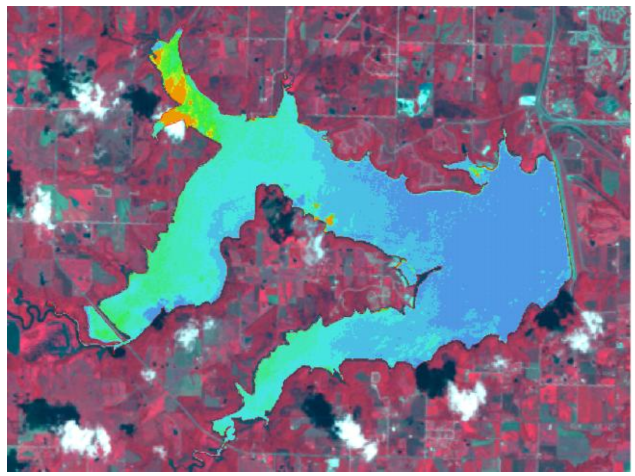
Determining the Utility and Adaptability of Remote Sensing in Monitoring and Assessing Reservoir Eutrophication and Turbidity for TMDL Assessments



Donald G. Huggins
Mark Jakubauskas
Debra S. Baker
Tara Hammer

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University of Kansas

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INTRODUCTION

Historically, the management of aquatic resources has relied on ground based monitoring. Due to the costs and time associated with such monitoring efforts, only a small percentage of the total sites are usually sampled for assessment each year. For example, the Environmental Protection Agency's (EPA) *2000 Water Quality Report* indicates that the number of lakes assessed in the United States may actually be decreasing. Those sites that are sampled are done so at spatial and temporal scales that do not allow for adequate assessment. For example, there is considerable spatial variation in the water quality conditions within the different zones of a reservoir (i.e. lacustrine, transitional, and riverine) on any given day (Thornton *et al*., 1990). Moreover, stressors such as algal blooms and high turbidity concentrations often vary temporally and thus may not be detected by single sampling events within a season (e.g. Wang *et al*., 2005). Therefore, monitoring techniques that complement current field monitoring programs are needed to allow resource managers to assess spatially and temporally diverse reservoirs over a more continuous, or semi-continuous time frame.

Fieldwork to measure water quality parameters in reservoirs presents numerous challenges. Sampling reservoirs is inherently time consuming and costly, and even with relatively large numbers of samples in a given reservoir, we cannot easily estimate the spatial variation of water quality across a water body simply using interpolation methods. Nor, without a major concerted and coordinated field campaign, can we simultaneously sample multiple points within multiple reservoirs on a given date. Furthermore, we cannot travel back in time to take samples from reservoirs that may have been under sampled or missed entirely in the past. As pointed out by the EPA (http://www.epa.gov/eerd/RemoteSensing.htm) and others (e.g. Heiskary *et al*., 2006), there are several advantages of using remotely sensed data in monitoring and assessment programs relative to ground based monitoring alone. Specifically, using remotely sensed data allows for a greater number of sites within a water body to be assessed more frequently. In addition, a greater number of waterbodies can be assessed for lower relative costs because field crews need not visit each waterbody and water quality samples are limited to only those lakes and impoundments requiring a more complete set of physical and chemical analyses.

Remote Sensing of Water Quality Conditions

Multispectral remotely sensed imagery provides an opportunity to extend our ability to measure water quality parameters in space and time. If statistically significant empirical models can be developed between reservoir water quality parameters (e.g., turbidity, chlorophyll, and temperature) and spectral reflectance values recorded for the same location, it would be possible to apply the models to remotely sensed imagery to produce maps of the desired water quality parameter(s). In other words, by calibrating remotely sensed multispectral data with field measurements, parameters measured at sample points can be extrapolated across a large geographic region. Such statistically valid models have been developed for a number of water quality parameters in many geographic regions and water body types throughout the United States. Brezonik *et al*., 2005; Chipman *et al*., 2004; Fraser, 1998; Kloiber *et al*., 2002; and Heiskary *et al*., 2006 reviewed the advantages and disadvantages of several remote sensing platforms such as Landsat, MODIS, and high-resolution commercial imagery (i.e. IKONOS and QuickBird). The selection of a particular platform for use in the assessment of water quality conditions depends on several factors including the size and number of lakes to be assessed, the desired degree of resolution, and the costs of applications (Heiskary *et al*., 2006).

The statistical relationships between multispectral imagery and water quality parameters such as turbidity and chlorophyll are well documented in the scientific literature. Phytoplankton, like any living vegetation, contains the photosynthetically active primary pigment chlorophyll-*a* and other accessory pigments. Each pigment absorbs and reflects radiant energy at differing wavelengths of the electromagnetic spectrum. The spectral response pattern of chlorophyll-*a* has been characterized as having a strong absorption of blue light between 400-500 nm; a strong chlorophyll-*a* absorption of red light or a reflectance minimum around 675 nm; a maximum reflectance peak in green light around 550 or 560 nm; and a prominent secondary reflectance peak around 685-715 nm (Rundquist *et al*. 1996; Jensen 2000; Gitelson *et al*. 1993). A water column containing chlorophyll-*a* absorbs more blue and red light and reflects more green light and NIR energy than a clear water column allowing the two water feature types to be spectrally discriminated from one another. Remote sensing technology measures the amount of energy absorbed or reflected by chlorophyll-*a* and can be used to detect and quantify the concentration of chlorophyll-*a* and therein estimate the abundance of phytoplankton present in an aquatic system. Furthermore, remotely sensed imagery could be used to detect differences between pigments from green algae and diatoms (chlorophyll-*a*) and cyanobacteria (phycocyanin; Vincent *et al*., 2004), which are associated with taste and odor events in drinking water reservoirs. Therefore, it is possible that phycocyanin concentrations from remotely sensed imagery and ratios of phycocyanin/chlorophyll-*a* can be used as potential warning indicators for taste and odor events. Specifically, this ratio could be used to determine when communities shift from dominance by green algae or diatoms to dominance by cyanobacteria.

The proven ability of remote sensing techniques to provide repeatable, quantitative estimates of Secchi disk depth and chlorophyll-*a* (e.g. Ritchie *et al*., 2003), two of the most important parameters for calculating Tropic State Indices (Carlson, 1977), suggest that this approach can be successfully integrated into a comprehensive, rapid response monitoring program. It is very important to stress that remote-sensing techniques cannot replace field and laboratory analysis based programs, but instead can complement existing programs by greatly increasing both the spatial and temporal capabilities of such programs. The potential rapid-response capabilities of remotely sensed data mean that managers can quickly assess specific water body information to make accurate and timely management decisions.

Objectives

A one-year proof-of-concept project was conducted to measure key water quality parameters in a series of Kansas reservoirs and use MODIS (Moderate-resolution Imaging Spectroradiometer) remotely sensed imagery to develop a series of predictive models to estimate the key measured parameters. The scientific objectives include:

- Develop statistical models between turbidity, Secchi disk, total suspended solids, chlorophyll-*a*, total phosphorus and spectral reflectance values;
- Evaluate and compare the models developed in this study with models described in the scientific literature;
- Examine both within-reservoir variability and between-reservoir variability in predicted water quality parameters.

PROJECT DESIGN, APPROACH, AND METHODS

Lake Selection and Sampling Plan

We examined four Kansas lakes (i.e. reservoirs) out of a pool of reservoirs that have been identified by the Watershed Planning Section of Kansas Department of Health and Environment (KDHE) as exhibiting impairment due to turbidity and eutrophication (Table 1). Two large lakes (Clinton Reservoir and Hillsdale Reservoir) and two small lakes (Centralia and Louisburg-Middle Creek) were selected as they are typical of impoundments found across much of EPA Region 7.

Clinton Lake (Figure 1)
Clinton Lake was constructed on the Wakarusa River approximately 1 mile west of the city of Lawrence, Kansas, and is operated by the U.S. Army Corps of Engineers. The lake was constructed to control flooding, for municipal and industrial water supply, fish and wildlife benefits, and recreation, and to maintain minimum stream flow on the Wakarusa and Kansas Rivers. The Wakarusa River is the main source of water flowing into Clinton Lake. The Wakarusa River Basin drains a total of 516 square miles, which extends west approximately 54 miles from its mouth on the Kansas River.

Hillsdale Lake (Figure 2)
Hillsdale Lake is one of the newest reservoirs in Kansas. Completed in 1982, the reservoir is part of a comprehensive flood control plan for the Osage and Missouri River basins, controlling the downstream flow of water from a 144 square mile drainage area. Hillsdale Lake provides flood protection along Big Bull Creek downstream from the dam. As part of the Osage River basin system of lakes, Hillsdale also contributes to flood protection on the Marais des Cygnes, Osage, and Missouri Rivers. Several public water suppliers have contracts or applications for contracts with the state for water supply from Hillsdale Lake.

Louisburg-Middle Creek Lake (Figure 3)
Louisburg-Middle Creek Lake was built as a water supply source for the City of Louisburg through a cooperative agreement between the city, the Natural Resources Conservation Service, and the Kansas Department of Wildlife and Parks. Construction and final agreements for the operation and maintenance of the lake were completed and signed in 1986. The lake and surrounding lands are managed by the Kansas Department of Wildlife and Parks for fishing and hunting purposes. The 250-acre lake has a maximum depth of 34 feet.

Centralia City Lake (Figure 4)
Centralia City Lake is located southwest of the town of Centralia, Kansas, in Nemaha County. The 400-acre lake is owned by the City of Centralia, serving as a water supply lake. In summer 2010, the lake was closed for several weeks by the Kansas Department of Health and Environment due to high concentrations of blue-green algae in the water.

Table 1. Reservoirs selected for study.

Lake	Area (acres)	County	Impairment	TMDL Priority
Clinton Lake	7,484	Douglas	EU	High
Hillsdale Lake	4,826	Miami	EU	High
Louisburg-Middle Creek	252	Miami	EU	High
Centralia City Lake	386	Nemaha	EU	Medium

EU – eutrophic

Figure 1. Clinton Lake, Douglas County, Kansas.

Figure 2. Hillsdale Lake, Miami County, Kansas.

Figure 3. Louisburg-Middle Creek Lake, Miami County, Kansas.

Figure 4. Centralia Lake, Nemaha County, Kansas.

Field Sampling Scenarios
Phase 1 sampling: All sites at each lake (Clinton and Hillsdale Lakes, 20 sites each; Centralia and Louisburg-Middle Creek Lakes, 10 sites each) were sampled in June 2009 and again in July 2009 for Component 1 (Phase 1 sampling) to collect data from which statistical models were built in conjunction with satellite imagery (Table 2). Parameters collected included temperature, turbidity, pH, chlorophyll-*a*, conductivity, DO and Secchi disk depth, as well as sample site latitude-longitude coordinates (using a GPS). The locations of lake sampling sites were selected to capture as many lake morphology differences as was practical (Figure 5 - Figure 8). Site coordinates are listed in Appendix 1.

Phase 2 sampling: To further examine the temporal variability within and between reservoirs, about half of the sites on each lake were sampled again in each of the four months beginning in August 2009 and ending in early December 2009 (Phase 2 sampling). The proposed schedule for the Phase 2 sampling was to capture field data approximately every 16-20 days to coincide with the MODIS over flights. This could not be accomplished because of subsequent cloud cover; field sampling dates had to be adjusted to accompany the best MODIS overpasses (e.g. least cloud cover, most nadir).

Table 2. Reservoir field sampling dates in 2009.

		Clinton	Hillsdale	Centralia	Louisburg
Phase 1	# sites	20	20	10	10
	June	6/18/09	6/17/09	6/18/09	6/17/09
	July	7/21/09	7/20/09	7/21/09	7/22/09
Phase 2	# sites	10	10	5	5
	August	8/27/09	8/28/09	8/27/09	8/28/09
	October	10/09/09	10/07/09	10/09/09	10/07/09
	November	11/12/09	11/10/09	11/09/09	11/10/09

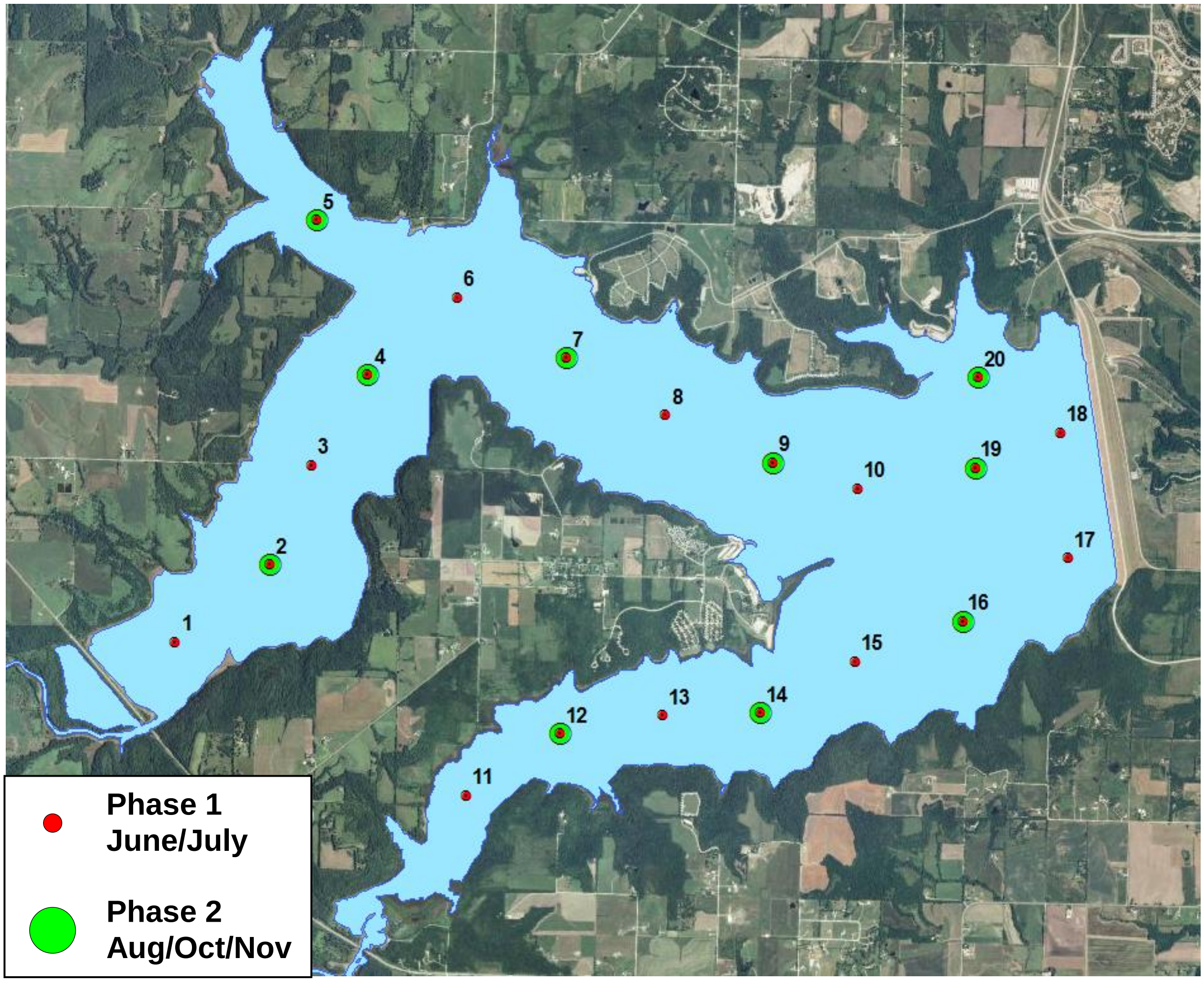

Figure 5. Clinton Lake field sampling locations, 2009.

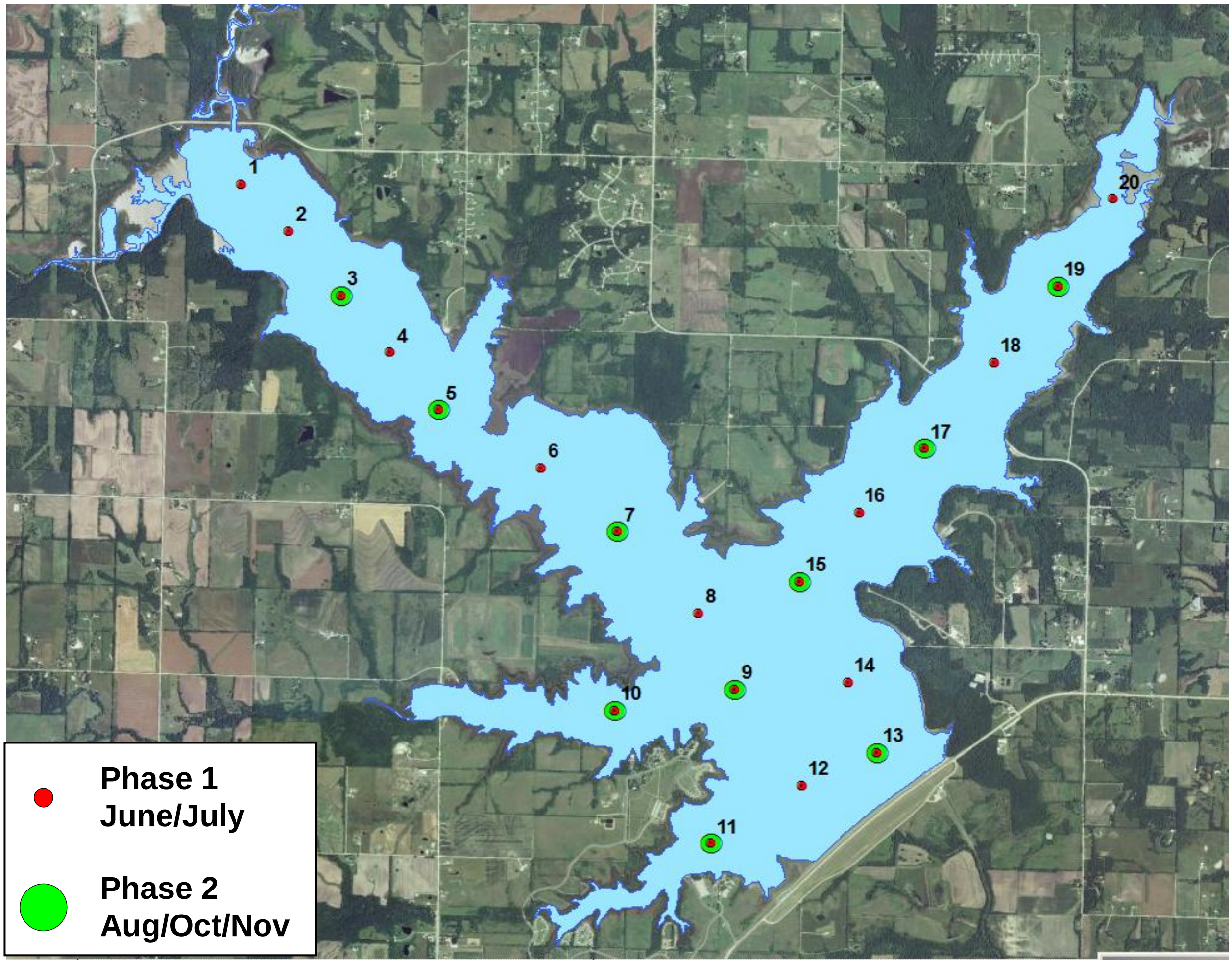

Figure 6. Hillsdale Lake field sampling locations, 2009.

