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## A 20-year Landsat water clarity census of Minnesota's 10,000 lakes

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## ABSTRACT

A 20-year comprehensive water clarity database assembled from Landsat imagery, primarily Thematic Mapper and Enhanced Thematic Mapper Plus, for Minnesota lakes larger than 8 ha in surface area contains data on more than 10,500 lakes at five-year intervals over the period 1985–2005. The reliability of the data was evaluated by examining the precision of repeated measurements on individual lakes within short time periods using data from adjacent overlapping Landsat paths and by comparing water clarity computed from Landsat data to field-collected Secchi depth data. The agreement between satellite data and field measurements of Secchi depth within Landsat paths was strong (average  $R^2$  of 0.83 and range 0.71–0.96). Relationships between late-summer Landsat and field-measured Secchi depth for the combined statewide data similarly were strong ( $r^2$  of 0.77–0.80 for individual time periods and  $r^2=0.78$  for the entire database). Lake clarity has strong geographic patterns in Minnesota; lakes in the south and southwest have low clarity, and lakes in the north and northeast tend to have the highest clarity. This pattern is evident at both the individual lake and the ecoregion level. Mean water clarity in the Northern Lakes and Forest and North Central Hardwood Forest ecoregions in central and northern Minnesota remained stable from 1985 to 2005 while decreasing water clarity trends were detected in the Western Corn Belt Plains and Northern Glaciated Plains ecoregions in southern Minnesota, where agriculture is the predominant land use. Mean water clarity at the statewide level also remained stable with an average around 2.25 m from 1985 to 2005. This assessment demonstrates that satellite imagery can provide an accurate method for obtaining comprehensive spatial and temporal coverage of key water quality characteristics that can be used to detect trends at different geographic scales.

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## 1. Introduction

Minnesota's numerous lakes are important recreational and aesthetic resources that add to the economic vitality and quality of life of the state. Protecting and monitoring lake water quality is a major concern for many state and local agencies and citizen groups. For effective lake management, it is essential to have long-term water quality information on a broad regional and spatial scale. Unfortunately only a small percentage of lakes in Minnesota are regularly monitored by conventional methods, and historical water quality data are sparse or lacking for most lakes. Although it is not possible to go backwards in time and collect historical water quality information using conventional field methods, Landsat images have been collected and archived regularly since the early 1970s, enabling extraction of some historical water quality information on lakes.

Landsat imagery has been used to estimate certain water quality characteristics of lakes (e.g., chlorophyll and water clarity, usually expressed in terms of Secchi depth) for over 30 years (e.g., Brown et al., 1977; Dekker & Peters, 1993; Lathrop, 1992; Lathrop et al., 1991;

Lillesand et al., 1983; Ritchie et al., 1990), but until recently such reports largely described exploratory efforts involving only one or a few lakes and/or short observation periods. One early exception is Martin et al. (1983) who used semi-automated procedures to assess the trophic status of around 3000 lakes in Wisconsin using Landsat Multispectral Scanner (MSS) imagery. Kloiber et al. (2002b) and Olmanson et al. (2001) described a practical and efficient procedure to use Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) imagery for routine, regional-scale assessments of lakes for water clarity, and Kloiber et al. (2002a) used this approach to measure spatial patterns and temporal trends of ~500 lakes within the seven-county metropolitan area of Minneapolis-St. Paul Minnesota. Olmanson et al. (2002) expanded this work to a statewide level, reporting the first census of Minnesota lakes for water clarity. Chipman et al. (2004) have conducted census-level analyses on lakes in Wisconsin using similar procedures for over 8000 lakes.

Using these methods we now have completed a 20-year, comprehensive water clarity database for lakes larger than ~8 ha (20 ac) in area. The database includes results for more than 10,500 lakes based on Landsat imagery at approximately five-year intervals for the time period 1985–2005 and includes almost 100,000 individual estimates of lake water clarity, which may be the largest database on lake clarity produced to date. The objectives of this paper are to describe how the

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lake water clarity database was assembled, assess its accuracy, and summarize initial analyses to evaluate spatial and temporal trends of lake water clarity in Minnesota over the past 20 years.

## 2. Methods

The long-term goal of our Landsat work has been to develop reliable and inexpensive techniques for synoptic measurements of key indicators of lake water quality that can be used by management agencies to complement water quality data obtained by ground-based sampling programs. One of the prime management issues for inland lakes is trophic state, and of the three most common indicators of trophic state – total phosphorus (TP), chlorophyll *a* (chl *a*), and Secchi disk transparency (commonly called Secchi depth, SD) – the latter two are amenable to measurement by satellite imagery. SD is the most commonly measured trophic-state indicator, and is strongly correlated with the responses in the blue and red bands of Landsat TM/ETM+ data (Kloiber et al., 2002b). Most of our work to date has involved

calibrating Landsat TM data with ground-based SD measurements and estimating  $SD_{Landsat}$  for all lakes in an image from the regression equation developed in the calibration step. The results then can be mapped as distributions of  $SD_{Landsat}$  in the lakes, and the estimated  $SD_{Landsat}$  can be converted to a trophic-state index based on transparency:  $TSI(SD_{Landsat}) = 60 - 14.41 \ln(SD_{Landsat})$  (Carlson, 1977).

It is important to recognize that other factors besides phytoplankton abundance (as measured by chlorophyll) may affect SD in lakes. Most important of these non-trophic-state factors are humic color and non-phytoplankton turbidity, including soil-derived clays and suspended sediment. For this reason, we report our results based on SD calibrations as satellite-estimated  $SD_{Landsat}$  or  $TSI(SD_{Landsat})$ , which identifies the value as an index based on transparency.

### 2.1. Satellite imagery and lake reference data

We used imagery from the Landsat 4 MSS, Landsat 5 TM, and Landsat 7 ETM+. The majority of the images were from Landsat 5 TM,

