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Monitoring spatial and temporal water quality changes in Iowa lakes using airborne hyperspectral imagery

Nathan Robert Green
University of Northern Iowa

MONITORING SPATIAL AND TEMPORAL WATER QUALITY CHANGES IN

IOWA LAKES USING AIRBORNE HYPERSPECTRAL IMAGERY

An Abstract of a Thesis

Submitted

in Partial Fulfillment

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Nathan Robert Green

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ABSTRACT

The U.S. Environmental Protection Agency (US EPA) has identified more than 20,000 water bodies across America as polluted mainly due to agricultural non-point source pollution. Current techniques for monitoring and assessing the quality of waters in streams, reservoirs, lakes, and estuaries involve on site measurements and/or the collection of water samples for subsequent laboratory analyses. While this approach yields accurate measurements for a point in time and space, it is expensive, laborious, and cannot provide a temporal or spatial overview of water-quality trends. To overcome this liability, state and local agencies are seeking alternative and more cost effective methods. A study was performed during the summer and fall of 2004 on two lakes in Eastern Iowa, Silver Lake and Casey Lake. The goal of the research was to explore whether the combination of hyperspectral remote sensing, GIS, and water sample analysis can simplify and accelerate the protocol for assessing water quality in Iowa lakes with an acceptable degree of accuracy. Hyperspectral images were collected using an airborne platform during the first week of the months from June through October 2004. Water samples and GPS points were collected nearly simultaneously with the hyperspectral images. By analyzing relationships between reflectance at specific wavelengths and water sample data, prediction algorithms were created. The prediction algorithms were applied to the hyperspectral images to create spatially continuous water quality maps. Maps of chlorophyll *a* were created for both lakes with an accuracy of R squared = 0.7672. The chlorophyll *a* maps showed highest concentrations of chlorophyll *a* in early July and lowest in September and October. Maps of turbidity were created for both lakes

also with an accuracy of R squared = 0.7620. The highest turbidity occurred in early July and the lowest occurred in September. Secchi disk depth maps were created for Silver Lake with an accuracy of R squared = 0.8888. The smallest Secchi disk depths occurred in June and July and increased into October. Secchi disk depths were unable to be predicted in Casey Lake due to the clarity of the water and bottom reflectance being collected by the hyperspectral sensor. Examination of the water quality maps made from the hyperspectral images provides a more complete record of the trend in water quality for these two lakes over the study period. They also supply a more detailed understanding of the spatial and temporal variation in the water quality of the two lakes.

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Date — Dr. Ramanathan Sugumaran, Chair, Thesis Committee

10-27-05

Date — Dr. David May, Thesis Committee Member

10/27/05

Date — Dr. Maureen Clayton, Thesis Committee Member

11-10-05

Date — Dr. Susan J. Koch, Dean, Graduate College

DEDICATION

This thesis is dedicated to my parents, Robert and Deborah Green, my brother Seth and his wife Audrey, and to my sister Shannon and her husband Jay. Without their love, support and patience, it would not have been possible to complete this research. Thank you very much.

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CHAPTER 1

BACKGROUND

Water quality is an extremely important issue not only in the United States, but also worldwide. Not only is the quality of the water we drink important, but the quality of our recreational waters and health of our ecosystems are important as well. Therefore, changes in water quality must be monitored and in a way that produces a complete assessment of the water quality of an area. The United States Environmental Protection Agency (US EPA) states that "water quality monitoring and assessment programs must be strengthened and upgraded across the country" (US EPA, Clean and Safe Water, 2003). Traditional methods of monitoring water quality do provide a very general understanding of water quality, but alternative methods may provide a cheaper, faster, and more complete representation of water quality. In this research, the method of hyperspectral remote sensing is tested to see if it can be used as an effective alternative to traditional methods.

Water Quality

Water quality is commonly defined by its physical, chemical, biological and aesthetic characteristics (US EPA, 2005). It is greatly influenced by watershed because pollutants will be carried by precipitation from the slopes of a watershed into streams, rivers and lakes. Water quality can be measured with five distinct indicators. The first is biological which is determined by the concentrations of bacteria and algae. The second indicator is physical, and includes the temperature, turbidity, color, suspended materials and salinity of the water. The third indicator is chemical, properties which include pH, dissolved oxygen, and nutrient amounts (e.g. nitrogen and phosphorous). The fourth indicator is aesthetic, which can be measured in color, odors, and floating matter. The final indicator is radioactive and is measured by amounts of alpha, beta, and gamma radiation emission.

Water Quality in the United States

Water quality issues in the United States are a major concern even though water quality has significantly improved over the last 30 years, and these concerns must be addressed (Environmental Protection Agency, 2004). In the Water Quality Inventory Report (2000), prepared under section 305(b) of the Clean Water Act, states, tribes, and territories reported that about 40% of streams, 45% of lakes, and 50% of estuaries were not clean enough to support recreational uses, such as swimming and fishing, and that 78% of assessed Great Lakes shoreline miles are impaired (EPA, 2000).

In July of 2003, the EPA published the Water Quality Standards and Criteria Strategy, which is designed to strengthen the nation's water quality standards. The EPA and local governments are coming up with new and more effective ways of monitoring lake water quality, as well as improving existing methods (EPA, 2004). In 2004, a new plan to restore, improve, and protect at least three million additional acres of lakes, rivers, and wetlands was announced (EPA, 2004). The reason for the new aggressive approach to water quality is the realization that water quality is a big problem in the United States. To determine what water-quality problems exist and where they are coming from, monitoring must be done, and it must be done at frequent intervals or periodically. This monitoring process, though necessary, is a time consuming process, as well as expensive

(Gons, 1999; Lillesand, Chipman, & Batzli, 2004; Olmanson, Bauer, & Brezonik, 2002; Rao, 1998; Reinhardt, 1998; Shafique, Autrey, Fulk, & Cormier, 2001; Turdukulov, 2003; Waldron, Steeves, & Finn, 2001).

Water Quality Status in Iowa

In the state of Iowa and other agricultural states, it has become a time sensitive and extremely important issue. The most common forms of impairment to Iowa lakes are organic enrichment, nuisance aquatic plants, turbidity, and siltation. Since land use is so closely related to water quality and many Iowa lakes lie in or within close proximity to farmland where fertilizers and manure are regularly applied, the quality of Iowa's lakes is among the worst in the nation (University of Northern Iowa Summer Lakes Study Report, 2000). With so much of the quality of lake water being determined by the land use in its watershed, it would be expected that lake water would be tainted by large amounts of nitrogen and phosphorous if large amounts of fertilizers and manure were used on the land in the watershed. Therefore, there is a great need for monitoring water-quality variables or other variables that are directly linked to them to insure the proper estimation of water quality.

In response to the poor water quality of water in Iowa lakes, government agencies have taken a proactive approach in correcting the situation. The Iowa Department of Natural Resources (IDNR), along with several agencies, participates in a variety of pollution control and restoration programs for Iowa lakes. These programs address sources of pollution, both agricultural and nonagricultural, and have significantly improved water quality and recreation potential at several Iowa lakes (IDNR, 2005).

Also, Iowa complies with section 305 (b) of the Clean Water Act, which requires each state to submit to the US EPA a biannual status report of the quality of its waters, by which the US EPA can get a good idea of the water quality in every state in the nation.

Current Monitoring Methods Used in Iowa

The quality of water in lakes, streams, and rivers in the state of Iowa is monitored by the IDNR in coordination with other groups and organizations. $2.5 million has been appropriated for Iowa's Ambient Water Monitoring Program in fiscal year 2002 (IDNR, 2004). This shows how important water quality monitoring is to government officials. Assissting the IDNR is an all volunteer organization called IOWATER. This is a group of citizens who monitor water bodies in their local areas. The methods that the IDNR and IOWATER use to monitor water quality include traveling to a location and performing tests. The volunteers take chemical, physical, and biological readings of the water body to gain an understanding of the quality of water and health of the ecosystem. In 2000, 53 counties in Iowa had volunteers in the IOWATER program taking readings. They logged 10,455 hours, which has saved the government $125,289. In 2001, 86 counties in Iowa had IOWATER volunteers who logged 15,680 hours, saving the government $224,224 (IDNR IGS/Water Monitoring).

A part of the lake water quality monitoring in the state of Iowa is done by the Limnology Laboratory of Iowa State University's Ecology, Evolution and Organismal Biology Department in coordination with the IDNR (IDNR, 2005). Two teams travel throughout the state and sample 132 of Iowa's lakes, including the study area of this research project, Casey Lake and Silver Lake. A single sample will be taken in an area representing the open water zone of each lake three times a year (spring-early summer, mid-summer, and late summer-fall). This single sample will represent the entire lake for that time period. Larger lakes will be sampled at multiple locations to provide water quality of vastly different regions of the larger lakes (Iowa State University, 2004). This five-year project will be ending in 2005, opening the opportunity for new monitoring methods.

There are many variables that comprise water quality. A few of these variables are temperature, pH, dissolved oxygen, total dissolved solids (TDS), specific conductivity, turbidity, chlorophyll a, and particle size distribution. These variables are tested in the upper mixing zone of each of the lakes. Tests are conducted for many other constituents that characterize bottom sediments and other water column characteristics. These other tests are not as closely related to this research and thus are not described here.

Limitations of Current Monitoring Methods

Although the current methods of monitoring the quality of water in Iowa's lakes do a good job of covering as many of Iowa's lakes as possible, they do generalize the water quality of each lake based upon quality at a single location. The water sample collected represents a small volume of water that may not be representative of a larger area or the entire lake (Huguenin, Wang, Beihl, Stoodley, & Rogers, 2004). Another problem is that plumes associated with point sources of pollution, such as waste water inputs, or non-point sources of pollution, such as agricultural runoff, are not visible with the conventional method. A third problem with this method is that it is a time consuming and resource demanding task. The lakes being studied by Iowa State University are spread throughout the entire 55,875 square miles of Iowa. Much time and money is required for traveling to the study areas and laboratory analyses on water samples are expensive and can take a long time to complete. A fourth problem, one more related to the IOWATER program, is that of inconsistent recording of data. The IOWATER program is made up of volunteer citizens with little training in the biological sciences who may not use consistent recording methods. Therefore, the current methods for monitoring the quality of Iowa's lakes provides data for a single point in a large number of lakes a few times a year, but doesn't provide spatially continuous data that recognizes pollutant plumes or influxes of pollutants. In addition, current water-quality monitoring requires a large amount of time and resources and may be compromised by inexperienced testers and the varying monitoring methods used.

Recently, the Iowa DNR has expressed interest in other water-quality monitoring methods that would provide better information on the water quality of Iowa's lakes. Lately, several researchers have noted the effectiveness of satellite and airborne remote sensing in testing water quality (Dekker, Malthus, & Seyhan, 1991; Gitelson, 1992; Kallio et al., 2001). Most of these studies have indicated that the higher the spatial and spectral resolution, the more accurate the results were, and a better understanding of water quality resulted. Although a few studies on rivers, lakes, and marine environments (Bagheri, Stein, & Dios, 1998; George, 1997; Gould & Arnone, 1998) have made use of high resolution hyperspectral data, not a single study has used multi temporal high resolution hyperspectral airborne images to study small freshwater lakes.

Goal and Objectives

The goal of this research is to determine trends in water quality of two lakes in Iowa, Silver Lake in Delaware County, and Casey Lake in Tama County, using geospatial technologies, such as remote sensing and geographic information systems (GIS). With not even a single study using hyperspectral data to test water quality of inland freshwater lakes over time, and with there being evidence showing that this method works on single date experiments, this method was chosen. Findings of this study may open the door for use of hyperspectral data in water quality monitoring studies of fresh water lakes over time.

On site testing for such water quality parameters as chlorophyll *a* content, Secchi disk depth, and turbidity has been done. All of these are vital to the water quality of a lake and, therefore, must be included in this study. Along with the hyperspectral remote sensing data, field spectrometer readings have been collected to correlate field measurements with the hyperspectral data. The use of GIS allows comparison of hyperspectral data with data collected in the field. These comparisons can be tested statistically to evaluate the accuracy of the remote sensing data. A GIS also aids in the presentation of findings in the form of maps, charts, graphs, and tables.

Objective 1: To determine if there are certain wavelengths that can aid in the prediction of different water-quality constituents.

Objective 2: To develop appropriate algorithms for mapping water-quality constituents.

Objective 3: To determine trends in water quality based upon the water-quality maps created from the hyperspectral data.

Objective 4: To compare the results from the remotely-sensed data with the traditional methods data.

Research Questions

The main question in this study is: Can hyperspectral remote sensing be used to determine chlorophyll *a* concentration, Secchi disk depth, and turbidity in a poor water quality lake and in a relatively good water quality lake in Iowa? Further questions include the following:

1. Which spectral wavelengths are most important in determining chlorophyll *a* concentration, Secchi disk depth, and turbidity?
2. What is the trend of the water quality in the two lakes during the study period?
3. Which months of the study period have the best and poorest water quality?
4. What advantages are there of monitoring water quality with hyperspectral remote sensing over traditional methods?

Thesis Organization

This thesis is organized into five chapters. Chapter one looks at the background to the study, definitions of water quality, water quality status in the United States and Iowa, current monitoring methods and their limitations, goals and objectives and research questions. Chapter two is a literature review in which past studies of water quality using traditional methods, ground-based remote sensing, airborne remote sensing and satellite remote sensing are review. There is also a summary of the literature review at the end of chapter two. In chapter three, the methodology of the study is given. In chapter three the study area is defined, current water quality and monitoring methods used at the study areas are explained, problems and limitations are discussed, and data collection and analysis are described. Chapter four is the results and discussion portion of the thesis. Lastly, chapter five provides conclusions and future directions. The work is summarized and conclusions are drawn. Further research directions are also provided in chapter five.

CHAPTER 2

LITERATURE REVIEW

Remote sensing can offer a better representation of water quality in lakes, streams, and reservoirs by producing continuous water quality maps. According to the US EPA (2004), remote sensing of water bodies is under development as a monitoring technology. In order to better understand the role of remote sensing in water quality studies, it is necessary to review the relevant literature. The review was based on the role of different types of remote sensing in the study of water quality as well as traditional methods. The different types of remote sensing examined are hyperspectral ground based studies, aerial studies, and satellite studies. The review also examined precise methods used in past studies to determine which remote sensing applications were most successful.

Traditional methods of monitoring water quality are those methods which involve on site testing and sample collection. These methods are currently used by federal agencies such as the US EPA, state agencies like the Iowa DNR, as well as other water quality monitoring agencies. Travel to location and retrieval of data is done by hand on location using these methods. The following paragraphs will describe past water quality research using the traditional methods of monitoring.

Traditional Method Studies

Bachmann, Johnson, Moore and Noonan (1980) studied Iowa lakes using the traditional method in 1979 and presented his findings in 1980. He again used the traditional method in the early 90's and presented his findings in 1994. Collection of water quality data in these studies was done using the traditional method. A single water sample was taken which represented the water quality for the entire lake. Methods which are used today by the limnology laboratory at Iowa State University are the same as the methods used by Bachmann et al. in 1979 and early 1990s to ensure comparability of water quality data from the different dates. This study is called The Iowa Lakes Survey which is a study being conducted by Iowa State University, contracted by the Iowa DNR. They are testing 132 of Iowa's lakes three times a year for five years (Downing, Ramstack, Haapa-aho, & Lee, 2003). A number of parameters are being tested for including the following; chlorophyll, dissolved oxygen, pH, temperature, total dissolved solids, and turbidity (Downing et al., 2003). It is a multiyear study because Iowa lakes vary in composition so much annually. The researchers use on site methods of collection of data and then analyze their samples in a laboratory setting. Ideally the researchers would like to test all the lakes many more times at many different points in each lake, but due to time and cost restraints, it is not possible. Results that the Iowa DNR have reported are approximately 63 percent of the 42,870 lake acres in Iowa during the 1994 to 1995 period were found to be fully supporting or fully supporting/threatened of their designated uses. About 26 percent were partially supporting, and 11 percent were found to be not supporting designated uses (Iowa DNR, 2005).

Along with the monitoring of lake water quality which is done by Iowa State, Iowa has implemented the help of its citizens. The IOWATER program has been used since 1998 and has grown every year. As was stated earlier, volunteer citizens monitor water quality in their local regions using test kits supplied by the IDNR. This program has greatly increased the number of lakes and streams monitored, but still only supplies water quality data for a single point in time which represents an entire lake or section of stream.

From the available literature it is clear that the use of in situ field samples is an extremely accurate method of determining water quality and measuring water quality variables. However, this method gives a limited spatial representation of the study area as well as being costly and time consuming (Ritchie & Cooper, n.d.). More problems involved with using the current methods are lack of continuous spatial coverage, inconsistencies in recording methods and the large amounts of resources and people needed to accomplish the task. An alternative to the current methods which may account for some of these problems is remote sensing. Remote sensing can provide continuous spatial coverage of a water body which supplies a much better representation of the water quality of an area. It also doesn't require a large number of people or large amounts of equipment. Remote sensing can be consistently done and on a predetermined temporal scale. It also can provide results quicker than the traditional methods. The following paragraphs will outline water quality monitoring studies performed using ground-based, airborne based, and satellite based remote sensing.

Ground Based Remote Sensing Water Quality Studies

Ground based remote sensing of water quality data is done using field-spectrometers. Field-spectrometers are used to collect spectral profiles from the water body. The spectral profiles are then analyzed by looking at specific wavelengths which are affected by changes in water quality. Researchers can then make assumptions about the water quality of that stream, river or lake based solely on the spectral information contained in the profile.

By using ground based remote sensing technology like a spectrometer, researchers gather upwelling and downwelling radiance values. These values can be used in the correction of atmospheric distortions or in band reduction of hyperspectral images. The most useful measurements taken by a spectrometer are those coordinated with acquisition of aircraft or satellite data (Campbell, 1996). This is a necessary step in using aerial or satellite based remote sensing data because images obtained from remote sensors mounted on aircraft or satellites are not immediately comparable to ground truth data or spectrometer data because of atmospheric distortion (Aspinall, Marcus, & Boardman, 2002). Difficulties which may arise when using spectrometers may come from field of view problems such as relation between the area to be studied and background surfaces, direction of solar illumination, and diffuse light from nearby objects. Campbell (1996) also states that measurements should be taken well clear of features of contrasting radiometric properties and that orientation of the sensor is important so that the user does not affect the data gathered. Also, it is important to include time, date, seasonal effects, weather conditions, conditions of illumination, and location of data gathered with the spectrometer (Campbell, 1996).

Nordheim and Lillesand (2004) measured upwelling and incoming radiation over 2048 spectral bands from 339.99 to 1023.9 nm for the purpose of developing a chlorophyll estimation algorithm. Using two Ocean Optics USB2000 spectroradiometers above and below the surface of 37 lakes in Northern Wisconsin and Michigan, reflectance spectra were taken at 6 sites directly above the surface and 6 sites immediately below the surface. They then classified the lakes into classes, oligotrophic or blue lakes, mesotrophic or green lakes, and high DOC or black lakes based on absorption spectra. They concluded that their estimates of chlorophyll concentration in "blue" and "green" lakes were reasonable while the estimates in "black" lakes were questionable due to the lack of variance in chlorophyll a concentrations.

In another study, monitoring of chlorophyll concentrations in the Blood River embayment of Kentucky Lake was performed by Reinhardt (1998). She wanted to see if Landsat TM data confirmed with Field Spectrometer values could accurately measure and display chlorophyll concentrations in the Blood River embayment of Kentucky Lake. Reinhardt concluded that remotely sensed data may be related to field spectrometer reflectance values using calibrated regression models.

An ongoing study to measure clarity of Wisconsin's inland lakes is being performed using a dual field spectroradiometer, Landsat imagery, and in situ ground measurements (Lillesand et al., 2004). The researchers are in the process of creating a unified database of satellite derived lake water clarity estimates spanning two decades for thousands of lakes statewide in Wisconsin. They created a spectral library of lake reflectance data using a handheld dual field spectrometer. They have cataloged downwelling solar irradiance and upwelling radiance and have also collected water quality data including water clarity, chlorophyll a, suspended solids, and DOC. Lillesand et al. (2004) are now using these libraries to try and model the optical and biophysical properties of lakes.

Gons (1999) used a PR-650 SpectraColorimeter handheld radiometer, which acquired spectra from 380 to 780 nm, to estimate chlorophyll *a* concentrations in turbid inland waters in widely variable solar elevations and weather situations. He could adequately predict chlorophyll *a* concentrations in well-mixed and optically deep water in lakes in The Netherlands, the Scheldt Estuary in Belgium, and Lake Tai in China. Handheld spectroradiometers can be deployed so that nearly real time assessment of data can be done. It has long been known that high concentrations of dissolved organic matter and total suspended matter interfere with optical determination of Chlorophyll a concentrations (Morel & Prieur, 1977) so any study on this topic should take that into consideration.

Ground based collection methods of water quality parameters have been used extensively since water quality monitoring began. Spectrometer readings of water quality provide a quicker method of detection of water quality than laboratory analysis of water samples. Using spectrometers for determining chlorophyll *a* concentrations was done successfully by Thiemann and Kaufmann (2000), Gons (1999), and Harrington and Repic (1994). Nordheim and Lillesand (2004) used readings from a spectroradiometer to develop an algorithm for estimating chlorophyll *a* concentrations in northern Wisconsin and Michigan lakes. Using their algorithm they determined that they could estimate chlorophyll concentrations in the waters of oligotrophic or blue lakes and mesotrophic or green lakes using radiance from a spectroradiometer. Reinhardt (1998) found that using spectrometer data to confirm Landsat data she could accurately map chlorophyll concentrations in a water body. Lillesand et al. (2004) used a dual field imaging spectrometer to create a library of lake reflectance spectra. They used this library to create water quality maps of thousands of Wisconsin lakes by comparing Landsat images of the lakes with the spectral library. Gons (1999) determined that he could accurately map chlorophyll concentrations in turbid inland waters using a handheld spectrometer. Liew, Kwoh and Lim (2002) found that they could use a handheld spectrometer to gather spectra from algal blooms and then simulate satellite bands with the spectrometer data to determine if satellites could be used in the detection and classification of algal bloom events. Rao (1998) estimated turbidity with an R^2 value of 0.5960, and suspended sediments with an R^2 value of 0.6046. There has not been much study on the use of a spectrometer for determination of turbidity, suspended sediment, DOC, phosphate and nitrate concentration, or dissolved oxygen.

The use of a handheld field spectrometer provides a quicker representation of water quality as well as being possibly cheaper. Chlorophyll *a* determination is possible to be done with great accuracy using this method. Problems that one may have using a field spectrometer are availability of the sensor, time of travel to the sight and gather spectra, and not a complete spatial representation of the study area. Other problems may include time of day, angle of the sensor with the surface to be monitored, and weather conditions.

Aerial Water Quality Studies

Airborne remote sensing data is gathered in the few bands of the Multi Spectral Scanner (MSS) to the many bands of hyperspectral data. Multispectral through hyperspectral sensors have been used to monitor water quality, however monitoring of water quality parameters such as chlorophyll *a,* turbidity, and suspended sediments is done more effectively with hyperspectral data due to the fact that there is more bands and consequently better spectral resolution which is required to measure the fine features of water quality characteristics (Ritchie & Cooper, n.d.).