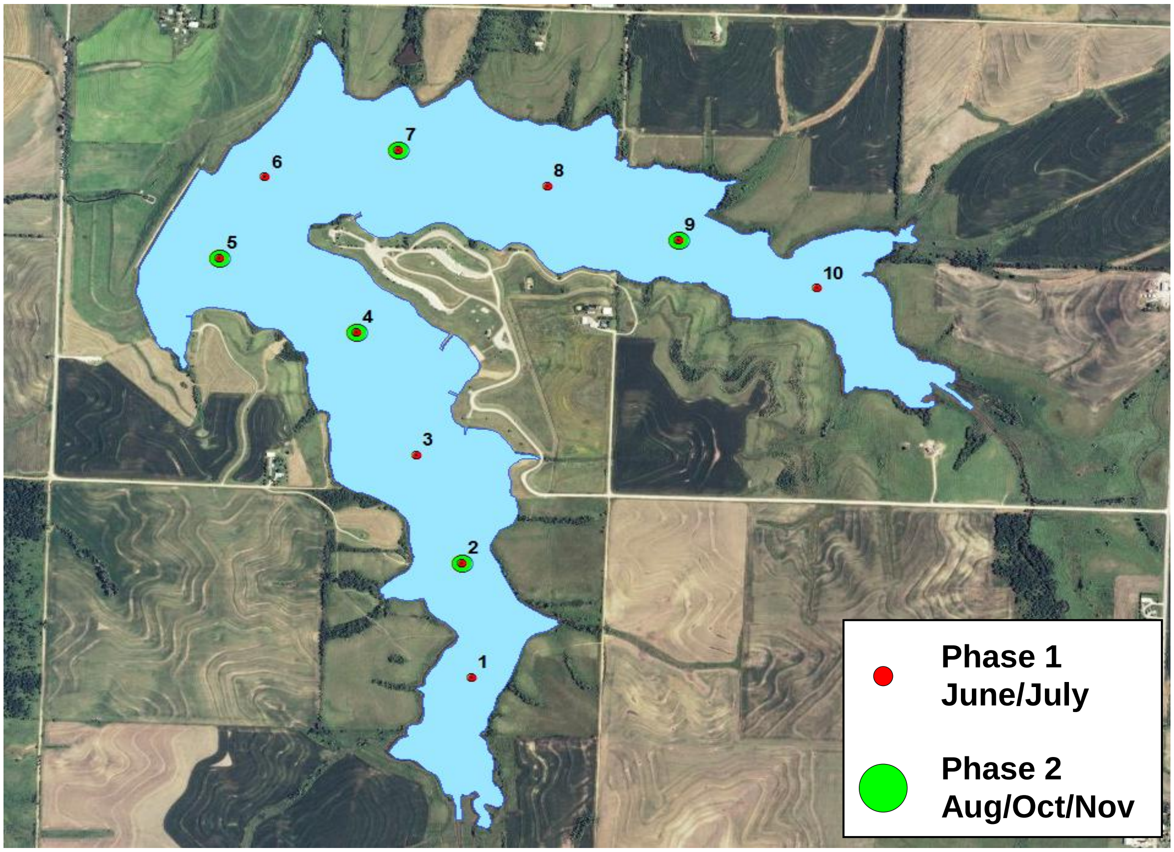

Figure 7. Centralia Lake field sampling locations, 2009.

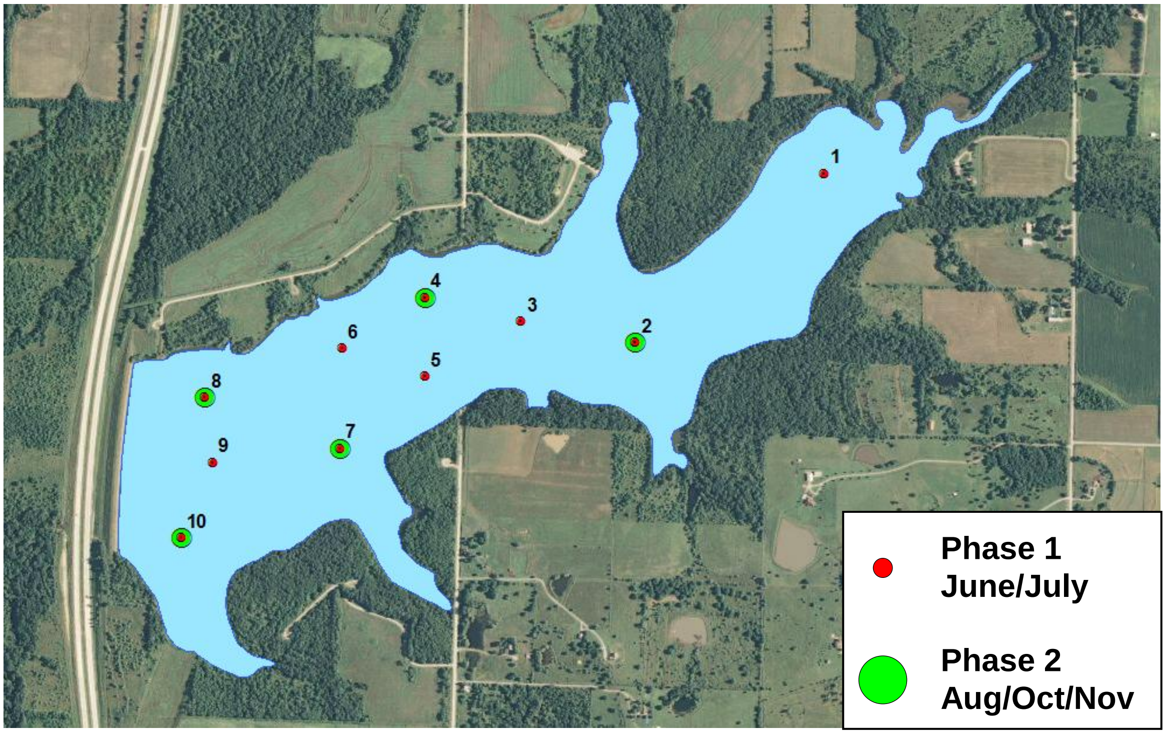

Figure 8. Louisburg-Middle Creek Lake field sampling locations, 2009.

Water Quality Sampling

Field sampling for selected parameters at each predetermined GPS site was accomplished with typically a 3-person boat crew that visited two lakes on each of two consecutive days according the overpass schedule. As previously mentioned, field data was collected under two scenarios. Phase 1 collections consisted of many lake sites that were sampled less frequently with long temporal periods between samples, while Phase 2 sampling was based on fewer lake sites but more frequent visits. This approach was taken to minimize sampling costs while still attempting to capture the frequency, duration, and magnitude of whole-lake concentration changes. At each lake site *in situ* turbidity (NTU), dissolved oxygen (mg/L), conductivity (mS/cm), pH, and water temperature (C) were measured near the surface (≈0.25m) with a Horiba® Model U-10 water quality meter. The Horiba® U-10 was calibrated (two-point) according to the Horiba® manual procedures prior to every collection event or once every other week in the field season, whichever came first. At each site a Secchi disk measurement was made and a surface-water sample taken and returned to the laboratory for later analysis of chlorophyll-*a*, total suspended solids (TSS), and total phosphorus (TP) concentrations. Typically all *in situ* measures and water samples were collected between 10am and 4pm to reduce daily variations. Water samples for the laboratory analyses for were collected in amber 1-L glass containers, placed on wet ice, and returned to the laboratory within 72 hours.

Satellite Imagery

MODIS satellite imagery

The MODIS is a payload scientific instrument launched into Earth's orbit by NASA in 1999 on board the TERRA (EOS AM) Satellite, and in 2002 on board the AQUA (EOS PM) satellite. The instrument captures data in 36 spectral bands from 0.4 µm to 14.4 µm and at varying spatial resolutions (2 bands at 250m, 5 bands at 500m, and 29 bands at 1km). The red and NIR bands are only available at 250m. Prior to field sampling a list of overpass dates, times, and view angles were obtained for eastern Kansas from the NASA Earth Observatory Overpass Predictor. Optimally, high nadir views (>70°) were desired; most of the optimal days for MODIS were also coincident with Landsat 5 and 7 overpasses for eastern Kansas.

Based on actual field sampling dates, a set of primary and alternate MODIS scene dates were assembled for both the TERRA and AQUA satellites. Using the NASA Warehouse Inventory Search Tool (WIST), those primary and alternate MODIS images (Datetypes: TERRA: MOD09GQ; AQUA: MYD09GQ) were downloaded, imported to ERDAS Imagine (*.img) format from the native NASA HDF format, the two 250-meter resolution red and near-infrared spectral reflectance bands extracted, and the data reprojected to WGS84 projection from the native MODIS sinusoidal projection. An example of the results of these processes is shown in Figure 9.

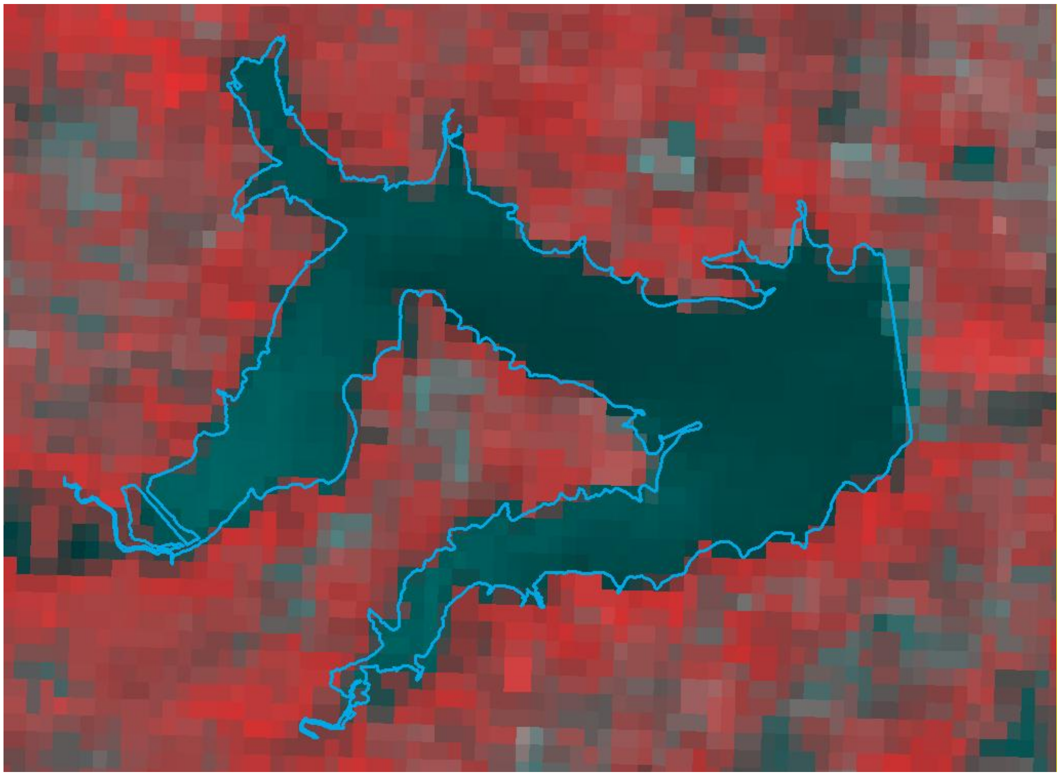

Figure 9. MODIS Image of Clinton Lake.

Images were reviewed for cloud cover and a set of cloud-free dates were selected for analysis. Image dates for the June, July, and November sampling events were nearly coincident or within 1-2 days of the field sampling event; cloud cover in August and October necessitated the use of images acquired by the satellite up to 6-7 days (August) earlier than the field sampling (Figure 10). Images used were exclusively from the MODIS TERRA system and the final image and sampling pairings are shown in Table 3.

Spectral reflectance values for each sample point were extracted from each image for the two spectral reflectance bands and the extracted values were used with the field data in developing statistical models relating water quality parameters to spectral reflectance values. Due to the coarse spatial resolution of the MODIS system (250 meters), we elected to perform the MODIS analysis only for the two large federal reservoirs, Clinton Lake and Hillsdale Reservoir.

Table 3. MODIS TERRA overpasses and field sampling dates.

MODIS Overpass	Clinton	Hillsdale	Centralia	Louisburg
June 18, 2009	6/18/09	6/17/09	6/18/09	6/17/09
July 22, 2009	7/21/09	7/20/09	7/21/09	7/22/09
August 21, 2009	8/27/09	8/28/09	8/27/09	8/28/09
October 5, 2009	10/09/09	10/07/09	10/09/09	10/07/09
November 11, 2009	11/12/09	11/10/09	11/09/09	11/10/09

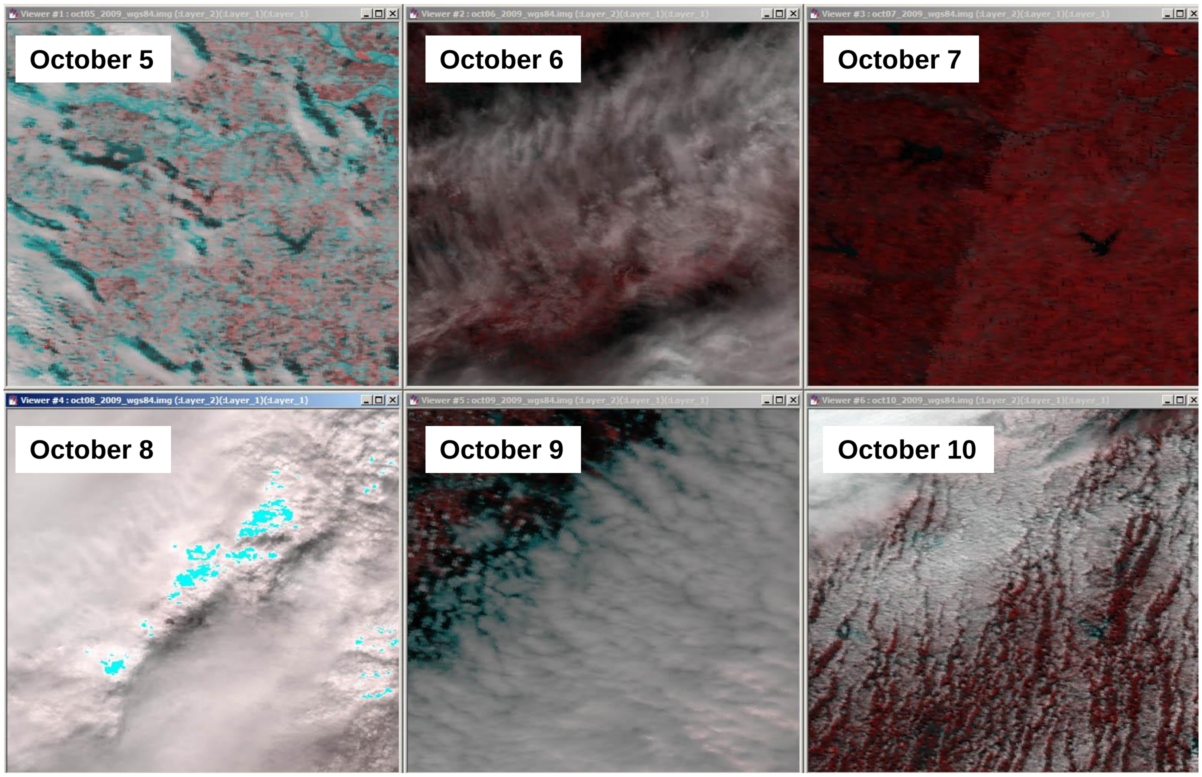

Figure 10. MODIS images of eastern Kansas including Clinton and Hillsdale Lake areas.

Landsat satellite imagery

Since both Louisburg-Middle Creek and Centralia Lake are small elongated lakes, it is difficult to obtain clean (i.e., water-only) pixel values for the samples sites on the 250-meter resolution MODIS visible-near IR reflectance imagery (Figure 11). Thus, we elected to acquire Landsat imagery, with a spatial resolution of 30 meters and six reflectance bands, of all four lakes coincident with the sampling periods. Fortunately, one Landsat image (WRS-2 Path 27, Row 33) is sufficiently large enough to include all four study lakes, as well as numerous other reservoirs in northeastern Kansas (Figure 12). Landsat 7 data suffers from a scan line corrector anomaly that significantly impacts the areas distal of the satellite nadir track such that significant portions of the image are missing or unusable. As a result, we elected to use only Landsat 5 imagery and scheduled field sampling periods according to the overpasses of that satellite. All Landsat 5 imagery was downloaded from the United States Geological Survey EROS Data Center using the GLOVIS Browse Image Viewer, often on the day after the satellite overpass. Nearly every Landsat 5 image was imaged within 0-3 days of a field sampling event, with the exception of the August 2009 event (7 days) (Table 4).

Image data were converted from brightness values to units of radiance (mW/cm2/sr/um) (Markham and Barker 1986) using gain and bias values from the image header files. Radiance data were then converted to reflectance (Table 5). Values for each sample point for all four reservoirs were extracted from each image for each of the six spectral reflectance bands. The extracted values were used with the field data in developing statistical models relating water quality parameters to spectral reflectance values.

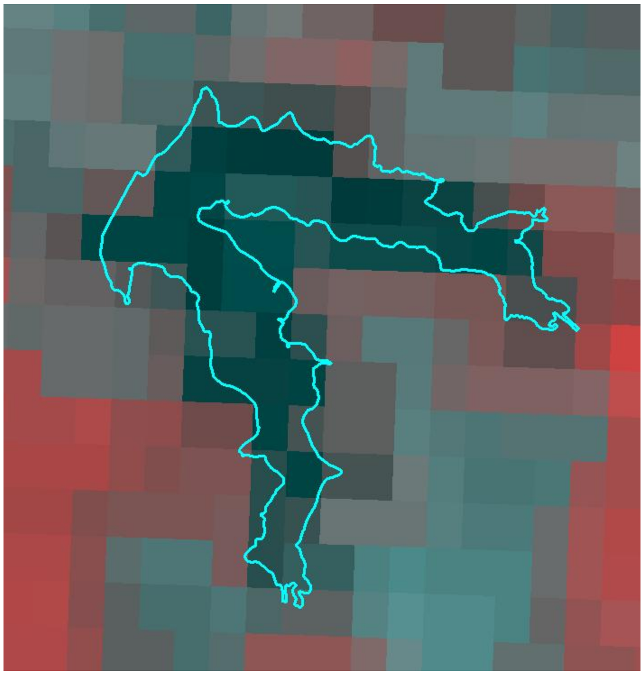

Figure 11. MODIS image of Centralia Lake.

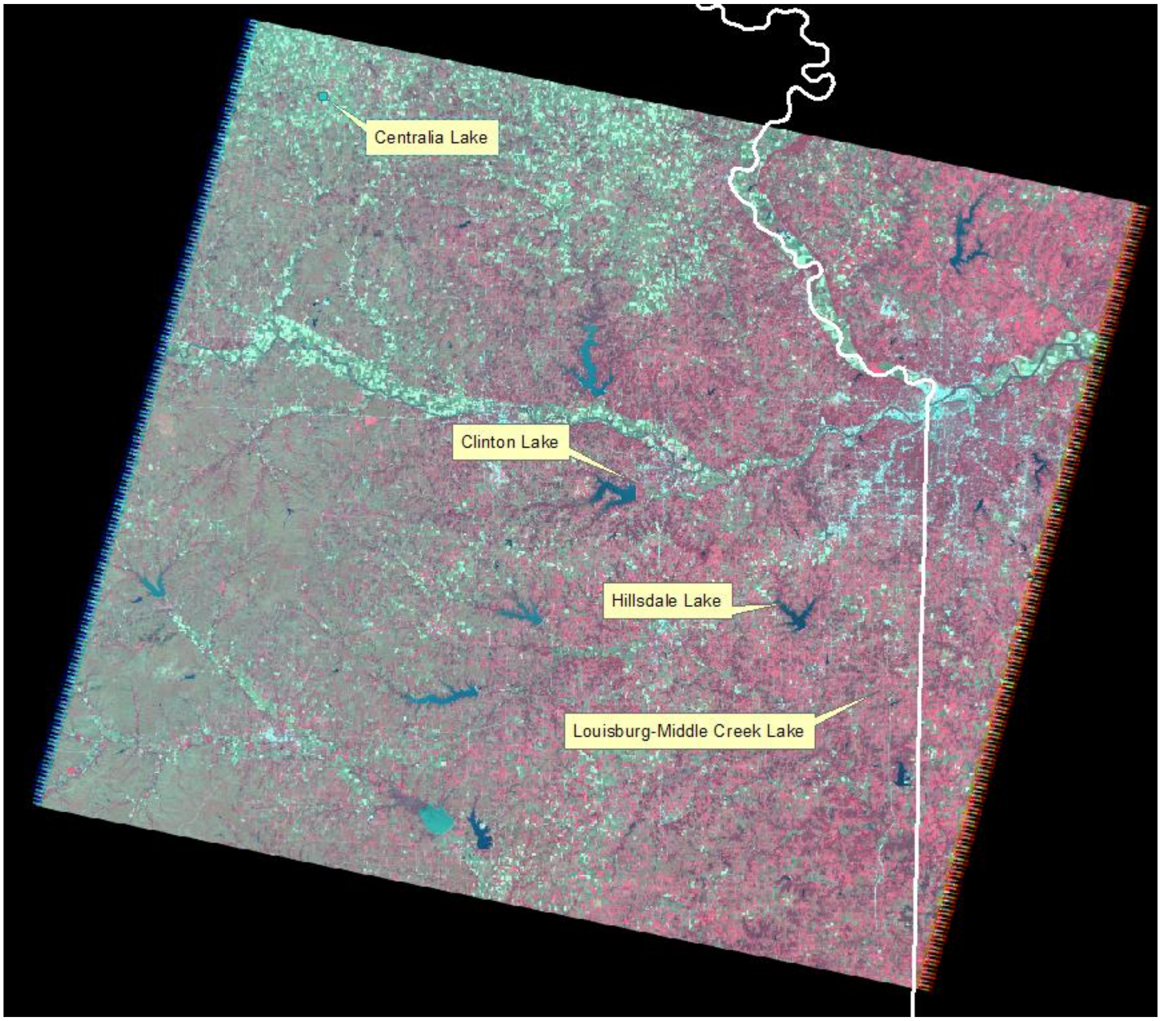

Figure 12. Landsat image of all four study lakes

Table 4. Landsat 5 overpasses and field sampling dates.

