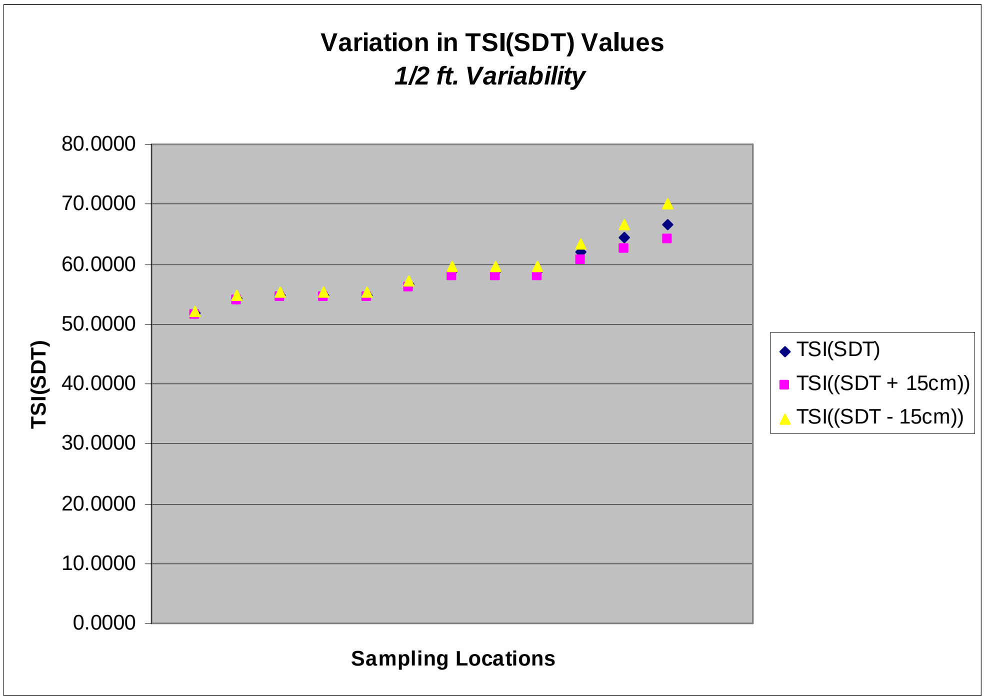


Figure 12. Effect of 1/2 foot variability in SDT measurement on TSI(SDT)

Figure 12 describes the effect of varying the SDT measurement by one-half foot (15cm). As illustrated in the figure, TSI(SDT) values below 60 (Eutrophic classification) appear to be unaffected by the change in SDT measurement. However, TSI(SDT) values in the higher range of the Eutrophic classification, greater than 60 TSI(SDT), appear to sensitive to the variation. As Figure 12 illustrates, the addition of 15cm to the SDT measurement transformed one of the sampling locations from a TSI(SDT) of approximately 66 to 70, changing the classification from Eutrophic to Hypereutrophic.

Based on the sensitivity analysis, the estimated precision of the TSI(SDT) calculation appears to be affected by no more than 1 TSI(SDT) unit at the lower range of TSI(SDT) values (0-60). However, at the higher range of TSI(SDT) values (60 or greater), the precision of the calculation appears to be affected by 2 to 5 TSI(SDT) units. As such, it appears that when TSI(SDT) values increase (indicating decreased water clarity), the precision of the calculation decreases. This means that a change in TSI(SDT) values of 5 units or greater is significant enough to be considered noteworthy change. Therefore, when considering the differences in TSI(SDT) values between the two study periods, as illustrated in Figure 10, changes reported in counties with small amounts of TSI(SDT) change (orange and yellow counties) may have actually changed very little, while counties with large change in TSI(SDT) values (green counties) may have significantly changed.

To understand how issues of scale affect the change in lake clarity values over time, average TSI values were calculated for each Michigan watershed. This also serves as an example of how EQI inputs could be calculated at a watershed level. Seven-digit Hydrologic Unit watershed boundaries from the Michigan Department of Environmental Quality (MDEQ) were used to calculate watershed level average index values from the USGS Statewide TSI 2005 data and the 1985 TSI data. The results of the watershed level analysis for both time periods are illustrated in Figure 13. The difference in the TSI values between the two time periods is illustrated in Figure 14.