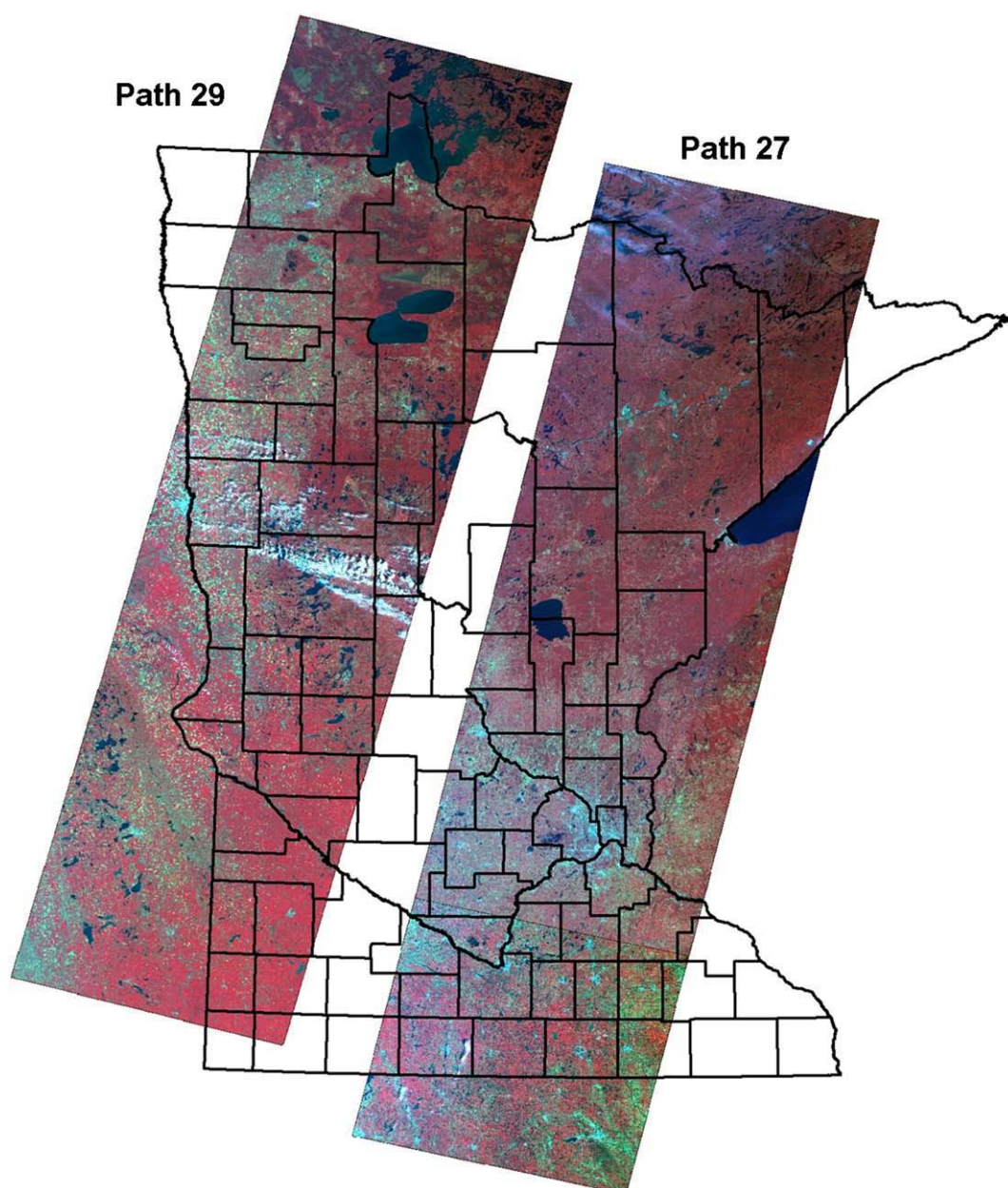


Fig. 1. Two Landsat paths of consecutive images used to assess water clarity.

which has been operating over the entire period. One Landsat 4 MSS image was used in the 1985 assessment because a clear TM image was not available for path 27 in this time period. Several Landsat 7 ETM+ images were used for 2000 assessment, and some Landsat 7 ETM+ with the scan line corrector off (SLC off) were used for the 2005 assessment. We found that Landsat 7 ETM+ (SLC off) imagery worked as well for water clarity assessment as earlier (intact) ETM+ imagery because only a representative sample of pixels is needed from each lake and the missing data generally did not affect the results.

To create the database we targeted clear paths of consecutive Landsat images from a late-summer index period (July 15–September 15, with a preference for August). This period was found to be the best index period for remote sensing of water clarity in Minnesota (Stadelmann et al., 2001). There are two advantages to using images from this index period: (1) short-term variability in lake water clarity is at a seasonal minimum, and (2) most lakes have their minimum water clarity during this period. In addition, it is preferable to have images from near anniversary dates for change detection.

For water clarity assessments it is critical to use imagery without cloud cover or haze because clouds, cloud shadows, and haze affect spectral-radiometric responses and cause erroneous results. Unfortunately, clear paths (five consecutive rows from the same orbital path) of imagery for all of Minnesota are rare. Fig. 1 illustrates some typical imagery that was used for these assessments. Although these images are clear through most of the state, path 29 has cloud cover in the middle of the imagery, and path 27 has haze in the northern portion. Therefore, we targeted the best available imagery, avoiding areas with

clouds and haze (discussed further in Section 2.2). Lakes in areas with cloud cover or haze in one image were assessed using a clear image from a different time. For each time period (nominally 1985, 1990, 1995, 2000 and 2005), 2–4 years (e.g., 2000 used imagery from 1999, 2000 and 2001) were needed to acquire clear imagery for the entire state (Table 1). Nonetheless, using paths of consecutive Landsat imagery with 2–5 images collected from the same path at the same time (instead of individual images) had several advantages, including decreased processing time (because several images could be processed simultaneously). The accuracy of the model also was improved because of the larger number of data points available for calibration and greater range of water clarity in calibration datasets with greater spatial coverage (Minnesota lakes tend to have lower clarity in the south and higher clarity in the north).

We acquired and processed more than 100 Landsat images from 37 dates (Table 1) and extracted water clarity information for more than 10,500 lakes in each time period. Because of the overlap (about 35%) of successive Landsat paths, the database includes almost 100,000 water clarity data points, with around 60% of the lakes having two or more data points for each time period. The number of times a lake was assessed in each of the time periods depended on the overlap area and number of images used in the assessment. The replicate data from adjacent paths provided useful information to evaluate the reliability of the Landsat results.

In-situ SD data for image calibration is readily available for most of Minnesota because of volunteer efforts of the Citizen Lake Monitoring Program (CLMP), combined with technical resources (training and

**Table 1**  
Landsat image data and calibration model statistics for Minnesota water clarity database

Image date	Path	Rows	Number Images	Sensor	Landsat	Estimated % clear	Days <sup>a</sup>	Model statistics				Number Lakes assessed
								N	SD range (m)	R <sup>2</sup>	SEE <sup>b</sup>	
8/13/1984	29	27–29	3	TM	5	75	8	17	0.9–5.5	0.91	0.144	3305
9/16/1984	27	26–30	5	MSS	4	95	7	70	0.4–7.0	0.80	0.325	4573
8/18/1985	27	29–30	2	TM	5	75	7	37	0.3–3.2	0.85	0.223	997
8/3/1986	29	26–28	3	TM	5	50	7	19	0.9–5.8	0.71	0.287	2685
8/21/1986	27	26–29	4	TM	5	75	7	105	0.3–7.0	0.79	0.324	4405
8/28/1986	28	26–28	3	TM	5	60	3	56	0.6–6.1	0.86	0.203	3646
8/30/1986	26	27	1	TM	5	85	9	22	0.9–7.3	0.94	0.159	1384
8/1/1987	26	29–30	2	TM	5	85	8	16	0.3–6.4	0.90	0.319	244
8/15/1987	28	28–29	2	TM	5	60	10	25	0.3–4.3	0.82	0.302	1237
8/7/1990	28	27–30	3	TM	5	85	3	211	0.15–9.5	0.77	0.322	4436
8/25/1990	26	29–30	2	TM	5	95	7	29	0.3–7.3	0.77	0.362	456
8/30/1990	29	26–29	4	TM	5	100	3	116	0.18–7.2	0.77	0.375	3784
8/19/1991	27	27	1	TM	5	75	7	36	0.4–8.4	0.88	0.279	1539
8/26/1991	28	29–30	2	TM	5	80	7	27	0.2–6.4	0.79	0.338	700
8/28/1991	26	27	1	TM	5	95	7	34	0.6–9.9	0.77	0.374	1462
9/4/1991	27	26–30	5	TM	5	85	3	169	0.15–9.1	0.79	0.372	4390
7/24/1994	29	28–29	2	TM	5	75	5	52	0.15–6.4	0.81	0.267	1534
7/29/1995	27	27–30	4	TM	5	90	3	212	0.15–8.2	0.83	0.297	4965
8/14/1995	27	26–28	3	TM	5	70	3	87	0.3–7.0	0.84	0.311	2433
8/21/1995	28	26–30	5	TM	5	100	3	278	0.15–8.8	0.83	0.265	5456
9/13/1995	29	26–28	3	TM	5	85	3	93	0.4–6.7	0.82	0.227	3310
8/25/1996	26	27–30	4	TM	5	90	10	30	0.15–8.2	0.86	0.406	1470
7/23/1999	28	26–30	5	ETM+	7	95	3	268	0.25–6.8	0.81	0.296	4773
9/11/1999	26	29–30	2	ETM+	7	100	7	21	0.3–6.4	0.92	0.317	487
8/10/2000	28	28	1	ETM+	7	70	3	89	0.15–7.0	0.89	0.249	972
9/5/2000	26	27	1	TM	5	60	7	16	0.8–5.5	0.96	0.141	900
9/12/2000	27	26–30	5	TM	5	95	3	227	0.15–14.6	0.82	0.370	4438
8/28/2001	29	26–28	3	TM	5	95	3	124	0.3–8.5	0.89	0.220	3768
8/13/2003	26	27	1	TM	5	50	10	21	0.5–7.3	0.81	0.381	1247
9/5/2003	27	26–29	4	TM	5	90	3	219	0.15–8.1	0.84	0.326	4569
8/5/2004	28	26–28	3	ETM+ SLC off	7	50	3	139	0.3–8.2	0.84	0.226	2671
8/21/2004	28	26–28	3	ETM+ SLC off	7	50	3	171	0.6–6.7	0.86	0.240	3694
9/16/2004	26	29–30	2	TM	5	100	7	13	0.3–5.5	0.90	0.318	425
7/30/2005	29	26–29	4	ETM+ SLC off	7	95	3	141	0.6–8.8	0.72	0.297	3760
8/7/2005	29	26–29	4	TM	5	80	3	127	0.3–8.2	0.81	0.302	3415
9/1/2005	28	27–30	4	TM	5	75	3	152	0.15–5.8	0.85	0.297	2983
9/2/2005	27	28–30	3	ETM+ SLC off	7	80	3	127	0.15–5.8	0.83	0.343	2450