Landsat 5 Overpass	Clinton	Hillsdale	Centralia	Louisburg
June 17, 2009	6/18/09	6/17/09	6/18/09	6/17/09
July 19, 2009	*7/21/09*	7/20/09	7/21/09	7/22/09
August 20, 2009	8/27/09	8/28/09	8/27/09	8/28/09
October 7, 2009	10/09/09	10/07/09	10/09/09	10/07/09
November 8, 2009	11/12/09	11/10/09	11/09/09	11/10/09

Table 5. Parameters used for converting Landsat 5 radiance values to reflectance values.

Parameter	6/17/2009	7/19/2009	8/20/2009	10/7/2009	11/8/2009
EDC filename	LT5027033 2009168EDC00	LT5027033 2009200EDC00	LT5027033 2009232EDC00	LT5027033 2009280EDC00	LT5027033 2009312EDC00
LMAX_BAND1	193	193	193	193	193
LMIN_BAND1	-1.52	-1.52	-1.52	-1.52	-1.52
LMAX_BAND2	365	365	365	365	365
LMIN_BAND2	-2.84	-2.84	-2.84	-2.84	-2.84
LMAX_BAND3	264	264	264	264	264
LMIN_BAND3	-1.17	-1.17	-1.17	-1.17	-1.17
LMAX_BAND4	221	221	221	221	221
LMIN_BAND4	-1.51	-1.51	-1.51	-1.51	-1.51
LMAX_BAND5	30.2	30.2	30.2	30.2	30.2
LMIN_BAND5	-0.37	-0.37	-0.37	-0.37	-0.37
LMAX_BAND6	15.303	15.303	15.303	15.303	15.303
LMIN_BAND6	1.238	1.238	1.238	1.238	1.238
LMAX_BAND7	16.5	16.5	16.5	16.5	16.5
LMIN_BAND7	-0.15	-0.15	-0.15	-0.15	-0.15
SUN_AZIMUTH	121.065	123.5519	135.2355	153.2629	158.9206
SUN_ELEVATION	64.7976	62.12664	56.02939	41.78235	31.68399
JULIAN DAY	168	200	232	280	312
EARTH-SUN DISTANCES	1.01595	1.01623	1.01186	0.99947	0.99078

Water Quality Analyses

All field measures and laboratory analysis methods used in this project are summarized in Appendix 2 and follow the QA/QC plan which was developed as part of this effort. Chlorophyll was analyzed fluorometrically using a Ratio-2 System Filter Fluorometer by Optical Technology Devices, Inc. The fluorometer was calibrated according to manufacturer procedures using chlorophyll-*a* standards purchased from either Sigma-Aldrich or Turner Designs. The fluorometer was calibrated for the conventional acidification method listed in 10200-H of Standard Methods (APHA *et al*. 2005). Total phosphorus was measured by first digestion at 250^{o}F followed by analysis with the Lachat QuikChem 8500 (Ebina *et al.* 1983). Total suspended solids (TSS) and volatile suspended solids (VSS) were determined either by EPA method 160.2 (see http://www.caslab.com/EPA-Method-160_2/) or Standard Methods 2540D and E. Inorganic suspended solids (ISS) values were determined by subtraction (i.e. TSS minus VSS).

RESULTS

Water Chemistry

The summary statistics for all lakes can be found in the project database at http://www.cpcb.ku.edu/research/html/2009_lakeMODIS.htm and will not be discussed in this section. The primary purpose for generating actual lake data was for its direct use in developing the respective remote sensing models for various lake parameters. These data were also used to examine trends within lakes and between lakes as well as to identify any temporal changes that might be of consequence. Additionally, relationships between various parameters were explored to address some basic limnological questions; 1) are the traditional relationships between nutrients and chlorophyll-*a* apparent in these lakes, 2) is turbidity related to either chlorophyll-*a* or TSS (or both), and 3) is turbidity or TSS a predictor of TP? Because much of the TP in lakes of the Central Plains is attached to sediment particles we anticipated that we could use either turbidity or TSS as a surrogate measure of TP and thus imagery estimates of turbidity can be used to estimate TP in many instances.

Lake and temporal trends

The most obvious lake trend was observed in total phosphorus, but differences were noted in most parameters (Figure 13 - Figure 20). There were little differences in lake dissolved oxygen, pH, or water temperature.

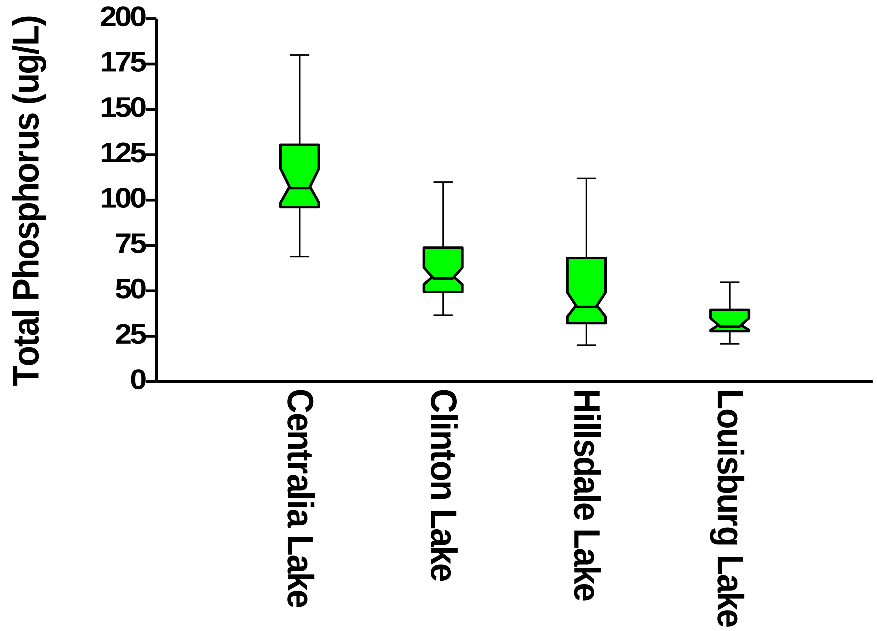

Figure 13. Box plot of total phosphorus by lake for all sampling events. Outliers not shown.

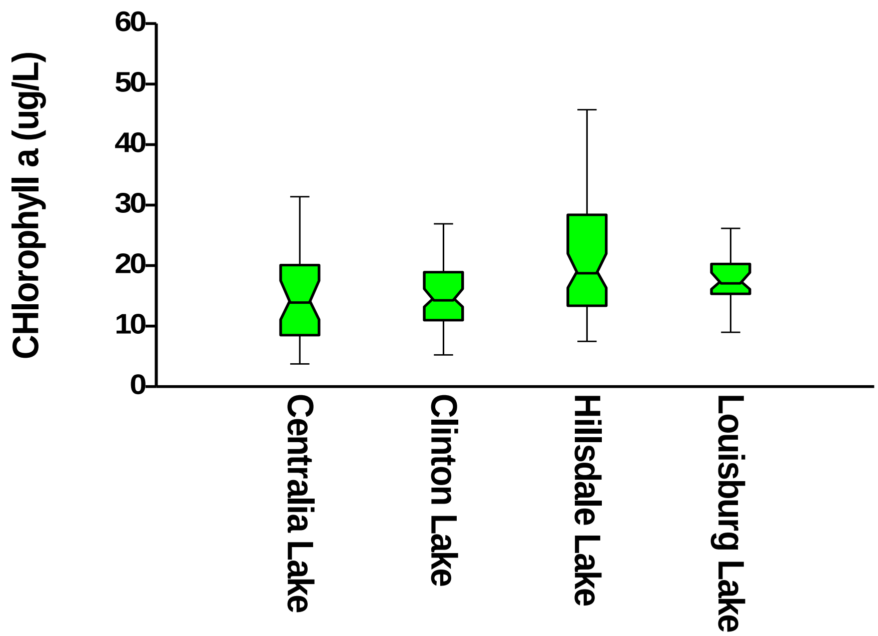

Figure 14. Box plot of chlorophyll-*a* by lake for all sampling events. Outliers not shown.

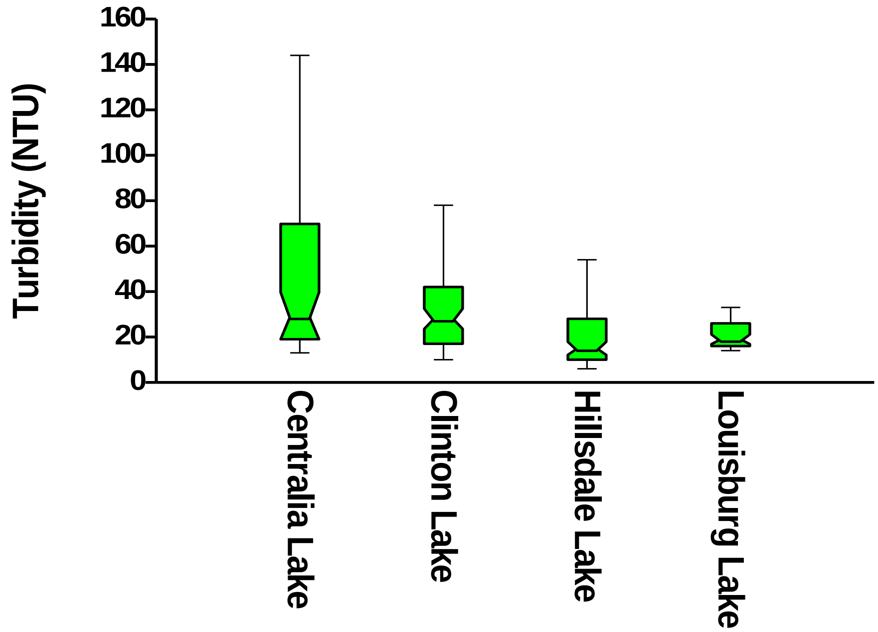

Figure 15. Box plot of turbidity by lake for all sampling events. Outliers not shown.

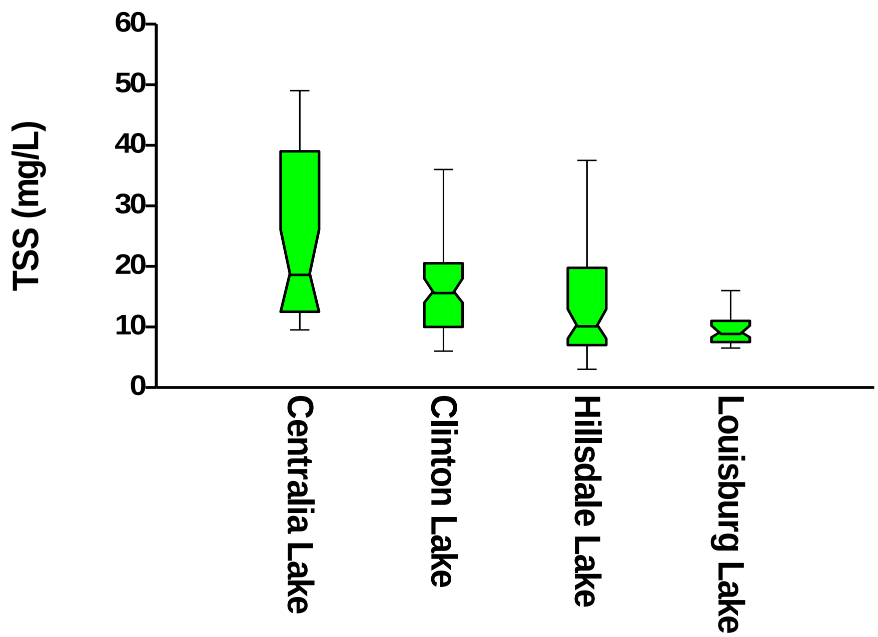

Figure 16. Box plot of total suspended solids (TSS) by lake for all sampling events. Outliers not shown

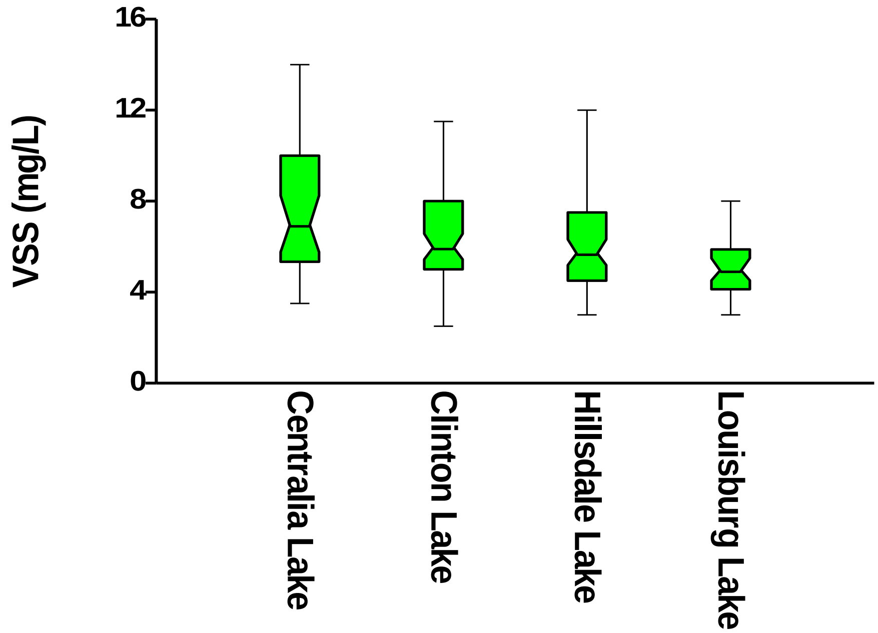

Figure 17. Box plot of volatile suspended solids (VSS) by lake for all sampling events. Outliers not shown.

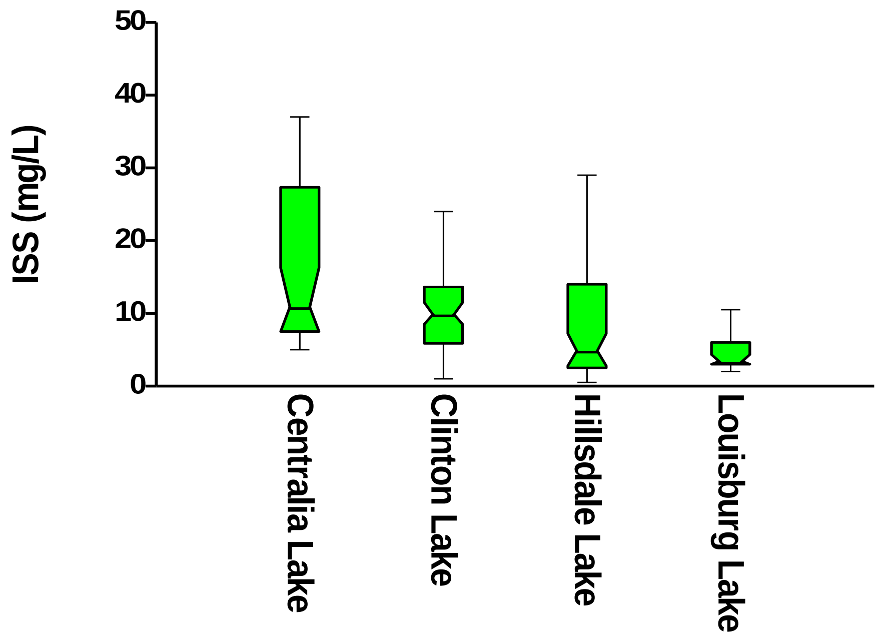

Figure 18. Box plot of inorganic suspended solids (ISS) by lake for all sampling events. Outliers not shown.

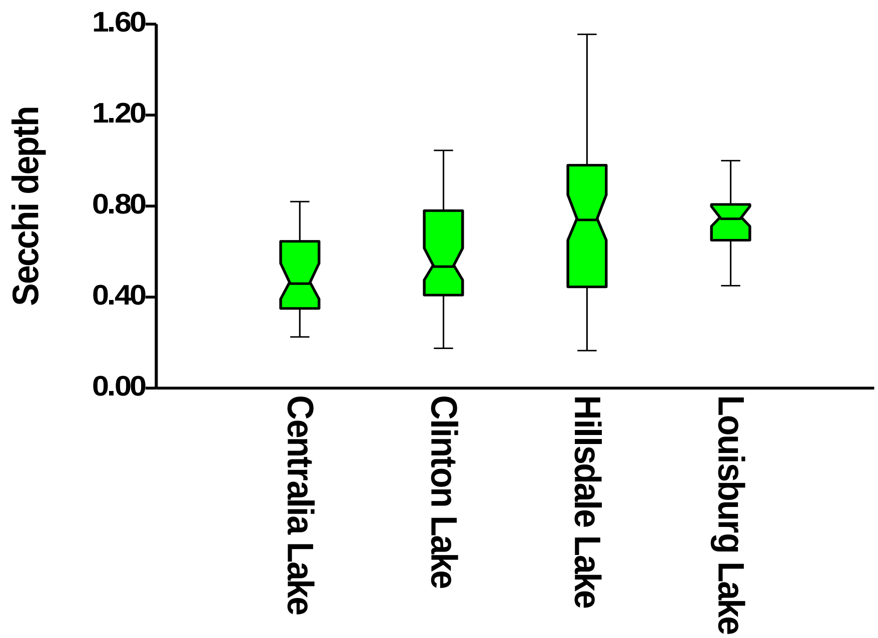

Figure 19. Box plot of Secchi depth (meters) by lake for all sampling events. Outliers not shown.

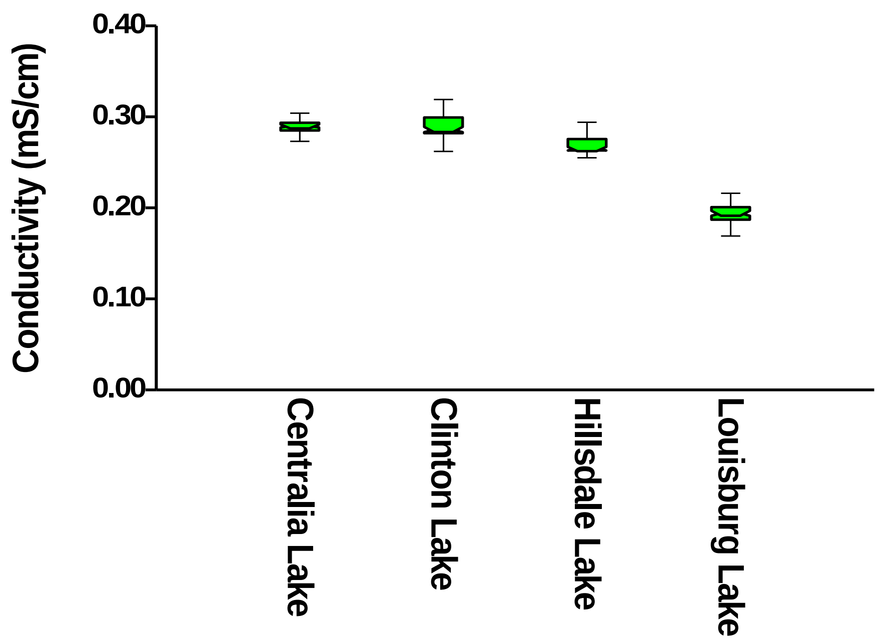

Figure 20. Box plot of conductivity by lake for all sampling events. Outliers not shown.