Schaale, Olbert, & Fischer (1999) used the multispectral sensor Compact Airborne Imaging Spectrometer (CASI) to monitor the water quality of lakes in Berlin, Germany. The nine bands that the CASI sensor gathered spectra in were set to collect spectra in the wavelengths that were optimal for detecting chlorophyll *a* and yellow substance. They were able to produce good representations of chlorophyll *a* concentrations in the form of maps. A problem which they encountered was unexplained patches in there lake maps. They determined that these patches were caused by large amounts algae in the water that floating mats of algae were present. The algorithm they used concluded that these mats were comparable to dry land and were not included in the classification of the waters. This multispectral approach worked quite well because the exact wavelength of the bands needed to determine chlorophyll *a* content was known and the sensor was adjusted accordingly before data collection.

Hyperspectral Remote sensing of inland water bodies like lakes and rivers can be a useful tool for monitoring water quality parameters according to Shafique, Fulk, Cormier, and Autrey (2001). Airborne hyperspectral remote sensing can be used to measure chlorophyll *a*, total suspended solids, turbidity, and Secchi depth (Dekker, 1993; Gitelson, 1992; and Kallio et al. 2001). The many bands available in hyperspectral sensors allow researchers to detect these water quality parameters unlike the few coarse bands of the multispectral sensors. By analyzing the hyperspectral profile of individual pixels, or groups of pixels, comparison between unknown profiles and library profiles can be made to determine what the water quality is at unknown locations.

Koponen, Pulliainen, Kallio, and Hallikainen (2001) used airborne hyperspectral images from the Airborne Imaging Spectrometer for Applications (AISA) to study 11 lakes over 8 days in southern Finland (Koponen et al.). The AISA sensor operates in the wavelength range of 450-900 nanometers (nm) and is divided into 286 channels (Makisara, Meinander, Rantasuo, Okkonen, Aikio, Sipola, Pylkko & Braam, 1993). They concluded that the classification of lake water quality, using parameters Secchi depth, turbidity, and chlorophyll *a*, is possible with airborne imaging spectrometers using a combination of two operational classification standards which are the Water Quality Classification of Inland Waters in Finland scheme and the OECD Lake Classification scheme. In most cases, the classification is possible even without concurrent ground truth data because when using separate sets of test data, the algorithm classified the data accurately even without training the algorithm. They conclude that their classification system was developed for the month of August only and for lakes of similar types to the ones tested here. Also, the algorithm should be thoroughly tested before using it for classification of lakes during other seasons.

Marcus, Legleiter, Aspinall, Boardman, and Crabtree (2003) used high spatial resolution hyperspectral imagery to assess mountain streams in the northern region of Yellowstone National Park. They used the Probe-1 sensor mounted on a helicopter flying at an elevation of 600 meters. The sensor gathered spectra over 128 contiguous bands from the visible to shortwave infrared portion of the spectrum at 1 meter resolution. They found that their research accuracies approached or exceeded the 85% value typically expected for remote sensing mapping. They state that any researchers using high spatial resolution hyperspectral imagery have hurdles to overcome. Coordination of over flights with field teams given the dependence on weather, stream conditions, availability of hyperspectral sensors, and the large number of people that must be mobilized to collect sufficient ground data in a timely fashion is one of those hurdles.

A study on a river system in southwest Ohio which included the Great Miami River, a tributary of the Ohio River, was conducted by Shafique, Autrey, Flotermersch, and Fulk. (1999). They used the Compact Airborne Spectrometer Imager (CASI) which acquired data in 19 spectral bands at a resolution of 2m, and the HyMap which acquired data in 126 spectral bands. Using ENVI software, they determined that the two bands, 672 nm and 705 nm, correlated the ground truth data with the remote sensing data the best. They also state that the use of hyperspectral imagery to assess water quality issues of chlorophyll a and turbidity was an accurate way of mapping spatially continuous data. They found that by using a ratio of 705 and 672 nm they produced good correlation for chlorophyll *a* with ground truth data (R^2 = 0.74), and by using the first derivative of 700 and 675 they accurately predicted turbidity (R^2 = 0.79).

Karaska, Huguenin, Beacham, Wang, Jensen, and Kaufmann (2004) performed a study on the Neuse River of North Carolina using Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS) images to measure chlorophyll, suspended minerals, DOC, and turbidity to determine source points of pollution and areas that on site measurements should be concentrated. Applying the digital image processing algorithm Quantitative Shoreline Characterization, Version 1.0 (QSC1) to the AVIRIS images, they created chlorophyll measurements that correlated well with the field measurements of chlorophyll (r = 0.84). The team concluded that AVIRIS has the ability to directly measure chlorophyll concentrations in the Neuse River. In the case of dissolved organic carbon and suspended minerals, field sampling was inadequate to assess these values. Therefore the team concluded that accuracy of hyperspectral measurements of suspended minerals, dissolved organic carbon, and turbidity measurements remains uncertain.

During late 2000 and the first half of 2001, a team affiliated with the Naval Research Laboratory set out to test airborne hyperspectral data in the characterization of coastal waters (Davis, 2001). In collaboration with Paul Bissett at the Florida Environmental Research Institute (FERI), the team hoped to correlate detailed on site measurements with hyperspectral imagery and then used the combined data to develop algorithms for characterization of coastal ocean waters using the hyperspectral data Davis, 2001). The researchers used the Ocean Portable Hyperspectral Imager for Low-Light Spectroscopy (Ocean PHILLS), which is a new hyperspectral imager specifically designed for imaging coastal ocean waters (Davis, Kappus, Bowles, Fisher, Antoniades & Carney, 1999). This sensor can collect images in 64 or 128 bands over the range of 400 to 1000 nm. Good correlation between the ground truth data and the hyperspectral images was reported at the time this article was written. The team continues to use the hyperspectral data to develop algorithms for characterization of the coastal ocean and hopes that these algorithms will be transitioned into Naval EarthMap Observer (NEMO) and other Department of Defense (DOD) hyperspectral programs.

It is evident from the reading that the use of airborne remote sensing of water quality is an outstanding method of monitoring chlorophyll *a* and other water quality variables of water bodies due to the speed, accuracy, amount of data that can be collected and the temporal spacing of the data. The use of airborne multispectral sensors for water quality monitoring is limited by the small number of bands and the fact that many bands are required to monitor the large number and fine spectral features of water quality parameters involved in water quality (Ritchie & Schiebe, 2000). The more bands a sensor has results in that sensor being more effective in water quality monitoring. Therefore hyperspectral sensors are optimal for this task. It has been demonstrated that chlorophyll, turbidity, total suspended solids, and Secchi depth can be determined using the aerial hyperspectral method (Dekker, 1993; Gitelson, 1992; Kallio et al., 2001; Karaska et al. 2004; Koponen et al. 2001; Marcus et al. 2003; Shafique et al. 1999).

Satellite Water Quality Studies

Water quality assessment of ocean and inland waters using satellite data has been carried out since the first remote sensing satellite, Landsat-MSS, has been operational (Ortiz Casas & Martinez Pena, 1987). According to Huguenin et al. (2004), retrieval of water clarity information from satellite multispectral imagery has been attempted with mixed success for inland lake waters. Studies have shown a good correlation between Landsat MSS or TM data and ground truth data of clarity and chlorophyll a concentrations (Olmanson et al. 2002; Brown, Warwick, Cavalier and Roller 1977; Lillesand , Johnson, Deuell, Lindstrom, & Meisner 1983; Lathrop & Lillesand 1986;

Lathrop 1992; Cox, Forsythe, Vaughan, & Olmsted, 1998). Khorram and Cheshire (1985) used Landsat MSS in the Neuse River to estimate salinity, chlorophyll and turbidity in the Neuse River estuary in North Carolina. Projects using Landsat MSS data to study Wisconsin lakes were performed by Scarpace, Holmquist, and Fisher (1979); Boland (1976); Brown, et al. (1977); Witzig and Whitehurst (1981); and Lillesand et al. (1983). Later, Landsat Thematic Mapper was used to study Wisconsin lakes by Lathrop and Lillesand (1986) and by Lathrop, Lillesand, and Yandell (1991). Likewise, Olmanson (1997) used Landsat TM data to estimate the trophic state of lakes in the Minneapolis/St. Paul, Minnesota metropolitan area. Satellite Probatoire d'Observation de la Terre (SPOT) satellite imagery has also been proven to successfully assess water quality conditions (Lathrop and Lillesand, 1989; Yang and Yang, 1999). Recent advancements in technology have made more and better information available. New satellites such as the Sea-viewing Wide Field of View Sensor (SeaWiFS), Earth Observing Systems (EOS), Modular Optoelectronic Scanner (MOS), OrbView, IKONOS and new sensors such as the hyperspectral sensor Hyperion on the Earth Observer-1 (EO-1) spacecraft, have recently been launched or will be launched soon and this will aid the process of remote sensing of water quality of inland lakes (United States Department of Agriculture, 2004). Data from several recently launched satellite sensors (i.e., SeaWiFS, MOS, and Ocean Color Temperature Scanner [OCTS]) have great promise for measuring chlorophyll concentrations in water bodies.

Lillesand found good correlation between in situ and remote sensing water clarity testing in the 1970s using Landsat TM (Olmanson et al., 2002). Later, Olmanson et al.

(1997) at the U of Minnesota started a project to measure water quality of lakes around the Minneapolis/St. Paul region. They then analyzed Landsat images similarly to the way Lillesand did years earlier and compared it to known Secchi disk depths and found a strong correlation. Brezonik, Kloiber, Olmanson and Bauer (2002) at the University of Minnesota then started up a project to expand the remote sensing testing of water quality to the entire state of Minnesota. When the study was completed, the team found definite trends in water quality of Minnesota lakes. The quality of lake water decreased as one moved from northeast Minnesota to southwest Minnesota. Brezonik believes that the cause of this trend is that more people and farming is done in the southern portions of the state and that lake depth in the southwest was generally shallower than lake depth in the northeast. The team of Brezonik and Bauer would never have gotten data for every lake in the state of Minnesota using on site measurements. They were able to see results that would have been much more difficult, time consuming and costly to produce if it were not for remote sensing technology being used.

Emch (2002) used Landsat TM data from 1986 and 2000 to describe water clarity. The team centered their study on Casey Lake and Silver Lake in Iowa. In order for the team to determine if their satellite data was accurate, on site sampling data was obtained at the same time of the satellite imagery acquisition to determine if there was a good correlation. Emch determined that the water quality in Casey Lake has not changed much over the study period of 1986 to 2000 based on estimated Secchi disk transparency levels and estimated chlorophyll *a* levels, but that Silver Lake's water quality seems to have degraded. The values which the team used to make these assumptions were estimated from Landsat images from the 1970's and the year 2000, inferred from on site sampling in the summer 1999.

A 2001 study by Mervyn Lynch and Peter Fearns, called "Water Quality in Coastal Waters" discusses the issue of using satellite images to access the water quality of the coastal waters of Western Australia. The remote sensing data that the team of researchers used in this case came from a number of polar orbiting satellites mounted instruments as well as SeaWiFS. A number of on site measurements were made in the study area such as, temperature, phytoplankton and zooplankton quantities, and chlorophyll concentrations. After examining the remote sensing data, Lynch and Fearns concluded that remote sensing was a reliable way to determine temperature, and chlorophyll concentrations for off shore coastal waters. Near shore measurements were not as accurate due to large amounts of substrate in the water. Overall, the researchers were pleased with the remote sensing data but wished that they had access to more accurate sensors like the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensors. These were restricted by access as well as temporal and spatial coverages.

A study concerning the Great Lakes in the United States was conducted in the summer of 2000 to study cyanobacterial blooms in Lake Erie (Vincent, Qin, McKay, Miner, Czajkowski, Savino, & Bridgeman, 2004). Two primary questions were put to the test in this study. The first being: if concentration and spatial distribution of cyanobacteria could be determined by using Landsat TM's six bands with 28.5 meter resolution and by what margin of error. Secondly, can created algorithms be used to predict when the next large bloom event will occur based on early stage formations of cyanobacterial blooms. The team claims that this is the first effort that employs Landsat TM for mapping of phycocyanin in fresh water lakes. They also claim to affirmatively answer their first question posed at the beginning of their report, being if one could map concentration and spatial distribution of cyanobacteria using Landsat data. The team did not answer the second question due to some discrepancy in a predicted bloom. Conclusions that the team came up with were that the Landsat TM sensor can be used to evaluate water quality by detecting pigments of algae like phycocyanin. The algorithm they came up with can be used with Landsat 7 and 5 images and provides data in 8 day increments. They don't yet know if their algorithm can be used with saltwater bodies.

During the summers of 1996, 97, and 98 a study was performed on Massachusetts lakes to determine water quality, trophic state, and macrophyte distributions (Waldron et al. 2001). The researchers took samples of phytoplankton, chlorophyll concentration, Secchi disk transparency, and color at 97 lakes throughout Massachusetts all within 24 hours of a pass from the Landsat Thematic Mapper to assess water quality of Massachusetts lakes. Waldron et al. (2001) determined that they could not develop predictive relationships between the sample criteria studied and various combinations of TM bands due to extremely low chlorophyll concentrations and highly variable DOC concentrations. They determined that phytoplankton-chlorophyll concentrations were inversely correlated with Secchi disk transparency. Field observations of open water, submerged vegetation, and surface vegetation closely matched predicted values from the Landsat TM images.

Using remote sensing shows many interesting results as is shown in this paper for coastal areas, streams and rivers, and lakes and reservoirs. These studies show the capability of remote sensing in monitoring water quality criteria such as; chlorophyll *a,* turbidity, secchi disk depth, suspended sediments, and DOC. There has been however very few studies which use airborne hyperspectral data to study inland lake water quality temporally. This study focuses on the use of airborne hyperspectral remote sensing imagery of two Iowa lakes and the temporal monitoring of each lake's water quality.

Summary of Literature Review

From the review of the literature, it is apparent that remote sensing can and has been used to accurately estimate water quality. Studies show that ground, airborne and satellite based remote sensing has been used to accurately estimate chlorophyll *a*, turbidity and Secchi disk depth in both marine and freshwater environments. Researchers note improved accuracy results from higher spatial and spectral resolution. Though multispectral sensors like the ones on the Landsat satellite series have been used to measure water quality, the higher spatial resolution which accompanies airborne images increases the understanding of the dynamics of water quality. The higher spectral resolution, which is supplied by hyperspectral sensors, also greatly improves the accuracy of water quality estimations (Ritchie & Cooper, n.d., Pulliainen, Vepsalainen, Kallio, Koponen, Pyhalahti, Harma, and Hallikainen, n.d.). With this information, it is apparent that the ideal instrument for monitoring water quality would be an airborne hyperspectral sensor.

With the knowledge gained from the literature review that an airborne hyperspectral sensor is the ideal instrument for monitoring water quality, focus on specific wavelengths, or bands, which are most important in determining concentrations of certain water quality constituents was done. From the available literature, it is apparent that for monitoring water quality constituents such chlorophyll *a*, turbidity and Secchi disk depth, concentration on wavelengths in the red and near infrared (IR) portion of the electromagnetic spectrum should be done. Researchers reported that specific wavelengths in which successes occurred were located throughout the range of 675 nm to 705 nm. A wide variety of band combinations such as band ratios, derivatives of individual bands and mathematical equations involving bands, were reported as being successful in the determination of chlorophyll *a*, Secchi disk depth and turbidity.

CHAPTER 3

METHODOLOGY

Study Area

The two lakes that comprise the study area are Casey Lake and Silver Lake. They are located in the eastern third of Iowa (Figure 1). Casey Lake is in northeastern Tama County, about 25 kilometers (km) south of Waterloo, Iowa. The lake is a 54-acre impoundment created in 1971 and is in Hickory Hills Park. The park provides facilities for boating, fishing, camping, and hiking and the lake is considered to be a premier fishing area for large-mouth bass in eastern Iowa. The watershed is roughly 740 acres. 63% of the watershed is parkland, 34% is cropland and 3% is forest (Figure 2). There are settling ponds located on the three input streams to settle out sediments and nutrients that might pollute the lake. There are also buffers of vegetation known as riparian buffers and forest between the lake and agricultural land. These features serve to minimize pollutants flowing into the lake. The lake has a maximum depth of 25 feet and an average depth of 10 feet. The length of the shoreline is 4,000 meters and there is thermal stratification present (Bachmann et al. 1980).

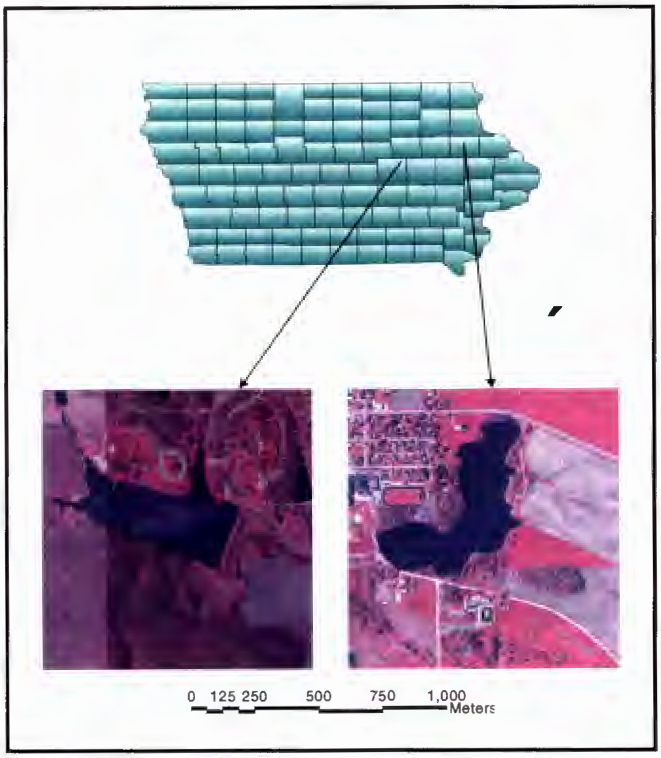


Figure 1. Study area.

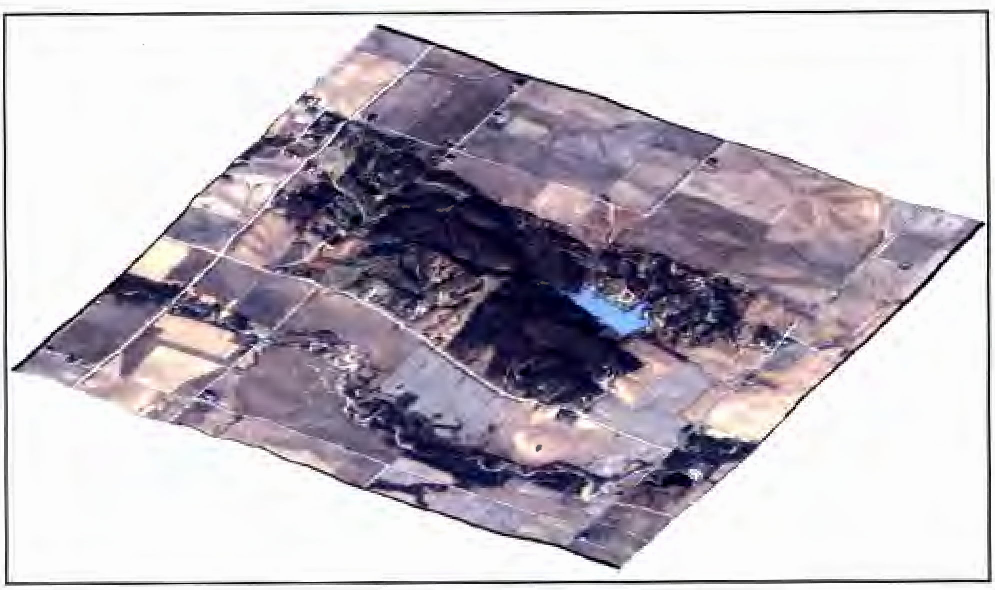


Figure 2. Casey Lake and watershed on Quickbird image and digital elevation model (DEM).

Silver Lake is located in central Delaware County, about 60 km west of Dubuque, Iowa. The lake is a 35-acre natural lake near Delhi. Delhi is a small rural town with population of 458 in 2000 (United States Census Bureau, 2000). The lake is located in Silver Lake County Park and provides facilities for fishing, boating, and picnicking. Silver Lake's watershed is roughly 187 acres. 69% of the watershed is in cropland, 12% pasture and hay-land, 11% timber, and 8% urban (Figure 3). There are no riparian buffers to separate the lake from agricultural lands and urban grass lawns. This allows for agricultural and urban fertilizers, pesticides, nutrients, and sediments to enter the lake uninhibited. The lake has a maximum depth of 15 feet with an average depth of 6 feet. The length of the shoreline is 2,161 meters and the lake is partially thermally stratified.

Figure 3. Silver Lake and watershed on aerial image and DEM.

Water Quality of Casey Lake and Silver Lake

The water quality of Casey Lake was first studied by Roger Bachmann of Iowa State University in 1979 and then again by Bachmann between 1990 and 1992 (Bachmann et al. 1994). According to Bachmann (1980), chlorophyll *a* concentrations in 1979 at Casey Lake were around 125 micrograms per Liter (*u*g/L) and Secchi disk depths were around 45 centimeters (cm). Chlorophyll *a* concentrations were much lower in 1990, around 40 *u*g/L, while Secchi disk depths were much higher, around 150 cm, suggesting an improvement in water quality (Bachmann et al.,1994). Studies from 2000, 2001, 2002, 2003, and 2004 state that chlorophyll *a* concentrations were all below 50 *u*g/L and Secchi disk depths were generally around the 150 cm range (IDNR, 2005). It appears that the water quality of Casey Lake has significantly improved since 1979 and has been consistently good from 2000 to 2004 (Figure 4).

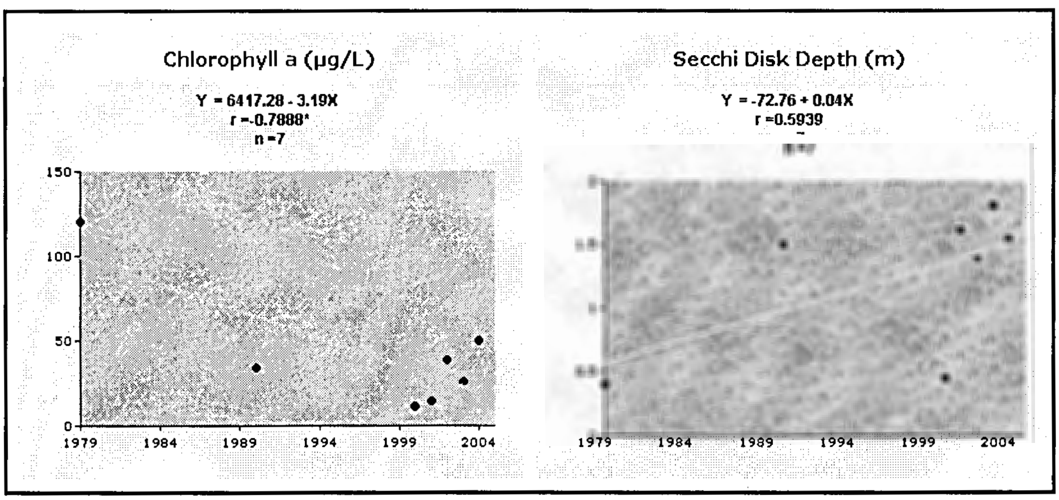


Figure 4. Trends in chlorophyll *a* and Secchi disk depth in Casey Lake. Source: Iowa DNR website, 2005.