<sup>a</sup>SD data used for calibration within no. of days of Landsat overpass.

<sup>b</sup>Standard Error of Estimate.



management) of the Minnesota Pollution Control Agency (MPCA). The CLMP program began in 1973 at the University of Minnesota's Limnological Research Center. Initially, fewer than 200 lakes were monitored each year, but starting in 1985 the number began to increase and reached ~1100 in 2005. Nonetheless, only about 10% of the lakes statewide (12% in the seven-county Twin Cities metropolitan area) were monitored for water clarity in 2005. In some parts of the state the fraction monitored is much lower. CLMP-monitored lakes tend to be recreational lakes that are larger (median size of 75 ha and average size of 333 ha), than Landsat-monitored lakes (median size of 18 ha and average size of 99 ha). It also should be noted that CLMP lakes are selected by interest of volunteers and not randomly. Therefore, the data cannot be reliably extrapolated to the larger population of Minnesota lakes, and such use may result in biased and misleading conclusions (Peterson et al., 1999).

To calibrate the imagery we used water clarity data (in-situ SD) usually collected within  $\pm 3$  days of the image acquisition date, but the window was increased to up to  $\pm 10$  days in several cases where data were sparse. Kloiber et al. (2002b) found that ground observations within one day of the satellite yielded the best calibrations, but the larger number of ground observations with the longer time window offsets some of the loss of correlation. Chipman et al. (2004) had similar findings and determined that model parameter values did not change significantly with a wider time window. We found that for images where in-situ data were sparse the larger number of ground observations with longer time window improved the calibration of the imagery. For example, for comparisons of models using in-situ data acquired within  $\pm 1$  and  $\pm 7$  days of an August 25, 1996 TM image, the number of ground observations increased from 12 to 26 with the longer time window and  $R^2$  values increased from 0.85 to 0.88, and the Standard Error of Estimate (SEE) decreased from 0.444 to 0.375. We conclude that measurements taken within a few days ( $\pm 3$  to 10 days) of image acquisition provide strong relationships. This is because water clarity (Secchi depth) usually does not exhibit large and rapid fluctuations in a given lake during the relatively stable late-summer index period (although there are strong seasonal patterns in clarity) (Stadelmann et al., 2001). For a few images where data were too sparse (less than 15 data points) or not well distributed throughout the range of typical water clarity conditions, supplemental data were acquired from water clarity measurements extracted from the overlap area of adjacent Landsat images (see Olmanson et al., 2002 for more information on this method). The number of SD measurements available for calibration ranged from 13–16 in the Arrowhead and Driftless areas in the northeast and southeast, respectively, to 278

through the middle of the state in Landsat path 28. The average number of measurements used for image calibration was 97. The calibration data generally had a wide range of SD values (Table 1).

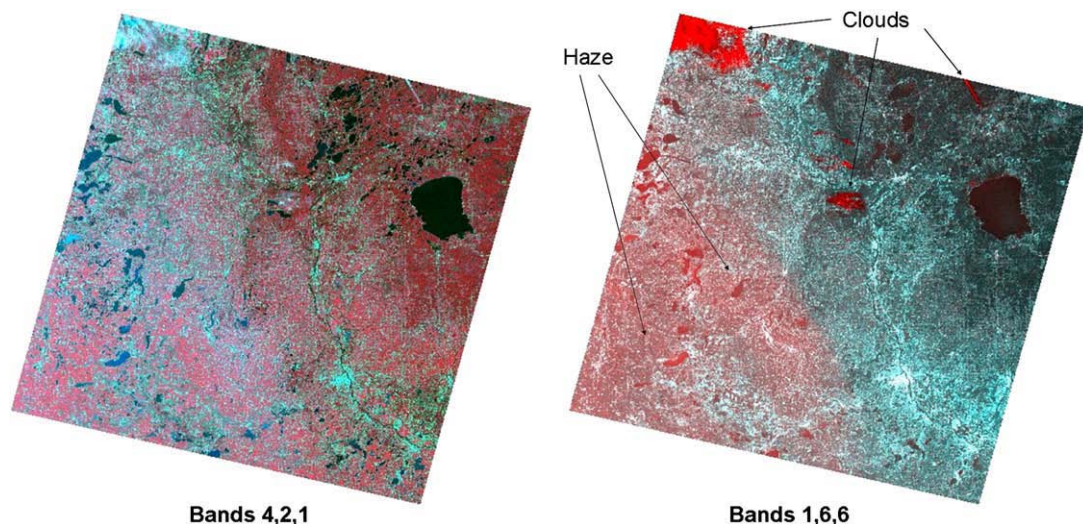
Field-collected SD data from the CLMP program also were used to validate the accuracy of Landsat water clarity database (discussed in Section 2.3). The average water clarity for each field data collection point and each lake polygon (that had field data) was calculated from late-summer (July 15 through September 15) CLMP SD data for each of the time periods.

## 2.2. Image preprocessing and classification

The image classification procedures used for this paper are documented by Olmanson et al. (2001), and the rationale for the procedures was described by Kloiber et al. (2002b). Some modifications were made as appropriate when experience and advances in software and computer hardware enabled simpler or improved image processing procedures. We used Leica Geosystems ERDAS Imagine and ESRI ArcGIS for image processing. Acquiring a representative sample from the image for each lake was a primary objective, and image samples generally were near the center of a lake, where reflectance from aquatic vegetation, the shoreline, or the lake bottom did not affect the spectral-radiometric response.

Initial preprocessing included image rectification using road intersections from a Minnesota Department of Transportation highway GIS data layer as ground control points (GCPs). We used ~40 well distributed GCPs, with a positional accuracy (RMSE) on the order of  $\pm 0.25$  pixels, or 7.5 m. The next step, if necessary, was to combine consecutive images from the same orbital path and date into one uniform image. We clipped areas covered with clouds from this image and checked for haze by visually inspecting the image using the (RGB) band combination 1,6,6 (TM1 (Blue), TM6 (Thermal), TM6 (Thermal)). Fig. 2 illustrates a Landsat TM image using the (RGB) band combination 4,2,1 typically used to highlight green vegetation and (RGB) band combination 1,6,6 used to highlight haze as a red color. Areas with high levels of haze were clipped. Because each image (path) was calibrated individually with field data, we did not perform atmospheric correction or normalization of the image brightness data.

