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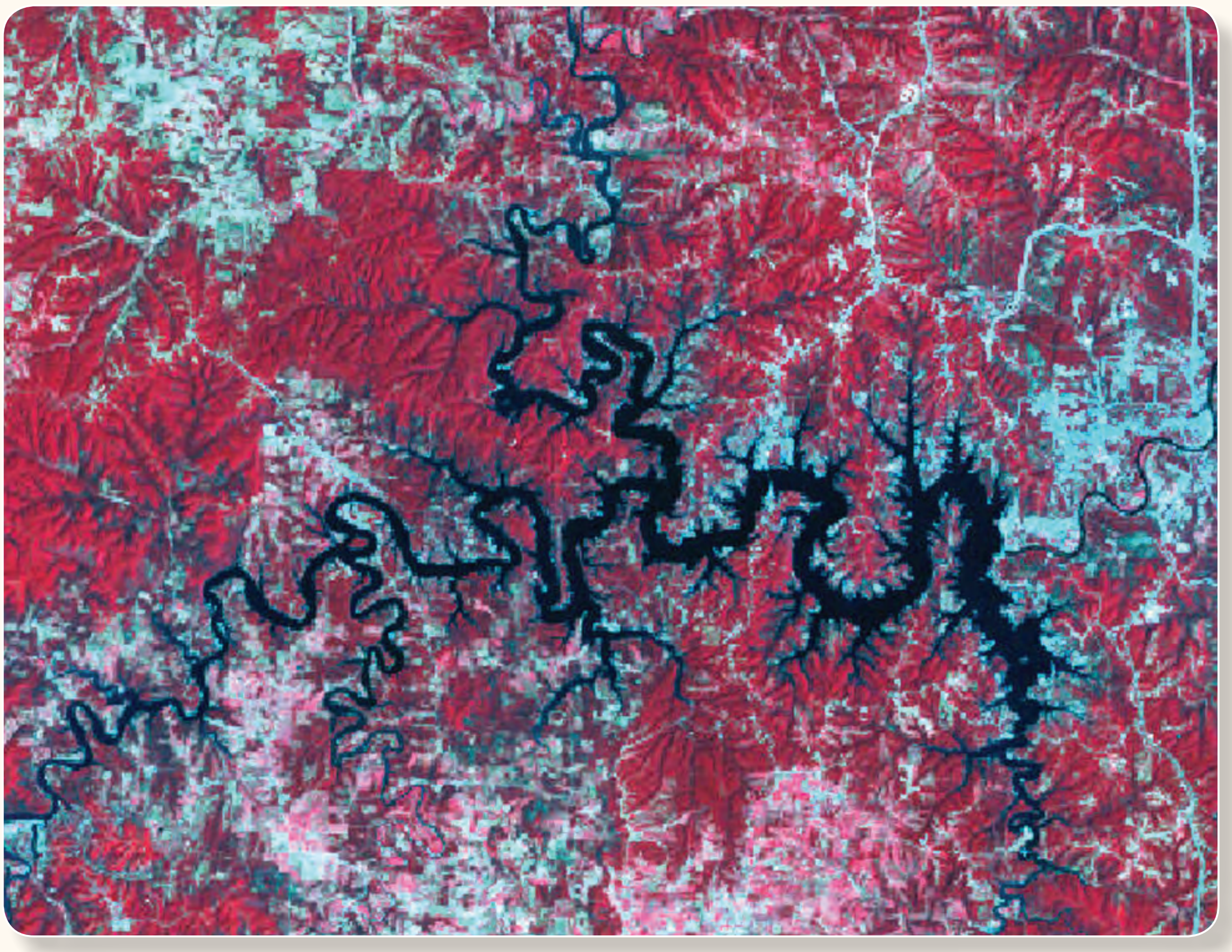
Table Rock Lake Water-Clarity Assessment Using Landsat Thematic Mapper Satellite Data



Scientific Investigations Report 2009–5162

U.S. Department of the Interior
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Cover illustration. Landsat satellite image from the Table Rock Lake area, southwestern Missouri and northwestern Arkansas.

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Conversion Factors, Abbreviations, and Datums

Inch/Pound to SI

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square hectometer (hm^2)	2.471	acre
square kilometer (km^2)	247.1	acre

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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Abstract

Water quality of Table Rock Lake in southwestern Missouri is assessed using Landsat Thematic Mapper satellite data. A pilot study uses multidate satellite image scenes in conjunction with physical measurements of secchi disk transparency collected by the Lakes of Missouri Volunteer Program to construct a regression model used to estimate water clarity. The natural log of secchi disk transparency is the dependent variable in the regression and the independent variables are Thematic Mapper band 1 (blue) reflectance and a ratio of the band 1 and band 3 (red) reflectance. The regression model can be used to reliably predict water clarity anywhere within the lake. A pixel-level lake map of predicted water clarity or computed trophic state can be produced from the model output. Information derived from this model can be used by water-resource managers to assess water quality and evaluate effects of changes in the watershed on water quality.