Silver Lake was given high priority by the IDNR after it appeared on the 1998, 2002 and 2004 303d Impaired Waters Listing. The impairments are organic enrichment and nutrients. Bachmann et al. (1980) studied Silver Lake in 1979 and found that chlorophyll *a* concentrations were around 10 *u*g/L and Secchi disk depths were around 200 cm. In 1991, chlorophyll *a* concentrations increased to about 100 *u*g/L and Secchi disk depths dropped to 90 cm (Bachmann et al., 1994). Studies performed by the Iowa State Limnology Laboratory in 2000, 2001, 2002, 2003, and 2004 show concentrations of chlorophyll *a* at 220 *u*g/L, 205 *u*g/L, 175 *u*g/L, 25 *u*g/L and 140 *u*g/L relatively (Figure 5). The studies also showed that Secchi disk depths were all below 50 cm during the same time. This trend in chlorophyll *a* concentrations and Secchi disk depths supports the local feeling that the lake once was a pristine water body with a diverse ecosystem that has become degraded over the years to a level where it is now uninhabitable for most fish species.

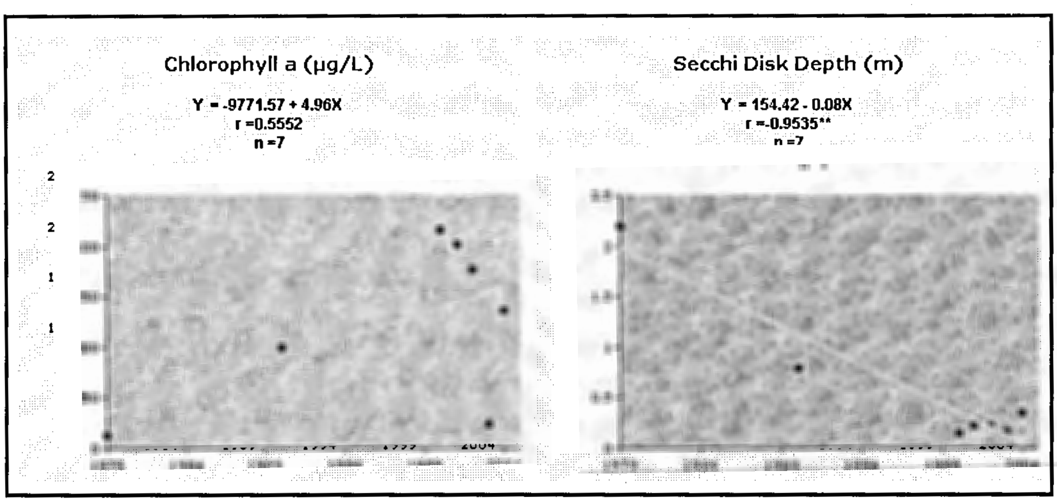


Figure 5. Trends in chlorophyll *a* and Secchi disk depth in Silver Lake. Source: Iowa DNR website, 2005.

Current Monitoring of Casey and Silver Lake's Water Quality

As has been mentioned earlier, Casey and Silver Lake are currently monitored by the Limnology laboratory of Iowa State University. A single water sample collected three times a year in the open water zone of the lakes is how the lakes are currently monitored by ISU. These lakes are also monitored by the University of Northern Iowa Summer Lakes Study team. This research team is composed of professors and students from UNI who monitor the two lakes during the summer months. The study has been ongoing since the summer of 2000. Between 20 and 23 locations are sampled on each sampling date. With 23 sampling locations instead of 1, a much better record of the water quality of the lakes is provided. This is much more time consuming and resource demanding than the ISU method and would be extremely difficult and costly to do on the 132 lakes that ISU studies.

The IDNR also monitors Silver Lake's water quality closely due to it being included on the 303d Impaired Waters Listing in 1998, 2002, and 2004. Since 1998, an aeration system has been in place to create a column of rising water that interacts with the atmosphere. This aerator increases dissolved oxygen in the water. In the summer the aerator breaks up the thermal stratification in the lake and mixes the water, while in the winter it leaves an open water region. Further actions performed by the IDNR include an intentional fish kill in the Fall of 2003 to remove the bullhead population and improve water clarity. Furthermore, the lake was stocked with bluegill, largemouth bass and channel catfish in the Spring of 2004 by the IDNR. The IDNR reported that the aerator started functioning on June 18 of 2004. There was a partial fish kill in early August of

2004, and the aerator was shutdown on August 10 with no plans to restart it. The IDNR stated that the aerator did not prevent fish kills due to the extremely large quantity of planktonic algae in the lake, so IDNR decided to let the lake function on its own. In the Summer of 2004, the lake stayed highly turbid. However, it was reported that in the Summer of 2005, the lake cleared and good dissolved oxygen was present all Summer (B. Hayes, personal communication, August 15, 2005).

Problems/Limitations

Current water-quality monitoring methods use single data points to represent an entire area or use a series of data points to estimate water quality at unknown locations. With a single water sample sometimes not representing the area in which it was collected (Huguenin, Wang, Beihl, Stoodley, & Rogers, 2004), incorrect assumptions about the water quality of a lake may be the result. The method used to monitor Casey Lake and Silver Lake that is used by the Limnology laboratory at ISU involves a single water sample that represents the open water region of the lake. This method does not supply water quality information for important near-shore areas where nutrients and sediments enter the lake. The lack of information on the quality of the near shore areas makes it impossible to study the spatial extent of pollutant plumes entering the lakes from agricultural fields or small drainage basins supplying the lakes. Even with the much more time consuming and resource demanding nature of the method used by UNI, water quality is known only for precise locations. This method does supply a broader representation of the water quality in the lakes, but it cannot monitor the spatial extent or precise origin of pollutants entering the lakes.

Data Collection

Data was collected in coordination with a University of Northern Iowa biology research team led by Dr. Maureen Clayton throughout the Summer and Fall of 2004 including the months of June, July, August, September and October. All available data collected for Casey Lake are shown in Table 1 and for Silver Lake in Table 2. Water samples, on-site measurements of water quality, GPS points, and field spectrometer readings were collected at 20 sampling locations in Silver Lake and 21 sampling locations in Casey Lake (Figure 6). The naming scheme for the sampling locations divided the sites into 5 transects that contained 4 points each for both lakes along with points that represented locations of inflow for Casey Lake. Each location was then given an abbreviated name such as T3S2 (transect 3, site 2), that represented the second sampling location on transect 3. The inflow location on Casey Lake was named inflow3. The naming scheme for the sites was used in previous studies. I used this convention to make it easier to compare water quality data from past studies.

Table 1. *Available data and dates recorded for Casey Lake.*

Chlorophyll-a	Total Phosphorus	Secchi disk depth	Turb.	pH	Bottom Dissolved Oxygen	Surface Dissolved Oxygen	Bottom Temp.	Surface Temp.	Depth	In situ reflect.	Hyperspectral Aerial Images
June 2, 2004	June 2, 2004	June 2, 2004	June 2, 2004	June 2, 2004					June 2, 2004		June 3, 2004
June 4, 2004	June 4, 2004	June 4, 2004	June 4, 2004	June 4, 2004		June 4, 2004	June 4, 2004	June 4, 2004	June 4, 2004	June 4, 2004	
June 21, 2004	June 21, 2004	June 21, 2004	June 21, 2004	June 21, 2004	June 21, 2004	June 21, 2004	June 21, 2004	June 21, 2004	June 21, 2004		
June 29, 2004	June 29, 2004	June 29, 2004	June 29, 2004	June 29, 2004	June 29, 2004	June 29, 2004	June 29, 2004	June 29, 2004	June 29, 2004		
July 7, 2004	July 7, 2004	July 7, 2004	July 7, 2004	July 7, 2004	July 7, 2004	July 7, 2004	July 7, 2004	July 7, 2004	July 7, 2004		
July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004
July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004		
August 1, 2004	August 1, 2004	August 1, 2004	August 1, 2004		August 1, 2004	August 1, 2004	August 1, 2004	August 1, 2004	August 1, 2004	August 1, 2004	July 31, 2004
Sept. 9, 2004	Sept. 9, 2004	Sept. 9, 2004	Sept. 9, 2004	Sept. 9, 2004	Sept. 9, 2004	Sept. 9, 2004	Sept. 9, 2004	Sept. 9, 2004	Sept. 9, 2004	Sept. 9, 2004	Sept. 2, 2004
Oct. 5, 2004	Oct. 5, 2004	Oct. 5, 2004	Oct. 5, 2004		Oct. 5, 2004	Oct. 5, 2004	Oct. 5, 2004	Oct 5, 2004	Oct 5, 2004	Oct 5, 2004	Oct 5, 2004

Table 2. *Available data and dates recorded for Silver Lake.*

Chlorophyll-a	Total Phosphorous	Secchi disk depth	Turb.	pH	Bottom Dissolved Oxygen	Surface Dissolved Oxygen	Bottom Temp.	Surface Temp.	Depth	In situ reflect.	Hyperspectral Aerial Images
June 3, 2004	June 3, 2004	June 3, 2004	June 3, 2004	June 3, 2004			June 3, 2004	June 3, 2004	June 3, 2004		June 3, 2004
June 14, 2004	June 14, 2004	June14, 2004	June 14, 2004	June 14, 2004	June 14, 2004	June 14, 2004	June 14, 2004	June 14, 2004	June 14, 2004		
June 28, 2004	June 28, 2004	June 28, 2004	June 28, 2004	June 28, 2004	June 28, 2004	June 28, 2004	June 28, 2004	June 28, 2004	June 28, 2004	June 28, 2004	
July 6, 2004	July 6, 2004	July 6, 2004	July 6, 2004	July 6, 2004	July 6, 2004	July 6, 2004	July 6, 2004	July 6, 2004	July 6, 2004		
July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004	July 8, 2004
July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004	July 20, 2004		
August 1, 2004	August 1, 2004	August 1, 2004	August 1, 2004		August 1, 2004	August 1, 2004	August 1, 2004	August 1, 2004	August 1, 2004	August 1, 2004	July 31, 2004
Sept. 8, 2004	Sept. 8, 2004	Sept. 8, 2004	Sept. 8, 20004	Sept. 8, 2004	Sept. 8, 2004	Sept. 8, 2004	Sept. 8, 2004	Sept. 8, 2004	Sept. 8, 2004	Sept. 8, 2004	Sept. 2, 2004
Oct. 6, 2004	Oct. 6, 2004	Oct. 6, 2004	Oct. 6, 2004		Oct. 6, 2004	Oct. 6, 2004	Oct. 6, 2004	Oct. 6, 2004	Oct. 6, 2004	Oct. 6, 2004	Oct. , 2004

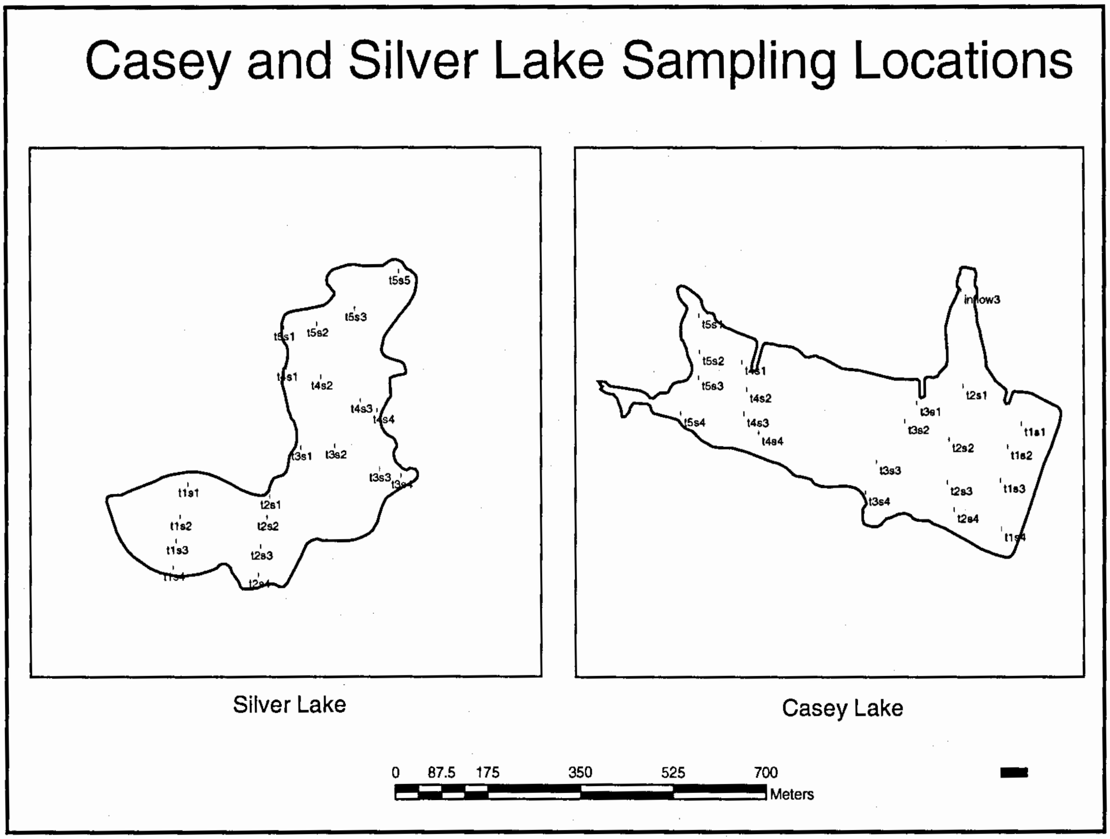


Figure 6. Sampling locations on Casey Lake and Silver Lake.

<u>Water Samples/On Site Measurements/GPS Points/ASD Field Spectrometer Readings</u>

Water samples and on-site measurements were collected on 9 dates between June 3 and October 6, 2004. Water samples were collected in plastic bottles, stored on ice and returned to a biology research laboratory at the University of Northern Iowa for analysis. The samples were analyzed to determine chlorophyll *a* concentration in micrograms per liter (*u*g/L) and total phosphorous concentration in *u*g/L. High concentrations of total phosphorous promote the growth of plant life (algae, as detected by concentrations of chlorophyll *a*) in a water body and lead to the depletion of dissolved oxygen and occasionally the extinction of other organisms. If a lake has these problems then it is said to be eutrophic.

On-site measurements were collected simultaneously with the water samples. On site measurements included Secchi disk depth, depth, pH, turbidity, surface temperature, bottom temperature, surface dissolved oxygen (DO), and bottom DO. Secchi disk depth readings were done with a black and white disk that has a diameter of 25 cm (Figure 7) and were recorded in cm. It was lowered into the water until it was no longer visible. Depth, pH, turbidity, surface temperature, bottom temperature, surface dissolved oxygen (DO) and bottom DO were all measured with portable electronic devices designed for measuring those specific water-quality characteristics. Depth was measured in meters (m), turbidity was measured in Nephelometric Turbidity Units (NTU), surface and bottom temperature were measured in degrees Celsius (°C), and surface and bottom DO were measured in milligrams/L (mg/L).

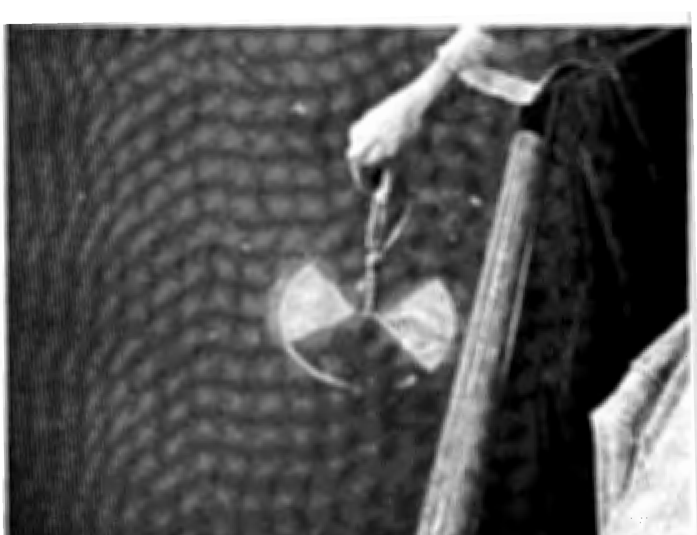


Figure 7. Measuring Secchi disk depth.

GPS points were collected while water samples and on site measurements were taken so that precise geographic coordinates could be applied to the water-quality data. GPS points were collected using a Trimble GeoXT by gathering a minimum of 20 locations to estimate the exact location of each point. Differential correction was performed on the GPS points to improve their accuracy. This method provided sub-meter accuracy to ensure accurate readings. GPS points were also gathered throughout the watersheds of both lakes to be used for geometric correction of the aerial images. A minimum of 50 locations were taken for each ground control point (GCP) to ensure highly accurate readings

Field spectrometer readings were taken simultaneously with water samples and on-site measurements for as many locations as battery life allowed. Reflectance measurements were taken with an Analytical Spectral Devices (ASD) handheld field-spectrometer that collected reflectance from 325 nm to 1,075 nm (Figure 8). A white reference disk was used to calibrate the instrument to ensure that absolute reflectance values were recorded. The spectrometer was attached to a 1-meter long metal bar and extended away from the boat so that shadow and surface effects from the boat didn't affect the readings (Figure 9). The spectrometer was held roughly .5 meters above the surface of the water with collection time of 25 seconds.

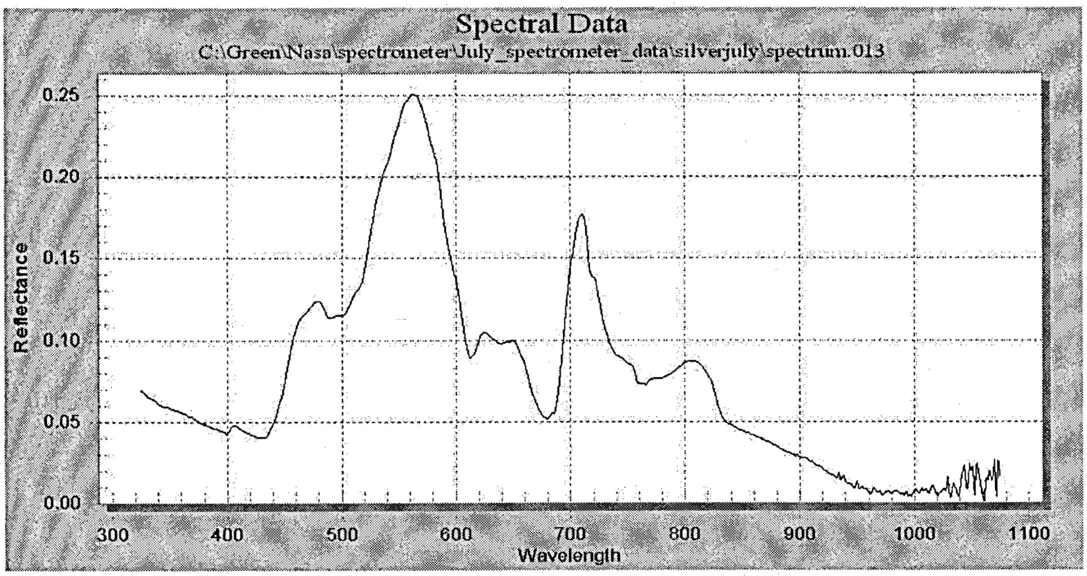


Figure 8. Sample spectra taken with ASD field-spectrometer of Silver Lake.

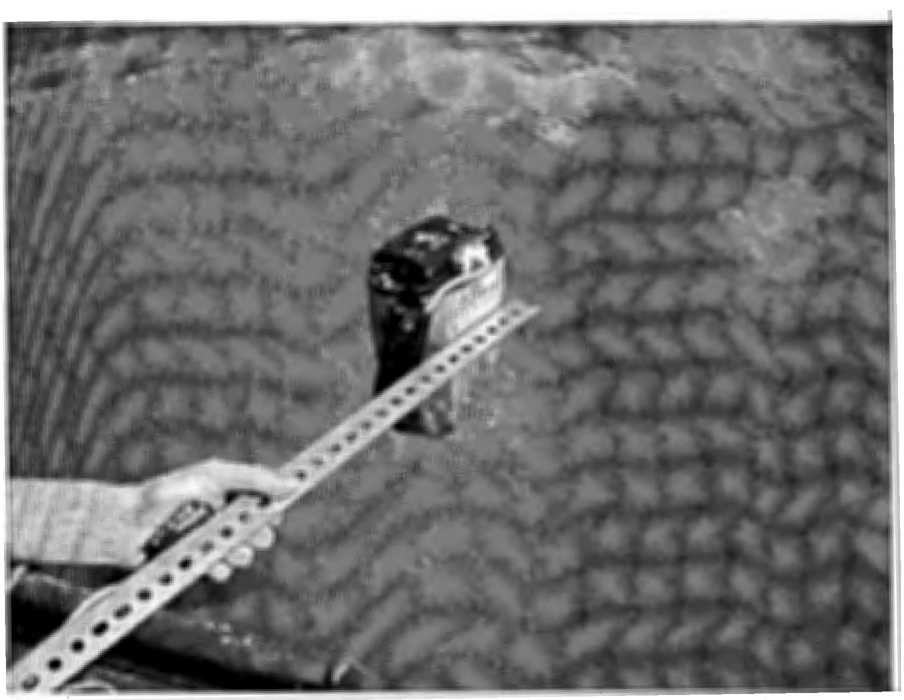


Figure 9. Field spectrometer reflectance collection in the field with ASD field-spectrometer.

<u>Weather Data</u>

Water quality is very sensitive to weather changes. According to Jeng, Englande, Bakeer and Bradford (2005), improved water quality is present during dry periods, while during storm and runoff events water quality diminishes. Increased precipitation carries large amounts of nutrients from the watershed into the water body. The loading of nutrients, particularly nitrogen and phosphorous, may cause the increased production of algae and bacteria and subsequently reduced water quality.

Weather conditions during or immediately prior to data collection helped explain the water-quality conditions in the two lakes. Looking at precipitation rates on days or weeks prior to aerial image capture may explain chlorophyll *a* concentrations, turbidity measurements, or Secchi disk depths. Precipitation data was obtained from the Iowa Environmental Mesonet, which is an archive of past weather data, constructed by Iowa State University's Department of Agronomy (Mesonet, 2005). Many weather stations throughout the state are included in this archive. However, there were no stations located exactly at the site of the two lakes. Therefore, the closest weather station to each lake was used. For Silver Lake the Manchester, Iowa station was used. It is located roughly 10 miles to the northwest of Silver Lake. For Casey Lake, the Vinton, Iowa station was used which is roughly 17 miles to the east-southeast of Casey Lake. Rainfall amounts for these two locations are given in Figure 10. These graphs show that large amounts of rain fell in the time periods leading up to the capture of the first two images but not in the time periods leading up to the capture of the last three images (Figure 11). In the two weeks before image capture on June 3 and July 8 for Silver Lake, there were 5.43 inches and 2.43 inches of precipitation, respectively. In the same two weeks at Casey Lake, there were 7.84 inches and 1.68 inches respectively. In the 2 weeks prior to the last three images at Silver Lake, there was 1.05 inches, 1.94 inches and 0.62 inches respectively. At Casey Lake during the same three weeks, there was 0.33 inches, 1.19 inches, and 1.08 inches. These numbers suggest a decrease in precipitation over the study period.

