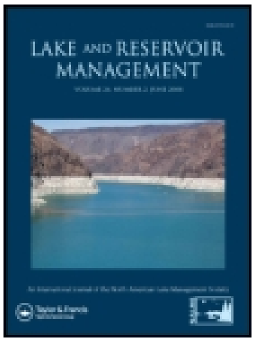

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Detection of Spatial and Temporal Trends in Wisconsin Lake Water Clarity Using Landsat-derived Estimates of Secchi Depth

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Abstract

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The existence of large-scale spatial and temporal trends in Wisconsin's lake water clarity is a topic that has not been thoroughly investigated. This study is an effort to reliably detect these trends by utilizing three inventories of satellite-derived lake water clarity predictions for over 2,000 lakes statewide. The data were analyzed statistically on a statewide, regional, lake type, and lake area basis. Statistically significant trends in clarity were found for the state overall, as well as for particular U.S. Environmental Protection Agency Ecoregions, Wisconsin Department of Natural Resources hydrologic lake types, and lake area categories. Results will aid in the establishment of a statewide lake water clarity database and demonstrate the effectiveness of satellite-based assessments in detecting trends in water transparency over the past three decades and into the future. Documenting such trends is essential to targeting and evaluating lake management practices as well as raising public awareness of lake clarity conditions throughout the state.

Key Words: Wisconsin lakes, Landsat, Secchi depth, water clarity, ecoregion, trends

Despite the availability of data that might reveal them, currently little is known about the existence of trends in water clarity and quality in a vast majority of Wisconsin lakes over the past few decades. This is especially true for the three inventories of Landsat-derived lake water clarity estimates, one from each of the past three decades. Regression models using Landsat imagery and Secchi disk measurements were developed to predict water clarity or lake trophic state at the time for a large number of the lakes in Wisconsin, but no formal investigation has been made into the relationship between these three sets of data.

In situ monitoring of a large number of lakes is not only extremely expensive, it is very difficult to achieve. Remote sensing has been shown to be an effective method of estimating clarity for a large number of lakes (Lillesand 1983, Chipman *et al.* 2004), and this study demonstrates the effectiveness of using three sequential decades of satellite estimates to gain a "big picture" perspective of the changes taking place in lake water clarity in the state over this time scale. It is of the utmost importance to know the condition of the waters we depend upon and how these conditions are likely to change in the future. Results of this study could be used as a tool to aid in how we use and manage our lakes in the future as well as increasing public awareness of trends in lake water clarity. These management decisions are crucial at a time when recreational lake use and intensive shoreline development, as well as their coincidental impacts on riparian zones and lake water quality, are increasing.

The intent of this study was to evaluate three decadal "snapshots" of Landsat-derived Secchi depth estimates to detect any spatial or temporal trends. This large-scale evaluation is appropriate because temporal trends have been detected by other researchers in smaller data sets in both field and satellite-based measurements of Secchi depth. Temporal trends in the Wisconsin Department of Natural Resources' (WDNR) "50 Long-Term Trends" lakes were evaluated by Webster (1998) who found significant trends in lake clarity in nine of these 50 lakes from 1986-1996. Bruhn and Soranno (2005) found significant trends in 26 of 71 volunteer-sampled lakes in Michigan from 1974-2001. In addition, Kloiber *et al.* (2002a) found significant temporal trends in 64 of 482 lakes in the Twin Cities Metropolitan Area (TCMA) of Minnesota over a 25-year period using Landsat-derived estimates. The current study tested the hypothesis that remotely sensed estimates of Secchi depth can be reliably used to detect spatial and temporal change in the water clarity of lakes sampled in Wisconsin over the past three decades.

Water clarity is one important indicator lake health, algal biomass, and trophic condition. The importance and need for measuring lake clarity using a Secchi disk are outlined by Bruhn and Soranno (2005), and these principles extend to satellite-based estimates of Secchi depth as well. While field measurements of lake water quality in Wisconsin started in the 1920s, satellite-derived water quality predictions for Wisconsin lakes began about three decades ago (relatively soon after the 1972 start of the Landsat program). In a joint lake classification project between the University of Wisconsin-Madison and the WDNR during the mid-to-late 1970s, a method was developed in which data from the Landsat Multispectral Scanner (MSS) was used to predict the trophic state of more than 2,900 lakes in the state (Scarpace *et al.* 1979, Martin *et al.* 1983). This effort utilized 34 images collected from 1979 to 1981. Two additional inventories of satellite-derived water clarity estimates for more than 7,000 lakes in the state of Wisconsin were generated using imagery from the Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+), aboard Landsat-5 and Landsat-7, respectively. These two assessments, created at the University of Wisconsin Environmental Remote Sensing Center (UW/ERSC), covered the periods of 1991-1994 and 1999-2001 and were constructed using 12 and 17 Landsat scenes respectively. Image dates were restricted to an "index period" of July 15 to September 15 based on findings by Stadelmann *et al.* (2001) and follow the image processing protocol described in Kloiber (2002b). Because of improvements in spatial and radiometric resolution of TM/ETM+ sensors versus MSS, the number of lakes in the latter two assessments increased as well as the reliability of the estimates. In addition, the model developed using the TM/ETM+ was quite robust, field measurements of Secchi depth were strongly correlated with the ratio of the blue-to-red spectral bands, and the same model form was applied to all acquired imagery, although the coefficients in the model were specific to each image collected. The scene-specific model coefficients were derived using Secchi measurements made by volunteers who sampled lakes as close to the Landsat overpass as possible. In contrast, the MSS assessment models varied by region and were more complex in nature (see Martin *et al.* 1983 for model definitions). These regions were selected to group lakes with similar characteristics.

