

1993

## **An Assessment Of Spectral Response Curves For Selected Coal Mine Lakes In Southwestern Indiana**

Randall Lee Repic  
*Indiana State University*

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**An assessment of spectral response curves for selected coal mine  
lakes in southwestern Indiana**

**Repic, Randall Lee, Ph.D.**

**Indiana State University, 1993**

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AN ASSESSMENT OF SPECTRAL RESPONSE CURVES  
FOR SELECTED COAL MINE LAKES  
IN SOUTHWESTERN INDIANA

---

A Dissertation  
Presented to  
The School of Graduate Studies  
Department of Geography and Geology  
Indiana State University  
Terre Haute, Indiana

---

In Partial Fulfillment  
of the Requirements for the Degree  
Doctor of Philosophy

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by  
Randall Lee Repic  
May 1993

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## APPROVAL SHEET

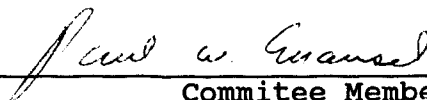
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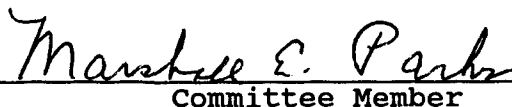
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**ABSTRACT**

Water quality is an important environmental variable as it affects human health, ecosystem health, and economic activity. Surface water quality from the affects of coal mining has been recognized as a major environmental problem in southwestern Indiana, as well as, mining areas world wide. Airborne or polar orbiting instruments seem to represent the only practical means of obtaining large regional estimates which spatially characterize or map with reasonable time resolution. Remotely sensed estimation of water quality within the small lakes and impoundments found within the coal mine environments present an interesting challenge to Remote Sensors and Physical Geographers.

This study analyzed spectral reflectance and trace metal concentration relationships over six abandoned coal mine surface waterbodies in southwestern Indiana; a state fishing impoundment was included as a seventh waterbody. A portable field data-logging spectroradiometer was used to gather hyperspectral radiometric data. Portable chemical analysis were used to measure hydrological contamination in the water column. This research analyzed these two data sets to determine the differences between the lakes sampled.

The data were independently generalized into 4 classes based on spectral curves, pH, and Secchi depth. Classification of the data on spectral curves emphasized differences in peak reflectance and overall brightness

across the spectrum, pH classes were developed by graphing pH along a continuum from 0 to 10, and Secchi depths were classed by plotting depths along a continuum of 0 to 8 feet.

Type 1 lakes are composed of surface water with metals dissolved in the water column. Type 2a lakes are lakes with metals partitioned to sediments in well mixed water columns and Type 2b were those with metal partitioned to sediments in stagnant water columns. Type 3 lakes included surface water without any indication of the influence of acids or sediments. Type 4 lakes are composed of acid water columns with negligible metal concentrations or sediments.

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## Chapter 1

### INTRODUCTION

The problem of environmental degradation caused by surface mining is widespread and serious (USEPA, 1974). In the past, mining practices were all too often conducted for the purpose of recovering the minerals by the simplest and cheapest way possible, without regard for the preservation of land and water.

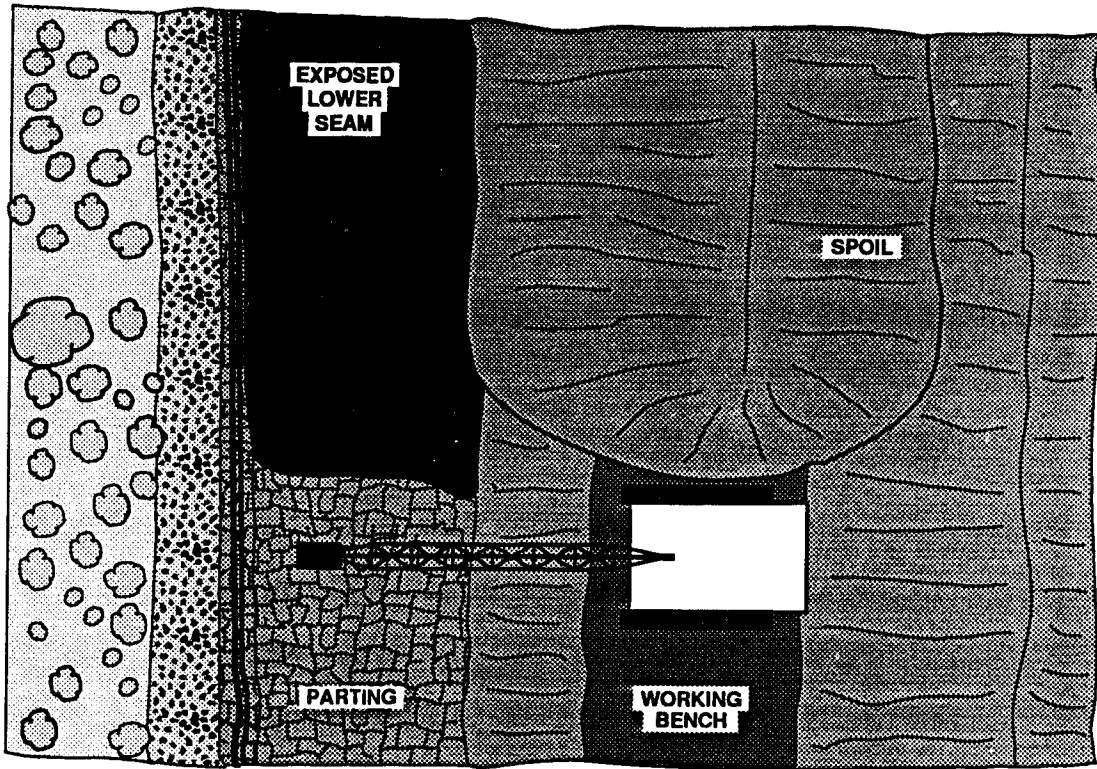
The most important mineral resource in southwestern Indiana has been coal, and for many years Indiana has been an important coal producer (Harper, 1985). For the southwestern twenty counties of Indiana, which compose the eastern most portion of the Eastern Interior Coal Basin, coal mining has been part of both the physical and cultural environment since 1812 when the first mine was commercialized in Perry County (Environmental Systems, 1983). Since then more than 150,000 acres of land have been mined for coal (IDNR, 1992).

#### The Mining Process

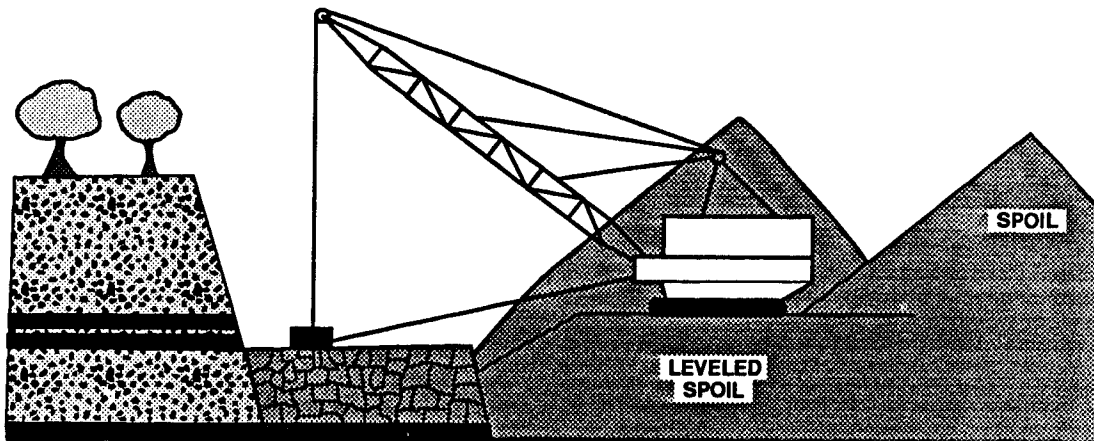
Southwestern Indiana has experienced both surface (strip) and underground coal mining. Strip mining is a surface engineering process that consists of nothing more

than the removal of overburden, the soil solum and the regolith which lie above the coal seam, thus exposing the coal seam for production. The coal is then removed from the exposed seam. Underground mining for coal is a process whereby the coal seam is accessed through a series of shafts which penetrate the subsurface to the coal seam. In practice, however, both processes are considerably more complex.

In strip mining a trench or "box cut" is made through the overburden to expose a portion of the coal seam, the overburden is piled adjacent to the cut and the coal then removed. Most often the initial cut is placed at the minable limits of the seam or at the edge of the lease (U.S. Department of the Interior, Office of Surface Mining Reclamation and Enforcement, 1977). Then, succeeding parallel cuts are made, the overburden (spoil) is deposited in the cut just previously excavated with the top soil placed at the bottom of the cut, and the strata immediately overlying the seam of the current cut is placed on top of the spoil bank. The final cut leaves an open trench as deep as the overburden and the thickness of the seam of coal (Figure 1). It is this final cut which most often fills with water, creating lakes. The landscape extending from the initial box cut to the final cut often resembles the ridges of a gigantic washboard interspersed with small impoundments of water and ending in a strip pit lake. The surface material comprising these disturbed landscapes does



PLAN VIEW



SECTION VIEW

After U.S. Dept. of Interior, 1977  
Repic, King 10-92

Figure 1. Surface Mining Method for Coal.

not have the characteristics of the original soil solum; these soils lack any recognizable soil structure, are for the most part void of organic and aerobic microbial organisms, and tend to be acidic (Meeks et al., 1988).

The underground mining method most used in Indiana is "room and pillar." Room and pillar mining includes a variety of methods, but all operations remove coal in rooms, leaving about 50 percent of the coal in place as pillars to provide surface support (U.S. Department of the Interior Office of Surface Mining, 1977, Figure 2). In a typical room and pillar mining, wide straight tunnels or "entries" are mined out first. The entries are used as haulage ways, but also provide ventilation ducts. Every 75 to 100 feet an area is mined perpendicular to the entry. These areas, known as rooms, are where the majority of the coal is extracted. Once the coal is extracted from the room, the gob (coarse refuse) which has been mechanically separated from the coal is stowed in a previously mined room. In Indiana, underground mines often fill with water. Flowing water often fills the entries and unstowed rooms because coal acts as an aquifer, and the roof (overlying strata) often cracks and creates conduits for percolating water to enter the mine. This circulating water acts as a solvent which often becomes contaminated with iron, sulfur, and a variety of other impurities which are residuals of the mining process (Brauner, 1973). In addition, coal processing at the surface contaminates vast volumes of

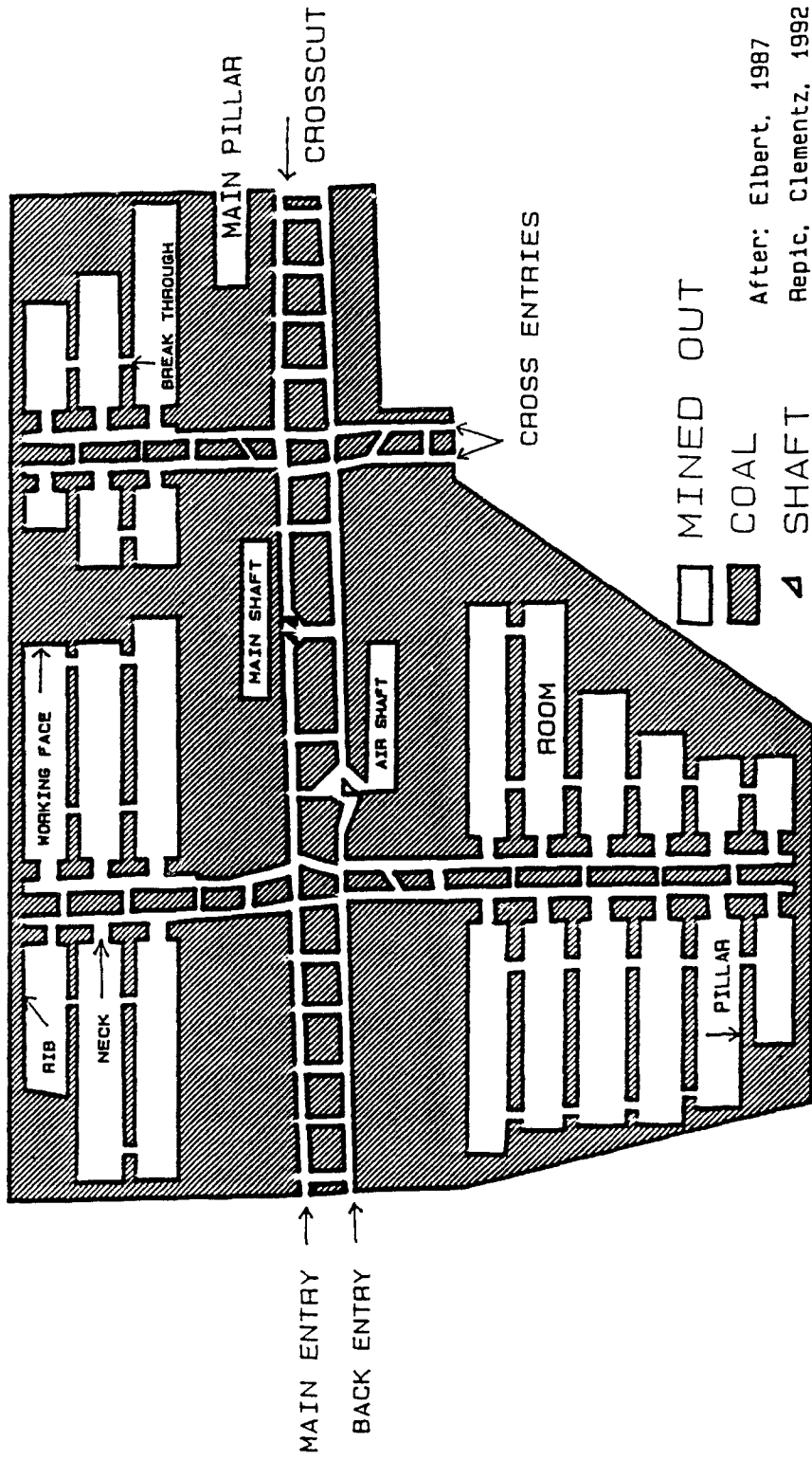


Figure 2. Plan View of a Typical Room and Underground Pillar Mine.

water. Lakes or engineered impoundments of water are constructed on the surface to "wash" the coal. Washing cleanses the coal of sand and other impurities such as shale and pyrite. This is accomplished because coal is porous, traps air, and thus floats, whereas the heavier contaminating shale and pyrite sink and settle out. Therefore, chemically contaminated surface lakes are created by the mining process. In addition, advancements in surface mining technology now allow miners to remove overburden to greater depths. Operators are returning to once abandoned shaft or under-ground room and pillar mines to recover the coal left as pillars and are encountering and exposing the contaminated subsurface waters. In many cases these waters are incorporated into surface lakes.

#### Environmental Degradation

Prior to 1977, the methods and the sites for the disposal of coal mine refuse were often determined by convenience and economic considerations. Little or no thought was given to the long term environmental consequences. Gob was usually dumped near the preparation plant, often creating large steep-sided piles. Effluent (slurry) from the coal washing was routed or pumped to a nearby impoundment or box cut where the solids were allowed to settle out. While present-day mine operations are required by law to use disposal methods and sites which minimize environmental damage, many abandoned (pre-regulation era) mine sites remain today as serious



environmental, economic, and aesthetic problems.

When pyritic material, often associated with coal refuse, is exposed at the surface, oxidation and hydrolyzation occur and strong acids are formed. Acidic overland flow from refuse sites degrades surface water quality and causes deterioration of the aquatic environment. Water with high concentrations of sulfate and metal ions and low pH may contaminate local hydrologic systems (U.S. EPA, 1974). In addition, acidic refuse material creates adverse conditions for the establishment and propagation of vegetation. Without protective vegetative cover, the refuse material is easily eroded, and the resultant sediments are carried onto adjacent areas. Erosion of gob piles uncovers unweathered pyritic material; this leads to additional oxidation, hydrolysis, and further creation of acid. Theoretically, this acid production cycle continues to degrade the environment until source pyritic materials are exhausted.

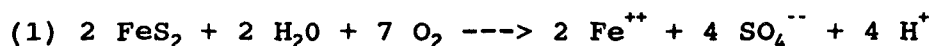
Mining in southwestern Indiana has left about 150,000 acres of disturbed land and more than 5,000 waterbodies that are larger than 0.5 acres (USGS, 1979). Some lakes exhibit potential for use as fisheries or for recreational development, while others are part of larger drainage basins and affect down stream water quality (USGS, 1979). The Indiana Department of Natural Resources (IDNR) estimates that in excess of 200 Indiana waterbodies are contaminated by the effects of acid mine drainage (Herbert, 1991). This

study focuses on a selected sample of these abandoned mine sites which contain waterbodies exhibiting optical characteristics indicative of variations in contamination and acidity as recorded by the AML (Abandoned Mine Lands) inventory files and the Gazetteer of Coal Mine Lakes in southwestern Indiana (IDNR, 1992; USGS, 1979).

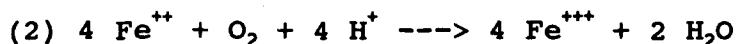
#### Nature of Acid Mine Drainage

Acid mine drainage (AMD), the detachment and transport of solid particles by flowing water, and the subsequent settling of those particles (sedimentation) are the major water quality problems caused by surface mining (USDA, 1990). AMD alters and impairs natural ecosystems. When water and oxygen come into contact with pyrite and occasionally marcasite, minerals contained within the strata or gob oxidize and release sulfuric acid and ferric sulfate (USEPA, 1974).

When pyrite oxidizes (equation 1), it releases dissolved ferrous iron, sulfate, and free acid ( $H^+$ ) into the receiving water:

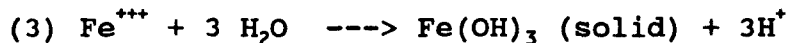


The ferrous iron then is oxidized to ferric iron (equation 2):

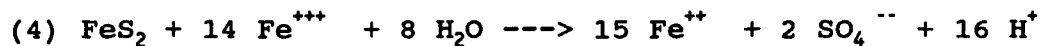


The ferric iron is then hydrolyzed (equation 3), forming insoluble ferric hydroxide and releasing more acid into the receiving water, causing the chemical reaction

represented by equation three (3). This reaction imparts the red and yellow-orange colors to the receiving water. The precipitated iron hydroxide is commonly called yellow-boy (Renn, 1989).



Pyrite can reduce to ferric iron directly (equation 4); the sulfide in the pyrite is oxidized, releasing ferrous iron (which may then re-enter the cycle at equation 2), sulfate, and free acid into the receiving water:



As long as pyrite, oxygen, and water (equations 1-3), or pyrite, ferric iron, and water (equation 4) are available, the process can continue indefinitely. The rate of the chemical reaction can be accelerated by the iron bacteria Thiobacillus ferroxidans (Singer and Strum, 1970). Singer and Strum (1970) provide evidence that the rate of pyrite oxidation is much faster for equation (4) than for equation (1) at pH values less than 4.0 and in the presence of Thiobacillus ferroxidans.

The pH of the water is lowered through these reactions to approximately 2.5 to 4.5 (USEPA, 1974). At these pH levels, the breakdown of carbonates and clay materials (Renn, 1989) and the dissolution of other constituents including aluminum, manganese and zinc is accelerated (Blevins, 1989). These constituents then enter into solution and further pollute the water. These products of oxidation along with assorted acid-soluble trace elements

compose acid mine drainage which may lead to serious water pollution problems.

The concentration and distribution of metals in aquatic systems are influenced significantly by pH (Wilber et al., 1985). Moreover, the presence of acidity and high metals concentrations in surface waterbodies influences the optical characteristics of the water (Repic et al., 1991). Visual color may range from a very translucent aqua to a very opaque red (USGS, 1979; Repic, 1992). Low pH water with metal contamination supports only limited water flora and will not support fish life, thereby eliminating a significant part of the aquatic ecosystem (Repic et al., 1991).

#### Purpose of the Study

This research project investigated reflectance spectra of contaminated surface waters in coal mine lakes. Increasing environmental legislation, in the form of the Surface Mining Control and Reclamation Act (30 U.S.C. 1201. 1977), Safe Drinking Water Act (42 U.S.C. 300 f-300j-11 1974), Clean Water Act (33 U.S.C. 1251-1376 1977), and the National Pollution Disposal Elimination System (NPDES) Act (40 CFR Parts 121-125, 1977), supports the need for advanced research and further development of investigative methods and data acquisition.

This study analyzed spectral radiance and trace metal concentration relationships over six abandoned coal mine lakes in southwestern Indiana; a state fishing impoundment

was included as a seventh waterbody. A portable field data-logging spectroradiometer was used to gather hyperspectral radiometric data. Portable chemical analysis instruments were used to measure hydrologic contamination in surface coal mine areas. This research analyzed these two data sets to determine the differences between lakes sampled.

This study was inductive; observations were generalized/classified as a first step toward theory building. The major justification for this work was that little scientific research and data are available concerning hyperspectral radiometric responses for waterbodies with metal contamination (Repic, 1991).

Further, remote sensing systems planned for the next decade are scheduled to incorporate narrow band radiometers. The presentation and understanding of the spectral interactions with various water columns and the development of spectral curves provide important insights for the interpretation of the digital data gathered by remote sensing using airborne and orbiting platforms.

The purpose of this research was to make available to investigators using remote sensing methods hyperspectral resolution reflectance data for representative coal mine lake environments. These data are accompanied by supporting hydrologic chemical observations and analyses obtained simultaneously with spectral data acquisition. Thus, this study provides a reference source for representative spectral reflectance data covering a variety of

scientifically characterized coal mine waterbodies.

## Chapter 2

### SURVEY OF THE LITERATURE

This review of the scientific literature regarding water quality and the remote sensing of coal mine lakes emphasizes two distinct classes of published research. The overall emphasis of this published research surveyed can be divided into two sections: "Surface Water Quality in Coal Mine Environments" and "Remote Sensing of Surface Waters."

Water quality in mined areas has long been a research subject, and a large body of literature addresses this subject. Public Law 95-87 (30 U.S.C. 1201 et. seq. 1977) prompted a significant amount of the published research regarding surface mine waters. Initially, research was performed to inventory and describe the extent and nature of mine-related water problems in the United States. This initial research was, for the most part, conducted prior to or at the beginning of the enactment of Public Law 95-87. Research, since the enactment of the law, has been directed towards reclamation strategies: in efforts to monitor reclamation, in the investigation of the effects of reclamation, and to assess the ongoing impacts of abandoned mine lands and coal mine reclamation on the environment.

Section 505(b)(11) of the law mandates that extensive research be conducted to provide information about the probable hydrologic consequences of mining and the subsequent reclamation. This information is required in any application for a permit to mine so that the regulatory authority can estimate the potential cumulative impact of mining on the hydrology of the area.

The second part of this literature review chapter surveys literature published on the remote sensing of surface waters. "Remote Sensing of Surface Waters" examines the remote sensing research on surface waters and further explores the use of close-range remote sensing specifically, high resolution narrow band or hyperspectral radiometers in remote sensing research.

#### Surface Water Quality in Coal Mining Environments

The United States Department of the Interior Final Environmental Statement (1977) provides that "the protection of the Nation's water resources is a major emphasis of the regulatory program." The regulatory program promulgated by Public Law 95-87 focuses on measures such as the control of sediment movement, chemical contaminants, and maintenance of surface and groundwater quality. The chief of the U.S. Army Corps of Engineers (H. Rept. 95-218, 95th Congress, 1st and 2nd Session, p. 59, 1977) in testimony before Congress stated:

The most widespread damages resulting from the effects of mining upon water resources are environmental in nature. Water users and developers incur significant



economic and financial losses as well.

Further testimony (H.R. Rept. 92-218, 95th Congress, 1st Session at 58, 1977) revealed that acid mine drainage from coal mining had contaminated over 11,000 miles of streams. Spaulding and Ogden (1968) found that 15,000 acres of contaminated water impoundments associated with mining operations in 20 states could provide suitable fish and wildlife habitat, if the sources of acid pollution of these impoundments were sufficiently reduced. Kosowski (1973), Emrich and Merritt (1969), and Caruccio and Parizek (1968) revealed that most acid mine drainage was caused by the oxidation of pyrite associated with coal seams, whether exposed by surface or underground mining. Spaulding and Ogden (1968), U.S. Environmental Protection Agency (1974), and Grim and Hill (1974) provide evidence that iron and manganese are the primary toxics in the contamination of surface waters. These investigations reveal that ferrous hydroxide ( $\text{Fe}(\text{OH})^3$ ) forms by hydrolysis and coats stream and lake bottoms, and that manganese is soluble in acidic conditions. Further, these studies show that both contaminants affect ecosystems and public use of the water.

In 1979, the U.S. Geological Survey published Water Resources Investigations 79-67. This monograph catalogs 1,000 of the 5,000 surface coal mine lakes in southwestern Indiana that are 0.5 acres or larger. The lakes are listed by 7.5 minute quadrangle topographic map name, lake identification number, latitude and longitude, and county.

Concurrent with this lake documentation project was the collection of field data for 287 of these lakes. Data collected included pH, specific conductance, apparent color of the lake, and shoreline vegetation. The data revealed pH ranges extending from 2.5 to 10, specific conductance ranging from 99 to 3,800 micromhos per centimeter at 25 degrees Celsius, and apparent colors including aqua, blue, brown, lime green, red, and green.

Hartke et al. (1983) examined the surface water quality and the effects of surface coal mining on watersheds in Vigo County of southwestern Indiana. Their research reports that acid mine drainage has negative effects on sedimentation, pH, and metal contamination in stream flows and lakes.

Wilber et al. (1985) analyzed the effects of land use and surficial geology on flow and water quality of streams in the coal mining region of southwestern Indiana. These authors compared and contrasted streams in unmined or reclaimed areas to those on unreclaimed or abandoned mine lands. Their results reveal the median pH for streams on reclaimed mined watersheds was 7.8 and the median pH for forested and agricultural watershed streams was 8.0. In contrast, the pH for streams draining unreclaimed or abandoned mine land watersheds was considerably more acidic with several pH measurements less than 5.0. In addition, this research showed that concentrations of dissolved constituents in streams affected by mining were significantly higher than those in streams unaffected by

mining. Wilber et al. (1985) attribute the high concentrations of dissolved constituents to the oxidation of pyrite and marcasite. In addition to low pH values created by the oxidation of pyrite and marcasite, acid mine drainage increases the concentrations of most major dissolved and suspended constituents, including aluminum, iron, manganese, and some trace elements. Further, the median concentration of iron for streams draining unreclaimed lands was four times that of agricultural or reclaimed lands, and the median concentrations for manganese, nickel, aluminum, and zinc for streams draining unreclaimed or abandoned mine lands were significantly greater than median values in unmined areas.

Packard et al. (1988) characterized the effects of coal mine drainage from abandoned mines on the water quality of small receiving streams in the 11 coal bearing areas of Washington State. Their assessment shows that sulfur (as sulfuric acid) and the metal contents of the coal are likely to be the controlling factors associated with the degradation of receiving streams. In similar research on water chemistry in north-central Missouri, Blevins (1989) identified that runoff from coal wastes contributed large quantities of acid drainage to streams during storms. The pH of the runoff ranged from 2.1 to 2.8 and the concentrations of some dissolved metals were a few to several hundred times greater than that of the established federal and state water quality standards. Blevins used three factors, based

upon U.S. Department of the Interior criteria, to identify acid mine drainage:

1. Specific Conductance values greater than 1,000 micro-siemens/cm at 25 degrees celsius (Indicators of large sulfate concentrations).
2. Values of pH less than 6.0
3. Red or orange staining of ground or stream bed (indicator of large iron concentrations).

Martin and Crawford (1987) statistically analyzed surface water quality parameters for areas drained by the East Fork of the White River, White River, Patoka River, and Wabash River in the Eastern Interior Basin of southwestern Indiana. They reported strong relationships between dissolved solids concentrations and specific conductance ( $r^2=.92$ ), and between sulfate concentrations and specific conductance ( $r^2=.85$ ).

Renn's (1988) study on stream flow revealed that the recommended levels for concentrations of iron and manganese were exceeded, and that, in general, specific conductance and concentrations of dissolved sulfates increased from the upstream to downstream sites. Iron in streams was generally found in a suspended phase when pH values were greater than 6.0, and in a dissolved phase in cases where the pH was less than 6.0. Manganese, however, was found primarily in a dissolved phase regardless of pH.

Elder's (1988) study established pH, hydrologic features, sediment grain size, and the existence of clay minerals, organic matter, and hydrous oxides of iron and manganese as important controlling factors in the

biogeochemical partitioning of metals. Similar work by Moran and Wentz (1974) reported that acidity tends to solubilize metals and greatly increase their mobility. Mining activities may alter speciation and transport in streams, not only by releasing metals directly into waters, but also causing perturbations that affect the metal. Modification of pH, increased sedimentation, and increased input of organic material are examples of perturbations.

Elder (1988), Horowitz (1985), Faust and Aly (1981), and Brownlow (1979) have investigated the general partitioning of metals among different phases. Their studies concurred in finding that partitioning is the process by which any solute, including contaminants, may transfer among the different phases and components of a surface water system and that the transfer pathways are nearly always bi-directional. Elder (1988) described the nature of partitioning among different phases in aquatic systems by classification into three broad abiotic phase categories which include the soluble phase, suspended sediment phase, and bottom sediment phase. The soluble phase is favored under conditions of low pH, a reducing environment, low particulate loads (both organic and inorganic), and high concentrations of dissolved organic matter. If pH and particulate loads increase, while hydraulic energy of the system is high enough to sustain suspension of the particles, partitioning is likely to shift to the suspended sediment phase. Finally, high pH and

oxidizing conditions, combined with elevated concentrations of organic matter in bottom sediments, are conditions which favor partitioning in the bottom sediment phase.

Further, Elder's (1988) investigation revealed that within the suspended sediment phase, metals may be associated with inorganic particles, organic particles, or biota. The dominant mechanism of such association is adsorption, or linkage to the surface of solid particles by charge attraction between the solid surface and the dissolved ions. Similar research by Benjamin and Leckie (1981) and Davis and Leckie (1978) documented the effects of pH on adsorption and on organometallic interactions. They cited adsorption capacity and sorption of metals on humic acids as a function of pH.

Early discussions of the importance of sorption of metals on iron and manganese hydroxides were focused on geochemistry in marine systems (Jenne, 1966; Krauskopf, 1956; and Goldberg 1954). These studies show that amorphous iron and manganese tend to exist as coatings (usually on clay particles rather than as discrete particles), thus having high surface to volume ratios.

In summary, this review found that much of the existing literature documented that stream and river flows in abandoned or unreclaimed mine environments exhibit impacts of acid mine drainage. Southwestern Indiana hydrologic systems receiving AMD are contaminated with metals, sulfates, acid, and have an altered apparent water color.

Further, the review revealed that considerable research has investigated the biogeochemical partitioning of metals in aquatic systems. Biogeochemical partitioning is largely affected by pH and that acidic conditions tend to solubilize metals and increase their mobility. The review also revealed that mining activities may alter metal speciation and transport in streams by releasing metals directly into waters and causing perturbations that affect partitioning.

#### Remote Sensing of Surface Water

Remote sensing research objectives concerning surface water bodies can be dynamic or static. Static objectives are concerned with establishing current rates of storage, normally for inventory purposes, whereas dynamic objectives are concerned with monitoring changes in behavior over time (Hockey et al., 1990). Studies over the last two decades concerning the remote sensing of surface water in coal mine environments have most often been of a static nature. They have focused on the planimetric and topographic relationships of water, in particular spatial patterns (e.g., Mausel et al., 1981; Sharber and Shahrokhi, 1977; Anderson et al., 1977; and Henkes, 1971), while those which have been dynamic in nature have, for the most part, focused on much larger waterbodies (e.g., Lathrup and Lillesand, 1988; Huang and Lulla, 1986; Lodwick and Harrington, 1985; Deutch and Estes, 1980; and Weisblatt et al., 1973). There are numerous remote sensing research investigations regarding suspended sediments (Harrington et al., 1992; Bhargava and Mariam,

1991; Bhargava and Mariam, 1990; Curran and Novo, 1988; Moore, 1980; Hoyler, 1978; and Moore, 1977). The potential of using remote sensing of water color to determine water content has been recognized for many years. Moore's water quality studies (1980, 1977) indicated the feasibility of measuring water color and turbidity. He assessed water quality by the analysis of light and water interaction processes. This work demonstrated that differences in water color and turbidity affect the signals in the visible, very near ultraviolet, and in the near infrared. Moore explained that increases in water color decrease the energy flux reaching the sensor and that increases in turbidity increase energy reaching the sensor. Amos and Topliss, (1985), Brown et al. (1985), Feldman et al. (1984), Khorram, (1981), and Hovis et al., (1980), all using Coastal Zone Color Scanner (CZCS) demonstrated that water color variations could be used for the purpose of water quality mapping. However, NASA (1987a) warns that retrieval validity is limited by a lack of knowledge of the role of sub-pixel scale regarding pigment and sediment variability. The present spatial resolution has limited the use of CZCS to the study of oceanic features with spatial scales of five kilometers or larger (NASA, 1987b).

Morel (1980) and Vertucci and Likens (1989) used spectral measurements based on upwelled radiance in the computation of spectral values of the diffuse reflectance yielding information about the color and brightness of the



water. Morel (1980) emphasizes the need for better knowledge of the spectral signatures of plankton and of the materials occurring within the sea. Further, he recognized variation in sea waters ranging from dark green to turquoise or to a milky and yellowish green. He classified sea reflectance into "green water" and "blue water."

The research of Vertucci and Likens (1989) was more closely related to the present study. These authors gathered hyperspectral reflectance data from lakes in the Adirondack Mountain region. The insitu reflectance data they gathered provided ground-truth for remote sensing of water quality in this region. The spectral reflectance curves gathered for the study were grouped into five distinct empirical classes based solely on reflectance variations.

