THE LANDSAT-1 MULTISPECTRAL SCANNER AS A TOOL IN THE CLASSIFICATION OF INLAND LAKES

E-11

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ABSTRACT

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This study has focused on relationships between LANDSAT-1 multispectral scanner (MSS) data and the trophic status of a group of lakes located in the north-northeastern part of the United States. MSS data were used to predict the magnitudes of two trophic state indicators, estimate lake position on a multivariate trophic scale, and automatically classify lakes according to their trophic state.

Initially, principal component ordination was employed to ascertain the trophic state of 100 lakes using the indicators: chlorophyll a, conductivity, inverse of Secchi transparency, total phosphorus, total organic nitrogen, and productivity as measured by a standard algal assay yield test. The resultant PC1 values are indicative of the lakes' positions on a multivariate trophic scale.

MSS data for some 20 lakes were extracted from computer-compatible tapes (CCT's) using a binary marking technique. Output was in the form of descriptive statistics and photographic concatenations. MSS color ratios were incorporated into regression models for the prediction of Secchi disc transparency, chlorophyll a, and lake position on the trophic scale. Lake trophic state-MSS relationships were also examined using three-dimensional color ratio models. Automatic image processing techniques were used in conjunction with MSS data and trophic state index values to classify each lake pixel-by-pixel. Classification products included both gray scale and color-coded photographic prints.

The study results indicate that the LANDSAT-1 system, although handicapped by both low spectral and spatial resolution as well as excessive cloud cover, can be used as a supplemental data source in lake survey programs. The sensor's usefulness is most apparent when the seasonal contrasts between lakes at different points on a trophic scale are at a maximum. The use of CCT's along with digital image processing techniques is essential if maximum benefits are to be derived from the sensor.

INTRODUCTION

The United States is estimated to have some 80,000-100,000 lakes. Rational management of the nation's lacustrine resource necessitates, as a first step, an assessment of each lake's trophic status. Data collection for the determination of trophic state is a costly, time-consuming process, especially when thousands of lakes are to be evaluated. The need exists to find a method of rapidly and economically assessing the trophic condition of our lakes.

Satellite-borne sensors, such as those found on the LAND SATELLITE-1 (LANDSAT-1), merit close scrutiny as tools with the potential to collect data relevant to lake monitoring and survey programs. They are endowed with a synoptic view, yield a time record, and expand the spectral limits of the human eye. The successful orbiting of LANDSAT-1 and LANDSAT-2 affords the opportunity to investigate the capabilities of one type of sensing system. This paper reports the progress of an on-going investigation which is examining relationships between multispectral scanner (MSS) data and the trophic state of lakes in Minnesota, Wisconsin, Michigan, and New York[1] (Figure 1). More specifically, the MSS was scrutinized as to its capability for estimating lake area, predicting two trophic state indicators, and classifying lakes according to a ground truth-derived trophic scale. The project, a cooperative effort of the U.S. Environmental Protection Agency's (EPA) Pacific Northwest Environmental Research Laboratory and the National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory (JPL), was initiated in early 1973.

BACKGROUND

Eutrophication Survey personnel at EPA's Pacific Northwest Environmental Research Laboratory visually examined lakes on MSS imagery received shortly after spacecraft launch. Tonal differences were noted and it was conjectured the differences might correlate with the trophic status of the lakes. While tonal variations were observed for lakes in many states (e.g., Florida, South Dakota, Minnesota), MSS Scene 1017-16093, recorded at an altitude of approximately 917 kilometers over southeastern Wisconsin and northeastern Illinois on 9 August 1972, will serve to illustrate this point.

Figure 2 is a reproduction of an EROS Data Center photograph of the scene as recorded in the near-infrared (IR2; 800 to 1,100 nanometers) spectral band. Water bodies, including the larger streams, stand out boldly against the lighter-toned land features. The labelled lakes, excluding Lake Michigan, were sampled by EPA's National Eutrophication Survey (NES) during the 1972 open-water season. Gray tone differences are not evident among the lakes, nor are tonal patterns visible on any of the lakes. IR2 is, however, a good spectral band for the location and demarcation of water bodies. Some caution is necessary when conducting a lake enumeration on the photograph because some of the "lakes" are in reality shadows cast by cumulus clouds.

Figure 3 is the same scene recorded in near-infrared (IR1; 700 to 800 nanometers). Tonal differences are apparent, at least on the original photographic print, among the lakes, and patterns are evident on some of the lakes (e.g., Lake Koshkonong). Lakes are readily located and their boundaries delimited in this band.

Figure 4 is a red light (RED; 600 to 700 nanometers) MSS photograph of the scene. Marked gray tone differences are apparent among the lakes. Lakes commonly recognized as eutrophic (e.g., Lake Como) tend to appear light in tone and meld in with the land features. Lakes with relatively good water quality are characterized by darker tones.

The green light (GRN; 500 to 600 nanometers) sensed by the MSS was used to produce the Figure 5 photograph. Although the lakes are difficult to discern, a result of low contrast among the scene elements, differences among the lakes can be detected with the unaided eye.

It is apparent from the visual examination of MSS scene 1017-16093 and additional scenes from several other states that the satellite-borne MSS is collecting data which may be of value in the classification and monitoring of lentic bodies. The examination results suggest that GRN, RED, and IR1 contain most of the information relating to the assessment of trophic status.

Lake Color

It is readily apparent, even to the casual observer, particularly if he or she is looking downward from an aircraft, that lakes differ in color. Many investigations have

1. The geographic scope has been expanded to include lakes sampled by EPA's National Eutrophication Survey in the Southeast (1973), West (1974), and Far West (1975).

been undertaken to develop a comprehension of the processes which result in the observed phenomena (ref. 1). Scherz, et al. (ref. 2) have investigated the total reflectance (surface reflectance plus volume reflectance) curves of pure water and natural waters under laboratory conditions using a spectrophotometer. They reported that the addition of dissolved oxygen, nitrogen gases, and salts (e.g., NaCl, Na_2SO_4) had no apparent effect on the reflection curve. However, water from lakes in the Madison (Wisconsin) area had reflectance curves that both differed from the distilled water curve and from each other (Figure 6). The lake water differences can be attributed to the presence of different algal organisms. Filtration of the lake waters produced similar reflectance curves.

The color of a lake is a function of the electromagnetic energy backscattered from the lake body to the sensor. Lake color ranges from the blue of pure water through greenish blue, bluish green, pure green, yellowish green, greenish yellow, yellow, yellow brown, and clear brown. Lake color need not be, and is usually not the same as, the color of lake water. Lakes which are blue in color lack appreciable quantities of humic materials and colored material in suspension (e.g., phytoplankton). Waters with high plankton content possess a characteristic yellow-green to yellow color.

Figure 7 depicts the spectral reflectance curve for chlorophyll-bearing plants (refs. 3, 4, 5). The reflectance of the chlorophyll-bearing plants varies greatly as illustrated. by the curve with an abrupt increase at about 700 nanometers. Although the water tends to attenuate the infrared energy in a relatively short distance, the magnitude of the plant reflectance in the near-infrared should make it possible to detect chlorophyll at or near the water surface. However, the chlorophyll signature may be masked by other materials, for example suspended sediments.

Peripheral Effects

The character of the electromagnetic energy received by the sensor, in this case the LANDSAT-1 MSS, has been shaped through interaction with numerous environmental phenomena. The degree of scattering and absorption imposed on the signal returned from water bodies is related to atmospheric transmittance and can result in changes in lake color when sensed at aircraft and satellite altitudes (ref. 6, 7). The magnitude of the adverse atmospheric effects can be reduced, though not completely eliminated, by using MSS data collected on clear days with little cloud cover. The use of MSS color ratios in lieu of raw data values may be of value in reducing the magnitude of solar angle induced effects and atmospheric effects.

Most of the electromagnetic energy entering a lake is attenuated through the process of absorption. Although only a small percentage of the incident energy is backscattered from the lake water volume, it is the focus of interest in remote sensing of water quality. Its spectral characteristics have been shaped by the materials found in the lake water (e.g., dissolved and suspended materials, plankton, aquatic macrophytes). Lake bottom characteristics will also affect the intensity and/or the spectrum of the volume reflectance in settings where water transparency permits the reflection of a significant amount of energy from the bottom materials. In studies involving the estimation of water depth or the mapping of bottom features, it is essential that the lake bottom be "seen" by the sensor. Bottom effects are capitalized upon and put to a beneficial use. However, in this investigation bottom effects are considered to be an undesirable peripheral effect. A sensor with the capabilities of the MSS in not able to "see" much deeper into a lake than secchi disc transparency depth. The Secchi transparencies of the NES-sampled lakes were, in most cases, relatively small when compared to the mean depth of each respective lake. The assumption was made that bottom effect was relatively insignificant when considering each of the selected lakes as an entity.