Once image preprocessing was complete, a "water-only" image was produced by performing an unsupervised classification method based on ISODATA clustering. Because water features have different spectral characteristics from terrestrial features, water pixels were grouped into one or more distinct classes that could be easily identified. We then masked out terrestrial features to create a water-only image, performed



**Fig. 2.** Examples of Landsat TM band combinations 4,2,1 (RGB) typically used to highlight green vegetation and 1,6,6 which can be used highlight haze and cloud cover (Path 28/Row 28, August 8, 2000).

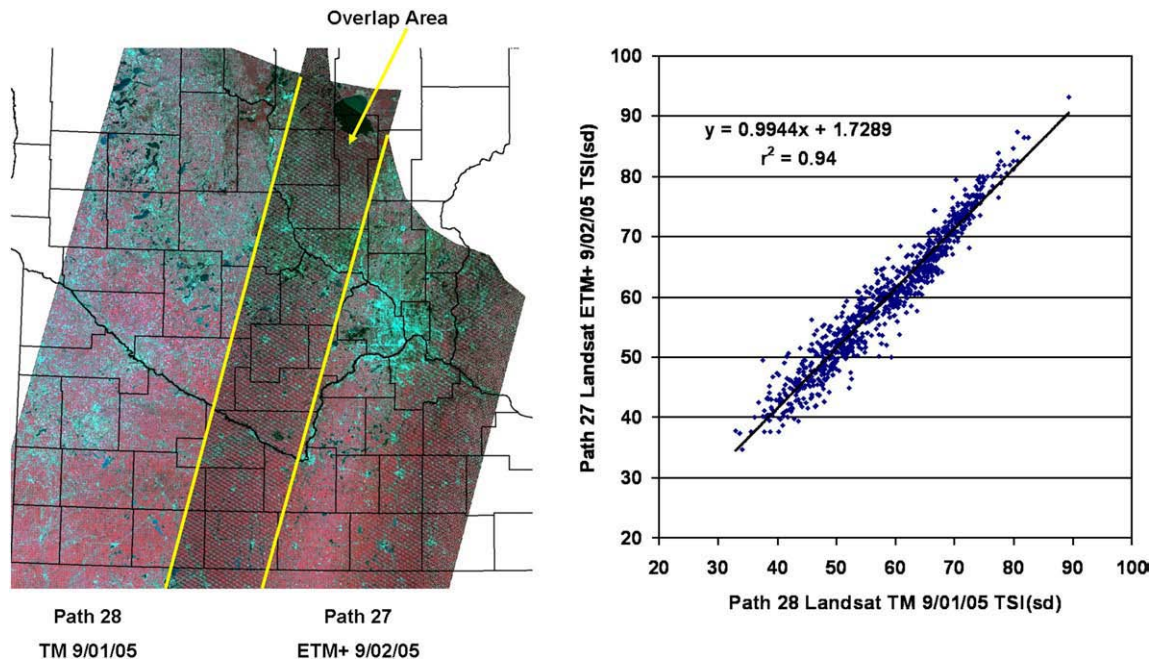


Fig. 3. Water clarity assessment comparison for Landsat TM vs. ETM+ SLC off data for 925 lakes in the overlap area of paths 27 and 28.

an unsupervised classification on this image, and generated spectral signatures of each class. We used these signatures, along with the location where the pixels occur, to differentiate classes containing open water and shallow water (where sediment and/or macrophytes affect spectral response). These areas tend to have high spatial variability compared to open-water portions of the lake. Based on this analysis, we removed the affected pixels. Next, the spectral-radiometric data from the “open-water” image were obtained to develop relationships with

measured SD. For these assessments, we used a lake polygon layer (Olmanson et al., 2001) to help automate the process. The polygon layer used for this purpose has 12,049 polygons delineating lakes or lake basins. Lakes with multiple basins were split into separate polygons. The polygon layer was constructed to include all Minnesota lakes and open-water wetlands 8 ha and larger. We used the signature editor in ERDAS Imagine to extract spectral data from the image for all lakes in the image.

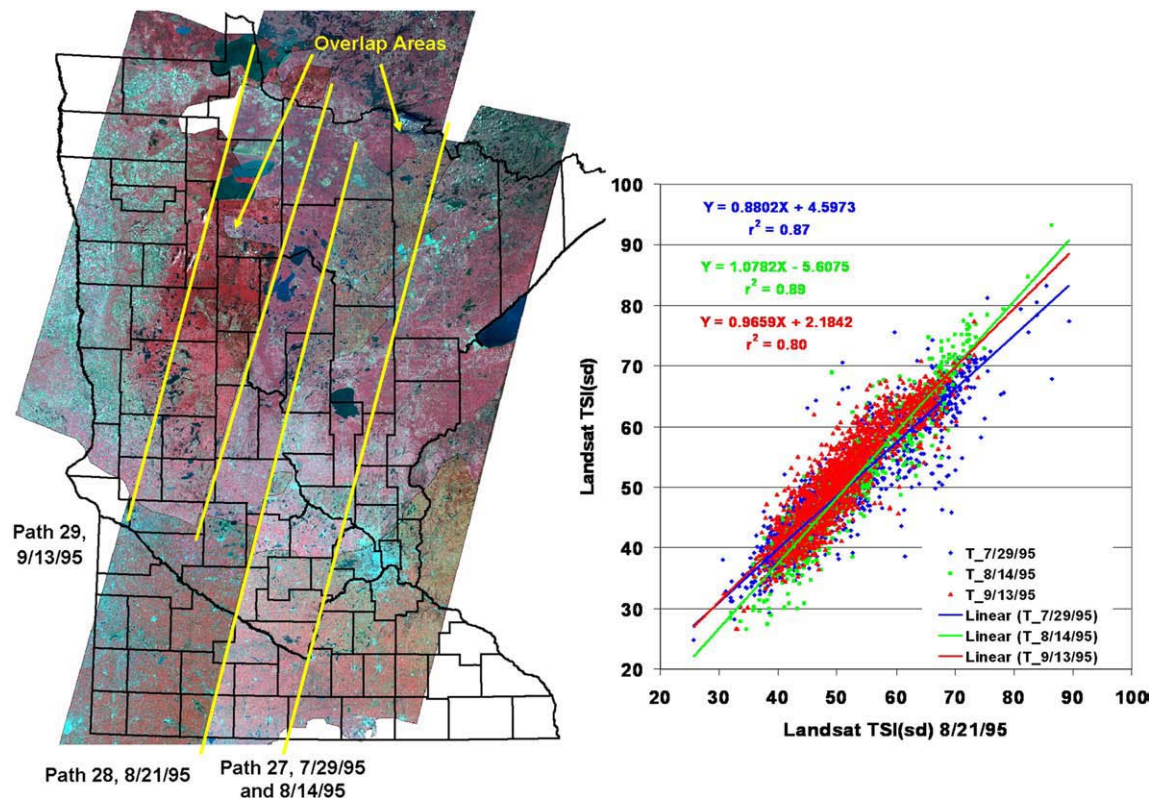


Fig. 4. Water clarity assessment comparison in the overlap areas of paths 27–29 for 1995 Landsat images.



Using log-transformed SD data as the dependent variable and TM band 1 and the TM1:TM3 ratio as independent variables, we performed least-squares multiple regression using the general form:

$$\ln(\text{SD}) = a(\text{TM1}/\text{TM3}) + b(\text{TM1}) + c$$

where  $a$ ,  $b$  and  $c$  are coefficients fit to the calibration data by the regression analysis,  $\ln(\text{SD})$  is the natural logarithm of Secchi depth for a given lake, and TM1 and TM3 are the Landsat brightness values for the selected lake pixels in the blue and red bands, respectively. Kloiher

et al. (2002b) found that this band combination was a dependable predictor of SD.