Introduction

Table Rock Lake is a primary water resource located in southwestern Missouri with tourism related activities within the watershed accounting for more than a billion dollars in revenue each year (Missouri Department of Natural Resources, 2005). Decreasing water clarity in Table Rock Lake has caused concern with water-resource managers and private watershed groups. The reservoir was listed in 2002, in accordance with section 303(d) of the Federal Clean Water Act, as having impaired water quality because of nutrient enrichment. Long-term monitoring of the reservoir by University of Missouri researchers documents an increase in nutrients and chlorophyll with a corresponding decrease in water clarity over the past 20 years (Jones and Perkins, 1999). Increases in nitrogen and phosphorus inputs to the reservoir have been attributed to point and nonpoint sources, with major contributions from wastewater treatment, urban storm water, and agricultural runoff (Missouri Department of Natural Resources, 2005). This report evaluates a remote sensing methodology for predicting water quality using satellite reflectance data and water clarity measured by secchi disk transparency.

Purpose and Scope

The purpose of this report is to describe the methods and techniques used to develop a predictive model for estimating Table Rock Lake water quality based on satellite observations combined with field-data collection. The techniques described can be used to calculate estimates of water clarity from secchi disk transparency or a lake trophic state index derived from these measurements. Model outputs can be applied to the entire water body enabling water-resource managers to identify areas of potential concern.

Background

Eutrophication is the process of organic enrichment of lake water with respect to time (Wetzel, 2001). It is a natural aging process experienced by all lakes. Nutrient supplies primarily are derived from atmospheric and terrestrial sources, the latter being more significant with runoff being the principal source of nutrients in lakes. Increased levels of nutrients result in increased biological productivity, which can have harmful effects to water supplies.

Trophic state is a measure of a lake's productivity and is commonly used to assess water quality. Eutrophy is a state of high nutrient enrichment usually associated with declining water quality. The Carlson trophic state index (1977) is a numeric index commonly used for trophic state assessment of lakes, and is based on the relation between algal biomass and secchi disk transparency depth. The index ranges from 0 to 100 with each increase of 10 units on the trophic state index equivalent to a doubling of algal biomass and can be computed from chlorophyll a concentration, total phosphorus concentration, or secchi disk transparency values.

Remote sensing methods can be effective for water-quality monitoring and water-resource assessments (Ritchie and others, 2003). Advantages include multispectral band capabilities, repetitive coverage, a historical archive dating from the early 1970s, and the ability to cover large geographic areas with a single image scene. Early studies by Boland