Absolute quantification of remotely sensed phenomena requires that all of the effects be accounted for in the return signal. Although the approach used here to reduce the magnitude of the undesirable peripheral effects might be criticized as simplistic or naive, it does serve as a starting point in the investigation of lake color-trophic state relationships using satellite-borne sensors.

METHODS

Lake Ordination Using Principal Component Analysis

One hundred lakes sampled during the 1972 open-water season by EPA's National Eutrophication Survey were selected for the development of a multivariate trophic state index (ref. 8). A careful examination of the physical, chemical, and biological parameters measured by NES helicoptor-borne scientists resulted in the selection of six trophic indicators for incorporation into the index, namely: chlorophyll a, (CHLA), conductivity (COND), total phosphorus (TPHOS), total organic nitrogen (TON), Secchi disc transparency (SECCHI), and productivity as measured by a standardized algal assay test (AAY). The inverse of Secchi disc transparency (ISEC) was employed so that all of the indicators would increase as trophic status increases. The six indicators were selected because they are quantitative, considered to be important measures of trophic state and satisfy Hooper's (ref. 9) criteria. Annual mean values for CHLA, TPHOS, ISEC, and COND were used in the analysis. AAY and TON measurements were limited to the fall overturn sample, precluding the use of an annual mean.

Principal components analysis may be used to reduce the dimensionality of a multivariate system by representing the original attributes as functions of a smaller number of uncorrelated variates which are linear functions of the attributes. The objective is to summarize most of the variance in the system with a lesser number of "artificial" variates (i.e., principal components). The data for each of the trophic indicators were transformed with natural logarithms and further standardized to zero mean and unit variance. Following the development of the normalized eigenvectors and eigenvalues, the first principal component was evaluated for each of the 100 lakes under study.

Extraction of Lake Data from Computer-Compatible Tapes

Transparencies and CCT's for 12 different dates of MSS coverage were processed to extract pertinent lake data. Data extracted from transparencies using a microdensitometer contained a lot of "noise" and the approach, although initially attractive, was dropped in favor of using the CCT's. The processing of the CCT's was accomplished at JPL's Image Processing Laboratory (ref. 10, 11).

Processing commenced with a change of tape format and expansion of the data to 8-bits of precision giving 256 (0-255) digital number (DN) levels. Previous testing indicated that the LANDSAT-1 IR2 band gives a good indication of surface water extent. Water-related intensity values fall toward the lower end of the DN range. A binary mask was created from the IR2 data by setting all DN values at or below a specific numerical value to a value of 1, and setting all other values to 0. The IR2 DN level of 28 was selected as the upper limit for water-related features.

The binary mask was upgraded by eliminating all of the lakes, ponds, streams, and any wetland features which may be present, leaving just the lake of interest. After an examination of a test multiplication, each spatially equivalent picture element (pixel) within each MSS band (GRN, RED, IR1, IR2) was multiplied by the mask, thereby extracting the subject lake from its terrestrial matrix. Descriptive statistics were then generated (e.g., number of pixels, mean DN for each band). Lake area was determined from pixel counts using the conversion factor: 1 pixel = 0.47 hectares.

Estimation of Trophic Indicators and Trophic State

Ideally, the estimation of the magnitude of trophic state indicators should be done using concurrent data to derive the maximum benefit. However, in this investigation, it was necessary to use what may be termed "near-concurrent" ground truth which was collected several days before or after the time of satellite overflight. Nevertheless, models developed from such a temporal arrangement are of some value in demonstrating general trends existing between MSS data and ground truth.

Although attempts were made to estimate trophic indicators for other dates of MSS coverage, for purposes of this paper, attention will focus on MSS Scenes 1017-16091 and 1017-16093 recorded over eastern Wisconsin on 9 August 1972. These scenes were selected on the basis of temporal proximity to NES ground truth sampling dates, the high quality of the MSS data, and the presence of a relatively large number of NES-sampled lakes (N = 20).

The areal and spectral resolution of the LANDSAT-1 MSS should permit the detection of phenomena related to eutrophication; for example, Secchi disc transparency and chlorophyll a. Initially, an R-mode Pearson product-moment correlation analysis was made using MSS data, including MSS ratios, and the recorded Secchi disc and chlorophyll a values for the 20 lakes (Table I). Several multiple regression models were developed to predict each of the indicators using MSS colors and color ratios. The use of color ratios as independent variables had appeal because this approach normalizes the MSS data by removing the brightness components.

While the estimation of specific trophic indicators is of value in studies of lake water quality, the question arises, "Can a lake's position on a trophic scale be predicted using MSS data?" With this in mind, MSS coverage of the 20 lakes for three dates (9 August 1972, 11 June 1973, 17 July 1973) were examined for correlation with the trophic state index (PC1) values of the lakes (Table II). Multiple regression was then used to predict lake position on the scale using MSS color ratios as the independent variables.

A less rigorous approach to the study of PC1-MSS relationships was undertaken using three-dimensional plots of the MSS color ratios GRNIR1, GRNRED, and REDIR1.

Multispectral Classification of Lakes Using Digital Processing Techniques

Lake classification using the 9 August 1972 MSS data and the trophic state index (PC1) values of the 20 NES lakes was attempted using the maximum likelihood algorithm. The classification was conducted using the spectral bands GRN, RED, and IR1; the IR2 band was not utilized since it resulted in little or no spectral separation of classes. The number of spectral classes was set by establishing one class for each different PC1 value among the 20 Wisconsin lakes. This resulted in 19 different classes (Table III). Butte des Morts and Nagawicka have the same PC1 value and were assigned to the same class. Statistical samples were obtained for each lake as belonging to a particular class. For example, the computer was trained to perceive Beaver Dam Lake as belonging to Class 19. Each pixel in the 20 lakes was then classified by the computer into one of the 19 classes. The classification results were put out in the form of descriptive statistics and both black and white and color-coded photographs.

RESULTS AND DISCUSSION

Lake Area Estimation

The surface areas of the 20 Wisconsin lakes for 9 August 1972 (Scenes 1017-16091 and 1017-16093) are generally within 10% of values derived from U.S.G.S. topographic sheets. Adding the 20 lake map-derived area estimates and then comparing the resultant value with the composite value derived from MSS data resulted in a ratio of 1.016:1.000. A visual examination of area ratio for lakes in other MSS scenes indicated that the MSS can give adequate estimates of lake surface area when a DN value of 28 is used as the "cutoff" point for extracting lakes from their terrestrial matrix. The area estimation capabilities of the MSS are of value, not only in the study of lakes with known area but also in geographic regions for which there is no accurate topographic or photographic coverage.

Trophic Indicators and Trophic State

Efforts to use 9 August 1972 MSS color ratios for the prediction of mean Secchi disc transparency resulted in a multiple regression model which explains about 87 percent of the variance about the mean (ref. 1). Although the number of observations (N = 20) is rather small, the results suggest that the MSS scanner can be used to predict Secchi transparency.

The attempt to predict mean chlorophyll a levels in the same lakes resulted in a model which explains about 83 percent of the variance about the mean. The model does a fair job of estimating mean chlorophyll a levels in the 20 lakes. Large residuals are evident, primarily in the cases of lakes which have very poor water quality.

Regression models were also developed to predict the trophic state of the 20 Wisconsin lakes for three dates of MSS coverage (9 August 1972, 11 June 1973, 17 July 1973). The coefficients of multiple determination (R^2 x 100) are respectively 81 percent, 70 percent, and 81 percent. Efforts to develop a single model which could be used to estimate trophic state for each of the MSS sampling dates drew negative results. Indeed, the use of regression techniques for the 12 different dates of MSS coverage resulted in 12 different models for the prediction of trophic state. Models constructed using MSS data collected early in the open-water season were generally inadequate.

A less sophisticated but practical approach to evaluating relationships between MSS data and trophic state involves the visual examination of MSS data in light of a general knowledge of the lakes as well as their trophic state index values (PC1). Although this could be done through the use of matrices, the use of a three-dimensional color ratio model was favored because it is very conducive to pattern detection and interpretation.