The model developed for each path of Landsat images was applied to brightness values (digital numbers) for the sample of pixels from each lake to calculate water clarity ( $\text{SD}_{\text{Landsat}}$ ). The number of lakes assessed per image (path of consecutive images from same date) ranged from 244 to 4965 with an average of 2675 lakes. To create maps the computed  $\text{SD}_{\text{Landsat}}$  data were linked to the lake polygon layer. The lake-level polygon method has an advantage over pixel-

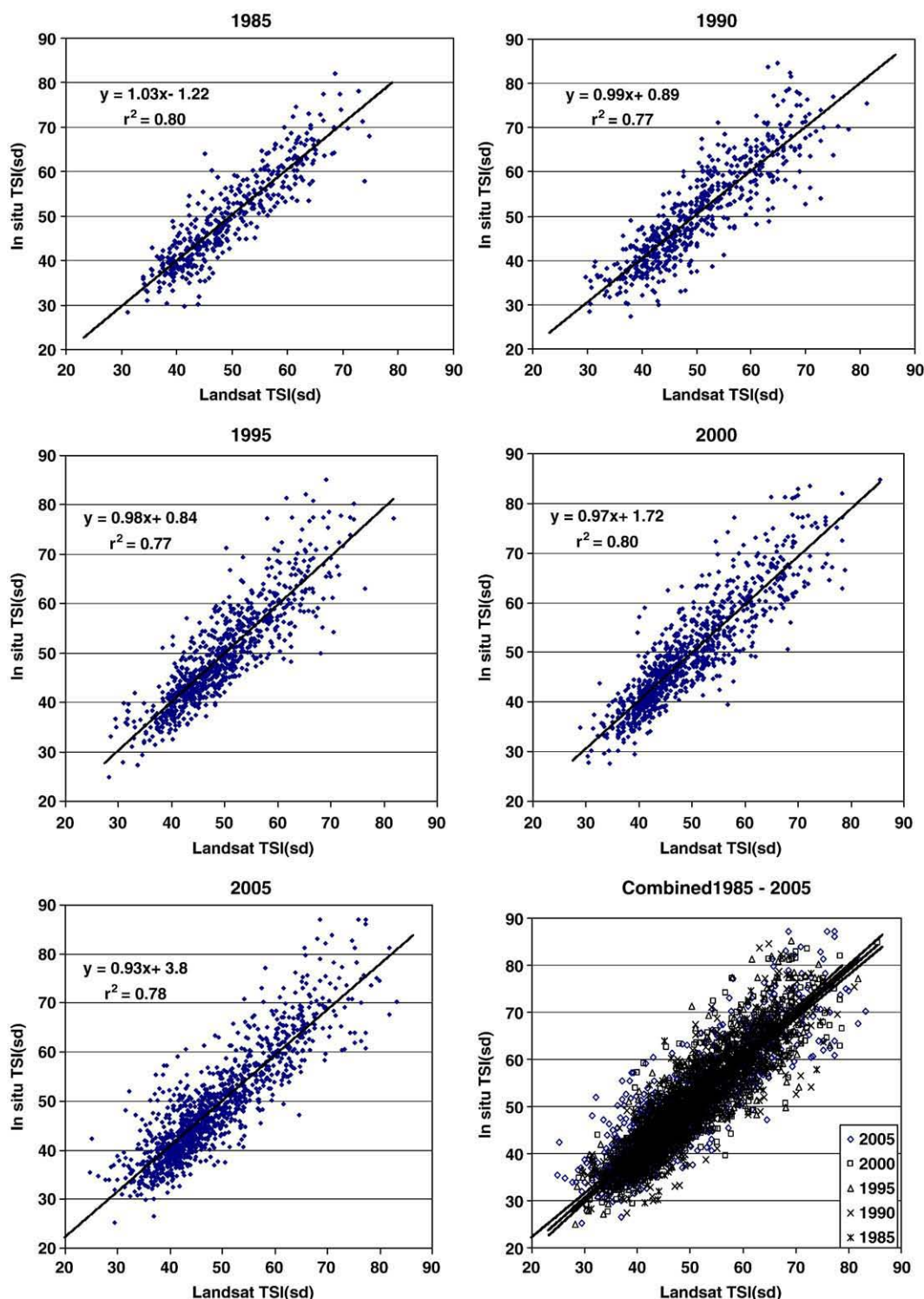


Fig. 5. Scatter plots of Landsat TSI(SD) vs. In-situ late-summer lake polygon mean TSI(SD) for each time period.

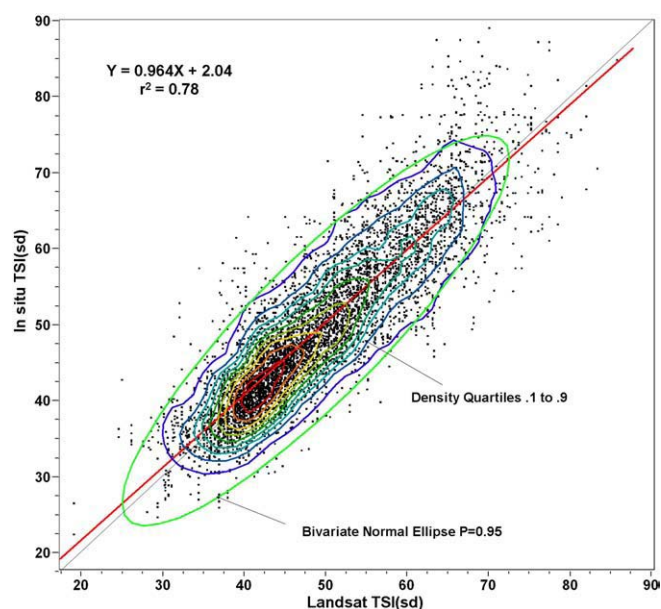


Fig. 6. Scatter plot of Landsat TSI(SD) vs. In-situ late-summer mean TSI(SD) for 6216 lake points.

level maps because by generating a single clarity value for each lake the data can be easily included in a water clarity database and used in other analyses. The final image processing step was to edit the maps to remove lakes with faulty results due to such conditions as haze, small clouds, or cloud shadows that were not clipped. This was accomplished using the RGB 1,6,6 band combination to highlight areas with haze which was used to target problem areas.

### 2.3. Water clarity database development

To create the water clarity database the final classifications for each path of Landsat imagery were combined and minimum, maximum and mean water clarity values were calculated for each lake in each time period. The number of lakes assessed for each time period ranged from 10,516 in ~2000 to ~11,241 in ~2005. Because the image processing procedure targeted clear imagery and open-water areas, some lakes were not assessed in a given time period. The main reason for some lakes not being assessed was pervasive presence of aquatic vegetation in wetlands and shallow lakes resulting in insufficient unaffected pixels for accurate water clarity assessment. Other reasons included severe phytoplankton blooms (floating mats of phytoplankton were masked off since their spectral characteristics are more similar to green vegetation than water), and clouds or haze.

## 3. Results and discussion

### 3.1. Evaluation of Landsat estimates of lake clarity

Production of the five semi-decadal lake clarity assessments required 109 Landsat images from 37 dates. Models developed for each path of imagery from the same date showed strong relationships between ground-based water clarity data (SD from the CLMP) and spectral-radiometric responses of the Landsat data. The SD range,  $R^2$ , SEE and the number of lakes for each model are listed in Table 1.  $R^2$  values for the regression relationships to establish the coefficients of the model equations ranged from 0.71 to 0.96 (average of 0.83) and SEE ranged from 0.141 to 0.406 (average 0.292). Given that ground-based measurements of SD are themselves subject to some imprecision, we consider these relationships to be very good. Similar strong relationships also were found by Kloiber et al. (2002a) and Chipman et al. (2004). In contrast, Nelson et al. (2003) reported low  $r^2$  values