Methods

Study Area

The study area for this project was the entire state of Wisconsin. This Midwestern U.S. state has more than 15,000 lakes that range from <1 ha to >50,000 ha, from completely undeveloped to surrounded by urbanization, and from clear and deep to shallow and sediment-laden. While these lakes are located throughout all areas of the state, higher concentrations occur in the forested areas of Northern Wisconsin, with some of the largest lakes in the agricultural and urban southern portions of the state. This large variety of lakes is an invaluable source of recreation, wildlife and fish habitat, drinking water, and industrial livelihood, to name just a few.

Data Acquisition

The satellite-derived estimates of Secchi depth used in this study were generated by the studies described above. In addition, some data necessary for the analysis were obtained from other sources. Most of the data used were accessible and ready for use, while some needed further evaluation and processing. The data can be divided into four categories.

Landsat TM and ETM+ based estimates

The Landsat-5- and Landsat-7-derived water quality data for the early and late 1990s were available through UW/ERSC. Both sets were generated using methods described by Chipman *et al.* (2004). These data were imported into a relational database to enable linkage to other satellite-based inventories as well as the ecoregion and lake-type data. In addition, the late 1990s estimate was also available in a format compatible with ArcGIS through the ERSC SDE database; it consists of polygons for all lakes that have a Secchi estimate along with many other fields, including the Water Body Identification Code (WBIC) number, and will be denoted as the 'lakes layer' in this paper.

Landsat MSS-based estimates

The late 1970s-early 1980s water clarity data derived from the Landsat MSS sensor was published in Martin *et al.* (1983), *Wisconsin Lakes–A Trophic Assessment Using Landsat Digital Data*. Lake trophic conditions were reported as a trophic state index (TSI) value, a log transformation of Secchi depth based on the methods of Carlson (1977). All TSI values for each lake from this data set were manually entered into a Microsoft Access database. In addition, a unique WDNR WBIC was determined for each individual lake.

Field data

Two different sets of field-measured Secchi depth were utilized in this study, both obtained from the WDNR. Data from the Self Help Lake Monitoring Program (Chipman *et al.* 2004) covering periods 1990-1994 and 1999-2001, along with WDNR Bureau of Research data from 1979, provided ground-based measurements for more than 200 lakes each year and were well distributed across the state.

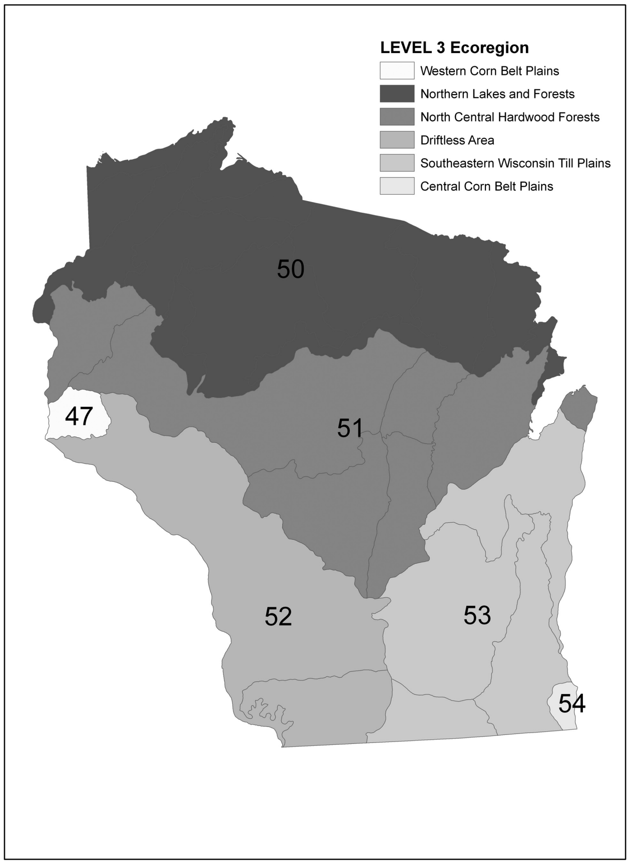

Figure 1.-Level 3 Ecoregions of Wisconsin.

Other data

In addition to the lake clarity data described above, two other sources of data were used in this project. First, a spreadsheet was obtained from the WDNR that contained a wealth of information for 5,188 unique lakes. Similar information is also published in the book *Wisconsin Lakes* (WDNR 2001). Included in this spreadsheet was the hydrologic lake type (lake types explained in detail below). The data file was organized by WBIC number, and was easily integrated with other data in the relational database. Second, the ecoregion data were obtained from the U.S. EPA's website, available for free in a coverage format for use in ArcGIS. The regional scheme used in this project was the Level 3 Ecoregions (see below).

Project Design

The primary investigation in this study was whether lake water clarity data predicted by Landsat models indicate changes that may be occurring over time and space. To accomplish this, the data were subset using several criteria. Analysis was applied to detect decreases or increases in lake transparency on a statewide, regional (ecoregion), lake type and lake area basis.

Ecoregions

Again, the regional division scheme used in this project was a subset of the Environmental Protection Agency's Upper Midwest Ecoregions (Fig. 1). The six ecoregions that divide Wisconsin capture the most important land use and environmental characteristics that affect aquatic ecosystems and were derived from soils, land use, land-surface form, and potential natural vegetation maps (Omernik and Gallant 1988). In the data compiled for this study, four ecoregions had a sufficient number of lakes for analysis: Northern Lakes and Forests (Ecoregion 50); North Central Hardwood Forests (Ecoregion 51); Driftless Area (Ecoregion 52); and Southeastern Wisconsin Till Plains (Ecoregion 53).