The color ratio model for 9 August 1972 is found in Figure 8. The numerals inside a "ball" are the lake's serial number and those near the lake's name represent its PC1 value. There is a very definite trend for the color ratios to increase as one moves from lakes considered to be located near the eutrophic end of the scale (e.g., Beaver Dam) toward those situated more closely toward the oligotrophic end (e.g., Green)[2]. It

2. The mean IR1 DN level for several hypereutrophic lakes located in Minnesota actually exceeded their mean RED DN levels, effectively isolating them from other NES-sampled lakes in the color ratio model (Figure 9).

is unrealistic to expect complete agreement between the position of the lakes in the color ratio model and their respective PCl values. However, assuming that the PCl value of Middle Lake is representative of its trophic state, it is "out of place" relative to the other lakes. Its color ratio coordinates are indicative of a lake situated more closely toward the eutrophic end of the trophic scale. Several factors may be responsible for this apparent misclassification. The sensor may very well be "seeing" large masses of aquatic macrophytes and/or the lake bottom. Middle Lake is known to have macrophyte problems and extensive shallows.

The 11 June 1973 model at the same 20 lakes is shown in Figure 10 along with three other lakes. Many of the lakes have shifted their position significantly. The color ratio-trophic state index relationships so evident in the 9 August 1972 model are not as obvious.

Figure 11 depicts the Wisconsin lakes in a model constructed from 17 July 1973 color ratios. Although not identical in all respects, the model bears a marked resemblance to the 9 August 1972 model.

An examination of both the three-dimensional color ratio models and their associated regression models for the 12 dates of coverage suggested that the utility of the MSS for the estimation of trophic state is dependent to a substantial degree upon the time of the year. MSS data recorded early in the open-water season correlate poorly with lake PCl values; the correlations are better in the case of MSS data recorded later in the growing season.

Multispectral-Trophic Classification

Many of the data processing systems which automatically classify LANDSAT-1 MSS-sensed phenomena can output the reduced data in the form of both descriptive statistics and some sort of imagery. If the classificatory statistics would indicate that each lake is homogenous, the analysis could stop at this point. However, it is unlikely to find a lake that has the same trophic characteristics throughout its areal extent. The question arises, "What trophic-related patterns exist in each lake?" This necessitates the development of some sort of imagery.

Images of the machine-classified lakes can be produced in the form of line printer copy using different symbols to represent the various trophic classes and also as photographic products. The photographic approach is attractive because they are compact, easily handled, have much greater resolution than line printer copy of equal size, and are readily interpretable, particularly when in color.

The multispectral classification results for the 20 Wisconsin lakes (9 August 1972) are displayed as a color-coded concatenation (Figure 12). Class 1 pixels, represented by black, are located toward the eutrophic end of the trophic scale and Class 19 pixels (dark blue) toward the oligotrophic end. It would be incorrect to call a Class 19 pixel or lake oligotrophic because none of the Wisconsin lakes meet the criteria normally attributed to oligotrophic lakes. The pronounced linear features in Figure 12 are an artifact introduced by a defect in the MSS.

Differences among and within the lakes are readily apparent. Some of the lakes (e.g., Kegonsa and Beaver Dam) present a relatively homogenous appearance. Others (e.g., Winnebago and Poygan) exhibit a diversity of trophic classes. Some of the lakes have features which bear mentioning.

The appendix-like structure which appears attached to the northeast quadrant of Delavan Lake is the entry point of Jackson Creek, the lake's major tributary. Its waters, known to be nutrient rich through contributions from sewage treatment plants and agricultural drainage, have been placed in Class 1.

In this study, Lake Tichigan has been defined to include the lake proper and what is commonly referred to as the "widening" in the Fox River. The lake proper has been assigned to Class 5 and the "widening" to several classes including 1, 2, and 4. Ground truth measurements indicate that the "widening" has a smaller Secchi disc transparency and a substantially higher chlorophyll a level than the lake proper.

The Class 1 water found along the northern shore of Lake Pewaukee may be related to the presence of algae and macrophytes. The helicopter-borne survey teams reported algal scum covering the surface of the northern portion of the lake. Heavy growths of emergents covered the lake shallows.

The appendix-like portion of Green Lake, located at its northeast end, is the area into which Silver Creek flows. The area receives a substantial nutrient load from a sewage treatment plant and the surrounding agricultural lands. Its pixels have been classified as belonging to Class 1 and Class 2.

White areas within the lake images are indicative of either clouds or land-related phenomena. The white area in the northeastern portion of Lake Winnebago represents cloud cover. The north-south oriented linear feature located in the eastern end of Lake Butte des Morts is a roadway.

Complete accord does not exist between the trophic index values of the 20 lakes and the results of the multispectral classification. The disparity is very evident in the cases of Lakes Nagawicka, Koshkonong, and Oconomowoc where few, if any, pixels were found that fell into the class for which the lake served as a training area. This is not surprising because there was an indication in the three-dimensional color ratio model and the PC1 regression model for 9 August 1972 that a disparity existed between some of the lake PC1 values and their MSS data.

An examination of the 9 August 1973 MSS descriptive statistics for the 20 lakes indicated that the use of fewer trophic classes would yield a classification product more in tune with reality. The computer was retrained as indicated in Table III and the lakes were then reclassified. The revised classification, consisting of 11 classes (Figure 13), may be more representative of lacustrine trophic state than the 19-class scheme.

CONCLUSIONS

The LANDSAT-1 multispectral scanner is collecting data which can be incorporated into lake monitoring and survey programs. The interim results reported here suggest that MSS color ratios can be used to predict the magnitude of selected trophic state indicators and a multivariate trophic state index. However, the accuracy of the predictions varies considerably from date to date. The development of a trophic state classification employing computer-generated color-coded photographs should aid investigators in classifying large numbers of lakes both rapidly and economically. The use of CCT's along with digital image processing techniques is essential if maximum benefits are to be derived from the sensor.

It appears that the LANDSAT-1 MSS has the capability of providing supplemental data relating to water quality in inland lakes. Further refinement both in the sensor and the data processing techniques should make multispectral imagery collected from space platforms a valued tool in lake survey and monitoring activities.

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TABLE I CORRELATIONS BETWEEN GROUND TRUTH AND LANDSAT-1 MSS DATA (COLORS AND COLOR RATIOS) FOR 20 LAKES IN SCENES 1017-16091 and 16093

MSS COLORS AND RATIOS	PC1	CHLA	LNCHLA	SECCHI	LNSECCHI
GRN	0.518	0.812	0.718	-0.623	-0.662
RED	0.722	0.888	0.860	-0.788	-0.857
IR1	0.807	0.899	0.886	-0.741	-0.866
IR2	0.589	0.680	0.696	-0.492	-0.542
GRNRED	-0.823	-0.821	-0.886	0.865	0.919
GRNIR1	-0.806	-0.777	-0.838	0.685	0.803
GRNIR2	-0.470	-0.422	-0.521	0.357	0.476
REDIR1	-0.544	-0.476	-0.505	0.274	0.430
REDIR2	-0.026	0.028	-0.017	-0.156	-0.042
IR1IR2	0.516	0.522	0.474	-0.527	-0.507

TABLE II CORRELATIONS BETWEEN LANDSAT-1 MSS DATA (COLORS AND COLOR RATIOS) COLLECTED ON THREE DATES AND THE TROPHIC STATUS OF 20 WISCONSIN LAKES

MSS COLORS AND RATIOS	DATE OF LANDSAT-1 FLYOVER		
	9 AUGUST 1972	11 JUNE 1973	17 July 1973
GRN	0.518	0.151	0.479
RED	0.722	0.533	0.721
IR1	0.807	0.512	0.836
IR2	0.589	0.174	0.628
GRNRED	-0.823	-0.712	-0.749
GRNIR1	-0.806	-0.540	-0.820
GRNIR2	-0.470	-0.091	-0.485
REDIR1	-0.544	0.084	-0.422
REDIR2	-0.026	0.298	0.109
IR1IR2	0.516	0.445	0.479

TABLE III LAKE TROPHIC STATE INDEX CLASS ASSIGNMENTS FOR THE MULTISPECTRAL CLASSIFICATION TECHNIQUE

LAKE NAME	SERIAL NUMBER	PCI VALUE	COMPUTER TRAINED TO RECOGNIZE AS CLASS:	COMPUTER RETRAINED TO RECOGNIZE AS CLASS:
Beaver Dam	53	3.29	1	1
Tichigan	63	3.11	2	2
Koshkonong	56	2.45	3	5
Winnebago	49	2.36	4	3
Delavan	66	2.03	5	4
Poygan	47	1.68	6	5
Kegonsa	54	1.48	7	5
Butte des Morts	48	1.27	8	2
Nagawicka	61	1.27	8	9
Como	67	1.15	9	5
Pewaukee	62	0.59	10	6
Okauchee	59	-0.62	11	7
Pine	60	-0.71	12	8
Browns	64	-1.07	13	6
Rock	55	-1.21	14	10
Lac la Belle	57	-1.43	15	9
Green	51	-1.57	16	10
Geneva	68	-1.71	17	11
Oconomowoc	58	-1.82	18	10
Middle	65	-2.29	19	8