While both Centralia and Clinton Lakes had the highest TP concentrations throughout the study, Hillsdale and Louisburg Lakes often had higher levels of chlorophyll-*a*. Similarly Centralia and Clinton Lakes exhibited higher turbidity, TSS, VSS, and ISS values while the other two lakes remained fairly clear and had somewhat longer Secchi depths. Overall, the water clarity of these lakes is low compared to many reservoirs in the US, with turbidity values ranging from 6 to 220 NTUs (mean = 32.7, median = 23.0 NTU). TSS levels were generally high (range = 3 to 107.5, mean = 17.8, median 12.5 mg/L) and tended to follow the same lake and seasonal patterns noted for turbidity.

Few water quality parameters displayed much temporal variance when comparisons were made between sampling periods (i.e. five sampling events). Dissolved oxygen, pH, and conductivity remained similar through the study (see
Figure 21 as an example) while turbidity, suspended solids measurements (i.e. TSS, ISS), and Secchi depths indicated that lakes in general were becoming more turbid from inorganic sediment later in the study (

Figure 22 -

Figure 25). Examination of the temporal changes of TP (

Figure 26) revealed a similar pattern of higher fall values as with the various measures of turbidity and suspended solids. Chlorophyll-*a* was noted to peak in late August (sampling period 3) when all the lakes were considered in the analysis (

Figure 27).

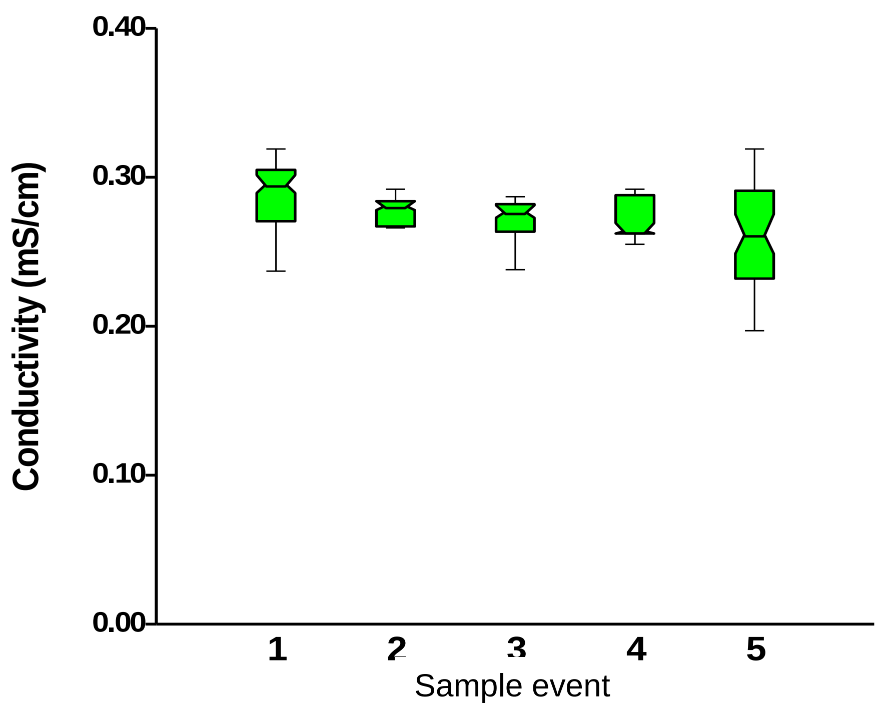

Figure 21. Box plot of conductivity by sampling event for all lakes beginning with the first June sampling event. Outliers not shown.

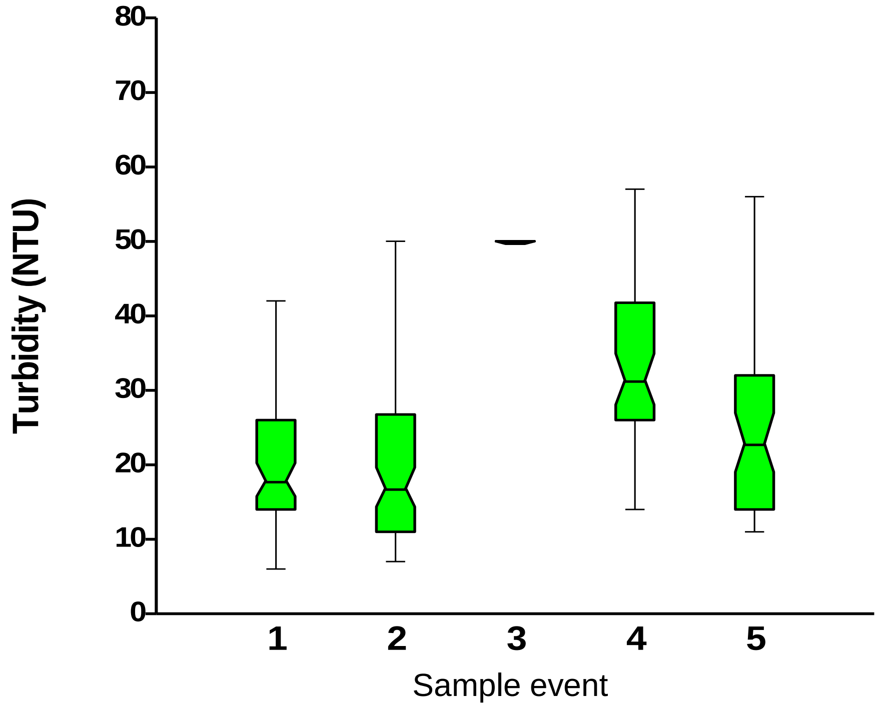

Figure 22. Box plot of turbidity by sampling event for all lakes beginning with the first June sampling event. Outliers not shown. There are few turbidity measures in event 3 due to instrument failure.

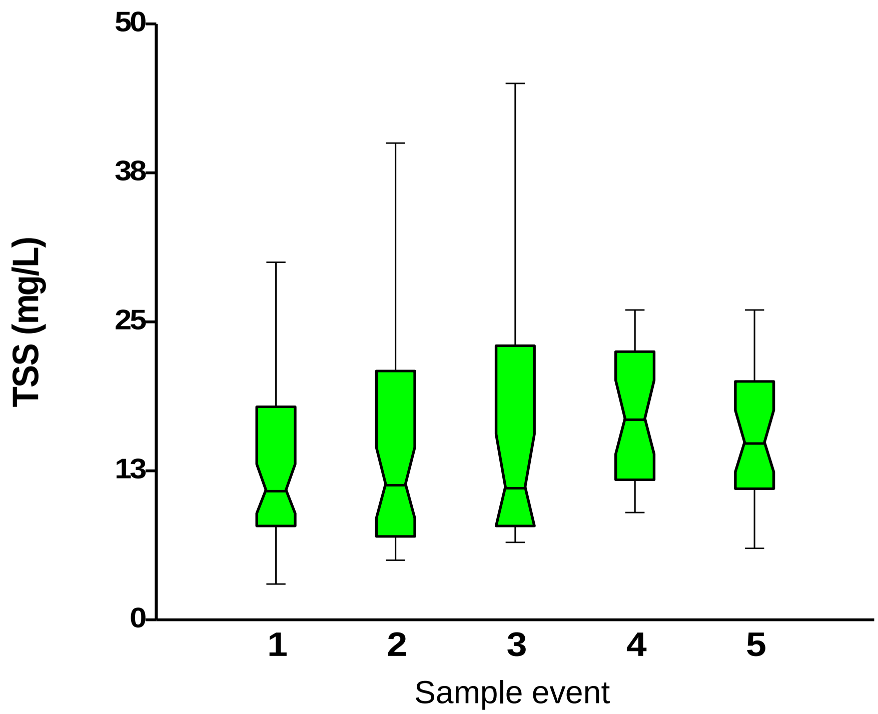

Figure 23. Box plot of TSS by sampling event for all lakes beginning with the first June sampling event. Outliers not shown.

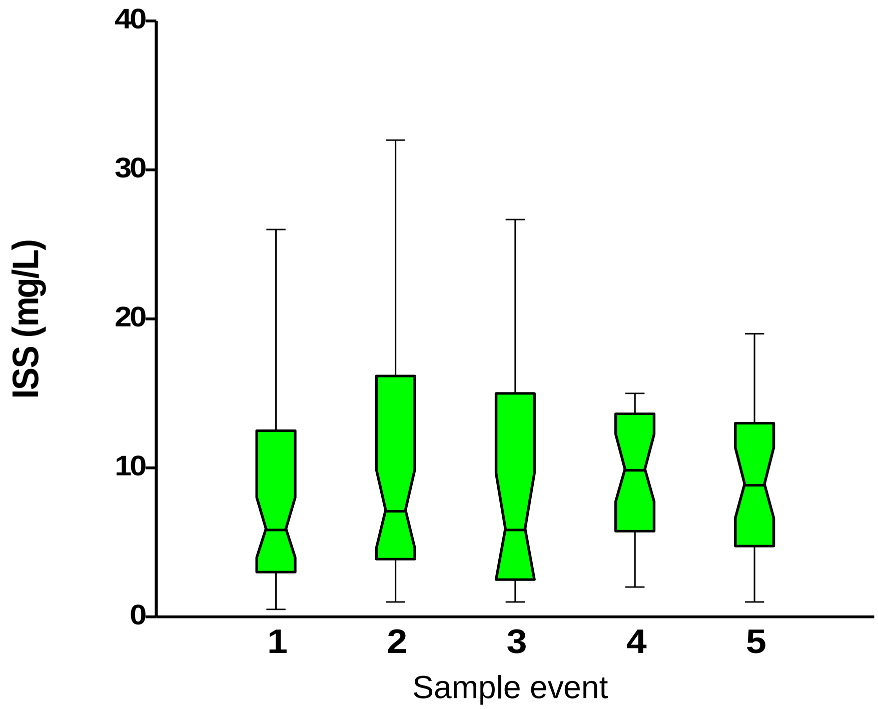

Figure 24. Box plot of ISS by sampling event for all lakes beginning with the first June sampling event. Outliers not shown.

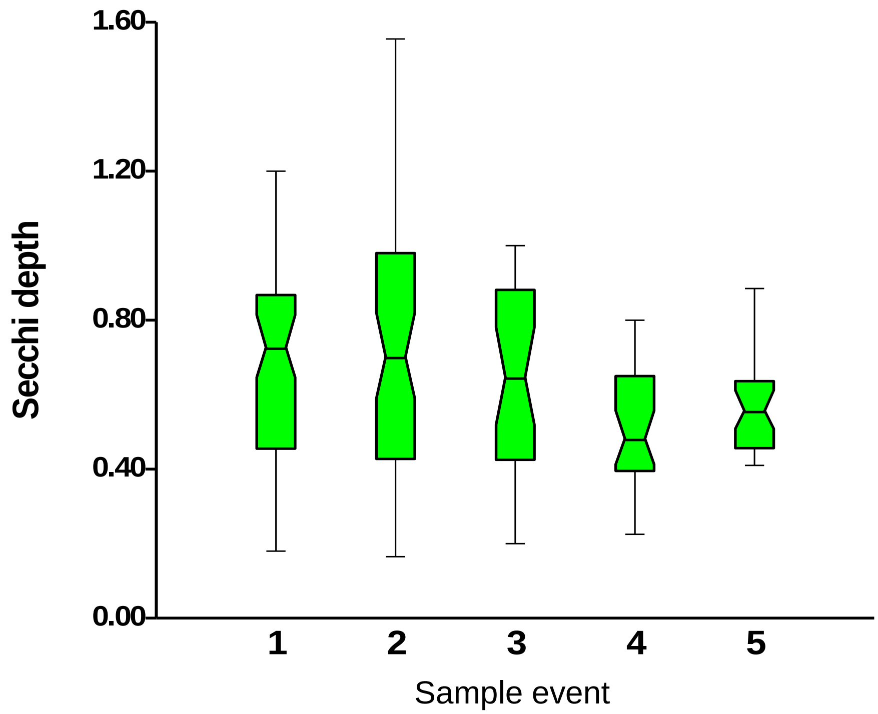

Figure 25. Box plot of Secchi depth (meters) by sampling event for all lakes beginning with the first June sampling event. Outliers not shown.

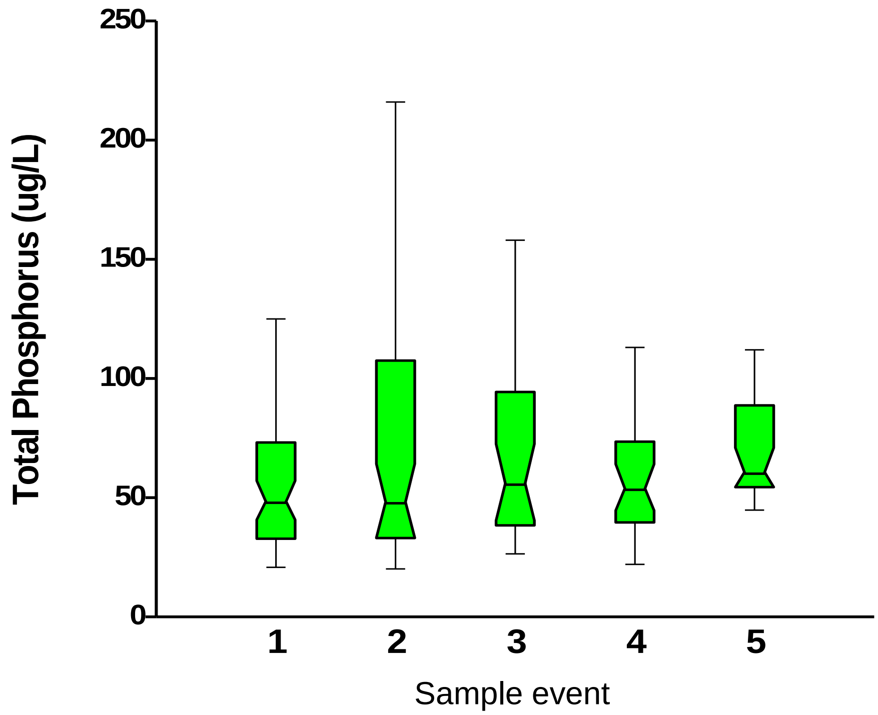

Figure 26. Box plot of total phosphorus by sampling event for all lakes beginning with the first June sampling event. Outliers not shown.

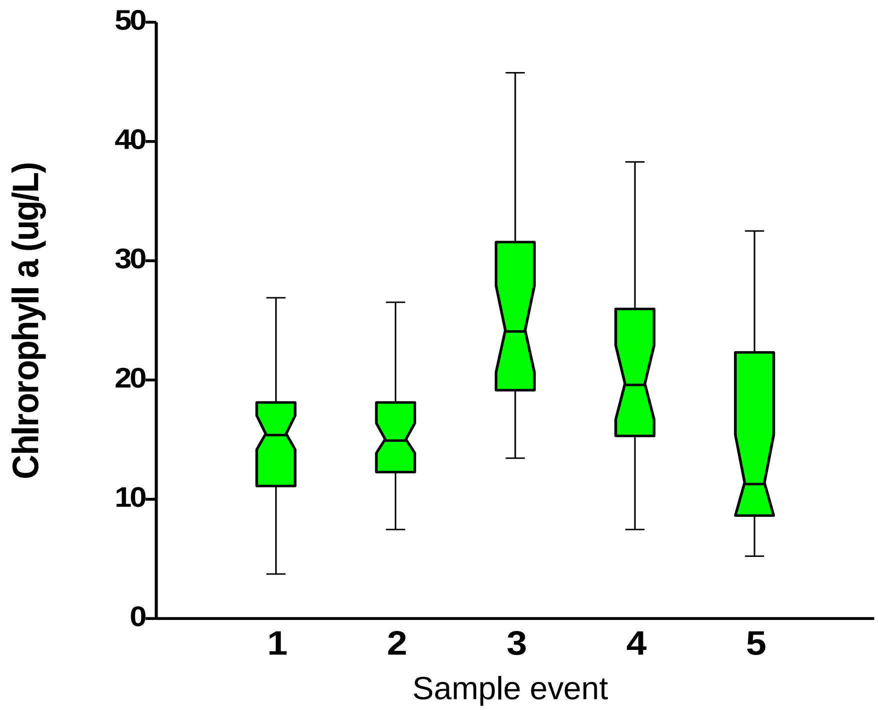

Figure 27. Box plot of chlorophyll-*a* by sampling event for all lakes beginning with the first June sampling event. Outliers not shown.

Nutrient and Chlorophyll Relationships

Robust regression was used to identify possible relationships between TP and chlorophyll-*a*. The general relationships between the macro-nutrients (i.e. nitrogen and phosphorus) and algal production and biomass is well understood (e.g. Wetzel 2001). More often TP is the limiting nutrient in lakes and reservoirs in our region and thus our analysis was limited to just looking at TP/chlorophyll relationships. Both TP and chlorophyll variables were normalized by log transformation and then used in a robust regression analyses. Regression models for both individual lakes and all lakes as a single population were determined (Table 6).

Table 6. Robust regression models for chlorophyll-*a* using TP as the independent variable. Models for individual lakes and all lakes were generated using data from all dates.

Lake Model	Sample size	Significant model (p value)	R^2 value	Relationship (slope)
Clinton	70	NS (0.7480)	-	-
Hillsdale	70	>0.0000	0.35	+0.511
Centralia	35	>0.0000	0.61	+1.886
Louisburg-Middle Creek	32	>0.0000	0.57	-0.775
All lakes model	207	NS (0.052)	-	-

Three of the four study lakes were found to have significant relationships between chlorophyll-*a* and TP, however the Louisburg-Middle Creek model indicated that this relationship was negative (Table 6). Increases in TP most often lead to increases in chlorophyll concentration assuming that no other factors are controlling plant growth. A negative regression relationship is probably not biologically significant and is most likely an anomaly. In addition, the Clinton Lake or All Lakes models were significant and no model explained more than about 60% of the variation in chlorophyll-*a*.

Another potential relationship was also explored using robust regression – that between turbidity or suspended matter in lakes and TP concentrations. It was hypothesized that TP in lakes within our region could be predicted using either a measure of suspended material in lakes or turbidity itself. Thus a series of robust regressions were run using TSS, VSS, ISS, and turbidity as separate independent variables that might estimate TP concentrations. Only a general lake model was investigated, thus all lake data was combined into a single database. All lake models were highly significant positive models with the Turbidity Model having the highest R^2 value (Table 7, Figure 28). The TSS model had the next highest R^2 value followed by the ISS and VSS models. It appears that turbidity is the best predictor of TP for these study lakes and might be used to estimate whole lake values of TP if a corresponding remotely sensed model for turbidity can be developed.

Lastly, the possible relationships between chlorophyll-*a* and turbidity or measures of suspended solids were again examined by robust regression. Only the VSS model (sample size = 207, p >0.0000) was significant but it only explained 11% of the variance between VSS and chlorophyll-*a*. No other water quality variables measured in this study were found to be predictors of chlorophyll-*a*.

Table 7. Robust regression models for TP using turbidity and three measures of suspended solids as the independent variable. All model variables were log transformed and all models were developed using all date and lake data.

"Turbidity" Model	Sample size	Significant model (p value)	R^2 value	Relationship (slope)
Turbidity (NTU)	170	>0.0000	0.81	+0.604
Total suspended solids (mg/L)	207	>0.0000	0.75	+0.659
Volatile suspended solids (mg/L)	207	>0.0000	0.56	+1.040
Inorganic suspended solids (mg/L)	204	>0.0000	0.57	+0.442

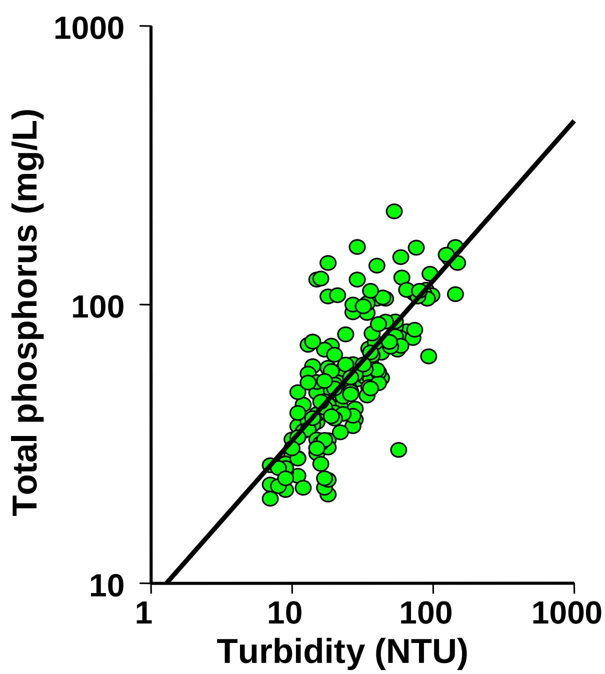

Figure 28. Scatter plot of TP verses turbidity for all dates and all lakes.

