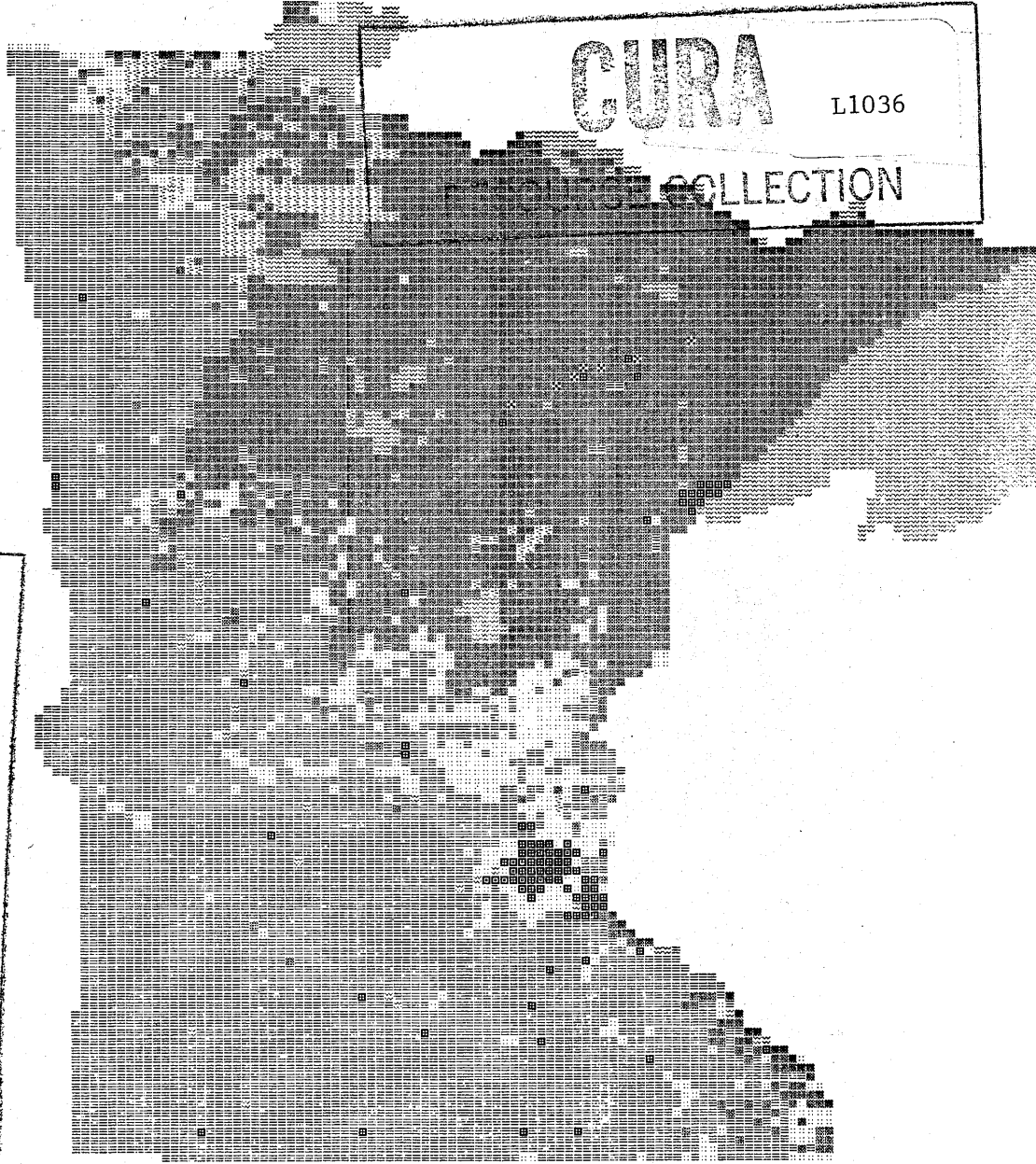


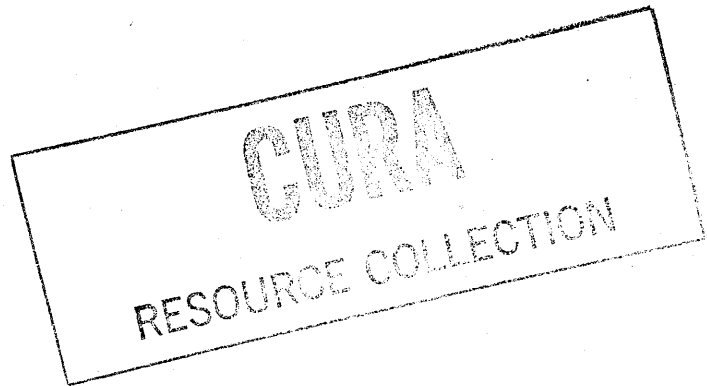
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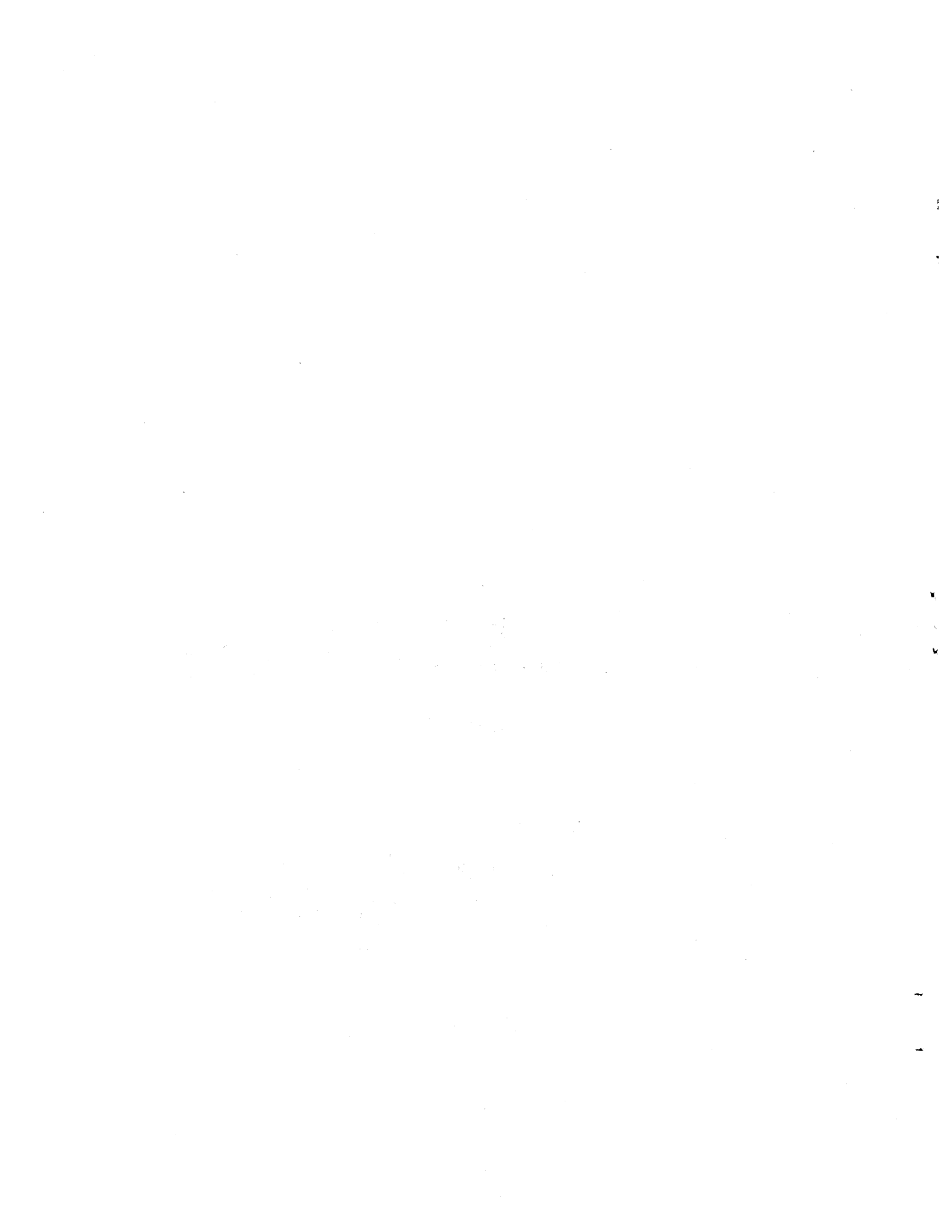
STATE PLANNING AGENCY

**RECONNAISSANCE ANALYSIS OF LAKE CONDITION
IN EAST CENTRAL MINNESOTA**

5022

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ROBERT WARWICK
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ABSTRACT

The condition of East Central Minnesota Lakes is examined using LANDSAT digital data on lake reflectance for August 7, 1975. Lakes are grouped into condition classes by multiple discriminant function analysis, which groups lakes of unknown condition around lakes of known condition, according to the satellite measured reflectance. The centroids of these classes are selected to maximize differences in condition. The data extraction methods are described and the classification is discussed and presented in map form. Problems of cell size of analysis and wind effects are described along with the limitations imposed by single time period analysis.