Hockey et al. (1990), in their examination of the water quality of small, closed basins, emphasized the need for research on the spectral properties of water. They report that:

spatial characteristics of water quality, unlike spatial patterns of soil moisture for instance cannot be related to other relevant coincident surface characteristics, for there are none to relate to other than the surface roughness and outline of the waterbody itself.

Their research concluded that in the remote sensing of water quality there has to be strong reliance on the spectral properties of the water.

Current remote sensing methods have had only modest success in the examination of inland waters (Hilton, 1984).

The NASA Instrument Panel Report (1987b) revealed that the Landsat MSS has been the primary satellite-borne radiometer used for observing inland waters, and this broad-band system permits only limited discrimination of surface water properties. Hence, the modest success stems in part from the spectral band width characteristics of MSS (broad-bands), the remote sensing of complex and variable optical properties of inland waters, and the influence of atmospheric and specular reflection from the water surface on the signal. Because of sensor configuration and design emphasis of the MSS, little is known regarding radiometric responses for coal mine lakes with both metals and suspended sediment contamination. Moreover, scientific literature concerned with water quality affected by acid mine drainage is limited. RESORS, GEOREF, and NASA remote sensing reviews and bibliographic searches specific to coal mine hydrologic features have been conducted and analyzed (Repic, 1991). These efforts had little success in identifying published research with a combined remote sensing and coal mine lakes emphasis. The coarse spatial resolution of the Landsat MSS and TM sensors compared to the size of the strip mine lakes is a major factor in the lack of remote sensing applications in coal mine lake environments.

Recent research by Mausel et al. (1990) and Repic et al. (1991) document the use of multispectral videography as a means to investigate water quality in contaminated strip mine lakes in Indiana. Both studies provided insight into

the potential application of three wide spectral bands with refined spatial resolution (2.0 meters) in the dynamic remote sensing of relatively narrow orange-colored coal mine lakes.

Research by Bhargava and Mariam (1991) and Augenstein et al. (1991) has demonstrated that coincident ground level measurements of abiotic/biotic features and the associated spectra obtained from a spectroradiometer provides a practical means of studying narrow band multispectral and multitemporal patterns. Both studies developed generalized models and acquired insights into the explanation of interference effects of environmental properties. These research efforts demonstrate that spectroradiometers comparable to the sensors carried on satellites are effective in the evaluation of the overall effects of the ground conditions.

The factor which has limited the use of satellite remote sensing in the small or relatively narrow water bodies in surface coal mine environments has been the spatial resolution of the sensor packages on satellites. Recent technological advances in spatial resolution (e.g., the Landsat TM, SPOT, or video systems, as well as satellites planned for later this decade, Eos program, which will incorporate narrow band radiometers [NASA, 1987]) suggest that we may soon be able to monitor strip mine lakes from space based platforms. The High Resolution Imaging Spectrometer (HIRIS) scheduled for deployment in the next

decade will employ a spectrometer providing highly programmable localized measurements of biogeochemical processes at a spatial resolution of 30 meters. Spectral coverage will range from 0.4 to 2.5 micrometers at 10 nanometers resolution in 196 spectral bands (NASA, 1987a).

In summary, previous research has demonstrated the effectiveness of remote sensing instruments and techniques in the analysis of surface water conditions. However, research is generally lacking in the areas of inland waters contaminated by heavy metals, and is virtually non-existent for coal mine lakes. Present earth observation systems, such as Landsat MSS and TM, SPOT HRV1, and NOAA Nimbus, measure earth surface reflectance patterns in fewer than 10 broad visible and near infrared bands. These sensors exhibit relatively poor spatial and spectral resolution when compared to the proposed Eos sensor system planned for launch in the next decade. The configuration of the proposed Eos system may allow it to be more sensitive to variation in inland water patterns (NASA, 1987b), a factor often representative of contamination (Moore, 1980).

Although this review recognizes several studies regarding water quality, few have analyzed small inland basins or investigated spectral reflectance at close range. Moreover, this literature survey has demonstrated that, in general, remote sensing research regarding contaminated coal mine lakes is limited.

## Chapter 3

### METHODS

Remote sensing is used in both scientific and technological approaches to scientific research. In the scientific approaches (of which empirical is the most popular) the motivation is curiosity, the goal is knowledge, and the methods are often either induction to derive theory or deduction to verify theory (Curran, 1987). Inductive methods are used to build up an objective description of observed facts or phenomena which are then refined and ordered to derive theory and thereby knowledge. This investigation uses an inductive approach. The intent of this study is the development and understanding of spectral response curves for AMD contaminated surface water in coal mine strip lakes. The proposed research embraces both the man-land and earth-science traditions of geography (Pattison, 1964).

The primary data types used in this study are spectral radiometer reflectance measurements of the water column at the lake surface and chemical measurements acquired in situ and from laboratory analyses of water samples obtained at each site. Thirty-five millimeter color slide photographs

of the lakes were acquired along with the radiometric samples to help document the water and site characteristics. Collateral data on water temperature, air temperature, apparent optical water color, and percentage of sky cover were also obtained with each data acquisition. The term "apparent" refers to an assessment of the water color based on human judgment of color observed on site and recorded in photographs. Two sets of data, July and August, were acquired for each site to assess potential summer season variability in lake conditions.

#### Selection of Study Sites

The sites analyzed in this research were selected in a supervised manner. Criteria used in site selection included:

1. The sites were selected to provide a sample of the variety of water color found in Indiana's coal field.
2. Each site displays an apparent optical quality uncharacteristic of a normal healthy waterbody as documented in USGS 1979 Gazetteer of Coal Mine Lakes and in the literature.
3. Each site is located in the Wabash Valley Low - lands physiographic province.
4. Each site is identified in the State of Indiana Abandoned Mine Lands (AML) program as a Health Safety and General Welfare (HSGW) priority, and will be reclaimed as part of the directives of

Public Law 95-87.

The rationale for these selection criteria are as follows. The criteria of color comes from Repic et al. (1991) and Lee and Repic (1988), which identified water color as a surrogate for contamination.

#### Nature of the Study Area

Located in the southwestern part of Indiana, the coal field occupies 6500 square miles, or roughly one-sixth of the state. In Indiana there are 14 major Pennsylvanian-age coal seams, which dip from their eastern outcrop zones to the west toward the center of the basin at a rate of 20 to 30 feet per mile. The thickest, most continuous, and most numerous beds are in Warrick, Vigo, Vermillion, Clay, Greene, Knox, and Gibson counties (Environmental Systems, 1983).

The Eastern Interior Coal Basin in southwestern Indiana occurs in parts of three broad land surface types referred to as physiographic provinces: Crawford Upland, Tipton Till Plain, and Wabash Valley Lowland. Coal deposits can be found in each of these provinces; however, practically all of the mining and all of the known reserves for the state exist in the Wabash Valley Lowlands physiographic province (Figure 3). It is in this province that most coal mining has occurred, and where the majority of the end-cut lakes and impoundments of the Indiana coal field are located.

The geographic coordinates of the Wabash Valley Lowlands extend from 39 37'30" to 37 50'00" north latitude,

and from 87 37'30" to 86 52'30" west longitude. Extensive mining has occurred in this region. The mining of coal by underground methods has disturbed approximately 180,000 acres (280 square miles) in a 12 county area, while surface mining has disturbed approximately 100,000 acres (156 square miles) in 15 counties (Environmental Systems, 1983).

Land within the Wabash Valley Lowlands is characterized by gently rolling hills and flat river valleys (Environmental Systems, 1983). The bedrock is of the Pennsylvanian Period and contains large deposits of bituminous coal and is covered by glacial sediments in the north and by glacial outwash and loess in the south (Powell, 1972). The coal-bearing rocks of the Pennsylvanian age are classified into eight divisions based on the main coals, as devised by Ashley and others in 1899 (Harper, 1985). Under this system the coal beds were assigned Roman numerals in ascending stratigraphic order. Minor beds within each division were designated by the addition of lower-case letters immediately following the Roman numeral.

In Indiana, the majority of underground mining occurred from 1880 to 1940, while surface or strip mining has predominated since World War II (Figure 4). Surface production reached a maximum in 1977 (Powell, 1972), the year the Surface Mining Control and Reclamation Act (SMRCA, Public Law 95-87) was enacted. Therefore, the majority of Indiana coal mining preceded the Reclamation Act of 1977 and



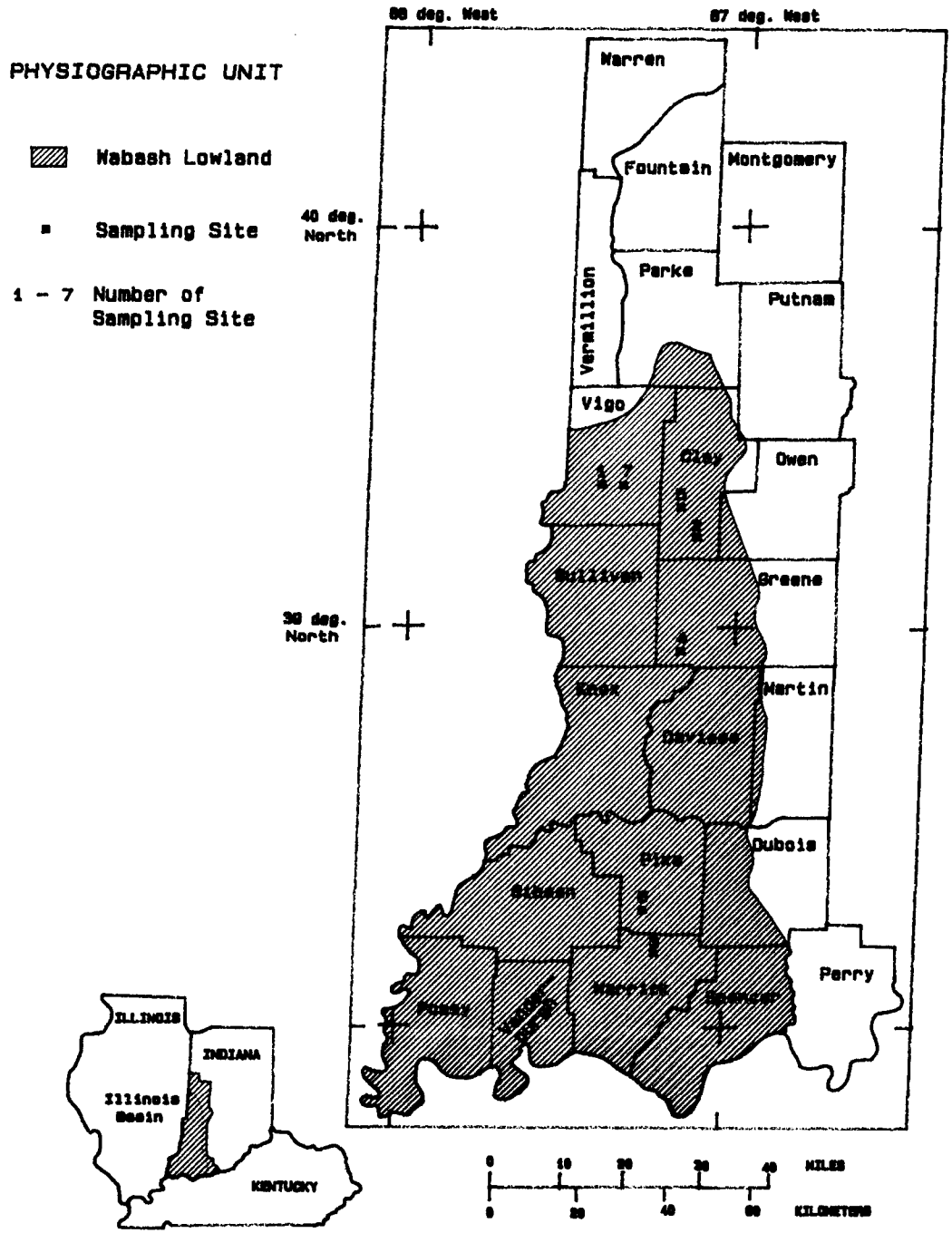


Figure 3. Location of the Wabash Valley Lowland Physiographic Province and Sampling Sites in the Coal Mining Region of Southwestern Indiana.

little, if any, evidence of reclamation exists on these sites.

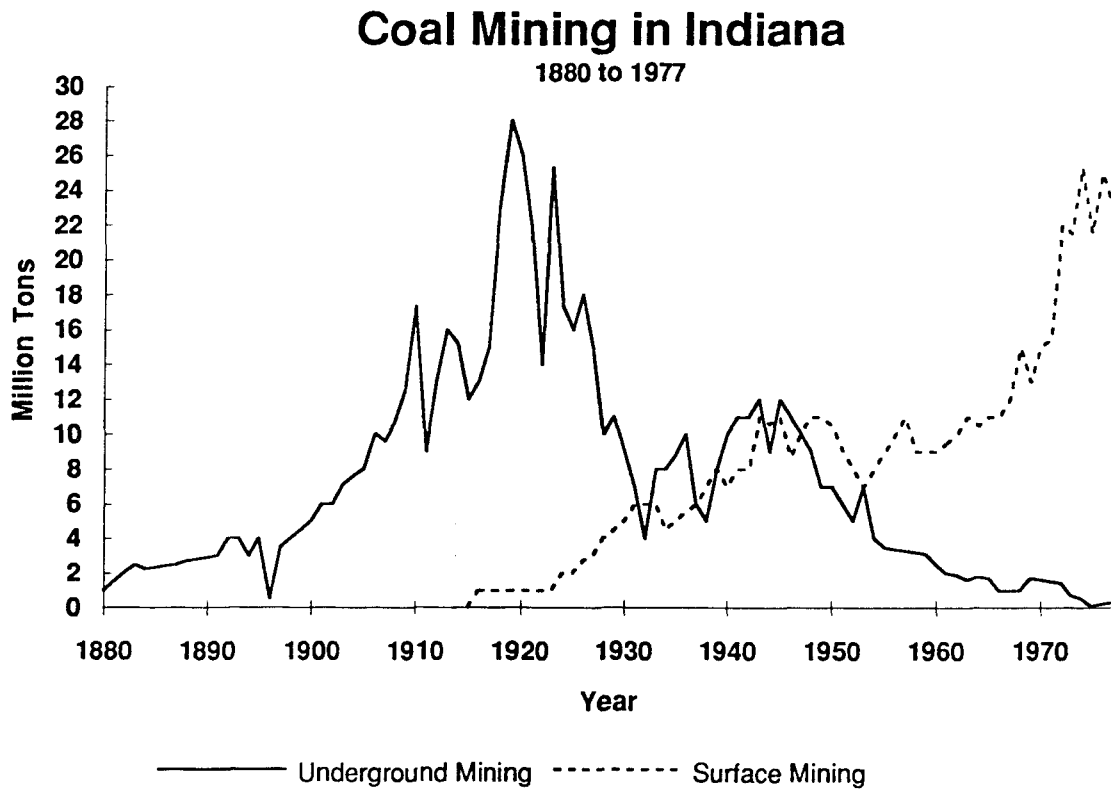
### Climate

The climate of the study area is characterized as Humid Continental (USDA SCS, 1974). The average daily maximum temperatures range from 35 degrees Fahrenheit (in January) to 86 degrees Fahrenheit (in August), with an average minimum temperature range from 17 degrees F to 64 degrees F. Mean monthly precipitation is evenly distributed throughout the year with slightly greater amounts in the spring (USDA SCS, 1974). The average yearly precipitation is 37 inches, with the highest monthly average of 4.6 inches in July. Past research has established that this climate is conducive to the production of acid water from the weathering of coal mine residues (USGS, 1983).

### The Study Sites

Each of the seven study sites used in this research either was included in the Abandoned Mine Lands (AML) inventory update (IDNR, 1992), identified in the 1979 USGS Gazetteer of Coal Mine Lakes, or both. Criteria for inclusion in the AML program are that the mine or effects of the mine impact the health, safety, and general welfare (HSGW) of citizens living in or accessing the mine area, while criteria for inclusion in the Gazetteer are based on hydrologic and limnologic management and planning concerns.

The sites were chosen based on optical characteristics



Source: USGS, 1979

Figure 4. Annual Production of Coal in Indiana.

and water quality measures identified via the AML inventory program, Indiana Fish and Wildlife property managers, and personal experience. All sites included within this study were mined prior to 1977 and thereby fall under the promulgation of Public Law 95-87; the Surface Mining and Reclamation and Control Act. These sites were chosen to provide a representative sample of the variations in contaminated surface water common to the Indiana coal field. The discussion of study sites concludes with site descriptions, maps, and photographs of the seven sites:

Site One: Problem Area (PA): No. IN0039

PA Name: Green Valley

County: Vigo

USGS Quadrangle: Sanford, Indiana

Latitude: 39° 10' 51" N

Longitude: 87° 31' 00" W

The Green Valley site contains a seven acre water body exhibiting optical red color. The lake is a remnant from the underground mine's surface washing operations and its bed and banks are composed of gob and slurry (Figures 5 and 6). Surrounding the lake are steep sided walls of piled gob. V-shaped channels have been cut into the gob by erosion.

Site Two: Problem Area (PA): No. IN0399

PA Name: Peavy Cemetery

County: Clay

USGS Quadrangle: Jasonville, Indiana

Latitude: 39° 10' 51" N

Longitude: 87° 09' 40" W

The Peavy Cemetery site has an approximately three acre strip lake resultant of surface mining activities which exhibits a red-orange color (Figures 6 and 7). The small lake is an end cut and is surrounded by a highwall to the south and 32 acres of spoil to the north, east, and west. The steeply piled spoil is barren (void of life discernable by the naked eye) and shows evidence of erosion.

Site Three: Problem Area (PA): No. IN0358

PA Name: Big Creek

County: Warrick

USGS Quadrangle: Lynnville, Indiana

Latitude: 38° 10' 05" N

Longitude: 87° 16' 42" W

Big Creek Mine contains a 9.1 acre waterbody which exhibits a lime green color (Figures 7 and 8). This site is an end cut lake, the banks are unvegetated, and there is no evidence of living organisms. The surrounding spoil area is partly vegetated with conifers, with the remaining area being unvegetated gob. Erosion of the steep banks is evident and a sulfurous odor emanates from the lake. Concrete foundations next to the lake provide evidence that coal processing may have taken place here.

Site Four: Problem Area (PA): No. IN0131

PA Name: Reservoir 29

County: Greene

USGS Quadrangle: Linton, Indiana

Latitude: 38° 59' 59" N

Longitude: 87° 14' 37" W

Reservoir 29 exhibits combined impacts of both surface and underground mining. Recent reclamation efforts have split the waterbody via an earthen embankment faced with rip-rap; the south side of the reservoir is brown, while the north is green (Figure 9 and 10). The gob surrounding the water body has been contoured, covered, and vegetated in attempt to assist reclamation. The lake appears void of life, except for some water striders present near the shoreline. This is the site of the first natural restoration, no use of neutralizing chemicals, of mine water project in Indiana (Herbert, 1992).

Site Five: Problem Area (PA): AMAX

PA Name: I-70

County: Clay

USGS Quadrangle: Staunton, Indiana

Latitude: 39° 26' 49" N

Longitude: 87° 11' 10" W

This strip lake lies just south of the east bound lane of Interstate 70. It is approximately 2.1 acres in size with an optical quality of yellow-orange (Figure 11 and 12).

The waterbody is void of physically recognizable life. The spoil area surrounding the lake is covered by conifers, and the bank sediments are stained an orange color.

Site Six: Problem Area (PA): IN0262

PA Name: Lake Augusta

County: Pike

USGS Quadrangle: Augusta, Indiana

Latitude: 38° 22' 29" N

Longitude: 87° 16' 25" W

This strip lake measures approximately 14.1 acres and lies within the Sugar Ridge Fish and Wildlife Area. The lake is an end cut of surface mining and the water is acidic. The water is aqua in color, very clear, and apparently void of life (Figures 13 and 14). The shoreline is void of vegetation; the landscape surrounding the lake consists of areas of partially vegetated spoil, primarily coniferous trees, and areas of eroded barren spoil. Acidic water can exit this waterbody via a spillway in the northwest corner of the impoundment. IDNR has strong interest in research of reclamation strategies for this site, it lies in the heart of the Fish and Wildlife Area.

Site Seven: Problem Area (PA): Not Listed in AML

PA Name: State Fishing

County: Vigo

USGS Quadrangle: Sanford, Indiana

Latitude: 39° 10' 51" N

Longitude: 87° 09' 40" W

This impounded stream valley provided the source water for the coal washing, processing, and mine cooling operations at the Green Valley Mine. The lake currently covers approximately 10 acres surrounded by actively managed agricultural land. The lake exhibits algae growth and aquatic vegetation, and is actively fished (Figures 15 and 16). This lake was chosen as a control for comparisons of chemical and spectral data. This lake is part of the Vigo County Park system.

#### Sampling Protocol

Both spectral and chemical samples were acquired from the surface of the water column approximately every 300 meters across each of the seven study sites. Due to the length of several of the lakes, a total of 12 spectral and associated chemical samples were acquired for each sampling date. The sampling along the midline of each lake was instituted to insure acquisition of volume reflectance and to eliminate the influences of bottom reflectance, sediment perturbations by inflows and falling debris, and shadowing of near shore vegetation (USGS, 1979). Spectral sample integrity was insured via duplicate measurements of a barium sulfite ( $\text{Ba}_2\text{SO}_4$ , white) panel for reflectance reference followed by triplicate sampling of the radiation field backscattered from the water column. These data were later used as calibration factors to derive



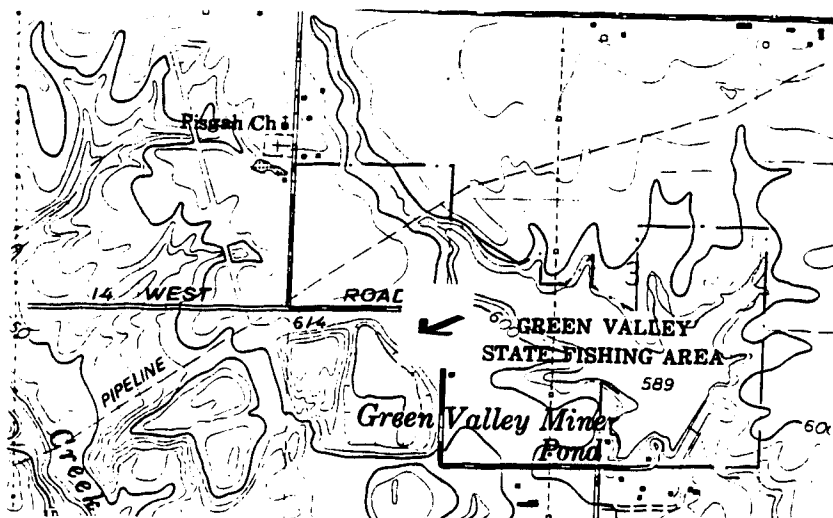


Figure 5. A Portion of the U.S.G.S. 1:24,000 Sanford, IN. Quadrangle Showing the Location of Green Valley.

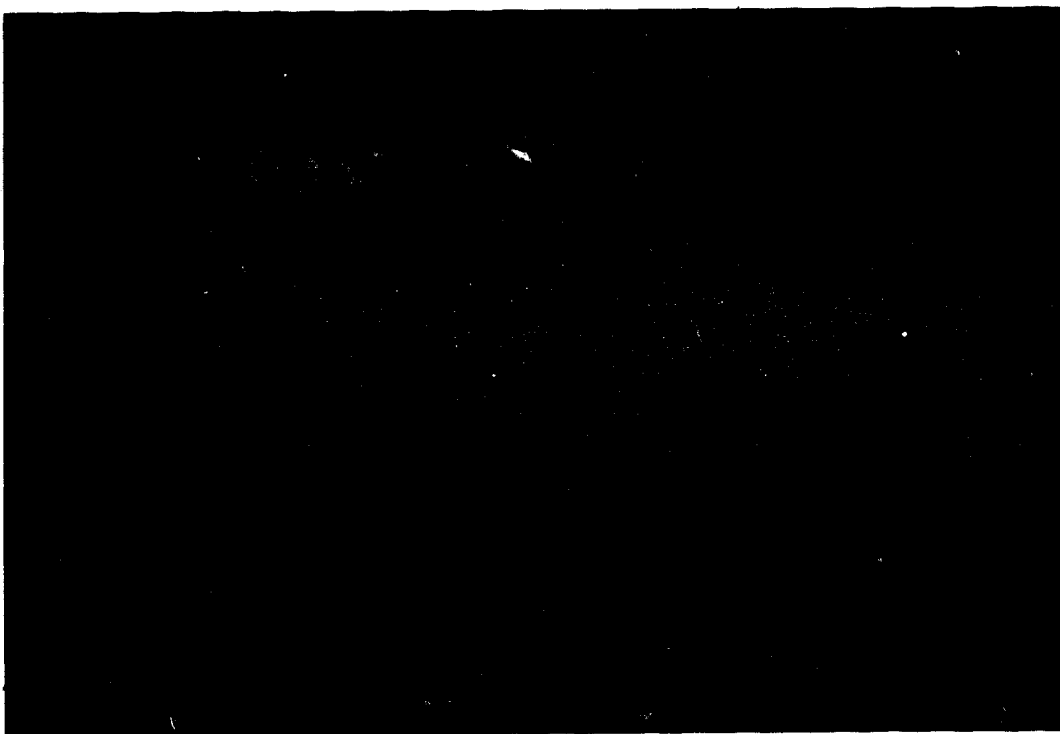


Figure 6. Green Valley Study Site; View Looking Southeast, July 1991.

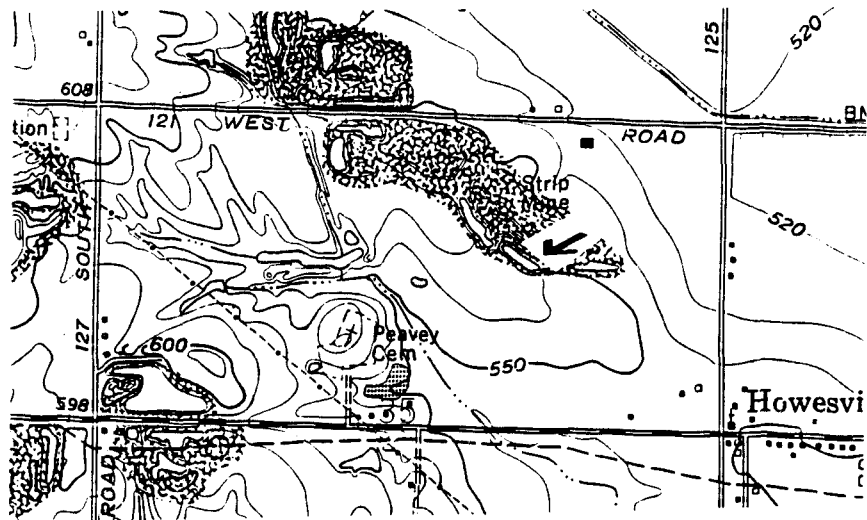


Figure 7. A Portion of the U.S.G.S. 1:24,000 Jasonville, IN. Quadrangle Showing the Location of Peavy Cemetery.

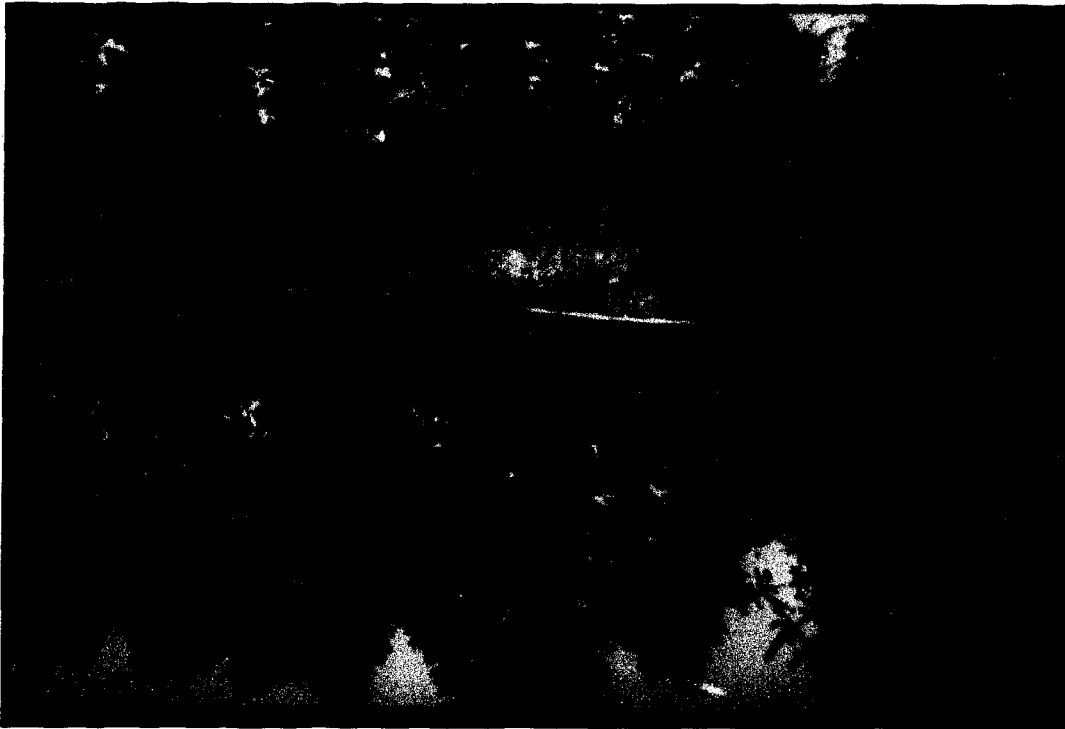


Figure 8. Peavy Cemetery Study Site; View Looking North, July 1991.

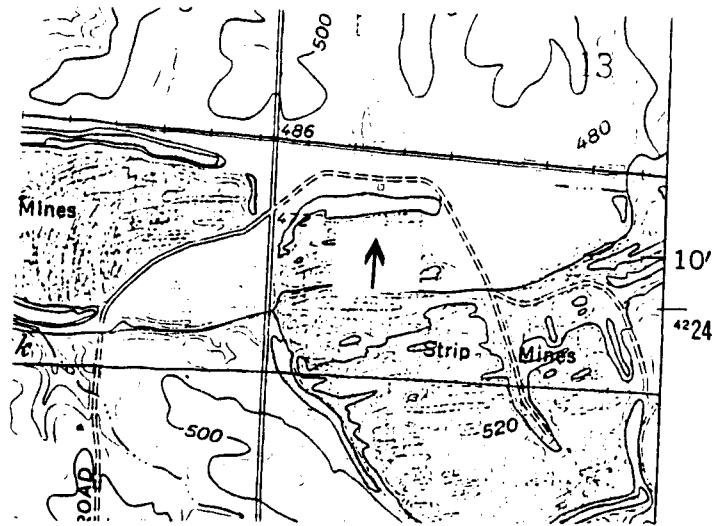


Figure 9. A Portion of the U.S.G.S. 1:24,000 Lynnville, IN. Quadrangle Showing the Location of Big Creek.

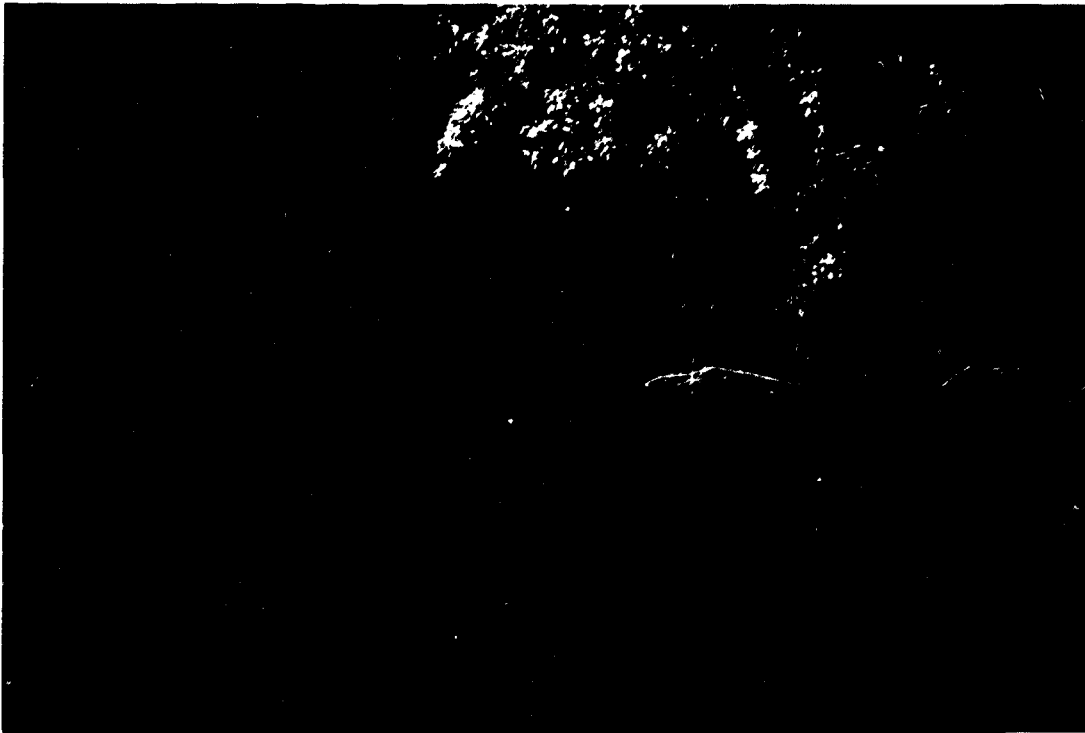


Figure 10. Big Creek Study Site; View Looking South, July 1991.