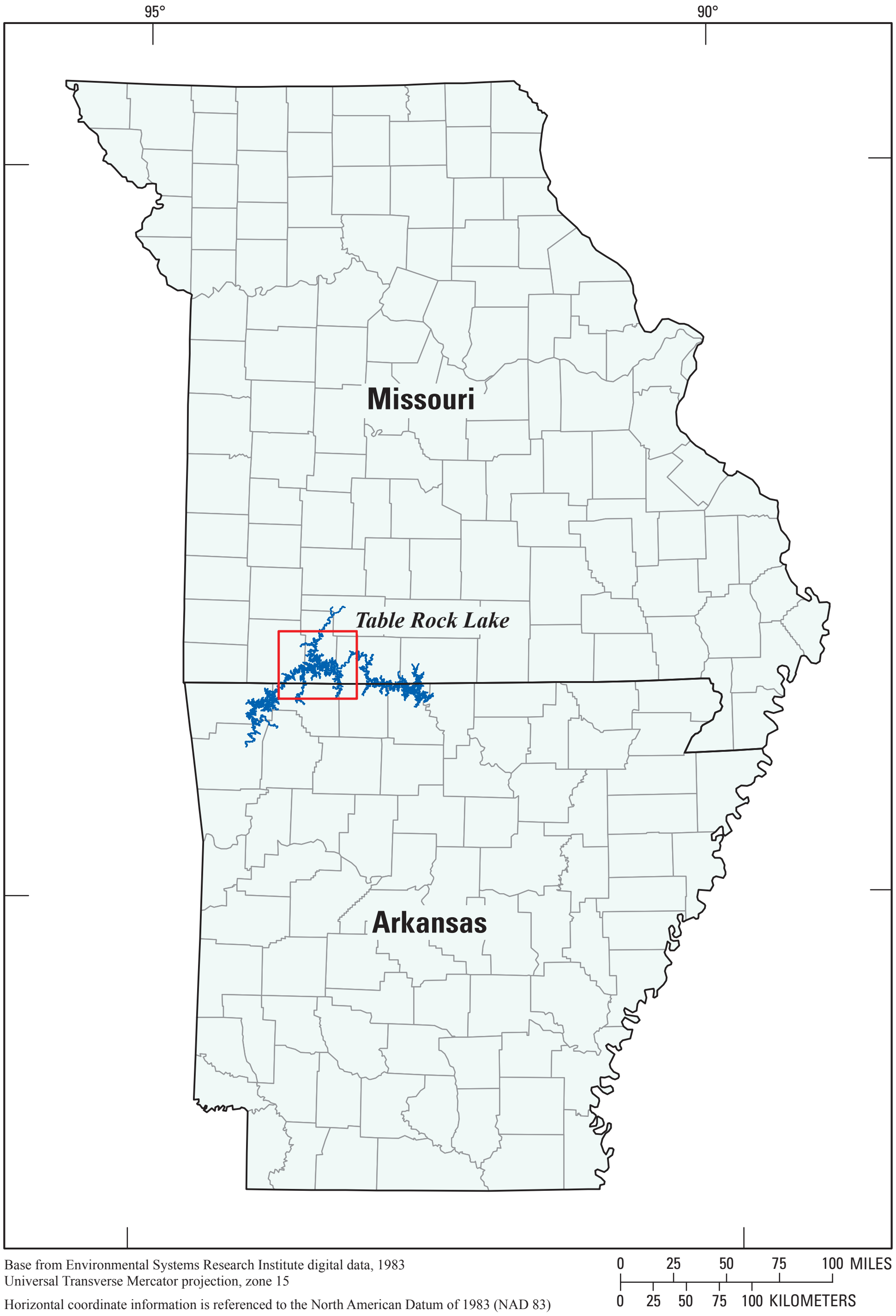

Figure 1. Study area location.

(1976) and Wezernak and others (1976) utilized complex multivariate statistical techniques for computation of a trophic state index based on reflectance data obtained from Landsat Multispectral Scanner (MSS) data. Their studies found that secchi disk transparency and chlorophyll a concentration could be used in conjunction with Landsat mean reflectance values to accurately predict lake trophic state. Increased spatial and radiometric resolution of the Thematic Mapper (TM) sensor provided improved accuracy of water-quality models derived from satellite observations (Lathrop and Lillesand, 1986). The empirical relation between secchi disk depth measurements and Landsat TM reflectance has been used to predict region-wide lake water clarity (Chipman and others, 2004; Fuller and others, 2004). Previous studies of Ozark lakes have shown that Landsat MSS and TM data can be effective in predicting water quality based on regression models developed from chlorophyll a and secchi disk depth data (Krizanich, 1986; Allee and Johnson, 1999).

Study Area

Table Rock Lake, located in southwestern Missouri and northwestern Arkansas (fig. 1), is a U.S. Army Corps of Engineers reservoir completed in 1959 to provide flood control and power generation in the Upper White River Basin. The reservoir has a surface area of 43,100 acres with 745 miles of shoreline. It is one of four reservoirs impounding the White River with Beaver Lake immediately upstream and Lake Taneycomo and Bull Shoals Lake downstream. Table Rock Lake is located within the Springfield Plateau of the Ozark Dome, an area dominated by relatively flat-lying carbonate rocks. Land cover of the area is predominantly forest and pasture, but increasing urban development within the watershed has the potential to affect water quality (Thorpe and others, 2005).

Methods

Two Landsat 5 Thematic Mapper scenes (8/22/2003, 8/11/2005) were purchased from the Earth Resources Observation and Science (EROS) center in Sioux Falls, South Dakota. Landsat images were formatted as GeoTIFF and projected to Universal Transverse Mercator, North American Datum 1983, Zone 15. Both scenes are from Worldwide Reference System 2 path 25, row 35 and were selected based on minimal scene cloud cover and closeness of the scene date to field data collection. The scenes were processed by EROS to level 1P specifications, which include radiometric and geometric correction as well as the use of 25 ground-control points to improve geometric accuracy.