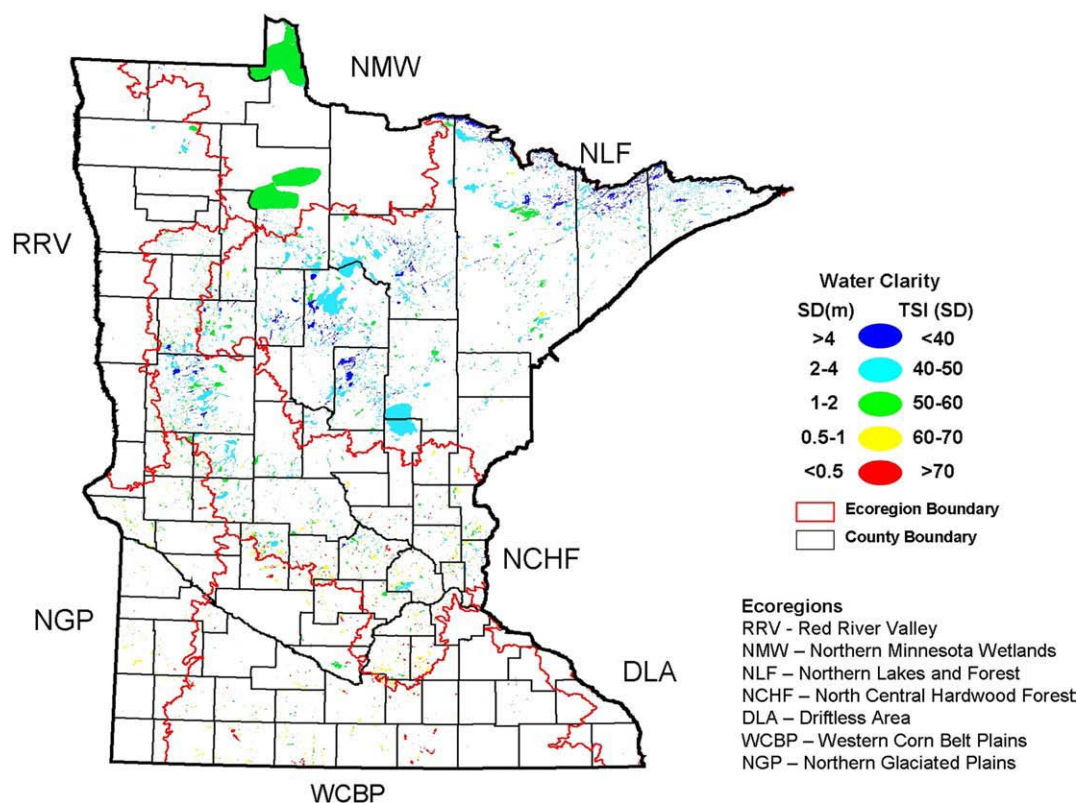


Fig. 7. Minnesota 2005 lake clarity with county and ecoregion boundaries.

(0.43) that they attributed to the distribution of SD values in their calibration dataset. Our study and Chipman et al. (2004) obtained strong relationships for images over a wide range of SD values some of which would be similar to those used in Nelson et al. (2003). Cloud cover was present in much of the imagery used by Nelson et al. (2003) and this likely affected the spectral-radiometric responses.

To evaluate the comparability of the different sensors and images from the different dates used to create the water clarity database we examined lake water clarity data from the overlap areas of adjacent Landsat images. First, we examined how well water clarity results from a September 1, 2005 Landsat 5 TM image compare with results from a September 2, 2005 Landsat 7 (SLC off) image. Because the images were within one day of each other we assumed that water clarity conditions would be very similar for both images and the water clarity assessments would be highly correlated; this was the case. Fig. 3 shows the overlap area of the images and a scatter plot with regression line of the Landsat-inferred TSI(SD<sub>Landsat</sub>) values for the overlap area of each image. The two images were calibrated separately, but because of the geographic overlap and closely spaced image acquisition dates, some calibration data from the overlap area were used to calibrate both images. The calibration fits were similar for the two images ( $R^2=0.85$  for September 1 and  $R^2=0.83$  for September 2), but the model coefficients (especially  $a$ ) were rather different. Nonetheless, agreement between the two sets of Landsat-inferred TSI(SD<sub>Landsat</sub>) values is very strong ( $r^2=0.94$ ), and the results parallel the 1:1 line, indicating that water clarity results from the two sensors and dates are highly comparable.

To evaluate the variability in SD<sub>Landsat</sub> results over the range of the late-summer index period, we examined the overlap areas of three late summer 1995 Landsat TM images (path 27, July 29, Path 27, August 14 and path 29, September 13) with an August 21 path 28 Landsat TM image (Fig. 4). Although the relationships are not as strong as those for images acquired within one day, they are still strong with  $r^2$  values of 0.87, 0.89 and 0.80. The range of image dates (July 29–September 13) covers most of the late-summer index period (July 15–September 15). The August 14 image is closest in time to the August 21 image, and regression line for the two sets of results is close to parallel with the 1:1 line indicating similar water clarity conditions. The regression line for the July 29 image is slightly skewed toward higher water clarity in the eutrophic lakes, which may reflect seasonal differences in the early portion of the late-summer window. The regression line for the September 13 image is also close to parallel

with the 1:1 line indicating a similar distribution of water clarity conditions.

The results in Fig. 4 suggest that restricting satellite-based lake clarity assessments to the late-summer index window limits, but does not eliminate minor seasonal differences. A further narrowing of the window (e.g., to August images only), might further decrease uncertainties caused by seasonal variations, but considering the frequency of cloud cover in Minnesota (Kloiber et al., 2002b) and that the current eight-day overpass cycle of Landsats 5 and 7 is not sustainable (both Landsats 5 and 7 have exceeded their expected life), this option does not appear to be practical. Considering the availability of other measures for most lakes are sparse and subject to some errors, we regard the accuracy of Landsat water clarity assessment using a two-month late-summer index period to be acceptable, especially since this method allows all lakes to be assessed in a uniform way.

The overall objective of this study was to create a comprehensive statewide water clarity database that represents water clarity conditions in five semi-decadal time periods. Therefore, it is important to assess how well the Landsat water clarity database, which consists of the average Landsat water clarity value calculated for each lake polygon (see Section 2.3), relates to field-measured water clarity data, which is the average late-summer CLMP SD data (see Section 2.1), for each time period. Regression analyses were conducted with Landsat-derived TSI (SD<sub>Landsat</sub>) as the dependent variable and average field-measured late-summer TSI(SD) as the independent variable for each time period and for a combined dataset containing 6216 field observations. The  $r^2$  values for the five time periods range from 0.77 to 0.80 (Fig. 5), and  $r^2=0.78$  for the combined dataset (Fig. 6), indicating a consistently strong relationship between Landsat-derived and field-measured late-summer SD. However, because small percentages (4.1–8.1%) of the CLMP SD data used to calculate the average late-summer CLMP SD also were used for image calibrations and could bias validation of the relationship, an independent subset was created. The independent subset was the average late-summer CLMP SD data for lakes not used to calibrate any of the images in each time period. Values of  $r^2$  from regression analyses for the independent subset were slightly lower than the full dataset for each time period and range from 0.74 to 0.79 with an average of 0.76, which still represents a consistently strong relationship between Landsat-derived and field-measured late-summer SD. This is especially true considering that some of the reduction in  $r^2$  may be due to data year disparity, since each time period consists of multiple years of data (see Section 2.1) and removal of the calibration lakes left data from years