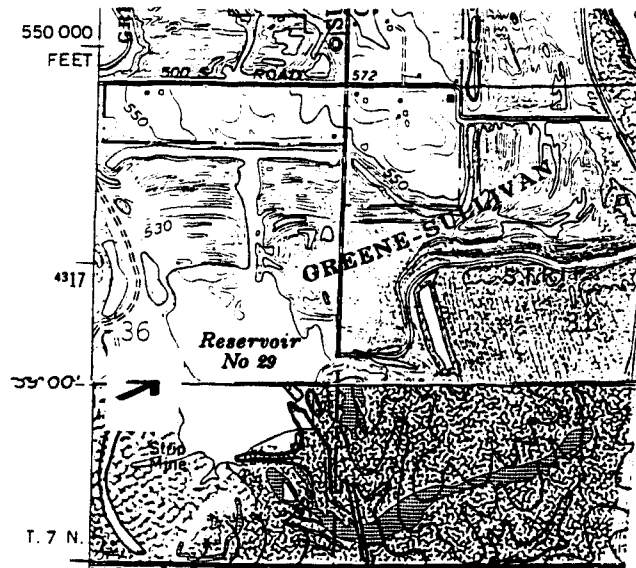


Figure 11. A Portion of the U.S.G.S. 1:24,000 Linton, IN. Quadrangle Showing the Location of Reservoir 29.



Figure 12. Reservoir 29 Study Site; View Looking North, July 1991.

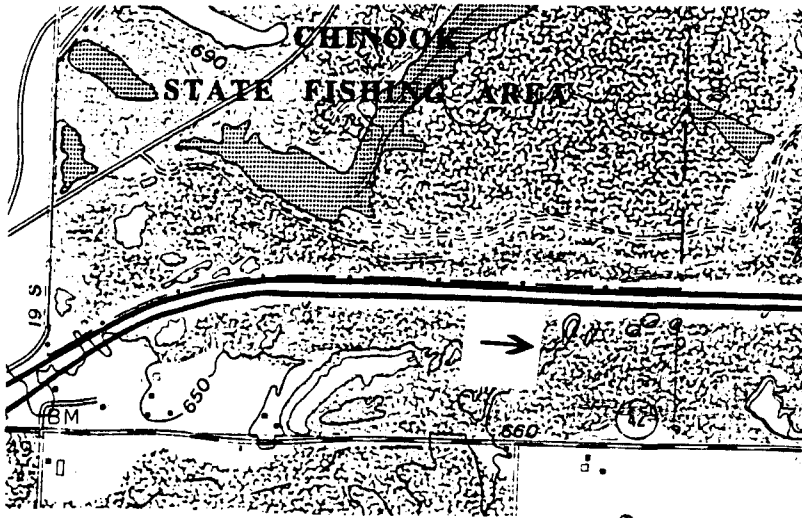


Figure 13. A Portion of the U.S.G.S. 1:24,000 Staunton, IN. Quadrangle Showing the Location of I-70.

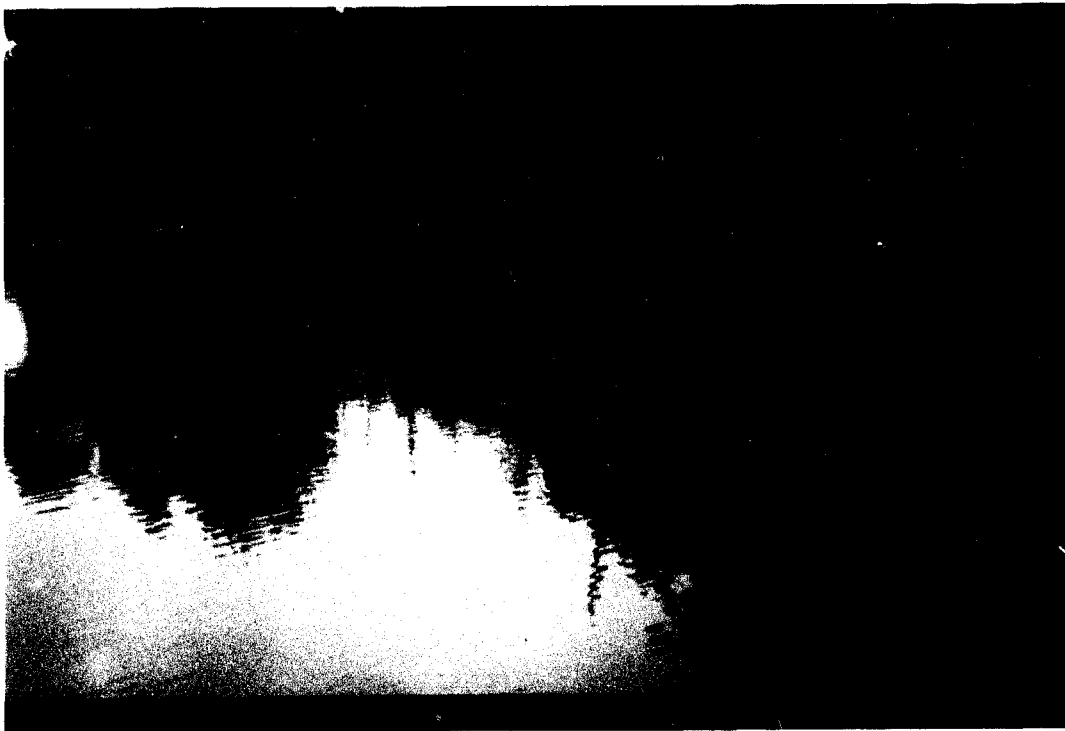


Figure 14. I-70 Study Site; View Looking South, July 1991.

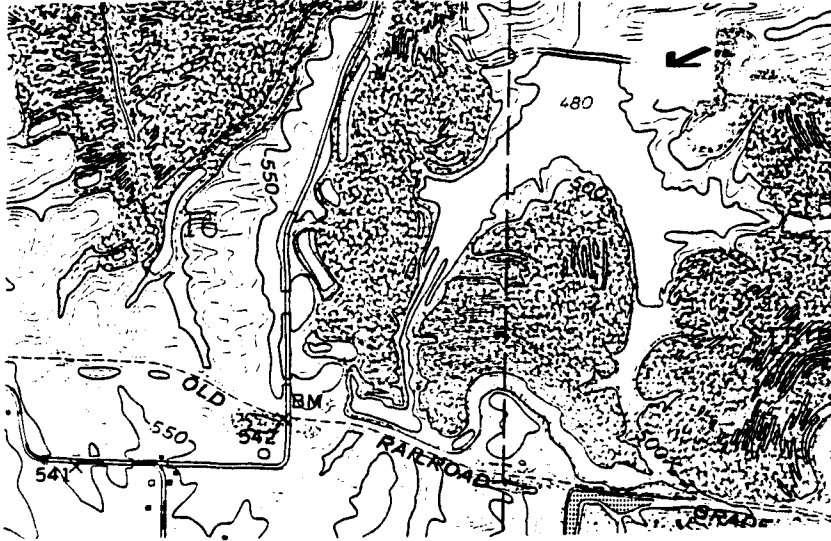


Figure 15. A Portion of the U.S.G.S. 1:24,000 Augusta, IN. Quadrangle Showing the Location of Lake Augusta.



Figure 16. Lake Augusta Study Site; View Looking South, July, 1991.

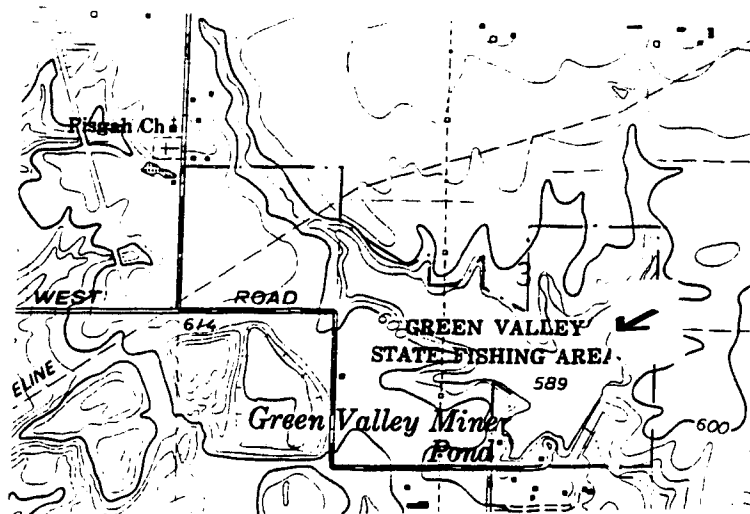


Figure 17. A Portion of the U.S.G.S. 1:24,000 Sanford, IN. Quadrangle Showing the Location of State Fishing Area.



Figure 18. State Fishing Area Study Site; View Looking Northeast, July 1991.

spectral reflectance from spectral radiance measurements. The chemical sampling protocol followed USGS (1989), EPA (1983), and ASTM (1978) guidelines for sampling technique, preservation, and analytical guidelines.

### Spectra Acquisition

Spectral radiance data were acquired from a boat over open water along the midline of the study lakes between the hours of 11:00 a.m. and 2:00 p.m. Eastern Standard Time on cloudless to near cloudless days using a Spectron Engineering Model SE 590 Field Portable Data Logging Spectroradiometer/Spectrometer mounted on a boom. The SE590 Field Portable Data Logging Spectroradiometer from Spectron Engineering, Inc. incorporates a photodiode array-based Spectral CE390 detector head which simultaneously acquires a continuous spectrum in 252 bands. Due to the problems associated with low amounts of available energy and sensor noise at both the shorter and longer wavelengths, data were processed from 450 nanometers to 850 nanometers. The radiometer collected spectra with a 6 degree IFOV from 368 to 1113 nanometers in 6 nanometer band widths at an elevation approximately one meter at nadir over the water surface along the midline of the lake. This IFOV an elevation provides for a "pure" radiometer sample of the surface water column, with little (if any) path radiance.

Spectral data were then ported from the Spectron CE 500 Microprocessor Based Portable Controller and Data Logger via RS232C output port to a Zenith 286 pc. Lotus 123



Release 2.3 was used for the development of spectral curves. Using the Lotus 123 Release 2.3 software and equations provided by Spectron Engineering, the raw lake spectral data were converted to radiance data and calibrated with the reflectance panel data to provide sample reflectance. These reflectance data were then ported to the Lotus graphing program and spectral curves, providing percent reflectance with wavelength, were produced.

#### Chemical Data Acquisition

Applicable procedures for data collection, data processing, and laboratory analyses of water grab samples are based on criteria of the Surface Mining Control and Reclamation Act of 1977 and methods from the Office of Water Coordination's National Handbook for Water Data Acquisition (USGS, 1984), USEPA (1983), and ASTM (1984). This approach keeps sampling and analytical techniques consistent with procedures of the Department of the Interior Office of Surface Mining and Indiana Department of Natural Resources Reclamation Division. Spectral and chemical samples were acquired during a two-month period in an effort to minimize seasonal variations in climate. Additionally, sampling was not conducted within 24 hours after rain events.

Data were collected in both July and August to assess variability of inflow into the basins. During the summer of 1991, June and July were dry in southwestern Indiana (NOAA, 1991); thus, data could be used to assess conditions of reduced inflow in the basins, whereas early August was wet

(NOAA, 1991), creating conditions of increased inflow into the basins. Water sample characteristics were measured in the field for odor and appearance (O/A), temperature in degrees Celsius, pH, specific conductance, and Secchi depth, and in the laboratory for metals (iron, manganese, aluminum, zinc).

Field measurements for O/A included observations for apparent color and odor, water temperature in degrees Celsius for the top four centimeters of the water column, pH using a calibrated portable Hach pH meter, specific conductivity via a LaMotte Chemical portable conductivity meter complete with temperature calibration, and light extinction depth using a Secchi disk. Light extinction was measured via a calibrated drop line attached to a circular white disk (8 inch diameter), and a measurement was obtained for the depth at which the disk became invisible; it was then lowered past this depth and then the depth of initial visibility noted as the disk was retrieved. This operation was conducted in triplicate, with the average measurement being recorded.

Metals, specifically iron, manganese, aluminum, and zinc, established in the literature as primary metal contaminants in the coal mine waters of southwestern Indiana, were analyzed by atomic absorption methods in the laboratory. Water grab samples for metal analysis were obtained using clean two-liter plastic bottles. The sampling technique recovered water samples within the top

four centimeters of the water column by placing a capped bottle beneath the water surface, then opening and evacuating any air from the container, and then capping the bottle beneath the surface to obtain a complete sample. To preserve sample integrity, the samples were immediately acidified with Nitric Acid ( $\text{HNO}_3$ ) to a pH less than 2 and placed in an iced cooler to insure a sample temperature of less than 4 degrees Celsius. Both samples and calibration standards were directly aspirated into a Pye Unicam Atomic Absorption Instrument located at Rose Hulman Institute of Technology, and the results were recorded.

#### Spectral Classification

The method used to group or type the acquired spectral and chemical data has its basis in the close-range remote sensing research of Morel (1980) and Vertucci and Likens (1989). Spectral curves are classified based only on reflectance properties. Differences in acquired spectra allow for the classification of various lake reflectance into types or groups.

In summary, the primary sources of data in this study are biogeochemical data acquired via field sampling and measurement, laboratory analysis for metals, and reflectance spectra collected and developed from radiometer measurement of the water surfaces.

Spectral signatures derived from these methods provide surface water reflectance from each of the seven study sites and seven apparent optical classes of water. Inference is

made between biogeochemical data and spectral curves in an effort to identify the potential to associate spectral responses with specific chemical characteristics of the lakes. This type of information is of key importance in the analyses of spectral data from remote sensing devices planned for the upcoming decade; moreover, it provides insights as to the transfer value of remotely sensed data to other areas both within and beyond the geographic boundaries of the Wabash Valley Lowlands physiographic province and the Eastern Interior Coal Basin. The methods incorporated into the research design allow reproducibility, have a basis in proven technically reviewed standards, and include accepted methods that contribute to theory development.

## Chapter 4

### RESULTS AND DISCUSSION

The primary emphases of this research were to acquire water chemistry data through field sampling and spectral data using a hand-held spectroradiometer. For each of the lakes sampled, remotely sensed reflectance was measured over 180 narrow bands, each of 6 nanometers in wavelength. In all, 24 spectra were obtained for 7 lakes during two field surveys conducted in July and August 1991. All spectral results are reported as percent reflectance. The acquired spectral data are presented in the form of spectral curves or signatures for each study site.

In addition to the spectra and chemical data, statistical summaries for the average reflectance of visible energy for wavelengths ranging from 450-500, 500-600, and 600-700 nanometers (nm) respectively are presented. These groupings of energy were selected as a reference to existing satellite-based sensor packages. The groupings are coincident with band-widths within the Thematic Mapper (TM) Multispectral Scanner (MSS), and SPOT sensor configurations. The energy grouping 450-500 nm coincides with Thematic Mapper band 1 (450-520 nm). The groupings 500-600 nm

coincide with TM band 2 (520-600 nm), MSS band 4 (500-600 nm), and SPOT Multi-spectral band 1 (500-590 nm), while the grouping 600-700 is coincident with TM band 3 (630-690 nm), MSS band 5 (600-700 nm), and SPOT MS band 2 (610-680 nm).

Included with the graphic presentation of each site's spectral reflectance is a brief discussion of the spectral curve and chemical data, as well as a table which summarizes reflectance in the visible range. In addition, collateral data regarding acidity, specific conductance, apparent optical color, and milligrams per liter of the metals iron, manganese, aluminum, and zinc are displayed with the spectra to enhance description of the chemical nature of the coal mine lake.

The organization of the results is based on the study site number: Green Valley (Figures 19, 20, and Table 1), Peavy Cemetery (Figures 21, 22, and Table 2), Big Creek (Figures 23, 24, 25, 26, and Tables 3 and 4), Reservoir 29 (Figures 27, 28, 29, 30, 31, 32, 33, 34, and Tables 5 and 6), I-70 (Figures 35, 36, and Table 7), Lake Augusta (Figures 37, 38, 39, 40, and Tables 8 and 9), and State Fishing Area (Figures 41, 42, and Table 10).

The next part of this chapter reports the classification of the seven study sites based on spectra and on chemistry. The spectral basis for classification provides four distinct types or classes of lakes (Figures 43, 44, 45, and 46). The basis of lake classification is on differences in reflectance and is made independent of consideration of

water color and water quality characteristics. The waterbodies are then classified according to chemical characteristics, specifically Ph and Secchi depth, independent of spectral reflectance. Again four classes are evident. The final part of the chapter provides a discussion which generalizes the spectral/chemical relationships for each lake.

#### Spectral/Chemical Relationships Green Valley

The spectral curves for Green Valley for both the July (Figure 12) and the August sampling (Figure 13) yielded nearly identical results with the only variation being that the July sampling had slightly higher reflectance. Both curves had an overall maximum reflectance intensity of less than 1 percent, with an average visible reflectance of 0.77 for July and 0.67 for August. In general, the overall tendency revealed by the curves is of nearly equal reflectance across all bands sampled (Table 1). The greatest maximum reflectance, approximately 0.8 percent occurred in two minor peaks at 635 and 700 nanometers (red energy) in the August sampling.

Chemically, the lake is highly acidic, the Ph of both samples being less than 2.0. This highly acidic condition provides for the dissolution of soluble materials, as evidenced by specific conductivity values of 5400 micromhos per centimeter (micromhos/cm) for July and 5200 micromhos/cm for August. Dissolution of metals is known to increase light absorption in a water column (Moore, 1980). Average

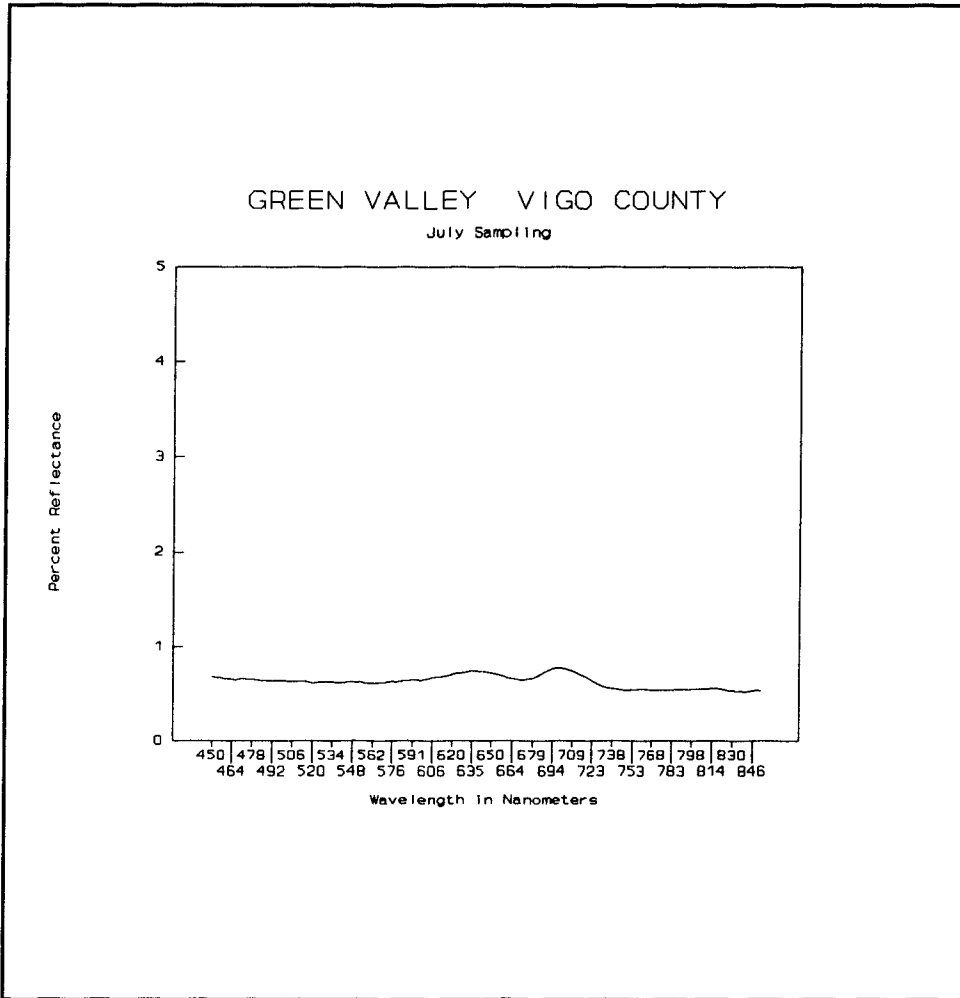
Secchi depths of 1.5 and 2.0 feet correspond with the low reflectance. High levels of iron and aluminum, presumably resulting from very acidic conditions, were measured by atomic absorption analysis of the water samples. Optically the lake appeared a very dark red.

#### Peavy Cemetery

Spectral sampling for Peavy Cemetery for both sampling dates yielded similar spectral curves (Figure 16 and 17), with the only variation being that July was slightly brighter. The average visible reflectance for July was 0.73 percent, while August measured 0.52 (Table 2). Energy was preferentially absorbed from 450 to 550 nanometers (0.13 and 0.10 percent for July and August respectively) and from 730 to 850 nanometers. Both curves had a maximum reflectance intensity between 1 and 2 percent. Maximum reflectance for both dates occurred at about 650 and 695 nanometers (red energy). The average percent reflectance was also maximized in the red, with 1.47 percent for July and 0.97 percent for August. Further, the spectral signatures were characterized by absorption in a band of approximately 20 nanometers ranging from 660 and 680 nanometers.

Chemically, the Peavy Cemetery water column had an apparent color of red-orange and was very acidic with pH values less than 2.2. This low pH promotes dissolution of soluble materials, hence the relatively high conductivity values, ranging from 3700 to 4200 micromhos/cm. The dissolved materials in the water, primarily iron ranging





**AIR TEMPERATURE: 30.5 C**

**WATER TEMPERATURE: 31 C**

**pH: 1.96**

**SPECIFIC CONDUCTIVITY: 5400  
(micromhos/cm)**

**SECCHI DEPTH: 1.5 feet**

**APPARENT COLOR: Dark red/black**

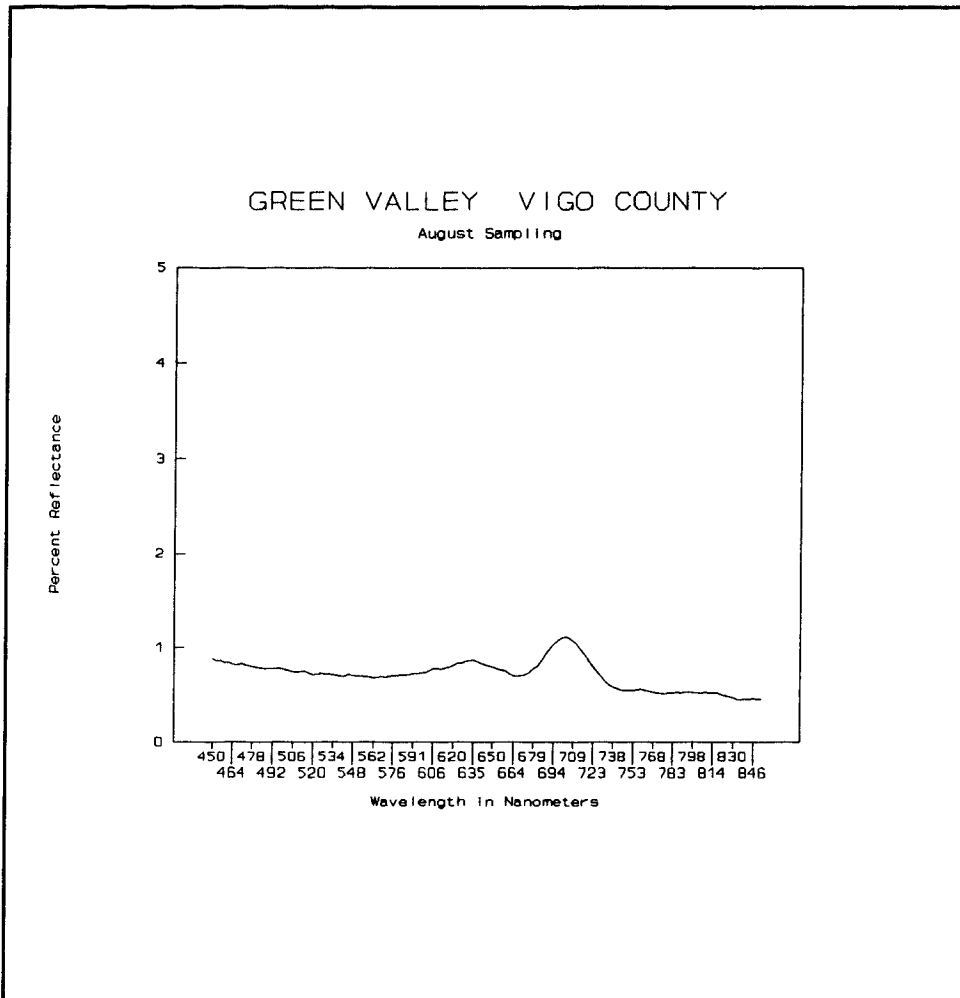
**IRON: >400 mg/l**

**MANGANESE: 7 mg/l**

**ALUMINUM: 120 mg/l**

**ZINC: <5 mg/l**

**Figure 19. Spectral and Chemical Characteristics for the July Sampling of Green Valley.**



AIR TEMPERATURE: 30.5 C

WATER TEMPERATURE: 30 C

pH: 1.67

SPECIFIC CONDUCTIVITY: 5200  
(micromhos/cm)

SECCHI DEPTH: 2.0 feet

APPARENT COLOR: Dark red/black

IRON: >400 mg/l

MANGANESE: 7 mg/l

ALUMINUM: 120 mg/l

ZINC: <5 mg/l

Figure 20. Spectral and Chemical Characteristics for the August Sampling of Green Valley.

Table 1. Statistical Summaries for Average Percent Reflectance of Visible Energy for the Green Valley Study Site.

GREEN VALLEY	STATISTICAL SUMMARIES FOR AVERAGE PERCENT REFLECTANCE OF VISIBLE ENERGY				
	Blue	Green	Yellow	Orange	Red
ENERGY					
JULY SAMPLING	0.81	0.71	0.71	0.76	0.83
AVERAGE OF VISIBLE ENERGY FOR JULY	0.77				
AUGUST SAMPLING	0.66	0.63	0.64	0.67	0.71
AVERAGE VISIBLE ENERGY FOR AUGUST	0.67				

AVERAGE PERCENT REFLECTANCE FOR MULTISPECTRAL SCANNER NOMINAL BANDWIDTH			
BANDWIDTH IN NANOMETERS	450-500	500-600	600-700
JULY SAMPLING	0.66	0.63	0.71
AUGUST SAMPLING	0.81	0.71	0.82

from 225 to 400 mg/l, aluminum with 100 milligrams per liter, and manganese with 40 milligrams per liter, contributed to absorption of incident radiation and an average Secchi depth measurement of 2 feet.

#### Big Creek

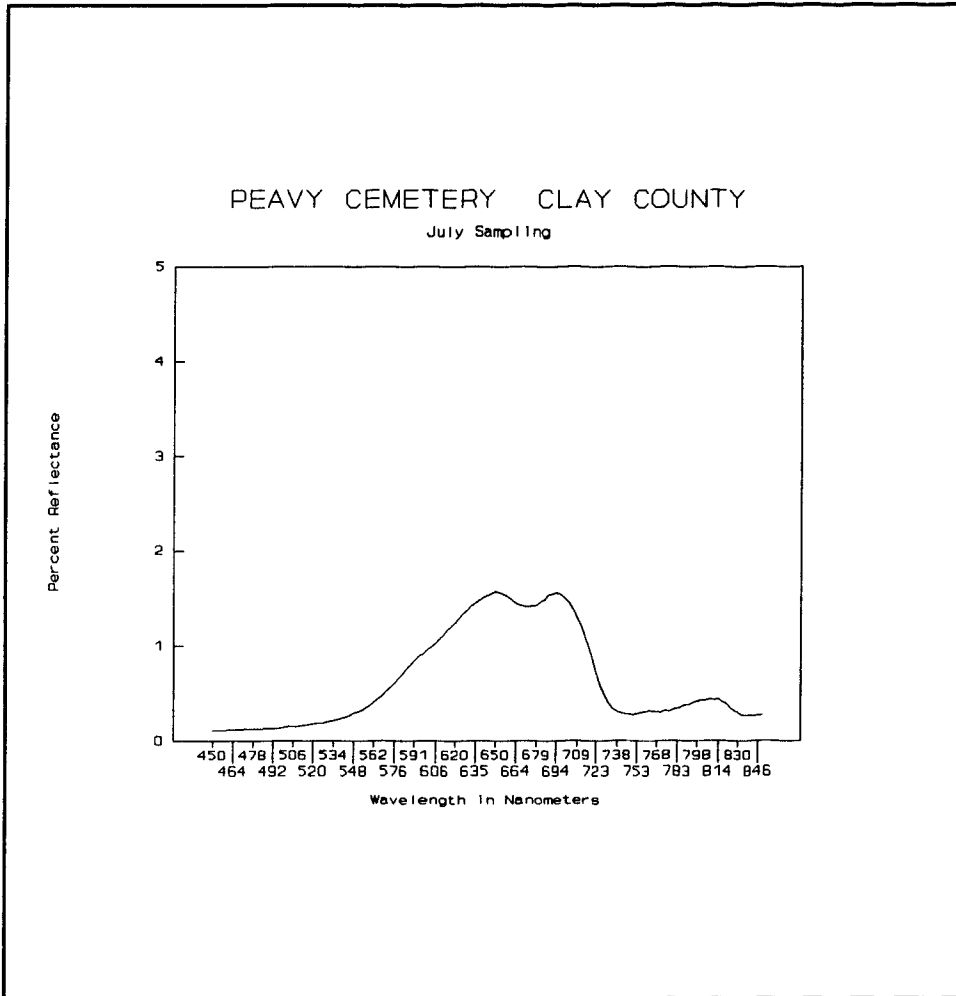
Spectral sampling for two locations over two dates yielded similar spectral curves with the only variation that the July sampling was brighter, with an average visible reflectance of 4.79 and 4.81 percent (Figures 19, 20 and Table 3) in July and 3.53 and 3.79 for August (Figures 21, 22 and Table 4). Maximum reflectance intensity of slightly

over 8 percent occurred for July while the maximum reflectance intensity for August was about 5.5 percent. Higher reflectance values were evident from 500 to 620 nanometers with maximum reflectance intensity at about 540 nanometers (green energy). Overall, the average percent reflectance was maximized in green and yellow energy. A much smaller second response in reflectance was noticeable at 695 nanometers (red energy). Energy was preferentially absorbed from 450 to 500, 660 to 680, and 725 to 850 nanometer wavelengths.

Chemically, little variation was noted between locations and dates. Optically, the waterbody is bright with an apparent color of green/yellow. Water acidity measured as pH ranged from 2.74 to 2.93, while specific conductivity ranged from 550 to 1100 micromhos/cm. Light extinction as measured by Secchi disk ranged from 6.0 to 6.5 feet and dissolved metals measured by atomic absorption identified the influence of iron, manganese, aluminum and zinc at 7 milligrams per liter or less per metal.

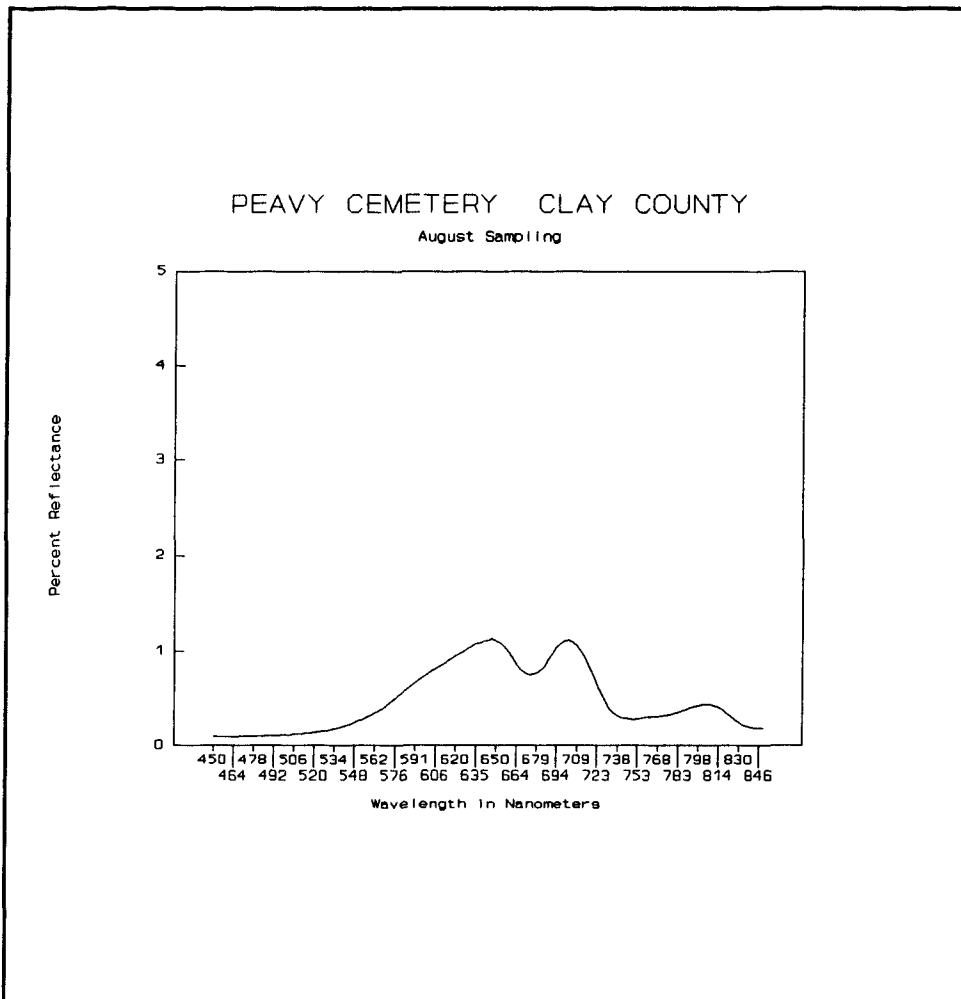
#### Reservoir 29

Spectral samples were acquired over four locations for each sample date. The resulting spectral curves exhibit similar reflectance across the wavelengths for all sites (Figures 23-27). Average visible reflectance for July and August sample dates were as follows: Area A 1.67 and 1.60, Area B 1.82 and 1.74, Area C 2.63 and 2.08, and Area D 1.47



AIR TEMPERATURE: 34.5 C    WATER TEMPERATURE: 35 C  
 pH: 2.18    SPECIFIC CONDUCTIVITY: 4200 (micromhos/cm)  
 SECCHI DEPTH: 2 feet    APPARENT COLOR: red/orange  
 IRON: 225 mg/l    MANGANESE: 40 mg/l  
 ALUMINUM: 100 mg/l    ZINC: <5 mg/l

Figure 21. Spectral and Chemical Characteristics for the July Sampling of Peavy Cemetery.