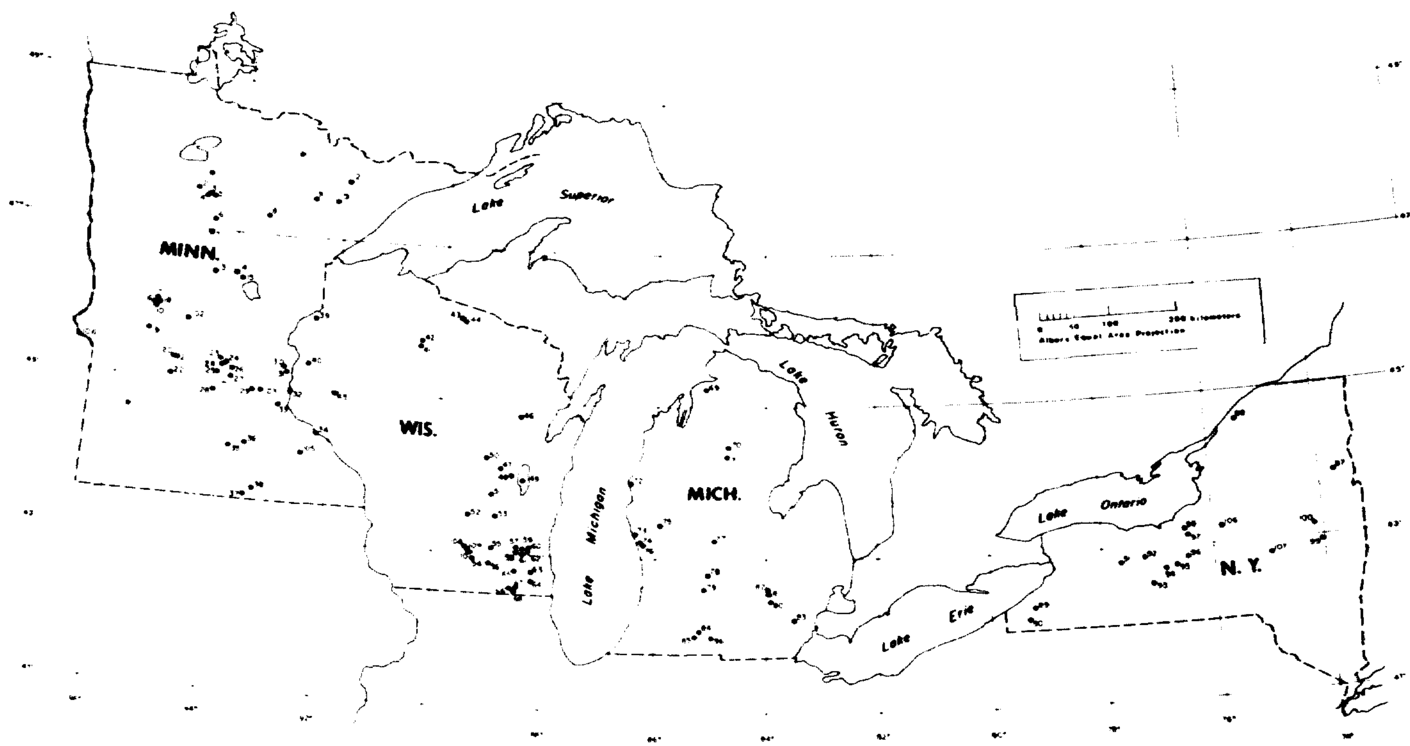

Figure 1. Location of the study lakes. The lakes with serial numbers 1-100 were used in the principal component ordination analysis. The lakes in east-southeastern Wisconsin serve as a focus for this paper.

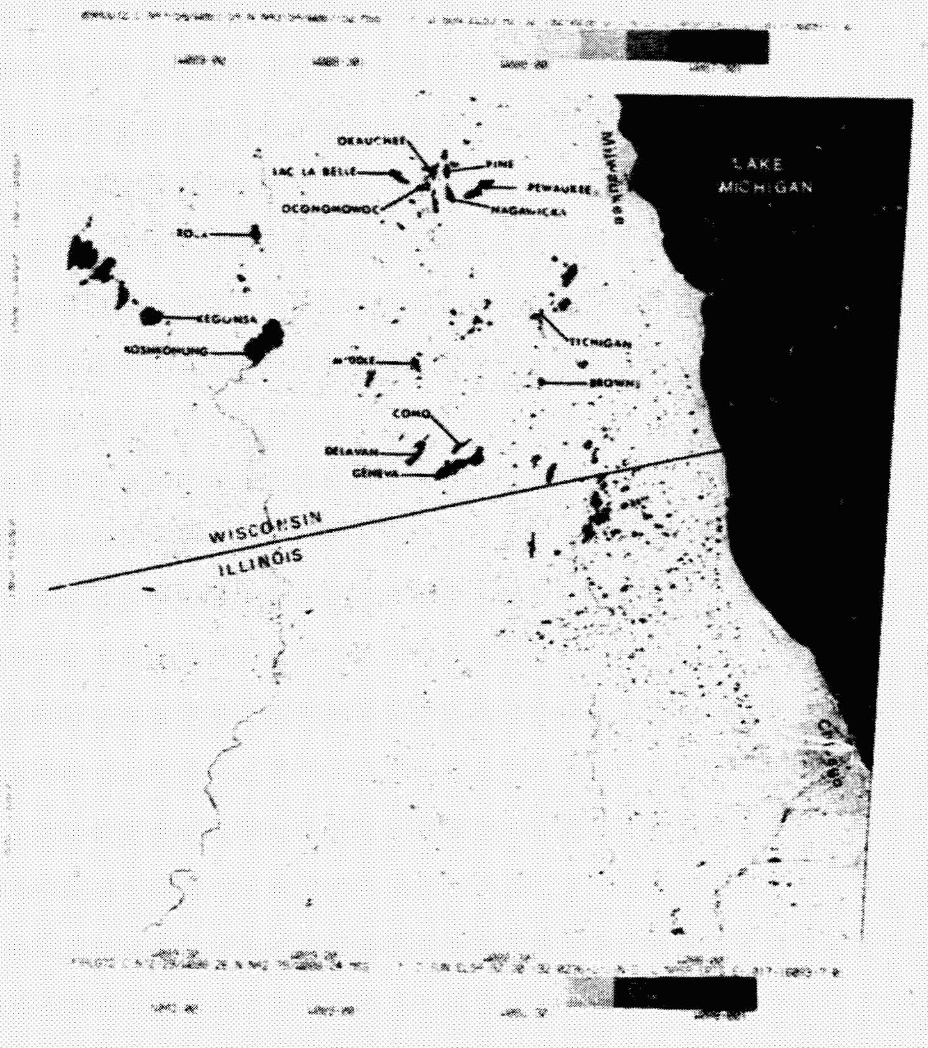

Figure 2. Reproduction of an EROS Data Center IR2 print of Scene 1017-16093 (9 August 1972). Water bodies stand out in stark contrast to the lighter-toned land features. The labelled lakes, excluding Lake Michigan, were sampled by the National Eutrophication Survey during 1972. The photograph covers a distance of approximately 185 kilometers along each edge.