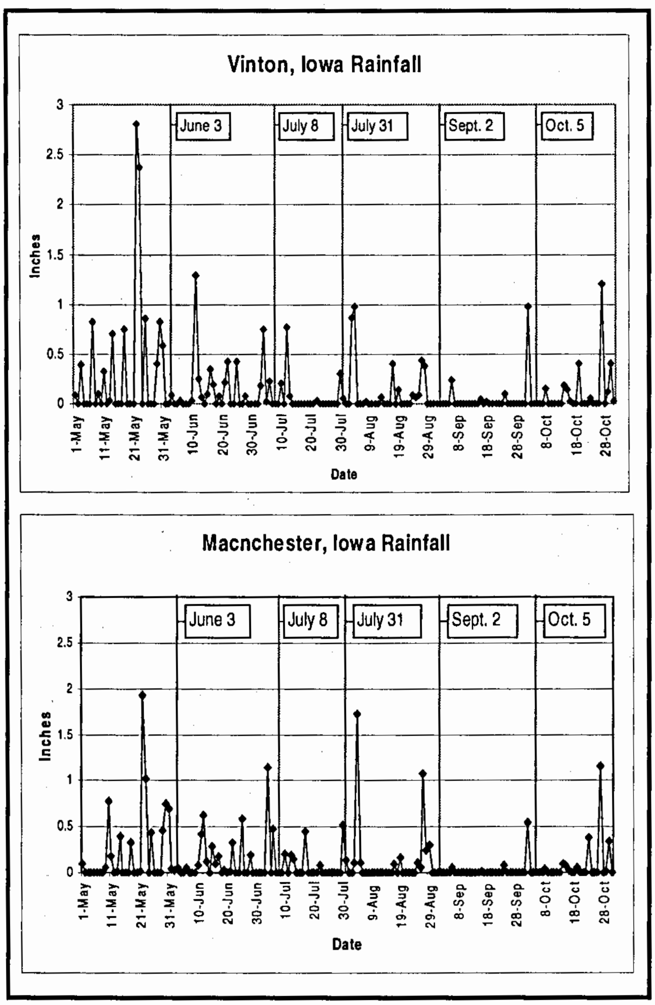


Figure 10. Rainfall amounts for Manchester and Vinton Iowa from May 1 to October 31. Source: Iowa Environmental Mesonet, 2004.

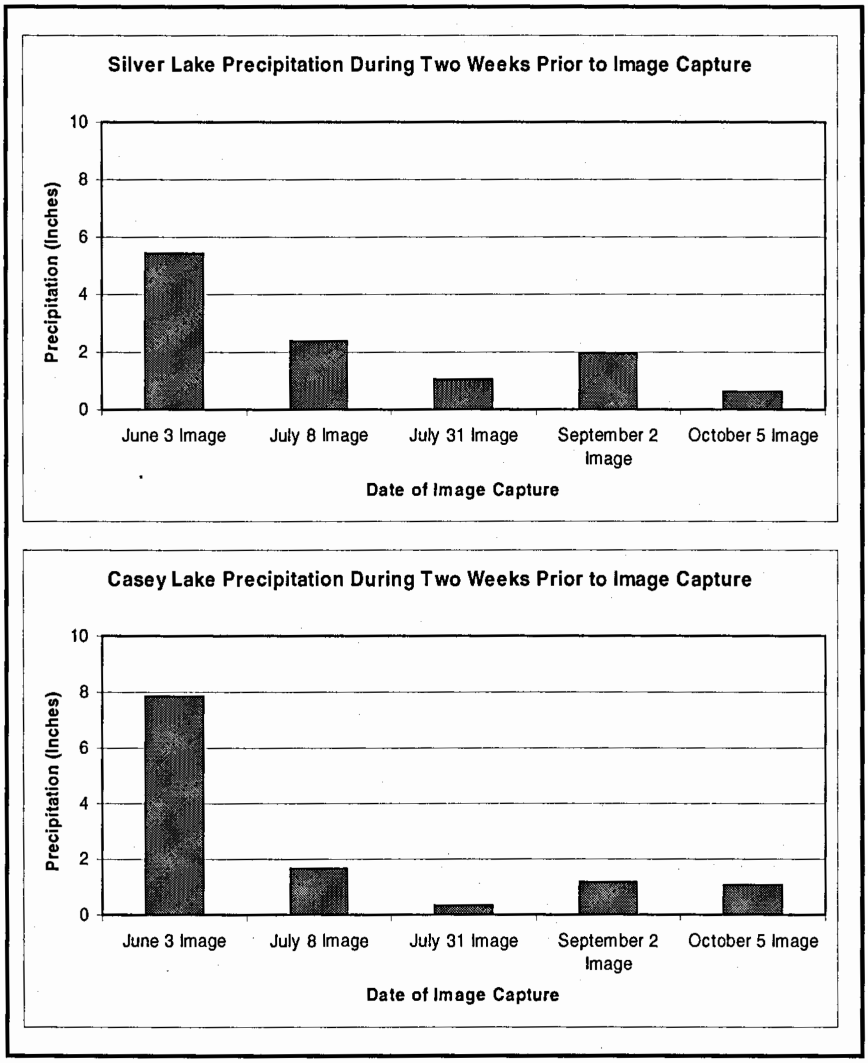


Figure 11. Rainfall in inches during the two weeks prior to each of the hyperspectral images.

Hyperspectral Aerial Image Collection

Hyperspectral aerial images were collected near the first week of the months of June through October, 2004 (Figure 12). Images were collected on five dates so that the variation in water quality over time could be examined. It was necessary to collect images over the five months so that the effects of agricultural fertilizers could be seen as well as how they dissipated throughout the year. The Center for Advanced Land Management Information Technologies (CALMIT) was contracted to perform the image collection. The images were collected using the Airborne Imaging Spectroradiometer for Applications (AISA) sensor. The AISA sensor is a push-broom sensor that collected 30 bands of spectral information from 440.52 nm to 848.91 nm with 2.5 meter spatial resolution and a swath width of roughly 860 meters. The images were collected in the late morning to reduce sun glint on the lake surfaces.

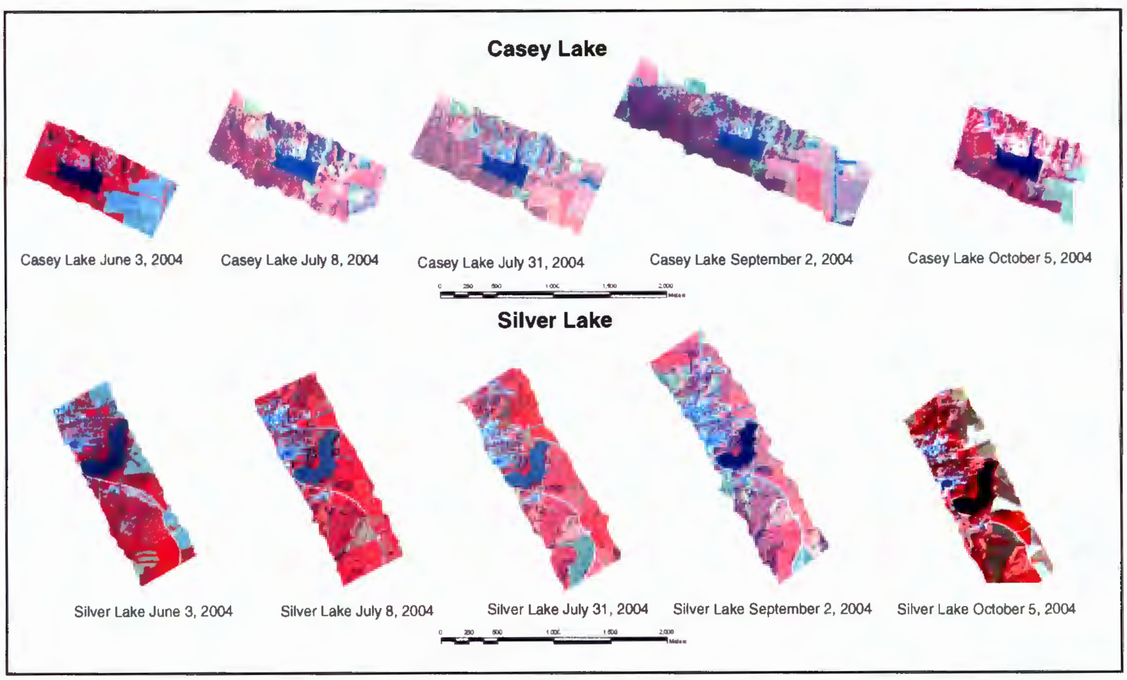


Figure 12. Hyperspectral aerial images with Red = Band 19 (826.68 nm), Green = Band 16 (691.59 nm), Blue = Band 2 (473.70 nm).

Laboratory Analysis

Laboratory analysis on the water samples was conducted by the biology research team led by Dr. Maureen Clayton. To determine the amount of chlorophyll *a* present in each water sample, a known volume of the sample was filtered through a glass fiber filter. The filter was then ground using a tissue grinder in 90% acetone. 10 milliliters (mL) of the resulting solutions were steeped at 4 °C for 2 hours. The 10 mL solutions were then centrifuged for 20 minutes at 500 g. The amount of chlorophyll *a* was then extracted from the clear extract and measured in micrograms per liter (*u*g/L).

Water Quality Constituent Selection

There are many factors that affect water quality, many of which were tested for in this study. I concentrated on chlorophyll *a*, Secchi disk depth and turbidity because these are among the most common trophic parameters used in hyperspectral remote-sensing studies (Carlson, 1977; Schafer, 1997; Schroder et al., 2004; and Jorgensen & Vollen-weider, 1989). They were also selected because these constituents have optical properties that allow them to be tested with remote sensing, while factors such as temperature and pH have no direct optical properties, and thus cannot be tested with remote sensing. Phosphorous has no optical properties and cannot be measured with remote sensing devices. However it is generally the limiting factor for plant growth and is usually correlated with chlorophyll amounts (Olmanson, Bauer & Brezonik, 2002).

Chlorophyll *a* is the dominant type of pigment found in algae and cyano-bacteria, and therefore, is a measure of the abundance of algae and cyano-bacteria in the water column. As unconsumed algae and bacteria die, they sink to the bottom and decay. This process uses up all the available dissolved oxygen that other plants and animals need to survive and in turn they die. This leads to oxygen depletion in a lake and the eutrophication of the water body.

Secchi disk depth originated with Fr. Pietro Angelo Secchi in the 1860's (Carlson and Simpson, 1996) and is used as an important indicator of trophic state (Kirk, 1994) and overall clarity of the water. It is also described by Schafer (1997) as a measure of the transparency of the water column. It is generally a measure of how clear the water column is and how many large particles are suspended therein. A lake with poor water quality and large amounts of chlorophyll *a* and suspended sediments would have small Secchi disk depths.

Turbidity is similar to Secchi disk depth, but turbidity includes the analysis of microscopic particles in the water column. High turbidity reduces the amount of sunlight reaching plants rooted in the floor of a water body and limits their growth. Lower dissolved oxygen also results from high turbidity because oxygen is more easily dissolved into water with low amounts of suspended materials.

Ground-Based Water Quality Maps

Creation of thematic chlorophyll *a*, Secchi disk depth, and turbidity maps was done using field and laboratory data with ArcGIS 9.0. Field and laboratory data were added to shape-files that represented sampling locations on each of the lakes. Using Interpolate to Raster in the Spatial Analyst extension, Inverse Distance Weighted (IDW) density maps were made for each lake for all five sampling dates for chlorophyll *a*, Secchi disk depth, and turbidity. According to ESRI, IDW predicts values at unknown locations by explicitly analyzing distances from known locations. An example is if an unknown turbidity value is exactly half way between 10 NTU and 0 NTU, then IDW predicts that the turbidity value at the unknown location is 5 NTU. Because water is fluid and disperses pollutants easily, IDW was selected.

Preprocessing Hyperspectral Data

File Conversion

Hyperspectral images of both lakes were downloaded from a secure .ftp site in ENVI format as they became available. They were generally available a few weeks after being flown due to some processing by CALMIT. Once the images were downloaded from CALMIT, file conversion was done. The images were received in ENVI file format, which was not recognizable by ERDAS Imagine or ArcMap software. Therefore, they were converted to Imagine image format (*.img*) by first converting the ENVI format files to ERDAS *.lan* and then importing them to *.img* using ERDAS Imagine 8.6. The images were received in NAD 83 projection and were converted to UTM WGS 84 Zone 15N. This projection was used exclusively in this research.

Geometric Correction

The images received from CALMIT were geographically corrected but not to the accuracy needed. To insure that precise geographic locations of water samples were known, further geometric correction was done. Using a Trimble GeoXT and Terrasync software, ground control points (GCP) were collected in the immediate vicinity of both lakes for geometric correction. A minimum of 40 GPS locations were used for each GCP to insure highly accurate GCP locations. Using 12 ground control points (GCP) for

Casey Lake and 24 GCPs for Silver Lake, geometric correction was done using ERDAS Imagine 8.7. The Silver Lake July 8 image and the Casey Lake July 31 image were corrected with the GCPs and subsequent images were corrected from them to insure that all images were registered from the same geographic coordinates.

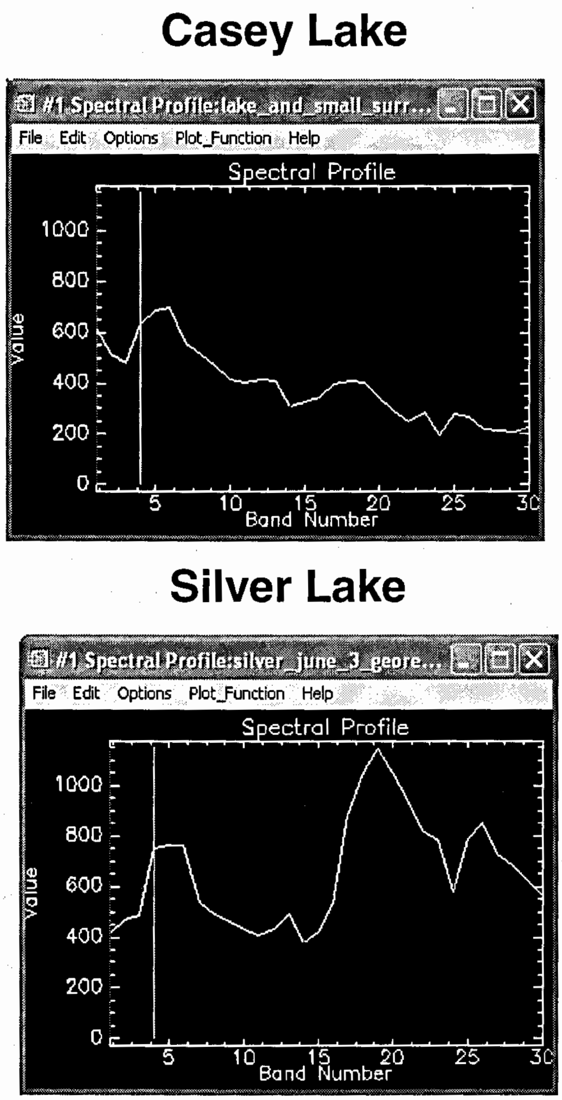
Image Subsetting

To increase processing time and remove unwanted data, the lakes were removed from each image using ENVI software. Using ENVI's region of interest (ROI) tools, each lake was digitized individually. This was done because the water level of the lakes is not consistent from month to month. If the images were clipped by a single shape-file representing each lake, a low water level month may contain non water surfaces and a high water month may not include the entire lake. Manual digitization of the images resulted in images that contained only the lakes and none of the surrounding watershed.

Processing Hyperspectral Data

Band Selection

Band selection is the process of reducing the dimensionality of hyperspectral data. One of the keys to working with hyperspectral data is reducing it overall size. This study uses 30 bands of data with example spectral profiles from each lake shown in Figure 13. With each lake covering roughly 20,000 pixels and the images being 30 layers deep, 600,000 pixels per lake was the working dataset. With ten images, each containing 600,000 pixels, reducing the dimensionality was a major concern. In reviewing the relevant literature I discovered which bands, or wavelengths, were most important for chlorophyll *a*, Secchi disk depth, and turbidity.



Band	Wavelength
Band 1	440.52 nm
Band 2	473.70 nm
Band 3	499.77 nm
Band 4	542.43 nm
Band 5	550.33 nm
Band 6	561.39 nm
Band 7	585.09 nm
Band 8	597.03 nm
Band 9	609.21 nm
Band 10	621.39 nm
Band 11	631.83 nm
Band 12	638.79 nm
Band 13	650.97 nm
Band 14	670.11 nm
Band 15	684.75 nm
Band 16	691.59 nm
Band 17	700.14 nm
Band 18	705.27 nm
Band 19	710.40 nm
Band 20	715.53 nm
Band 21	720.66 nm
Band 22	727.50 nm
Band 23	749.73 nm
Band 24	763.41 nm
Band 25	773.67 nm
Band 26	807.87 nm
Band 27	813.00 nm
Band 28	819.84 nm
Band 29	826.68 nm
Band 30	848.91 nm

Figure 13. Example spectra from Casey Lake and Silver Lake. Red, Green, and Blue wavelengths are shown by the corresponding colored lines. Bands and corresponding wavelengths are also given.

For chlorophyll *a* determination, researchers have focused on using hyperspectral bands close to and in the near infrared region of the spectrum. Strong correlations between surface chlorophyll *a* concentrations and near infrared reflectance have been found (Ekstrand, 1998). Gitelson (1992) and Quibell (1992) found strong correlations with single bands and chlorophyll *a* concentrations around the near infrared region, particularly the 705 nm region. Others (Mittenzwey, Gitelson, & Kondratyev 1992; Rundquist, Luoheng Han, Schalles, & Peake 1996) found that using a ratio of near infrared to red gave better results. Also, Gitelson et al. (1992) states that the visible spectral regions lose their correlation with chlorophyll concentrations when the suspended matter levels are high, but that the wavelengths above 700 nm are still strongly correlated with chlorophyll concentrations. Another method that was used was the regression analysis method (Keiner & Yan, 1998; Nordheim & Lillesand 2004; Koponen et al. 2001; Emch 2002). The best regression equations for determining chlorophyll concentrations using hyperspectral images seems to be centered on using the wavelength of the peak near 700 nm in the numerator and the wavelength corresponding with the absorption feature near 670 nm. For chlorophyll *a* the bands near the red and near IR portions of the spectrum were used.

For determination of turbidity and Secchi disk depth, the regression method is the most common (Rao, 1998; Emch, 2002; Keiner & Yan, 1998). Rao (1998), Emch (2002), & Keiner & Yan, (1998) all used various Landsat MSS and TM bands in determining Secchi disk depth or turbidity. Their studies focused again on the near IR to red ratio and bands in that portion of the electromagnetic spectrum. For hyperspectral images, the best equation for determining turbidity is the first derivative of: (reflectance at 700 nm – reflectance at 675 nm) / 25 (Shafique et al. 2001). For determining turbidity and Secchi disk depth, concentration on spectral bands near the near IR and red regions of the spectrum was done.

The AISA bands that corresponded to the near IR and red regions of the spectrum are bands 14 through 19. Concentration on these bands was done in this study to predict chlorophyll *a* concentrations, Secchi disk depths, and turbidity.

<u>Principal Components Analysis</u>

Having reduced the hyperspectral data to the most useful bands in predicting chlorophyll *a*, Secchi disk depth, and turbidity (Figure 14), further reduction of the data was done using principal components analysis (PCA) in ENVI image processing software. According to Richards (1999), PCA is a method of data reduction and removal of noise and other unwanted data. The resulting principal components images are made up of uncorrelated bands that accentuate spectral differences. The first principal component band (PC1) contains the largest amount of data variance and is therefore the most useful. The last principal component band contains very little data variance and appears noisy because it is mostly composed of instrument noise and other unwanted data. By performing the PCA on each of the images containing bands 14 through 19, ten four band images made up of the first six principal components were created (Figure 15). In every image, PC1 of bands 14 through 19 contained more than 99% of the data variance (Figure 16). This means that 99% of the data variance in bands 14 through 19 of the original hyperspectral images was contained in PC1. Therefore, this band was solely used in this study.

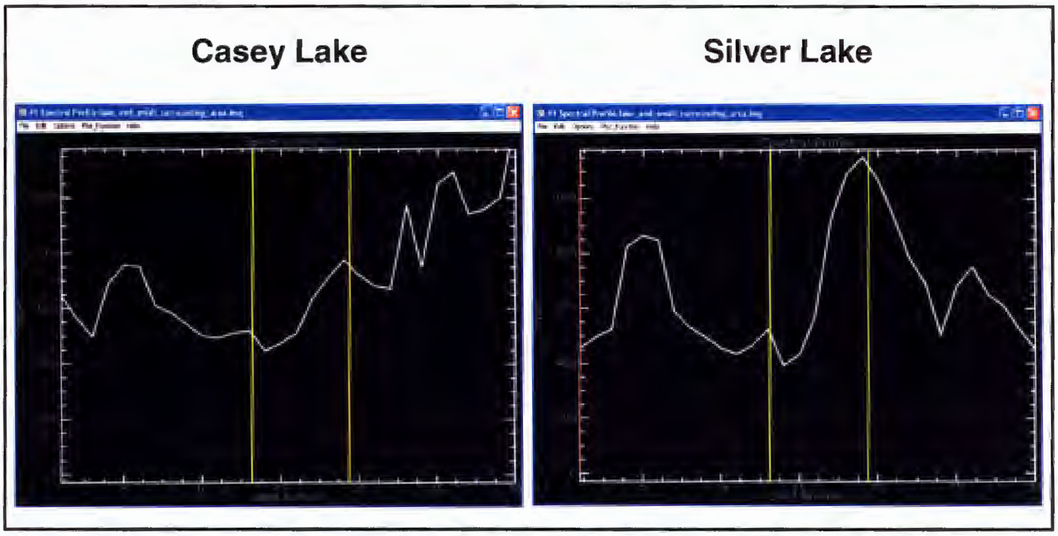


Figure 14. Spectra from Casey Lake and Silver Lake with the area used in PCA marked by vertical lines.

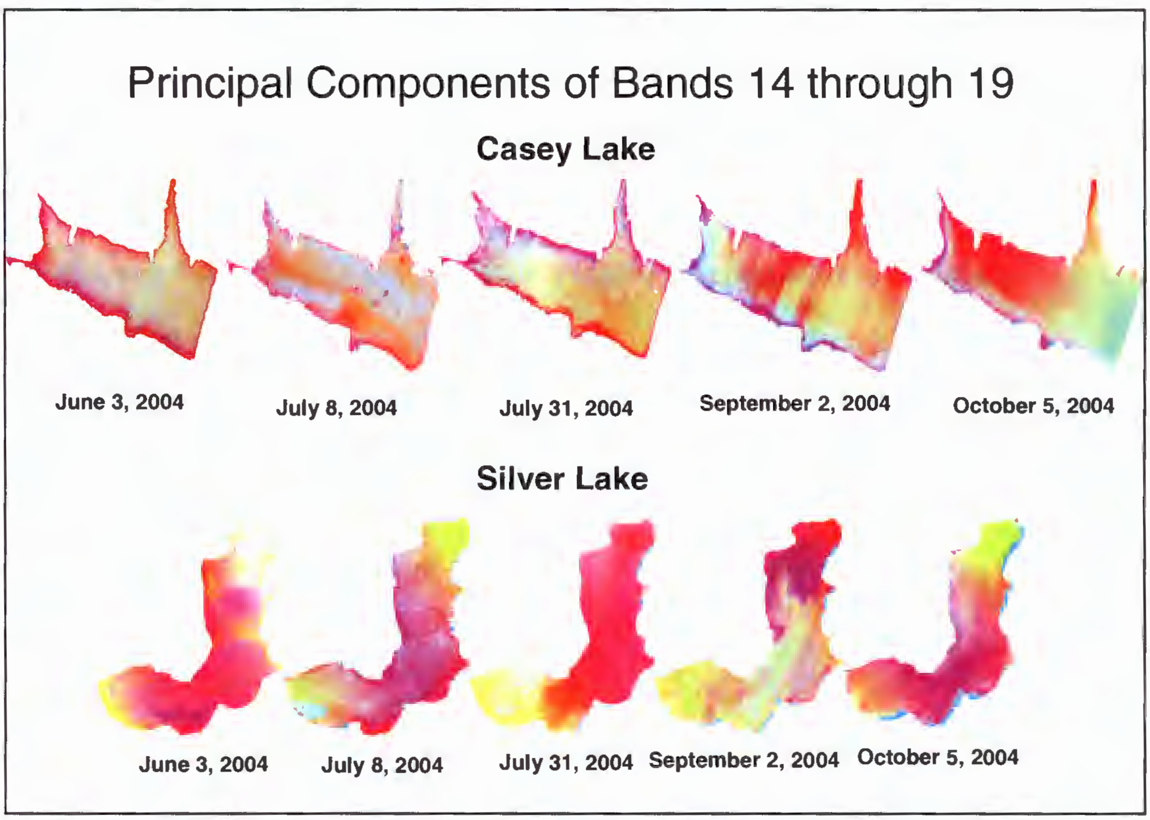


Figure 15. Principal components images of both lakes with PC1 = Red, PC2 = Green, and PC3 = Blue.