Hydrologic lake type

In addition to the regional analysis, lakes were evaluated by their hydrologic type, a typical method of classifying lakes based on their water source and outflows. The WDNR (2001) has identified four categories in Wisconsin Lakes: drainage, seepage, spring, and drained lakes. Drainage lakes are those whose main source is from stream drainage, and they have both an inlet and an outlet. Seepage lakes, the most common type in Wisconsin, do not have an inlet or outlet; their water sources are precipitation, runoff, and groundwater. Spring lakes, common in the northern regions of the state, have no inlet, but do have an outlet; their primary water source is from groundwater. Finally, the least common of the hydrologic lake types is the drained lake; they also have no inlet and a continuously flowing outlet, but their source of water is not from groundwater. These classifications have been assigned to most lakes in the WDNR spreadsheet.

Lake area

Water clarity data were also analyzed with respect to surface area of the lakes involved. Data were analyzed using four area categories chosen to allow enough lakes in each category for analysis while still representing an interpretable gradient of lake-size categories. The smallest category was lakes <10 ha, followed by lakes 10-50 ha, then 50-200 ha, and finally lakes >200 ha. Other category definitions were tested to ensure that results were not sensitive to the divisions selected.

Data Synthesis

Once all WBIC numbers were found for MSS lakes and the manual data entry was completed, the data were converted into a form suitable for R, both a language and environment developed for statistical computing very similar to S (Venables and Smith 2002). Some information was extracted using ArcGIS, and a series of queries were constructed in the relational database to create one table with the columns of data required for the ensuing statistical analysis.

To create the satellite-based data file, the average Secchi estimate was first computed for the MSS inventory. Dates of imagery outside the window period were excluded, each TSI value was converted to Secchi depth through a lookup table, and the average value was computed for each sampling location. Next, the early 1990s (E90) and late 1990s (L90) estimates were manually edited in Excel prior to importing them into Access to ensure unique WBICs, because some water bodies in the lakes GIS layer had the same WBIC number. Typically, these were river systems as well as bays or basins of the lake separate from the main body that had unique clarity estimates. This was a problem because the MSS assessment only assigned one estimate per lake, with the exception of Lake Winnebago. These duplicate WBICs were removed prior to importing them into Access because the data structure required each WBIC to be a unique value in each table for the queries to function properly. When duplicate WBICs occurred, the entry with the largest surface area was retained. This method was used to ensure the best alignment between the MSS and later assessments, because lakes of 25 acres (10.12 ha) and smaller were not classified using the MSS sensor. Typically, one WBIC with a large surface area and one or more duplicates with much smaller areas were encountered, so determining the proper water body was in most cases straightforward.

To determine the appropriate ecoregion for each lake, the lakes layer was converted to a coverage and then intersected with the ecoregion coverage. The ecoregion coverage was first transformed to the Wisconsin Transverse Mercator (WTM) projection for compatibility with the lakes layer. To import the attribute table from this intersection, it was first exported from ArcGIS as a database file (.dbf) and then imported into Access where it could be linked to other tables.

Finally, a set of coordinates for each lake was needed to compute semivariograms. To accomplish this, the Arcview 3.2 xtools extension was used to compute and extract centroids for all of the polygons in the lakes layer. These centroid locations were in units of meters and in the WTM projection. This file was then imported into Access the same way as the ecoregion data and linked to the table from the lakes layer through a common identification number.

Once all data were edited and extracted and the associated tables imported into the database, the final queries were constructed. Appropriate relationships were established between the tables to obtain the desired data elements in the same table. After the query was built and successfully run, the results were exported to a comma-separated text file for use in R.

Statistical Analysis

The data structure used for statistical analysis was created through constructing a query of the various tables in Microsoft Access and exporting query results into the aforementioned comma-separated text file. The first step in the process was exploratory data analysis. The normality of the difference in Secchi depth between two satellite inventories was explored, followed by examination of spatial dependence in this difference.

After the exploratory analysis, the overall means for each year or satellite inventory versus time were plotted along with 95% confidence intervals. Then, repeated measures analysis was performed to assess the significance of time, ecoregion, lake type, and lake area. A linear mixed-effects model was fit to the entire data set using restricted maximum likelihood. The data were formatted so that each WBIC had three time points, where 1, 2 and 3 corresponded to the MSS, E90, and L90 respectively. If the factor under investigation was significant in the repeated measures, then a paired t-test was implemented to compare the difference between time-consecutive averages for each level of the factor (ecoregion, lake type or area). This method was used to determine if the t-test was appropriate for the desired factors. If a certain factor was significant in the repeated measures analysis, the difference in the Secchi depth was computed for each lake between time points 1 and 2 and between 2 and 3 and the overall mean was tested for significant difference from zero. Significance was assessed at the 0.05 level in all tests, and the difference was computed between the 1979-1981 and 1991-1994 inventories and between the 1991-1994 and 1999-2001 inventories. This procedure was implemented on a statewide, ecoregion, lake type, and lake area basis.

The benefit of the analysis of means is the possibility that it can overcome random errors introduced by the method of Secchi estimation because these errors are assumed to be randomly distributed with mean zero. This is especially true when the overall trends this study is aiming to detect may be on the same order of magnitude as the original satellite-based model variation. For example, the RMS error of the late 1990s assessment was about 0.7 m (Chipman *et al.* 2004). Because of the large number of lakes in the satellite assessment, the variance in the mean of the ecoregions, lake types, and lake areas should be low enough to detect small but significant changes in average clarity over time.