LANDSAT measured lake reflectance seems to provide a valuable means of extending secchi disc transparency measurements, which provide the necessary basis for reconnaissance analysis of lake condition using LANDSAT data.

INTRODUCTION

This paper attempts a reconnaissance analysis of lake conditions in East Central Minnesota based on the interaction between incident light and the materials contained in lakes, which results in selective absorption, transmission, reflection, and scattering of the spectral components of incident light. The reflectance spectra resulting from incident solar energy - lake material interactions, as collected by the LANDSAT satellite, are employed to evaluate lake condition.

This report will briefly describe the basis for using reflectance of solar energy to monitor the condition of lakes, review the study area, and provide the background of LANDSAT data applications

to problems of lake condition. The analytical procedures will then be outlined, the results evaluated, and finally conclusions drawn about lake conditions and the problems and prospects of performing reconnaissance analysis of Minnesota Lake conditions with LANDSAT data. The term "reconnaissance analysis" implies that the results should be a first look at lake conditions to guide detailed ground based analysis and not as the final word on condition. It is hoped that the map will give water resource planners, managers, policy formulators, and limnologists some idea about the locations and numbers of lakes in general condition classes.

BACKGROUND

The interaction of solar radiation with the water, the material it contains, and lake bottom materials are fundamental to the application of satellite collected data to a reconnaissance analysis of lake conditions (Figure 1). The LANDSAT scanner system detects the intensities of reflected green light (.5-.6 μm , band 4), red light (.6-.7 μm , band 5) and two spectral bands of reflected near infrared radiation (.7-.8 μm , band 6; and .8-1.1 μm , band 7). Unlike true or thermal infrared, bands 6 and 7 do not detect thermal differences but do respond much like the visible bands to wet, black plowed fields and to bright white snow or clouds. The important difference comes in the way the near infrared bands respond to growing plants and to water. While plants are actively photosynthesizing they reflect very high portions of the near infrared radiation. When plants die or become dormant the infrared reflectance falls off dramatically, even though they remain green. Most of the near infrared radiation is absorbed by the first meter of pure water while over 95% of green and almost 80% of the red spectral bands penetrate the top meter of water (Figure 2). The differential water transmittance of green and near infrared