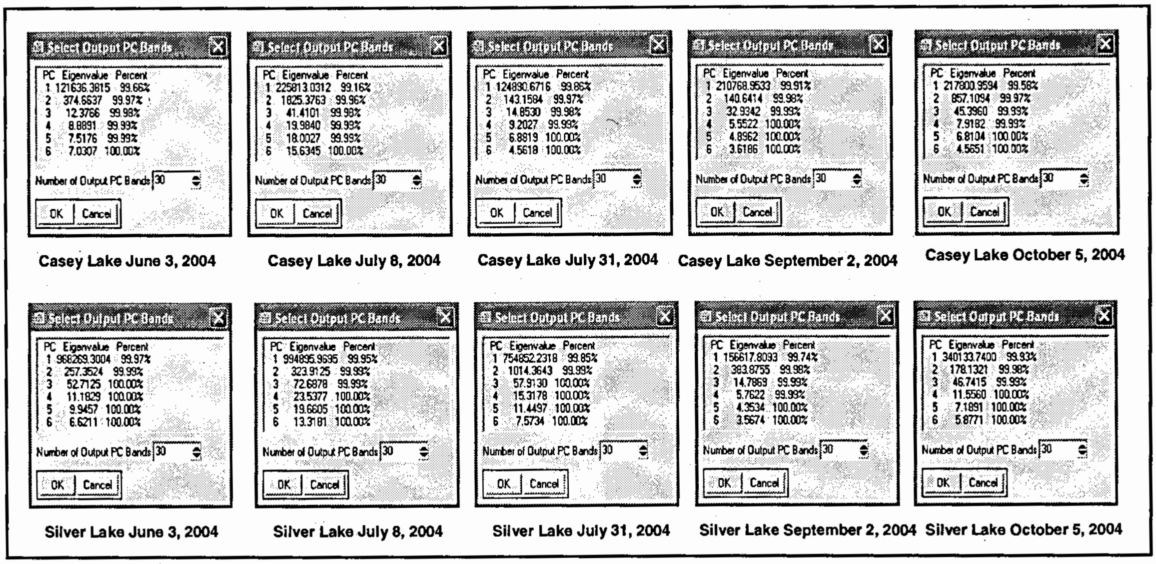


Figure 16. Percentage of data contained in principal component bands of bands 14 to 19.

Data Extraction

Extraction of data from the PC1 images was done so that comparison of spectral data could be directly compared to water quality data numerically. The extraction of the PC1 data was done using ERDAS Imagine's area of interest (AOI) tools and the "export pixels to ASCII" functionality. Pixels that were exported to ASCII (American Standard Code for Information Interchange) format were selected by first overlaying the GPS points that were collected at every water sample location on top of the images. Each pixel was 2.5 meters by 2.5 meters. The boat itself was roughly 5 meters long and would cover about two pixels. Therefore, an average of 9 pixels which surrounded each sampling location was used to ensure the exact sampling location was included (Figure 17). By doing this, each chlorophyll *a* concentration, Secchi disk depth, and turbidity value was related to a certain PC1 value.

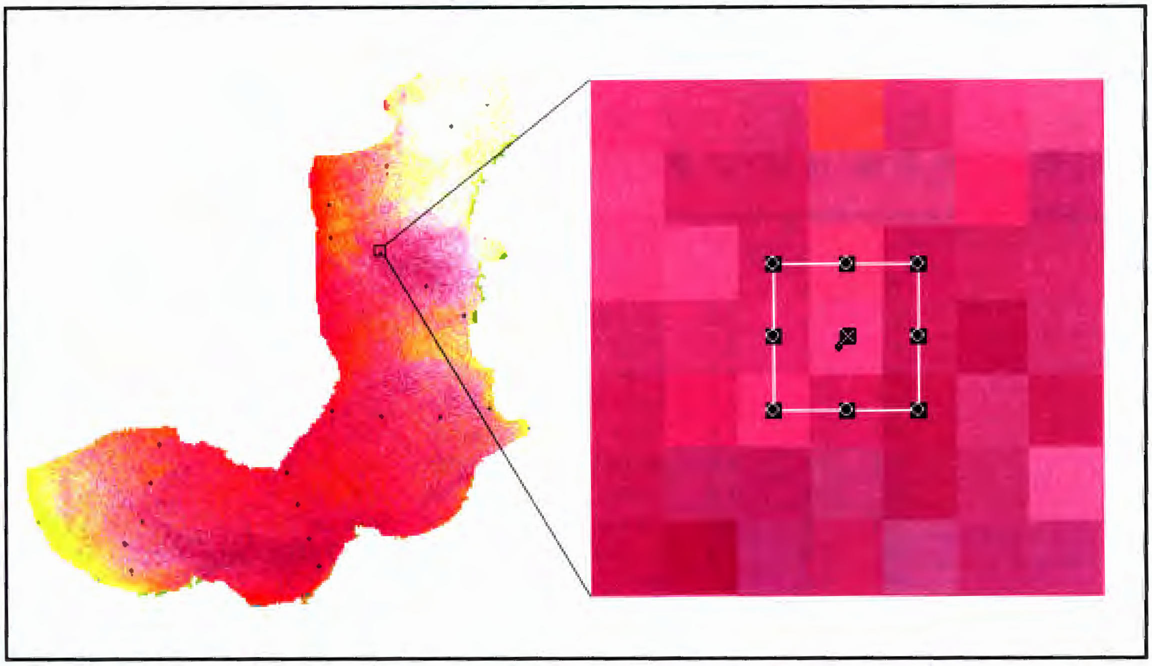
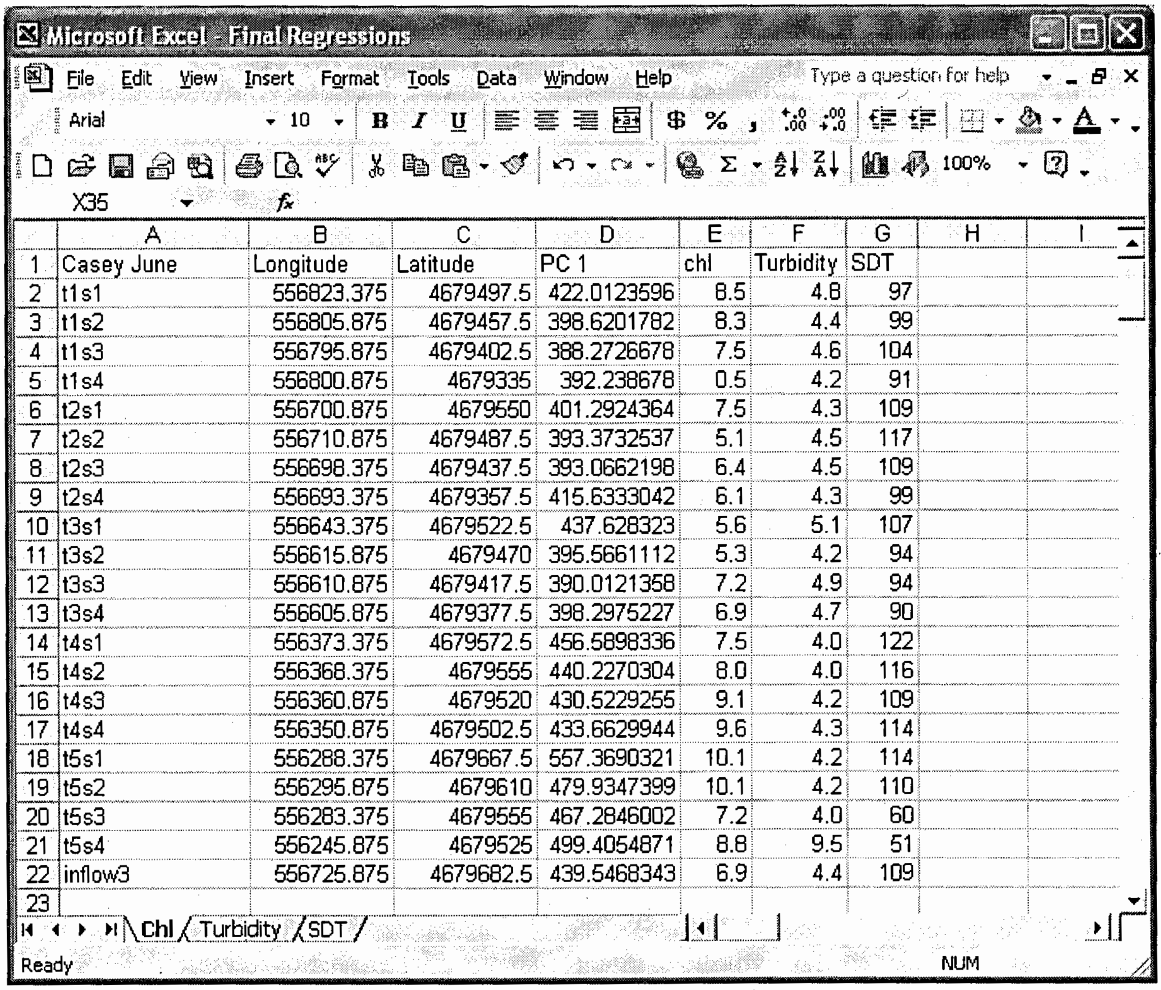


Figure 17. GPS point on principal component image with AOI drawn.

Algorithm Creation

The exported ASCII files that represented PC1 values of each sampling location were opened in Microsoft Excel and saved as a workbook. This was done for each of the ASCII files so that ten separate Microsoft workbooks resulted. Chlorophyll *a* concentrations, Secchi disk depths, and turbidity values were then added to the data set. Finally, all ten workbooks were combined to form a database that contained information on both lakes for all five months. The final result was a Microsoft workbook that had the name of the sampling location (i.e. T1S1), geographic latitude and longitude, PC1 value, chlorophyll *a* concentration, Secchi disk depth, and turbidity value (Figure 18).



	A	B	C	D	E	F	G
1	Casey June	Longitude	Latitude	PC 1	chl	Turbidity	SDT
2	t1s1	556823.375	4679497.5	422.0123596	8.5	4.8	97
3	t1s2	556805.875	4679457.5	398.6201782	8.3	4.4	99
4	t1s3	556795.875	4679402.5	388.2726678	7.5	4.6	104
5	t1s4	556800.875	4679335	392.238678	0.5	4.2	91
6	t2s1	556700.875	4679550	401.2924364	7.5	4.3	109
7	t2s2	556710.875	4679487.5	393.3732537	5.1	4.5	117
8	t2s3	556698.375	4679437.5	393.0662198	6.4	4.5	109
9	t2s4	556693.375	4679357.5	415.6333042	6.1	4.3	99
10	t3s1	556643.375	4679522.5	437.628323	5.6	5.1	107
11	t3s2	556615.875	4679470	395.5661112	5.3	4.2	94
12	t3s3	556610.875	4679417.5	390.0121358	7.2	4.9	94
13	t3s4	556605.875	4679377.5	398.2975227	6.9	4.7	90
14	t4s1	556373.375	4679572.5	456.5898336	7.5	4.0	122
15	t4s2	556368.375	4679555	440.2270304	8.0	4.0	116
16	t4s3	556360.875	4679520	430.5229255	9.1	4.2	109
17	t4s4	556350.875	4679502.5	433.6629944	9.6	4.3	114
18	t5s1	556288.375	4679667.5	557.3690321	10.1	4.2	114
19	t5s2	556295.875	4679610	479.9347399	10.1	4.2	110
20	t5s3	556283.375	4679555	467.2846002	7.2	4.0	60
21	t5s4	556245.875	4679525	499.4054871	8.8	9.5	51
22	inflow3	556725.875	4679682.5	439.5468343	6.9	4.4	109
23							

Figure 18. Final data set in Microsoft Excel.

With the data now in a single location, relationships between the first principal component and chlorophyll *a* concentrations, Secchi disk depths, and turbidity values could be made. A subset of the sampling locations (Figure 19) was used to create algorithms that could be used to predict chlorophyll *a* concentrations, Secchi disk depths, and turbidity values. A subset of the data was used to ensure that the remaining portion of the data did not affect algorithm creation and could be used in accuracy assessment.

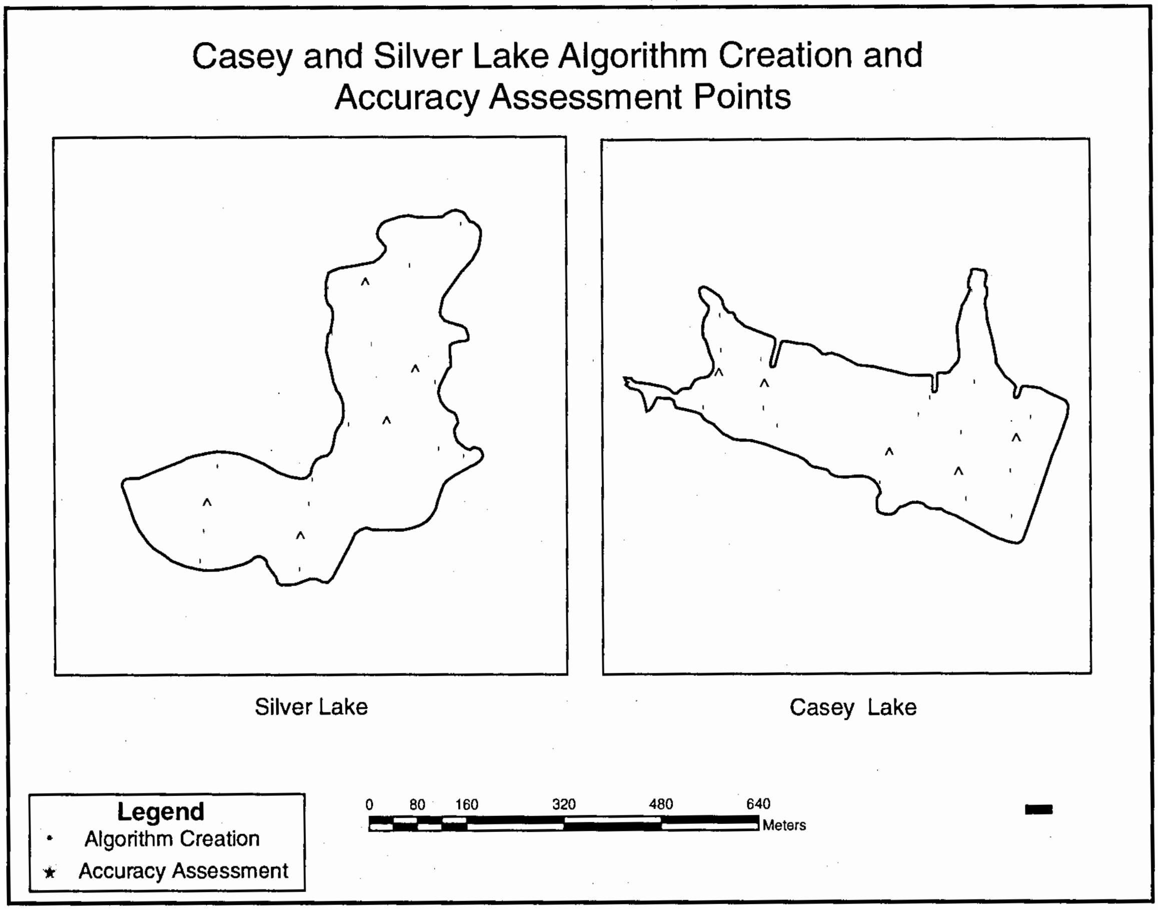


Figure 19. Points used for algorithm creation and accuracy assessment.

The creation of prediction algorithms was done first by creating scatter plots of the first principal component against chlorophyll *a* concentrations, Secchi disk depths, and turbidity values. Trend lines were added to see if a linear equation could describe the data set (Figure 20). The equations for the lines which described the scatter plot were used for predicting the respective water quality constituent.

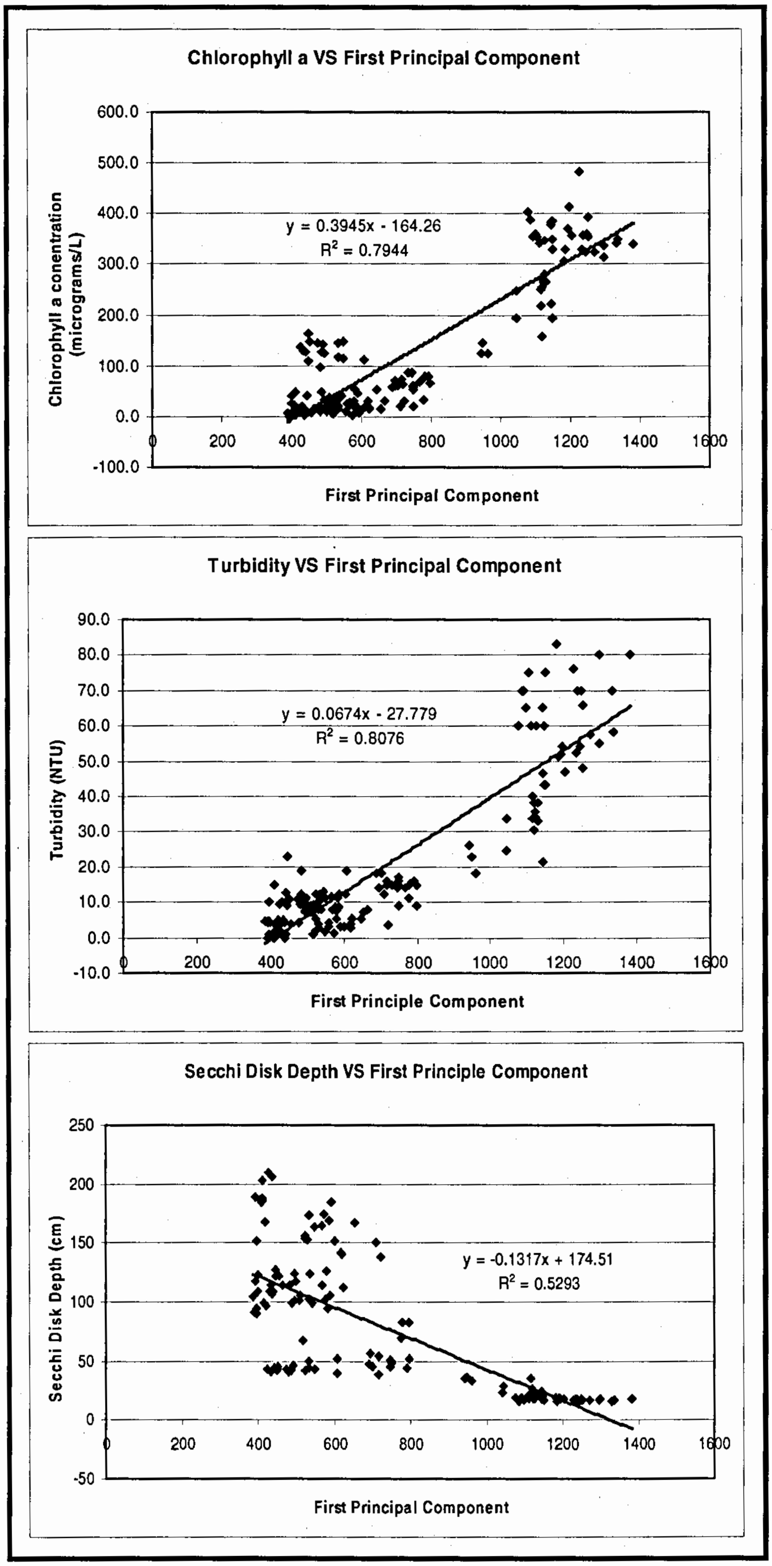


Figure 20. First principal component vs. chlorophyll *a*, Secchi depth, and turbidity plots.

Application of Algorithm

Implementation of the predictive algorithms was done using ERDAS Imagine's Model Maker functionality. A relatively simple model was needed to apply the algorithm to every pixel in the first principal component images (Figure 21). In Figure 21, the feature at the top that looks like a stack of papers represents the input raster. The input raster in this case is the 4 principal component bands taken from bands 14 to 19 of the June 3, 2004 Silver Lake image. This raster is fed into a function, the round feature in the center of the model. The function in this case is the predictive chlorophyll *a* algorithm. The last feature in the model is the output raster. This is the output image in which every pixel has been given a chlorophyll *a* concentration in *u*g/L based upon the prediction algorithm.

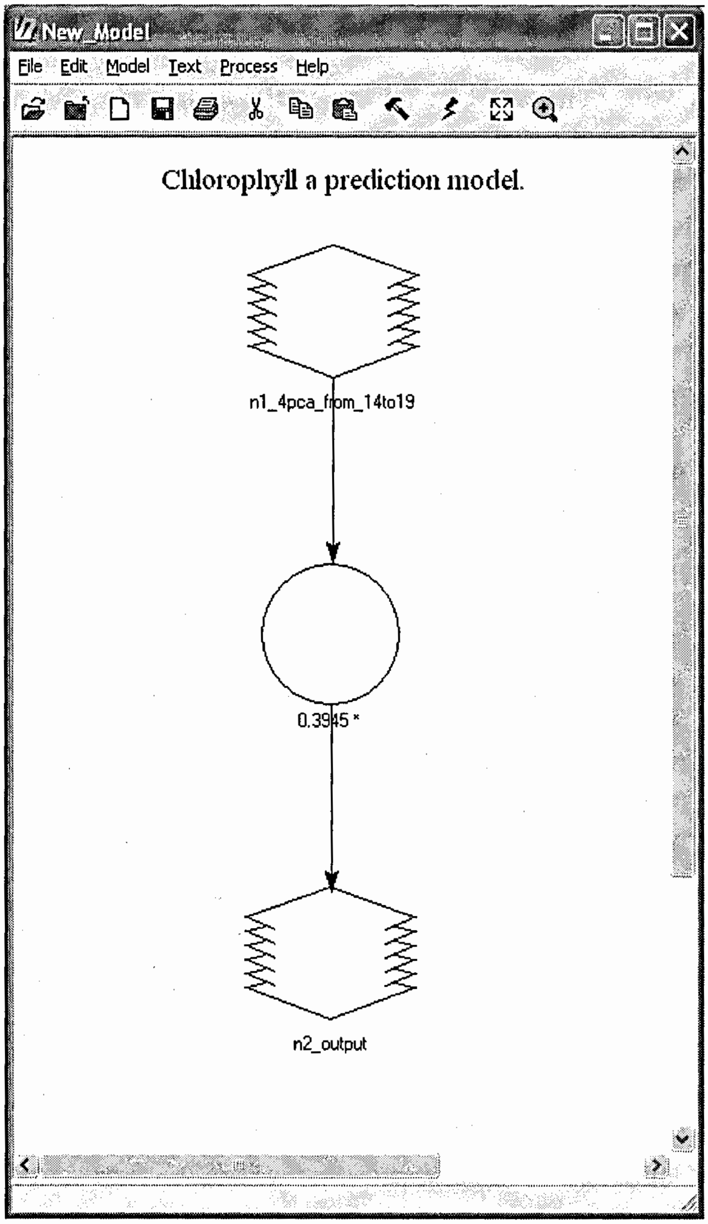


Figure 21. Prediction model in ERDAS Imagine Model Maker.