AIR TEMPERATURE: 34.5 C

WATER TEMPERATURE: 35 C

pH: 1.45

SPECIFIC CONDUCTIVITY: 3700  
(micromhos/cm)

SECCHI DEPTH: 2 feet

APPARENT COLOR: red/orange

IRON: >400 mg/l

MANGANESE: 40 mg/l

ALUMINUM: 100 mg/l

ZINC: <5 mg/l

Figure 22. Spectral and Chemical Characteristics for the August Sampling of Peavy Cemetery.

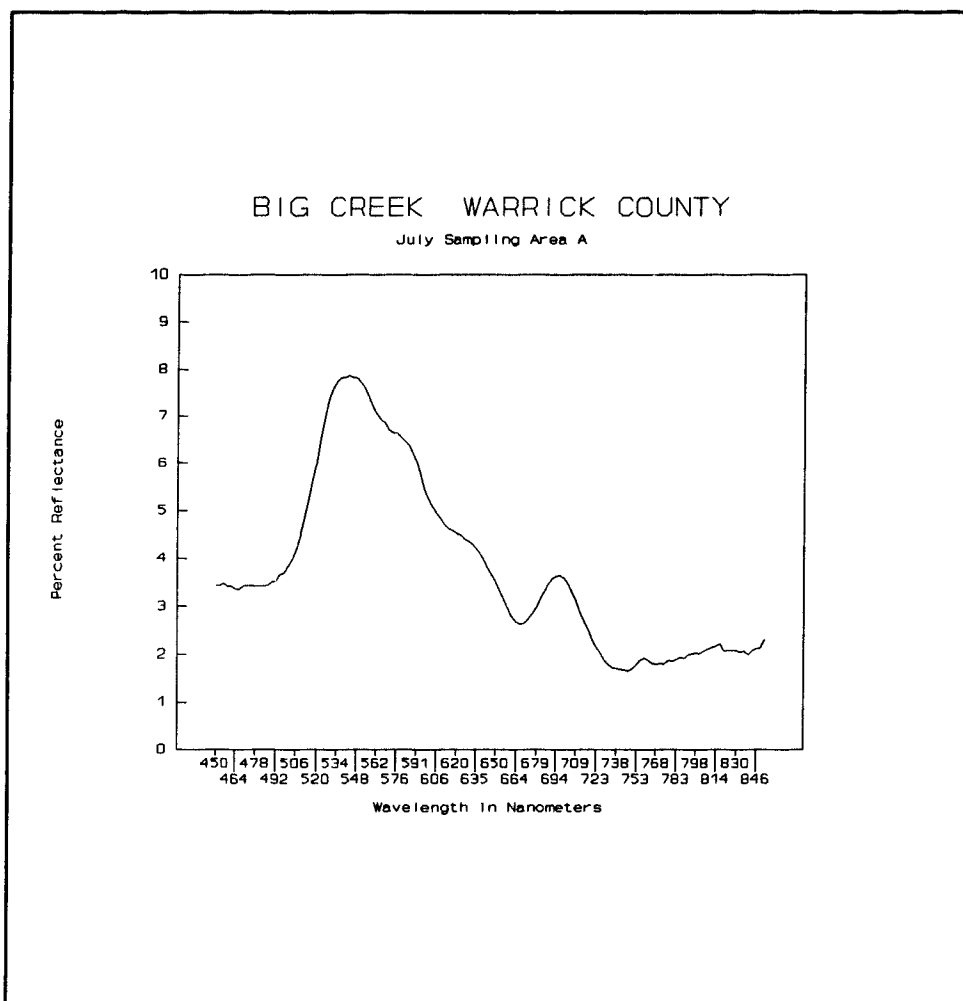
Table 2. Statistical Summaries for Average Percent Reflectance of Visible Energy for the Peavy Cemetery Study Site.

PEAVY CEMETERY	STATISTICAL SUMMARIES FOR AVERAGE PERCENT REFLECTANCE OF VISIBLE ENERGY				
	Blue	Green	Yellow	Orange	Red
JULY SAMPLING	0.13	0.30	0.75	1.04	1.47
AVERAGE OF VISIBLE ENERGY FOR JULY	0.73				
AUGUST SAMPLING	0.10	0.24	0.60	0.82	0.97
AVERAGE VISIBLE ENERGY FOR AUGUST	0.52				

AVERAGE PERCENT REFLECTANCE FOR MULTISPECTRAL SCANNER NOMINAL BANDWIDTH			
BANDWIDTH IN NANOMETERS	450-500	500-600	600-700
JULY SAMPLING	0.13	0.40	1.39
AUGUST SAMPLING	0.10	0.33	0.95

and 2.55 percent respectively (Table 5 and 6). The highest reflectance varied from approximately 2.5 percent to 4 percent, with a peak from 530 to 550 nanometers in wavelength (green energy). Blue reflectance at 450 to 500 nanometers ranged from approximately 1.5 to 2.75 percent. The majority of spectral reflectance was recorded as green wavelengths followed by blue. Energy from approximately 600 nanometers to 850 was preferentially absorbed at the Reservoir 29 study sites. However, at 695 nanometers there was evidence of a small reflectance peak in the spectra.

The average percent reflectance for July and August



AIR TEMPERATURE: 34 C

pH: 2.74

SECCHI DEPTH: 6.3 feet

IRON: 7 mg/l

ALUMINUM: 5 mg/l

WATER TEMPERATURE: 28 C

SPECIFIC CONDUCTIVITY: 900  
(micromhos/cm)

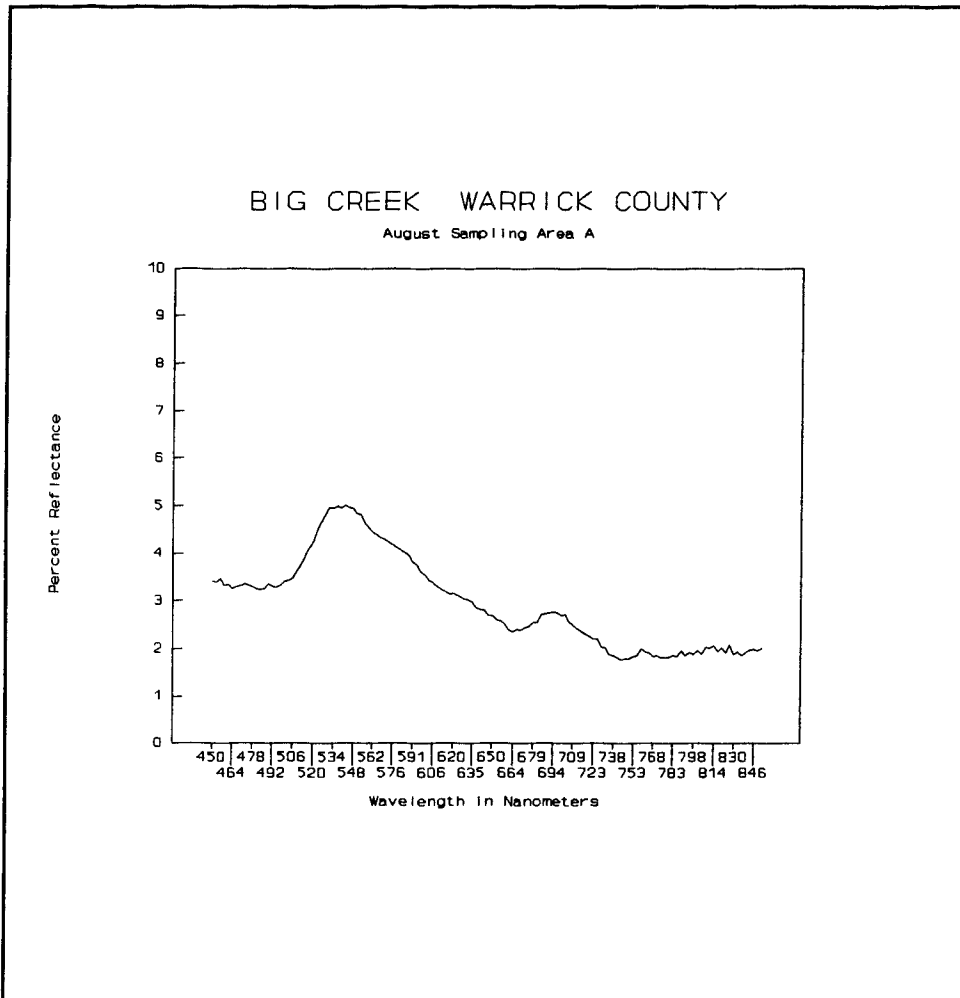
APPARENT COLOR: yellow/green

MANGANESE: <5 mg/l

ZINC: <5 mg/l

Figure 23. Spectral and Chemical Characteristics for the July Sampling of Big Creek Area A.





AIR TEMPERATURE: 34 C

WATER TEMPERATURE: 27.5 C

pH: 2.96

SPECIFIC CONDUCTIVITY: 1100  
(micromhos/cm)

SECCHI DEPTH: 6 feet

APPARENT COLOR: yellow/green

IRON: 7 mg/l

MANGANESE: <5 mg/l

ALUMINUM: 5 mg/l

ZINC: <5 mg/l

Figure 24. Spectral and Chemical Characteristics for the July Sampling of Big Creek Area B.

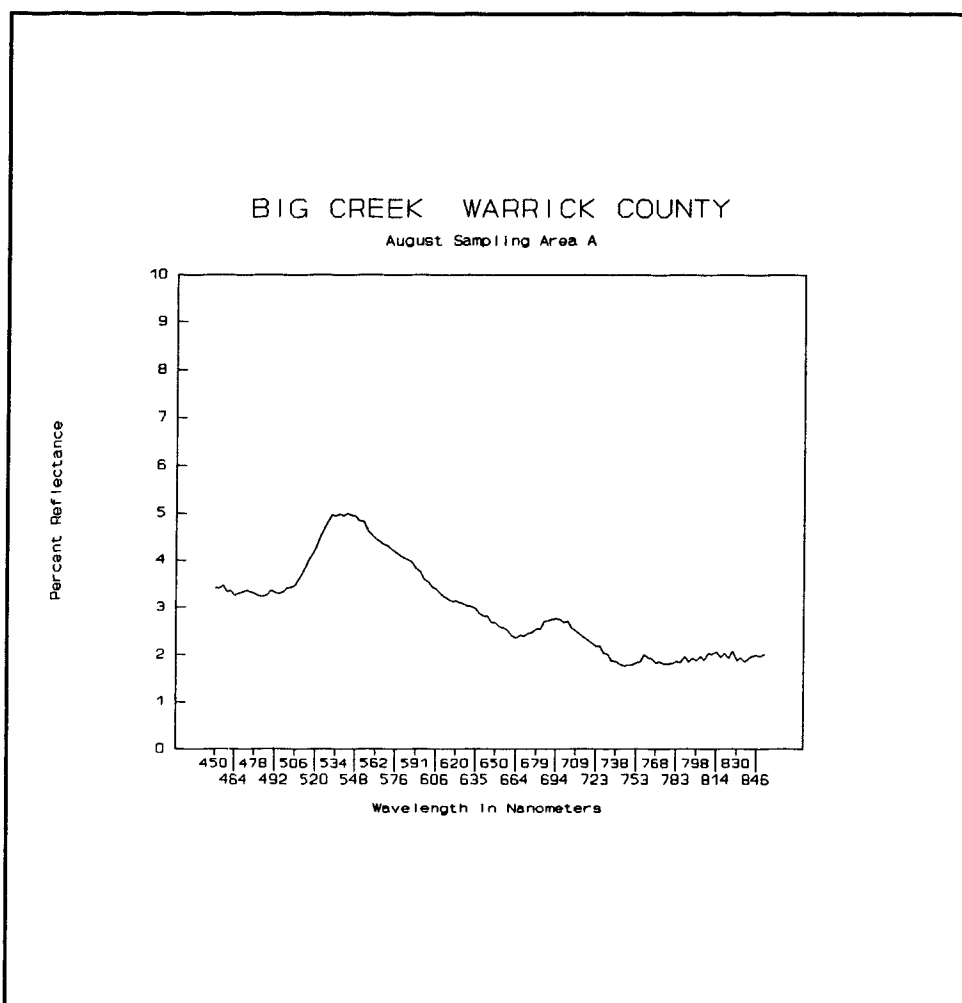
Table 3. Statistical Summaries for Average Percent Reflectance of Visible Energy for the Big Creek Study Site.

BIG CREEK JULY SAMPLING	STATISTICAL SUMMARIES FOR AVERAGE PERCENT REFLECTANCE OF VISIBLE ENERGY				
	Blue	Green	Yellow	Orange	Red
ENERGY					
AREA A SAMPLING	3.48	6.57	6.32	5.06	3.51
AVERAGE OF VISIBLE ENERGY FOR AREA A	4.79				
AREA B SAMPLING	3.57	6.76	6.21	4.85	3.42
AVERAGE VISIBLE ENERGY FOR AUGUST	4.81				

AVERAGE PERCENT REFLECTANCE FOR MULTISPECTRAL SCANNER NOMINAL BANDWIDTH			
BANDWIDTH IN NANOMETERS	450-500	500-600	600-700
AREA A SAMPLING	3.48	6.45	3.78
AREA B SAMPLING	3.57	6.57	3.66

show that reflectance in energy ranging from 500 to 600 nanometers yielded the highest reflectance on all samples, while energy in 600 to 700 nanometers was preferentially absorbed for all samples.

Chemically, the samples provided similar results for the characteristics measured. Optically the water was very clear with Secchi disk measurements exceeding 8 feet in all cases (the entire length of the leader), with a slight blue-green cast. Acidity was indicated by pH ranges from 2.65 to 3.04, and conductivity extends from 600 to 1400 micromhos/cm. In all cases the iron, manganese, aluminum,



**AIR TEMPERATURE: 31.5 C**

**pH: 2.92**

**SECCHI DEPTH: 6.5 feet**

**IRON: 6 mg/l**

**ALUMINUM: 5 mg/l**

**WATER TEMPERATURE: 26 C**

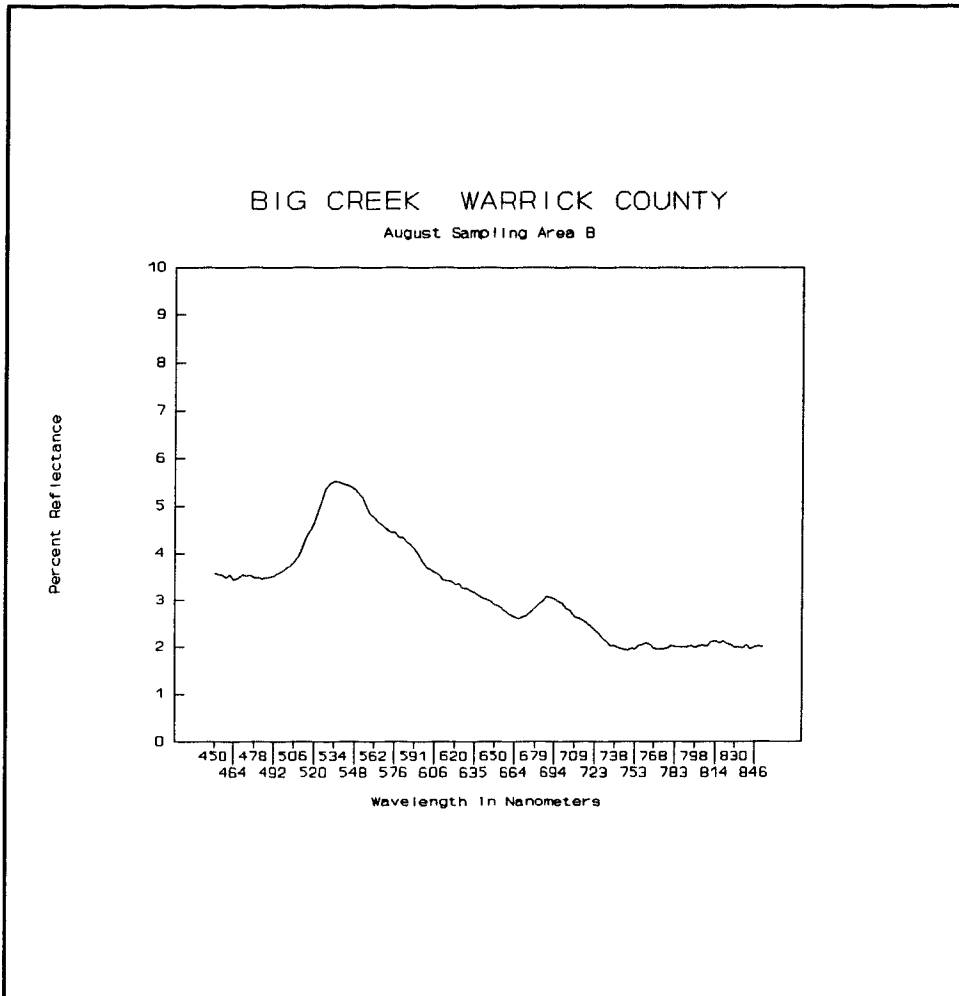
**SPECIFIC CONDUCTIVITY: 950  
(micromhos/cm)**

**APPARENT COLOR: yellow/green**

**MANGANESE: <5 mg/l**

**ZINC: <5 mg/l**

**Figure 25. Spectral and Chemical Characteristics for the August Sampling of Big Creek Area A.**



**AIR TEMPERATURE: 31.5 C    WATER TEMPERATURE: 26 C**

**pH: 2.93**

**SPECIFIC CONDUCTIVITY: 550  
(micromhos/cm)**

**SECCHI DEPTH: 6.5 feet**

**APPARENT COLOR: yellow/green**

**IRON: 7 mg/l**

**MANGANESE: <5 mg/l**

**ALUMINUM: 6 mg/l**

**ZINC: <5 mg/l**

**Figure 26. Spectral and Chemical Characteristics for the August Sampling of Big Creek Area B.**

Table 4. Statistical Summaries for Average Percent Reflectance of Visible Energy for the Big Creek Study Site.

BIG CREEK AUGUST SAMPLING	STATISTICAL SUMMARIES FOR AVERAGE PERCENT REFLECTANCE OF VISIBLE ENERGY				
	Blue	Green	Yellow	Orange	Red
AREA A SAMPLING	3.33	4.39	3.99	3.41	2.71
AVERAGE OF VISIBLE ENERGY FOR AREA A	3.52				
AREA B SAMPLING	3.52	4.76	4.23	3.64	2.96
AVERAGE VISIBLE ENERGY FOR AREA B	3.79				

AVERAGE PERCENT REFLECTANCE FOR MULTISPECTRAL SCANNER NOMINAL BANDWIDTH			
BANDWIDTH IN NANOMETERS	450-500	500-600	600-700
AREA A SAMPLING	3.33	4.28	2.83
AREA B SAMPLING	3.52	4.63	3.07

and zinc measured 7 milligrams per liter or less.

#### I-70

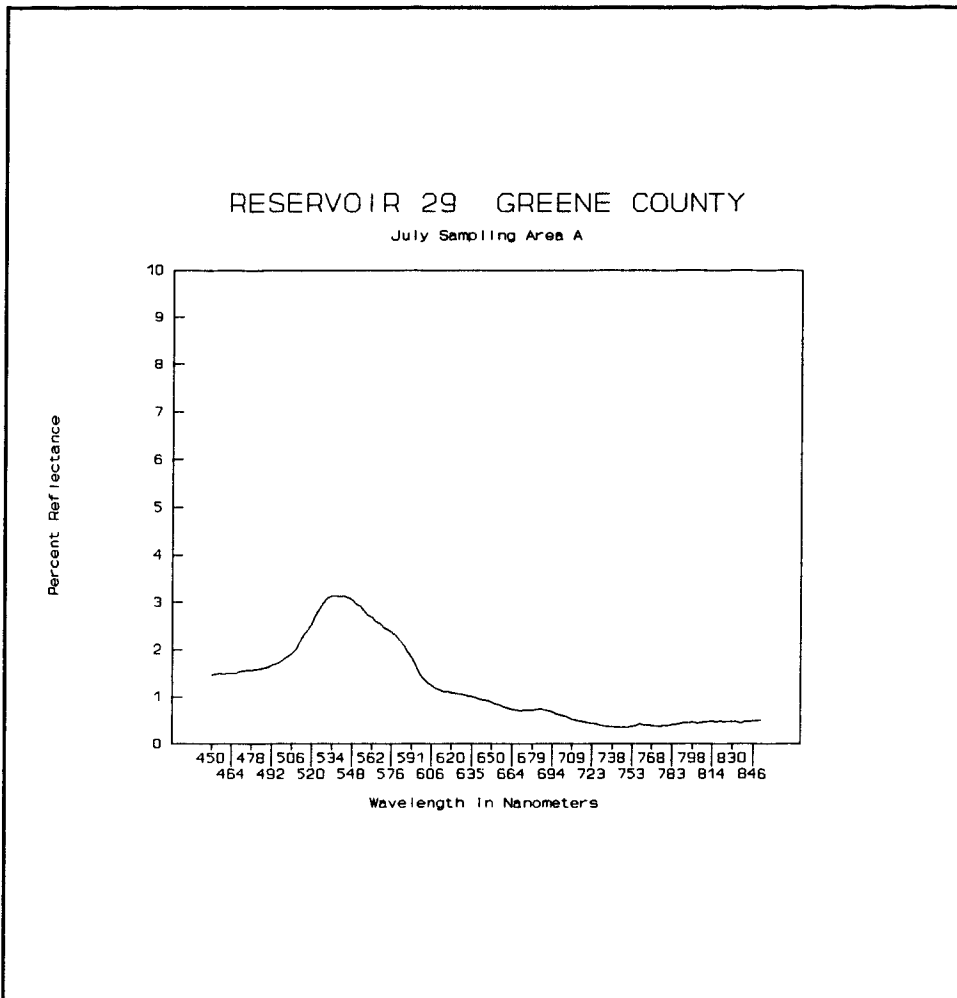
Spectral curves for the small turbid lake just south of I-70 in Clay County exhibited the highest reflectance intensity of all samples in this study, with maximum values of 12 percent for July and nearly 19 percent for August (Figures 28 and 29). The average visible reflectance was 7.98 for July and 10.81 for August (Table 7). Reflectance reached the highest values for the entire spectra between 635 and 695 nanometers (red wavelengths), peaking at 660

nanometers. The overall brightness of the curve was exhibited by increasing reflectance extending from green through red. In general, the average visible reflectance predominates in yellow (9.01, 12.9), orange (10.21, 14.73), and red energy ( 11.39, 17.42) for the July and August sampling, respectively. In addition to the primary spectral response, a second peak was evident at about 800 nanometers.

Chemically, the pH was nearly buffered with values of 7.1 for July and 6.4 for August. Secchi depth ranged from 0.75 feet for August to 1 foot in July, which correspond to the on- site visual assessments of very turbid conditions. There was significant variation in conductivity between dates. July had a conductivity of 3500 micromhos/cm, while August recorded nearly three (3) times greater, with a value of 9100 micromhos/cm. Analysis for metals in the surface water column revealed that manganese predominated with 15 milligrams per liter, while iron, aluminum, and zinc all had values of 5 milligrams per liter or less. The water color appeared bright orange.

#### Lake Augusta

Lake Augusta reflectance data provided similar spectral curves, with the only variation being that July was somewhat brighter (Figures 30-33). Maximum reflectance values were evident in a rather broad peak, ranging from about 3.25 to about 4.25 percent in intensity, with highest reflectance values in blue, green, and yellow wavelengths. The average



**AIR TEMPERATURE: 34 C**

**pH: 2.75**

**SECCHI DEPTH: >8 feet**

**IRON: <5 mg/l**

**ALUMINUM: 5 mg/l**

**WATER TEMPERATURE: 30 C**

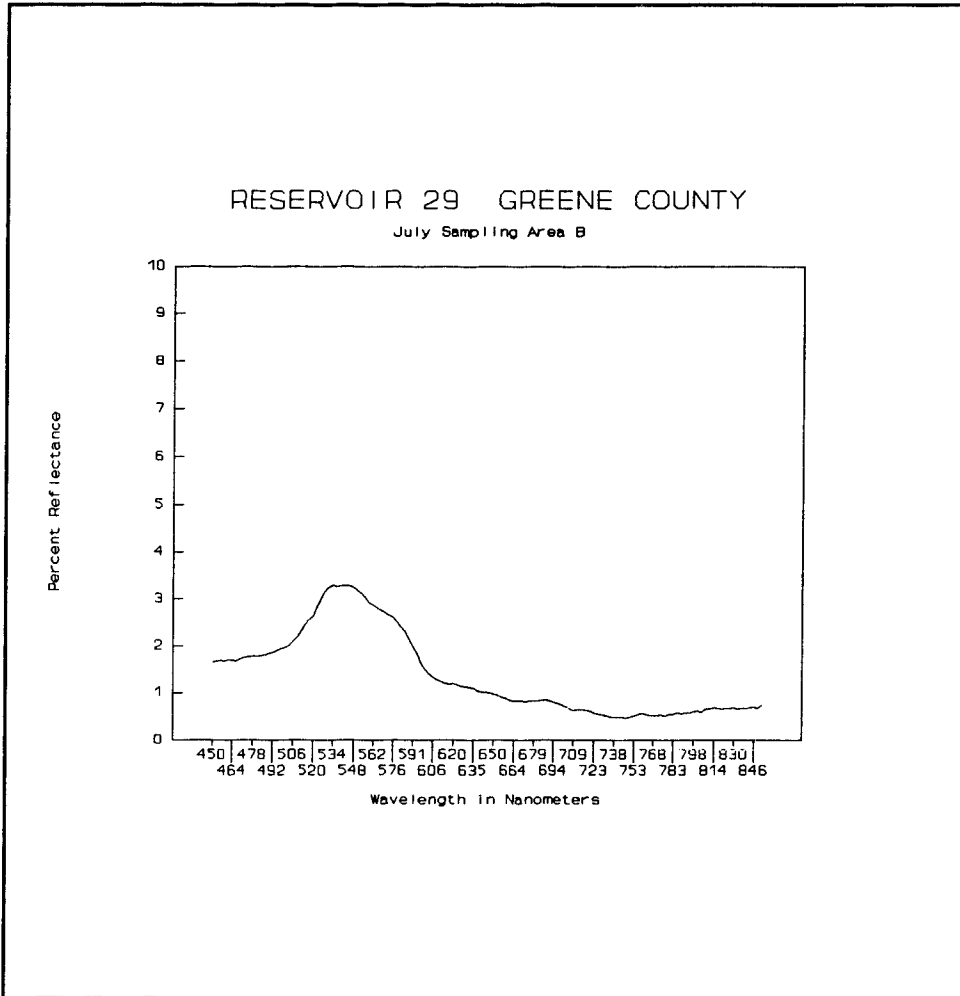
**SPECIFIC CONDUCTIVITY: 600  
(micromhos/cm)**

**APPARENT COLOR: clear/green**

**MANGANESE: 7 mg/l**

**ZINC: <5 mg/l**

**Figure 27. Spectral and Chemical Characteristics for the July Sampling of Reservoir 29 Area A.**



AIR TEMPERATURE: 34 C

pH: 2.68

SECCHI DEPTH: >8 feet

IRON: <5 mg/l

ALUMINUM: 5 mg/l

WATER TEMPERATURE: 29 C

SPECIFIC CONDUCTIVITY: 1000  
(micromhos/cm)

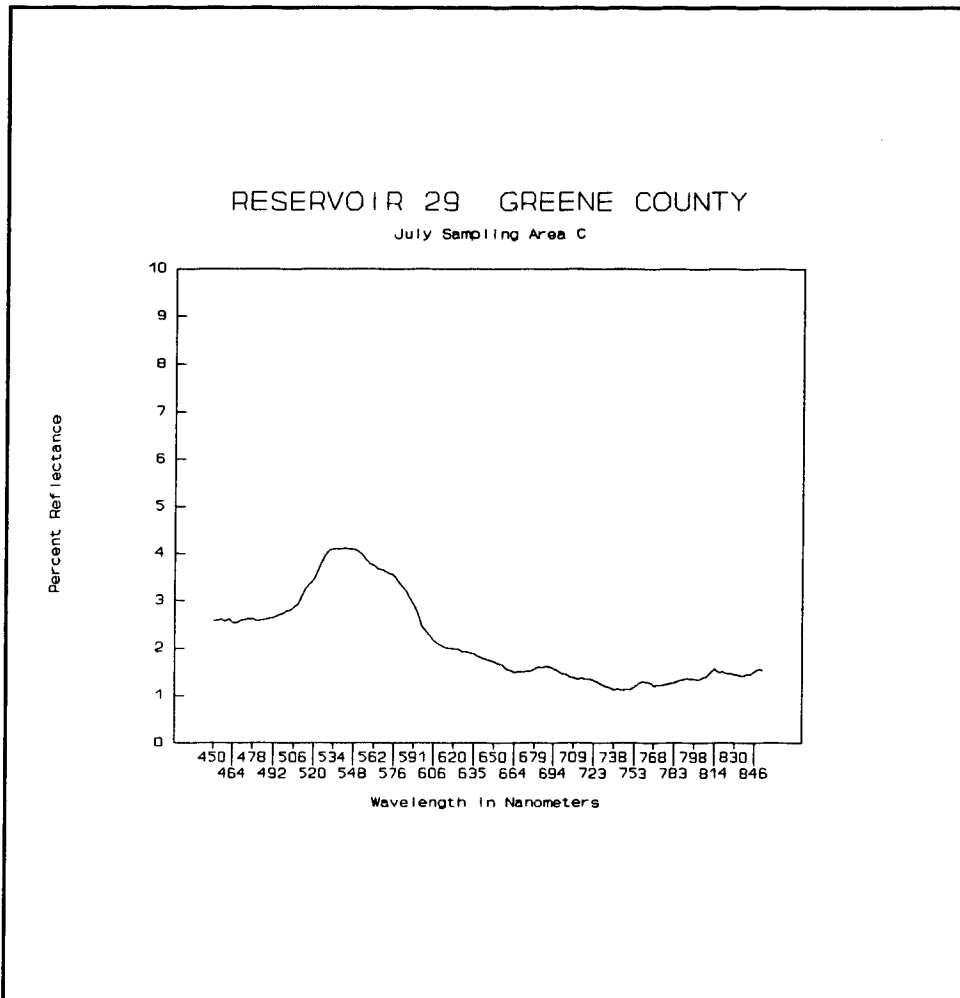
APPARENT COLOR: clear/green

MANGANESE: 7 mg/l

ZINC: <5 mg/l

Figure 28. Spectral and Chemical Characteristics for the July Sampling of Reservoir 29 Area B.