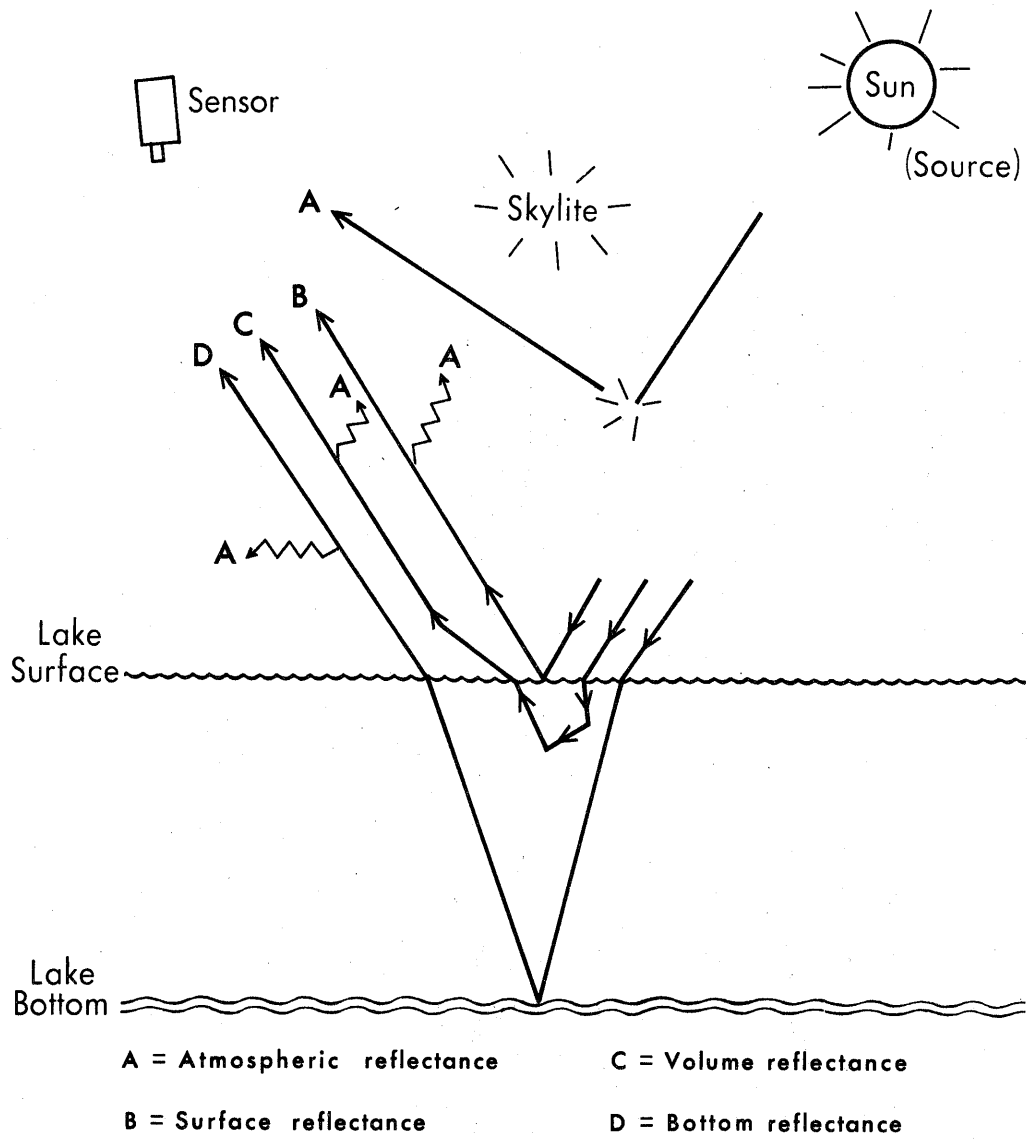


FIGURE 1. Reflected solar energy flows for a lake.

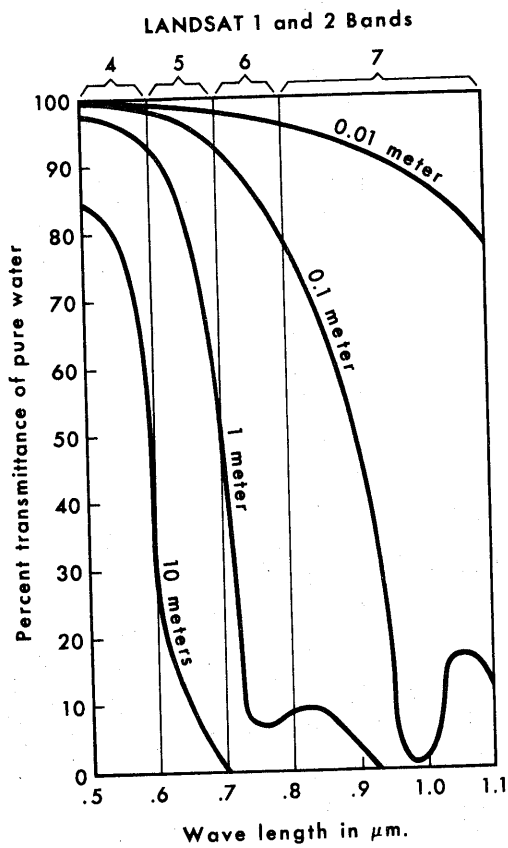


FIGURE 2. Spectral transmittance of pure water for different path lengths (Adapted from Work and Gilmer, 1976).

radiation can be used to infer that aquatic vegetation is at or near the surface if both the green and the near infrared bands show strong signals, if only the green reflectance is high, the aquatic vegetation is probably a meter or more below the surface.

Bottom conditions of shallow lakes create considerable difficulty for interpretation of lake condition. Shallow, clean lakes with muck bottoms produce a reflectance spectrum that is very similar to that for a deep, clear lake with heavily tannin stained water. Further complications arise where lake bottoms are visible only to green light. Under these conditions a 50% cover of bottom vegetation over muck would appear as a much lower reflectance than over a light colored bottom. When the lake is shallow enough for red light to be reflected from the bottom, it can show a response only to the light colored sediments, and bottom sediments can be differentiated from vegetation.

Where algae produces a high green reflectance the relative depths of algal concentrations may sometimes be inferred from the differences between the amount of reflection detected by band 6 and band 7. Band 7 reflectance increases with algae in the first half meter of the water column. The response to suspended mineral sediments also can be detected; but, the spectral response depends on sediment color. In some instances it may be necessary to use spatial patterns to separate the signal of suspended mineral sediments from algal concentrations.

STUDY AREA

The area included in this applications study incorporates a variety of lakes, mostly natural and of late Wisconsin glacial origin. The lakes are water filled depressions on glacial till and outwash

with a few reservoirs on major streams. Three major groups of lakes lying northeast, northwest, and south southwest of the Mississippi and Minnesota Rivers junction are included. The surrounding land cover grades from urban metropolitan, surrounding the rivers' junction, to forest, marsh, grass, and modest agricultural crops to the northeast, to agricultural crops, marsh, and some forest to the northwest. Agricultural crops dominate to the south-southwest. Over 1000 lakes larger than 20 hectares (50 acres) are included in the area that covers all or parts of 18 east central Minnesota counties.