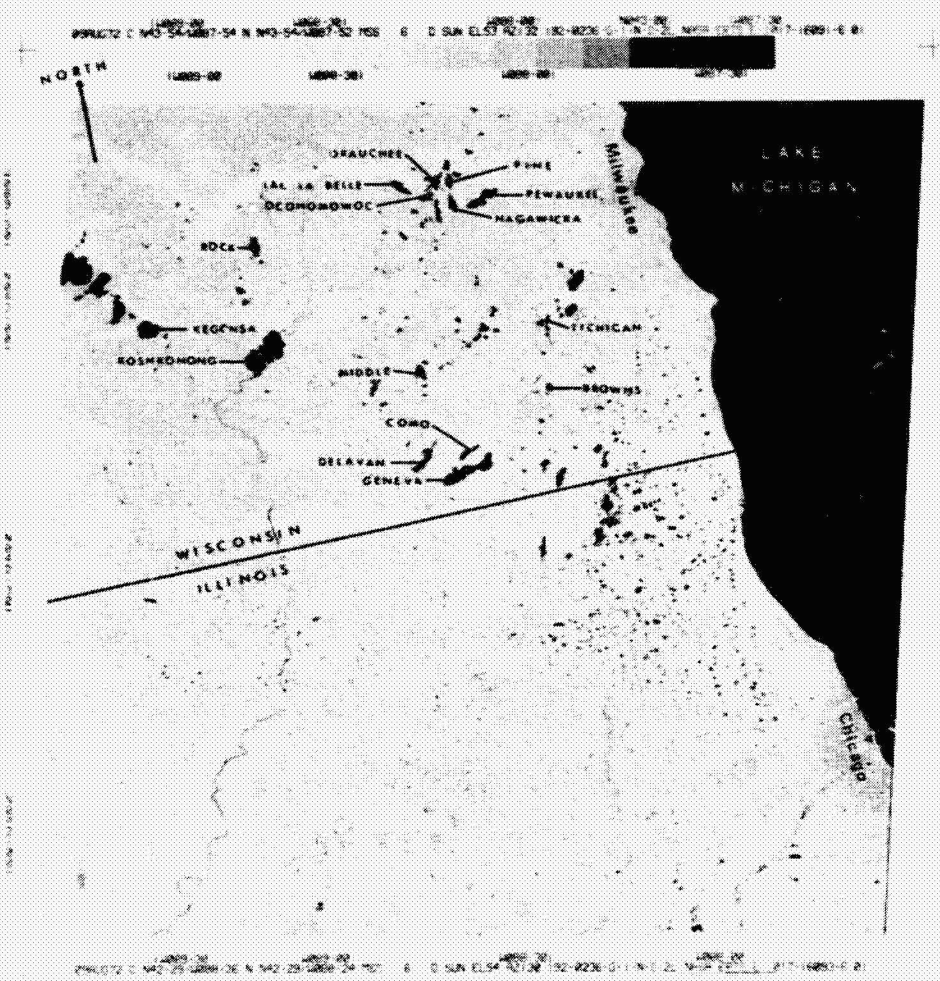

Figure 3. Reproduction of EROS IR1 print of Scene 1017-16093 (9 August 1972). Surface patterns are evident on some of the lakes (e.g., Lake Koshkonong). Each edge of the picture is equivalent to a ground distance of approximately 185 kilometers.

Figure 4. Reproduction of EROS RED (MSS Band 5) print of Scene 1017-16093 (9 August 1972). Variations in gray tone are readily apparent among the lakes and suggest differences in water quality. Lake Geneva, characterized by relatively high water quality, is dark in tone compared with, for example, eutrophic Lake Koshkonong. The small ball-like white objects between Milwaukee and Chicago are cumulus clouds. Each edge of the picture is equivalent to a ground distance of approximately 185 kilometers.

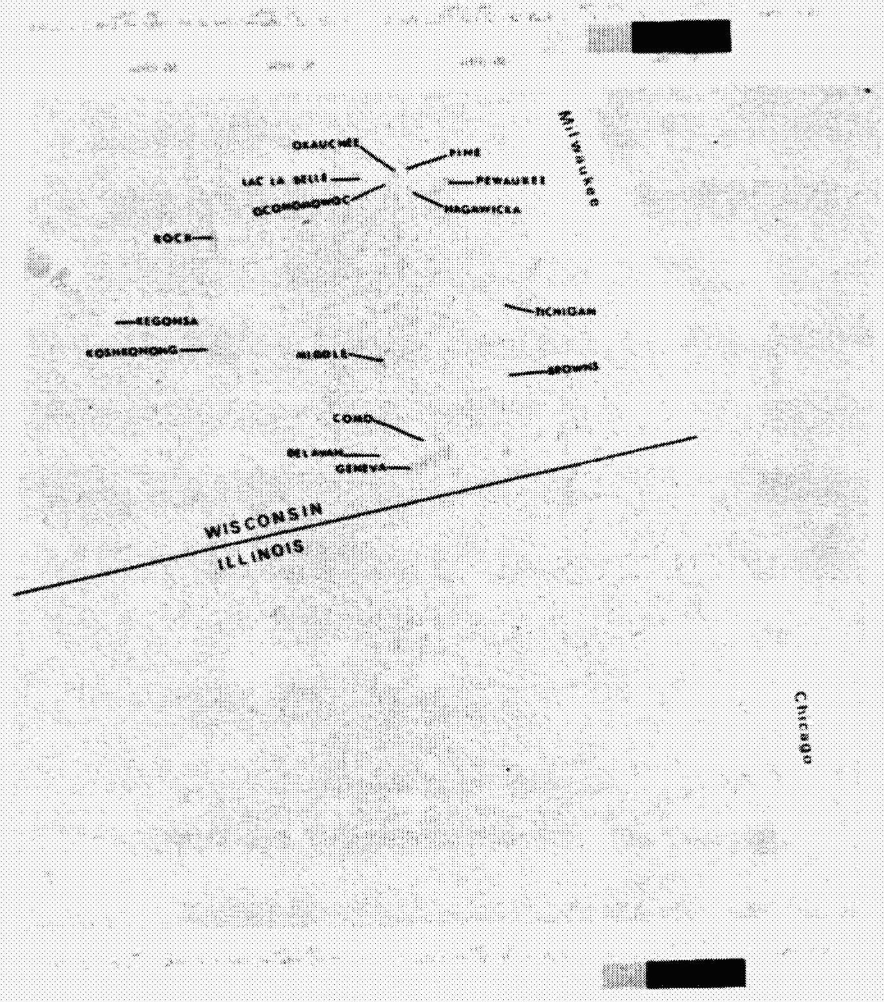

Figure 5. Reproduction of EROS GRN (MSS Bard 4) print of Scene 1017-16093 (9 August 1972). Scenes recorded in the green band generally lack contrast, but contain information useful in monitoring earth resources.

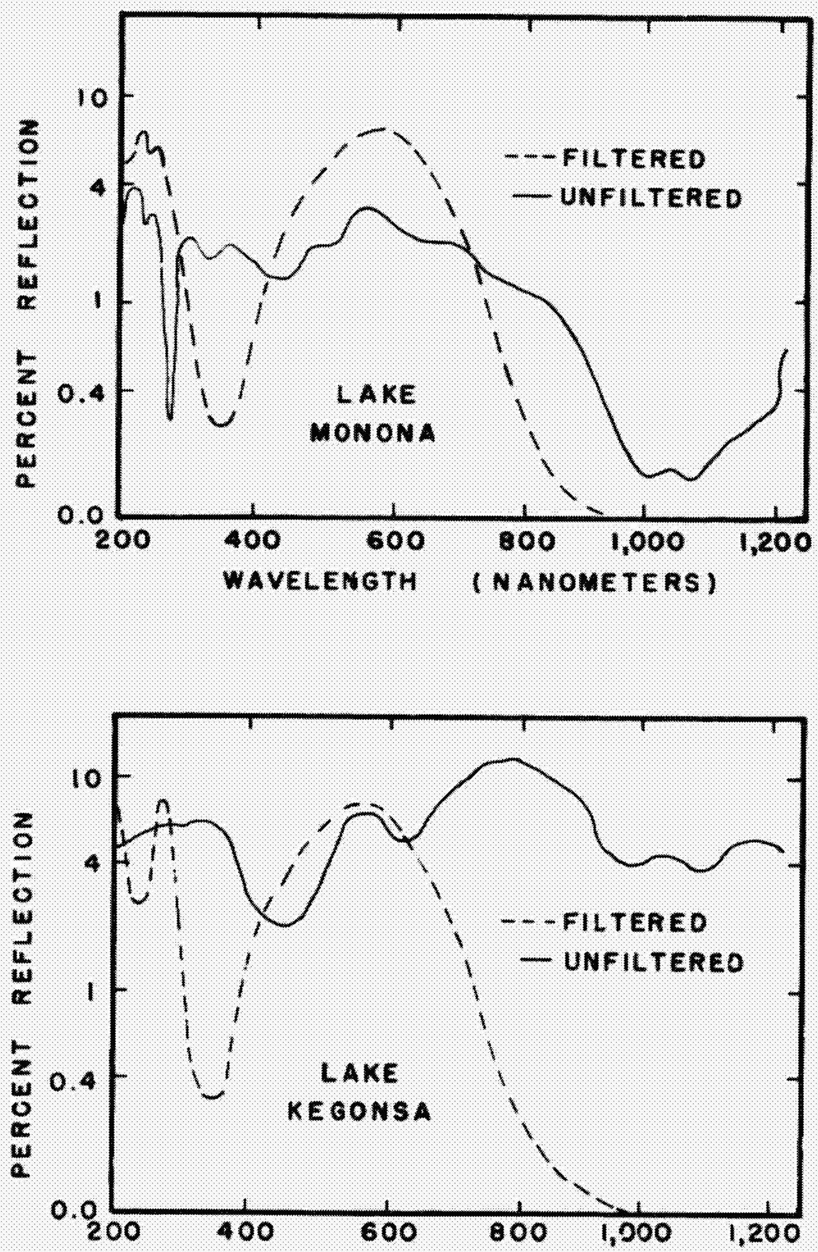

Figure 6. Reflection characteristics of filtered and unfiltered water samples from two Wisconsin lakes in the area of Madison. Adapted from Scherz, et al. (ref. 2).