<u>Temporal Anlaysis</u>

Temporal analysis of the chlorophyll *a* concentrations, turbidity and Secchi disk depths was done by analyzing these variables on a month to month basis. Plots were created by producing the most common occurring estimations of chlorophyll *a*, turbidity and Secchi disk depth values for each month to show the trend in these variables over the study period. By creating these plots, the overall water quality trend was more easily seen for the entire lake

Trophic State Index

It was necessary to be able to relate my findings to other researchers in other regions of the country. To do this, a standard unit for describing water quality was needed. Carlson's (1977) Trophic State Index (TSI) is such a standard and is used commonly in water quality research. Carlson's index can be calculated for chlorophyll *a*, Secchi disk depth or total phosphorous by entering these parameters into specified equations. This research does not include the monitoring of total phosphorous and therefore the TSI for total phosphorous has not been included. Equations for calculating chlorophyll *a* and Secchi disk depth are shown.

For chlorophyll *a*, the TSI equation is:

$$TSI = 30.6 + 9.91 * \ln(\text{chlorophyll } a \text{ in } ug/L)$$

For Secchi disk depth, the TSI equation is:

$$TSI = 60 - 14.41 * \ln(\text{Secchi disk depth in meters})$$

where:

TSI = Carlson's Trophic State Index

ln = natural logarithm

Trophic State Indices were calculated for chlorophyll *a* and Secchi disk depth. This was done by first computing the average pixel value from each month of the classified hyperspectral images. This average value was then entered into the appropriate equation. Plots were then created showing the TSI indices for chlorophyll *a* and Secchi disk depth over the five month period. This provided a temporal representation of the change in water quality based upon a standard unit, the trophic state index.

CHAPTER 4

RESULTS AND DISCUSSION

The following section will discuss the results of the ASD field spectrometer readings, water samples and subsequent maps and hyperspectral image classification. Detailed discussion of chlorophyll *a*, turbidity and Secchi disk depth trends will be included in this section. Temporal analysis as well as trophic state index analysis will also be discussed.

ASD Field-Spectrometer

The use of the ASD field-spectrometer data was limited because of both the quantity and quality of the data retrieved. As was mentioned earlier, battery life hampered data collection so that between five and ten spectra were collected at each lake on every date that data were collected. The usable spectra were further reduced by the inconsistencies of the instrument and inexperience by the users. For unexplained reasons, the instrument would collect reflectance at one location and collect radiance at another. Comparison between reflectance spectra and radiance spectra cannot be done and therefore many of the field-spectrometer readings were unusable.

Ground Based Water Quality Classification

Chlorophyll *a*

The results of the ground-based water-quality classification of Casey Lake's and Silver Lake's laboratory chlorophyll *a* concentrations during the study time period are shown in Figure 22. Different colors represent estimated ranges of chlorophyll *a* distribution throughout the lakes as is seen in the legend. The trend of chlorophyll *a* for

Casey Lake is an overall increase in concentrations from 1 to 25 *u*g/L on June 4 to concentrations in the upper 200 *u*g/L range and lower 300 *u*g/L range on September 2 and October 5. Highest concentrations are seen near sampling location "inflow3". This is an area where runoff enters the lake. High concentrations of chlorophyll *a* were thought to be explained by the large amounts of runoff entering the lake here.

Chlorophyll *a* concentrations in Silver Lake behaved in an opposite manner through time than concentrations at Casey Lake. Concentrations in Silver Lake started in the upper 300 *u*g/L range and lower 400 *u*g/L range on June 4 and steadily declined throughout the study period until concentrations on October 6 ranged from 50 *u*g/L to 100 *u*g/L. This trend can be explained by precipitation in the region. Precipitation was much greater during the weeks prior to the June 4 and July 8 images, which had very high chlorophyll *a* concentrations, than it was during the weeks prior to the last three images, which show lower chlorophyll *a* concentrations. An interesting "bulls-eye" like feature in the August 1 map is present in the southwest portion of Silver Lake. This feature is in the same location as the oxygen bubbler that was installed by the IDNR. The map indicates that very high chlorophyll *a* concentrations are occurring in the immediate vicinity of the oxygen bubbler. This is unexpected since the oxygen bubbler is used for improving water quality. An explanation of this discrepancy may be that the water sample taken at that sampling location was uncharacteristic of the actual chlorophyll *a* concentration of the water in that area by including a large piece of floating vegetation in the water sample. This would make that water sample unrepresentative of the area in which the sample was taken. Further evidence that this chlorophyll *a* reading was incorrect lies in the fact that turbidity values were low and Secchi disk depths were high for the same location. If chlorophyll *a* concentrations were actually this high, Secchi disk depths would be much lower than they actually were. This highlights a major problem with the density map method. One incorrect reading can have extreme effects on the output.

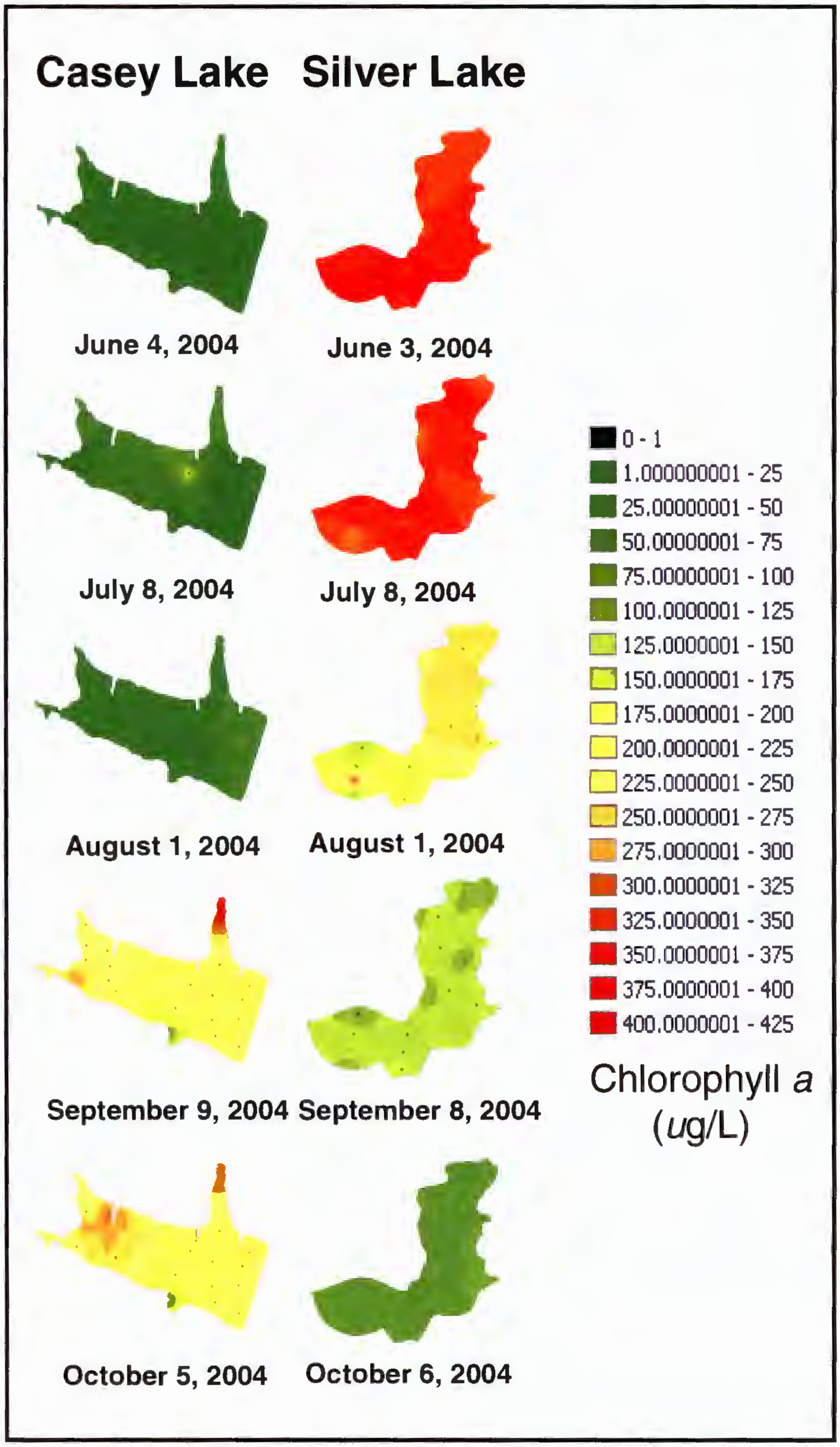


Figure 22. Chlorophyll *a* density maps.

Turbidity

Ground-based density maps of on-site turbidity values at Casey and Silver lakes are shown in Figure 23. Turbidity values at Casey Lake are consistently between the range of 0 NTU and 30 NTU for June 4, July 8, August 1, and September 2. On October 5, the majority of the lake is again in the 0 to 30 NTU range. The eastern third of the lake, however, jumps up to greater than 100 NTU. Secchi disk depths for the same region of Casey Lake are around 100 cm, suggesting that the turbidity measurements are inaccurate. Precipitation seems not to have a large affect on the turbidity of Casey Lake. As precipitation varies from month to month, turbidity appears unaffected.

Silver Lake's turbidity ranges from 40 to 80 NTU on June 4 and July 8. This may be explained by the large amounts of precipitation during this time. Turbidity sharply decreases to between 10 and 40 NTU on August 1 corresponding to a decrease in precipitation. On September 2 and October 5, turbidity values were even lower with values ranging from 1 to 20 NTU. In the area around the oxygen bubbler turbidity values were lower than surrounding areas. This suggests that the oxygen bubbler had a positive affect on water quality. The ArcGIS maps of turbidity in Silver Lake suggest that turbidity is closely related to precipitation. As precipitation decreases, less sediment laden runoff enters the lake, and thus, fewer suspended materials, which leads to lower turbidity.

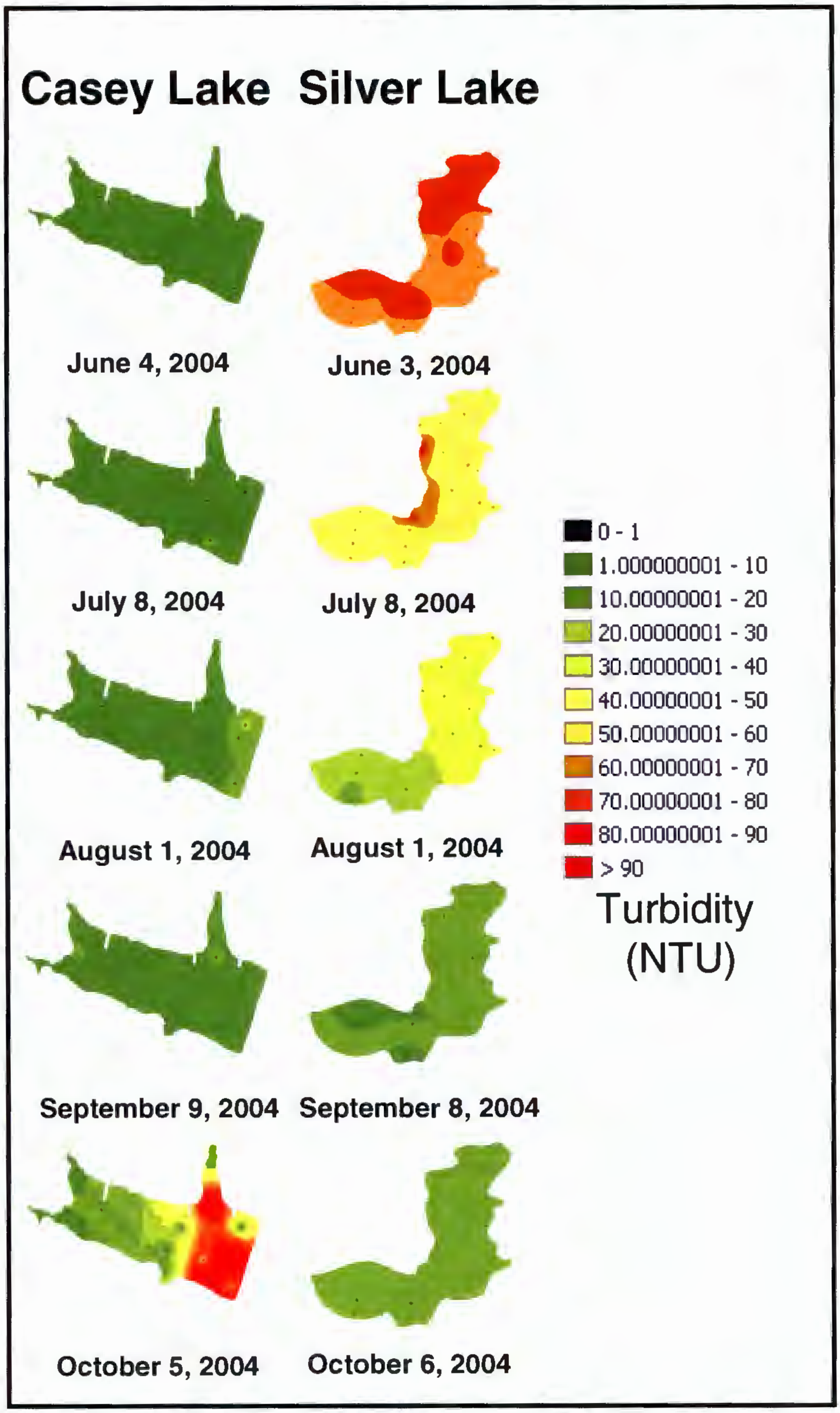


Figure 23. Turbidity density maps.

Secchi Disk Depth

Secchi disk depth maps for Casey and Silver lakes that were created using ArcGIS are shown in Figure 24. Secchi disk depths for Casey Lake range from less than 25 cm up to 225 cm. Secchi disk depths increase from June 4 to August 1 in Casey Lake and then decrease from August 1 to October 5. Larger Secchi disk depths tend to occur in the eastern third of the lake that happens to be the deepest section of the lake. The smallest Secchi disk measurements occur in the far west part of the lake. The reason for this is that the water is so clear that one can see to the bottom in the western part of the lake. Therefore, Secchi disk depth can only be as deep as the water. Secchi disk depth doesn't appear to be effected by precipitation in Casey Lake.

Silver Lake's Secchi disk depths show a slow increase from June to October. On June 4, Secchi disk depths in Silver Lake ranged from 0 to 25 cm. Secchi disk depths on October 5 range from 25 to 75 cm. Secchi disk depths correlate well with precipitation. When large amounts of precipitation occur, Secchi disk depths are shallower in Silver Lake. Likewise, when less precipitation falls, Secchi disk depths increase. This can be explained by the fact that when large amounts of precipitation falls, large amounts of sediments flow into Silver Lake. The sediments cloud the water and Secchi disk depths decrease.

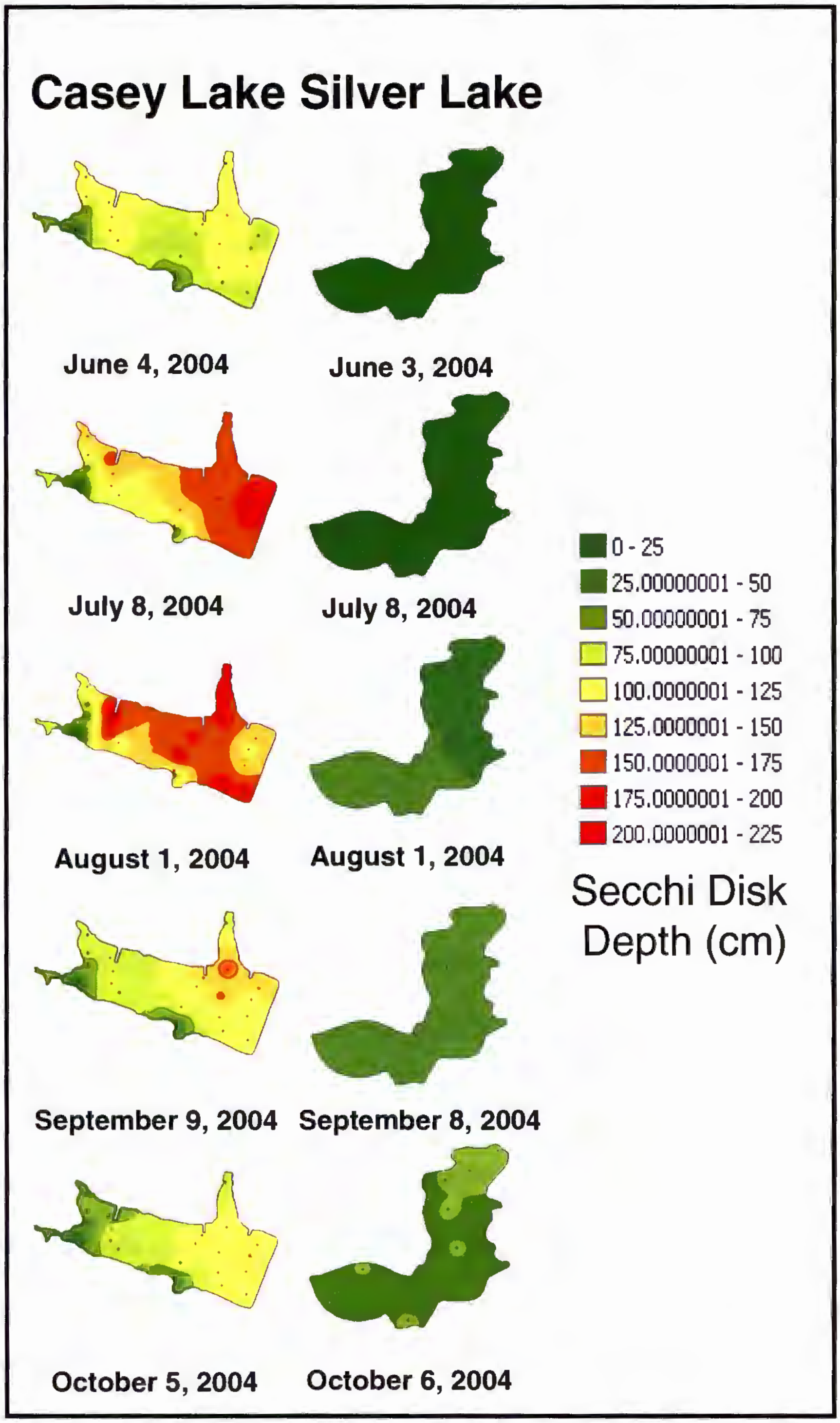


Figure 24. Secchi disk depth density maps.

The ground-based density maps made from the results of laboratory analyses of the data present estimates of chlorophyll *a* concentrations, turbidity values, and Secchi disk depths based upon readings at selected geographic coordinates. ArcGIS estimates the water quality at unknown locations by examining distances from known locations. These estimates may be off considerably because they rely on distances alone. Also, a single water sample that may not actually represent that area of the lake will have dramatic effects on the results (e.g. bulls-eye effect). Methods used by the IDNR and ISU in which a single sample is taken from a lake will not show the distribution of water-quality constituents across a lake. Even with up to 20 points collected in a single lake as is done by UNI, distribution of constituents is not seen to the level of detail needed.

Hyperspectral Water Quality Classification

Accuracy Assessment

After application of prediction algorithms for chlorophyll *a*, Secchi disk depth, and turbidity, an accuracy assessment of the predictions was done. Using the remaining sampling locations that were not used in the creation of the algorithm, an accuracy assessment was performed. Using the nine pixels that were extracted from the first principal component images and subsequently averaged, calculations of the predicted chlorophyll *a*, Secchi disk depth, and turbidity were done for those sampling locations. This was done by entering the nine pixel average into the necessary algorithm. The result was predicted chlorophyll *a*, Secchi disk depth, and turbidity for the locations that were not used in the creation of the algorithm. To test the accuracy of these values, scatter plots of predicted vs. actual chlorophyll *a*, Secchi disk depth, and turbidity values were created. A linear trend line was added that described the data and the R-squared value of that line can be used a measure of the accuracy. An R-squared value of 1 meant that the prediction algorithm was a perfect predictor (i.e. predicted chlorophyll *a* concentration of 350.3 *u*g/L, actual chlorophyll *a* concentration of 350.3 *u*g/L). The accuracy assessment plots are shown in Figure 25.

The chlorophyll *a* and turbidity prediction algorithms did very well with R-squared values of 0.7672 and 0.762 respectively. However, the Secchi disk prediction algorithm did not do very well with an R-squared value of 0.4867. A new prediction algorithm was needed to predict Secchi disk depth in Casey Lake and Silver Lake. Many methods were tried using data from both lakes to accurately predict Secchi disk depth. However, when Casey Lake's data was included in the model, the accuracy dropped considerably, and therefore, Casey Lake's Secchi disk depths were left out so that estimation of Secchi disk depths for Silver Lake could be done. The final prediction algorithm for Secchi disk depth was similar to a method used by Shafique et al (2001). It used original reflectance instead of principal component data and produced very accurate results. The algorithm used the spectral index of :(band 19 – band 14) ÷ 40. Figure 26 shows a plot of the spectral index vs. Secchi disk depths for Silver Lake. An accuracy assessment plot of that algorithm is shown in Figure 27. The accuracy of this prediction algorithm is much better with an R-squared value of 0.8888.