The area was selected because it contained the highest concentration of lakes with existing current information on lake transparency and because of the recreational importance of lakes in the most populous region of the state. LANDSAT reflectance data from 81 lakes with known transparency formed the basis for classifying and describing lakes of unknown condition. From this lake inventory 421 of the larger lakes were selected for study.

METHODOLOGY

A number of studies have developed a variety of methodologies and procedures that use LANDSAT data and the solar energy flux for lakes to interpret lake conditions (Boland, 1974; Scherz, 1975; Rogers et al., 1975 and Warwick, 1977). The techniques have been further applied to specific problems or areas by Scherz (1977) and by Brown et al., (1977). Most of these researchers used LANDSAT digital tape data and differ primarily in the ways that data are extracted, size of the study unit, method of classifications, and degree of automation. Warwick (1977), who studied the use of both digital tape data and less expensive black-and-white film transparencies, found the latter produced different results on several data

extraction trials with both a density slicer and a micro-densitometer. Scherz (1977) used a Bendix interactive system to classify individual ground resolution cells (pixels). Warwick also used the system in a brief experiment. Although such a system has time and certain other advantages, it was not employed in this study.

Non-automated data extraction from digital tapes was selected over the Bendix or similar interactive systems because it was considered more important to classify whole lakes or bays rather than pixels because the former are normally the management units. Additionally, variations among the LANDSAT 1 detector elements were considered to create problems especially in band 7, where small variations created important classification changes in sample studies by Warwick (1977). Brown et al. (1977) attempted to minimize the effect of detector element differences on classification by averaging multiple pixel data for polygons including data from several detectors.

Although multiple date classification is not attempted in this classification it was used by Brown et al. (1977) and could be done, given adequate LANDSAT data, with the methods employed in this study. The cost of using multiple dates in an automated system that classifies individual pixels would multiply rapidly because of the need to pre-register multiple date scenes, making data input costs climb from approximately \$200 per ground scene to about \$2000.

DATA EXTRACTION

The data for lake classification in this study were extracted from LANDSAT 1 digital tapes for August 7, 1975. The tapes were reformatted using programs developed by Minnesota Land Management Information Systems personnel. These programs produced reformatted

tapes in the Environmental Planning Programming Language (EPPL4) and imposed a grid system on the reformatted tapes. Other programs were used to print the reflectance data for the area surrounding each lake or group of lakes included in the study at a 1:31,000 scale. The study was limited to major lakes, including most lakes over 40 hectares (100 acres). Some smaller lakes were included to help define the lake classes if ground based information was available.

A computer printout map was produced for the reflectance values of each of the four LANDSAT multispectral scanner (MSS) bands. The previously mentioned need to classify whole lakes or bays and the need to avoid the bias of a single detector made it desirable to extract an average response taken from several scan lines in a polygon that, if possible, avoided edge and shallow water effects. These polygons of generally 20 pixels (9 hectares or 22 acres) were identified and outlined on band 7 computer printout. The band 7 printout was then successively registered on the other three bands on a light table, the polygons outlined, and the values recorded and averaged by hand. In some larger lakes multiple samples were taken, e.g., 22 sites in Lake Minnetonka were sampled. In all a total of 619 observations for 421 lakes were classified with LANDSAT data. Ground collected data for 81 lakes were used to define and describe the classes of lake condition.

CLASSIFICATION

The classification procedure employed multivariate discriminant analysis to assign each of the 619 observations to one of 10 classes. A discriminant function routine was selected as opposed to the cluster analysis used by Brown et al. (1977) because the large number of samples to be classified would be much more costly with cluster

routines and would necessitate modifying available programs. The ground data for 81 lakes was used to identify the classes necessary for discriminant analysis, which groups the lakes of unknown condition according to their reflective similarities to the pre-defined groups. Forty-four lakes with ground data were used to specify 10 groups, and the remainder of the lakes with ground data were grouped in the same manner as those with no ground data. These lakes of known condition were used in developing class descriptions. Use of cluster analysis would not identify the probability that a lake is similar to more than a single class of water condition, which is useful information because of the intergrades that exist between the artificially discrete classes.

Table 1 shows the number of observations which were statistically similar to more than one class, with .30 - .49 and .10 - .49 probabilities of being members of a second class. Six classes were aggregated from the original ten classes to simplify the map. Table 1 illustrates the near border relationships between the water condition of a number of observations in each class. The percentage of observations in each class with a less than .10 and less than .30 probability of being in a second class gives an idea about the clustering of observations around the class cores. It also provides insight into the degree of confusion among the classes.