Error Considerations

One major concern was the quality of archival data derived from the MSS sensor due to the spatial and radiometric sensor limitations. In addition to manual processing, this data was re-evaluated to determine whether water clarity predictions can be compared to those developed by current

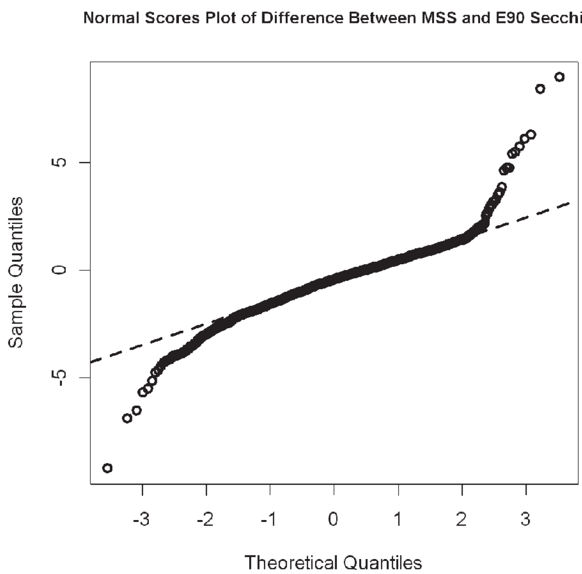

Figure 2.-Normal scores plot for the difference in Secchi estimates between satellite-based assessments.

models. Based on review of past water quality models using the MSS sensor, there is variation among different studies and, in general, correlation between MSS satellite data and field measurements is lower than with the TM and ETM+ data. Brief analysis of field versus satellite data yielded RMS errors comparable to those of the TM and ETM+. Despite these limitations, results of this study show that the number of lakes in the satellite-based estimates can overcome these limitations and reveal large-scale trends in lake clarity.

Also of concern was within-lake variation of clarity. A Secchi disk measurement is a point estimate of transparency, while the satellite estimate is obtained through a complex image processing algorithm outlined in Kloiber *et al.* (2002b). Effectively, a Secchi estimate is computed based on spectral radiance measured in the "darkest" region of the lake, where near-shore areas, islands, and vegetation would be masked out. Because most Secchi disk measurements are taken in the "deep hole" of the lake, this measurement is assumed to represent the in-lake conditions found in the area extracted for the Landsat assessment. Problems could arise when, for example, a given lake has a high degree of in-lake spatial variation of water clarity or has more than one major basin. Misalignment between field sample and satellite estimate is a possibility. This was somewhat accounted for in the later two Landsat assessments. Lake areas extracted for a clarity estimate were based on the WDNR's hydrography GIS layer. For a unique lake with more than one basin, this data layer has unique identification values for the different basins. This method was not used in the MSS-based estimate, resulting in one estimate for each lake (except Lake Winnebago). Again it appears the effect of errors arising from within-lake variation is minimized by sample size.

Results and Discussion

Exploratory Data Analysis

Both satellite and field data sets were first evaluated to explore distributions and to determine spatial dependence. The variable of interest in this study was the difference in water clarity estimates for unique lakes between successive time periods. The goal was to determine whether the overall mean of this difference was significantly different from zero. Two of these differences are found in the satellite data set – between MSS and E90 and between the E90 and L90.

Normality

The normality of the satellite data was investigated using normal-scores plots using the R function 'qqnorm'. This function plots the expected Z-scores for the data if they were sampled from a normal distribution versus the observed values. If the random variable is in fact sampled from a normal distribution, the normal-scores plot will be approximately linear. Based on this analysis, there was no reason to question the normality of the difference in Secchi depth estimates because the plots were very linear through the majority of the range and for the vast majority of observed values. Therefore, it can be concluded that these random variables were sampled from a normal or approximately normal distribution, and hence testing lake clarity means using the t distribution was appropriate. The plot for the satellite data is MSS minus E90 (Fig. 2).

Analysis of spatial dependence

To perform the paired comparison of means, the difference in Secchi was investigated for spatial dependence by computing semivariograms with simulation envelopes for the random variables (difference in Secchi depth). Semivariance was plotted versus distance between lake locations, and the simulation envelopes were computed by permutation of the actual data at the spatial locations of the lakes. These plots enabled the detection of data clustering, or possible dependence in the Secchi difference based on spatial separations. If the semivariance plot of the data was outside the simulation envelope, then the null hypothesis of complete spatial randomness (CSR) was rejected at the 2% level (because 100 simulations were used). Results from these plots showed that for both the satellite and field data, the difference in Secchi depth between consecutive satellite and field measurements did not depart from the assumption of CSR (Fig. 3). Given this result, it was appropriate to proceed with the analysis