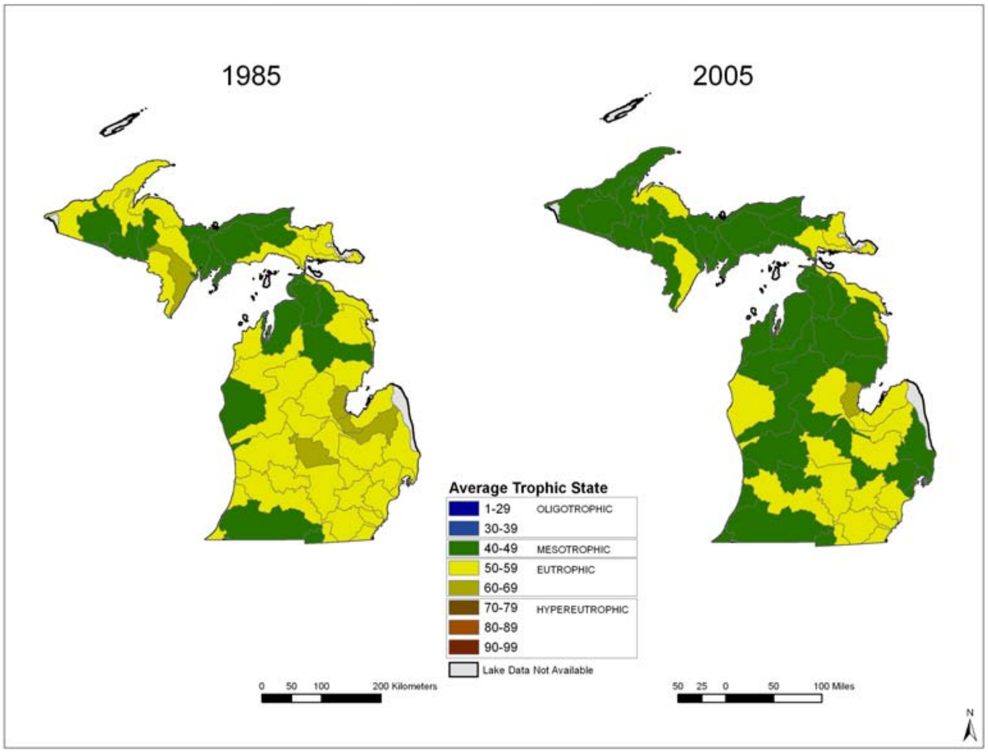


Figure 13: Comparison of TSI(SDT) values 1985 vs. 2005 by watershed. *7-digit Hydrologic Unit Code (HUC) watersheds were used as a reasonable scale for statewide analysis.*

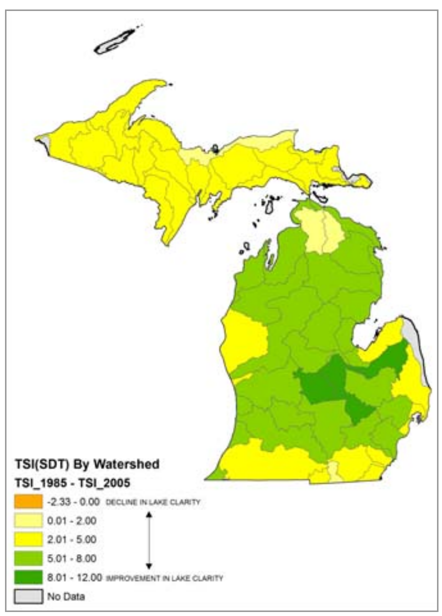


Figure 14: Differences in TSI(SDT) values between 1985 and 2005 by watershed. *At the 7-digit HUC scale, 23 of the 56 watersheds in Michigan with calculated TSI values had changes of five or more TSI units (green and dark green watersheds), all showing improvement in lake clarity.*

Accuracy Assessment

To evaluate the accuracy of the TSI values derived from the 1985 Landsat data, an accuracy assessment was performed using a small collection of historic water quality data. The U.S. Environmental Protection Agency's STORET (STOrage and RETrieval) repository for water quality data was initially evaluated as a data source for modeling the relationship between in-situ measurements and the 1985 Landsat data. Although the limited availability of this data excluded this approach, the data that was available is suitable for comparison with the 1985 TSI data.