The lakes were mapped according to the dominant class identified from the discriminant analysis (Map inside back cover). Most lakes have been classified as a unit although multiple observations from some of the larger lakes were treated independently in the discriminant analysis. Where the classification of the multiple observations differed within a lake, possible bottom effect classes were ignored and the resulting classification represents the best conditions found

TABLE 1. -- NUMBER OF OBSERVATIONS WITH MODERATE OR HIGH PROBABILITY OF A SECOND CLASS MEMBERSHIP BY FIRST AND SECOND MOST PROBABLE CLASS OF MEMBERSHIP

Class Assignment	Second Most Probable Class														% with Probability of Second Class Assignment of:		Total in Class
	.10-.49 Probability of Second Class Assignment							.30-.49 Probability of Second Class Assignment									
	1	2	3	4	5	6	Sub-Total	1	2	3	4	5	6	Sub-Total	<.10	<.30	
1	-	0	2	3	0	0	5	-	1	8	6	0	0	15	83	94	88
2	0	-	3	0	1	0	4	0	-	12	0	2	0	14	75	91	55
3	1	1	-	3	0	0	5	5	5	-	10	9	0	29	68	94	90
4	8	0	6	-	3	1	18	12	0	15	-	13	4	44	78	91	204
5	0	1	3	1	-	0	5	0	2	6	8	-	0	16	79	93	76
6	0	0	0	3	0	-	3	0	0	0	7	0	-	7	93	97	106

in the lake except where relatively discrete bays are classified differently. Lake Minnetonka, because of its many distinct bays, was treated differently. Samples of 22 areas were used to assign various parts of the lake to different classes.

The descriptions of the six mapped classes were interpreted from the 81 ground based transparency observations that were included in this study. The range in conditions of the ground data sub-set is not as great as for the entire group of study lakes. This is to be expected because ground data are collected from lakes of greater public importance, which is selective and biased toward larger, deeper, better quality lakes. This bias created problems for separation of shallow lakes with visible dark bottoms.

Differences in the reflectance spectra for the different lake classes can be seen more easily when the reflectance from a very clear lake, in this instance the average of Square and Christmas lakes, is subtracted from the mean spectra of the centroid around which lakes of unknown condition are assigned. These residual curves are shown in Figure 3.

Where two residual curves are shown in Figure 3, two different groups of lakes were used in the statistical classification procedure and later combined for mapping purposes. The general characteristics of these combined classes are similar, but they differ in the concentrations of material in the water. The within class variations are controlled by the degree to which the training set incorporates the full range of lake conditions. Class 7 is the prime illustration of this problem. In the discriminant analysis these shallow lakes were grouped in class 1. Sixty percent of these lakes are transitional between classes 1 and 3 or 1 and 4. The remaining 40% have