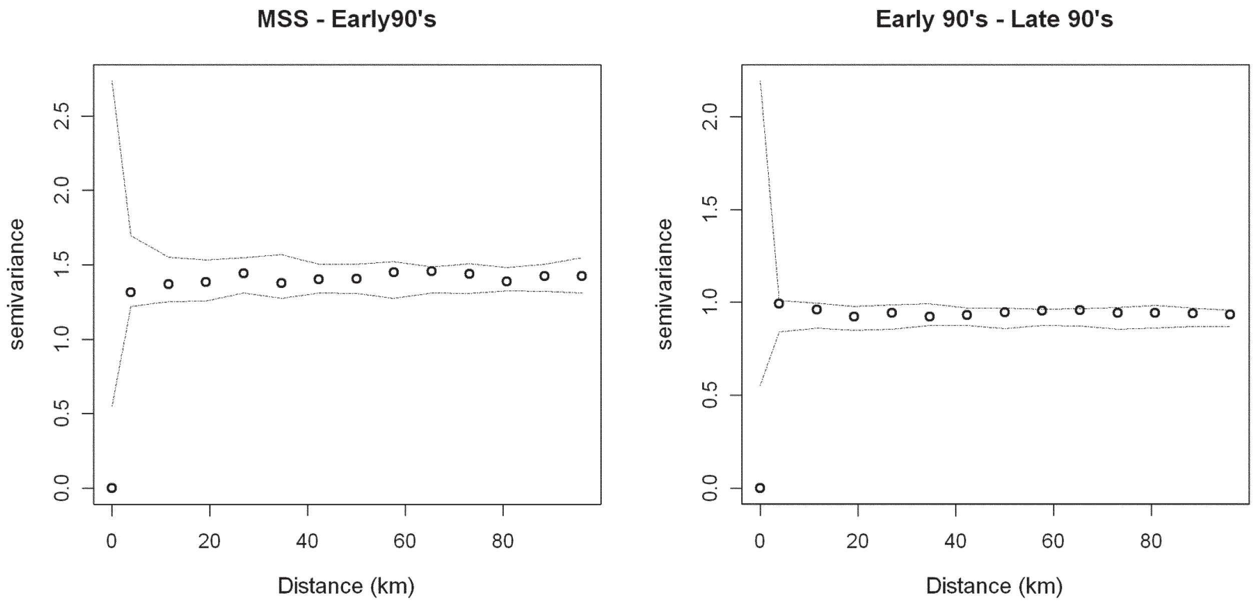

Figure 3.-Semivariograms for the difference in Secchi estimates between satellite-based asessments. Semivariance for lakes between satellite assessments versus the distance between lakes are plotted.

of the data on a statewide, ecoregion, lake type, and lake area basis.

Satellite Data Analysis

Following the exploratory analysis, satellite-derived estimates were analyzed for trends. The data set consisted of 2,467 lakes common to all three satellite inventories, which facilitated repeated measures analysis and paired t-tests for all lakes in the data set.

Statewide analysis

The first step in the trend analysis was to consider the state as a whole. First, the statewide average clarity was plotted versus time along with 95% confidence intervals for those means. Note that these were not the means tested for significance but are for general understanding, and the points chosen for time values in the plot are the years that best represent the center of the satellite assessment (Fig. 4).

Next, a repeated measures analysis was performed to test whether time was a significant factor in the Secchi depth transparency of lakes statewide. Time was very significant, with $p<0.001$. With this result, the next step was to compare the averages of each assessment and the average of the difference between successive assessments. By performing a paired t-test, an estimate of the overall change in lake clarity statewide between successive satellite inventories

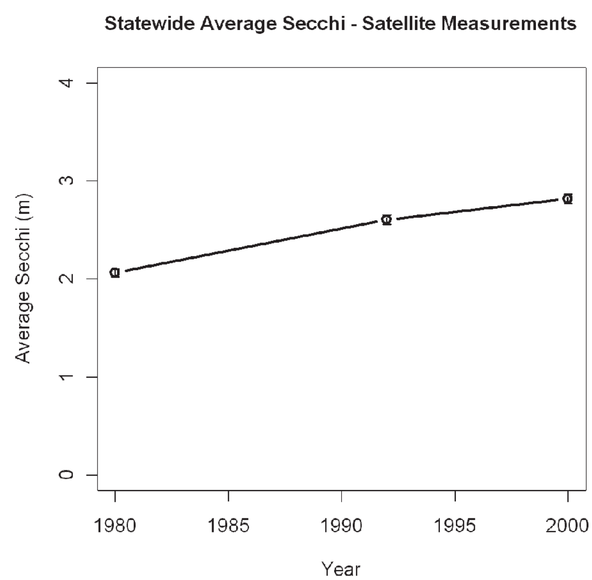

Figure 4.-Statewide lake clarity averages based on Landsat-derived estimates of Secchi depth. Average clarity versus time is plotted, where the corresponding year represents the “center” of the respective assessment.

Table 1.-Paired t-test results for statewide satellite data. Consists of the decades compared, the estimated difference, where positive numbers indicate an increase in clarity, and p-value resulting from testing the null hypothesis that the difference was equal to zero.

Decade	Estimated Difference (m)	p-value
1980 to 1990	0.54351	<2e-16
1990 to 2000	0.21495	<2e-16

and whether it was significantly different from zero was determined (Table 1). Based on the t-test analysis and the changes in the overall mean (Fig. 4), the overall average lake water clarity in Wisconsin has significantly increased over the past three decades based on satellite estimates. An estimated increase of about 0.54 m occurred between the MSS and E90 estimates, and an estimated increase of 0.21 m occurred between the E90 and L90.

Ecoregion analysis

Following the statewide investigation, the satellite data were subset by U.S. EPA Ecoregion. Analysis was completed for Ecoregions 50, 51, 52 and 53. First, the average Secchi depths were plotted versus time for each ecoregion (Fig. 5). The repeated measures analysis for the entire state was modified to include the ecoregion as a factor in the model. Like time, ecoregion was also highly significant with a $p<0.0001$. Since ecoregion was a significant factor in lake clarity, the paired t-test procedure was performed (Table 2). Ecoregion 50 showed highly significant and relatively large increases in clarity between both time periods, with estimated changes in the mean of about 0.54 and 0.27 m, respectively. Although no significant trend was found for Ecoregion 51 between the later two assessments, the estimated difference between MSS and E90 is 0.80 and highly significant ($p < 2.0 \times 10^{-16}$). Ecoregions 52 and 53 showed little change over time. The only statistically significant change was for 53 in the latter decade, with a relatively small estimated increase of about 0.12 m. The lack of significant trends in Ecoregion 52 is likely due to the small number and large variability of lakes in the region.