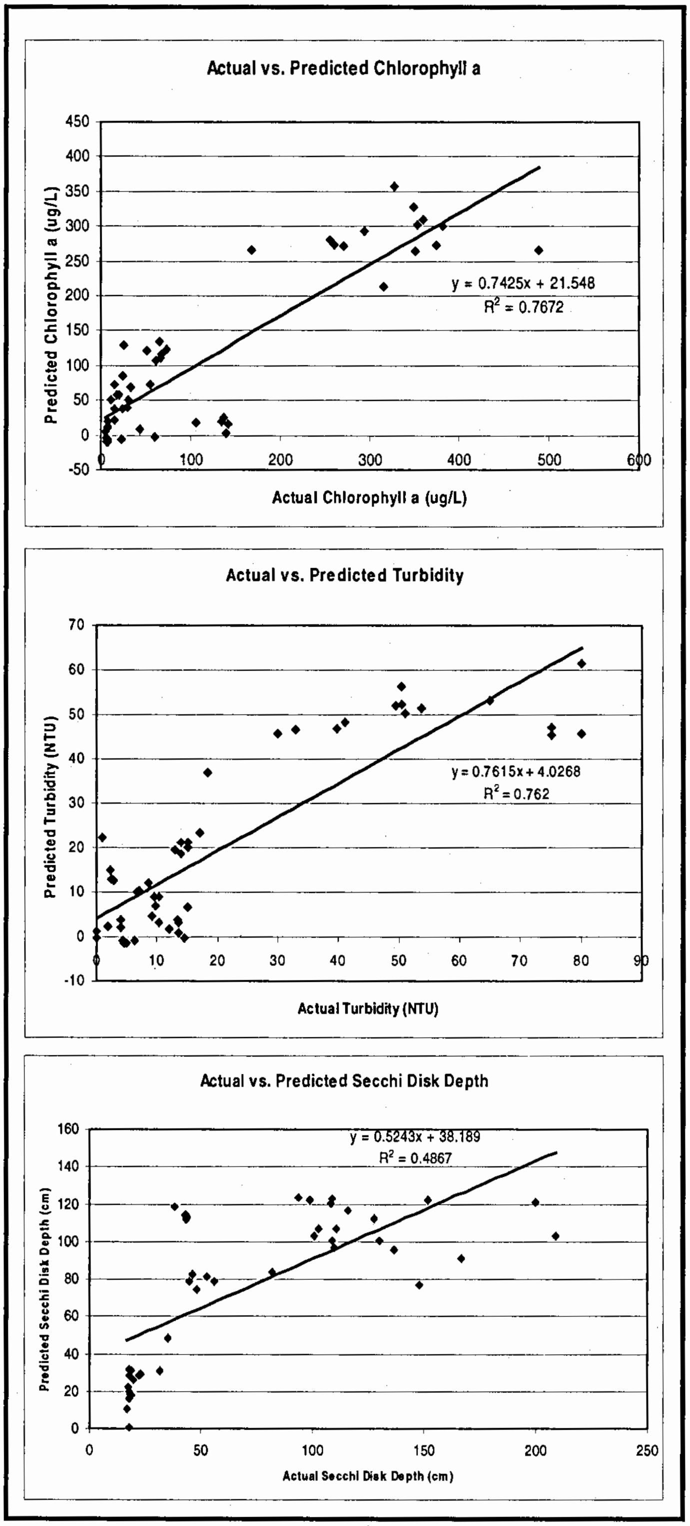


Figure 25. Accuracy assessment plots for chlorophyll *a*, Turbidity, and Secchi disk depth.

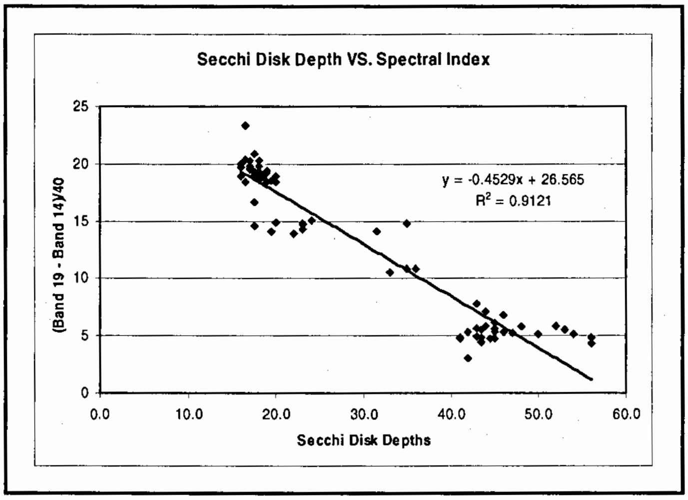


Figure 26. Secchi disk depth vs. Spectral index prediction algorithm.

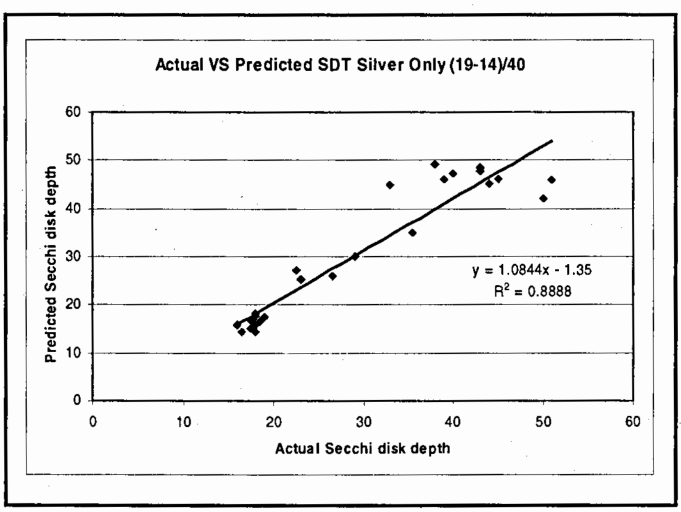


Figure 27. Accuracy assessment plot of Secchi disk depth prediction algorithm for Silver Lake.

Chlorophyll *a*

Chlorophyll *a* concentration maps classified from the hyperspectral images are given in Figure 28. Prediction of chlorophyll *a* concentrations in Casey Lake and Silver Lake has been done with acceptable accuracy (R-squared = 0.7672). Unlike the ArcGIS thematic maps, the maps provided in Figure 28 are spatially continuous. Every pixel in these images is calculated based upon its unique spectral characteristics, not distance from a known data point.

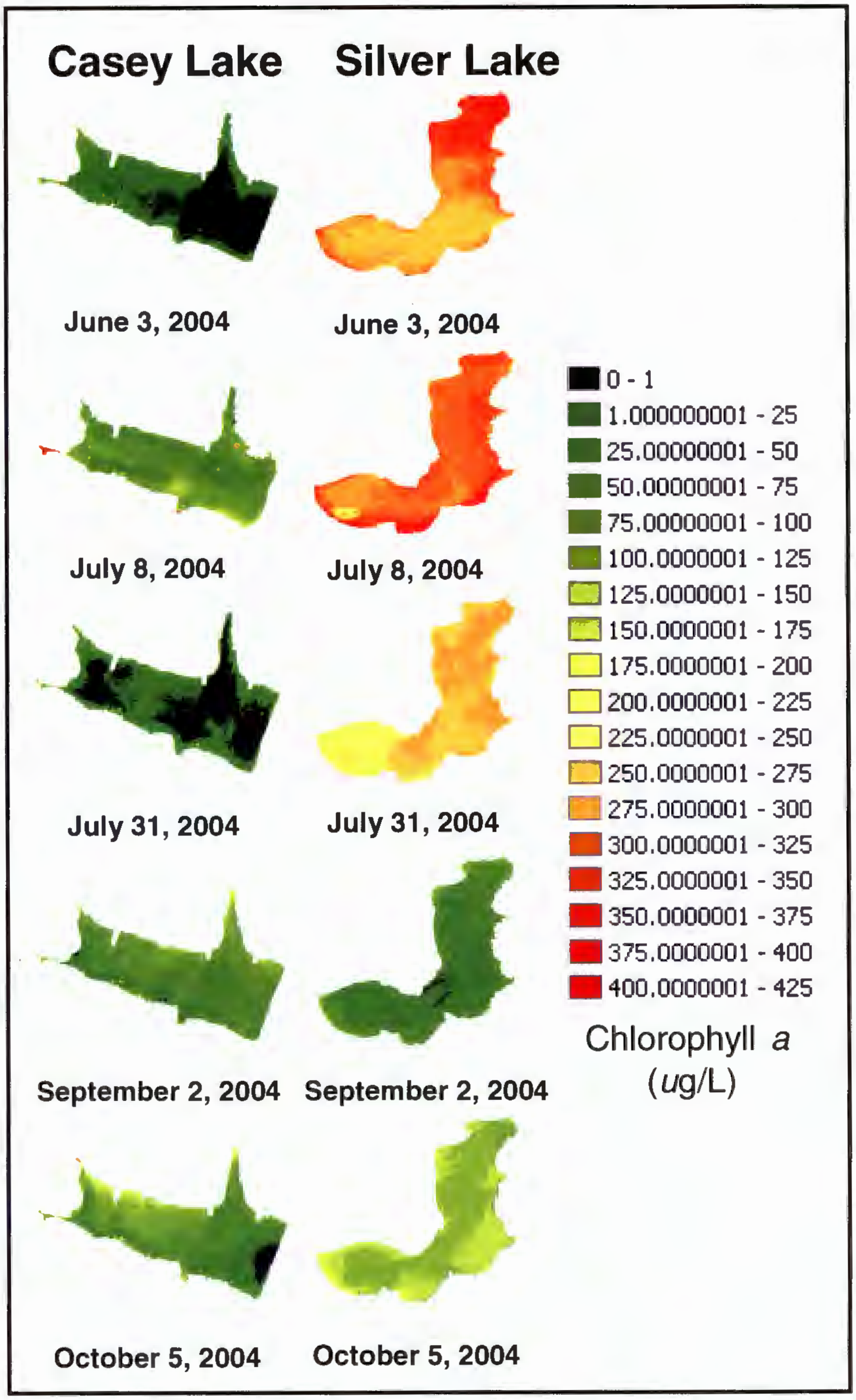


Figure 28. Chlorophyll *a* maps from hyperspectral images.

Casey Lake's chlorophyll *a* concentrations on June 3 are very low, 0 to 25 *u*g/L. On July 8, concentrations are higher, ranging from 0 to 150 *u*g/L for most of the lake. A few localized areas on July 8 are extremely high, greater than 350 *u*g/L. These areas are composed of shallow water where streams enter the lake. The high readings may represent floating vegetation such as algal mats, or very high concentrations of chlorophyll *a* in the water column caused by large amounts of nutrients entering the lake at these locations. On July 31, Casey Lake's chlorophyll *a* concentrations dropped to the 0 to 25 *u*g/L range. Chlorophyll *a* concentrations on September 2 ranged from 0 to100 *u*g/L for most of the lake, while localized areas in the inflow regions had concentrations in the 200 *u*g/L range. On October 5, concentrations showed a large range, 0 to 400 *u*g/L. The reason for this variety of concentrations may be explained by dredging along the northwest shore of the lake by the park service. Dredging the sediments may have stirred up large quanitities of nutrients, such as phosphorous, contained in the sediments. The nutrients stirred up by the dredging would likely cause a bloom of algae and increase the chlorophyll *a* in the area. One can see the effects of this bloom in the October 5 image and see how the bloom spreads to the east where water flows out of Casey Lake, and continues downstream.

Silver Lake's chlorophyll *a* concentrations vary greatly throughout the study period. Concentrations on June 4 are very high ranging from 250 to 400 *u*g/L. This was a time of heavy precipitation and very warm temperatures. Heavy precipitation brought large amounts of nutrients into the lake and with the warm sunny conditions led to the bloom of algae, and thus, large amounts of chlorophyll *a*. Higher concentrations of chlorophyll *a* are located in the northern regions of the lake where an agricultural field drains into the lake by means of a tiling system. Concentrations of chlorophyll *a* in Silver Lake are higher on July 8 than on June 4 with concentrations ranging from 225 to 425 *u*g/L. The lowest concentrations (225 *u*g/L) on this date were in the immediate vicinity of the oxygen bubbler installed by the DNR. It is unclear if the oxygen bubbler simply pushed chlorophyll *a* away from the area or actually limited the growth. The highest concentrations, which are in the lower 400 *u*g/L range, are located along the south and southeast shoreline. This shoreline is adjacent to pasture land with no riparian buffer and a rural road. Livestock from the pasture are allowed direct access to the lake in this location, which would allow nutrients from animal waste to enter the lake directly. This abundance of nutrients may be responsible for the large quantity of algae and chlorophyll *a* in this region. On July 31 the full effects of the oxygen bubbler are seen. Chlrophyll *a* concentrations in a large region of the lake in which the bubbler is located are substantially lower than the rest of the lake. A distinct line can be seen dividing the lower concentrations around the bubbler (150 to 250 *u*g/L) and the higher concentrations (250 to 325 *u*g/L) of the rest of the lake. Overall concentrations on July 31 are lower than the previous two dates and that may be explained by the decrease in precipitation and the full effects of the oxygen bubbler. A dramatic decrease in chlorophyll *a* concentrations is seen in the September 2 image of Silver Lake. Concentrations are much lower on this date, ranging from 0 to 100 *u*g/L. The open water regions of the lake are generally in the 0 to 50 *u*g/L range, with the highest concentrations limited to near shore areas. The obvious decrease in chlorophyll *a* concentrations can be attributed to the lack of rain during the month of August and lack of abundant sunshine. Algae require sunlight to grow abundantly, and if a week of cloudy weather occurs much of the algae may die, reducing chlorophyll *a* concentrations greatly. The effects of the oxygen bubbler are not seen in this image since the machine was shut down due to the limited effects that the IDNR suspected it had upon water quality in the lake. Concentrations of chlorophyll *a* on October 5 range from 100 to 175 *u*g/L. These concentrations were higher than they were on September 2. The reason for this increase cannot be attributed to higher amounts of precipitation because less rain fell in the two weeks prior to October 5 than in the two weeks prior to September 2. Another possible explanation for the increase is more sunlight was available before October 5 than was available before September 2.

Chlorophyll *a* maps from the hyperspectral images show that concentrations of chlorophyll *a* are much lower in Casey Lake on June 4, July 8, and July 31 than they are in Silver Lake on the same dates. Both lakes received similar amounts of precipitation, but Casey Lake seemed less effected by the large amounts of rain than did Silver Lake. This is made evident by the increase of chlorophyll *a* in Silver Lake with large amounts of rain and the steady concentrations of chlorophyll *a* in Casey Lake with large amounts of rain. Effects of an oxygen bubbler installed in Silver Lake are clearly seen in the classified hyperspectral images and the exact extent of those effects is seen only in the hyperspectral classified images, not the ArcGIS images. Both Casey Lake and Silver Lake have relatively low concentrations of chlorophyll *a* on September 2 and October 5, which may be attributed to lesser amounts of precipitation and sunlight as well as lower temperatures.

Turbidity

The accuracy of the turbidity maps created from the hyperspectral images is acceptably accurate (R-squared =0.762) and the resulting images are shown in Figure 29. From Figure 29, one can see that turbidity in Casey Lake is consistently low with values ranging from 0 to 25 NTU with a few "hotspots" of greater than 90 NTU. The June 4 image of Casey Lake shows that turbidity values range from 0 to 10 NTU for most of the lake. The water is not very turbid and is free of large amounts of floating debris. Like the July 8 chlorophyll *a* map generated from the hyperspectral images, the July 8 turbidity map shows an increase in floating debris. Turbidity values range from 0 to 50 NTU for most of the lake with hotspots reaching > 90 NTU. The highest turbidity values are located in the inlets of the lake where sediment laden water enters the lake. Floating algal mats may also be responsible for the highest turbidity readings. On July 31, turbidity values are very low, ranging from 0 to 10 NTU. On September 2, turbidity values are a bit higher with values ranging from 0 to 20 NTU. October 5 turbidity values range from 0 to 40 NTU with the highest values being located in the area where the sediment dredging occurred. Dredging the sediments caused many minerals and other particles to become suspended in the water column and therefore increased the turbidity. One can see the direction of water flow once again as in the October 5 chlorophyll *a* image by noticing that the turbidity cloud stretches to the east as suspended materials are carried in that direction by the moving water.

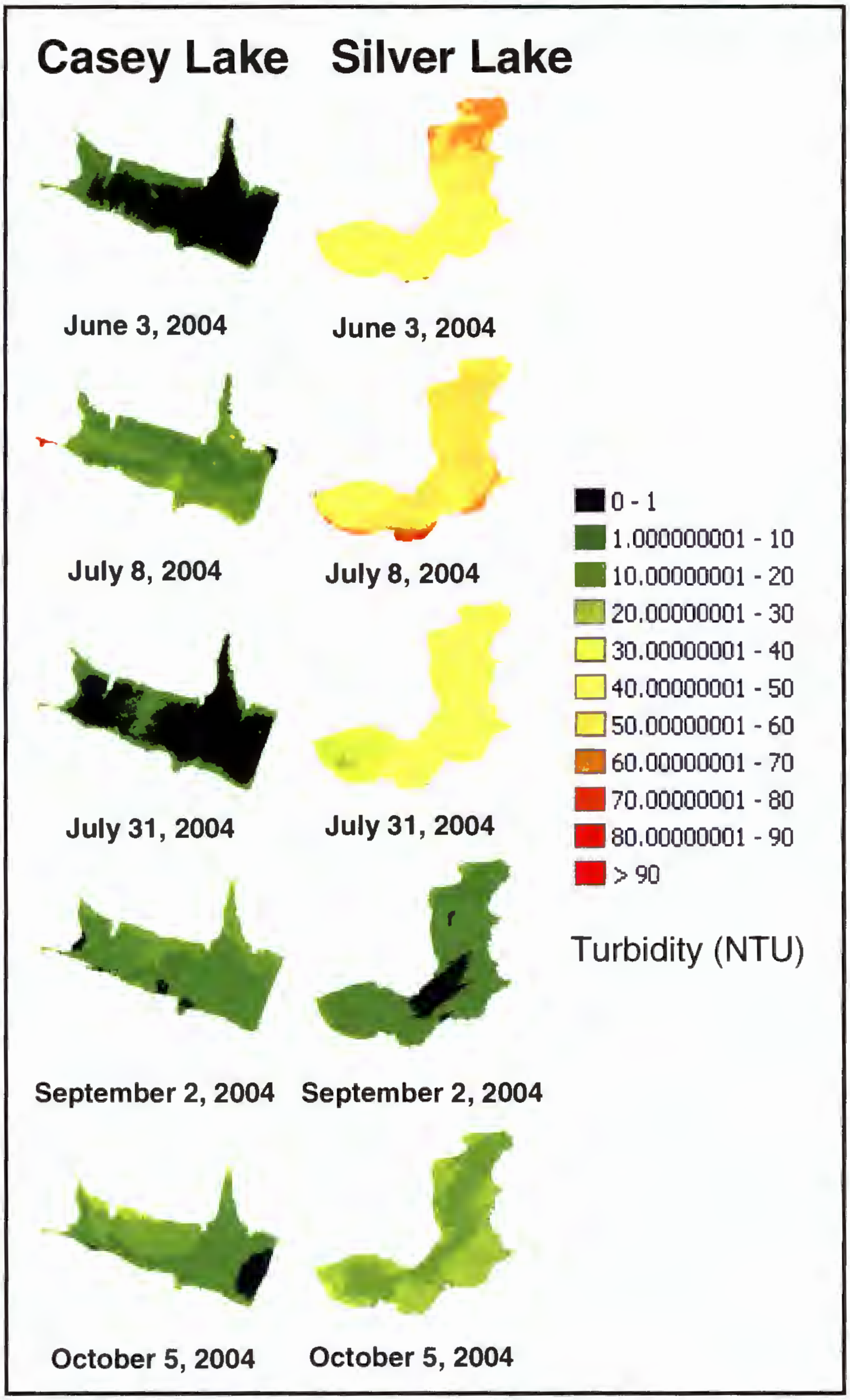


Figure 29. Turbidity maps from hyperspectral images.

Turbidity in Silver Lake behaves much like chlorophyll *a* by being high on June 4 and July 8 and decreasing to October 5. Turbidity throughout most of the Silver Lake on June 4 is in the range of 40 to 50 NTU. In the northern section where an agricultural field drains into the lake, turbidity values range from 50 to 70 NTU. This increase is no doubt caused by sediments from the field being carried into the lake with precipitation runoff. The highest turbidity in Silver Lake during the study period occurs on July 8 with turbidity values in the range of 20 to 90 NTU. The majority of the lake had values between 50 and 60 NTU. The initial effects of the oxygen bubbler are seen in a localized area of less turbidity in the southwestern section of the lake. A small area of turbidity values ranging from 25 to 50 NTU surrounds the oxygen bubbler suggesting the oxygen bubbler reduced the turbidity in the immediate vicinity. The highest turbidity occurs along the adjacent pasture land and rural gravel road. A possible explanation of the high turbidity in this region is that animals entering the lake may stir up bottom sediments which lead to high turbidity. Turbidity levels on July 31 are lower than on June 4 and July 8 with values ranging from 30 to 60 NTU. The full effects of the oxygen bubbler on turbidity are seen in the southwestern section of the lake in turbidity values that are lower than those of the rest of the lake. Turbidity values in this region are between 20 and 40 NTU, while those in the remainder of the lake are between 40 and 50 NTU. Turbidity shows a sharp decrease on the September 2 image from July 31. Values range from 0 to 20 NTU with most of the lake having turbidity values between 0 and 10 NTU. This drop in turbidity can be associated with the decrease in precipitation and the corresponding drop in chlorophyll *a* as was shown in the chlorophyll *a* maps. As precipitation decreased, smaller quantities of nutrients entered the lake. This caused a decrease in algae growth and chlolophyll *a*, as well as a decrease in suspended sediments. The decrease in these two water quality characteristics explains the decrease in turbidity for this date. The effects of the oxygen bubbler are not seen in this image due to the machine being shut down by the IDNR. October 5 shows a small increase in turbidity for Silver Lake with turbidity values ranging from 10 to 40 NTU. The increase in turbidity may be attributed to the increase in chlorophyll *a* concentration in the water column.

From Figure 29, one can see that turbidity in Casey Lake is much lower than in Silver Lake on June 4, July 8, and July 31. However, turbidity values are much closer on September 2 and October 5. This is a similar pattern to the one shown in the chlorophyll *a* images. Casey Lake may not be as affected by precipitation as much as Silver Lake. The effects of sediment dredging are seen on the October 5 image of Casey Lake and the extent of the turbidity plume are easily seen. Effects of the oxygen bubbler on turbidity are clearly seen on the July 8 and July 31 images of Silver Lake and the spatial extent to which it affected turbidity are also seen. Being able to see exact extents of chlorophyll *a*, turbidity and Secchi disk depth plumes is a great advantage of remote sensing over traditional methods in water-quality monitoring.

<u>Secchi Disk Depth</u>

Secchi disk depth maps created from the hyperspectral images are shown in Figure 30. The accuracy of the algorithm was very accurate in this case with an R-squared = 0.8888. Secchi disk depths for Casey Lake were unable to be mapped accurately using the first principal component as was used to determine chlorophyll *a* and turbidity. Secchi disk depths were also unable to be accurately mapped using various spectral indices and band combinations which other researchers had success using, Rao (1998), Emch (2002) & Keiner & Yan, (1998).