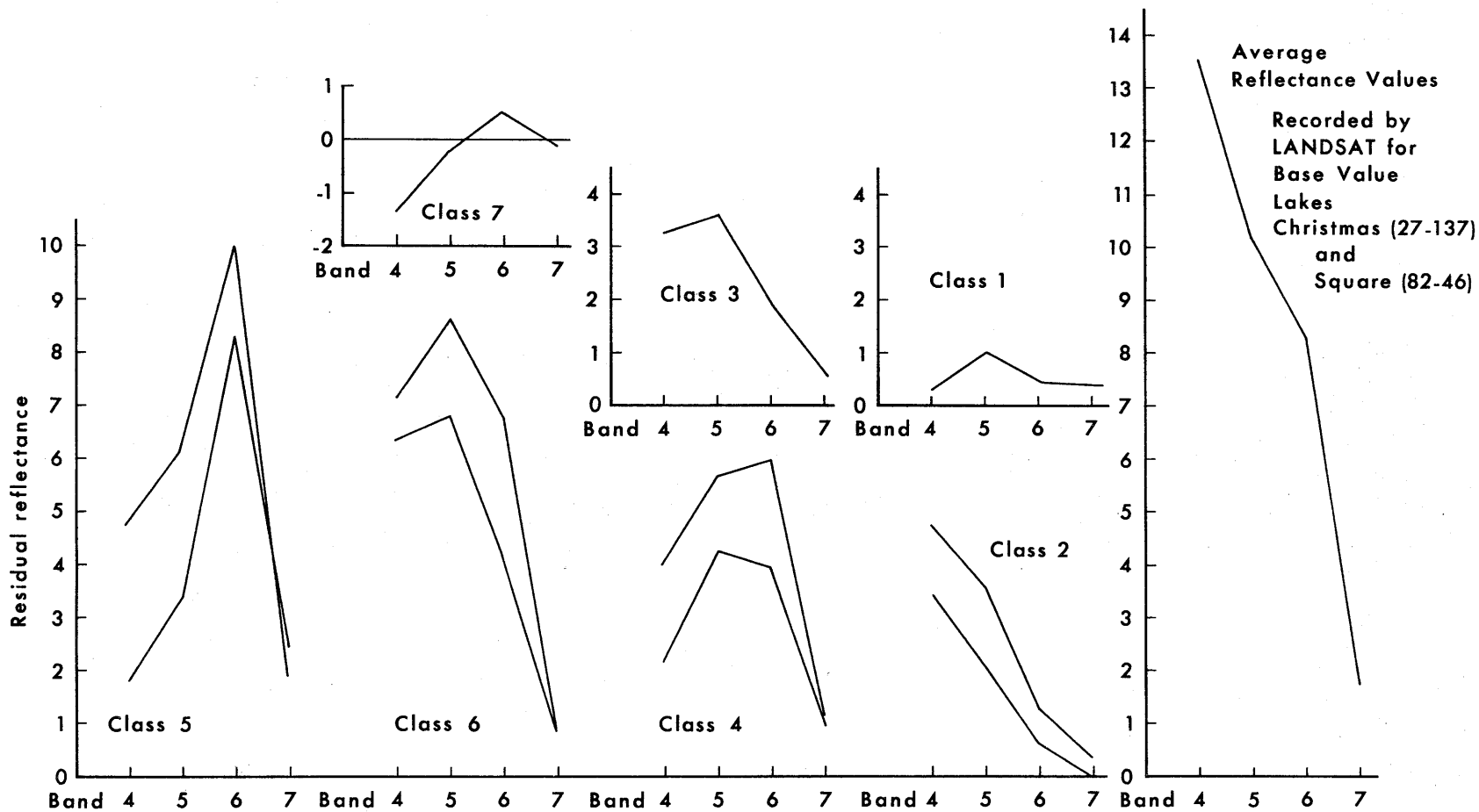


FIGURE 3. Residual reflectance for centroids of classes around which lakes of unknown condition were assigned by discriminant analysis. Residual values are the difference between the reflectance of lakes and the reflectance of a clear deep lake. The average for Christmas and Square Lakes was used here as the clear lake base. Class 7 is an extreme example of the clear, shallow lakes separated from class 1 because they were known to be shallower than the minimum transparency of 240 cm for class 1.

generally lower residuals on bands 4 and 5 and slightly higher residuals on band 6 than the class 1 centroid. If a clear shallow lake with a visible dark colored bottom had been included in the training set along with similar lakes with some algae and weeds, the post classification separation of class 7 might not have been necessary.

Lakes in class 1 as mapped generally have clear water and are tightly clustered. Class 2 lakes are relatively clear in the top meter, with weeds or algal concentrations in the lower illuminated zone. Class 3 lakes have higher algal concentrations and lower transparencies than class 2 lakes. Lakes in class 4 are either shallow with dark bottom sediments or have tannin stains. In either case algae and possible bottom weeds are present in sufficient quantity to produce a transparency range of 70-170 cm.

Conditions in class 5 lakes are similar to class 4 but algal concentrations are higher, resulting in lower transparency. Class 6 lakes are dominated by medium to heavy populations of algae, and have transparencies of 15-100 cm. Class 7 lakes are shallow, with some algae and weeds, but transparency generally exceeds depth.

The degree to which the classes intergrade into one another can be seen by analyzing the relative frequency of high probability of secondary class membership (Table 1). About 22% of the class 2 members have a probability of .10 or greater of class 3 membership. Few lakes in other classes have strong secondary probabilities of a class 2 assignment.

Class 3 has considerable transitional problems with 4 and 5 and to a lesser degree with 1 and 2. Class 4 is modestly confused with classes 3 and 5. The complex combination of conditions that are

found in this group indicate how numerous possible combinations of condition can produce similar reflectance spectra. Class 5 shows modest confusion with class 3 while class 6 shows very little confusion with any other classes.

The spatial pattern of the classes shown on the map (inside back cover) is difficult to analyze in terms of other resource information such as general land cover, soils, or geomorphology. About all that could be said is that there is a higher probability of a lake being in the better condition classes (1,2,or 3) in the northeastern part of the study area where somewhat more land remains in forest cover and less under cultivation or pasture. The most obvious conclusion that can be drawn from the map is that lake condition is strongly related local morphologic, drainage and,land cover conditions.