Lake type analysis

The possible association between lake clarity changes and hydrologic lake type was the next focus in the analysis. The average Secchi estimate for each satellite assessment was plotted versus time for each lake type (Fig. 6). Like the ecoregions, the lake types were significant in the repeated measures analysis, with a $p<0.001$. This allowed for testing the difference in Secchi estimates and plotting the averages for each of the different lake types (Table 3). Based on these results, there is an increasing trend in clarity based on hydrologic lake type. For seepage, drainage, and spring lakes the changes were significantly different from zero among all assessments, with the most notable increases for the seepage and spring lakes. The estimated increase from 1980 to 1990 for these lake types was >0.50 m. Between E90 and L90 the estimates were smaller but still highly significant. In addition, drained lakes showed a significant increase between E90 and L90.

Lake area analysis

Following the lake type analysis, the Secchi depth data were subset into area categories (Fig. 7). A paired t-test analysis was applied (Table 4) because the repeated measures analysis was significant ($p<0.0001$) when these area categories were treated as factors, and no interaction between time and lake area was apparent because the plot lines do not cross one another. Note that all tests were significant in the lake area categories, which show similar trends as well as similar estimated increases in clarity between decades. The mean clarity increased by more than an estimated 0.5 m in all cases between the MSS and E90 estimates. Between E90 and L90, estimated increase ranged between 0.144 and 0.266 m. It is also interesting to note that when the lakes are categorized in this manner, on average the smallest lakes are the clearest while the largest lakes have the lowest clarity (Fig. 7).

Field data analysis

Similar analysis was performed on the field data mentioned previously. While the full results are not described in detail here, in general they agreed with the satellite data analysis. Increasing trends were found at the statewide level, as well as for certain ecoregions and hydrologic lake types.

Conclusions

This study found that significant trends exist in satellite-derived and field-measured lake water clarity measurements made over the past three decades. Most of these trends showed an increase in average lake transparency over time, while only a few showed a decrease. More balanced results between increasing and decreasing were expected, although the findings seem to agree with other researchers: in studies at the individual lake level, Bruhn and Sorrano (2005) found 22 increasing and only four decreasing trends in 71 lakes studied in Michigan; Kloiber *et al.* (2002a) found 34 increasing and 15 decreasing trends in the 482 TCMA lakes; and Webster (1998) observed five significant increases and four decreases in clarity of the 50 LTT lakes studied. In the current study, significant trends in average clarity existed in both satellite estimates and field measurements of Secchi depth on a statewide, U.S. EPA Ecoregion, WDNR hydrologic lake type, and lake area basis. Trends were also found within ecoregions