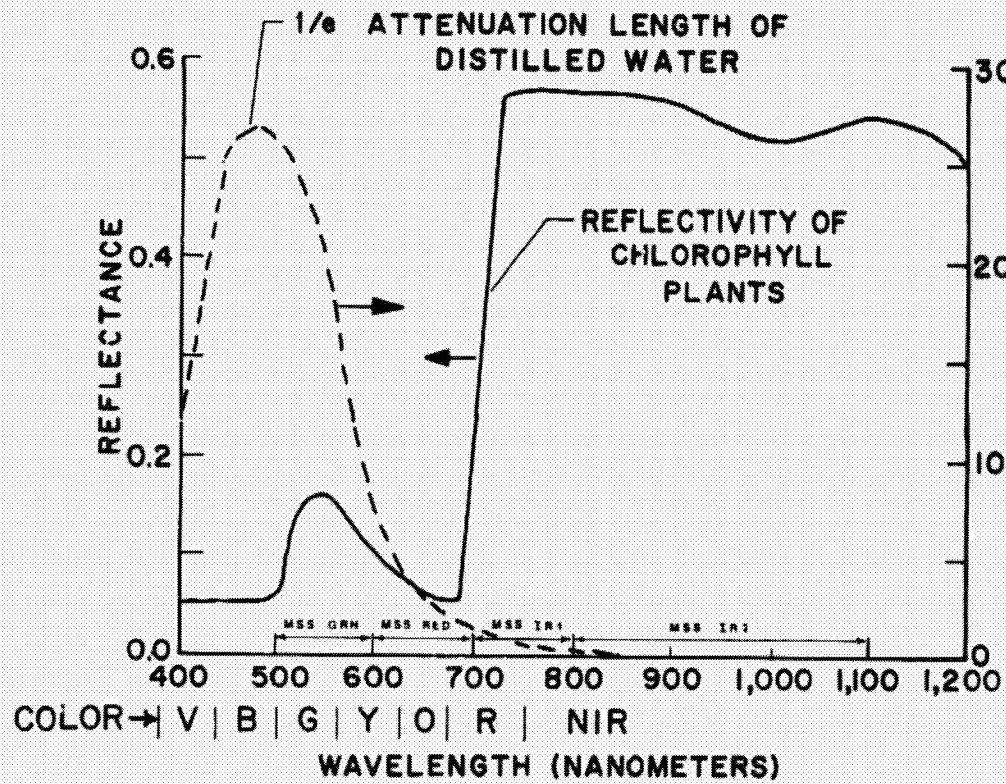

Figure 7. Comparison of the reflectance of chlorophyll-containing plants with the attenuation length of sunlight in distilled water. From Bressette and Lear (ref. 5). The attenuation curve is based on Spiess (ref. 6) and the plant reflectivity curve on Katzoff (ref. 7).

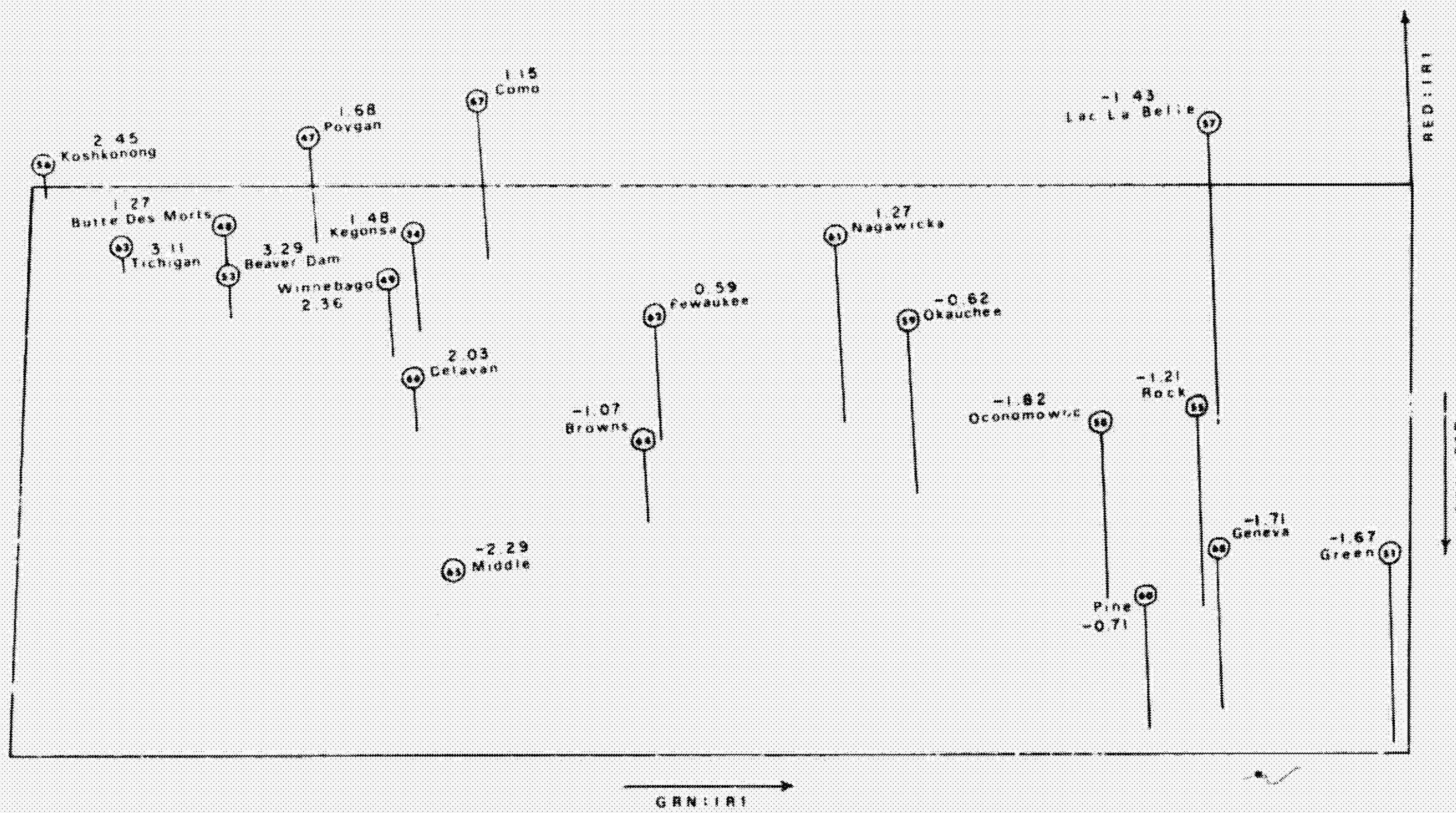

Figure 8. Three-dimensional color ratio model for 9 August 1972. The 20 Wisconsin lakes were extracted from LANDSAT-1 MSS Scenes 1017-16093 and 1017-16091. The scenes are in juxtaposition on the same flight line. The numerals inside the "balls" are lake serial numbers. The numerals near the lake names represent lake position on a trophic scale. Water quality decreases as the trophic index increases in magnitude.

