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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.

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,

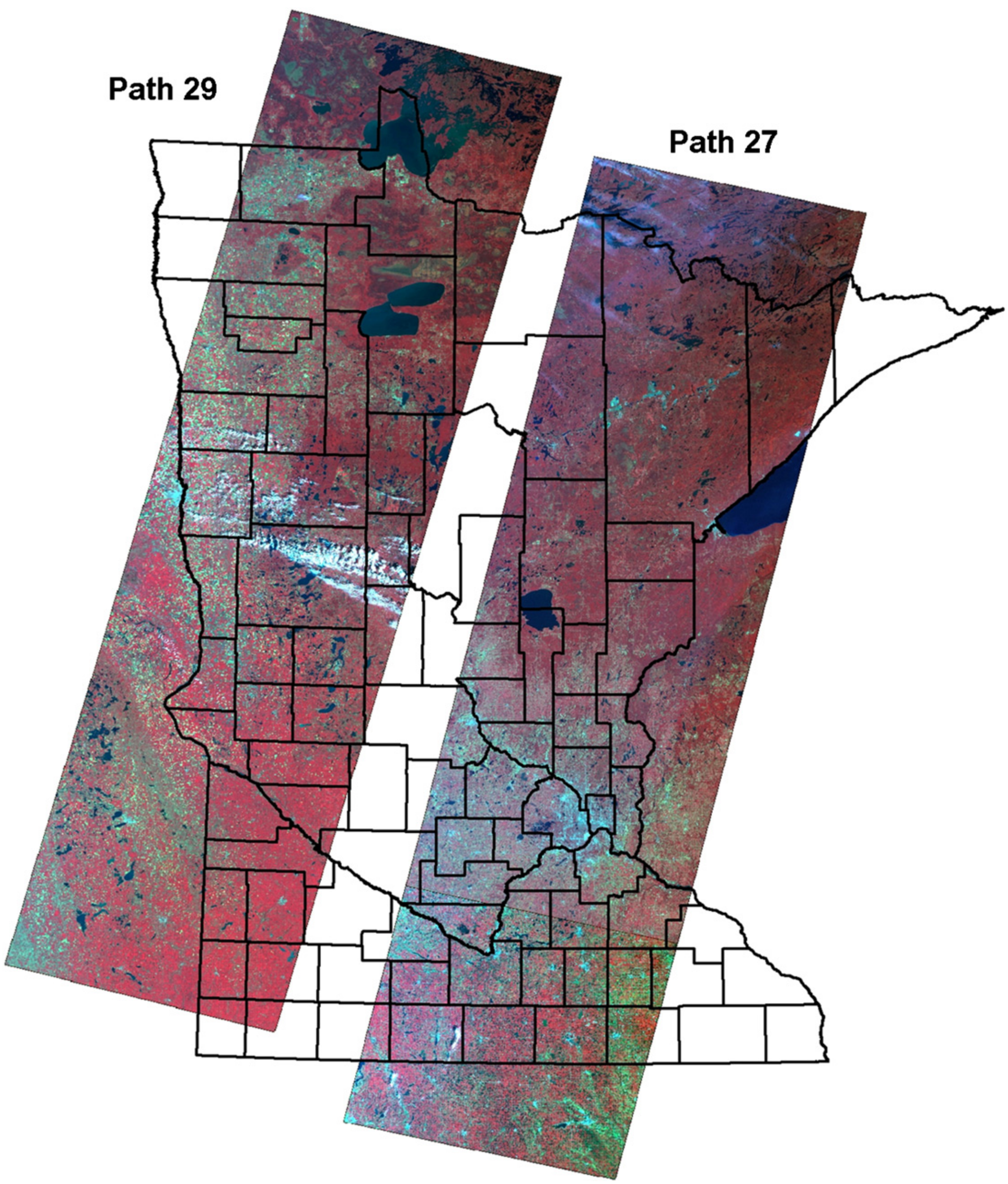

Fig. 1. Two Landsat paths of consecutive images used to assess water clarity.