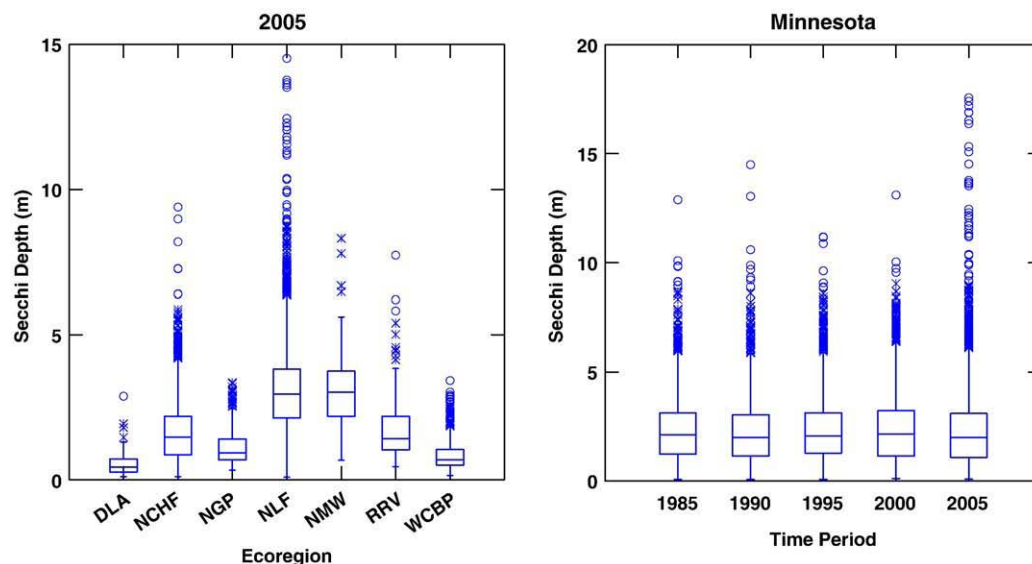


Fig. 8. Box plots of 2005 Minnesota lake clarity by ecoregion and statewide for 1985–2005.



without imagery to validate the water clarity of a lake. The regression lines closely match the 1:1 line for each time period and for the combined dataset indicating the Landsat-derived and field-measured SD results are comparable. Thus, Landsat images from the late-summer index period provide a reliable estimate of SD for the date of the imagery and the combined database provides a reasonable estimate of late-summer water clarity for each time period.

However, there is some lack of agreement for lakes with low water clarity ( $SD < 0.25$  m or  $TSI > 80$ ), for which Landsat  $SD_{Landsat}$  values generally were larger than field-measured values. This may reflect issues related to spatial variability of water clarity. Surface blooms of phytoplankton in eutrophic lakes are subject to concentration or dispersal by wind, which may result in variable concentrations of phytoplankton and SD across a lake (Dekker et al., 2002). The

procedure used to extract brightness data from Landsat images targeted the deepest and most central part of the lakes, which also may have the highest water clarity and may account for the differences from the field measurements for low clarity lakes.

### 3.2. Spatial and temporal analyses

Having evaluated the accuracy of the water clarity database and determined that we have a reasonable estimate of water clarity for the entire population of lakes in Minnesota for five semi-decadal time periods from 1985 to 2005, we can investigate spatial patterns and temporal trends of water clarity in Minnesota. To do that we analyzed spatial and temporal distributions of water clarity at the statewide, ecoregion and individual lake scales.

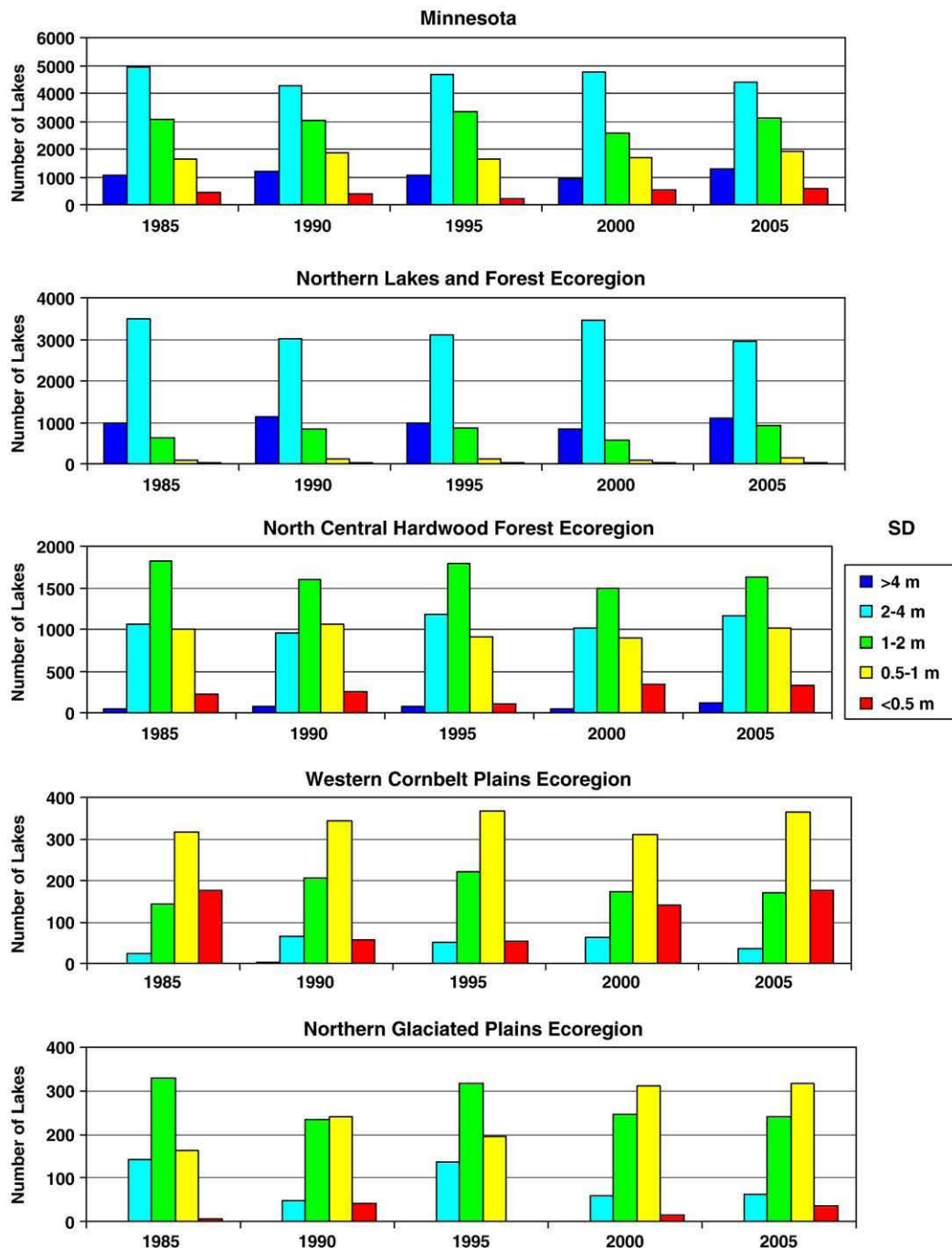


Fig. 9. Lake clarity distribution statewide and by ecoregion.

Water clarity in Minnesota tends to be low in the south and southwest and higher in the north and northeast (Fig. 7). At the statewide level water clarity has remained stable between 1985 and 2005 (Fig. 8) with mean water clarity of 2.25 m. One interesting discovery from the data is that many of the clearest lakes are abandoned iron ore mine pits that have filled with water. The increase in lakes with water clarity around 15 m in the 2005 time period (Fig. 8) needs further investigation, but could be due to changes in some mine operations.

### 3.2.1. Ecoregions

Lakes in Minnesota span seven natural ecoregions which differ in vegetation, soils, geology, climate, hydrology, and land use. We used the EPA Level III Ecoregions of Minnesota for analysis (Minnesota Land Management Information Center, 2006). That the distribution of water clarity differs among the ecoregions is apparent from the box plots for 2005 in Fig. 8. Water clarity distributions at the statewide level and for the four ecoregions that include most (96%) of Minnesota's lakes are shown in Fig. 9. The Northern Lakes and Forest Ecoregion (NLF), which has 46% of the state's lakes, has results concentrated in the higher water clarity classes and an average  $SD_{Landsat}$  of 3.09 m. The North Central Hardwood Forests Ecoregion (NCHF), which has 38% of the state's lakes, has a wide range of water clarity and an average  $SD_{Landsat}$  of 1.58 m. Lakes in the Western Corn Belt Plains Ecoregion (WCBP), which has 7% of the state's lakes, generally have lower water clarity (average  $SD_{Landsat}$  of 0.95 m). The Northern Glaciated Plains Ecoregion, with 6% of the lakes, also has low water clarity (average of 1.27 m).