MODIS and water chemistry models
As stated in a previous section, models relating MODIS reflectance to water chemistry data were explored only for the two large reservoirs in this study (Clinton Lake and Hillsdale Reservoir) due to the coarse spatial resolution of the MODIS 250-meter data. Initial data exploration of relationships between MODIS satellite imagery (red and near-infrared reflectance, MODIS TERRA Bands 1 and 2, respectively) indicated no discernible relationships between the near-infrared reflectance (Band 2) and any of the field sampled water chemistry variables. Thus, discussions below focus only on the relationship of MODIS Band 1 (red reflectance) to water chemistry variables.

Turbidity: Relationships between red reflectance and turbidity (NTU) were positive and non-linear (consistent with published literature), and strongest for summer sampling events (June and July). No turbidity values were recorded for the August sampling event due to equipment failure. Turbidity values for fall sampling dates (October and November) generally did not have a sufficient range of values to produce strong statistical relationships (Figure 29).

Total Suspended Solids (TSS) and LogTSS: Relationships between red reflectance and total suspended solids (TSS) were positive, non-linear, and strongest for summer sampling events (June and July). TSS values for fall sampling dates (October and November) generally were low in magnitude and did not have a sufficient range of values to produce strong statistical relationships (Figure 30). A log transformation of TSS yielded linear relationships (Figure 31), but with the same limitations in the fall dates as the untransformed data.

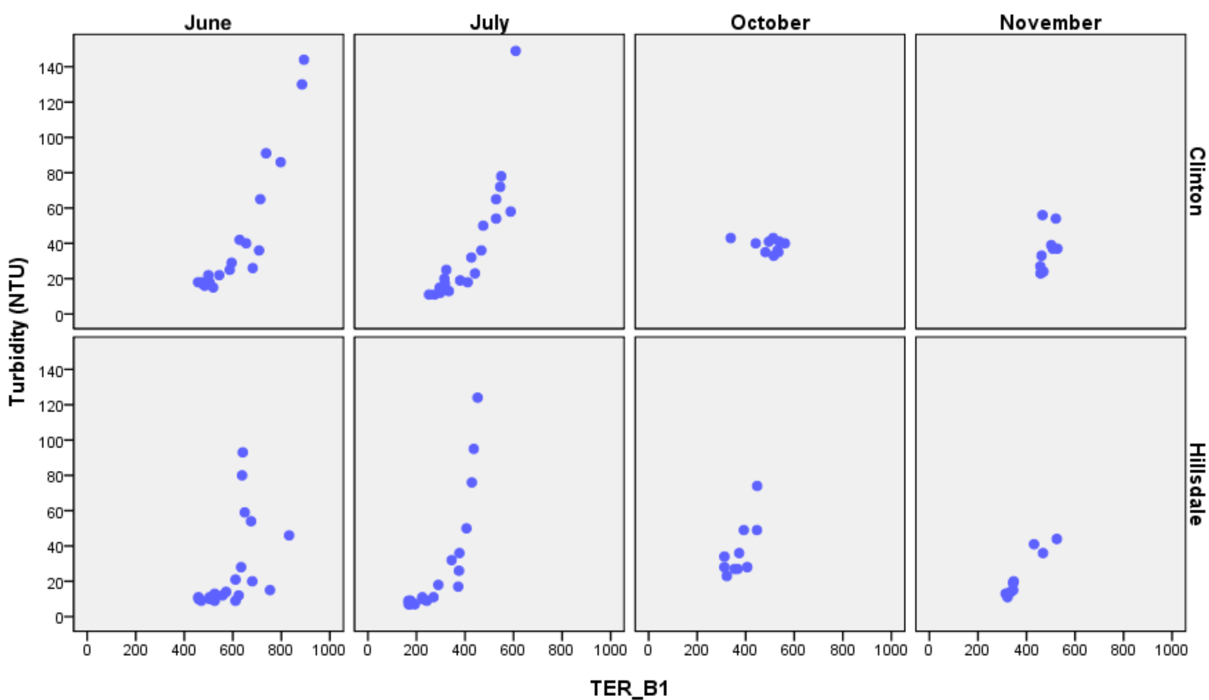

Figure 29. Scatter plots of MODIS TERRA Band 1 (red reflectance) and turbidity (NTU) for Clinton and Hillsdale Lakes, during summer and fall sampling events.

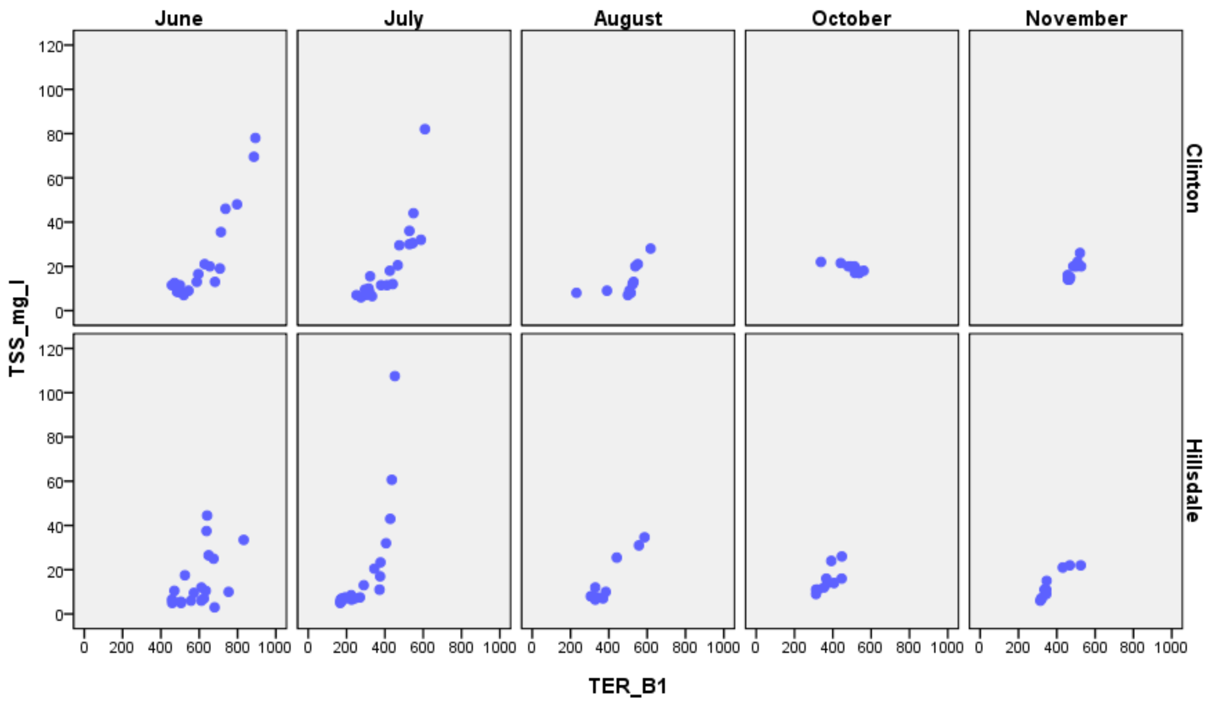

Figure 30. Scatter plots of MODIS TERRA Band 1 (red reflectance) and total suspended solids (TSS) for Clinton and Hillsdale Lakes, during summer and fall sampling events.

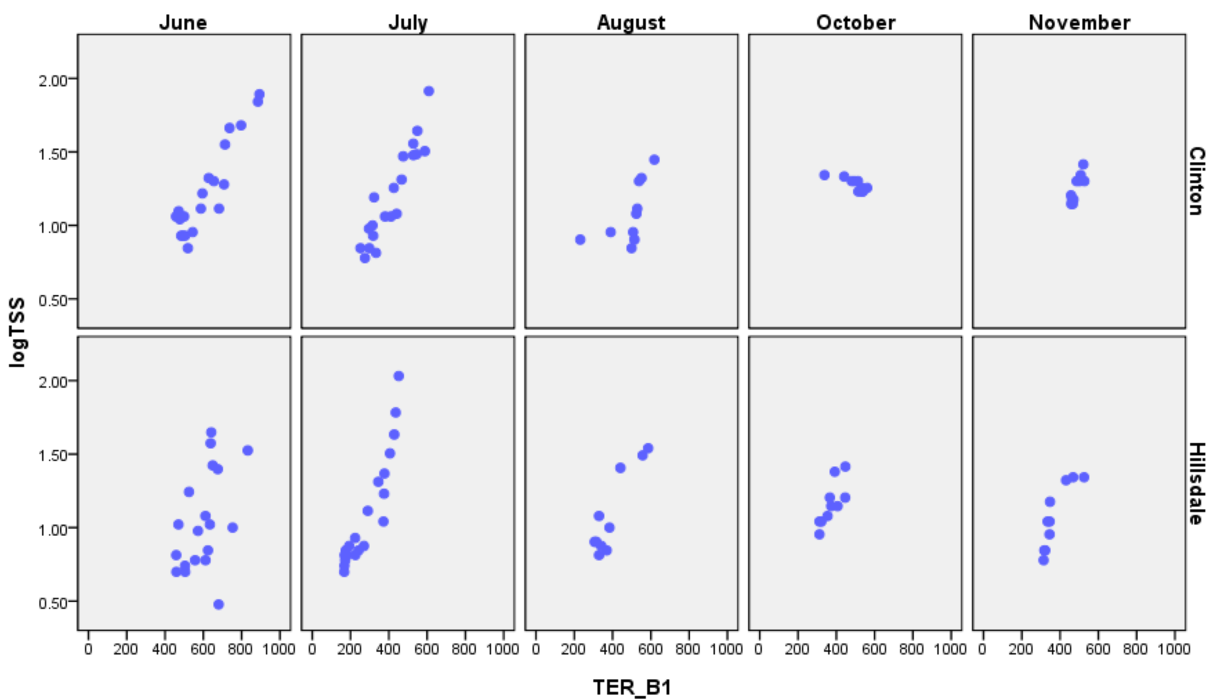

Figure 31. Scatter plots of MODIS TERRA Band 1 (red reflectance) and log-transformed total suspended solids (LogTSS) for Clinton and Hillsdale Lakes, during summer and fall sampling events.

Chlorophyll-a and pheophytin: Relationships between spectral reflectance and chlorophyll/pheophytin were ambiguous and contradictory. From a spectral-biophysical perspective, the expected relationship between chlorophyll and red reflectance should be negative, i.e., as chlorophyll-*a* increases, the reflectance in the red band of the spectrum should decrease due to absorption of red wavelengths by chlorophyll. For the June-Clinton lake event, the relationship follows this pattern (Figure 32); however, the relationship for the July-Hillsdale lake event is in the opposite. June-Hillsdale and July-Clinton showed no trends at all, and neither did the fall dates (October, November) for either lake (Figure 32). Pheophytin was significantly correlated with red reflectance only during the July event for both lakes (Table 8, Figure 33).

Table 8. Correlations between MODIS TERRA Band 1 (red reflectance) and selected water quality parameters.

Lake/Dates	Test	Turbidity (NTU)	TSS (mg/L)	Log of TSS	Ca (ug/L)	Pa (ug/L)
Clinton & Hillsdale combined, all months	Pearson Correlation	0.547**	0.487**	0.541**	-.074	-.041
	Sig. (2-tailed)	.000	.000	.000	.388	.630
	N	119	139	139	140	140
Clinton all months	Pearson Correlation	0.710**	0.682**	0.698**	.070	.137
	Sig. (2-tailed)	.000	.000	.000	.563	.260
	N	59	70	70	70	70
Hillsdale, all months	Pearson Correlation	0.347**	0.307*	0.370**	.037	.030
	Sig. (2-tailed)	.007	.010	.002	.759	.805
	N	60	69	69	70	70
Clinton June	Pearson Correlation	0.915**	0.906**	0.926**	-0.740**	-.373
	Sig. (2-tailed)	.000	.000	.000	.000	.105
	N	20	20	20	20	20
Clinton July	Pearson Correlation	0.842**	0.829**	0.933**	0.444*	0.681**
	Sig. (2-tailed)	.000	.000	.000	.050	.001
	N	20	20	20	20	20
Clinton August	Pearson Correlation	N/D	.608	.614	.053	.347
	Sig. (2-tailed)	0	.062	.059	.884	.325
	N	0	10	10	10	10
Clinton October	Pearson Correlation	-.374	-0.826**	-0.809**	-.487	-.480
	Sig. (2-tailed)	.287	.003	.005	.153	.161
	N	10	10	10	10	10
Clinton November	Pearson Correlation	.454	0.876**	0.887**	0.774**	.480
	Sig. (2-tailed)	.220	.001	.001	.009	.160
	N	9	10	10	10	10

Lake/Dates	Test	Turbidity (NTU)	TSS (mg/L)	Log of TSS	Ca (ug/L)	Pa (ug/L)
Hillsdale June	Pearson Correlation	0.486*	0.485*	0.467*	.318	0.544*
	Sig. (2-tailed)	.030	.035	.044	.172	.013
	N	20	19	19	20	20
Hillsdale July	Pearson Correlation	0.821**	0.750**	0.924**	0.795**	0.770**
	Sig. (2-tailed)	.000	.000	.000	.000	.000
	N	20	20	20	20	20
Hillsdale August	Pearson Correlation	N/D	0.950**	0.913**	0.873**	.540
	Sig. (2-tailed)	0	.000	.000	.001	.107
	N	0	10	10	10	10
Hillsdale October	Pearson Correlation	0.739*	0.746*	0.795**	.508	-.104
	Sig. (2-tailed)	.015	.013	.006	.134	.776
	N	10	10	10	10	10
Hillsdale November	Pearson Correlation	0.956**	0.923**	0.876**	.404	-.108
	Sig. (2-tailed)	.000	.000	.001	.246	.766
	N	10	10	10	10	10

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
N/D (No data) – Turbidity not measured due to equipment failure

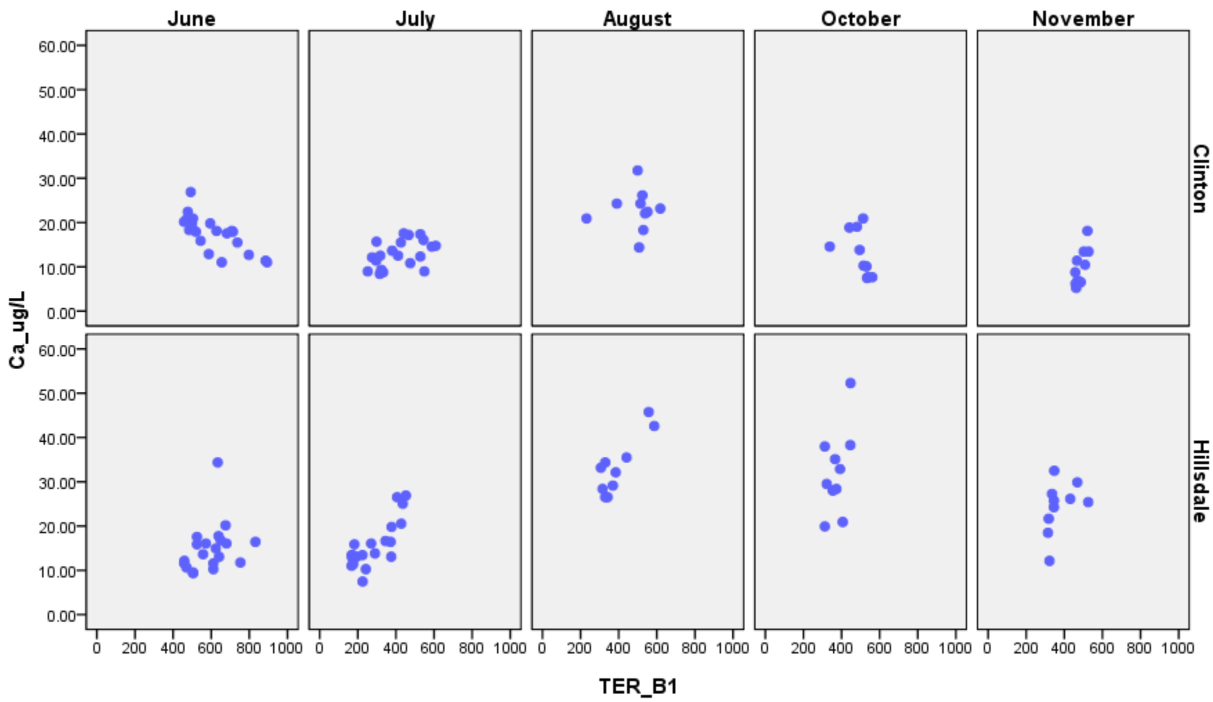

Figure 32. Scatter plots of MODIS TERRA Band 1 (red reflectance) and chlorophyll-*a* for Clinton and Hillsdale Lakes, during summer and fall sampling events.

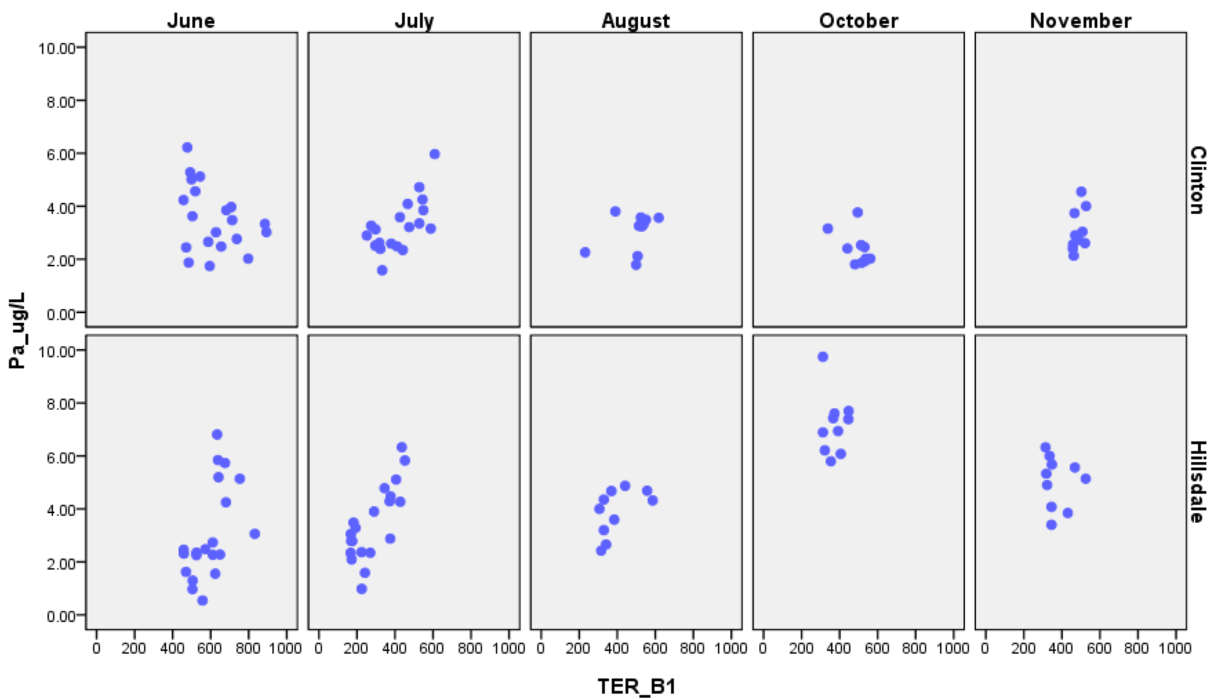

Figure 33. Scatter plots of MODIS TERRA Band 1 (red reflectance) and pheophytin for Clinton and Hillsdale Lakes, during summer and fall sampling events.