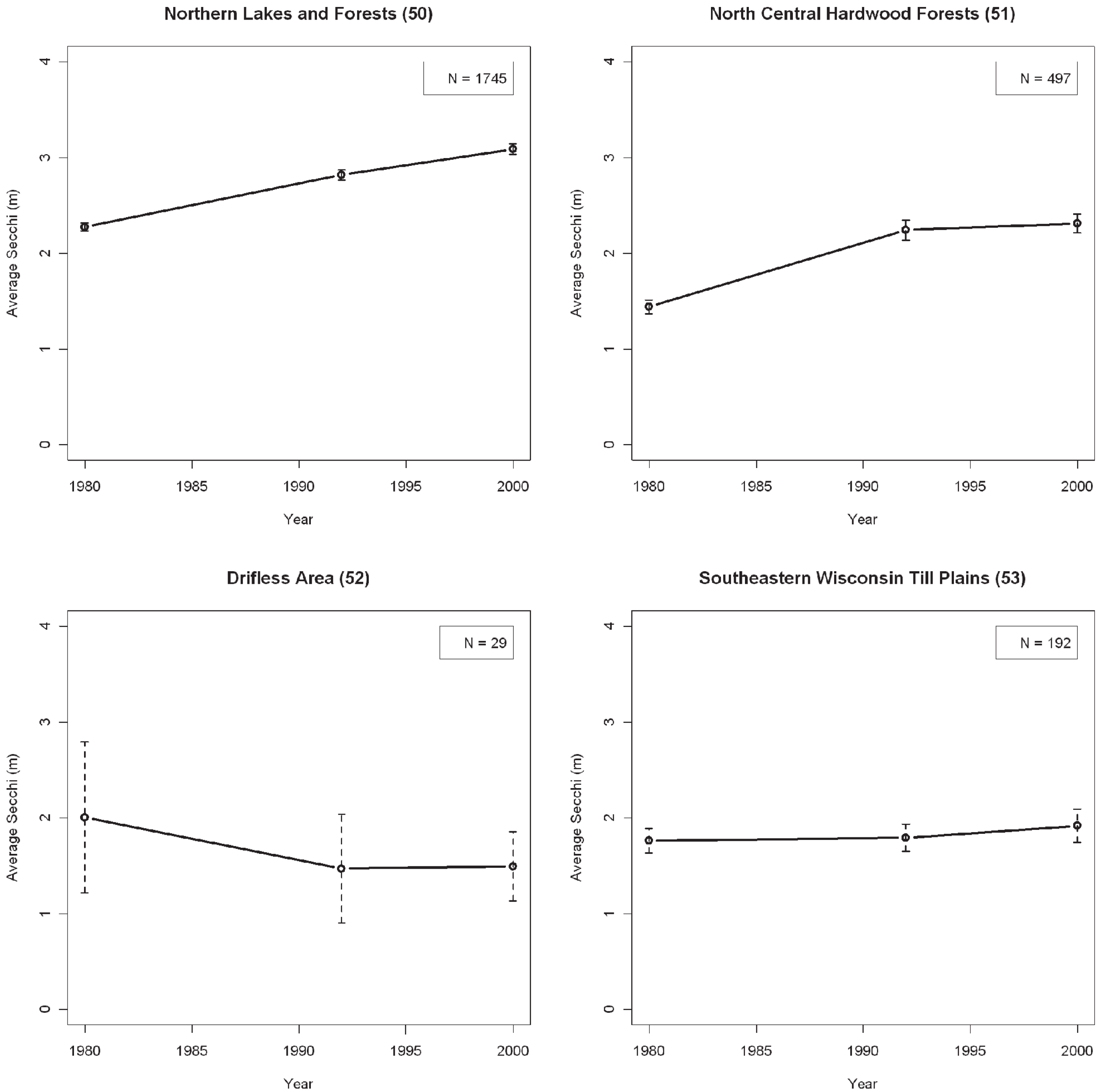

Figure 5.-Average clarity of sampled Wisconsin lakes by U.S. EPA Ecoregion over the past three decades based on satellite estimates of Secchi depth.

Table 2.-Paired t-test results by ecoregion. A column is included that indicates the number of lakes analyzed for each ecoregion.

Northern Lakes and Forests (50)				**North Central Hardwood Forests (51)**			
Decade	**Est. Diff**	**Lakes**	**pvalue**	**Decade**	**Est. Diff**	**Lakes**	**pvalue**
1980 to 1990	0.54456	1745	<2e-16	1980 to 1990	0.80256	497	<2e-16
1990 to 2000	0.26812	1745	<2e-16	1990 to 2000	0.06857	497	0.119
Driftless Area (52)				**Southeastern Wisconsin Till Plains (53)**			
Decade	**Est. Diff**	**Lakes**	**pvalue**	**Decade**	**Est. Diff**	**Lakes**	**pvalue**
1980 to 1990	-0.5359	29	0.162	1980 to 1990	0.02917	192	0.678
1990 to 2000	0.02414	29	0.9	1990 to 2000	0.12651	192	0.0462