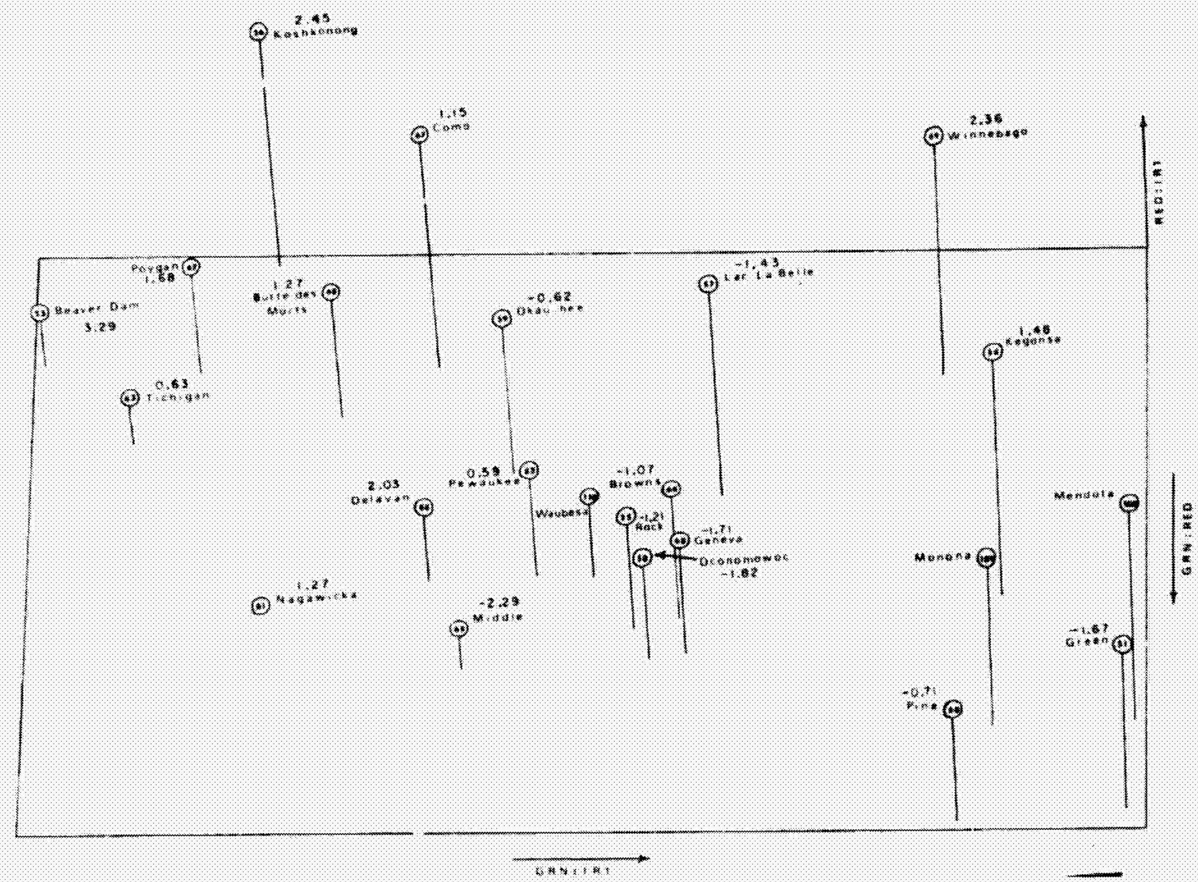

Figure 9. Three-dimensional MSS color ratio model of 8 Minnesota lakes extracted from LANDSAT-1 MSS Scene 1346-16381 (4 July 1973).

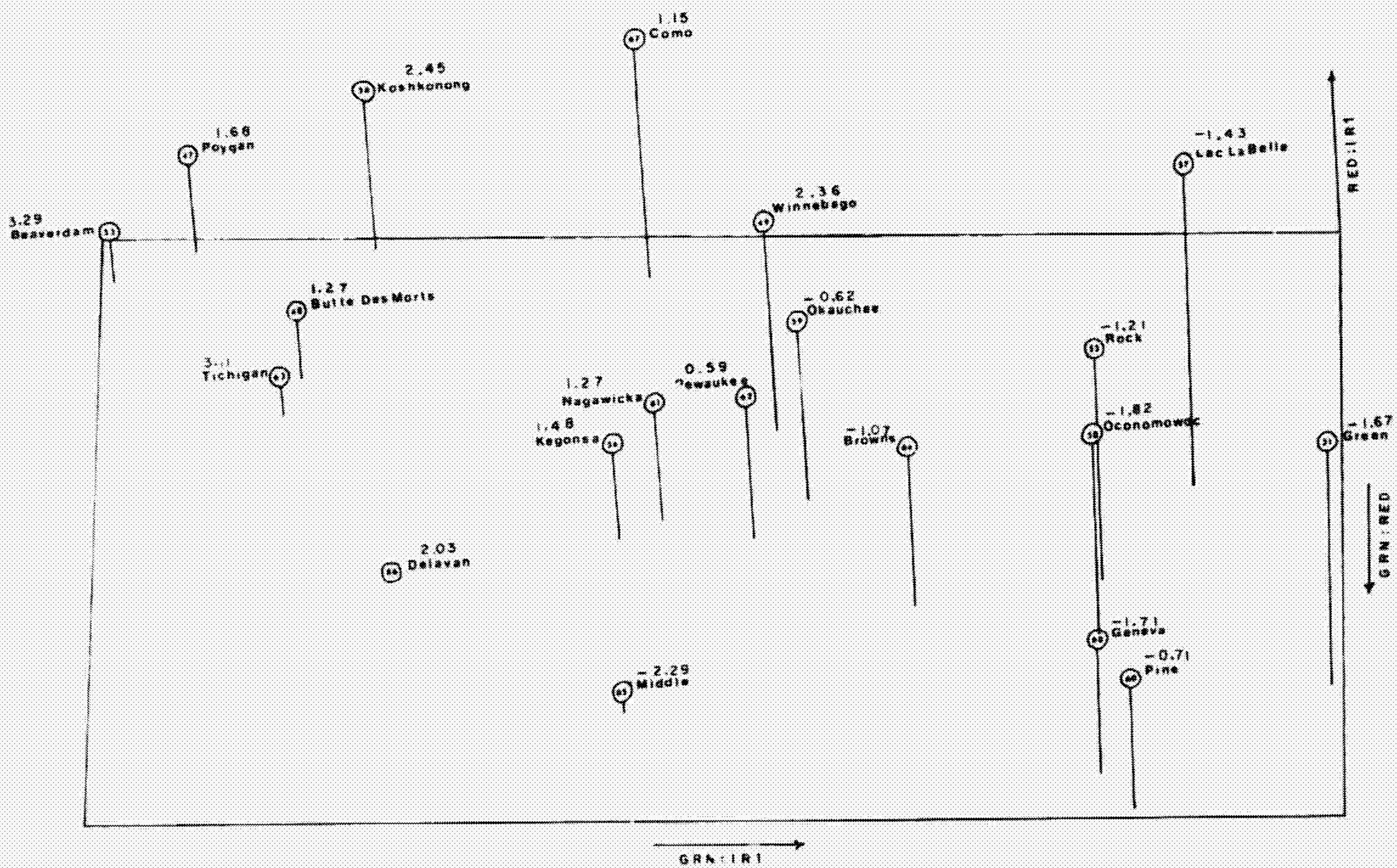

Figure 10. Three-dimensional color ratio model for 11 June 1973. The 23 Wisconsin lakes were extracted from LANDSAT-1 MSS Scene 1323-16100. Three of the lakes (Mendota, Monona, and Waubesa) fall outside the scope of the investigation, but are included because they are well-known by lake scientists.

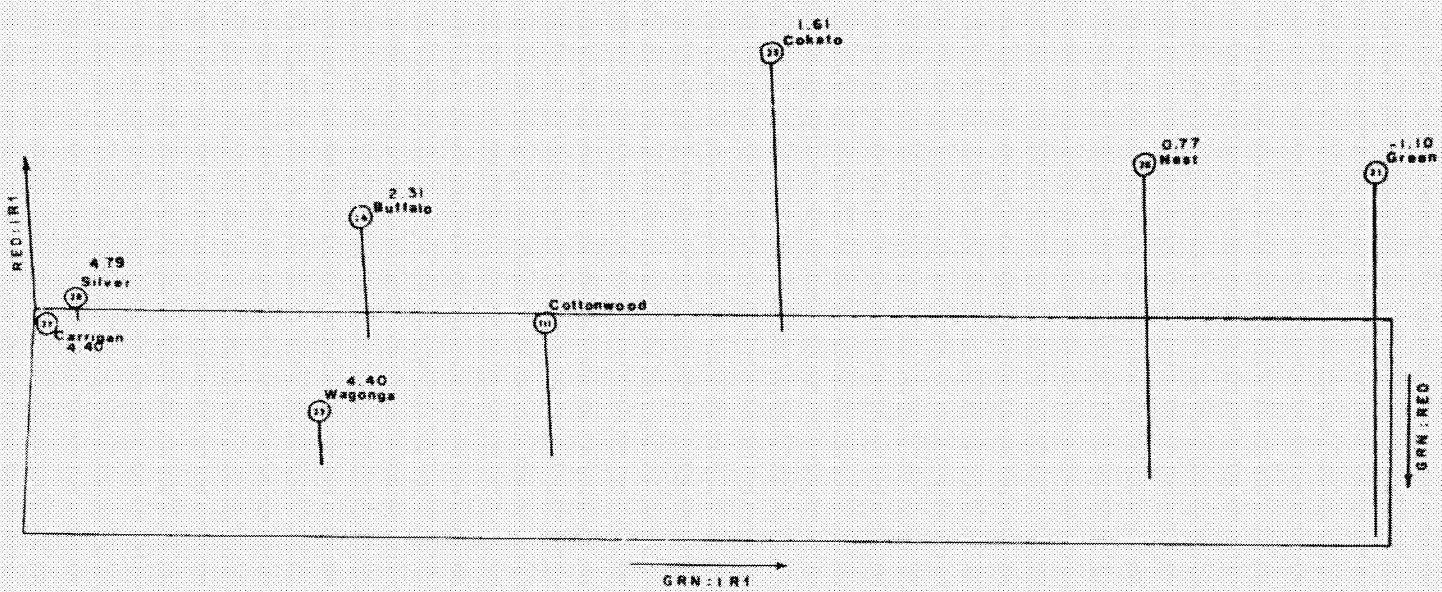

Figure 11. Three-dimensional color ratio model for 17 July 1973. The 20 Wisconsin lakes were extracted from LANDSAT-1 MSS Scenes 1359-16091 and 1359-16094.