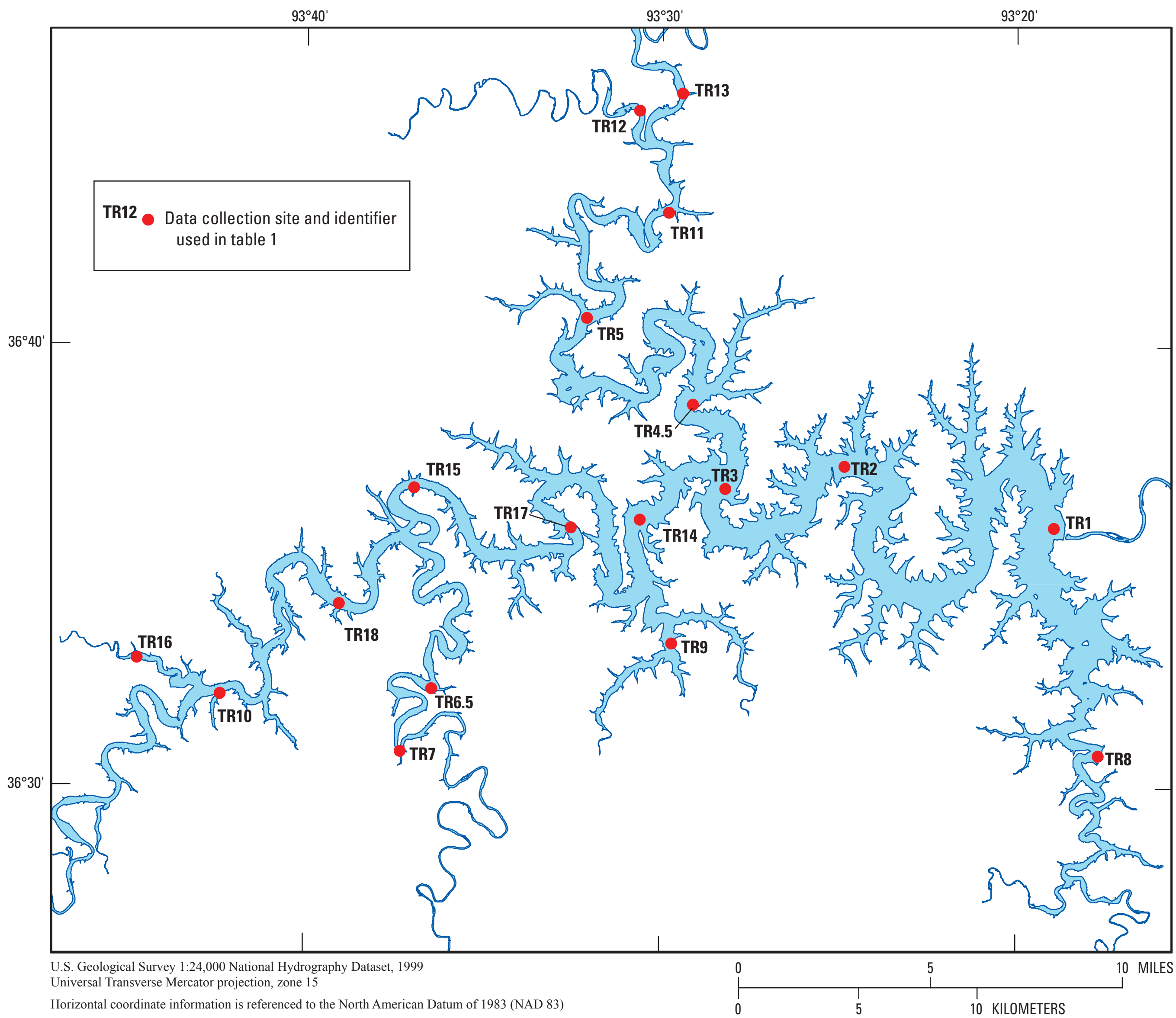

Figure 2. Table Rock Lake sample locations. Red dots indicate Lakes of Missouri Volunteer Program data collection sites.

Table 1. Mean Landsat brightness values for Table Rock Lake sample sites 2003 and 2005.

[TM1 and TM3, Thematic Mapper bands]

Data collection site (fig. 2)	Year	Pixel count	TM1	TM3	TM1/TM3	Secchi (meters)	ln Secchi (meters)
TR1	2003	9	80	24	3.3	4.9	1.6
TR2	2003	9	80	23	3.4	4.0	1.4
TR3	2003	9	78	22	3.5	3.9	1.4
TR4.5	2003	9	78	23	3.4	2.7	1.0
TR5	2003	9	79	24	3.3	1.9	0.6
TR6.5	2003	9	82	27	3.1	1.5	0.4
TR8	2003	9	75	21	3.6	3.5	1.3
TR9	2003	9	82	27	3.1	2.4	0.9
TR10	2003	9	83	26	3.2	2.4	0.9
TR11	2003	9	79	26	3.1	1.1	0.1
TR12	2003	9	80	28	2.9	0.8	-0.3
TR13	2003	9	80	27	3.0	0.9	-0.1
TR14	2003	9	77	22	3.5	3.8	1.3
TR15	2003	9	78	24	3.3	3.2	1.2
TR16	2003	9	80	28	2.9	1.4	0.3
TR17	2003	9	79	23	3.4	3.0	1.1
TR18	2003	9	86	28	3.1	3.0	1.1
TR1	2005	9	66	17	3.8	4.1	1.4
TR2	2005	9	67	17	3.8	2.0	0.7
TR3	2005	9	65	16	4.0	3.6	1.3
TR4.5	2005	9	65	16	4.0	2.6	1.0
TR5	2005	9	64	18	3.6	1.3	0.3
TR6.5	2005	9	64	19	3.4	1.6	0.5
TR7	2005	9	62	19	3.3	0.7	-0.3
TR8	2005	9	65	18	3.6	1.0	0
TR9	2005	9	65	18	3.6	3.0	1.1
TR10	2005	9	67	18	3.8	3.6	1.3
TR11	2005	9	65	19	3.4	1.1	0.1
TR12	2005	9	67	23	3.0	0.8	-0.2
TR13	2005	9	66	20	3.3	0.8	-0.2
TR14	2005	9	64	16	4.1	4.0	1.4
TR15	2005	9	66	15	4.3	4.6	1.5
TR16	2005	9	72	25	2.8	1.0	0
TR17	2005	9	65	16	4.1	3.8	1.3
TR18	2005	9	65	16	4.0	5.4	1.7