EVALUATION AND CONCLUSIONS

The only true evaluation of this reconnaissance analysis can come from scientists who study lakes and those with lake resource responsibilities. If it aids their work by guiding their ground based detailed studies effectively, it is successful; if not, it has failed to meet its objective. However, several technical evaluations related to problems of analysis and classification can be pointed out.

Alleviation of three problems encountered in this study might improve the results. First is the size of sample area of reflectance taken from each lake. The efforts to average reflectance over too large an area resulted in reduced homogeneity. This means that some sample pixels of deep, clear water may be averaged with pixels covering shallow areas or ones with emergent vegetation. The classification that results may be unsatisfying if compared with ground observations.

Lake Wabasso (82) in Ramsey County illustrates this case. It was classified as Class 4 when 20 pixels were included. By subtracting 7 pixels around the edge showing shallow-emergent vegetation, classification was changed to class 1 with reflectance values almost as low as the two clear lakes used as a base. The lake had several recorded transparency observations from late summer ranging from 3.5 to 5.5 meters, suggesting that the original classification was misleading.

The second problem is wind effect. On the morning of the LANDSAT overpass of August 30, 1975 the wind at Minneapolis - St. Paul Airport was southeast at 29 KM/hour (18 mph). This had some impact on the classification of pixels for some larger lakes. Lake Minnetonka and Bald Eagle both showed remarkably good conditions very near the windward shore of the lake and considerably higher concentration of algae on the down wind side (Warwick, 1977). Wind may be a partial factor in the dual classification of Lakes Waconia and Minnetonka. Either image dates should be selected to minimize wind or researchers should be aware of wind effects and sample lakes in a way that avoids a wind induced bias to the classification.

The third problem that should be avoided, if possible, is the limitation imposed by using only one date of LANDSAT coverage. Seasonal changes provide some insight into the biological calendar of lakes. Defining these seasonal trends should allow separation of lake condition problems by degree of severity. Differences in the seasonal dynamics of lakes that display similar spectral reflectance in August have been observed in western Minnesota Lakes (Brown et al., 1977), and may indicate variations in the thermal and nutrient regime. However, the validity of these inferences must still be substantiated by ground observations.

Cursory investigation of the results of reflectance spectral analysis without thoroughly knowing what on-the-ground observations might yield may lead to the conclusion that the procedures used here could substitute for on site studies. That is not the case. While LANDSAT reflectance data may extend the usefulness of secchi disc transparency data, it is also absolutely dependent on an abundance of ground-based transparency information to yield believable results. It should be kept in mind that this technique, which seems to the authors to be successful, extends a reconnaissance analysis and draws no conclusions about detailed lake water quality.

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ABOUT THE MAP

CONDITION OF SELECTED EAST-CENTRAL MINNESOTA LAKES

Purpose and Limitations

The map was made as an experiment to see if an analysis of reflected sunlight as measured by the Landsat satellite, could be used to allow us to take information from a group of well-known lakes and apply it to find out about a much larger number of lakes. Specifically, we would like to find out if the satellite can tell us about several different lake characteristics: the kind and amount of vegetation -- microscopic algae, floating or submerged plants -- in the water, the presence or absence of organic staining or suspended mud and other materials, the approximate depth of the water and the type of bottom if the bottom is visible.

The map is intended to assist people who are studying lakes by providing information on the distribution of lakes that appear similar. The classification scheme is a comparative one and is based on comparisons with Christmas Lake in Hennepin County and Square Lake in Washington County, two very clear and deep lakes.

The map is based on only one time period, August 7, 1975, and the conditions at that time should not be assumed to be the same at other seasons or in other years at the same season. On that date a strong southeast wind was blowing, and it appears to have moved some of the plants and suspended material in some larger lakes, and this may be responsible for the fact that some large lakes appear to have different characteristics in different parts of their basin areas.

How It Was Made

Lakes were classified according to the way green, red, and two bands of near infrared energy were reflected by the lakes, as measured the Landsat satellite. Different kinds of material in the water of a lake will reflect these four kinds of energy in different ways, and these apparent differences can be detected by the satellite, which measures the amount of reflected sunlight for each of the four types of light it monitors.

The classification was based around lakes whose condition was known when the satellite went over them; other lakes were included in a particular condition class if their reflectance pattern is close enough to the one for the "known" lakes that were used to define the class. The description of condition for each class was also aided by additional information about the transparency for some of the lakes that make up the class. Class 7 lakes are an exception. They were grouped by supplemental ground information on depth. It is possible that some members of class 1 belong in class 7 but could not be so assigned because of lack of depth information.

For additional technical information refer to Minnesota Land Management Information Report 5022 or contact Dwight Brown, Department of Geography, University of Minnesota, Minneapolis, MN 55455; phone, (612) 373-5372.