**AIR TEMPERATURE: 34 C**

**pH: 2.65**

**SECCHI DEPTH: >8 feet**

**IRON: <5 mg/l**

**ALUMINUM: 5 mg/l**

**WATER TEMPERATURE: 29 C**

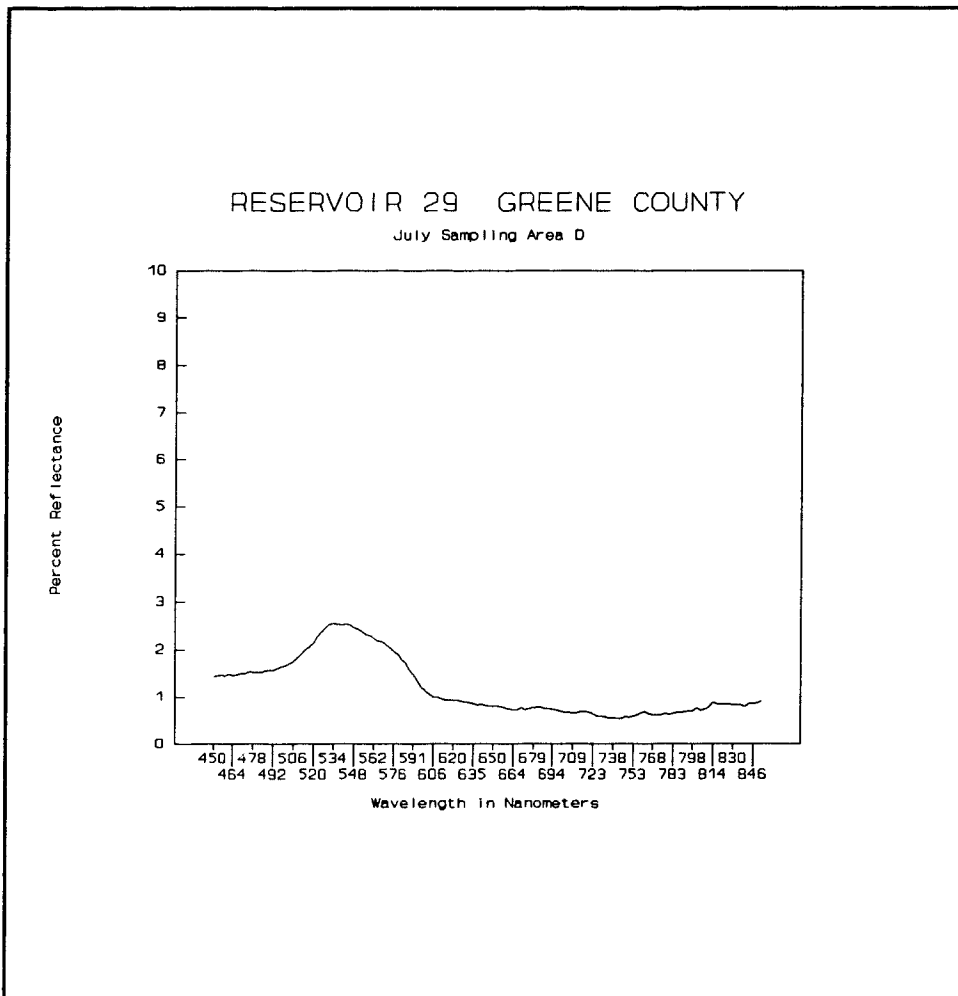
**SPECIFIC CONDUCTIVITY: 1200  
(micromhos/cm)**

**APPARENT COLOR: clear/green**

**MANGANESE: 7 mg/l**

**ZINC: <5 mg/l**

**Figure 29. Spectral and Chemical Characteristics for the July Sampling of Reservoir 29 Area C.**



AIR TEMPERATURE: 34 C

WATER TEMPERATURE: 29.5 C

pH: 2.70

SPECIFIC CONDUCTIVITY: 1350  
(micromhos/cm)

SECCHI DEPTH: >8 feet

APPARENT COLOR: clear/green

IRON: <5 mg/l

MANGANESE: 7 mg/l

ALUMINUM: 5 mg/l

ZINC: <5 mg/l

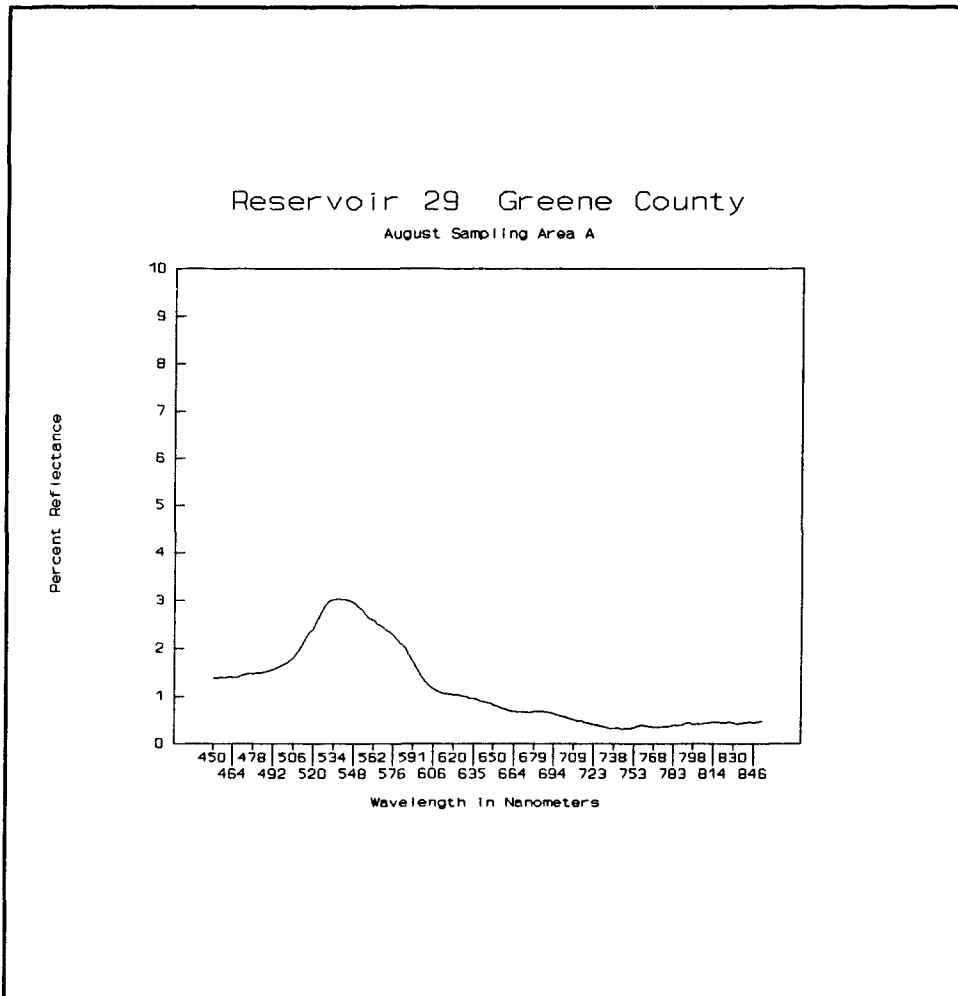
Figure 30. Spectral and Chemical Characteristics for the July Sampling of Reservoir 29 Area D.

Table 5. Statistical Summaries for Average Percent Reflectance of Visible Energy the Reservoir 29 Study Site.

RESERVOIR 29 JULY	STATISTICAL SUMMARIES FOR AVERAGE PERCENT REFLECTANCE OF VISIBLE ENERGY				
ENERGY	Blue	Green	Yellow	Orange	Red
AREA A SAMPLING	1.58	2.62	2.07	1.32	0.83
AVERAGE OF VISIBLE ENERGY FOR AREA A	1.67				
AREA B SAMPLING	1.76	2.79	2.26	1.43	0.93
AVERAGE OF VISIBLE ENERGY FOR AREA B	1.82				
AREA C SAMPLING	2.61	3.64	3.18	2.27	1.67
AVERAGE OF VISIBLE ENERGY FOR AREA C	2.63				
AREA D SAMPLING	1.52	2.20	1.69	1.09	0.79
AVERAGE VISIBLE ENERGY FOR AREA D	1.47				

AVERAGE PERCENT REFLECTANCE FOR MULTISPECTRAL SCANNER NOMINAL BANDWIDTH			
BANDWIDTH IN NANOMETERS	450-500	500-600	600-700
SAMPLING AREA A	1.58	2.46	0.94
SAMPLING AREA B	1.76	2.63	1.03
SAMPLING AREA C	2.61	3.49	1.79
SAMPLING AREA D	1.52	2.06	0.85

visible reflectance for July and August sample dates were as follows: Area A 2.64 and 2.75 percent, Area B 3.51 and 1.78 percent (Tables 5 and 6). The highest reflectance varied from approximately 3.0 percent to 4.25 percent with a peak from 530 to 550 nanometers in wavelength (green energy); overall green reflectance averaged from 2.78 to 4.11



**AIR TEMPERATURE: 30.5 C**

**pH: 3.00**

**SECCHI DEPTH: >8 feet**

**IRON: <5 mg/l**

**ALUMINUM: 5 mg/l**

**WATER TEMPERATURE: 29 C**

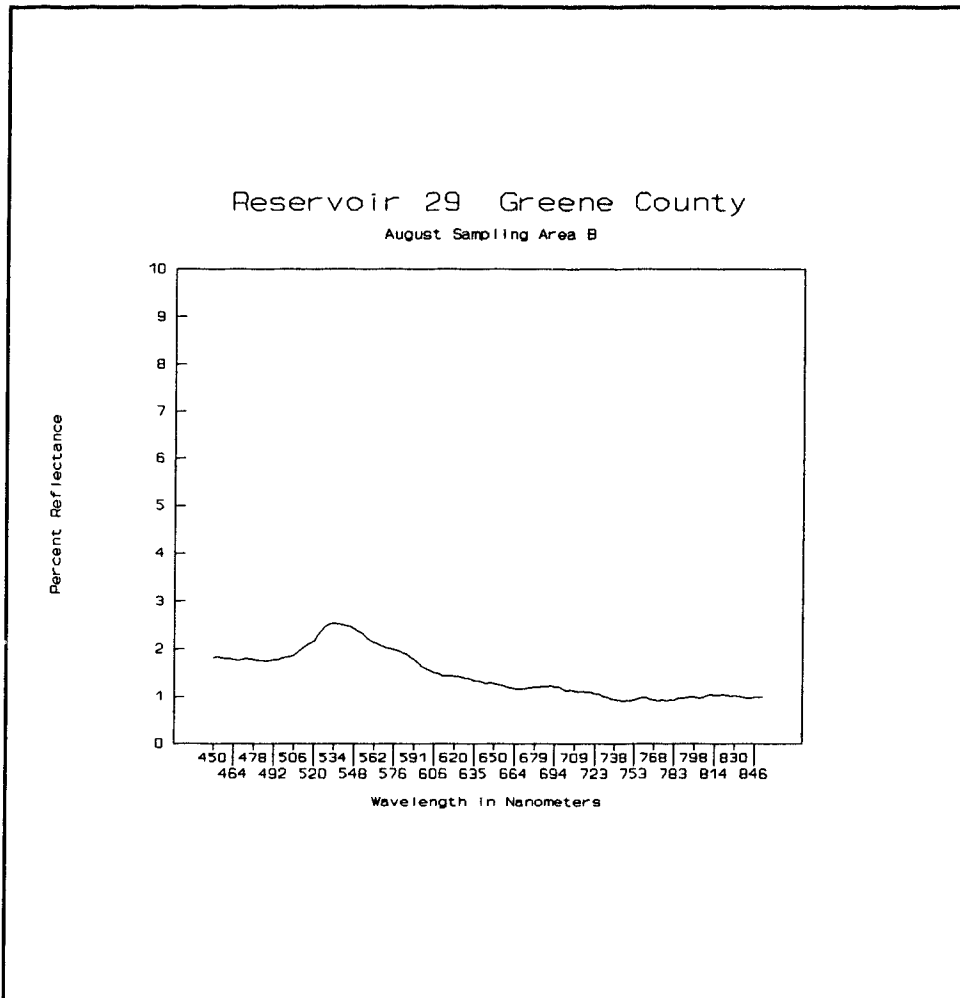
**SPECIFIC CONDUCTIVITY: 1400  
(micromhos/cm)**

**APPARENT COLOR: clear/green**

**MANGANESE: 7 mg/l**

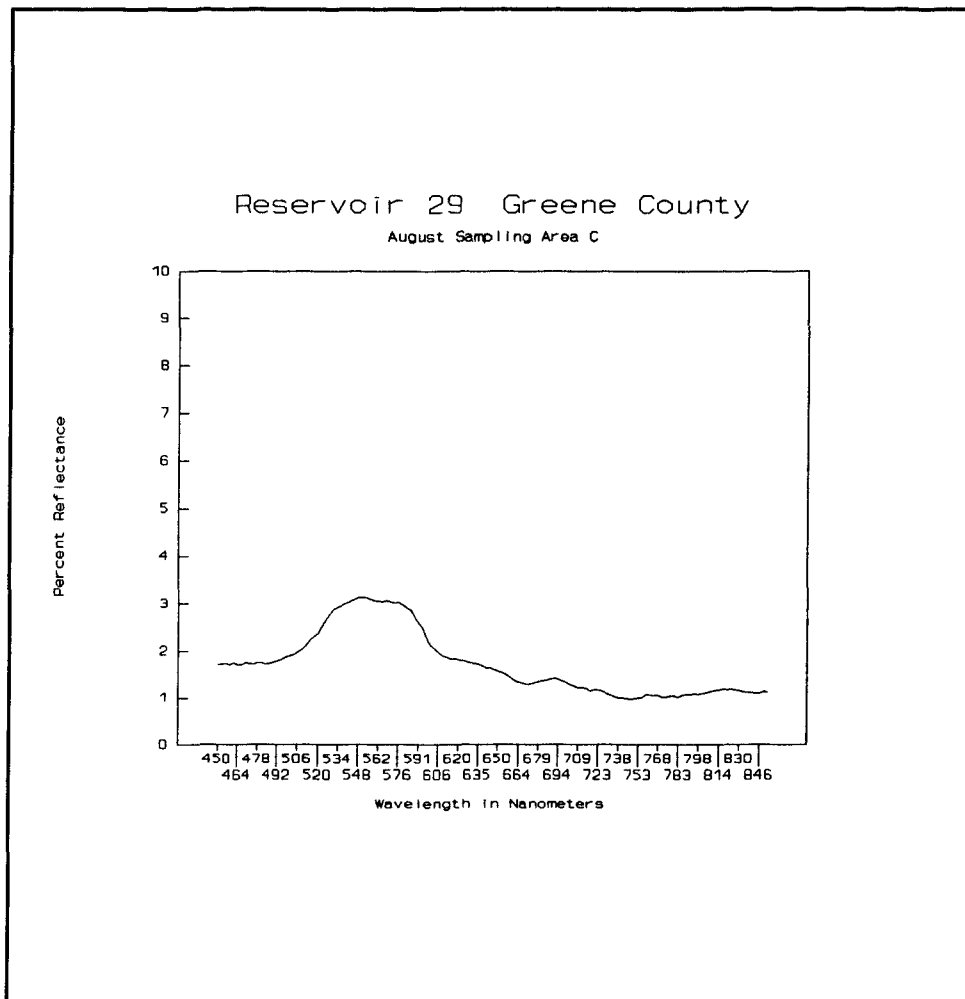
**ZINC: <5 mg/l**

**Figure 31. Spectral and Chemical Characteristics for the August Sampling of Reservoir 29 Area A.**



<b>AIR TEMPERATURE:</b> 30.5 C	<b>WATER TEMPERATURE:</b> 29 C
<b>pH:</b> 2.94	<b>SPECIFIC CONDUCTIVITY:</b> 1300 (micromhos\cm)
<b>SECCHI DEPTH:</b> >8 feet	<b>APPARENT COLOR:</b> clear/green
<b>IRON:</b> <5 mg/l	<b>MANGANESE:</b> 7 mg/l
<b>ALUMINUM:</b> 5 mg/l	<b>ZINC:</b> <5 mg/l

Figure 32. Spectral and Chemical Characteristics for the August Sampling of Reservoir 29 Area B.



**AIR TEMPERATURE: 30.5 C**

**pH: 3.04**

**SECCHI DEPTH: >8 feet**

**IRON: <5 mg/l**

**ALUMINUM: 5 mg/l**

**WATER TEMPERATURE: 30 C**

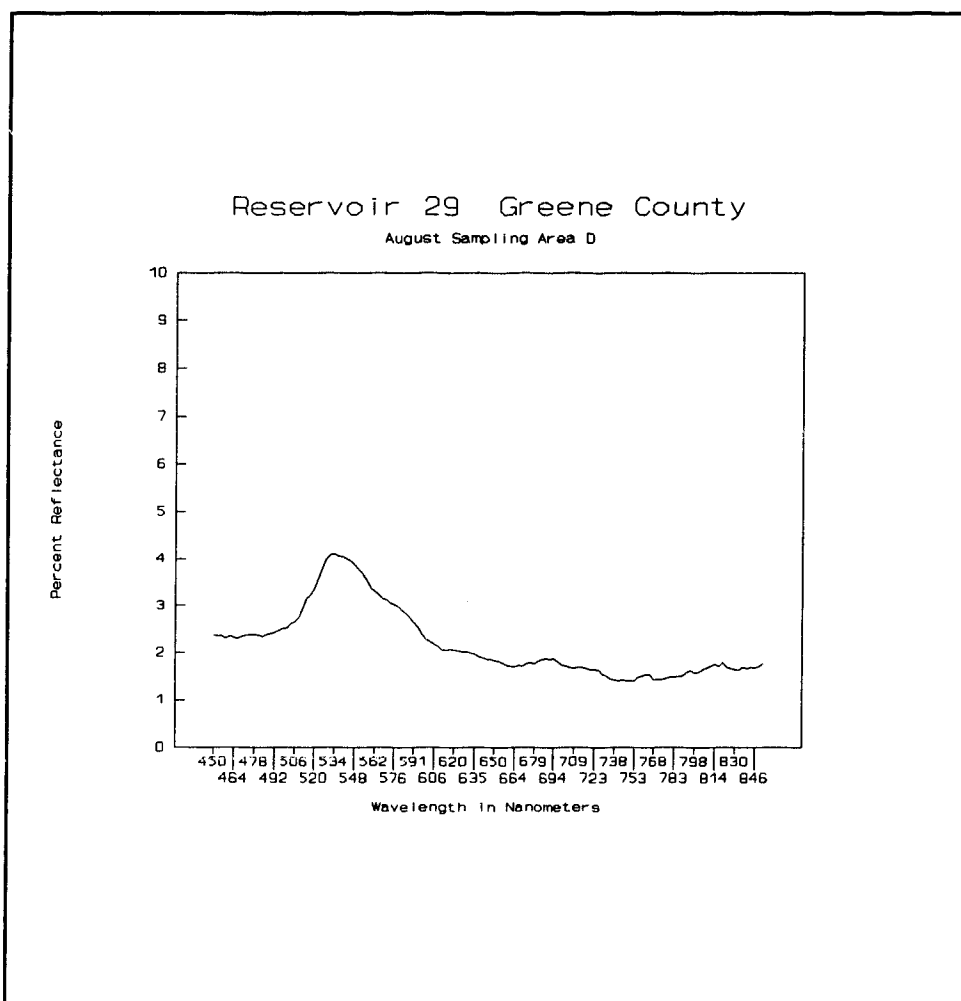
**SPECIFIC CONDUCTIVITY: 1200  
(micromhos/cm)**

**APPARENT COLOR: clear/green**

**MANGANESE: 7 mg/l**

**ZINC: <5 mg/l**

**Figure 33. Spectral and Chemical Characteristics for the August Sampling of Reservoir 29 Area C.**



AIR TEMPERATURE: 30.5 C

WATER TEMPERATURE: 29 C

pH: 2.91

SPECIFIC CONDUCTIVITY: 1200  
(micromhos/cm)

SECCHI DEPTH: >8 feet

APPARENT COLOR: clear/green

IRON: <5 mg/l

MANGANESE: 7 mg/l

ALUMINUM: 5 mg/l

ZINC: <5 mg/l

Figure 34. Spectral and Chemical Characteristics for the August Sampling of Reservoir 29 Area D.

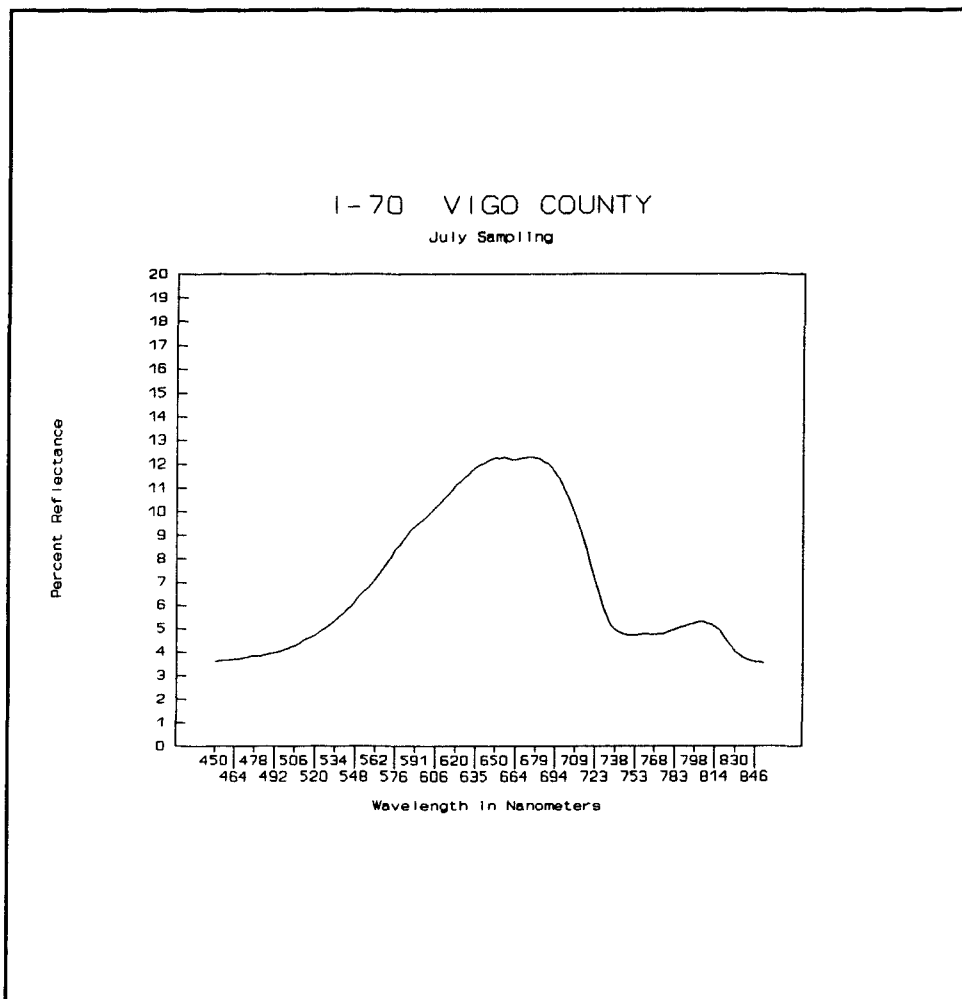
Table 6. Statistical Summaries for Average Percent Reflectance of Visible Energy for the Reservoir 29 Study Site.

RESERVOIR 29 AUGUST	STATISTICAL SUMMARIES FOR AVERAGE PERCENT REFLECTANCE OF VISIBLE ENERGY				
	Blue	Green	Yellow	Orange	Red
AREA A SAMPLING	1.48	2.52	1.98	1.25	0.79
AVERAGE OF VISIBLE ENERGY FOR AREA A	1.60				
AREA B SAMPLING	1.80	2.20	1.88	1.55	1.27
AVERAGE OF VISIBLE ENERGY FOR AREA B	1.74				
AREA C SAMPLING	1.76	2.74	2.81	2.07	1.51
AVERAGE OF VISIBLE ENERGY FOR AREA D	2.08				
AREA D SAMPLING	2.38	3.41	2.81	2.23	1.85
AVERAGE OF VISIBLE ENERGY FOR AREA D	2.55				

AVERAGE PERCENT REFLECTANCE FOR MULTISPECTRAL SCANNER NOMINAL BANDWIDTH			
BANDWIDTH IN NANOMETERS	450-500	500-600	600-700
AREA A SAMPLING	1.48	2.37	0.86
AREA B SAMPLING	1.80	2.12	1.31
AREA C SAMPLING	1.76	2.71	1.59
AREA D SAMPLING	2.38	3.25	1.91

percent. Blue reflectance at 450 to 500 nanometers averaged from 2.64 to 3.51 percent, and yellow reflectance ranged from 2.52 to 3.77 percent. The majority of spectral reflectance was green energy followed closely by yellow and blue. Reflected energy from approximately 600 nanometers to 850 was significantly reduced. A small, but noticeable, peak was





AIR TEMPERATURE: 30.5 C

WATER TEMPERATURE: 31 C

pH: 7.07

SPECIFIC CONDUCTIVITY: 3500  
(micromhos/cm)

SECCHI DEPTH: 1.0 foot

APPARENT COLOR: orange

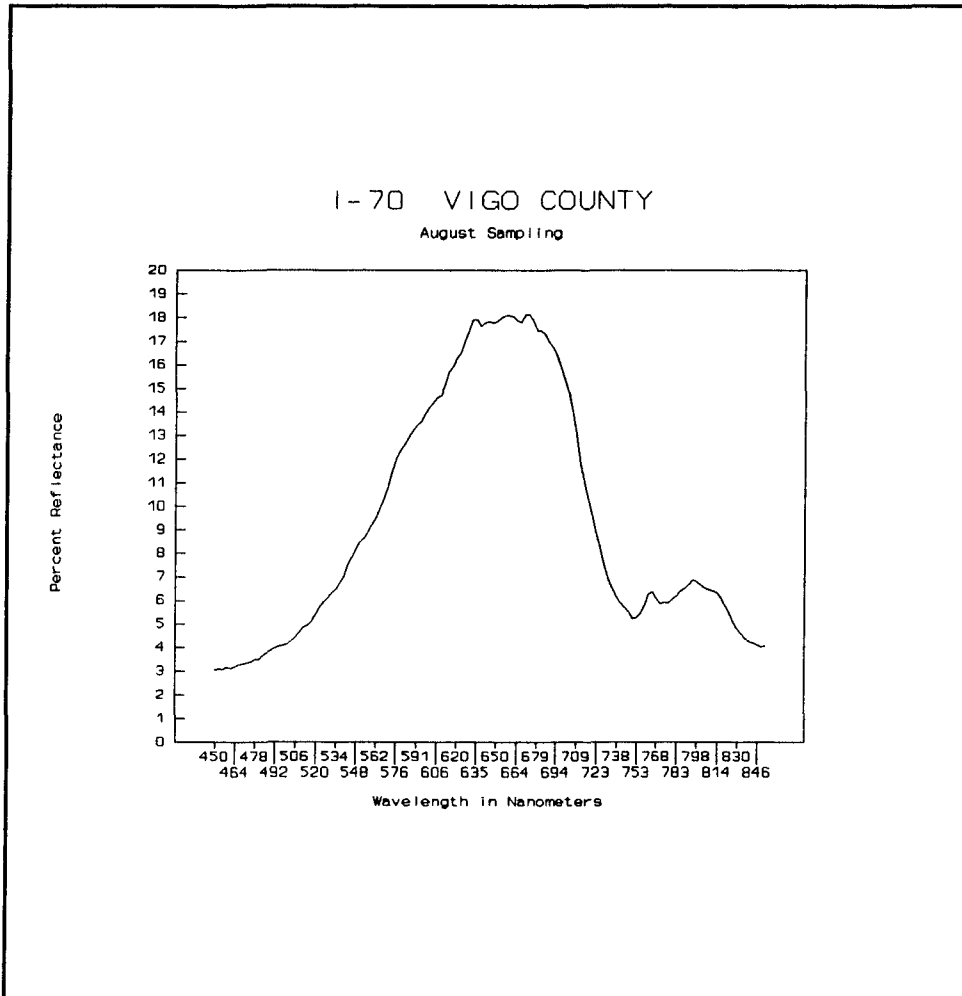
IRON: 5 mg/l

MANGANESE: 15 mg/l

ALUMINUM: <5 mg/l

ZINC: <5 mg/l

Figure 35. Spectral and Chemical Characteristics for the July Sampling of I-70.



**AIR TEMPERATURE: 30.5 C**

**pH: 6.40**

**SECCHI DEPTH: 0.75 feet**

**IRON: 5 mg/l**

**ALUMINUM: <5 mg/l**

**WATER TEMPERATURE: 29 C**

**SPECIFIC CONDUCTIVITY: 9100  
(micromhos/cm)**

**APPARENT COLOR: Orange**

**MANGANESE: 15 mg/l**

**ZINC: <5 mg/l**

**Figure 36. Spectral and Chemical Characteristics for the August Sampling of I-70.**

Table 7. Statistical Summaries for Average Percent Reflectance of Visible Energy for the I-70 Study Site.

I-70 ENERGY	STATISTICAL SUMMARIES FOR AVERAGE PERCENT REFLECTANCE OF VISIBLE ENERGY				
	Blue	Green	Yellow	Orange	Red
JULY SAMPLING	3.81	5.92	9.01	10.21	11.39
AVERAGE OF VISIBLE ENERGY FOR JULY	7.98				
AUGUST SAMPLING	3.50	7.48	12.90	14.73	17.42
AVERAGE VISIBLE ENERGY FOR AUGUST	10.81				

AVERAGE PERCENT REFLECTANCE FOR MULTISPECTRAL SCANNER NOMINAL BANDWIDTH			
BANDWIDTH IN NANOMETERS	450-500	500-600	600-700
JULY SAMPLING	3.81	6.58	11.62
AUGUST SAMPLING	3.50	8.63	16.90

evident at about 695 nanometers (red energy).

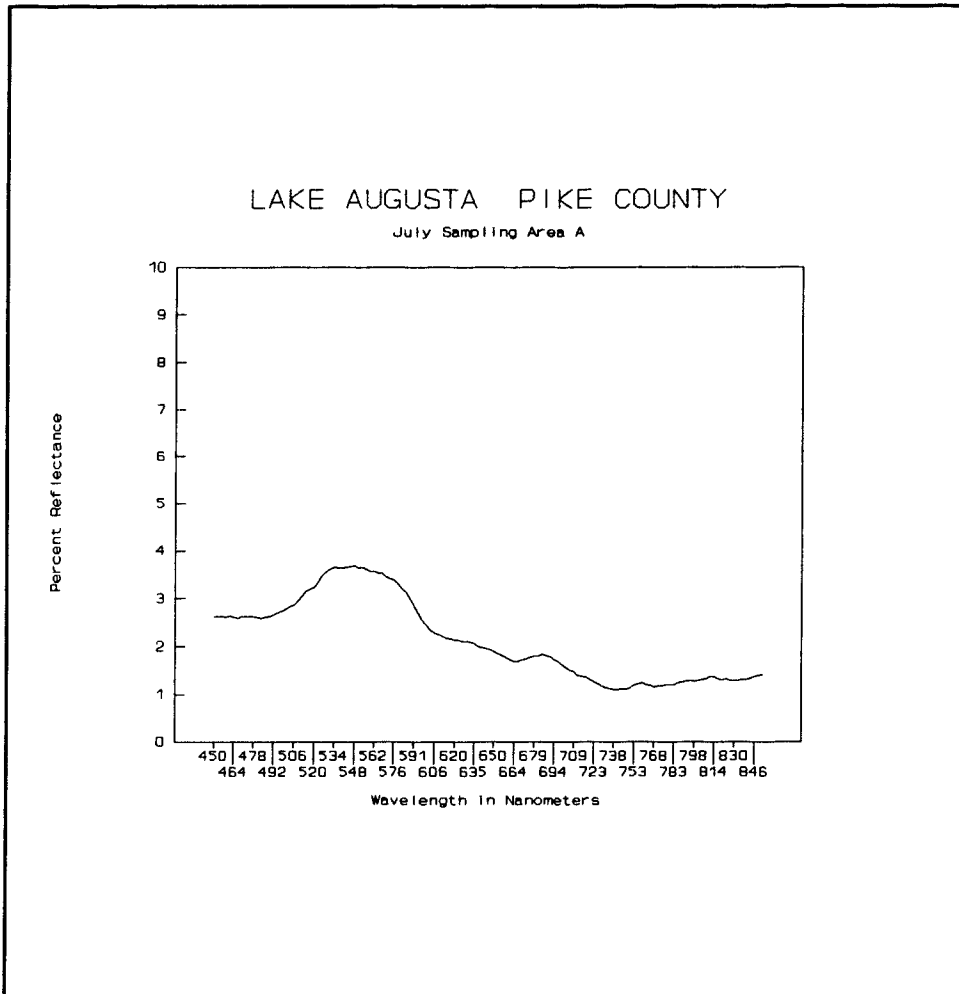
Chemically, Lake Augusta was acidic, with pH values ranging from 2.93 to 3.20. Optically, the water appeared relatively clear with a blue/green cast. Conductivity was constant throughout the sampling at 3,000 micromhos/cm providing evidence of dissolved constituents in the water column. Secchi depths, even with notable conductivity, were greater than eight feet (the entire length of the leader) for all measurements. Of the metals measured, manganese was predominant with values ranging from 25 to 28 milligrams per liter, followed by aluminum with 9 to 10 milligrams per

liter, and in all samples iron and zinc were less than 5 milligrams per liter.

#### State Fishing Area

Both sample dates exhibited similar spectral characteristics (Figures 34 and 35). However, in the sample for July the reflectance was slightly higher for blue energy as compared to the sample for August, whereas August reflectance was higher in the green, yellow, orange and red wavelengths. On average, visible reflectance for July was 3.12 percent and for August 3.47 percent. In both spectra maximum reflectance occurred from 550 to 575 nanometers (green energy). Reflectance at peak wavelength was about 4.25 percent in July, while in August a reflectance peak of about 5.50 percent was observed. A second, but much smaller, peak was apparent at about 695 nanometers (red energy). As was the case with other spectra, this weak reflectance peak at 695 was more evident with brighter reflectance spectra (in this case, August).