Water-quality data were obtained from the Lakes of Missouri Volunteer Program (LMVP). This program consists of citizen volunteers who are trained to collect and process water samples from Missouri lakes. Volunteers monitor surface-water temperature, water clarity (secchi disk transparency), chlorophyll, total phosphorus, total nitrogen, and total suspended solids according to procedures established by LMVP (Obrecht, 1992). Samples are collected once every 3 weeks between April and September for 18 sites (fig. 2) on Table Rock Lake. Repeat sampling is conducted by the same volunteer at each site with site occupation mostly dependent on aligning with visible landmarks. This method might

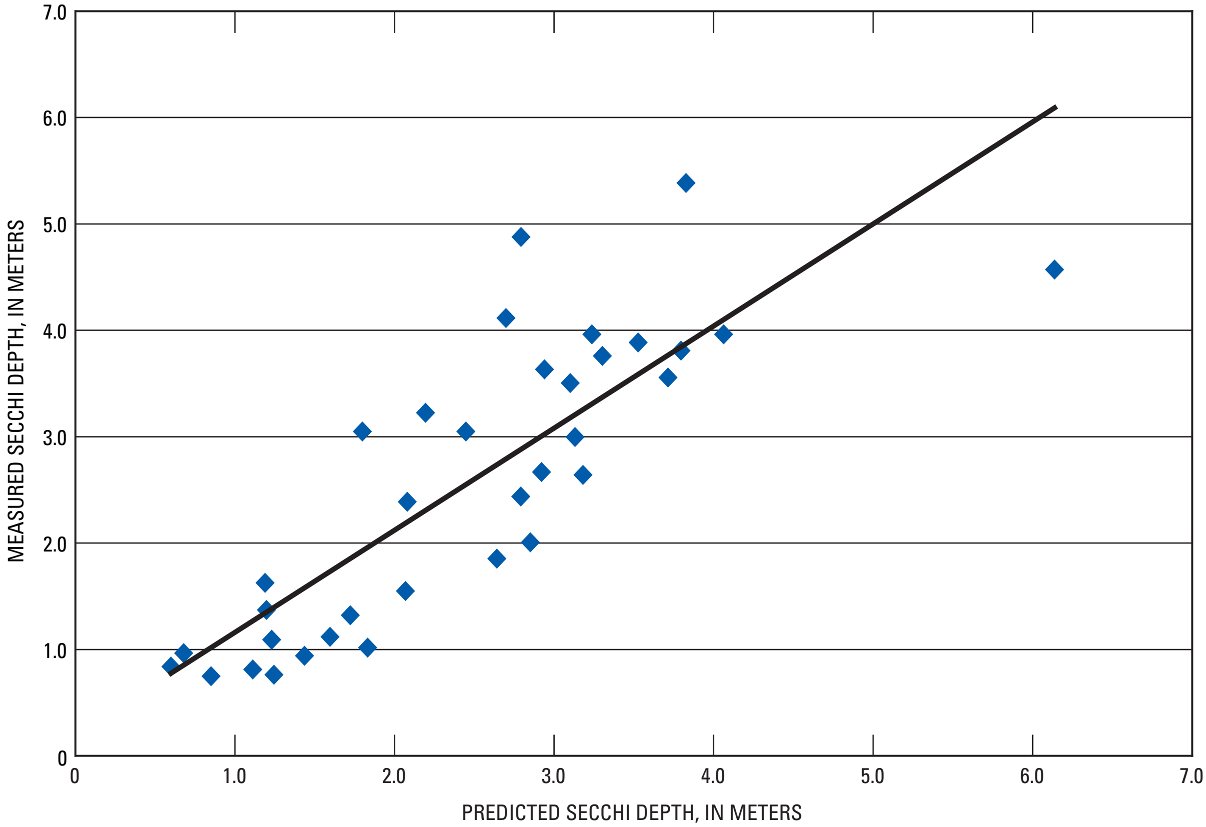

Figure 3. Relation between predicted and measured values of secchi depth for Table Rock Lake.

account for some error in consistently occupying the same sample location, but most volunteers are local residents and have an intricate knowledge of their sampling locations.

Processing of the satellite data was done using ERDAS Imagine software and modified from the procedures described by Olmanson and others (2001). The first step is to produce a water only image so that areas outside of the water body are eliminated from the analysis area. This is accomplished by performing an unsupervised classification on the Landsat image to differentiate water pixels from all others. The scene can then be recoded to create a binary image representing water and terrestrial areas. The water only image is further processed using an unsupervised classification to separate deep, open water areas from areas of the lake affected by vegetation, shoreline, or bottom effects. These areas should be avoided when choosing sample points in the satellite scene.