Application of regression equation to satellite imagery

A potentially useful application of the relationship between MODIS red reflectance and water quality parameters is the ability to treat a satellite image as an independent data set, applying a regression equation developed from field-sampled water quality data (Figure 34) to produce spatially-explicit representations of water quality patterns across a reservoir (Figure 35). As a demonstration of this, we computed a regression equation for July log-transformed total suspended solids using the July 22 MODIS red reflectance (Figure 36) as the independent variable. The July data for Clinton represents the best of the statistical relationships in any month for Hillsdale or Clinton Lakes (Figure 34).

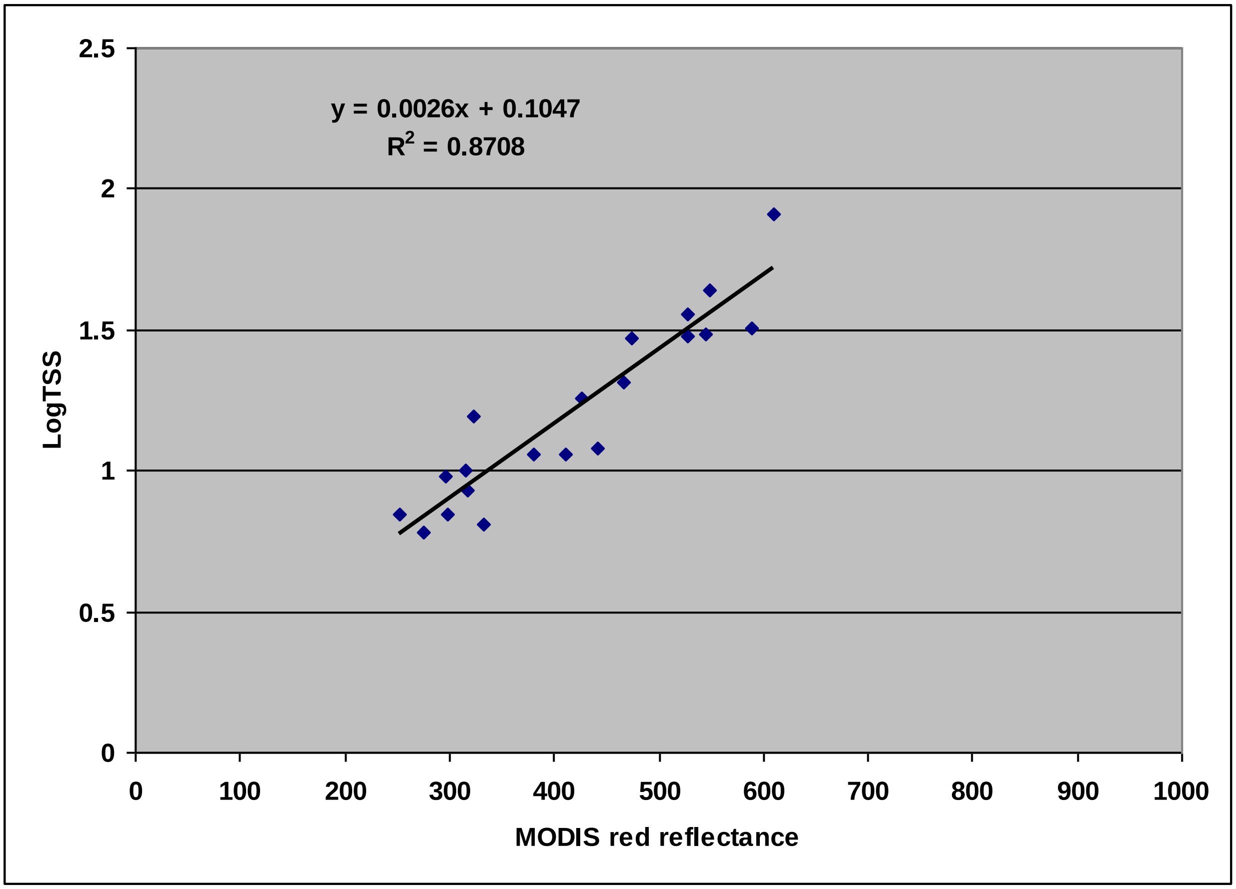

Figure 34. Scatter plot and regression equation predicting log-transformed total suspended solids (TSS) from MODIS TERRA Band 1 (red reflectance) for Clinton Lake during July sampling event.

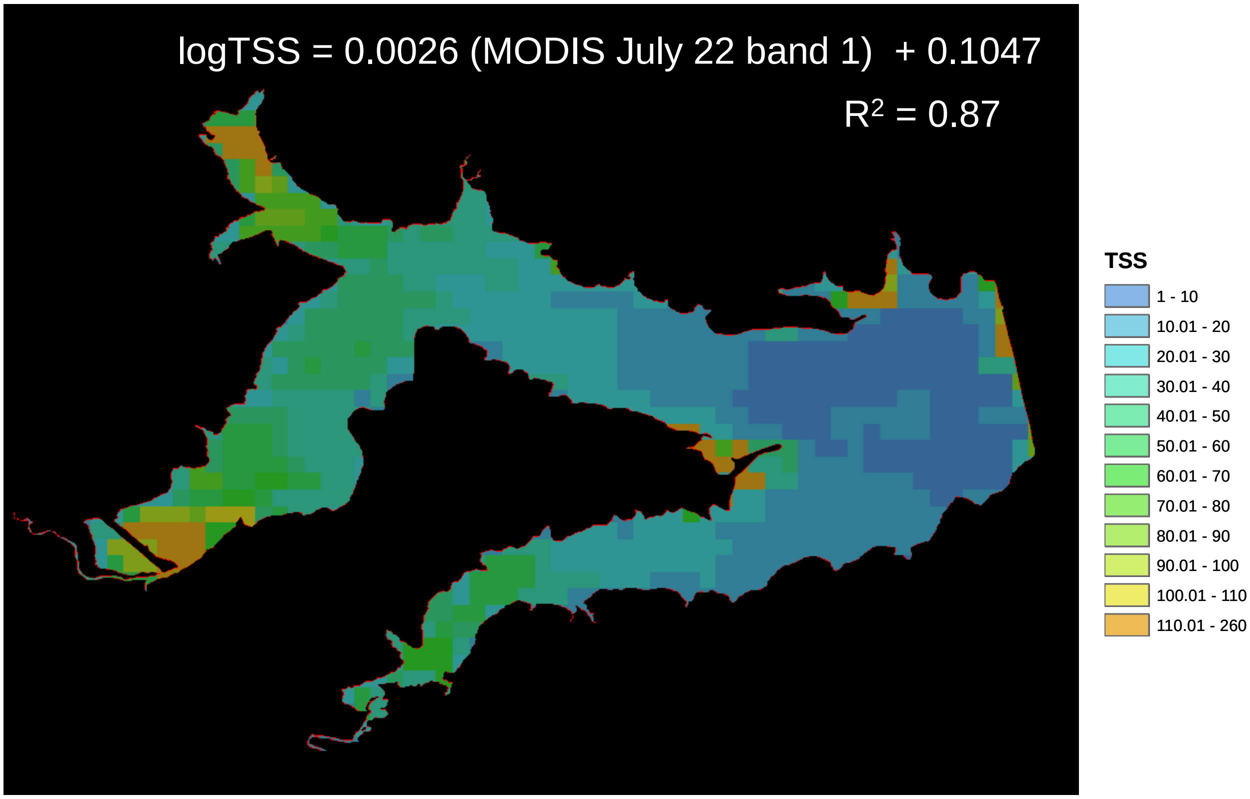

Figure 35. Results of applying a regression equation predicting log-transformed total suspended solids (TSS) to MODIS TERRA Band 1 (red reflectance) data for Clinton Lake during July sampling event.

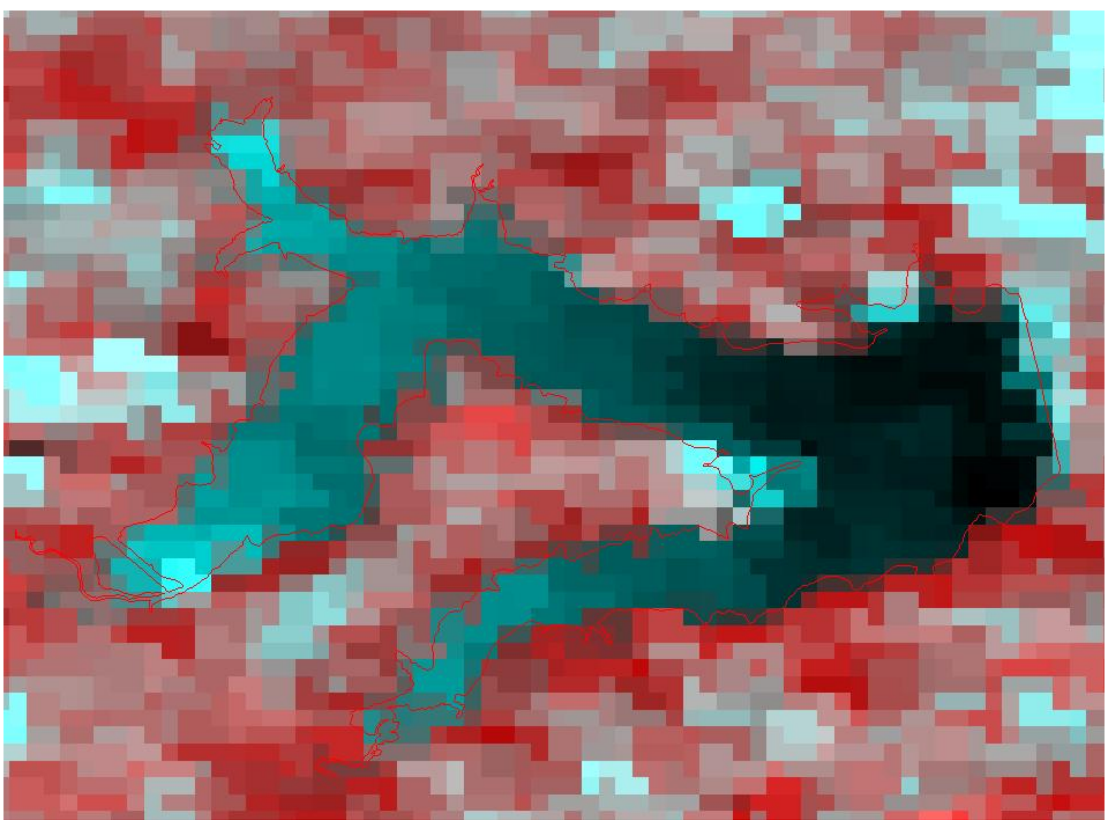

Figure 36. MODIS TERRA July 22, 2009 false-color composite image for Clinton Lake.

LANDSAT and water chemistry models

Models relating Landsat 5 Thematic Mapper spectral reflectance to water chemistry data were explored. Thematic Mapper bands 5, 6, and 7 (middle-infrared, thermal infrared, and middle-infrared, respectively) were not used in the statistical analysis, as water strongly absorbs these wavelengths of light. The June 17, 2009 Landsat scene was not used; scatter plots of invariant targets suggested an offset between the June data and other dates, indicating a possible problem either with gain/offset coefficients in converting to reflectance, a calibration issue, or excessive high-atmospheric haze. Unlike the MODIS 250-m spatial resolution data, the 30-m resolution of the Thematic Mapper allowed data from all four reservoirs to be used.

Chlorophyll-a and pheophytin: Relationships between chlorophyll and spectral reflectance were generally not significant (Table 9 - Table 14), and where statistically significant, an examination of the scatter plots for chlorophyll-*a* versus red reflectance and near-infrared reflectance shows that most reservoirs sampled, on most dates, did not have a wide range of chlorophyll values (Figure 37 - Figure 38). Typically when significant correlations were observed between chlorophyll-*a* and specific bands these correlations were negative for the smaller lakes (Centralia and Louisburg-Middle Creek) and both positive and negative for the larger lakes (Clinton and Hillsdale) depending on data dates used in the correlation matrix. Similar patterns of significance were found with pheophytin and spectral bands with large lake relationships showing mostly positive relationships between these factors while small lakes displayed either no or negative relationships. Except for October and November models most correlation coefficients were relatively small (<0.60) which along with temporally changing sign relations (positive to suggests that these relationships are weak or none existing.

Secchi depth., turbidity, and total suspended solids (TSS): As expected, turbidity and total suspended solids were positively correlated with all spectral reflectance bands (e.g., as the turbidity increases, the increasing density of particles in the water scatters more light back to the sensor). No turbidity values were recorded for the August sampling event due to equipment failure. However, the relationships were inconsistent from month-to-month and lake-to lake; Hillsdale and Clinton Reservoirs, with a greater diversity of conditions and greater number of sample points than Centralia Lake or Louisburg-Middle Creek Lake, exhibited significant correlations more often than the smaller lakes. An examination of the scatter plots for Secchi depth, turbidity, and total suspended solids versus Landsat TM Band 3 (red reflectance) (Figure 39 - Figure 42) shows that poor/non-existent correlations between the water quality variables and spectral reflectance was likely due to the insufficient range of data values, particularly in small lakes and during the fall sampling events.

Application of regression equation to satellite imagery

As with the MODIS imagery, as a demonstration of the potential to produce spatially-explicit estimates of water quality patterns across a reservoir, we computed a regression equation for July log-transformed total suspended solids using the July 19, 2009 Thematic Mapper red reflectance as the independent variable (Figure 43). The July data for Clinton represents the best of the statistical relationships in any month for Hillsdale or Clinton Lakes (Figure 43). The product is a map of predicted TSS in the reservoir on that date (Figure 44 - Figure 45).

Table 9. Significant correlations between Landsat Thematic Mapper spectral bands and selected water quality parameters. All sampling dates by lake / band. TSS – total suspended solids, Ca – chlorophyll-*a*, Pa – pheophytin.

Lake and bands	Secchi Depth (m)	Turbidity (NTU)	TSS (mg/L)	Ca (ug/L)	Pa (ug/L)
Centralia Lake					
TM Band 1 (blue)	-0.351*			-0.451**	
TM Band 2 (green)	-0.561**	0.447*		-0.338*	
TM Band 3 (red)	-0.633**	0.544**	0.393*	-0.446**	
TM Band 4 (NIR)					
Clinton Lake					
TM Band 1 (blue)					0.268*
TM Band 2 (green)			0.270*		0.323**
TM Band 3 (red)	-0.320**	0.419**	0.439**		0.300*
TM Band 4 (NIR)		0.327*	0.351**	0.337**	0.356**
Hillsdale Lake					
TM Band 1 (blue)				-0.282*	-0.291*
TM Band 2 (green)	-0.380**	0.307*			
TM Band 3 (red)	-0.379**	0.364**	0.279*		
TM Band 4 (NIR)				-0.398**	-0.386**
Louisburg-Middle Creek Lake					
TM Band 1 (blue)					-0.489*
TM Band 2 (green)					-0.471*
TM Band 3 (red)					-0.466*
TM Band 4 (NIR)					-0.485*

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

Table 10. Significant correlations between Landsat Thematic Mapper spectral bands and selected water quality parameters. All sampling dates (excluding June) by lake / band. TSS – total suspended solids, Ca – chlorophyll-*a*, Pa – pheophytin.

Lake and bands	Secchi Depth (m)	Turbidity (NTU)	TSS (mg/L)	Ca (ug/L)	Pa (ug/L)
Centralia Lake					
TM Band 1 (blue)				-0.519**	
TM Band 2 (green)	-0.572**			-0.439*	
TM Band 3 (red)	-0.685**	0.597**	0.415*	-0.474*	
TM Band 4 (NIR)					
Clinton Lake					
TM Band 1 (blue)	-0.399**				
TM Band 2 (green)	-0.549**	0.543**	0.462**		0.393**
TM Band 3 (red)	-0.608**	0.617**	0.505**		0.473**
TM Band 4 (NIR)		0.536**	0.399**	0.459**	0.553**
Hillsdale Lake					
TM Band 1 (blue)					
TM Band 2 (green)	-0.643**	0.457**	0.425**		
TM Band 3 (red)	-0.627**	0.561**	0.519**		
TM Band 4 (NIR)		0.363*	0.448**		-0.345*
Louisburg-Middle Creek Lake					
TM Band 1 (blue)					-0.587*
TM Band 2 (green)					-0.592*
TM Band 3 (red)					
TM Band 4 (NIR)					-0.640*

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

Table 11. Significant correlations between Landsat Thematic Mapper spectral bands and selected water quality parameters. July-only sampling event by lake / band. TSS – total suspended solids, Ca – chlorophyll-*a*, Pa – pheophytin.

Lake and bands	Secchi Depth (m)	Turbidity (NTU)	TSS (mg/L)	Ca (ug/L)	Pa (ug/L)
Centralia Lake					
TM Band 1 (blue)					
TM Band 2 (green)	-0.759*	0.888**	0.849**		
TM Band 3 (red)		0.811**	0.743*		
TM Band 4 (NIR)		0.780**	0.676*		
Clinton Lake					
TM Band 1 (blue)	-0.783**	0.574**	0.566**	0.579**	0.542*
TM Band 2 (green)	-0.856**	0.692**	0.683**	0.459*	0.626**
TM Band 3 (red)	-0.886**	0.733**	0.726**		0.662**
TM Band 4 (NIR)	-0.794**	0.710**	0.672**		0.597**
Hillsdale Lake					
TM Band 1 (blue)	-0.748**	0.723**	0.617**	0.612**	0.494*
TM Band 2 (green)	-0.836**	0.752**	0.661**	0.666**	0.601**
TM Band 3 (red)	-0.821**	0.824**	0.749**	0.688**	0.623**
TM Band 4 (NIR)	-0.557*	0.621**	0.554*	0.473*	
Louisburg-Middle Creek Lake					
TM Band 1 (blue)					
TM Band 2 (green)					
TM Band 3 (red)					
TM Band 4 (NIR)					

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

Table 12. Significant correlations between Landsat Thematic Mapper spectral bands and selected water quality parameters. August-only sampling event by lake/ band. TSS – total suspended solids, Ca – chlorophyll-*a*, Pa – pheophytin.

Lake and bands	Secchi Depth (m)	Turbidity (NTU)	TSS (mg/L)	Ca (ug/L)	Pa (ug/L)
Centralia Lake					
TM Band 1 (blue)		†			
TM Band 2 (green)					
TM Band 3 (red)					
TM Band 4 (NIR)					
Clinton Lake					
TM Band 1 (blue)		†			
TM Band 2 (green)					
TM Band 3 (red)	-0.660*		0.734*		
TM Band 4 (NIR)	-0.701*		0.754*		
Hillsdale Lake					
TM Band 1 (blue)		†			
TM Band 2 (green)					
TM Band 3 (red)					
TM Band 4 (NIR)					
Louisburg-Middle Creek Lake					
TM Band 1 (blue)		†			
TM Band 2 (green)					
TM Band 3 (red)					
TM Band 4 (NIR)					

† No turbidity values were recorded for the August sampling event due to equipment failure
** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

Table 13. Significant correlations between Landsat Thematic Mapper spectral bands and selected water quality parameters. October-only sampling event by lake / band. TSS – total suspended solids, Ca – chlorophyll-*a*, Pa – pheophytin.

Lake and bands	Secchi Depth (m)	Turbidity (NTU)	TSS (mg/L)	Ca (ug/L)	Pa (ug/L)
Centralia Lake					
TM Band 1 (blue)					
TM Band 2 (green)			-0.968**		
TM Band 3 (red)					-0.932*
TM Band 4 (NIR)					
Clinton Lake					
TM Band 1 (blue)			-0.693*	-0.774**	
TM Band 2 (green)				-0.766**	
TM Band 3 (red)					
TM Band 4 (NIR)			0.708*		
Hillsdale Lake					
TM Band 1 (blue)		0.663*			
TM Band 2 (green)		0.700*	0.653*		
TM Band 3 (red)	-0.789**	0.838**	0.734*		
TM Band 4 (NIR)	-0.640*	0.788**	0.729*		
Louisburg-Middle Creek Lake					
TM Band 1 (blue)					
TM Band 2 (green)					
TM Band 3 (red)			0.919*		-0.967**
TM Band 4 (NIR)					

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

Table 14. Significant correlations between Landsat Thematic Mapper spectral bands and selected water quality parameters. November-only sampling event by lake / band. TSS – total suspended solids, Ca – chlorophyll-*a*, Pa – pheophytin.