Over the 1985–2005 period, average water clarity remained relatively stable in lakes of the NLF and NCHF ecoregions but declined

slightly in the WCBP, where the highest average clarity (1.07 m) occurred in 1990 and the lowest (0.85 m) occurred in 2005. There also appears to be a trend of declining water clarity in the NGP ecoregion where the highest average water clarity (1.50 m) occurred in 1985 and the lowest (1.12 m) in 2005.

### 3.2.2. Individual lakes

Water clarity is a good indicator of user perception of water quality in lakes (Heiskary & Walker, 1988) and usually reflects the amount of phytoplankton or sediment present. Although lakes in Minnesota generally are more eutrophic (and less clear) in the south and less eutrophic (and clearer) in the north, at the regional and sub-regional levels conditions are quite variable. Fig. 10 shows the quartile distribution of water clarity within each ecoregion. While there is some clustering of lakes within higher and lower water clarity quartiles, lakes from the opposite quartiles are distributed throughout the ecoregions and state. The range of water clarity conditions throughout the state and even within ecoregions thus in most cases is large. The wide range of water clarity likely reflects both natural characteristics (e.g., depth, area and watershed) and effects of anthropogenic characteristics (i.e., land-use and management practices).

### 3.2.3. Comparison with other states

The above results contrast to the findings by Peckham and Lillesand (2006) who analyzed Landsat-estimated water clarity for 2467 Wisconsin lakes and found increasing water clarity in Wisconsin lakes at the statewide level and in some ecoregions. At the statewide level they reported a significant increase in mean water clarity of

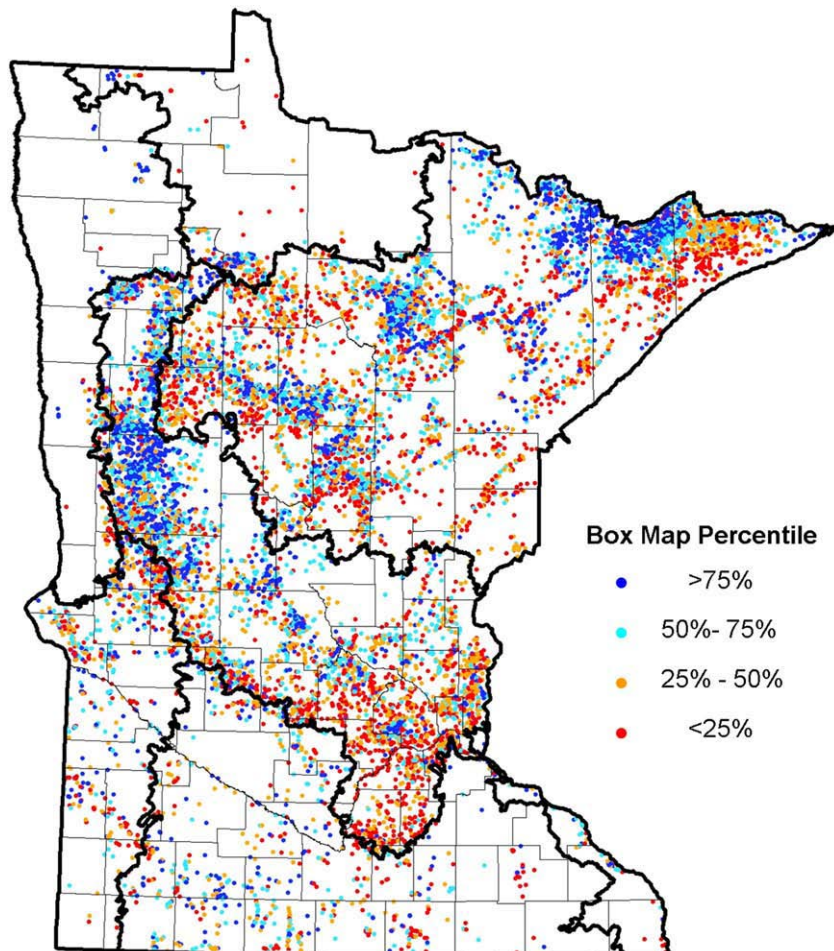


Fig. 10. Minnesota lake clarity 2005 quartile distribution within each ecoregion.

0.75 m from 1980 to 2000. The NLF ecoregion in Wisconsin had a mean water clarity increase of 0.81 m, and the NCHF ecoregion had an increase of 0.80 m.

Our results indicate that water clarity has been stable statewide in Minnesota and also within the NLF and NCHF ecoregions. It is not certain why there should be differences between the Minnesota and Wisconsin assessments, but different assessment designs could be a contributing factor. The methods we used are similar to the methods Peckham and Lillesand (2006) used for their 1990 and 2000 water clarity assessments, but their 1980 assessment was conducted using different methods and Landsat MSS imagery. It is uncertain whether the MSS assessment is entirely consistent with later TM-based assessments. Other differences between the two studies include the time frames of analysis – ten-year intervals (1980 to 2000) in Wisconsin vs. five-year intervals (1985 to 2005) in Minnesota, and the lakes assessed for temporal trends in Wisconsin were limited to those assessed in the MSS study (around 30% of the lakes in the later assessments).

#### 4. Conclusions

For effective environmental management, it is essential to have accurate long-term water quality information on a broad regional and spatial scale. Development and evaluation of a Minnesota statewide 20-year water clarity census of over 10,500 lakes has demonstrated that satellite imagery can provide an accurate method to obtain comprehensive spatial and temporal coverage of a key water quality characteristic. Although traditional monitoring programs are important, they largely rely on volunteers or agencies that target lakes of interest (i.e., are not randomly selected). Using data from such programs to extrapolate to larger regional assessments likely will lead to biased conclusions. However, by using the data from these programs to calibrate Landsat imagery, the entire population can be reliably assessed.

The Landsat water clarity database is being used in several research efforts where available field data were sparse. For example, Lindon et al. (2005) used it to target lakes in Cass and Crow Wing Counties that were large (>200 ha), lacked water quality data and were more eutrophic than typical for the area for additional monitoring. It was used in west central Minnesota for nutrient criteria research to target shallow lakes that represented a range of trophic status but lacked data (Heiskary & Lindon, 2005). The database was also used by Baker et al. (2004) to correlate water clarity to common loon populations. The comprehensive water clarity database can also be used in conjunction with morphometric, land-use and demographic data to analyze spatial patterns and temporal trends in lake clarity throughout the state and develop better understanding of the factors that affect these patterns and trends. Results of such analyses will aid local and state agencies in making informed decisions about development policy and improve the management of lake resources.

This study also demonstrates the significance of the Landsat program of continuous collection and archiving of moderate resolution imagery as a historical record of an important water quality variable. The current state of the Landsat program is unfortunate with both Landsats 5 and 7 operating past their expected life times and no replacement is expected for several years, which could result in a data gap. However, with recent technological advances, there also is great potential for an enhanced Landsat system that could improve monitoring of water resources. A new system with higher frequency of image acquisition, improved spectral bands, and improved atmospheric correction and radiometric calibration capabilities could enable the development of a universal equation that could minimize the need for calibration with field data. Even if these advances do not happen, there already is a massive 35-year archive of Landsat imagery available for regional assessments of water clarity.

Although assessment of water clarity is important, it is also important to make the results easily available to lake managers, government agencies and the public. The availability of such information is essential for a well-informed public and a prerequisite for effective environmental management. To make the data available we have created "LakeBrowser," a MapServer application, at <http://water.umn.edu/>, where data for individual lakes, counties, and ecoregions can be accessed.

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