The STORET Legacy system was queried for SDT data in Michigan lakes. Data was available for approximately 40 lakes in Michigan's Lower Peninsula for the summer months (July and August) between 1972 and 1985. SDT was converted from feet to meters and used to calculate trophic state using Carlson's equation (1977). Zonal statistics were calculated using the pixel-level trophic state values derived from the 1985 Landsat data and the MGFv6 lake polygon to calculate average TSI for the entire lake. In-situ SDT data was available for 41 lakes. Of these, 37 were classified as Eutrophic and 4 as Hypereutrophic according to Carlsons equation. According to the results of the 1985 TSI assessment, 32 of the eutrophic lakes were classified correctly and 1 of the hypereutrophic lakes was classified correctly. The results of the accuracy assessment are described by the error matrix in Table 5. User's accuracy describes errors of commission which result when a lake is committed to an incorrect class. User's accuracy is 91% for the eutrophic class and approximately 17% for the hypereutrophic class. The low accuracy of the hypereutrophic class is likely to be a function of the small number of samples of the class. The producer's accuracy details the errors of omission. An error of omission results when trophic state is incorrectly classified into another trophic state category. Producer's accuracy is approximately 86% for the eutrophic class and 25% for the hypereutrophic class. The overall accuracy, the number of incorrect observations divided by the number of correct observations, is approximately 80%. Table 6 lists the input data used to compile the error matrix and assess the accuracy of the 1985 TSI data set. Within the table, ACTUALTSI field and ACTUAL_STATE fields represent the TSI(SDT) value and trophic state class from the in-situ data respectively. PREDTSI represents the TSI(SDT) value calculated from the 1985 Landsat data while PRED_STATE describes the related trophic state class. The DIFF field lists the absolute difference of the ACTUALTSI value and the PREDTSI value.

Table 5: Error matrix comparing in-situ TSI(SDT) with 1985 Predicted TSI(SDT) for 41 test lakes in Michigan. *33 of the 41 (80%) lakes were classified with the correct trophic state using MTRI's analysis.*

		Reference Data			
		Eutrophic	**Hypereutrophic**	**Row Total**	**User's Accuracy (Commission Error)**
Classification Result	**Eutrophic**	**32**	3	35	**91.43%**
	Hypereutrophic	5	**1**	6	**16.67%**
	Column Total	37	4	**41**	
	Producers Accuracy *(Omission Error)*	**86.49%**	**25.00%**	**Overall Accuracy**	**80.49%**

Table 6: Reference data for the assessing accuracy of the 1985 TSI(SDT) data.

NAME	COUNTY	ACTUALTSI	ACTUAL_STATE	PREDTSI	PRED_STATE	DIFF
Sand Lake	Iosco	53.03	Eutrophic	52.98	Eutrophic	0.05
Long Lake	Ionia	53.19	Eutrophic	53.00	Eutrophic	0.19
Cedar Lake	Washtenaw	52.15	Eutrophic	51.84	Eutrophic	0.31
Lobdell Lake	Genesee	54.37	Eutrophic	54.75	Eutrophic	0.38
Green Lake	Washtenaw	52.43	Eutrophic	51.72	Eutrophic	0.71
Sugarloaf Lake	Washtenaw	54.83	Eutrophic	55.59	Eutrophic	0.76
Lake Hudson	Lenawee	66.47	Hypereutrophic	67.49	Hypereutrophic	1.02
Lake Lansing	Ingham	54.42	Eutrophic	55.52	Eutrophic	1.10
Miner Lake	Allegan	52.15	Eutrophic	51.00	Eutrophic	1.15
Mill Lake	Washtenaw	52.43	Eutrophic	53.66	Eutrophic	1.23
Intermediate Lake	Antrim	53.29	Eutrophic	54.60	Eutrophic	1.31
Van Etten Lake	Iosco	57.79	Eutrophic	56.48	Eutrophic	1.31
Round Lake	Hillsdale	55.72	Eutrophic	54.41	Eutrophic	1.31
Wiggins Lake	Gladwin	54.42	Eutrophic	53.03	Eutrophic	1.39
Lake Thumb	Charlevoix	52.24	Eutrophic	53.79	Eutrophic	1.55
Thornapple Lake	Barry	59.16	Eutrophic	60.84	Hypereutrophic	1.68
Joslin Lake	Washtenaw	52.43	Eutrophic	54.44	Eutrophic	2.01
Lake Bellaire	Antrim	54.83	Eutrophic	52.81	Eutrophic	2.02
Round Lake	Lenawee	52.73	Eutrophic	55.15	Eutrophic	2.42
Devils Lake	Lenawee	54.83	Eutrophic	52.13	Eutrophic	2.70
Manistee Lake	Kalkaska	53.68	Eutrophic	50.96	Eutrophic	2.72
Lake Charlevoix	Charlevoix	53.07	Eutrophic	50.34	Eutrophic	2.73
Pleasant Lake	Jackson	54.42	Eutrophic	57.23	Eutrophic	2.81
Murray Lake	Kent	53.03	Eutrophic	50.10	Eutrophic	2.93
Coldwater Lake	Isabella	54.42	Eutrophic	57.76	Eutrophic	3.34
Gun Lake	Barry	53.60	Eutrophic	57.31	Eutrophic	3.71
North Lake	Washtenaw	54.42	Eutrophic	50.69	Eutrophic	3.73
Winnewana	Washtenaw	60.56	Hypereutrophic	56.68	Eutrophic	3.88
Bear Lake	Hillsdale	54.42	Eutrophic	50.52	Eutrophic	3.90
Wamplers Lake	Jackson	57.36	Eutrophic	53.08	Eutrophic	4.28
Grass Lake	Jackson	52.72	Eutrophic	57.32	Eutrophic	4.60
Halfmoon Lake	Washtenaw	55.72	Eutrophic	60.52	Hypereutrophic	4.80
Fourmile Lake	Washtenaw	56.77	Eutrophic	61.67	Hypereutrophic	4.90
Belleville Lake	Wayne	60.57	Hypereutrophic	55.35	Eutrophic	5.22
Pickerel Lake	Emmet	52.97	Eutrophic	58.22	Eutrophic	5.25
Lincoln Lake	Kent	51.38	Eutrophic	57.22	Eutrophic	5.84
Boyles Creek	Clare	56.22	Eutrophic	50.28	Eutrophic	5.94
Ford Lake	Washtenaw	63.93	Hypereutrophic	57.70	Eutrophic	6.23
Vineyard Lake	Jackson	53.86	Eutrophic	60.39	Hypereutrophic	6.53
Clark Lake	Jackson	51.63	Eutrophic	58.22	Eutrophic	6.59
Cedar Lake	Alcona	55.26	Eutrophic	62.36	Hypereutrophic	7.10