Chemically, the pH was slightly alkaline, with values of 9.10 and 9.16. Specific conductivity was relatively low from 400 to 450 micromhos/cm. Secchi depths were comparatively moderate, measuring an average of 3.0 feet on both occasions, indicating that the lake's turbidity was probably not associated with chemical solutes but with sediments partitioned to agricultural run off. In all cases, the results of metal analysis indicate concentrations less than 5 milligrams per liter. Optically, this waterbody



**AIR TEMPERATURE: 34 C**

**pH: 3.05**

**SECCHI DEPTH: >8 feet**

**IRON: <5 mg/l**

**ALUMINUM: 9 mg/l**

**WATER TEMPERATURE: 29 C**

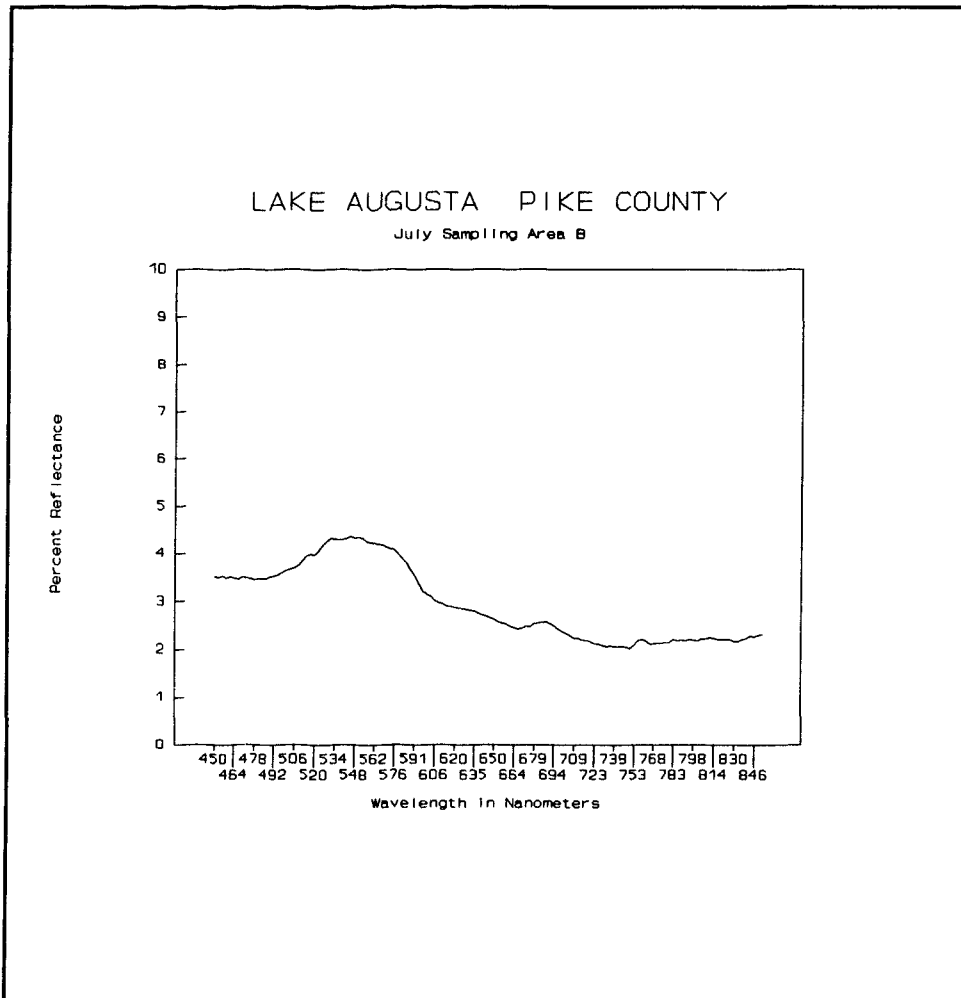
**SPECIFIC CONDUCTIVITY: 3000  
(micromhos/cm)**

**APPARENT COLOR: clear**

**MANGANESE: 25 mg/l**

**ZINC: <5 mg/l**

**Figure 37. Spectral and Chemical Characteristics for the July Sampling of Lake Augusta Area A.**



AIR TEMPERATURE: 34 C

WATER TEMPERATURE: 29 C

pH: 3.2

SPECIFIC CONDUCTIVITY: 3000  
(micromhos/cm)

SECCHI DEPTH: >8 feet

APPARENT COLOR: clear

IRON: <5 mg/l

MANGANESE: 25 mg/l

ALUMINUM: 10 mg/l

ZINC: <5 mg/l

Figure 38. Spectral and Chemical Characteristics for the July Sampling of Lake Augusta Area B.

Table 8. Statistical Summaries for Average Percent Reflectance of Visible Energy for the Lake Augusta Study Site.

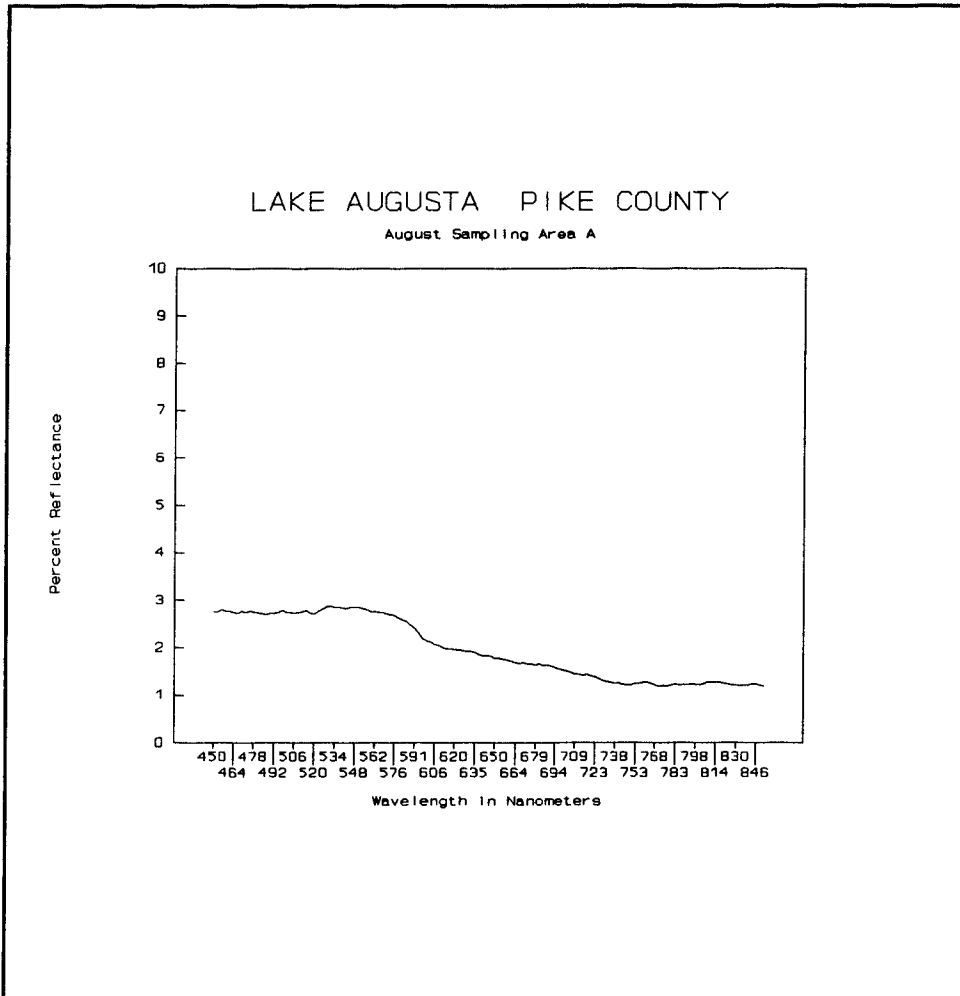
LAKE AUGUSTA JULY	STATISTICAL SUMMARIES FOR AVERAGE PERCENT REFLECTANCE OF VISIBLE ENERGY				
	Blue	Green	Yellow	Orange	Red
ENERGY					
SAMPLING AREA A	2.64	3.40	3.11	2.37	1.86
AVERAGE OF VISIBLE ENERGY FOR AREA A	2.63				
AREA B SAMPLING	3.51	4.11	3.77	3.09	2.61
AVERAGE VISIBLE ENERGY FOR AREA B	3.38				

AVERAGE PERCENT REFLECTANCE FOR MULTISPECTRAL SCANNER NOMINAL BANDWIDTH			
BANDWIDTH IN NANOMETERS	450-500	500-600	600-700
AREA A SAMPLING	2.64	3.29	1.94
AREA B SAMPLING	3.51	4.00	2.68

was an apparent blue-green color.

#### Spectral Classification

Using the lake classification method established by Vertucci and Likens (1989), 4 distinct types or classes of lakes are identified (Figures 36, 37, 38, and 39). The peak reflectance from the coal mine lakes sampled in this research varies across the visible regions of the spectrum. The lake classification was based on wavelength differences in peak reflectance and overall brightness across the visible spectrum. This classification was independent of visual observations of water color and water quality characteristics.



**AIR TEMPERATURE: 31.5 C**

**WATER TEMPERATURE: 28 C**

**pH: 2.93**

**SPECIFIC CONDUCTIVITY: 3000  
(micromhos/cm)**

**SECCHI DEPTH: >8 feet**

**APPARENT COLOR: clear**

**IRON: <5 mg/l**

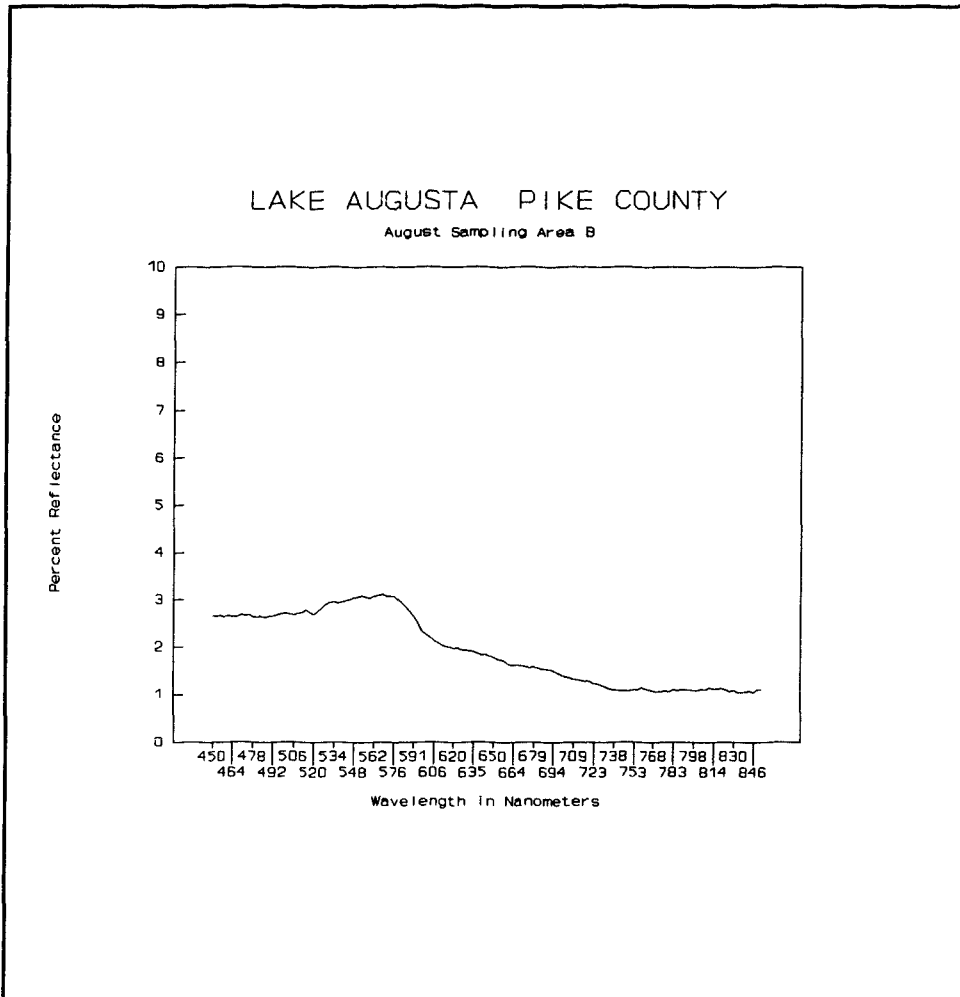
**MANGANESE: 28 mg/l**

**ALUMINUM: 9 mg/l**

**ZINC: <5 mg/l**

**Figure 39. Spectral and Chemical Characteristics for the August Sampling of Lake Augusta Area A.**





**AIR TEMPERATURE: 31.5 C**

**pH: 2.94**

**SECCHI DEPTH: >8 feet**

**IRON: <5 mg/l**

**ALUMINUM: 10 mg/l**

**WATER TEMPERATURE: 28 C**

**SPECIFIC CONDUCTIVITY: 3000  
(micromhos/cm)**

**APPARENT COLOR: clear**

**MANGANESE: 28 mg/l**

**ZINC: <5 mg/l**

**Figure 40. Spectral and Chemical Characteristics for the August Sampling of Lake Augusta Area B.**

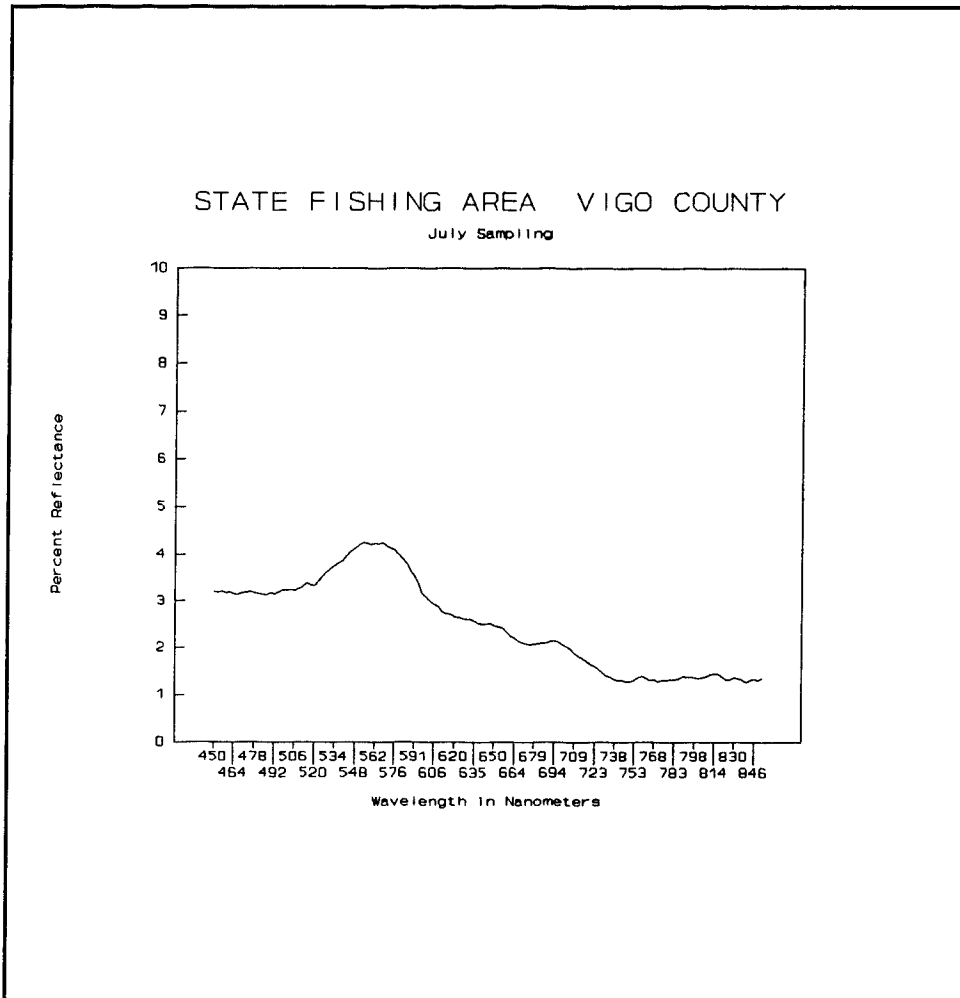
Table 9. Statistical Summaries for Average Percent Reflectance of Visible Energy for the Lake Augusta Study Site.

LAKE AUGUSTA AUGUST	STATISTICAL SUMMARIES FOR AVERAGE PERCENT REFLECTANCE OF VISIBLE ENERGY				
ENERGY	Blue	Green	Yellow	Orange	Red
SAMPLING AREA A	2.75	2.78	2.52	2.11	1.74
AVERAGE OF VISIBLE ENERGY FOR AREA A	2.36				
SAMPLING AREA B	2.66	2.92	2.84	2.20	1.70
AVERAGE VISIBLE ENERGY FOR AREA B	2.39				

AVERAGE PERCENT REFLECTANCE FOR MULTISPECTRAL SCANNER NOMINAL BANDWIDTH			
BANDWIDTH IN NANOMETERS	450-500	500-600	600-700
SAMPLING AREA A	2.75	2.70	1.81
SAMPLING AREA B	1.78	2.86	1.78

Type 1 lakes (Figure 36) have maximum reflectance intensities below 2 percent and reflectance peaks at about 650 (red energy) and 700 (red/near infrared energy) nanometers. This class of lakes demonstrated the lowest reflectance of all of the lakes in the study, and may be generally classified as absorbers of energy. Green Valley and Peavy Cemetery spectra for both dates compose the Type 1 lake class.

Type 2 lake (Figure 37) spectra exhibited the brightest maximum reflectance with intensities up to 18 percent.



AIR TEMPERATURE: 30.5 C

pH: 9.16

SECCHI DEPTH: 3.00 feet

IRON: <5 mg/l

ALUMINUM: <5 mg/l

WATER TEMPERATURE: 30 C

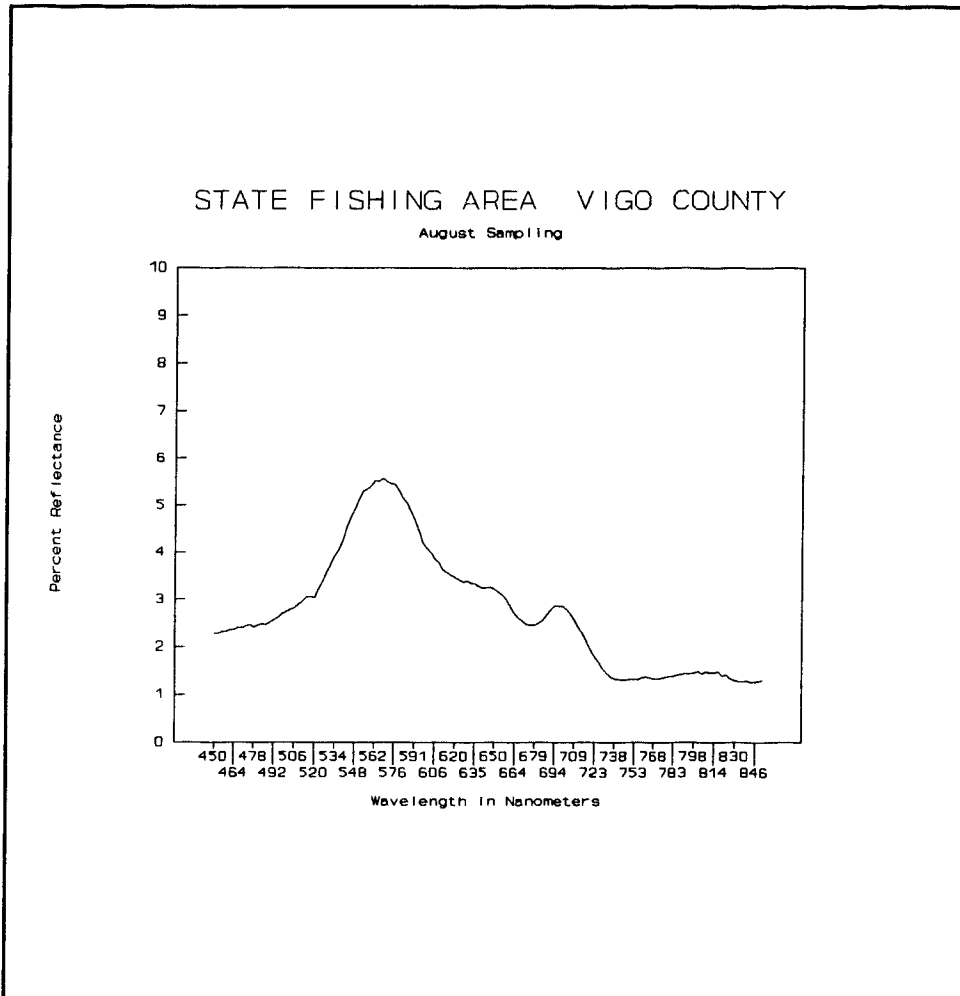
SPECIFIC CONDUCTIVITY: 450  
(micromhos/cm)

APPARENT COLOR: blue/green

MANGANESE: <5 mg/l

ZINC: <5 mg/l

Figure 41. Spectral and Chemical Characteristics for the July Sampling of State Fishing Area.



AIR TEMPERATURE: 30.5 C

pH: 9.10

SECCHI DEPTH: 3.00 feet

IRON: <5 mg/l

ALUMINUM: <5 mg/l

WATER TEMPERATURE: 30 C

SPECIFIC CONDUCTIVITY: 400  
(micromhos/cm)

APPARENT COLOR: blue/green

MANGANESE: <5 mg/l

ZINC: <5 mg/l

Figure 42. Spectral and Chemical Characteristics for the August Sampling of State Fishing Area.

Table 10. Statistical Summaries for Average Percent Reflectance of Visible Energy for the State Fishing Area.

STATE FISHING AREA	STATISTICAL SUMMARIES FOR AVERAGE PERCENT REFLECTANCE OF VISIBLE ENERGY				
	Blue	Green	Yellow	Orange	Red
ENERGY					
JULY SAMPLING	3.18	3.80	3.79	2.99	2.33
AVERAGE OF VISIBLE ENERGY FOR JULY	3.12				
AUGUST SAMPLING	2.46	4.25	5.02	3.93	2.96
AVERAGE VISIBLE ENERGY FOR AUGUST	3.47				

AVERAGE PERCENT REFLECTANCE FOR MULTISPECTRAL SCANNER NOMINAL BANDWIDTH			
BANDWIDTH IN NANOMETERS	450-500	500-600	600-700
JULY SAMPLING	3.18	3.75	2.44
AUGUST SAMPLING	2.46	4.33	3.12

Type 2 spectra had maximum reflectance at 650 nanometers (red energy); however, the curves are broad-based, with reflectance rising sharply from blue energy through near infrared, with the majority of reflectance in the yellow, orange, and red regions of the spectrum and falling rapidly in the near infrared. A second response, with a reflectance intensity of 5 percent, was evident at about 805 nanometers. Both sampling of I-70 fall into the Type 2 class.

Type 3 lakes (Figure 38) had a maximum reflectance of 5.5 percent from about 550 to 575 nanometers (green energy). Reflectance increased sharply at about 520 nanometers, peaking at about 565 nanometers and declining in a near

linear fashion through the red energy. A second peak at about 695 nanometers was evident with maximum reflectance of nearly 3 percent. Both sample dates of State Fishing Area compose the Type 3 class.

Type 4 lakes (Figure 39) exhibited maximum reflectance intensity ranging from just over 3 percent to just over 8 percent. Reflectance reached maximum intensities from 535 to 545 nanometers in wavelength (green energy). In all cases, blue energy was reflected at about one half of the maximum reflectance of green energy. After peaking at about 540 nanometers, the reflectance dropped in a linear fashion with wavelength reaching a low at 664 nanometers. A second small reflectance peak is evident at 694 nanometers. All spectra from Lake Augusta, Reservoir 29, and Big Creek compose Type 4 lakes.

#### Chemical Classification

Elder (1988) and Moran and Wentz (1974) recognized the influence of pH on chemical solubility and partitioning. Their work on metal speciation and transport in mine environments revealed pH as a primary perturbation to influence metal release in aquatic systems. In confirmation, Renn (1988) reported that iron was found suspended in solution for pH values greater than 6 and dissolved in more acidic pH waters. Moore's (1980) analysis of colored water revealed that colored or pigmented water absorbed visible energy. These studies provide support for the chemical and spectral classifications used in this study. This study classes

lakes according to pH, a relative measure of the activity of the hydrogen ion, and to Secchi depth, a measure of the depth to which light will penetrate in an aquatic system as measured by the visibility of a white Secchi disk (Tables 11 and 12). pH classes were developed by graphing pH along a continuum from 0 to 10 in which all values could be found. The study sites were then grouped (classed) according to similar pH values resulting in four classes. Similar methods were employed to class Secchi depth criteria. Depth were plotted along 0 continuum ranging from 0 to 8 feet, similar grouping were recognized and classed according resulting in four classes. The variability in percent reflectance in the waterbodies as compared to pure water was caused either by the constituents of the water, in this case the chemical solutes, or by sediments. Four classes of lakes were recognized in both chemical approaches to classification.

The classification based on pH and Secchi depth coincides with the classification based on spectra. Table 11 demonstrates relationships between study site, pH, water color of the lakes sampled, and the class of spectra derived from spectral classification, while Table 12 shows the relationship of Secchi depth to study site, water color, and the spectrally based classification. In each case the classification of lakes into types provided similar results to the classification based on reflectance alone. Generalization is a vital aspect of the inductive approach

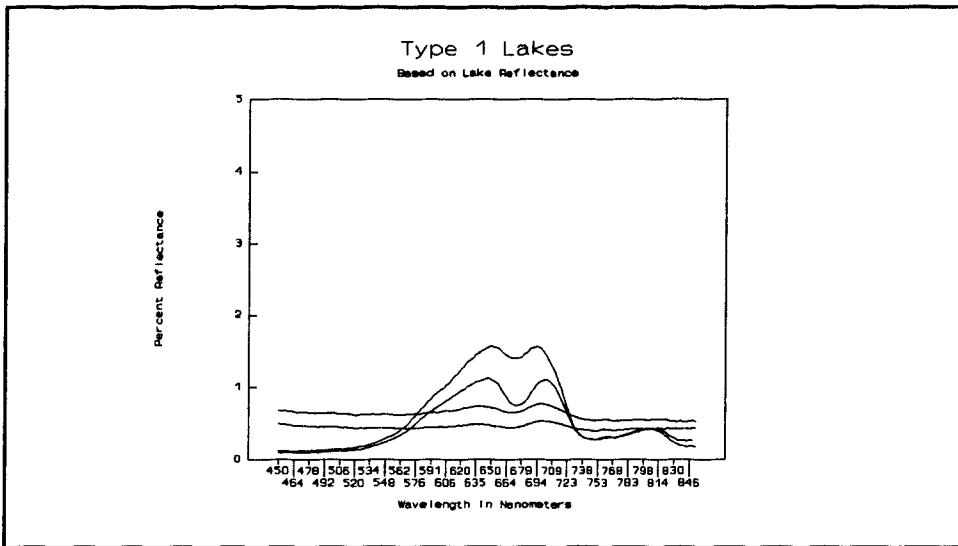


Figure 43. Typology of Coal Mine Lakes based on Lake Reflectance: Type 1 Lakes.

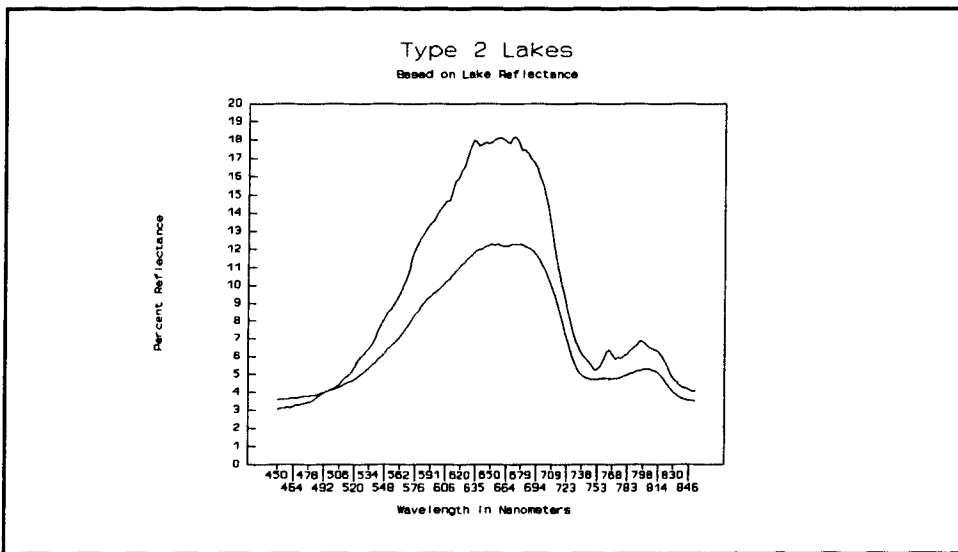


Figure 44. Typology of Coal Mine Lakes Based on Lake Reflectance: Type 2 Lakes.



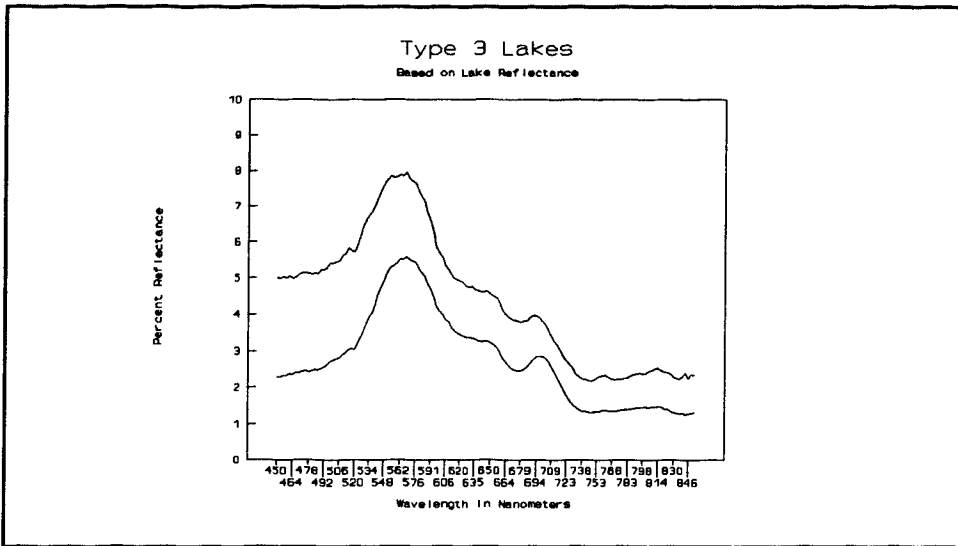


Figure 45. Typology of Coal Mine Lakes Based on Lake Reflectance: Type 3 Lakes.

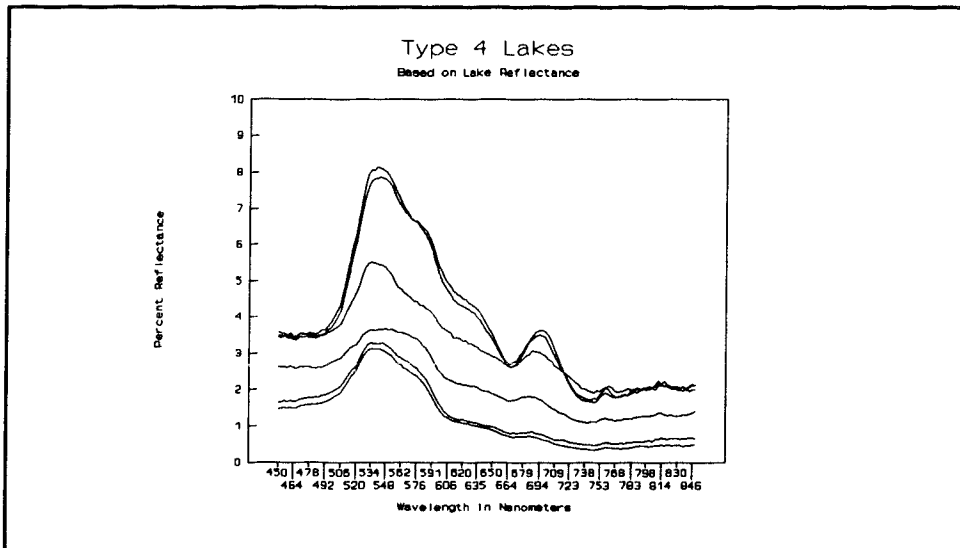


Figure 46. Typology of Coal Mine Lakes Based on Lake Reflectance: Type 4 Lakes.

to science (Curran, 1985). Generalizations regarding the nature of the developed spectral curves, the chemistry of the strip mined lakes and the interaction between these variables are important to scientists wishing to use remote sensing in the analysis of surface water. The following discussion presents generalizations regarding both the spectra and the water chemistry, but with primary emphasis on chemical/spectral interactions and responses.

Scatterplots were developed in an effort to aid visualization and assist in the generalization of the relationships regarding both the chemical and spectral data. All combinations of the chemical and spectral variables were examined. The individual scatterplots on which the discussion is based are recorded in Appendixes A, B, and C.

#### Chemical Variables

The relationships between pH and metals concentrations, conductivity, and Secchi depths, and conductivity and Secchi depth in feet are inverse (Figures 47-50): the lower the pH values, the greater the metals; the lower the pH the higher the conductivity, and the lower the Secchi depth the, greater the conductivity. In general, the overall relationship respective to these variables is that lower pH water results in increases of the metals in solution, thus increasing conductivity. Increase in conductivity implies an increase in the solute load in the aquatic system, thus reducing the ability of light to penetrate the water column,

which results in reduced Secchi depths. Further, the greater the concentrations of solutes (metals) in the water column, the greater the absorption of light energy; thus; reduced depth to extinction of light results. The only apparent positive relationship is between metals in solution and conductivity. Thus, as metals in solution increase, so does the conductivity.

When analyzing metal concentrations versus Secchi depth, a more complicated relationship is exhibited. The relationship between these variables seems to be associated to the potential loadings of the metals in the water column. Extremely low Secchi values, 1.0 or less, correspond to limited metals in mg/l, while for the Secchi range of about 1.5 to 3.0 feet metals are extremely high, and when Secchi depths are greater than 3 feet, metals once again are negligible. Theoretically, this may have basis in the partitioning of the metals, which is frequently associated with site characteristics other than individual chemical relationships, i.e., suspended versus dissolved metals. Low Secchi values, one or less, are probably associated with sediments, Secchi values from 1.5 to 3.0 feet are a result of dissolved metals in the water column, and Secchi values greater than 3 represent a water column relatively free of metals and sediments.

#### Visible Energy and Chemical Variables

The reflectance of visible wavelengths, specifically blue, green, yellow, orange, and red, and an overall average

Table 11. Grouping of Lakes Based on pH.

pH	STUDY SITE	WATER COLOR	CLASS OF SPECTRA
10			
9	STATE FISHING AREA	BLUE / GREEN	TYPE 4
8			
7			
6	I-70	ORANGE	TYPE 2
5			
4			
3	LAKE AUGUSTA BIG CREEK RESERVOIR 29	CLEAR	TYPE 3
2			
1	GREEN VALLEY PEAVY- CEMETERY	RED	TYPE 1
0			

of the these components plus reflectance grouped from 450-500 nm, 500-600 nm, and 600-700 nm were plotted against conductivity, metals, Secchi depth, and pH in an effort to

Table 12. Grouping of Lakes Based on Secchi Depth.