Sample sites for satellite signature acquisition were selected to coincide with the LMVP water-quality sites. A 3 by 3 (9 pixel) area of interest (AOI) was created for each of the sample sites. The AOI size was determined based on a previous study by Kloiber and others (2002) that showed correlation strength improved with an increase in AOI size from 1 to 9 pixels, but was marginal when the AOI was increased beyond 25 pixels. AOIs were centered over the LMVP sample site location and visual inspection performed to avoid areas with potential vegetation, shoreline, or bottom effects. Mean brightness values for each TM band were collected for each sample site AOI (table 1).

Regression analysis was performed using SPSS 14.0 for Windows (SPSS Inc., 2005). The following regression equation developed by Kloiber and others (2002) was used in the analysis of the two scene dates:

$$\ln(\mathrm{SDT}) = a(\mathrm{TM1}/\mathrm{TM3}) + b\mathrm{TM1} + c \qquad (1)$$

where

ln(SDT) is the natural log of secchi disk transparency depth, in meters, computed from the LMVP water quality data;

a, b, and *c* are the coefficients derived from the regression analysis; and

TM1 and TM3 are bands 1 [0.45-0.52 micrometers (µm)] and 3 (0.63-0.69 µm), respectively, from the Landsat 5 TM.

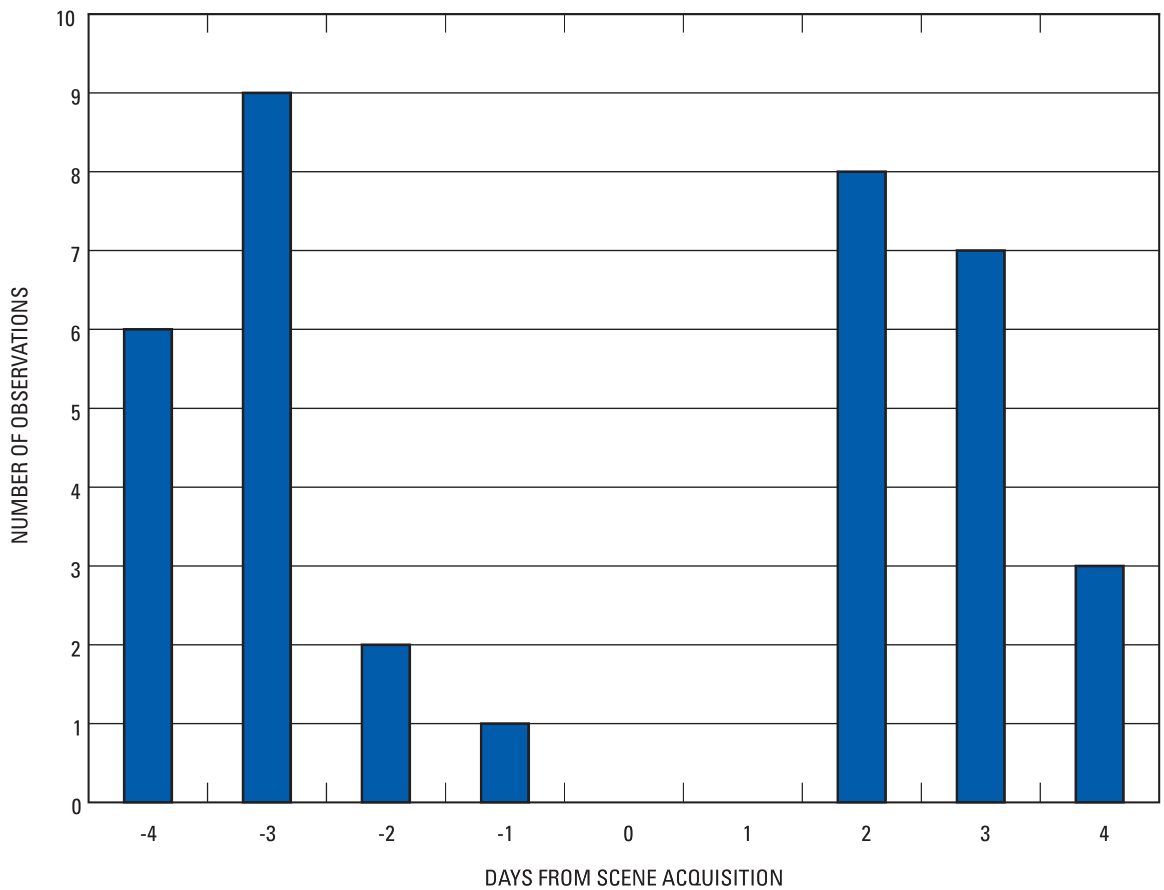

Figure 4. Distribution of field samples with respect to number of days within satellite overpass. All field samples were collected within 4 days with the largest percentage of samples collected 3 days from the time of satellite data collection.