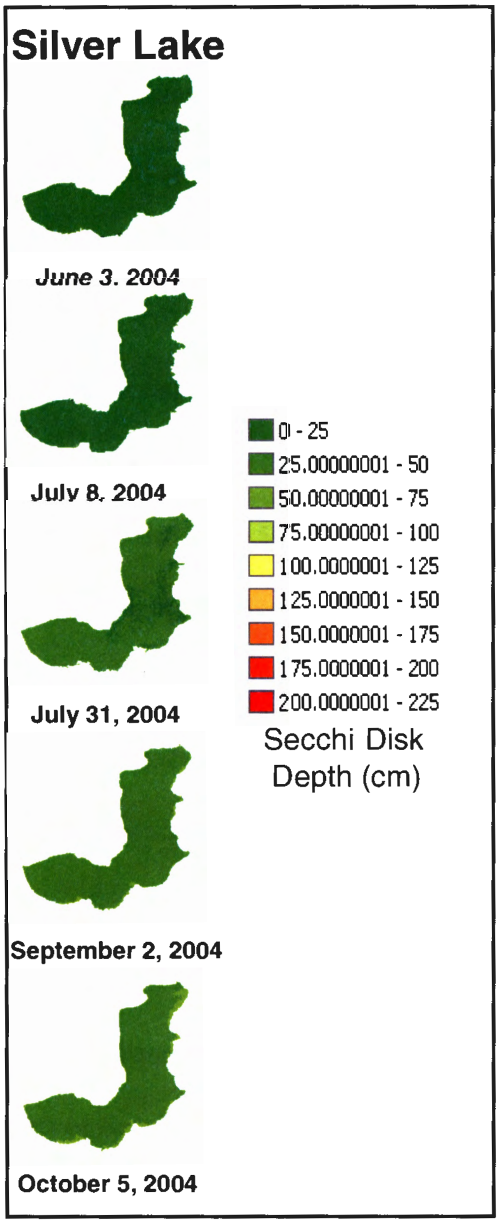


Figure 30. Secchi disk depth maps from hyperspectral images.

Silver Lake's Secchi disk depths show a small and gradual increase from June 4 to October 5. Secchi disk depths on June 4 range from 5 to 25 cm indicating the water in Silver Lake had poor visibility. Secchi disk depths were again very small on July 8 ranging from 4 to 25 cm. There was a slight increase in Secchi disk depths on July 31 with most of the lake having Secchi disk depths ranging from 25 to 50 cm. There were still areas of the lake with Secchi disk depths in the 0 to 25 cm range, but there was a definite increase in water clarity from July 8 to July 31. The change was probably the result of less precipitation falling before the July 31 image that would have decreased the amount of sediments and nutrients entering the lake. On September 2, the entire lake had Secchi disk depths in the range from 25 to 50 cm. This was a slight improvement from July 31. On October 5, Secchi disk depths ranged from 25 to 75 cm. Most of the lake was still in the 25 to 50 cm range, but there were a few areas where the water was beginning to get clearer and had greater Secchi disk depths. This was a similar trend as was found with chlorophyll *a* concentrations and turbidity values in Silver Lake. Secchi disk depths increased from June 4 to October 5, however the increase was not very large indicating a small improvement in the water quality of Silver Lake over the study period.

Direct comparison of Secchi disk depths in Casey Lake and Silver Lake could not be done using the hyperspectral images. This was impossible because Secchi disk depths could not be accurately predicted in Casey Lake. Comparison can be made between the maps of Secchi disk depths made from the hyperspectral images for Silver Lake and the ArcGIS thematic maps of Secchi disk depths for Casey Lake. The ArcGIS thematic maps may not provide accurate spatial patterns in the Secchi disk depths of Casey Lake, but the raw numbers of the sampling points may provide a limited understanding of the trend in Secchi disk depths in Casey Lake. When the comparison is made, it is clear that Secchi disk depths in Casey Lake are much greater for every month than they are in Silver Lake. Secchi disk depths in Casey Lake are generally above 75 cm with some areas having Secchi disk depths of over 200 cm. Silver Lake's Secchi disk depths on the other hand never get above 75 cm and are usually between 0 and 50 cm. It is evident that the water in Silver Lake has much more suspended minerals and floating aquatic plants than the water in Casey Lake. Secchi disk depths in Silver Lake appear to be affected by the amount of precipitation in the area, while they are not as affected by precipitation in Casey Lake.

<u>Temporal Analysis</u>

The results of the temporal analysis on the hyperspectral images are seen in Figure 31. The plots shown in figure 31 are graphs of the most common values present in each of the classified hyperspectral images. From the chlorophyll *a* and turbidity plots, one can see that water quality during June, July and August was much poorer in Silver Lake than in Casey Lake as indicated by much higher chlorophyll *a* concentrations and turbidity values during this time. Then some factor caused both chlorophyll *a* and turbidity to drop sharply in Silver Lake in early September producing an improvement in water quality. The Secchi disk depth plot also shows this improvement in water quality during this time in Silver Lake represented by the increase in Secchi disk depths. Leading into October, water quality in Silver Lake is somewhat deteriorating with chlorophyll *a* concentrations and turbidity growing and Secchi disk depths decreasing.

Casey Lake's chlorophyll *a* concentrations and turbidity values show little change throughout the study period and the lake generally has relatively good water quality. The plot for Secchi disk depths in Casey Lake is missing because Secchi disk depths in Casey Lake could not be predicted using the hyperspectral images.

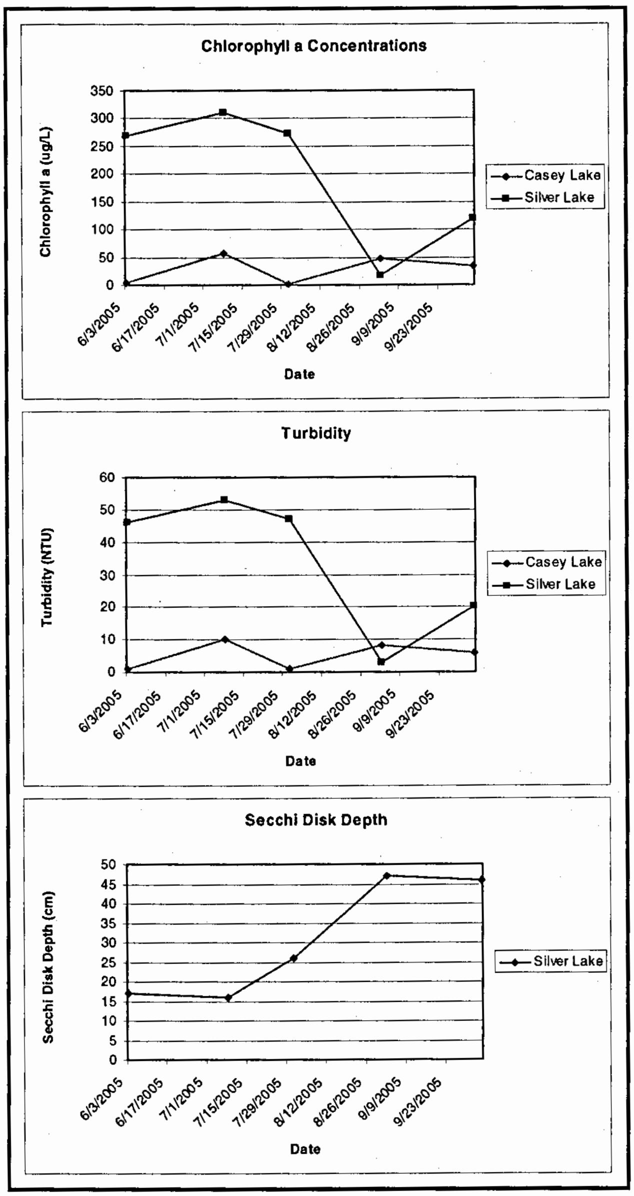


Figure 31. Chlorophyll *a,* Turbidity and Secchi disk depth most common estimations.

Trophic State Index

Chlorophyll *a* TSI values for Silver Lake and Casey Lake are shown in Figure 32. One can see in this figure that Silver Lake has chlorophyll a TSI values above 80 between June 3 and July 31, 2004. Chlorophyll *a* TSI values this high suggest summer fish kills and algal scums. On September 2, 2004 TSI values in Silver Lake drop to between 50 and 60. TSI values in this range suggest mildly eutrophic waters and Carlson (1977) suggests that the lake was supportive of all swimming and aesthetic uses during this time. Values increase to between 70 and 80 on October 5, 2004 with heavy algal blooms likely.

Casey Lake's chlorophyll *a* TSI values on June 3, 2004 are in the 40 to 50 range, or mildly eutrophic and supportive of all swimming and aesthetic uses. The values increase to around 70 on July 8, 2004, meaning algal blooms and scums possible. They drop to near 30 on July 31, 2004 which represents oligotrophic waters, or clear water. Values increase to between 60 and 70 on September 2 and October 5, 2004 representing a period of blue-green algae dominance.

One can see from Figure 32 that Silver Lake's chlorophyll *a* TSI values are higher than Casey Lake's on all dates except September 2, 2004. Excluding September 2, Silver Lake has chlorophyll *a* TSI values between 70 and 90 which suggests heavy algal blooms and algal scums are likely present during these periods. Casey Lake's waters range from the clear water of oligotrophic on July 31 to algal scums being present on July 8, 2004.

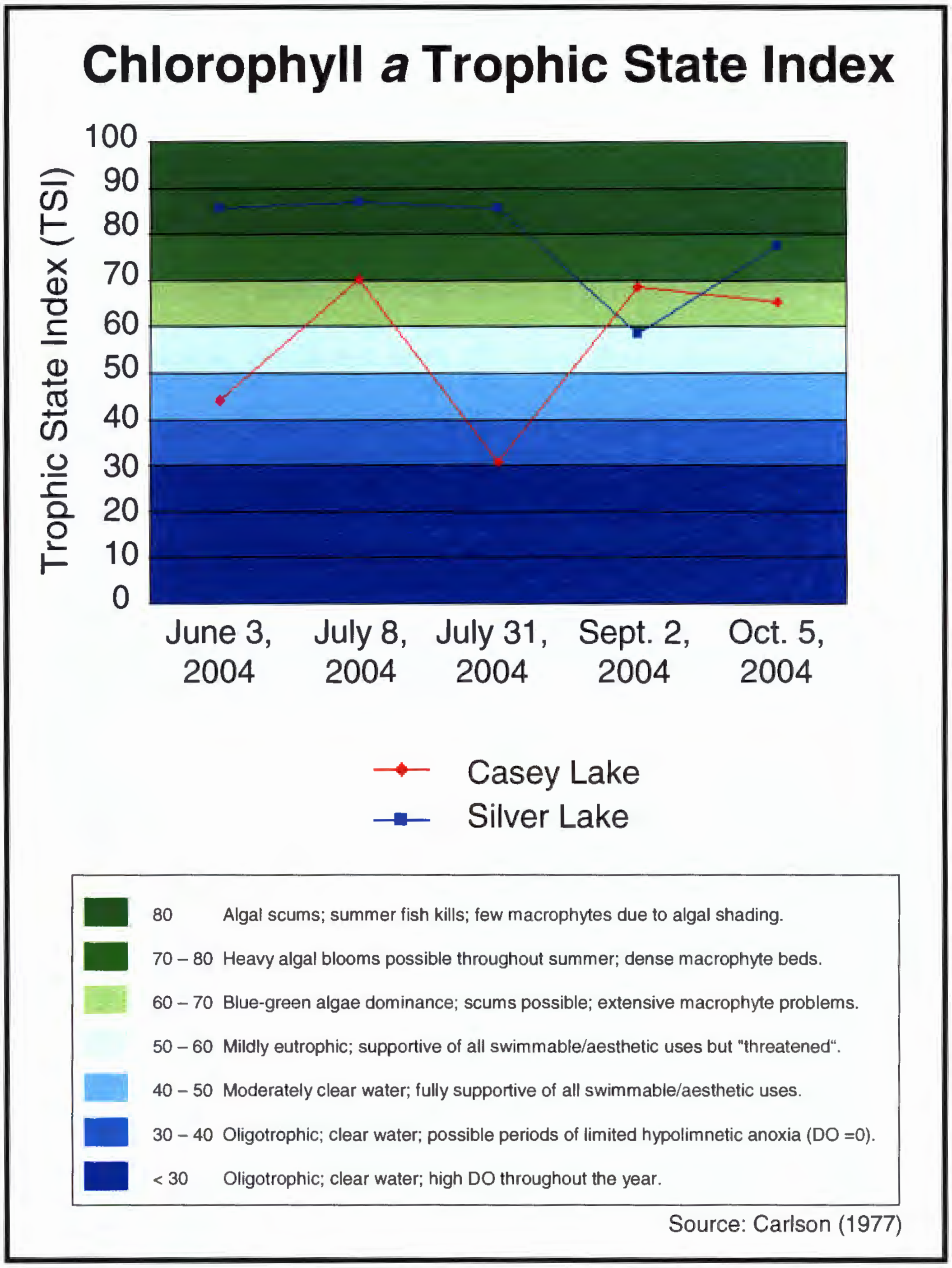


Figure 32. Chlorophyll *a* Trophic State Index.

Secchi disk depth TSI values are shown in Figure 33. There is no available data for Casey Lake because estimation of Secchi disk depth in Casey Lake was not possible using the hyperspectral images. Secchi disk depth TSI values in Silver Lake are above 70 throughout the five month period. Values are between 80 and 90 on June 3 and July 8 of 2004. Carlson (1977) states that TSI values this high result in summer fish kills and algal scums being present. Secchi disk depth TSI values drop to between 70 and 80 for July 31, September 2 and October 5, 2004. Heavy algal blooms are likely present during these periods. These values suggest very poor water quality in Silver Lake throughout the study period.

The results of the TSI analysis provide the water quality data in a form which is transferable to other studies performed in other regions of the world by using a standard method of quantifying the data. The results also show that Silver Lake's water quality is worse than Casey Lake's for most of the study period. However, both lakes have periods of very poor water quality with fish kills, algal blooms algal scums. The cause of the poor nature of the water quality in these two Iowa lakes may be attributed to agriculture, precipitation and other human factors.

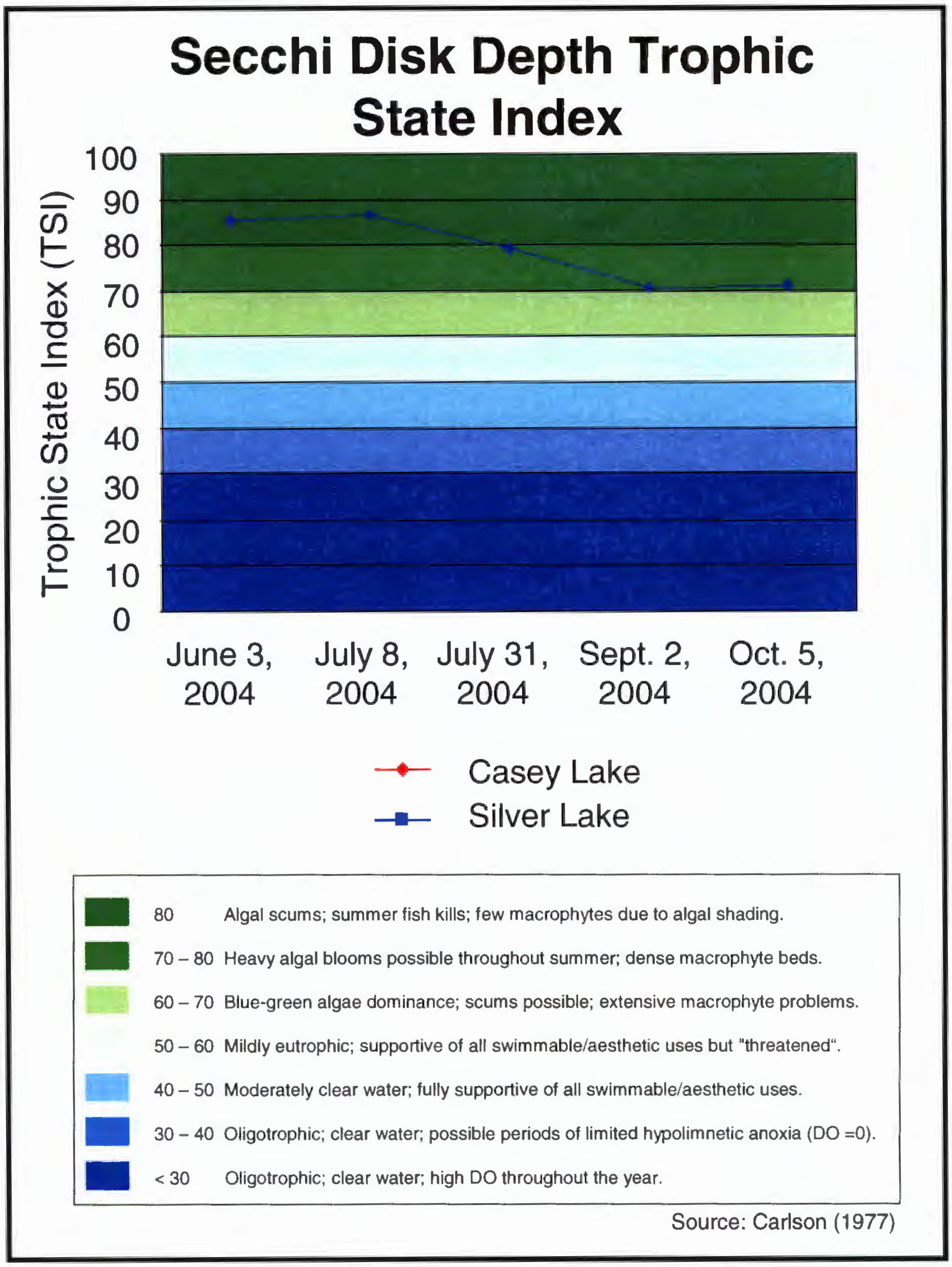


Figure 33. Secchi disk depth Trophic State Index.

Discussion

The chlorophyll *a*, turbidity, and Secchi disk depth maps generated from the hyperspectral images show interesting results. As expected, chlorophyll *a* concentrations and turbidity values were much lower in Casey Lake than they were in Silver Lake during the same time period. Both areas received similar amounts of precipitation. More precipitation fell during the time leading up to the first two images than did in the time leading up to the last three images. It appears that chlorophyll *a* concentrations and turbidity in Casey Lake are not as affected by large rain events as these concentrations in Silver Lake. This is made evident by the fact that chlorophyll *a* and turbidity do not change as one would expect them to under very wet or very dry conditions in Casey Lake. Instead, chlorophyll *a* and turbidity in Casey Lake stay consistently low throughout the study period suggesting Casey Lake's water quality is good and its watershed does an excellent job of protecting the lake from fertilizer runoff and sediments. Casey Lake's Secchi disk depths were unable to bemapped using the hyperspectral images. The reason for this problem may be that a large portion of the Secchi disk depths in Casey Lake actually were equal to the depth of the water. This means that the sediments at the bottom of the lake were being sensed by the sensor on the aircraft. Bottom reflectance would not represent the water column and would not correlate well with Secchi disk depths.

Silver Lake's water quality was very different than Casey Lake's. Silver Lake's water quality at the beginning of the study period was very poor. This is made evident by the high amounts of chlorophyll *a* and turbidity in the water column. However, at the end of the study period, the water quality of Silver Lake has greatly improved with chlorophyll *a* concentrations and turbidity values much closer to those of Casey Lake. Unlike Casey Lake, Silver Lake appears to be heavily affected by the amount of precipitation that falls in the area. During the time the first two images were captured, large amounts of rain fell, causing nutrients and sediments to enter the lake. This, in turn produced high concentrations of chlorophyll *a,* high turbidity, and low Secchi disk depths. In the last three months of the study period, less precipitation fell and the water quality started improving until it was similar to Casey Lake's in September and October. The introduction of oxygen bubbles by an aerator installed by the IDNR had a dramatic effect on the water quality of Silver Lake. After a month of use, water quality in the entire region of the lake in which the aerator was located had improved more than in the rest of the lake. Chlorophyll *a* concentrations and turbidity were down and Secchi disk depths were higher in this region of the lake.

CHAPTER 5

CONCLUSIONS AND FUTURE DIRECTIONS

Conclusion

The goal of this research was to determine water-quality trends using hyperspectral aerial imagery in two Iowa lakes that have very different water quality and watersheds. The integration of water-quality data collected on site and aerial hyperspectral aerial images in ENVI and ERDAS Imagine image-processing software, and ArcGIS was done. By studying correlations between reflectance at certain wavelengths and specific water-quality constituents, spatially continuous maps of those constituents were made.

The results of this research show that Casey Lake and Silver Lake have very different water qualities and each lake reacts differently to environmental factors. Casey Lake has near steady water quality that is not affected by precipitation. The reason for this may be attributed to the fact that Casey Lake has settling ponds located in the inflows of the lake that filter out sediments and nutrients, and the lake also has large riparian buffers separating the lake and agricultural lands. Silver Lake has highly variable water quality that starts out very poor in June, July and August. The water quality dramatically improves by September 2. The water quality then degrades slightly from September to October. Silver Lake's water quality is also highly affected by precipitation. The large affect precipitation has on the water quality of Silver Lake can be attributed to the fact that Silver Lake has no riparian buffers separating agricultural fields, pasture land, and urban lands from the lake. Effects of an oxygen bubbler are clearly seen in the results of this research as well. The oxygen bubbler improves water quality dramatically in the region of the oxygen bubbler after a month of use. When the oxygen bubbler is no longer used, the water quality in that region returns to the same conditions as the rest of the lake.

By combining the most useful wavelengths of the images into one principal component band, I was able to successfully reduce the data into a workable size. With all of the relevant information within bands 14 to 19 contained in the first principal component, I was able to create a single method for estimating chlorophyll *a,* turbidity and Secchi disk depth based upon reflectance, rather than a different method for each water quality constituent which past researcher's have done.

It is clear from this research that the use of high resolution hyperspectal remote sensing in monitoring water quality holds many advantages over traditional methods. Prediction and mapping of chlorophyll *a,* turbidity and Secchi disk depth in two small lakes in Iowa has been done successfully. At present cost and state of government resources, aerial hyperspectral remote sensing may not be an economical option for monitoring every small lake in Iowa. However, for monitoring larger lakes that are more economically and recreationally important as well as more diverse in their ecosystems, the method of aerial hyperspectral remote sensing would provide the best water quality data. In lakes such as Lake Okoboji, Lake Red Rock, Rathbun Lake and Lake McBride, high resolution hyperspectral imagery may provide information on point and non-point sources of pollution. With this knowledge, local officials could stop the influx of pollutants and protect the health of the human population much more effectively than if they used traditional methods.

Limitations

There were several limitations of this study. First and foremost was the timing of the collection of on-site sampling and aerial images. Ideally, the aerial images would be collected simultaneously or on the same day that the water samples were collected. This would enhance the accuracy of correlating hyperspectral reflectance with a particular water-quality characteristic. A second limitation of the research was the inconsistency of the ASD field spectrometer and the battery life. The instrument was very inconsistent in collecting reflectance for unknown reasons. Also, the battery life of the laptop that was needed to use the spectrometer was very limited. This only allowed for a small number of spectra to be collected at each lake on each collection date. The combination of inconsistency and battery life produced a total of 21 spectra that could be used. The small number of useful spectrum was not enough to develop correlations between reflectance and water quality and therefore was not used in the results of this research. A third limitation was the availability of GPS satellites. Some of the water samples were collected when the required number of satellites was unavailable. This made it impossible to determine which pixels represented the location of a water sample.

Future Directions

Based on the results and limitations of the current study, future research would involve increasing the accuracy of the prediction algorithms. This would be done by gathering more water quality data with hyperspectral data. By increasing the number of samples, an algorithm which better describes the relationship between water quality and reflectance can be created. Also, further analysis on why Secchi disk depths were unable to be predicted in Casey Lake with necessary accuracy will be performed. Determining relationships between other water quality constituents and reflectance may lead to the ability to predict water quality even further than was done in this study. In the future, application of the algorithms created in this study could be applied to future aerial images to determine if the algorithms are universal or confined to the two lakes used in this study. Finally, I would like to present my finding to the Iowa Department of Natural Resources so that they could determine if the methods and algorithms I created in this study could benefit the state of Iowa.

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