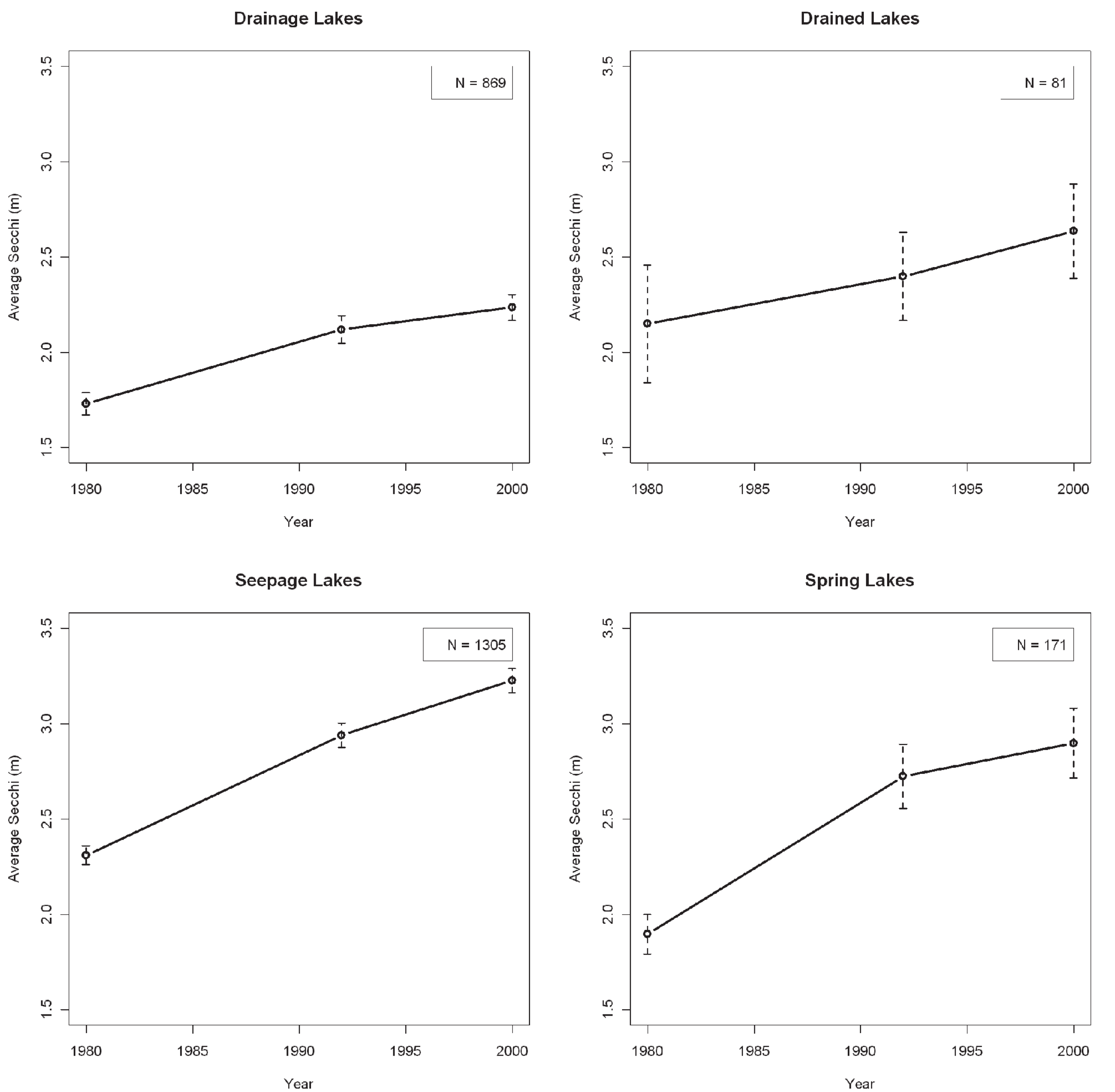

Figure 6.-Average clarity of sampled Wisconsin lakes by hydrologic lake type over the past three decades based on satellite estimates of Secchi depth.

Table 3.-Paired t-test results by lake type.

Drained				**Drainage**			
Decade	**Estimated Difference (m)**	**Lakes**	**p-value**	**Decade**	**Estimated Difference (m)**	**Lakes**	**p-value**
1980 to 1990	0.2489	81	0.104	1980 to 1990	0.38937	869	<2e-16
1990 to 2000	0.2378	81	0.0351	1990 to 2000	0.1163	869	6.56E-05

Seepage				**Spring**			
Decade	**Estimated Difference (m)**	**Lakes**	**p-value**	**Decade**	**Estimated Difference (m)**	**Lakes**	**p-value**
1980 to 1990	0.63037	1305	<2e-16	1980 to 1990	0.82772	171	2.81E-16
1990 to 2000	0.28691	1305	<2e-16	1990 to 2000	0.17421	171	0.00654

Table 4.-Paired t-test results by lake area category.

<10 ha				**10-50 ha**			
Decade	**Estimated Difference (m)**	**Lakes**	**pvalue**	**Decade**	**Estimated Difference (m)**	**Lakes**	**pvalue**
1980 to 1990	0.6979	275	2.57E-11	1980 to 1990	0.51892	1379	<2e-16
1990 to 2000	0.16467	275	0.0177	1990 to 2000	0.2661	1379	<2e-16

50-200 ha				**>200 ha**			
Decade	**Estimated Difference (m)**	**Lakes**	**pvalue**	**Decade**	**Estimated Difference (m)**	**Lakes**	**pvalue**
1980 to 1990	0.54289	565	<2e-16	1980 to 1990	0.51087	248	<2e-16
1990 to 2000	0.1443	565	0.000127	1990 to 2000	0.148	248	0.00308

on a lake type and lake area basis. Similarities were found between field and satellite trends in many of the analyzed categories, which were remarkable considering the difference in these sets of data.

Why these apparent increases have occurred over the past three decades is not within the scope of this study, but is an interesting question. Changes in land use patterns, shoreline setbacks and zoning changes, or stream and lakeshore buffering could have influenced the observed trends. On the other hand, these human impacts may not have significantly impacted lake water clarity. Instead, climactic or atmospheric conditions during the past three decades causing a change in phytoplankton (photosynthetic algae) density or the concentration of dissolved and suspended materials could be responsible for the observed changes in lake clarity. This question is one that certainly deserves further exploration.

This study shows that estimating lake water clarity using Landat imagery on a statewide basis is an effective tool for trend analysis on a rather small time scale. While annual and even daily variation in Secchi depth for any given lake can

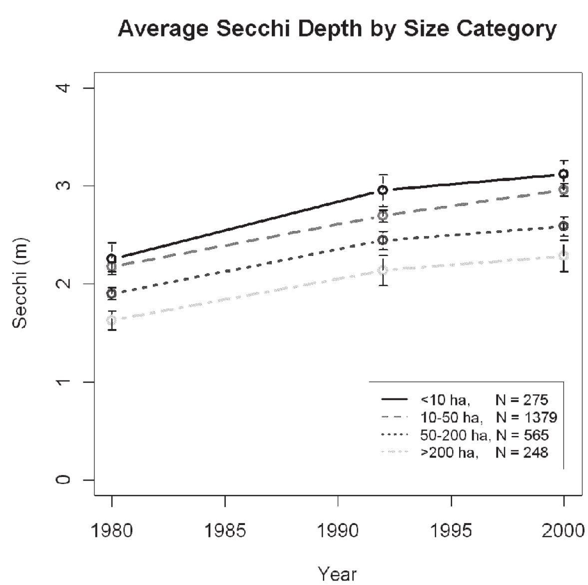

Figure 7.-Average clarity of sampled Wisconsin lakes by area category over the past three decades based on satellite estimates of Secchi depth.

be quite large, the number of lakes in each satellite assessment makes this a viable effort. Using satellite imagery also provides a method to monitor those lakes that have not been visited in the field and the ability to focus on a particular set of lakes. It also suggests that improvements in technology are improving the effectiveness of satellite-based monitoring efforts.

The comparison of Landsat-derived estimates and field measurements demonstrates the importance of both methods for lake clarity measurement. While they both seem to tell the same story of average clarity on a statewide basis and for certain ecoregions and lake types, the satellite estimates provide information for thousands of lakes that could not be sampled *in situ*. Conversely, the field data provide better temporal resolution with many more measurements per year, but for a greatly reduced set of lakes.

These results could aid in lake and watershed management and general public awareness of lake water quality throughout the state, as well as demonstrate the effectiveness and need for both satellite and field based monitoring of Wisconsin's lakes.

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