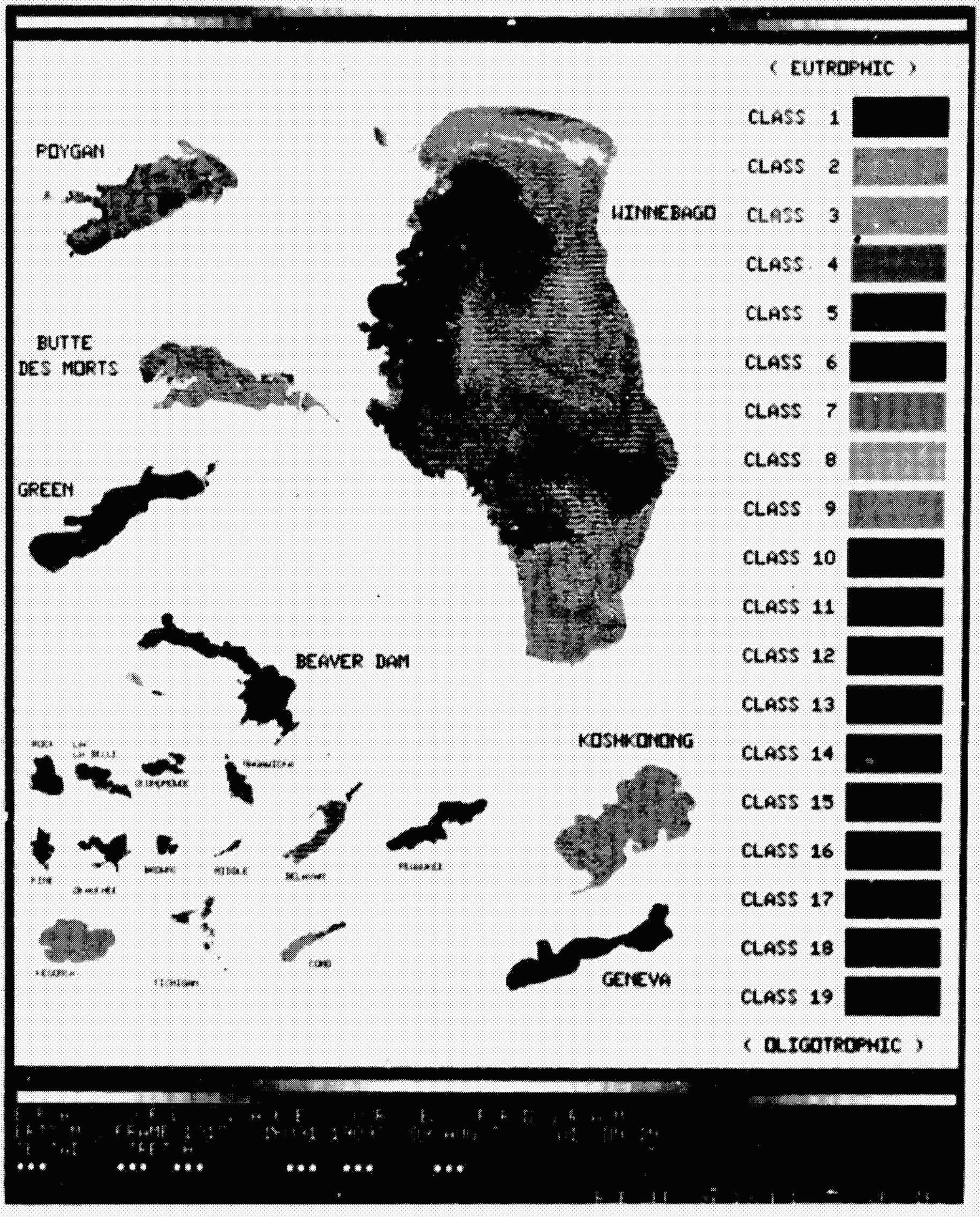

Figure 12. A color-coded concatenation of the 19-class classification of 20 Wisconsin lakes (9 August 1972). The scale labels merely indicate direction on the trophic scale.

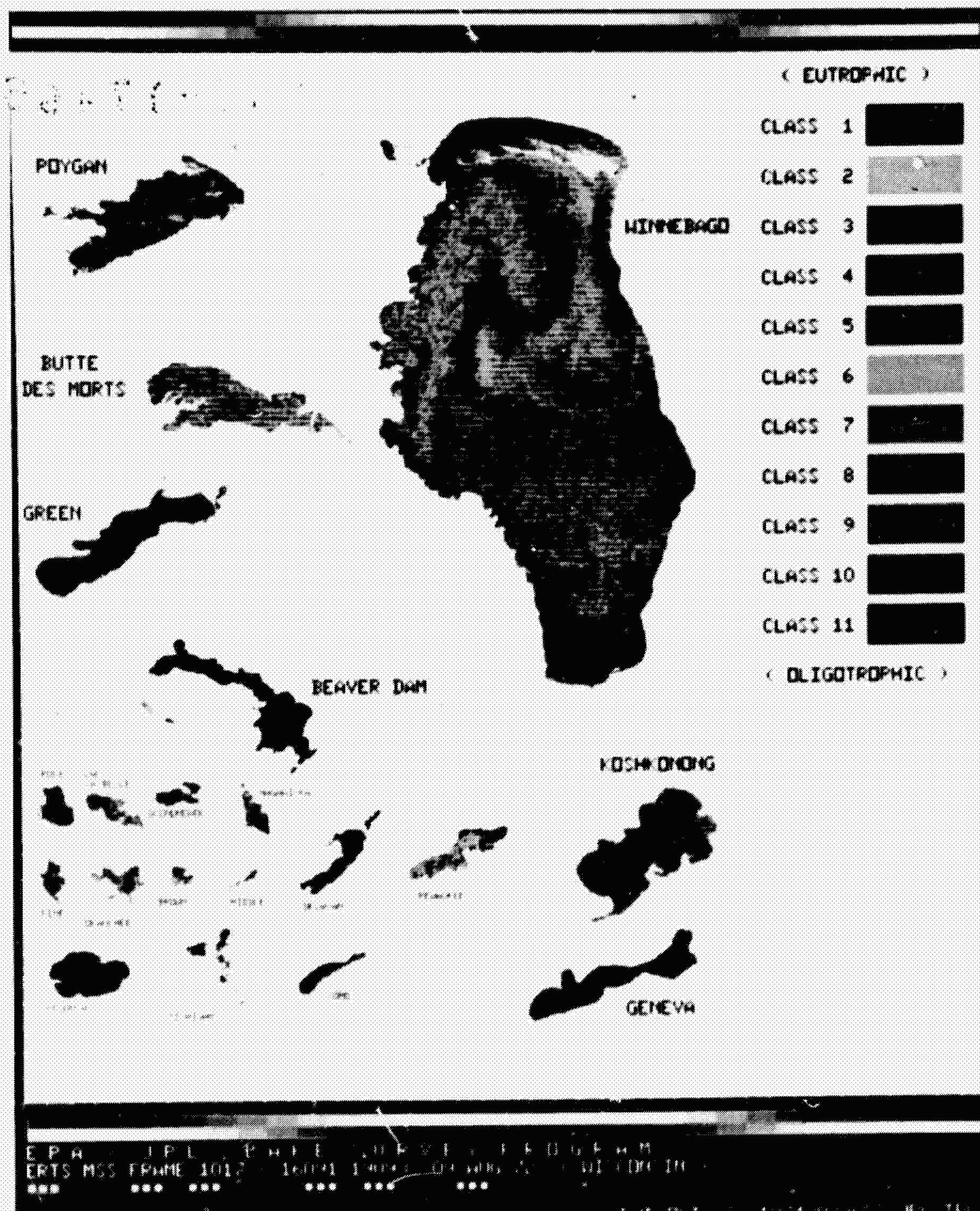

Figure 13. A color-coded concatenation of the 11-class classification of 20 Wisconsin lakes (9 August 1972). The scale labels merely indicate direction on the trophic scale.