Results

The regression analysis based on equation (1) produced the following linear model:

$$\ln(SDT) = -10.061(TM1/TM3) + 1.788(TM1) + 0.064 \quad (2)$$

with a reliability (R^2) of 0.76 and standard error of the estimate of 0.314. These results are consistent with similar studies using the TM1 and TM3 band relation to secchi disk transparency (Kloiber and others, 2002; Lathrop, 1992). Figure 3 is a plot of the relation between predicted and measured secchi depth for sample locations on Table Rock Lake. The plot shows a strong linear relation (r=0.83) between measured secchi depth and secchi depth predicted from mean Landsat reflectance values.

Field data collected on the same day as the satellite overpass result in the best regression results. Data collected from 1 to 7 days off the overpass date result in a decreasing strength of correlation (Kloiber and others, 2002; Chipman and others, 2004). All of the field data for this study were collected within 4 days of the satellite overpass (fig. 4) with a distribution as follows: same day (0 percent), 1 day (3 percent), 2 days (28 percent), 3 days (44 percent), and 4 days (25 percent). This distribution is inherent in the volunteer sample program as no effort is made to collect all samples on the same day.

Quality and reliability of volunteer collected data have been evaluated by Obrecht and others (1998). They found no statistical differences in data collected by volunteers and data collected by University of Missouri personnel for total phosphorus, total nitrogen, chlorophyll, or secchi depth.

Results of the regression analysis were used to create models using Imagine Spatial Modeler to output images showing the ln(SDT) and trophic state index (TSI) derived from ln(SDT) for the entire lake. The relation between TSI and secchi disk depth is defined as:

$$TSI = 60-14.41 \ln \text{secchi disk} \quad (3)$$

where

TSI is the Carlson trophic state index, and

ln secchi disk is the natural logarithm of the depth measurement, in meters.

Output images are pixel-level representations of transparency or trophic state that can be used to examine differences in

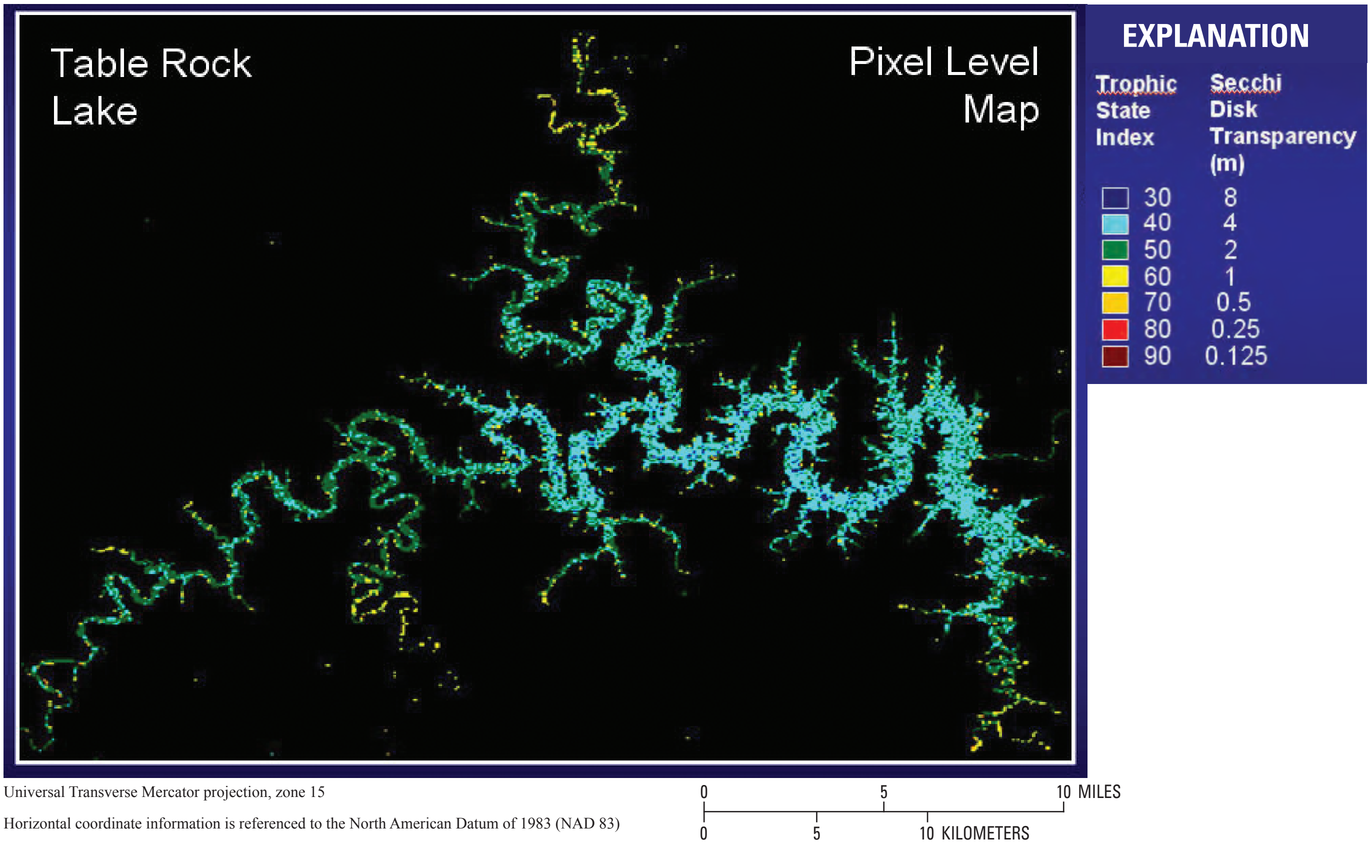

Figure 5. Model predicted trophic state for Table Rock Lake – August 2003. Water quality is degraded in the main tributaries compared to the main channel of the reservoir.