Lake and bands	Secchi Depth (m)	Turbidity (NTU)	TSS (mg/L)	Ca (ug/L)	Pa (ug/L)
Centralia Lake					
TM Band 1 (blue)					
TM Band 2 (green)		-0.995**		-0.897*	
TM Band 3 (red)					
TM Band 4 (NIR)					
Clinton Lake					
TM Band 1 (blue)		-0.827**		-0.693*	
TM Band 2 (green)	0.639*			-0.788**	
TM Band 3 (red)		-0.785*	-0.664*		
TM Band 4 (NIR)					
Hillsdale Lake					
TM Band 1 (blue)					
TM Band 2 (green)	-0.783**	0.875**	0.767**		
TM Band 3 (red)	-0.778**	0.881**	0.712*		
TM Band 4 (NIR)		0.633*			
Louisburg-Middle Creek Lake					
TM Band 1 (blue)					
TM Band 2 (green)					
TM Band 3 (red)					
TM Band 4 (NIR)					

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

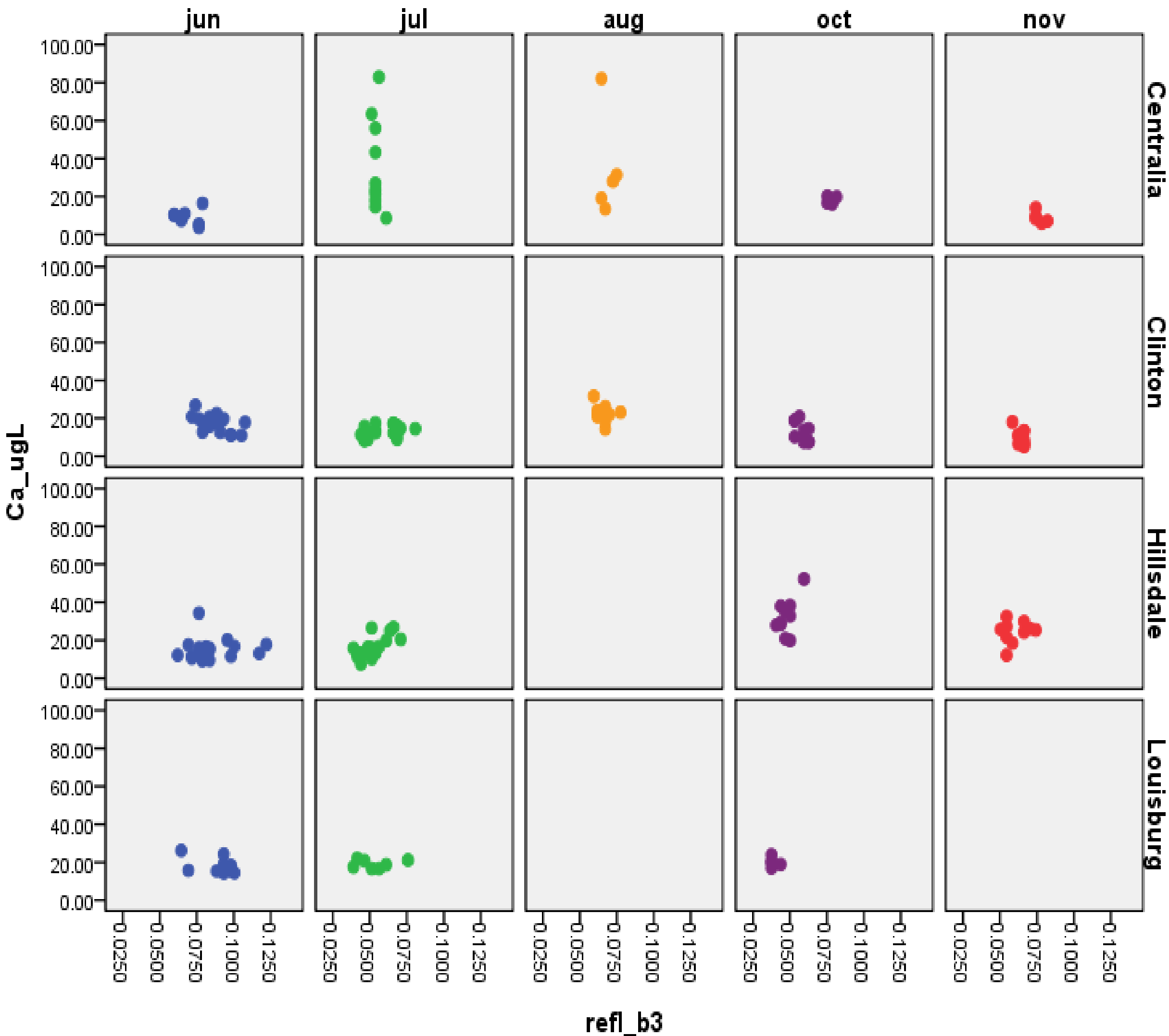

Figure 37. Scatter plots of Landsat 5 Thematic Mapper Band 3 (red reflectance) and chlorophyll-*a* for all four study lakes, during summer and fall sampling events.

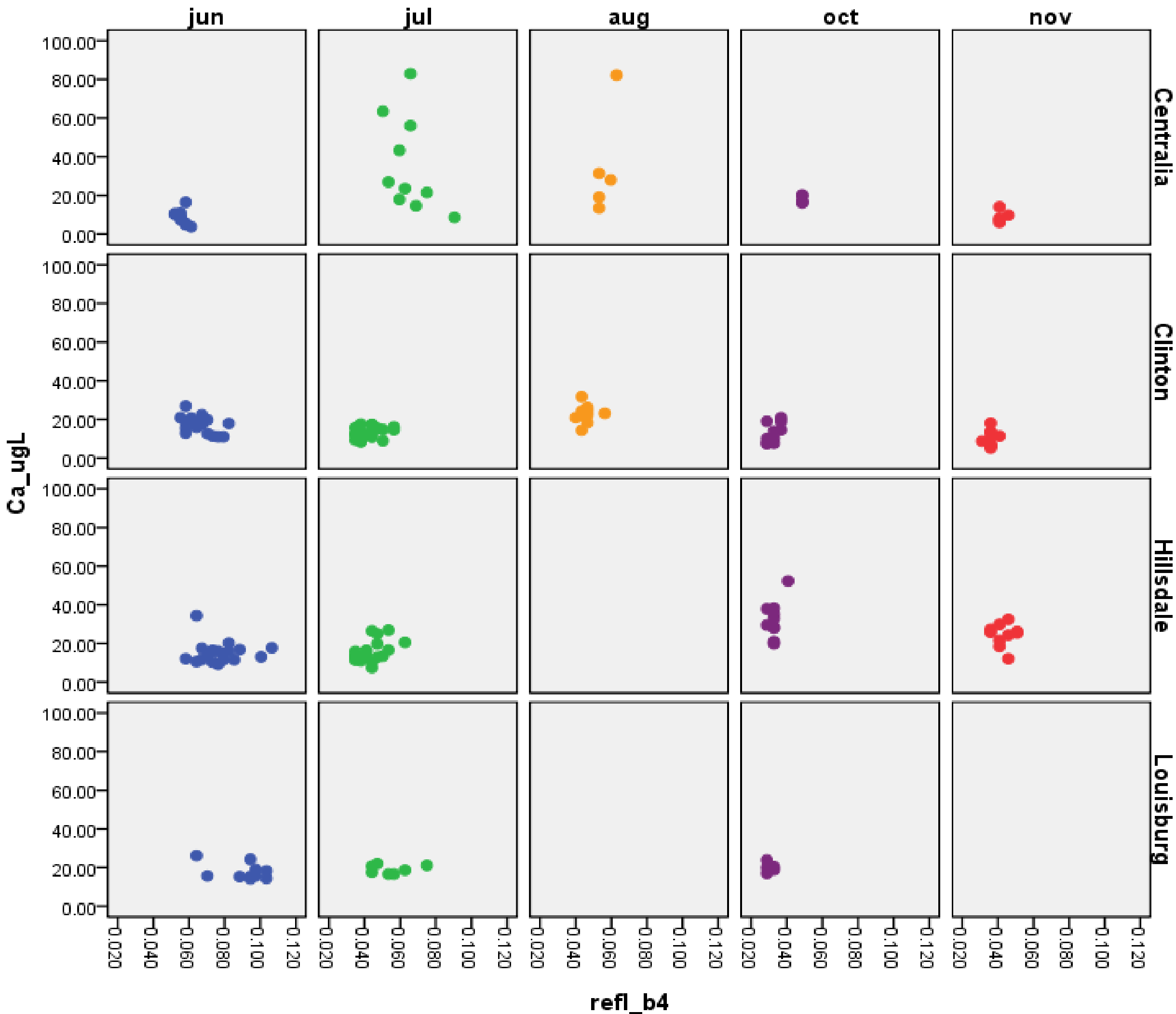

Figure 38. Scatter plots of Landsat 5 Thematic Mapper Band 4 (near-infrared reflectance) and chlorophyll-*a* for all four study lakes, during summer and fall sampling events.

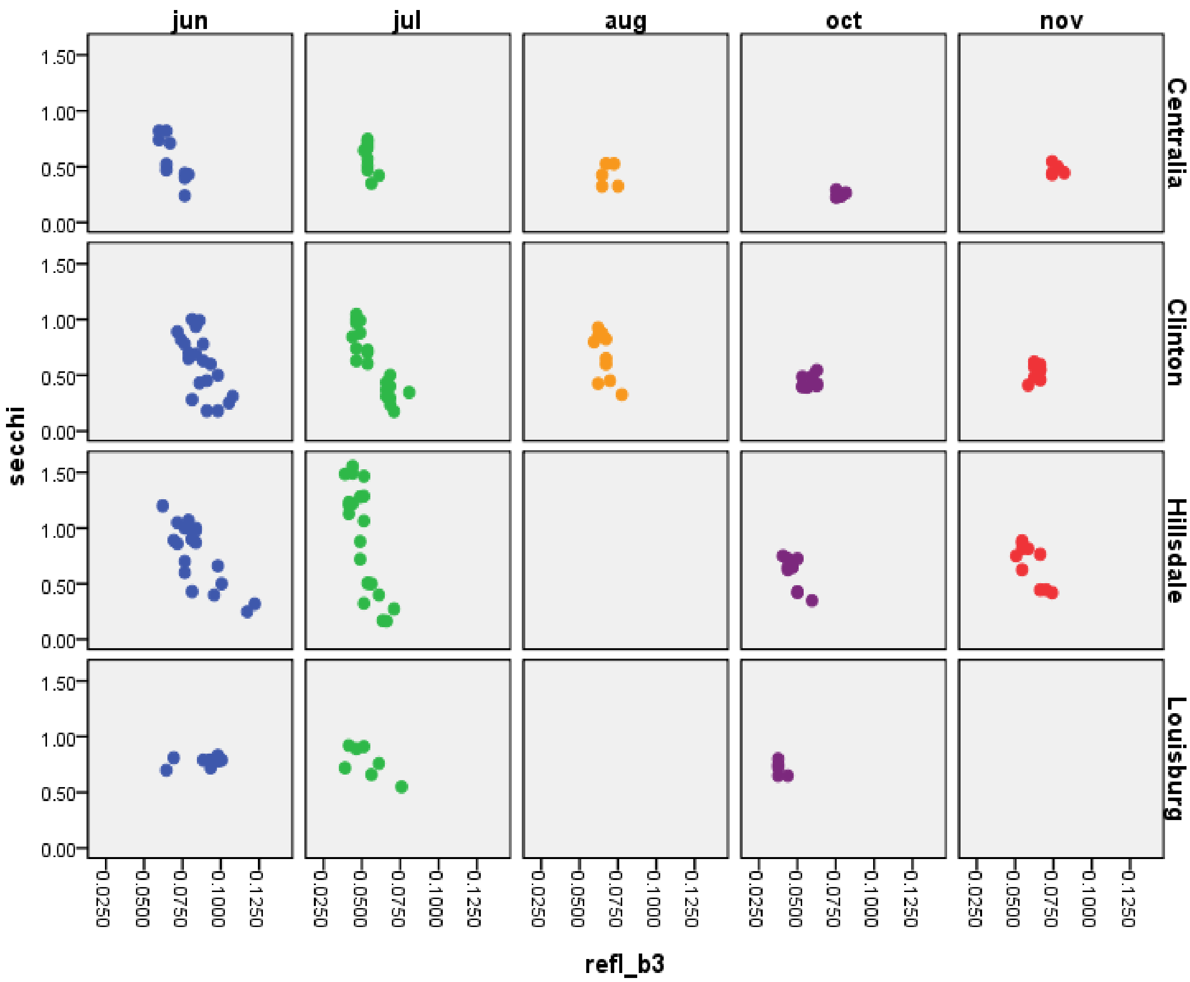

Figure 39. Scatter plots of Landsat 5 Thematic Mapper Band 3 (red reflectance) and secchi depth (meters) for all four study lakes, during summer and fall sampling events.

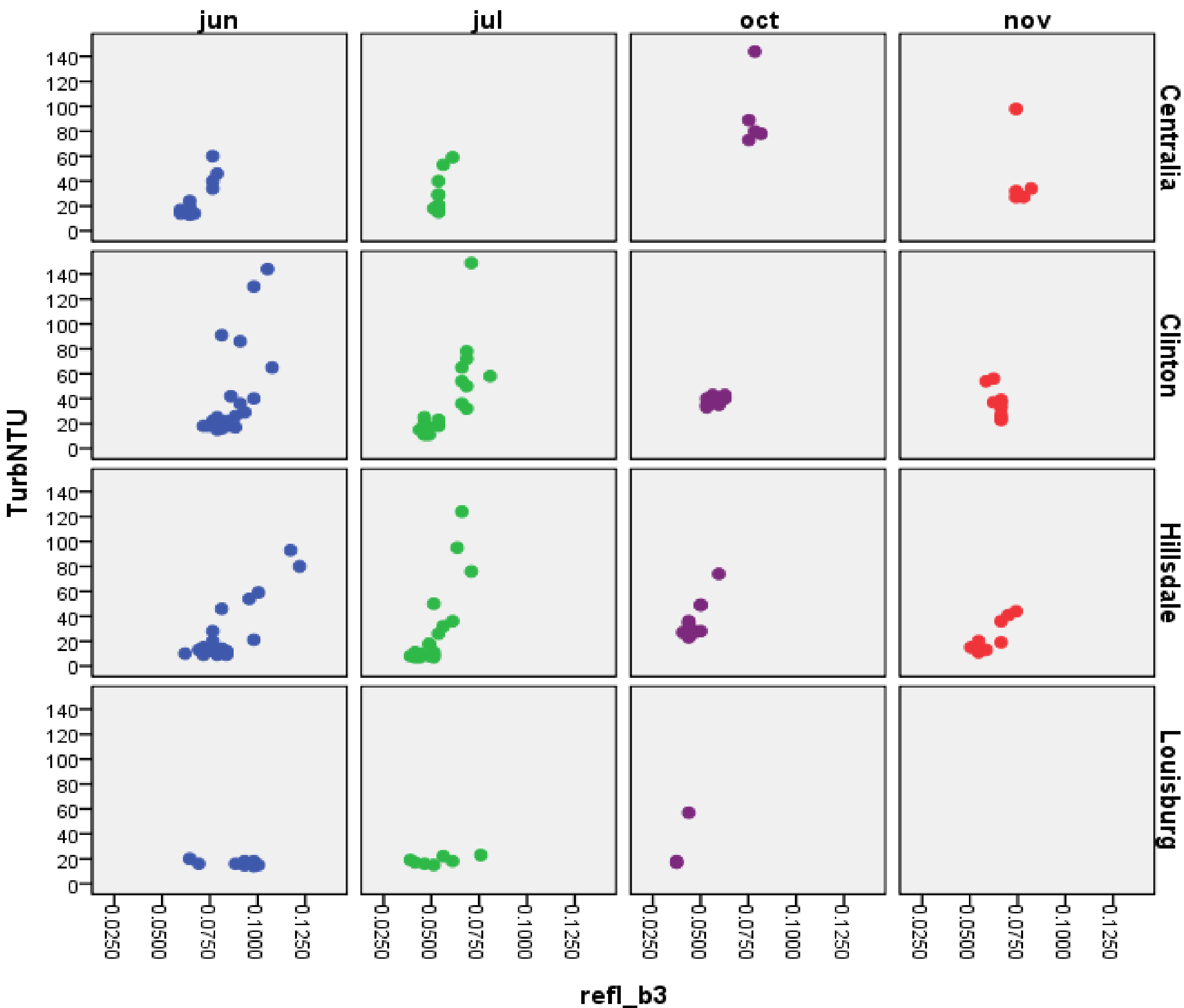

Figure 40. Scatter plots of Landsat 5 Thematic Mapper Band 3 (red reflectance) and turbidity (NTU) for all four study lakes, during summer and fall sampling events.

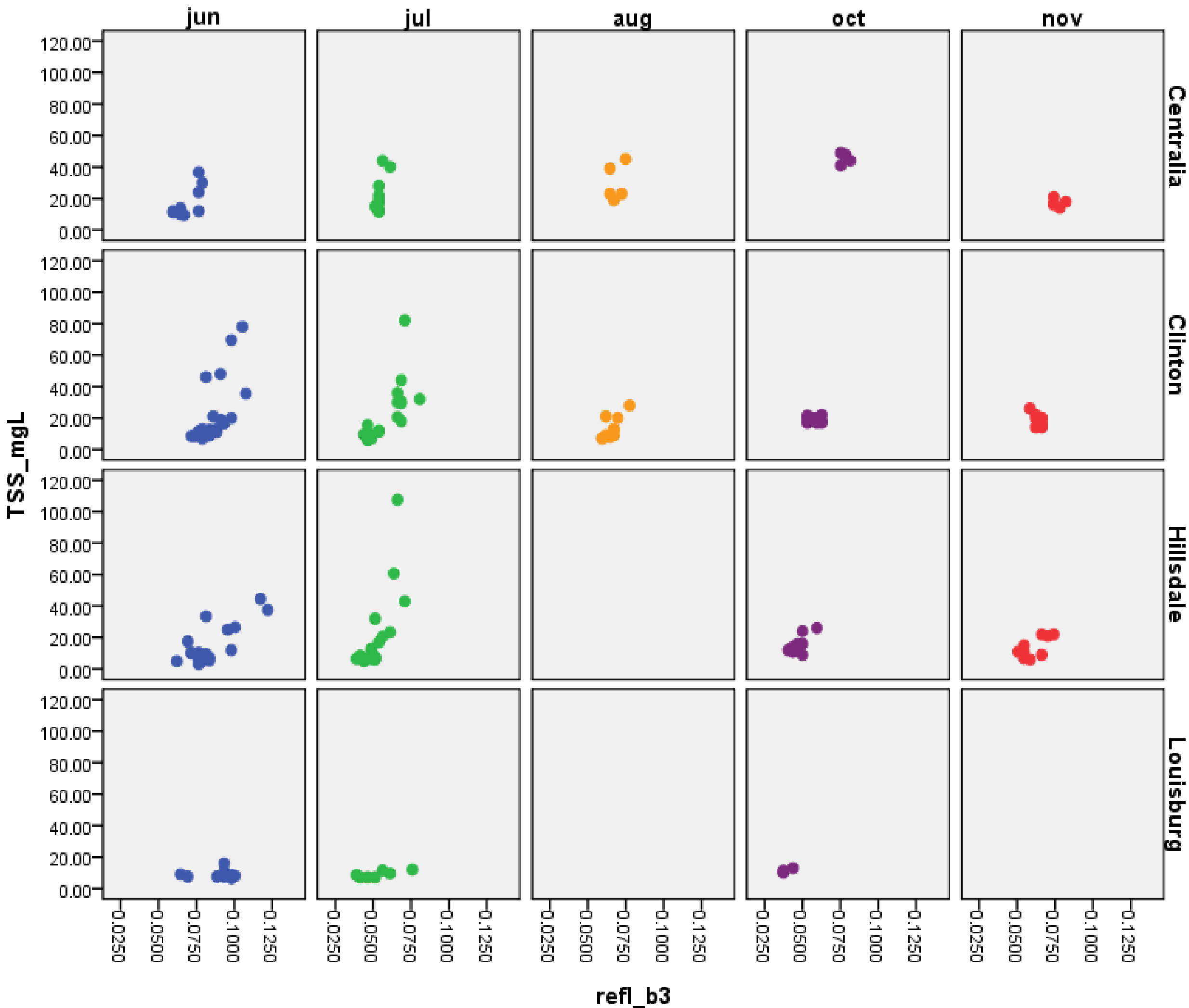

Figure 41. Scatter plots of Landsat 5 Thematic Mapper Band 3 (red reflectance) and total suspended solids (TSS) for all four study lakes, during summer and fall sampling events.