Section 6: Concluding Remarks

According to the results of the 1985 assessment, statewide water clarity is classified as Eutrophic. Of the 68 counties comprising the Lower Peninsula, 24 counties are classified as Mesotrophic and the remaining 44 counties are classified as Eutrophic, one trophic state worse water quality than Mesotrophic. Thirteen of the 15 Upper Peninsula counties are classified as Mesotrophic and the remaining two counties are classified as Eutrophic, indicating that the U.P. generally had better water quality in 1985.

The 2005 assessment indicates that statewide water clarity is classified as mostly as Mesotrophic. Within the Lower Peninsula, 28 counties are classified as Eutrophic (vs. 44 in 1985 for that lower quality trophic state), 39 counties are classified as Mesotrophic (up from 24 in 1985 for that better trophic state), and one county is classified as Oligotrophic. Interestingly, this is the same time period that NRCS programs have been impacting water quality in Michigan, starting with the conservation programs that were new in the 1985 Farm Bill. Like the 1985 lake clarity assessment, 13 of the 15 Upper Peninsula counties are classified as Mesotrophic and the remaining two counties are classified as Eutrophic, indicating that U.P. counties have maintained generally good water quality over the 20-year time period.

Thirty-two of Michigan’s 83 counties indicated a change in TSI values of five percent or greater, indicating that lake water clarity has improved in the time between 1985 and 2005. Six of the counties (Livingston, Wayne, Isabella, Charlevoix, Mecosta, and Clinton) indicated a change of ten percent or more, with seven counties (the previous list plus Genesee) having a noteworthy improvement in TSI of five units or more. Some of these changes are significant enough to change the trophic state classification of county lakes. For example, Mecosta County transitioned from the Eutrophic class to the Mesotrophic class. Decreases in water quality did not appear to be significant at the County scale. As indicated by the results of the accuracy assessment, TSI(SDT) values calculated by the new technique described here successfully classified the trophic state of 80% of the historic reference data available within the Lower Peninsula.

Our approach to remote sensing based water quality assessment, extended from USGS methods, has identified several areas for future research. Given the availability of in-situ turbidity data, the technique lends itself to the application of more frequent, regional scale assessments using moderate resolution remote sensing data. Also, the approach is suitable for use with very high resolution remote sensing data to assess special areas of concern at local scales. Specifically, we recommended that our approach be used to study changes in water quality over time for watersheds with relatively active levels of NRCS program effort. Regardless of the scale at which the method is applied, the water quality metrics developed by this approach provide valuable data for spatial and temporal analysis of changing environmental conditions.

Acronym List

EPA	Environmental Protection Agency
EQI	Environmental Quality Index
EROS	Earth Resources Observation & Science
HUC	Hydrologic Unit Code
MDEQ	Michigan Department of Environmental Quality
MGFv6	Michigan Geographic Framework Version 6
MTRI	Michigan Tech Research Institute
NRCS	Natural Resource Conservation Service
SDT	Secchi Disk Transparency (SDT)
STORET	STOrage and RETrieval
TM	Thematic Mapper
TSI	Trophic State Index
UP	Upper Peninsula (Michigan)
USGS	United States Geologic Survey
WRS2	Worldwide Reference System 2

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