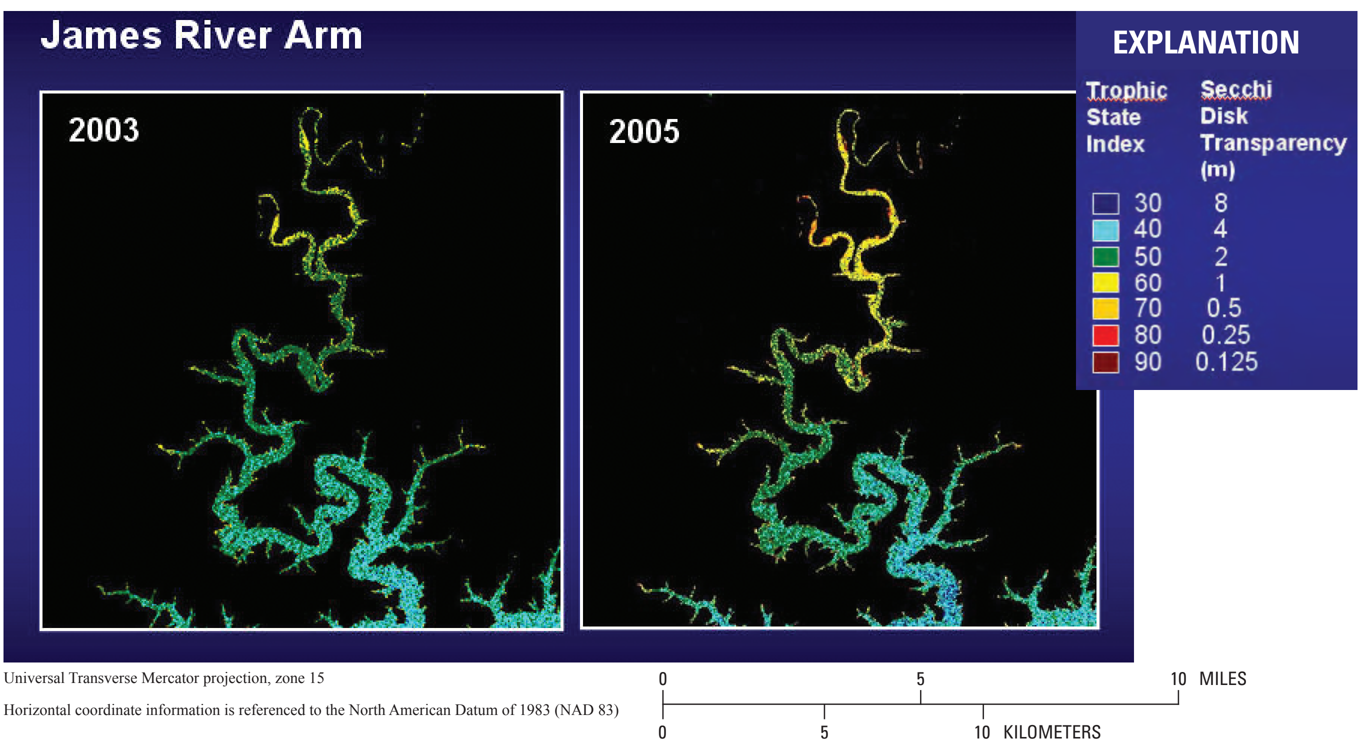

Figure 6. Temporal comparison of model results for the James River arm of Table Rock Lake. Water clarity has decreased in 2005.

water quality throughout the reservoir (fig. 5). Differences in water quality are readily apparent between the main channel and major tributaries with darker green and yellow pixels in the tributaries representing decreased water clarity. Temporal comparisons can also be made to assess changes in water clarity over time. Figure 6 shows the difference in water clarity for the James River arm of Table Rock Lake between the 2003 and 2005 scene dates. The increase in the TSI value can be seen extending much farther south in the James River arm in the 2005 image.

Summary

Remote sensing techniques can be effective in monitoring water quality in southwestern Missouri. Mean Landsat brightness values can be used with field data collected by citizen volunteers to produce reliable predictive models of water clarity and trophic state based on measurements of the secchi depth transparency. Predictive models can be used to supplement standard water-quality analyses during periods when field data are not being collected by volunteers. Temporal analyses are possible through the exploitation of the Landsat archive. Pixel-level representations of water clarity and trophic state provide a means of visually interpreting the status of water quality.

Acknowledgments

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