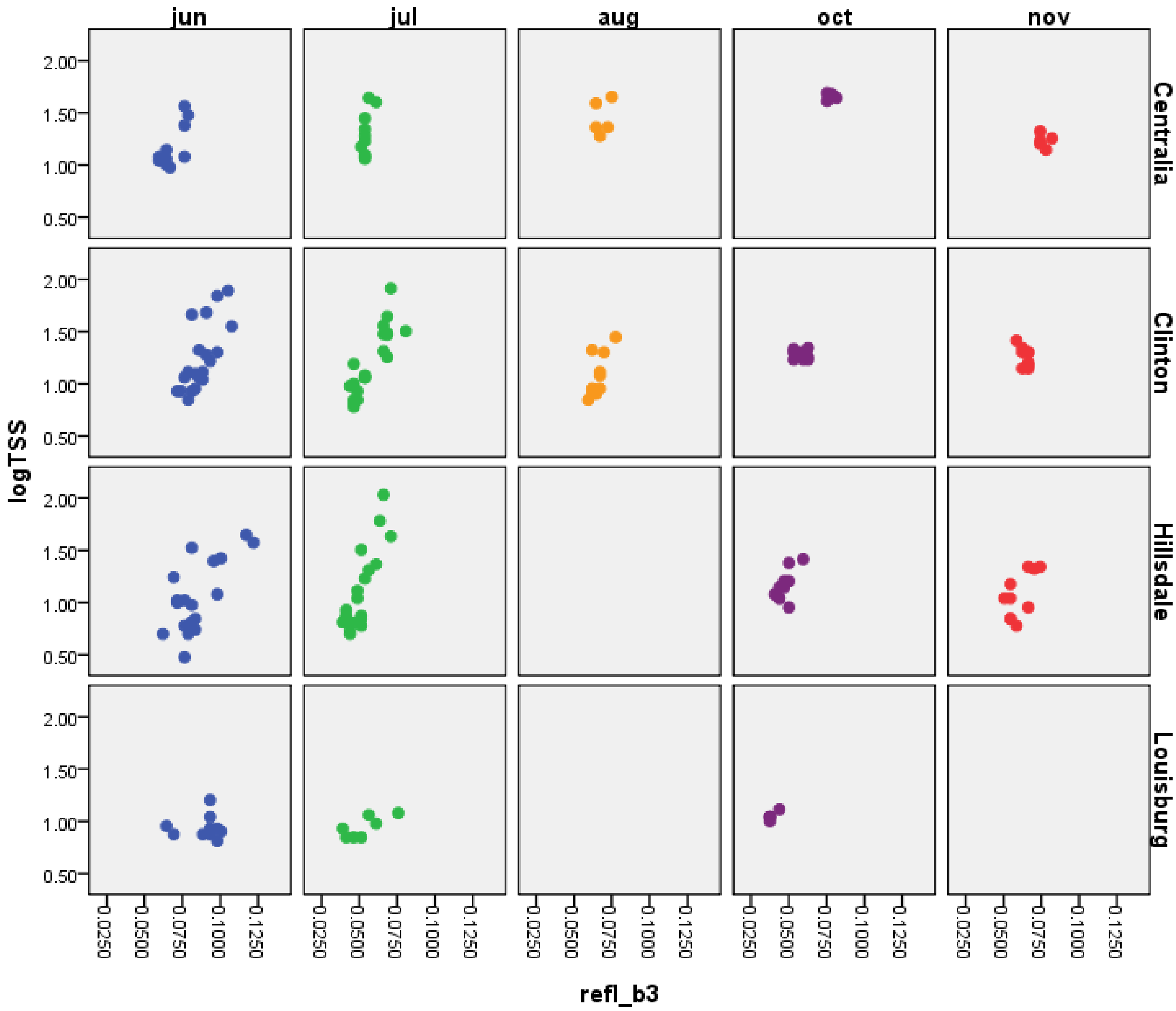

Figure 42. Scatter plots of Landsat 5 Thematic Mapper Band 3 (red reflectance) and log-transformed total suspended solids (TSS) for all four study lakes, during summer and fall sampling events.

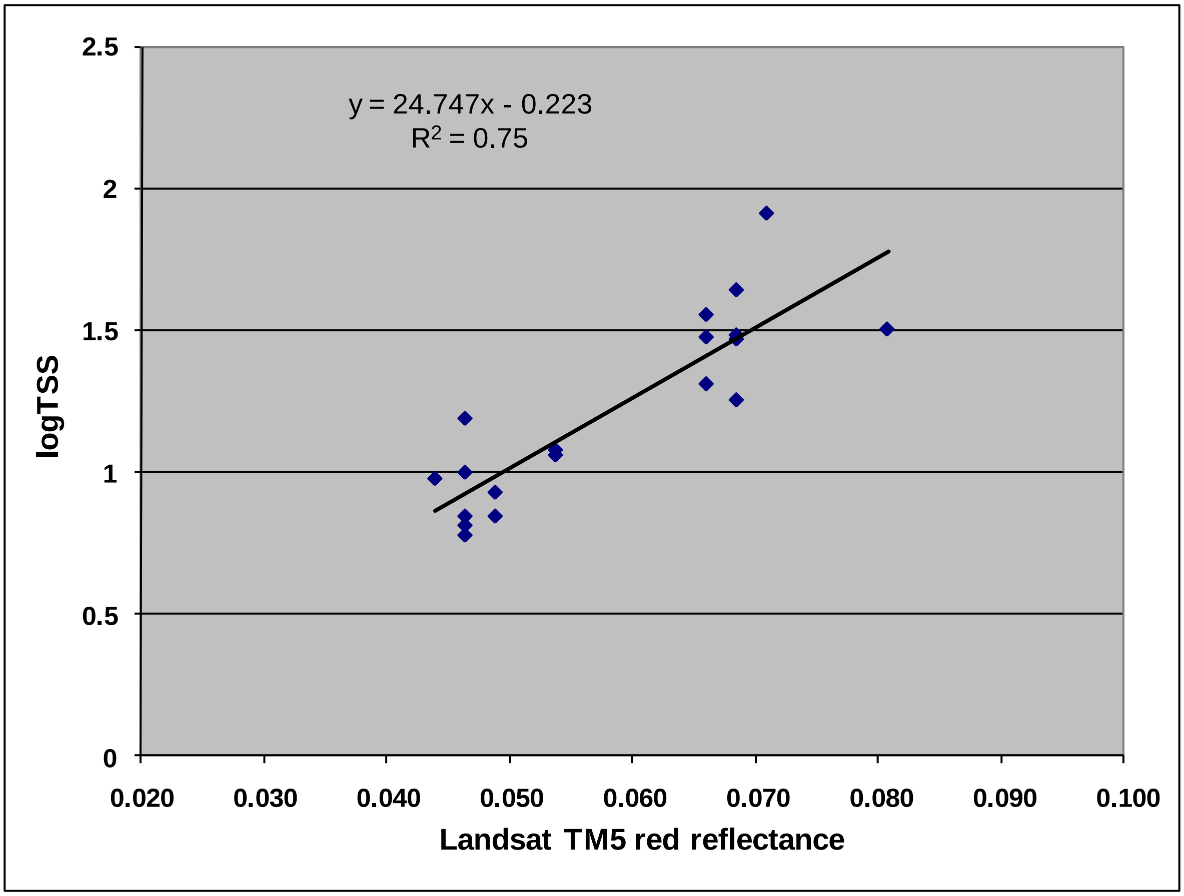

Figure 43. Scatter plot and regression model for July Landsat 5 Thematic Mapper Band 3 (red reflectance) and log-transformed total suspended solids (TSS) for Clinton Lake.

Figure 44. Landsat 5 Thematic Mapper July 19, 2009 image for Clinton Lake.

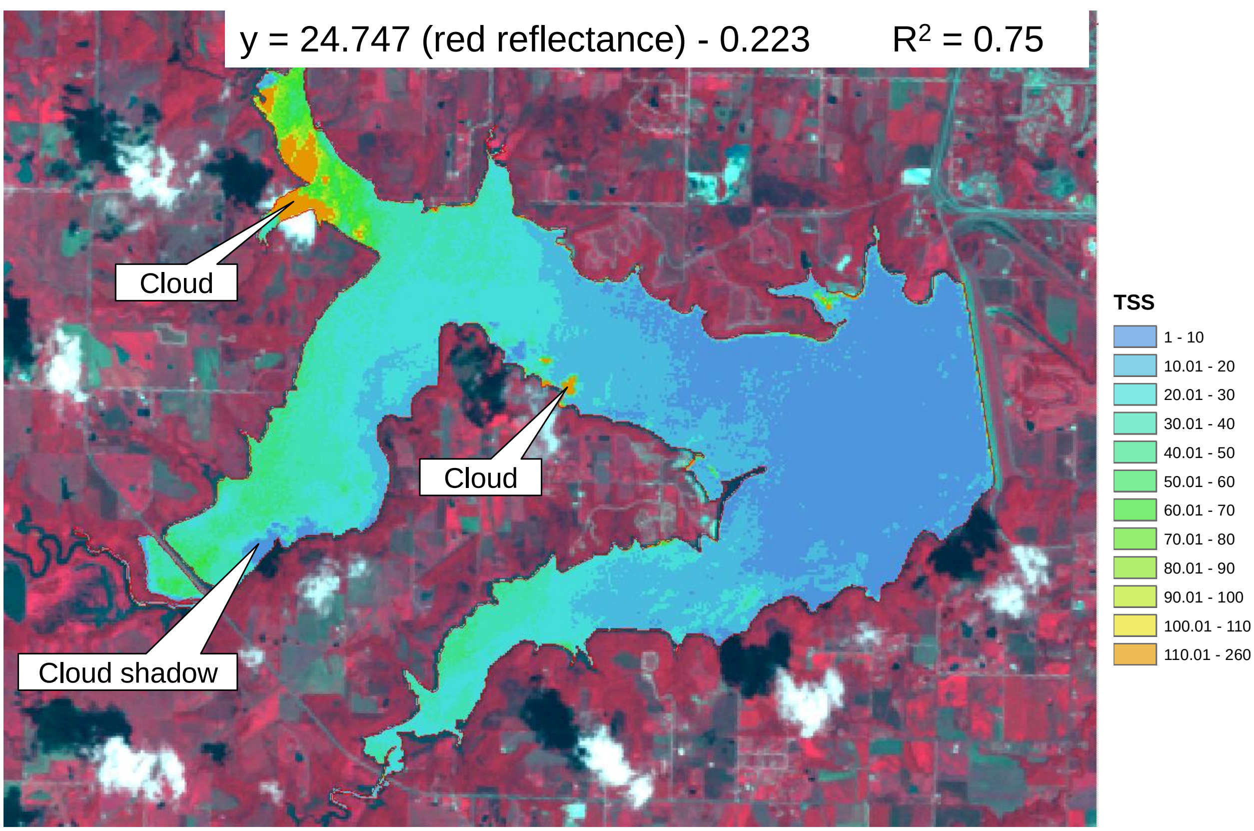

Figure 45. Map of TSS produced from regression model for log-transformed total suspended solids applied to July 19, 2009 Landsat 5 Thematic Mapper Band 3 (red reflectance) image, overlain on Landsat TM false-color composite image.

Summary and findings

- Water quality variables exhibited the greatest range of values during summer months and a restricted range during fall sampling events.
- Strongest lake water quality differences were with TP, TSS and conductivity.
- Median (23.0 NTU) and mean (32.7 NTU) turbidity values for our lakes exceeded turbidity levels for lakes used to develop current remote sensing models for chlorophyll a (e.g. Gitelson *et al.* 2008, 2009).
- Weak or no TP to chlorophyll-*a* relationships were found within individual lakes and the "all lakes" regression model.
- Strong TP to turbidity and TP to TSS relationships were found in all lakes and the "all lakes" regression model.
- Relationships between water quality and spectral reflectance can vary significantly both geographically and seasonally.
- The red reflectance band of both MODIS and Landsat Thematic Mapper was most consistently correlated with turbidity, TSS, and secchi depth.
- It was not possible to obtain enough clean (i.e., water-only) pixel values to develop meaningful models using 250-meter resolution MODIS visible-near IR reflectance imagery for small elongated lakes.
- Chlorophyll and pheophytin were poorly correlated with spectral reflectance in either the red or near-infrared reflectance bands of MODIS and Thematic Mapper.
- The near-infrared band of the MODIS sensor was not correlated with any of the water quality variables.
- Regression equations developed from field-sampled data and spectral reflectance values can be applied to a satellite image (MODIS or Thematic Mapper) to produce spatially-explicit maps of water quality parameters. This appears to be most feasible for mapping those parameters that exhibited the strongest relationships with spectral reflectance, i.e., turbidity, secchi depth, and total suspended solids.

Deliverables

The following deliverables are fulfilled as explained:

1. A QAPP that addresses field methods and *in situ* measurements and instruments, analytical laboratory methods for water chemistry variables, MODIS imagery processing and statistical and model development methodologies. Available for download as pdf at http://www.cpcb.ku.edu/research/assets/2009MODIS/QAPP_modis_r1_2009Jul25.pdf
2. Field and satellite data (both measured and derived variables) are available for download from http://www.cpcb.ku.edu/research/html/2009_lakeMODIS.htm.
3. All spatial and temporal models and their defined statistical relationships are available in this report and/or on project webpage.
4. Whole lake estimates of all water quality variables based on field data and satellite models are available in this report and/or on project webpage.
5. This report is available for download at http://www.cpcb.ku.edu/research/html/2009_lakeMODIS.htm.
6. All data and project results are available on the Central Plains Center for BioAssessment website at http://www.cpcb.ku.edu/research/html/2009_lakeMODIS.htm.

7. Project outcomes were presented at the USEPA Region 7 2010 Impaired Waters and Watersheds Conference: Determining the Utility and Adaptability of Remote Sensing in Monitoring and Assessing Reservoir Eutrophication and Turbidity for TMDL Assessments, Jakubauskas, Huggins, and Baker.

ACKNOWLEDGMENTS
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http://www.epa.gov/eerd/RemoteSensing.htm

http://www.caslab.com/EPA-Method-160_2/

APPENDIX 1: Lake sampling sites.

Clinton Lake Sample Site Coordinates

Site	Longitude	Latitude	UTMX	UTMY
1	-95.434747	38.905002	288875.7	4309052.7
2	-95.424253	38.911928	289806.3	4309797.2
3	-95.419827	38.920628	290215.7	4310752.6
4	-95.413657	38.928581	290774.1	4311621.1
5	-95.419976	38.941864	290265.4	4313110.0
6	-95.403729	38.935493	291655.0	4312365.6
7	-95.391108	38.930498	292734.5	4311782.4
8	-95.379645	38.925814	293714.7	4311236.5
9	-95.367351	38.921928	294769.3	4310777.4
10	-95.357553	38.919890	295613.1	4310529.3
11	-95.401273	38.892392	291741.9	4307576.2
12	-95.390732	38.897975	292672.4	4308171.8
13	-95.379062	38.899778	293689.9	4308345.5
14	-95.368061	38.900226	294645.3	4308370.3
15	-95.357343	38.904914	295588.2	4308866.6
16	-95.345304	38.908623	296642.9	4309251.3
17	-95.333473	38.914338	297685.1	4309859.2
18	-95.334686	38.925157	297610.7	4311062.8
19	-95.344312	38.921946	296767.0	4310727.8
20	-95.344140	38.929774	296804.2	4311596.3

Geographic coordinates in WGS84 datum.
UTM coordinates for NAD83 datum, Zone 15N, units meters.

Hillsdale Lake Sample Site Coordinates

Site	Longitude	Latitude	UTMX	UTMY
1	-94.967837	38.706411	328892.2	4286035.4
2	-94.962975	38.702564	329305.8	4285599.4
3	-94.957689	38.697314	329753.0	4285006.8
4	-94.952678	38.692663	330177.8	4284481.4
5	-94.947667	38.688012	330602.7	4283955.9
6	-94.937387	38.683347	331485.9	4283419.3
7	-94.929665	38.678136	332145.5	4282826.7
8	-94.921391	38.671523	332849.8	4282077.7
9	-94.917626	38.665238	333162.9	4281373.4
10	-94.929524	38.663329	332123.1	4281183.3
11	-94.919724	38.652409	332950.5	4279953.5
12	-94.910735	38.657392	333744.2	4280490.1
13	-94.903359	38.660232	334392.7	4280792.0
14	-94.906339	38.666027	334146.7	4281440.4
15	-94.911442	38.674305	333721.9	4282368.4
16	-94.905686	38.680141	334236.2	4283005.6
17	-94.899275	38.685584	334806.3	4283598.2
18	-94.892526	38.692846	335410.0	4284391.9
19	-94.886397	38.699292	335957.9	4285096.3
20	-94.881061	38.706631	336438.6	4285901.2

Geographic coordinates in WGS84 datum.
UTM coordinates for NAD83 datum, Zone 15N, units meters.

Centralia Lake Sample Site Coordinates

Site	Longitude	Latitude	UTMX	UTMY
1	-96.149504	39.691138	744428.9	4397362.3
2	-96.149976	39.694560	744376.3	4397740.9
3	-96.151643	39.697758	744222.1	4398091.4
4	-96.153824	39.701379	744022.3	4398487.4
5	-96.158520	39.703483	743612.3	4398708.2
6	-96.157111	39.705943	743724.4	4398985.1
7	-96.152658	39.706876	744102.9	4399100.8
8	-96.147628	39.705931	744537.6	4399009.7
9	-96.143153	39.704432	744926.6	4398855.4
10	-96.138425	39.703116	745336.7	4398722.2

Geographic coordinates in WGS84 datum.
UTM coordinates for NAD83 datum, Zone 14N, units meters.

Louisburg-Middle Creek Lake Sample Site Coordinates

Site	Longitude	Latitude	UTMX	UTMY
1	-94.665770	38.511142	354766.1	4263844.5
2	-94.671397	38.507062	354267.3	4263400.6
3	-94.674859	38.507507	353966.2	4263455.5
4	-94.677795	38.508039	353711.3	4263519.3
5	-94.677751	38.506159	353711.3	4263310.5
6	-94.680261	38.506796	353493.8	4263385.2
7	-94.680281	38.504420	353487.2	4263121.5
8	-94.684390	38.505569	353131.2	4263255.6
9	-94.684127	38.504028	353151.0	4263084.2
10	-94.685018	38.502233	353069.7	4262886.4

Geographic coordinates in WGS84 datum.
UTM coordinates for NAD83 datum, Zone 15N, units meters.

APPENDIX 2. Summary of analytical method, instrument detection limit, concentration of interest, and sample holding time of water-quality parameters analyzed in this project.

Parameter	Container	Instrument	Method Citation	Detection Limit	Conc. of Interest	Holding Time	Preservation
Laboratory Analyses							
Total Phosphorus	1L Amber Glass	Digestion @ 250°F, followed by Lachat QuikChem 8500	Ebina *et al.* 1983	5 µg/L	10 µg/L	28 days	pH <2 with H_2SO_4, 4°C
Chlorophyll *a*	1L Amber Glass	Optical Tech. Devices, Ratio-2 System Filter Fluorometer	21st Ed. Standard Methods 10200-H	1 µg/L	10 µg/L	28 days	Filtered, dark, -20°C
TSS	1L Amber Glass	Drying oven	21st Ed. Standard Methods	1 mg/L	2.5-200 mg/L	28 days	-
In situ Measurements							
pH	None	Horiba U-10 Water Quality Checker	21st Ed. Standard Methods	0.1 SU	< 4 or > 9	-	-
Specific Conductance	None	Horiba U-10 Water Quality Checker	21st Ed. Standard Methods	0.001 mS/cm	1 mS/cm	-	-
DO	None	Horiba U-10 Water Quality Checker	21st Ed. Standard Methods	0.1 mg/L	5 mg/L	-	-
Turbidity	None	Horiba U-10 Water Quality Checker	21st Ed. Standard Methods	1 NTU	-	-	-
Water/air Temperature	None	Horiba U-10 Water Quality Checker	21st Ed. Standard Methods	0.1°C	-	-	-
Secchi Transparency	None	Secchi disk	Wetzel 2001	-	-	-	-