SECCHI DEPTH	STUDY SITE	WATER COLOR	CLASS OF SPECTRA
8	LAKE AUGUSTA RESERVOIR 29	CLEAR	TYPE 4
7			
6	BIG CREEK	GREEN	TYPE 4
5			
4			
3	STATE FISH	BLUE / GREEN	TYPE 3
2	PEAVY CEMETERY	RED	TYPE 1
1	GREEN VALLEY	RED	TYPE 1
0	I-70	ORANGE	TYPE 2

describe the relationships of these energy reflectance with the chemical variables. In each case there was a negative or inverse relationship between reflectance and conductivity (Appendix A): reflectance increases as conductivity decreases. In describing metals compared to reflectance, there was a decrease in reflectance as dissolved metals

increase (Appendix B). This relationship was most prevalent in the shorter visible wavelengths of blue and green. The scatterplots comparing percent reflectance with Secchi depth show a direct relationship (Appendix C). Although all visible reflectance exhibited this tendency, the trend was less evident at longer wavelengths (orange and red energy). Scatterplots constructed to characterize pH versus percent reflectance exhibited random plots. These scatterplots seem to indicate that pH influenced conductivity, metals, and Secchi depth, all of which have relationships with visible reflectance. However, pH by itself revealed no such trends or relationships, and the plots appear random.

#### Spectral/Chemical Interaction

Based on appearance, I-70, Green Valley, and Peavy waterbodies appeared to be the most contaminated of the sites sampled, as they exhibit orange or red coloration. Chemical investigation shows clearly that Peavy and Green Valley are active chemically and dominated by metals in a dissolved state and free acid. This assertion is based on pH measurements of 1.96 and 1.67 for Green Valley and 2.18 and 1.45 for Peavy Cemetery, and toxic level metal concentrations: iron exceeds 400 Mg/l, manganese ranges from 7 to 40 Mg/l, and aluminum ranges from 100 to 120 Mg/l. Further, the average percent reflectance of visible spectra for both waterbodies is less than 1 percent.

Although I-70 exhibits a bright orange color, it has a buffered pH and contains relatively small quantities of

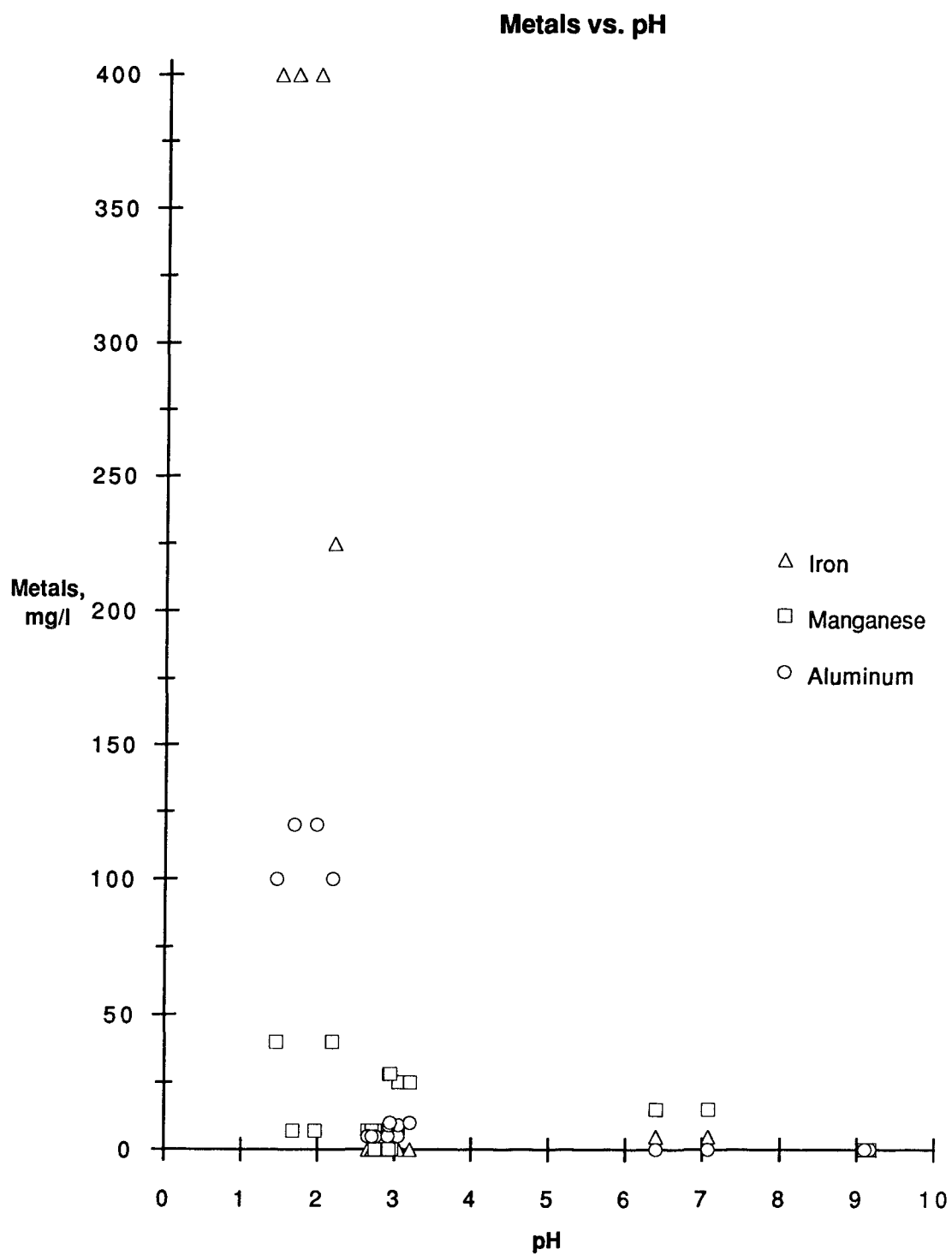


Figure 47. Values of pH Plotted Against mg/l of Metals in the Water Column.

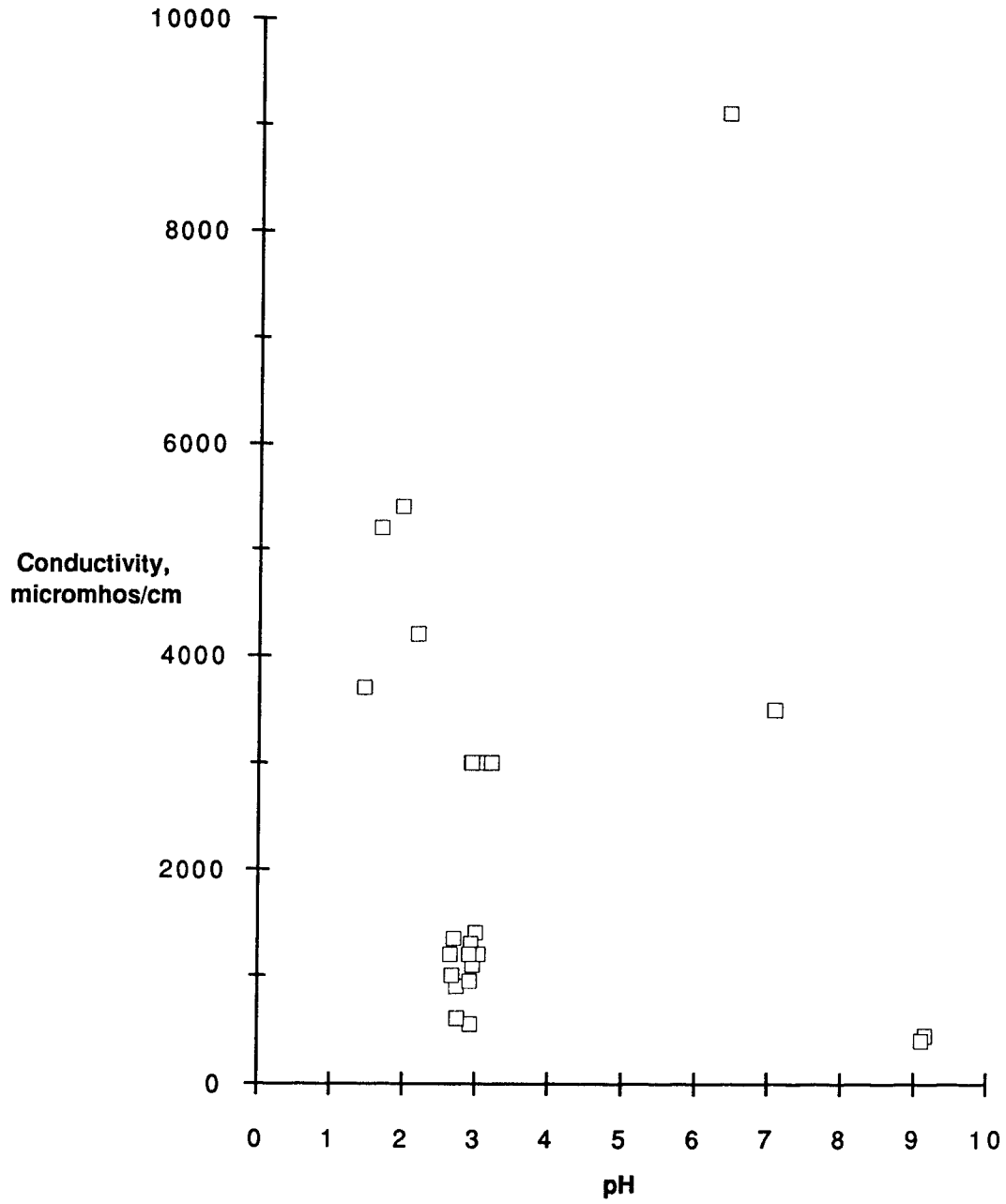
**Conductivity vs. pH**

Figure 48. Values of pH Plotted Against Conductivity in Micromhos/cm.



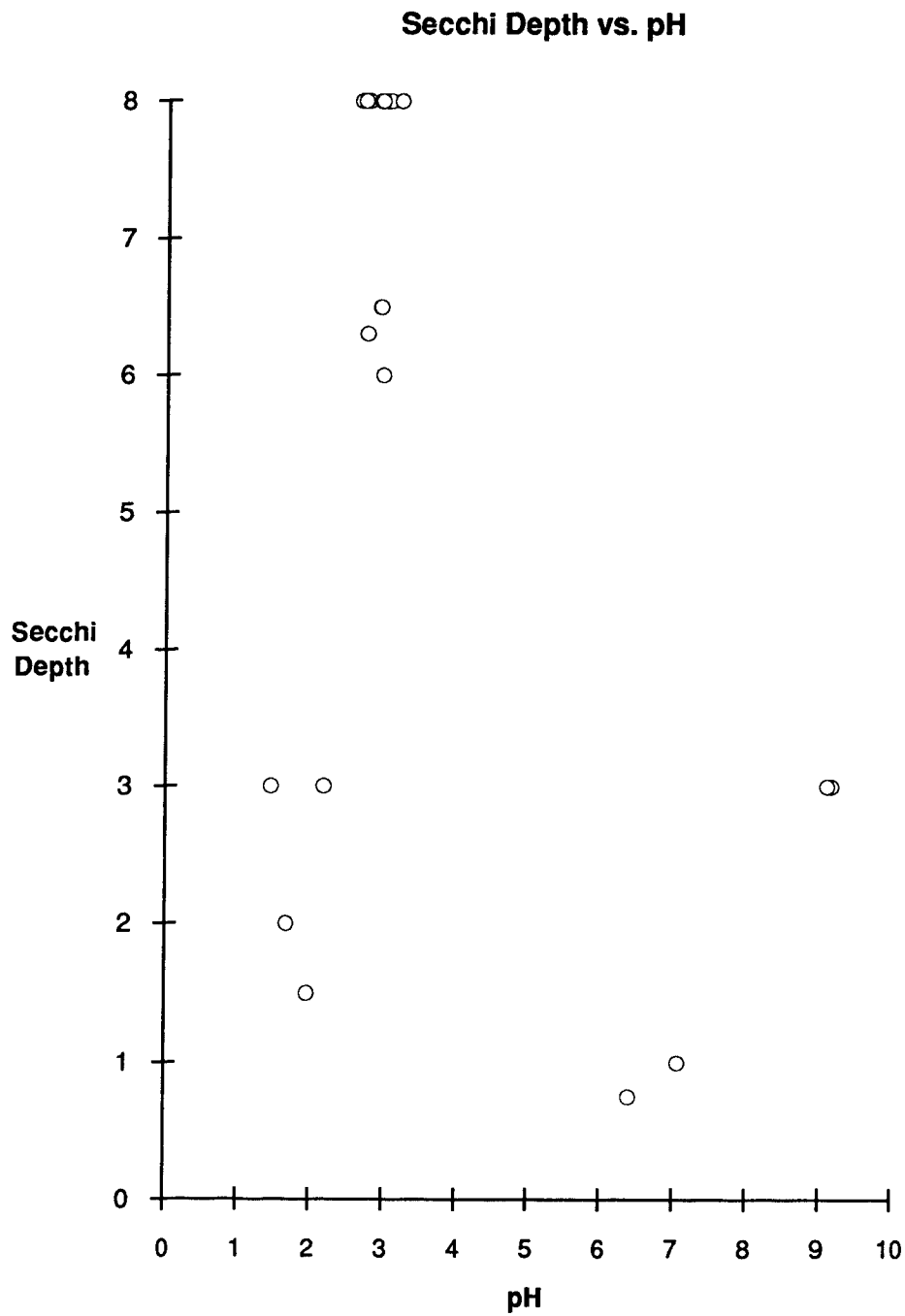


Figure 49. Values of pH Plotted Against Secchi Depth Measurement in Feet.

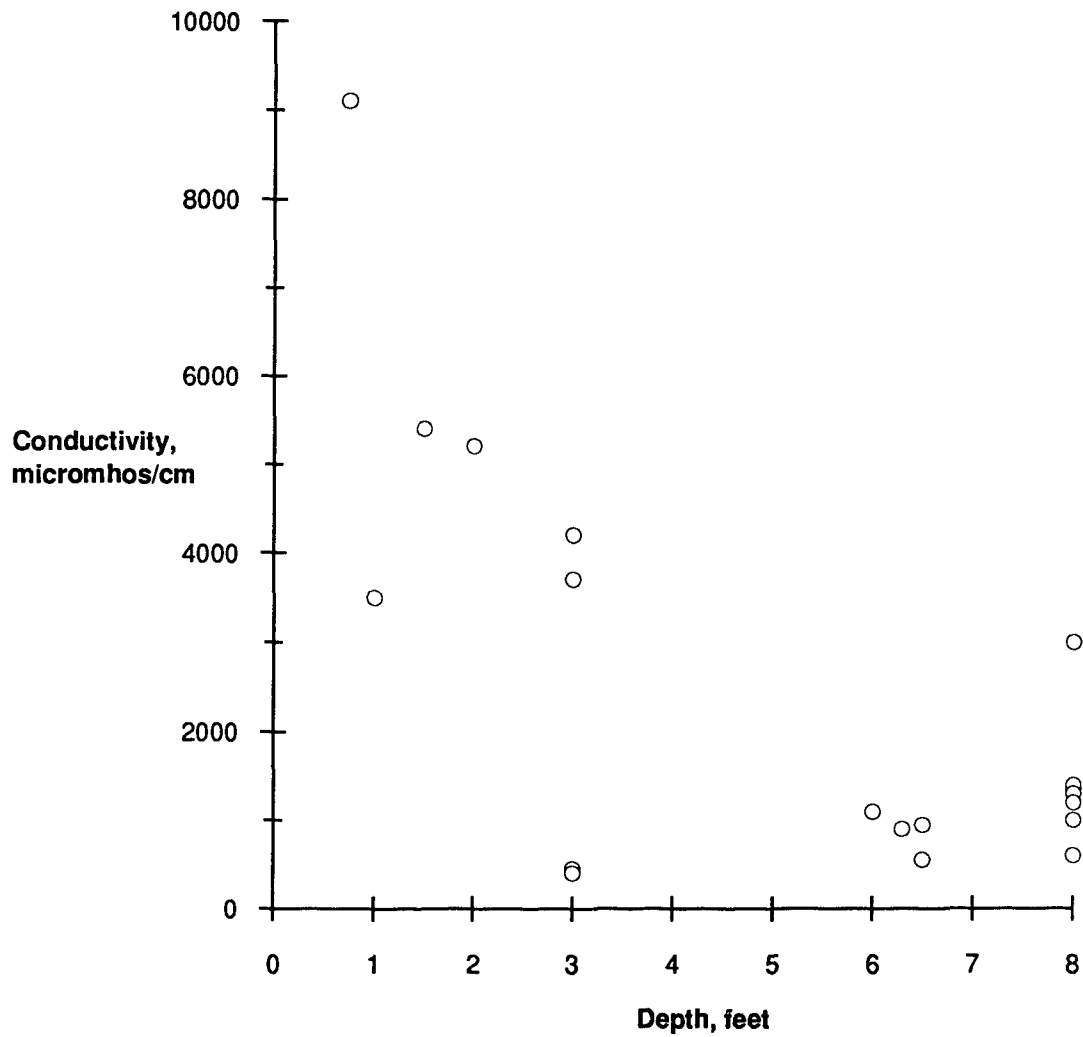
**Conductivity vs. Secchi Depth**

Figure 50. Conductivity in Micromhos/cm Plotted Against Secchi Depth in Feet.

metals. In addition to dissimilarities in chemistry, as compared to Peavy and Green Valley, there is also a significant contrast in reflectance. I-70 reflectance is an order or magnitude greater than Peavy or Green Valley, with an average visible reflectance of 7.98 percent in July and 10.81 in August.

These contrasting spectral and chemical relationships have a basis in pH. The hydroxide precipitate of most metals, iron in this case, is quite insoluble under natural water pH conditions (Brownlow, 1979; Hem, 1985; and Elder, 1988). All three water bodies have iron oxidized as  $\text{Fe}(\text{OH})^{+++}$  or reduced as  $\text{Fe}(\text{OH})^{++}$ . Because the hydroxide ion activity has a direct relationship to pH, the solubility of hydroxide precipitates increases sharply as pH decreases.

The pH levels at Peavy and Green Valley are very acidic, therefore making the iron hydroxides soluble and returning the iron to the solution. The color of the water in these waterbodies is caused by dissolved metals in solution. Colored or pigmented water absorbs electromagnetic energy (Moore, 1980; Morel 1980).

The pH levels at I-70 are buffered, with values near 7.0. The water column cannot dissolve the iron hydroxide, allowing it to partition either with high cation exchange (cec), humus colloids, or with clays into complex large-sized sediment precipitates or floccs. The humus is present because of the mixed forest mat surrounding the basin, and the clay is a product of the weathering of the shales

present in the overburden. These partitioned metals eventually flocc or precipitate into even larger sizes, either sinking to the benthic environments or settling in littoral sediments, bonding to submerged dead and decaying vegetation, or remaining suspended. If suspended beneath the top four centimeters of the water column, the partitioned iron would not be prevalent in the sample. Manganese, however, is soluble regardless of pH, and would not be affected by variation in pH between waterbodies.

In addition, the July sampling followed a rather dry month in which there was little flow into the basin; thus, both the reflectance and the conductivity were smaller than those of August, whose sampling followed a rather wet period when overland and subsurface flow moved humus and sediment into the waterbody. Further, the precipitation events preceding the August sampling provided for dynamic near surface conditions thus more suspended metal partitioned sediments and greater conductivity and overall reflectance.

In extreme contrast to the discolored water of the Peavy, Green Valley, and I-70 study sites are the waters of Reservoir 29 and Lake Augusta. Although pH values are similar to Peavy Cemetery and Green Valley, the optical characteristics of the clear, seemingly pristine waters of Reservoir 29 and Lake Augusta contrast significantly with the discolored metal contaminated waters of Green Valley and Peavy Cemetery. Secchi readings in these waters exceeded the eight-foot leader length. The only significant

difference between Lake Augusta and Reservoir 29 for the variables measured is conductivity. Lake Augusta has conductivity values of about 3000 micromhos/cm, while conductivity values for Reservoir 29 range from 650 to 1400. The effect of this differing conductivity can be demonstrated by the average visible reflectance of the two waterbodies. Lake Augusta, with 2 to 3 times the conductivity of Reservoir 29, has an average visible reflectance ranging from 1.78 to 3.51 percent compared to 1.47 to 2.55 percent for Reservoir 29. The pH and clarity of these waterbodies indicate that they are dominated by acid. The primary metals found in both water columns are manganese and aluminum. Dissolved manganese is colorless. These lakes are similar in optical characteristics, chemistry, and spectra; the only difference is that Lake Augusta has higher average reflectance across the entire visible spectrum. This appears to be a result of the solutes within the water column, of which Lake Augusta has higher complements of manganese and aluminum than Reservoir 29.

Big Creek spectrally is very similar to Reservoir 29 and Lake Augusta with pH, metals, conductivity, and reflectance spectra being similar. The most obvious difference is the green color of Big Creek water. The intensity of the reflectance was greater across the visible spectrum, particularly in the July sampling, with maximum reflectance of nearly 8 percent. Although the water

chemistries of Reservoir 29, Lake Augusta, and Big Creek are similar, Big Creek differs in that iron is the dominant metal. The iron appears to be in a reduced (ferrous) low oxygen state, and the lake appears green in color (the color of iron in a reduced state). Iron oxidized to its ferric state often forms hydroxides "yellow-boy" and appears orange or red in color. The primary reasons for a reduced state for iron are that dissolved oxygen levels are low, the iron is partitioned to other complexes, or the iron is precipitating rapidly and dropping to low oxygen benthic environments. In any case, the metals, pH, and conductivity are comparatively low at Big Creek. These characteristics resemble the lakes of similar spectral reflectance, specifically Lake Augusta and Reservoir 29. The increased brightness of the reflectance, as compared to Reservoir 29 and Lake Augusta, can probably be explained by a reduced Secchi depth of approximately 6.5 feet. This decreased Secchi disk measurement might be attributed to increased sediment flow into the waterbody, partitioning of metals to sediments or humus, or the presence of chemical solutes not measured. Regardless of the reason for the reduction in light penetration, visible reflectance is being back-scattered at levels greater than measured at Reservoir 29 and Lake Augusta.

The State Fishing Area, selected initially as a control, served to contribute another class of lake in this study, primarily because of its relative high pH values as

compared to those of the others. The importance of pH, as presented earlier, is its effects on other chemical variables more than a direct impact itself. Reflectance is probably most affected by agricultural run-off (e.g. lime and fertilizers), and its effects on the biota in the lake. The August spectral sampling achieved maximum reflectance in the green and reduced reflectance was noted in the blue and red, as well as in the 675-680 nm region, a region of chlorophyll absorption (Dekkar et al., 1991).

Since the August sampling followed a relatively wet period, overland flow and subsurface storm flow would have a major effect throughout the watershed. Moreover, this lake is an engineered impoundment of a portion of a stream network augmenting the inflow into the lake and retarding the outflow thus affecting water characteristics.

## Chapter 5

### SUMMARY AND RECOMMENDATIONS

This research project was focused upon seven lakes in southwestern Indiana. For each of the lakes sampled, remotely sensed reflectance was measured over 180 narrow bands, each of 6 nanometers in wavelength. In all, 24 spectra were obtained for 7 lakes during two field surveys conducted in July and August 1991. In addition to the spectra, water samples were collected in an effort to characterize the water quality for each site sampled.

Reflectance spectra were acquired from a boat over open water along the midline of each lake between the hours of 11:00 a.m. and 2:00 p.m. Eastern Standard Time on a cloudless to near cloudless day using a Spectron Engineering Spectroradiometer/Spectrometer mounted on a boom. Spectra ranging from 450 - 850 nanometers were collected with a 6 degree IFOV in 6 nanometer wavelengths approximately one meter at nadir over the water surface. Data were then ported from the Spectron CE Microprocessor/Data Logger via 232C output port to a Zenith 286 pc. Lotus 123 Release 2.3 was used for the development of spectral curves. Using Lotus 123 software and equations supplied by Spectron



Engineering, raw lake spectral data were converted to radiance data and calibrated with a reflectance panel to provide sample reflectance in percent.

The water grab samples were acquired using applicable procedures for data collection, data processing, and laboratory analyses based on criteria of the Surface Mining and Control Act of 1977, and methods from the Office of Water Coordination's National Handbook for Water Data Acquisition (USGS, 1984), USEPA (1983), and ASTM (1984). Water sample characteristics were measured in the field for odor and appearance, temperature of the top 4 centimeters of the water column in degrees Celsius, pH, specific conductance, and Secchi depth, and in the laboratory for metals (iron, manganese, aluminum, and zinc).

These data were independently generalized into 4 classes based on spectral curves, pH, and Secchi depth. Classification of the data based on spectral curves emphasized wavelength differences in peak reflectance and overall brightness across the spectrum and was made independent of consideration of water color and water quality characteristics.

Type 1 lakes have maximum reflectance intensities below 2.0 percent and reflectance peaks at about 650 (red energy) and 700 (red/near infrared energy) nanometers. This class of lakes demonstrated the lowest reflectance of all of the lakes in the study, and may be generally classified as absorbers of energy. Green Valley and Peavy Cemetery

spectra for both dates comprise the Type 1 lake class.

Type 2 lake spectra exhibited the brightest maximum reflectance with intensities up to 18 percent. Type 2 spectra had maximum reflectance at 650 nanometers (red energy); however, the curves are broad-based, with reflectance rising sharply from relatively low values in the blue wavelengths. The majority of reflectance is in the yellow, orange, and red regions of the spectrum and reflectance declines rapidly in the near infrared. A second minor peak, with a reflectance intensity of 5 percent, was evident at about 805 nanometers. Both samplings of the pond south of I-70 fall into the Type 2 class.

Type 3 lakes had a maximum reflectance of 5.5 percent from about 550 to 575 nanometers (green energy). Reflectance increased sharply at about 520 nanometers peaking at about 565 nanometers and declining in a near linear fashion through the red energy. A second peak at about 695 nanometers was evident with maximum reflectance of nearly 3 percent. Both sample dates for the State Fishing Area comprise the Type 3 class.

Type 4 lakes exhibited maximum reflectance intensity ranging from just over 3.0 percent to just over 8.0 percent. Reflectance reached maximum intensities from 535 to 545 nanometers in wavelength (green energy). In all cases, blue energy was reflected at about one half of the maximum reflectance of green energy. After peaking at about 540 nanometers, the reflectance dropped in a linear fashion with

wavelength reaching a low at 664 nanometers. A second small reflectance peak is evident at 694 nanometers. All spectra from Reservoir 29, Lake Augusta, and Big Creek compose Type 4 lakes.

This study also classed lakes according to pH, a relative measure of the activity of the hydrogen ion, and according to Secchi depth, a measure of the depth to which light will penetrate in an aquatic system as measured by the visibility of a white Secchi disk. Classification of pH was developed by graphing pH along a continuum from 0 to 10; the range in which all values were found. The study sites were then grouped (classed) according to similar pH values. This grouping according to natural divisions provided 4 classes.

Type 1 lakes are lakes exhibiting very acidic conditions. In all cases Type 1 lakes have pH values that are less than 2.0. Water with a pH of less than 2.5 can be characterized as corrosive or as providing conditions that promote corrosion (US Congress, 1977). Type 1 waterbodies exhibit the lowest pH measurements of all the waterbodies analyzed in this research. The Green Valley and Peavy Cemetery study sites compose the Type 1 class.

Type 2 class lakes are lakes with pH values near 7.0. The water in Type 2 lakes is nearly buffered, or almost chemically neutral with respect to the concentrations of hydrogen and hydroxide ions. The I-70 study site is representative of Type 2 waterbodies.

Type 3 lakes are lakes with a somewhat alkaline or

basic water column. Type 3 lakes exhibited the highest pH values measured in this research having pH values over 9. The State Fishing Area study site represents Type 3 lakes.

Type 4 class lakes have acidic water columns with pH values between 3 and 4. Waterbodies with acidities of less than 5 fall under the promulgation of the Clean Water Act (US Congress, 1977). Reservoir 29, Lake Augusta, and Big Creek study sites compose Type 4 lakes.

Classification of lakes according to Secchi depth was conducted by plotting Secchi depth along a continuum from 0 to 8 feet; 8 feet being the entire length of the leader of the Secchi disk used in this study. Classes were formed by grouping visual readings of similar depth. Based on this method 4 natural groupings or classes were made.

Type 1 lakes were lakes with visual range of light penetration greater than 1 foot but less than 2.5 feet as measured by Secchi disk viewed vertically. Green Valley and Peavy Cemetery compose Type 1 lakes.

Type 2 lakes are those lakes with a visual range of light penetration of less than 1 foot as measured by Secchi disk viewed vertically. Type 2 waterbodies had the smallest Secchi depth readings. The I-70 study site composes Type 2 lakes.

Type 3 lakes are those lakes with a visual range of light penetration of about 3 feet as measured by Secchi disk viewed vertically. The State Fishing Area study site composes Type 3 lakes.

Type 4 lakes are those lakes with a visual range of light penetration exceeding 6 feet as measured by Secchi disk viewed vertically. Type 3 waterbodies exhibited the highest Secchi depth readings, in fact light penetration exceeded the Secchi disk leader in Reservoir 29 and Lake Augusta. Reservoir 29, Lake Augusta, and Big Creek study sites compose Type 4 lakes.

Upon comparison of the 3 different classification schemes it was found that each classification method grouped the same lakes together. This convergence of classification results helps corroborate the suggestion that these classes or groupings are real. Further, these results suggest that the analysis of reflectance provides a method for the analysis and classification of water quality for small inland coal mine lakes. Classification of lake spectra facilitates the description of major patterns as opposed to the individual descriptions of each lake reflectance spectrum. Although each classification had a different basis and was evaluated separately, the resulting classes are similar.

This research further suggests that pH is a primary influence in the water column chemistry in coal mine lakes. The pH of the water affects Secchi depth, conductivity, and dissolution of metals. This study found, however, that pH cannot be inferred directly from reflectance. However, what can be inferred is the relative activity of the hydrogen ion as evidenced by the spectral and chemical relationships of

the metals, Secchi depth, and conductivity.

Sediment chemistry literature also recognizes the role of pH variability in the phases of metals, soluble, suspended sediment, and bottom sediment, present in the water column (Horowitz, 1985). This research builds upon the chemical partitioning triangle developed by Horowitz (1985), classification of sediment patterns in the water column presented by Harrington, et al. (1992), and Vertucci and Likens and the classification of acid lakes in the Adirondack Mountains (1989) to theorize about the impacts of chemical partitioning on reflectance (Figure 51).

Lakes with metals dissolved in the water column or soluble phase lakes (Type 1) are characterized by:

1. High levels of metals in mg/l.
2. Low (acidic) pH values.
3. Elevated conductivity.
4. Low Secchi depths.
5. Low levels of suspended sediments.
6. Reduced organic particulate or debris.
7. Low average visible reflectance.

Lakes with metals partitioned to sediments in dynamic or mixed water columns compose the suspended sediment phase (Type 2) and are characterized by:

1. Low levels of mg/l of metals.
2. Buffered or alkaline pH values.
3. Low conductivity.
4. Low Secchi depths.
5. High suspended sediments.
6. High organic particulate or debris.
7. High average visible reflectance.
8. Dynamic flow or lake circulation.

Lakes with metals partitioned to sediments in stagnant water columns compose the bottom sediment phase. The criteria for the bottom sediment phase are similar to the

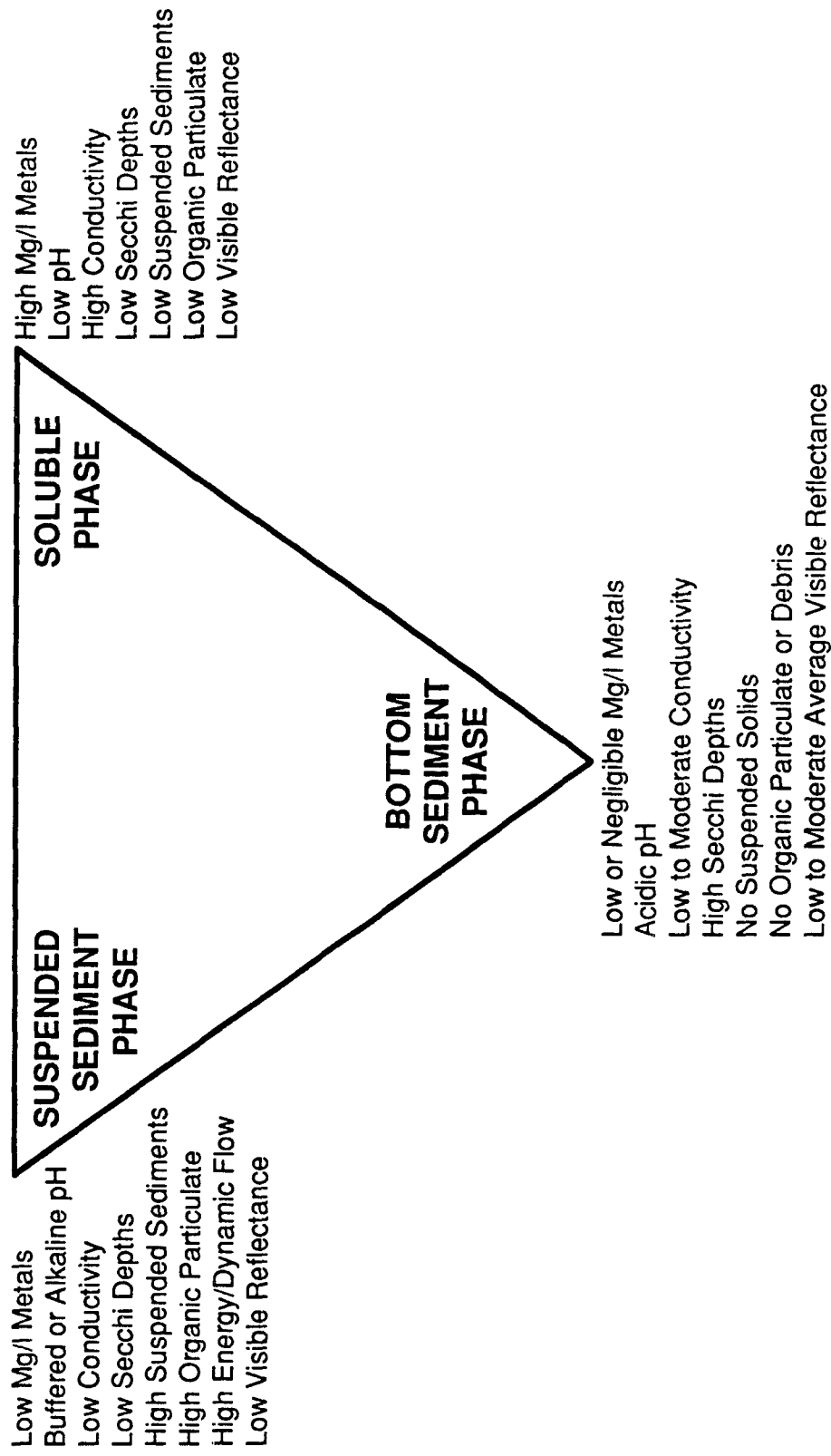
suspended sediment phase except for the fact that the water column is not dynamic (mixed) enough to support the sediments, thus they sink to the depths of the lake.

Lakes without any indication of the influence of acids or metals from the disturbed environments constitute Type 3 lakes. Type 3 lakes probably include several variations not directly addressed in this research design. Type 3 lakes may consist of: algal dominated or eutrophic lakes, sediment dominated or argillotrophic lakes, or perhaps rather clean and ecologically active oligotrophic lakes. A review of the sample chemistry and ecological nature visually evident at the State Fish site suggests that this site is somewhere between oligotrophic and eutrophic lending itself more towards eutrophic in spring and early summer because of increased nutrient loads in agricultural run-off.

Acidic lakes with negligible metal concentrations or sediments in the water columns (Type 4) comprise the sediment free phase and are characterized by:

1. Low or negligible mg/L of metals.
2. Low or acidic pH values.
3. Low to moderate conductivity.
4. Increased Secchi depths.
5. No suspended solids
6. No organic particulate or debris.
7. Low to moderate average visible reflectance.

All seven coal mine lakes examined in this study can be classified using these criteria. The lakes classified in this study fall into the following categories: Green Valley and Peavy Cemetery are soluble phase or chemically dominated lakes (Type 1), I-70 is both a suspended sediment and bottom



After Horowitz, 1985  
 Repic, 10-92

Figure 51. Spectral Reflectance and Chemical Partitioning in Coal Mine Surface Water; Major Phases are Inside the Polygon and Environmental Conditions are Outside.



sediment phase or chemically partitioned lake (Type 2), State Fishing Area is a suspended sediment lake (Type 3), and Reservoir 29, Lake Augusta, and Big Creek are sediment-free or acid-dominated lakes (Type 4).

In addition to the reflectance spectra and chemical data, statistical summaries for the average reflectance of visible energy for wavelengths ranging from 450-500, 500-600, and 600-700 nanometers (nm) respectively were presented. These groupings of energy were selected as a reference to existing satellite based sensor packages. The groupings are coincident with band-widths within the Thematic Mapper (TM) Multispectral Scanner (MSS), and SPOT sensor configurations. The energy grouping 450-500 nanometers coincides with Thematic Mapper band 1 (450-520 nm). The grouping 500-600 nanometers coincide with TM band 2 (520-600 nm), MSS band 4 (500-600 nm), and SPOT Multi-spectral band 1 (500-590 nm) while the grouping at 600-700 nanometers is coincident with TM band 3 (630-690 nm), MSS band 5 (600-700 nm), and SPOT MS band 2 (610-680 nm).

The scatterplots developed in this research suggest that shorter wavelength visible energy is more responsive to metals, turbidity (Secchi depth), and conductivity than were longer wavelengths. Scatterplots constructed to ascertain relationships between visible energy and chemical variables revealed that blue-green and yellow wavelengths were more responsive to individual chemical measures.

The spectral curves developed in this research provide

hyperspectral resolution reflectance data representative of AMD affected strip mine lakes. Currently, IDNR and OSM are interested in research regarding these sites as they are mandated by the Surface Mining Control and Reclamation Act of 1987 (U.S. Department of the Interior, 1977) to inventory, monitor, and develop reclamation strategies for AML sites. Spectra and classification schemes developed within this research could be used by these agencies in inventorying and planning.

In addition to the conclusions cited, this research provides a basis for further investigation of atmospheric path radiance effects. First, these data were collected with little, if any path radiance, thus providing a "pure" spectral response. These data could be contrasted with spectral data collected by airborne or spaceborne platforms to ascertain and calibrate path radiance interference.

Second, pH was recognized to have significant influence on water chemistry, but by itself showed little correlation to reflectance. Further research needs to evaluate alternative means, such as the role of sulfates, in determining the acidity of the water. Sulfate, the anion of the sulfuric acid group, is perhaps best suited to analyze acidity and correlate acidity with spectral reflectance.

The present research contributes to the scientific literature by providing insights regarding the acquisition, development, and analysis of hyperspectral reflectance data

for contaminated coal mine lakes and impoundments.

#### Recommendations

Future studies may be enhanced through the recognition of the following recommendations:

1. Ascertain the integrity of the reference panel. The reference panel is used to convert the radiometric response of the sensor to reflectance. Researched regarding degradation of the  $Ba_2SO_4$  paint film or the "whiteness" of the panel is appropriate; does it degrade when used in field work in strip mine environments. Also there is a need to compare and calibrate reference panels. Variability between reference panels, both of similar and differing design, should be assessed to answer the question: are they true Lambertian reflectors?
2. Ascertain the integrity of the sensor. Do the sensor's optics degrade between data acquisitions or are different calibration factors required with different illumination intensities?
3. Develop curve analysis methods. Analysis of the first derivative, slope to and from peak, and the measure of amplitude verses magnitude of the peaks needs to be researched to more accurately illustrate, define, and discuss variations in spectra.
4. Develop further methods of hydro-chemical and limnologic analysis foe lakes in strip mine environments. Analysis of sulfates would allow for additional measures of acidity and provide calibration of pH measures, measures for dissolved

oxygen, dissolved organic carbon, and chlorophyll, to aid in the identification of the biological nature of the water.

**BIBLIOGRAPHY**

## BIBLIOGRAPHY

- Alfodi, T.T., and J.C. Munday, Jr., 1978. Water Quality Analysis By Digital Chromaticity Mapping of Landsat Data. Canadian Journal of Remote Sensing. Vol. 4, pp. 108-126.
- American Society for Testing and Materials., 1984. Annual Book of ASTM Standards, Section II, Water. Philadelphia, American Society for Testing and Materials. Vol. 11, No. 1, 750 pp.
- Amos, C.L., and B.J. Topliss., 1985. Discrimination of Suspended Particulate Matter in the Bay of Fundy Using the Nimbus Coastal Zone Color Scanner. Canadian Journal of Remote Sensing. Vol. 11, No. 1, pp. 85-92.
- Anderson, A.T. and J. Schubert. 1976 ERTS-1 Data Applied to Strip Mining. Photogrammetric Engineering and Remote Sensing. Vol. 42, No. 2, pp. 211-219.
- Anderson, A.T., D. Schultz, T. Dorthy and H.M. Nock, 1977. A Demonstration of ERTS-1 Analog and Digital Techniques Applied to Strip Mining in Maryland and West Virginia. Photogrammetric Engineering and Remote Sensing.
- Augenstien, Eric W., Douglas A. Stow, and Allen S. Hope, 1991. Evaluation of SPOT HRV-XS Data for Kelp Resource Inventories. Photogrammetric Engineering and Remote Sensing. Vol 57, pp. 501-509.
- Barrett, E.C., M.J. Beaumont, and R.W. Herschy, 1990. Satellite Remote Sensing for Operational Hydrology: Present Needs and Future Opportunities. Remote Sensing Reviews. Vol. 4, No. 2, pp. 451-459.
- Benjamin, M.M. and J.O. Leckie, 1981. Multiple Site Adsorption of Cd, Cu, Zn, and Pb on Amorphous Iron Hydroxide. Journal of Colloid and Interface Science. Vol. 79, No.1, pp. 209-221.
- Best, R.G., M.E. Wehde, and R.L. Linder, 1981. Spectral Reflectance of Hydrophytes. Remote Sensing of Environment. Vol. 11, pp. 27-35.
- Bhargava, D.S., and D. W. Mariam, 1990. Spectral Reflectance Relationships to Turbidity Generated by Different Clay Materials. Photogrammetric Engineering and Remote Sensing. Vol. 56, pp. 225-229.

- Bhargava, D.S., and Dejene W. Mariam, 1991. Effects of Suspended Particle Size and Concentration on Reflectance Measurements. Photogrammetric Engineering and Remote Sensing. Vol. 57, pp. 519-529.
- Blevins, Dale W., 1989. Sources of Coal Mine Drainage and Their Effects on Surface Water Chemistry in the Claybank Creek Basin and Vicinity, North Central Missouri, 1983-84. U.S. Geological Survey Water-Supply Paper 2305, 38p.
- Bradford, Wesley L., and Arthur J. Horowitz, editors. The Role of Sediments in the Chemistry of Aquatic Systems Proceedings of the Sediment Chemistry Workshop. February 8-12, 1982. U.S. Geological Survey Circular 969, 75p.
- Brauner, Gehard, 1973. Subsidence Due to Underground Mining. United States Department of the Interior, Bureau of Mines.
- Brown, O.B., R. H. Evans, J.W. Brown, H.R. Gordon, R.C. Smith, and K.S. Baker, 1985. Phytoplankton Blooming Off the U.S. East Coast: A Satellite Description. Science. Vol. 229, pp. 163-167.
- Brownlow, Aurthur, 1979. Geochemistry. Prentice Hall, Inc., Englewood Cliffs, N.J. 190 pp.
- Campbell, William Giles, Stephen Vaughan Ballou, and Carole Slade, 1986. Form and Style Theses, Reports, Term Papers. Houghton Mifflin Company, Boston.
- Caruccio, F.T. and S. Parizek, 1968. An Evaluation of Factors Affecting Acid Mine Drainage Production and Ground-Water Interactions in Selected Areas Of Western Pennsylvania. Second Symposium on Coal Mine Drainage Research. pp. 107-151. Mellon Institute, Pittsburgh.
- Colley, R.J. Davies, and W.N. Vant. 1988. Estimation of Optical Properties of Water from Secchi Disk Depths. Water Resources Bulletin, American Water Resources Association. Vol. 24, No. 6, pp. 1329-1335.
- Curran, P.J., and E.M.M. Novo, 1988. The Relationship Between Suspended Sediment Concentration and Remotely Sensed Spectral Radiance: A Review. Journal of Coastal Research. Vol 4, pp. 351-368.
- Curran, P.J., 1987. Remote Sensing Methodologies and Geography. International Journal of Remote Sensing, 1987, Vol 8, No. 9, pp. 1255-1275.

- Curtis, Willie R., Kenneth L. Dyer, and George P. Williams, Jr., 1988. A Manual for Training Reclamation Inspectors in the Fundamentals of Hydrology. U.S. Department of Agriculture, Forest Service, Berea, Ky.
- Dalrymple, G. Brent, 1991. The Importance of "Small" Science. EOS. Vol. 72, pp. 1-4.
- Davis, J.A., and J.O. Leckie, 1978. Surface Ionization and Complexation at the Water/Oxide Interface. Journal of Colloid and Interface Science. Vol. 67, No. 1, pp. 90-107.
- Dekkar, Arnold G., Tim J. Maltus, and Ersin Seyhan, 1991. Quantitative Modeling of Inland Water Quality for High Resolution MSS Systems. IEEE Transactions on Geoscience and Remote Sensing. Vol. 29, No. 1, pp. 89-95.
- Deutch, M., and J.E. Estes, 1980. Landsat Detection of Oil from Natural Seeps. Photogrammetric Engineering and Remote Sensing. Vol. 46, No. 10, pp. 1313-1322.
- Elder, John F., 1988. Metal Biogeochemistry in Surface Water Systems. U.S. Geological Survey Circular 1013, 43p. Denver, CO.
- Emrich, G.H., and G.L. Merritt, 1969. Effects of Mine Drainage on Groundwater. Groundwater. Vol. 7, No.3, pp. 27-32.
- Environmental Systems Application Center School of Public and Environmental Affairs, 1983. Illinois Basin Planning Assistance Project, Vol. I. Coal Resources Fact Book. United States Geological Survey, Office of Earth Science Applications, Reston Virginia.
- Faust, Samuel D., and Osman M. Aly, 1981. Chemistry of Natural Waters. Ann Arbor Science Publishers, Inc. Ann Arbor, MI.
- Feldman, G., D. Clark, and D. Halpern, 1984. Satellite Color Observations of the Phytoplankton Distribution in the Eastern Equatorial Pacific During the 1982-1983 El Nino. Science. Vol 226, pp. 1069-1071.
- Fishman, Marvin J., and Linda C. Friedman, Editors, 1989. Methods for The Determination of Inorganic Substances in Water and Fluvial Sediments. Techniques of Water Resources Investigation of the United States Geological Survey. United States Government Printing Office, Washington.



- Fussell, Jay, Donald Rundquist, and John A. Harrington, Jr., 1986. On Defining Remote Sensing. Photogrammetric Engineering and Remote Sensing. Vol. 52, pp. 1507-1511.
- Goldberg, E.D., 1954. Marine Geochemistry, Chemical Scavengers of the Sea. Journal of Geology. Vol. 53, No.3, pp. 249-265.
- Grim, E.C. and Hill R.D., 1974. Environmental Protection in Surface Mining of Coal. U.S. Environmental Protection Agency. Publication EPA-670/2-74-093. 276 pp.
- Harper, Denver, 1985. Coal Mining in Vigo County, Indiana. Department of Natural Resources, Geological Survey Special Report 34. Bloomington.
- Harrington, John A. Jr., Frank R. Schiebe, and Joe F. Nix, 1992. Remote Sensing of Lake Chicot Arkansas: Monitoring Suspended Sediments, Turbidity, and Secchi Depth with Landsat MSS Data. Remote Sensing of the Environment. Vol. 39, pp. 15-27.
- Hartke, Edwin J., Joseph G. Hailer, and Gordon S. Fraser, 1983. Environmental Geology of Vigo County, Indiana An Aid to Planning. State of Indiana Department of Natural Resources, Special Report 31, 32p.
- Hem, J.D., 1985. Study and Interpretation of the Chemical Characteristics of Natural Water. United States Geological Survey, Water Supply Paper 2254, 263 pp.
- Henkes, W.C. 1971. Satellite Monitoring of Open Pit Mining Operations. U.S. Bureau of Mines. Information Circular 8530, Washington, D.C.
- Herbert, Steve, 1991. Personal Communication, July 21, 1991.
- Hilton, J., 1984. Airborne Remote Sensing for Freshwater and Estuarine Monitoring. Water Resources. Vol. 18, p. 1185.
- Hockey, B., T. Richards, and H. Osmaston. 1990. Prospects for Operational Remote Sensing of Surface Water. Remote Sensing Reviews 1990, Vol. 4, No. 2, pp. 265-283.
- Holyer, Ronald J., 1978. Toward Universal Multispectral Suspended Sediment Algorithms. Remote Sensing of Environment. Vol. 7, pp. 323-338.

- Horowitz, Arthur J., 1985. A Primer on Trace Metal Sediment Chemistry. U.S. Geological Survey Water-Supply Paper 2277, 67p.
- Hovis, W.A., D.K. Clark, F. Anderson, R.W. Austin, W.H. Wilson, E.T. Baker, D. Ball, H.R. Gordon, J.L. Mueller, S.Z. El-Sayed, B. Sturm, R.C. Wrigley, and C.S. Yentsch., 1980. Nimbus-7 Coastal Zone Color Scanner: System Description and Initial Imagery. Science. Vol. 210, No. 3, pp. 60-66.
- Huang, Kai-yi, and Kamlesh Lulla, 1986. Modelling Water Quality Using Thematic Mapper Data: Case of Lake Michigan. Geocarto International. Vol. 2, pp. 3-9.
- Indiana Department of Natural Resources, 1992. Indiana Department of Natural Resources AML Inventory Files. Division of Reclamation, Jasonville, Indiana.
- Jenne, E.J., 1966. Control on Mn, Fe, Co, Ni, Cu, and Zn concentrations in Soils and Water-The Significant Roles of Hydrous Mn and Fe Oxides. Advances in Chemistry Series No. 73. American Chemical Society, Washington D.C. C. 21, pp. 327-387.
- Khorrarn, Siamak, 1981. Use of Ocean Color Scanner Data in Water Quality Mapping. Photogrammetric Engineering and Remote Sensing. pp. 667-676.
- Kosowski, Z.V., 1973. Control of Mine Drainage from Coal Mine Mineral Wastes; Phase II Pollution Abatement and Monitoring. USEPA Technology Series Report EPA-R2-73-230. 83 pp. Washington.
- Krauskopf, K.B., 1956. Factors Controlling the Concentration of Thirteen Rare Metals in Sea Water. Geochimica Cosmochimica Acta. Vol. 9, Nos. 1-2, pp 1-32.
- Lathrop, R. G. Jr., and T. M. Lillesand, 1988. Utility of Spot-1 Data to Access Water Quality in Southern Green Bay Lake Michigan. Tech. Papers 1988 ACSM ASPRS. St. Louis. Vol. 4, pp. 102-111.
- Lee, J.K., and R.L. Repic, 1989. The Assessment of Water Quality in an Abandoned Mine Area Using Multi-spectral Video Data. Abstracts of the 85<sup>th</sup> Annual Meeting of the Association of American Geographers. Baltimore, Maryland.
- Lodwick, G.D., and R.D. Harrington, 1985. Deriving Sediment Information for Lake Athabaska Using Principal Components Analysis of Landsat Data. Canadian Journal of Remote Sensing. Vol. 2, pp. 4-16.

- Lulla, K., P. W. Mausel, D. Skelton, and W. Kramber, 1987. An Evaluation of Video-Based Vegetation Indices. Proc. of the 11th. Biennial Workshop on Color Aerial Photography and Videography in the Plant Sciences. ASPRS, pp. 270-279.
- Martin, Jeffrey D., Charles G. Crawford, Richard F. Duwelius, and Danny E. Renn, 1990. Description of the Physical Environment and Coal Mining History of West Central Indiana, with Emphasis on Six Small Watersheds. U.S. Geological Survey Water-Supply Paper 2368, 38p.
- Martin, Jeffrey D., Charles G. Crawford, and Richard F. Duwelius, 1990. Effects of Surface Coal Mining and Reclamation on the Geohydrology of Six Small Watersheds in West Central Indiana. U.S. Geological Survey Water-Supply Paper 2368, 113p.
- Martin Jeffrey D. and Crawford Charles G., 1987. Statistical Analysis of Surface Water Quality Data in and Near the Coal Mining Region of Southwestern Indiana, 1957-80. U.S. Geologic Survey, 1984. Water Supply Paper 2291. 92p.
- Mausel, P.W., R.C. Howe, and K. Lulla, 1981. Non-Parametric Classification of Abandoned Coal Mine Features using Multi-Oriented and Ratio Transformed Landsat Data. Proc. of the Fifteenth International Symposium on Remote Sensing of the Environment. Ann Arbor, MI. pp. 1397-1409.
- Mausel, P. W., M.A. Karaska, C. Y. Mao, D. E. Escobar, and J. H. Everitt, 1990. Insights into Water Turbidity Through the Computer Analysis of Multispectral Video Data. Proc. 12th. Biennial Workshop on Color Aerial Photography and Videography in the Plant Sciences. Reno. pp. 216-223.
- McKnight, D.M., B.A. Kimball, and K.E. Bencala, 1988. Iron Photoreduction and Oxidation in an Acidic Mountain Stream. Science. Vol. 240, pp. 637-639.
- Meeks, B.D., E.A. Rechel, L.M. Carter and W.R. Detar, 1988. Soil Compaction and its Effects on Alfalfa in Zone Production Systems. American Journal of Soil Science. Vol. 52, pp. 232-236.
- Menzel, R.G., W.W. Troeger, and F.R. Schiebe, 1989. Properties of Selected Oklahoma Lakes in Relation to Remote Sensing of Suspended Sediment. Lake and Reservoir Management. Vol. 5, No. 2, pp. 31-37.

- Mitchell, G.N., 1990. Natural Discoloration of Freshwater: Chemical Composition and Environmental Genesis. Progress in Physical Geography. Vol. 14, No.3, pp. 317-334.
- Moore, Gerald K., 1977. Satellite Surveillance of Physical Water-Quality Characteristics. 12th International Symposium on Remote Sensing of the Environment. Vol. 1, pp. 445-462.
- Moore, Gerald K., 1980. Satellite Remote Sensing of Water Turbidity. Hydrological Sciences Bulletin.
- Morel, Andre., 1980. In-Water and Remote Measurements of Ocean Color. Boundary Layer Meteorology. Vol.18, pp. 177-201.
- Moran, R.E. and D.A. Wentz, 1974. Effects of Metal-Mine Drainage on Water Quality in Selected Areas of Colorado 1972-73. Colorado Water Resources Circular No. 25. Colorado Water Conservation Board, Denver. 250 pp.
- Munday, John C., Jr., and Thomas T. Alfoldi, 1979. LANDSAT Test of Diffuse Reflectance Models for Aquatic Suspended Solids Measurement. Remote Sensing of Environment. Vol. 8, pp. 169-183.
- NASA, 1987a. From Pattern to Process: The Strategy of the Earth Observing System. Eos Science Steering Committee Vol II. National Aeronautics and Space Administration. 140 p.
- NASA, 1987b. HIRIS: High Resolution Imaging Spectrometer: Science Opportunities for the 1990s. Instrument Panel Report. National Aeronautics and Space Administration. 79 p.
- NASA, 1983. Middleton, Elizabeth M., and Richard F. Marcell, editors. Literature Relevant to Remote Sensing of Water Quality. National Aeronautics and Space Administration. Goddard Space Flight Center. Greenbelt, MA. 20771. July 1983.
- NOAA, 1991. Monthly Precipitation Departures from Individual Station Normals (1951-1980). Climatological Data, Indiana. July 1991. Vol. 96, No. 7.
- NOAA, 1991. Monthly Precipitation Departures from Individual Station Normals (1951-1980). Climatological Data, Indiana. August 1991. Vol. 96, No. 8.

- Packard, Frank A., Earl L. Skinner, and Luis A. Fuste', 1988. Effects of Coal Mine Drainage on the Water Quality of Small Receiving Streams in Washington, 1975-77. U.S. Geological Survey, Water-Resources Investigations Report 85-4275. Tacoma, WA.
- Pagenkopf, Gordon K., 1978. Introduction to Natural Water Chemistry. Marcel Dekker, Inc. New York.
- Pattison, W.D., 1964. The Four Traditions of Geography. Journal of Geography. Vol. 63, pp. 211-216.
- Powell, R.L., 1972. Coal Strip-Mined Land in Indiana. Geological Survey Special Report 6. 18 pp. Bloomington.
- Repic, R.L., J.K. Lee, P.W. Mausel, D.E. Escobar, and J.H.Everitt., 1991. An Analysis of Selected Water Parameters in Surface Coal Mines Using Multispectral Videography. Photogrammetric Engineering and Remote Sensing. Vol. 57, No. 12, pp. 1589-1596.
- Repic, R.L., 1991. Spectral Response of Coal Mine Lakes in Southwestern Indiana. Abstracts of the 87<sup>th</sup> Annual Meeting of the Association of American Geographers. Miami.
- Repic, R.L., 1992. An Assessment of Spectral Curves for Coal Mine Lakes in Southwestern Indiana. Abstracts of the 88<sup>th</sup> Annual Meeting of the Association of American Geographers. San Diego.
- Renn, Danny E., 1988. Streamflow and Stream Quality in the Coal Mining Region, Patoka River Basin, Southwestern Indiana, 1983-85. U.S. Geologic Survey, Water Resources Investigations Report 88-4150. 68 p.
- Rowe, James E., 1979. Coal Surface Mining: Impacts of Reclamation. Westview Press. Boulder, CO. pp. 74-139.
- Sharber, L.A. and F. Shahrohki, 1977. The Application of Satellite Data in Monitoring Strip Mines. Technical Papers, Sixth Annual Remote Sensing of Earth Resources Conference. Tullahoma, TN. pp. 499-514.
- Singer, P.C. and W. Strum, 1970. Acidic Mine Drainage The Rate Determining Step: Science. Vol. 167, pp. 1121-1123.
- Slater, Philip N., 1980. Remote Sensing, Optics and Optical Systems. Addison-Wesley Publishing Company, Inc. Reading, MA.

- Smith, Raymond C., and Karen S. Baker, 1978. Optical Classification Natural Waters. Limnology and Oceanography. Vol. 23, No. 2, pp. 260-267.
- Spaulding, W.M. Jr. and R.D. Ogden, 1968. Effects of Surface Mining on the Fish and Wildlife Resources of the United States. U.S. Fish and Wildlife Services. Publication 68. 51 p. Washington.
- Tucker, C.J., J.H. Elgin, Jr., J.E. McMurtrey III, and C.J. Fan, 1979. Monitoring Corn and Soybean Development with Hand-Held Radiometer Spectral Data. Remote Sensing of Environment. Vol. 8, pp. 237-248.
- United States Congress., 1974. U.S.C. Section 42, 300f-300j-11. Washington D.C.
- United States Congress., 1977. U.S.C. Section 30, 1201. Washington D.C.
- United States Congress., 1977. U.S.C. Section 33, 1251-1376. Washington D.C.
- United States Code of Federal Regulations., 1977. C.F.R. Section 40, Parts 121-125. Washington D.C.
- U.S. Department of Agriculture, Forest Service, 1990. A Manual for Training Reclaiming Inspectors in the Fundamentals of Hydrology. U.S.D.A., Forest Service, Northeastern Forest Experiment Station, Berea, KY. 59 pp.
- U.S. Department of Agriculture, Soil Conservation Service, 1974. Soil Survey of Clay County. Government Printing Office. Washington.
- U.S. Department of Agriculture, Soil Conservation Service, 1974. Soil Survey of Greene County. Government Printing Office. Washington.
- U.S. Department of Agriculture, Soil Conservation Service. 1974. Soil Survey of Pike County. Government Printing Office. Washington.
- U.S. Department of Agriculture, Soil Conservation Service. 1974. Soil Survey of Vigo County. Government Printing Office. Washington.
- U.S. Department of Agriculture, Soil Conservation Service. 1974. Soil Survey of Warrick County. Government Printing Office. Washington.

- U.S. Department of Interior, 1977. Permanent Regulatory Program Implementing Section 501(b) of the Surface Mining Control and Reclamation Act of 1977. Government Printing Office. Washington.
- U.S. Department of Interior, 1982. Guide to Reclamation Inspection. Office of Surface Mining, Reclamation and Enforcement. Government Printing Office. Washington.
- U.S. EPA, 1983. Methods for Chemical Analysis of Water and Waste. EPA-600/4-79-020.
- U.S. EPA, 1974. Environmental Protection in Surface Coal Mining. EPA-670/2-74-093
- U.S. Geological Survey, 1979. Gazetteer of Coal Mine Lakes in Southwestern Indiana. Water Resources Investigations 79-67. Indianapolis, IN.
- U.S. Geological Survey, 1984. National Handbook of Recommended Methods for Water Data Acquisition. Chapter 5: Chemical and Physical Quality of Water and Sediment. Office of Water Data Coordination. Washington.
- Vertucci, F.A., and G. Likens, 1989. Spectral Reflectance and Water Quality of Adirondak Mountain Region Lakes. Limnology and Oceanography. Vol. 34, No.8, pp. 1656-1672.
- Vogel, Willis G., 1988. A Manual for Training Reclamation Inspectors in the Fundamentals of Soils and Revegetation. U.S. Department of Agriculture, Berea, KY.
- Wangness David J., Robert Miller, Zelda Chapman Baily, and Charles Crawford. Hydrology of Area 32, Eastern Region, Interior Coal Province, Indiana. Water Resources Investigations, Open File Report 81-498. U.S. Geological Survey. Indianapolis, IN.
- Weisblatt. E.A., J.B. Zaitzeff, and C.A. Reeves, 1973. Classification of Turbidity Levels in the Texas Marine Coastal Zone. Proc. of the Symposium on Machine Processing of Remotely Sensed Data. IEEE Catalog No. 73 CHO 834-2ge, pp. 3a-42 to 3a-59.
- Weiss, Nancy E., Andrew A. Sobek, and Donald L. Streib, 1977. A Selective Bibliography of Surface Coal Mining and Reclamation Literature. U.S. Department of Energy, Argonne National Laboratory.

Whitlock, C.M., C.Y. Kuo, and S.R. Lecroy. 1982. Criteria for Using Regression Analysis for the Remote Sensing of Sediment and Pollutants. Remote Sensing of the Environment. Vol. 12, pp. 151-168.

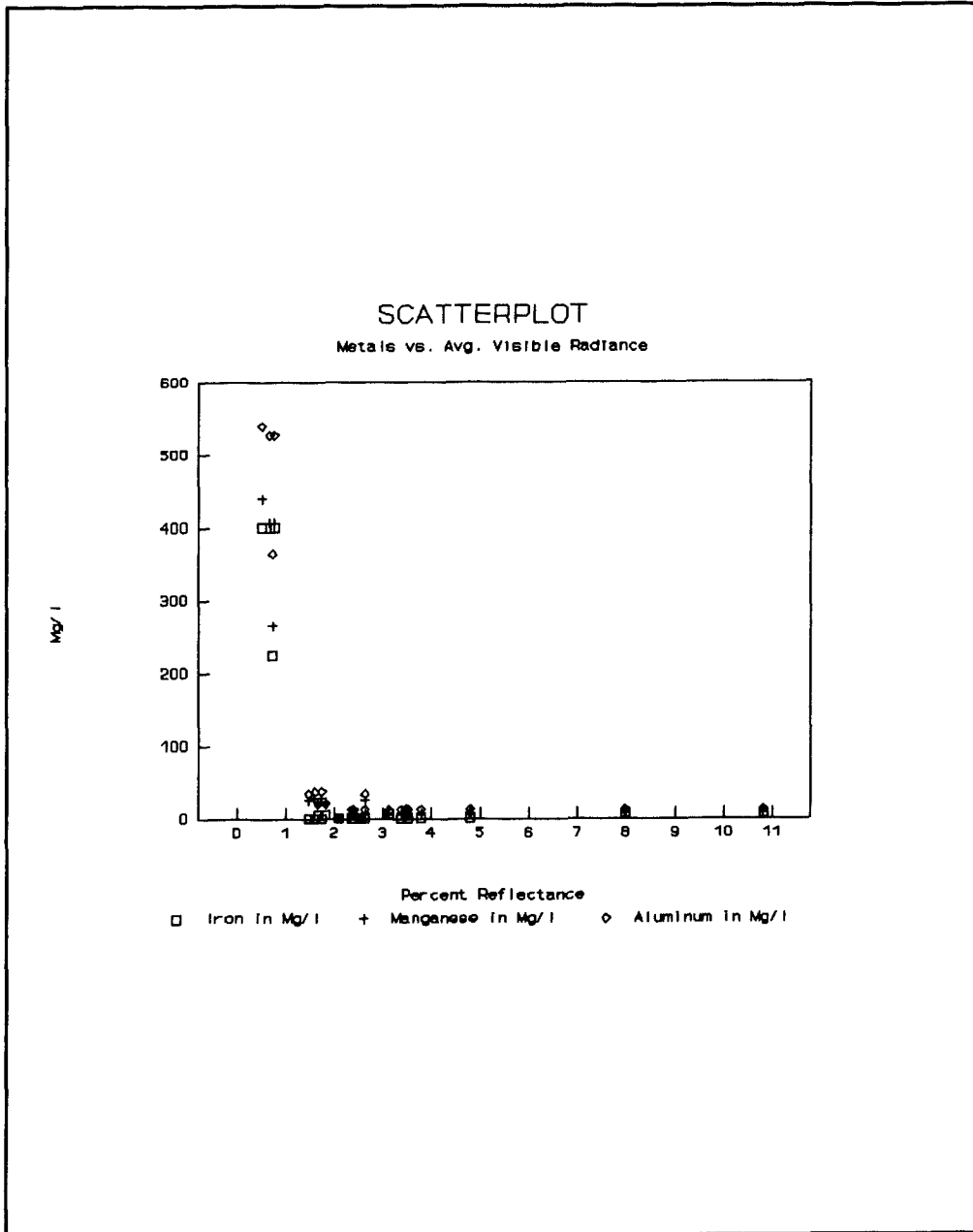
Wilber, William G., Danny E. Renn, and Charles G. Crawford, 1985. Effects of Land Use and Surficial Geology on Flow and Water Quality of Streams in the Coal Mining Region of Southwestern Indiana, October 1979 through September 1980. U.S. Geological Survey, Water-Resource Investigations Report 85-3234, 44p.



**APPENDIXES**

APPENDIX A

Scatterplot of Percent Reflectance and Mg/l of Metals



APPENDIX B

Scatterplot of Percent Reflectance and Secchi Depth

