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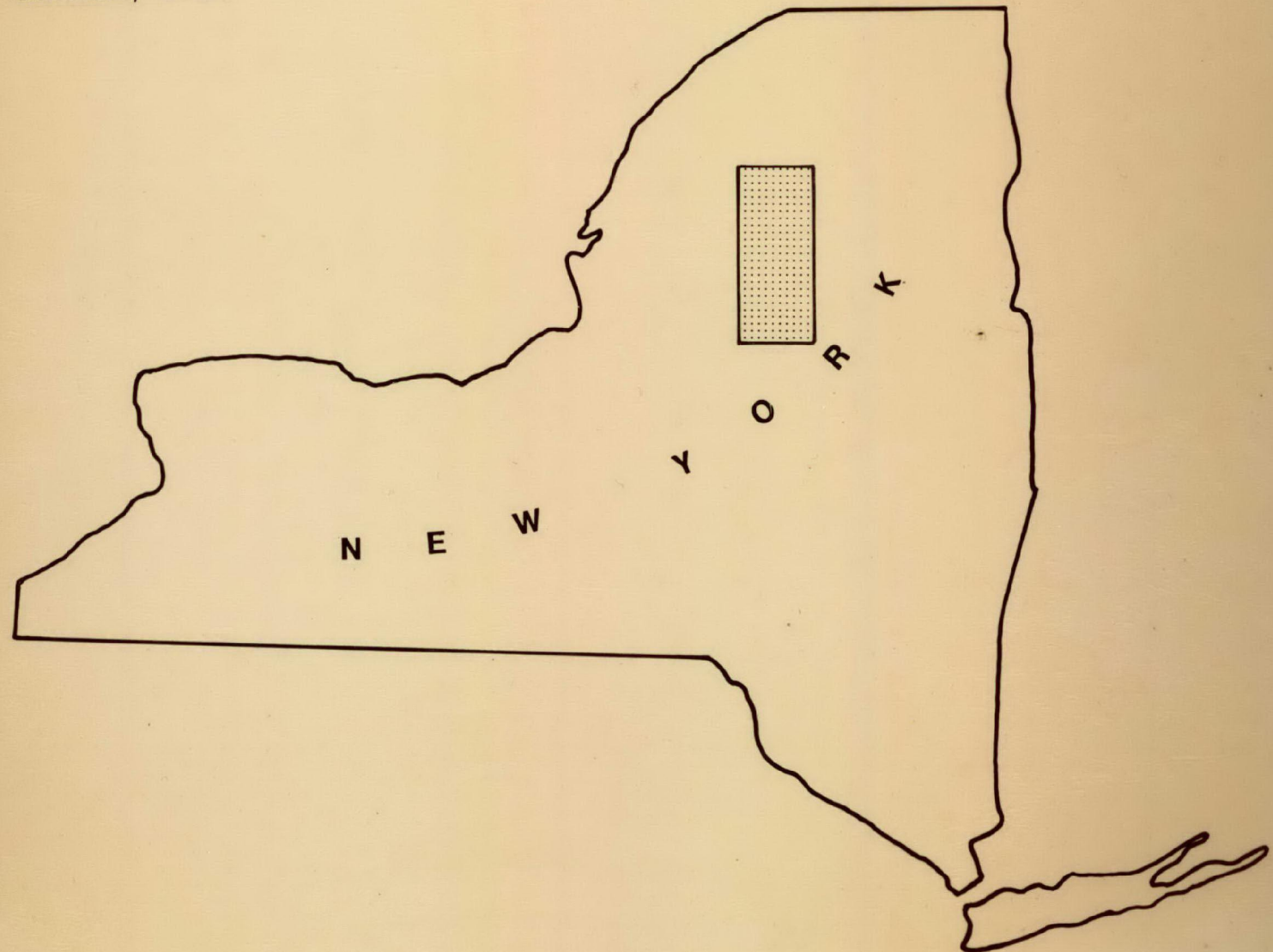
Environmental Monitoring
Systems Laboratory
P.O. Box 15027
Las Vegas, NV 89114

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ADIRONDACK LAKES ACID RAIN MULTISPECTRAL SCANNER SURVEY Adirondack State Park, New York

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Environmental Research Laboratory
Corvallis, Ore.



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ADIRONDACK LAKES
ACID RAIN MULTISPECTRAL SCANNER SURVEY

Adirondack State Park, New York

by

T. H. Mace
Environmental Programs
Lockheed Engineering and Management Services Company, Inc.
Las Vegas, Nevada 89114

Contract No. 68-03-3049

Project Officer

G. A. Shelton
Advanced Monitoring Systems Division
Environmental Monitoring Systems Laboratory
Las Vegas, Nevada 89114

ENVIRONMENTAL MONITORING SYSTEMS LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
LAS VEGAS, NEVADA 89114

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ABSTRACT

During the fall of 1981, the U.S. Environmental Protection Agency's Environmental Monitoring Systems Laboratory at Las Vegas, Nevada, conducted an aerial overflight and multispectral analysis of a portion of Adirondack State Park, New York with its 11-channel multispectral scanner to determine if relationships existed between acid rain-related water quality data and scanner imagery. Concurrent water sampling and laboratory analysis was conducted by Paul Smith's College and the USEPA Environmental Research Laboratory, Corvallis, Oregon. Strong linear relationships were found between the multispectral scanner data and the water quality parameters of Secchi depth and dissolved organic carbon. Weaker linear relationships were found between the scanner data and phaeophyton, chlorophyll a, total suspended solids, pH, and alkalinity. pheophytin

Radiances in the red and near-infrared regions of the spectrum proved most useful, and the results of this study suggest that the Thematic Mapper multispectral scanner aboard the Landsat D satellite may be useful for monitoring of water quality parameters related to acid precipitation effects.

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INTRODUCTION

THE NATURE OF THE PROBLEM

The effects of acid rain on the environment are among the most pressing environmental issues facing the industrial countries. Atmospheric pollution, caused by fossil fuel combustion, is carried across state and national boundaries producing national as well as international environmental degradation.

Scores of articles have been published outlining the possible effects of acid precipitation on sensitive areas, and no attempt to reproduce them will be made here. It may, however, be useful to outline some of the effects suggested by the literature.

Generally, sulfur and nitrogen oxides are produced in the process of fossil fuel combustion. These oxides combine with other atmospheric constituents to produce sulfuric and nitric acids. Normally, these acids would be buffered by atmospheric carbon dioxide to produce a pH of approximately 5.6 in rain. However, the pH of rainfall throughout most of the eastern United States has been reported at about 4.0 (Galloway et al., 1976).

This "acid rain" phenomenon has many, often conflicting, effects. Among these effects are increased erosion of statuary and historic buildings, crop and forest productivity reduction, increased acidification and leaching of soils, and degradation of biota in rivers and streams. These effects are particularly severe in those areas of crystalline bedrock and naturally acidic soils, where cation exchange capacity (buffering) is relatively low. Lakes and streams in these areas are very poorly buffered, and the plant and animal species reduction which results is severe.

As the lakes become more acid, organic matter decomposition decreases. Leaf

litter increases on the lake floor and a fungal mat may spread along the bottom. Additionally, magnesium and aluminum ions are liberated from the bottom sediments, increasing their concentrations in the lakes, while phosphorous decreases. The effect on biota is dramatic. The distribution and extent of macrophytes, phytoplankton, aquatic invertebrates, and fish decreases markedly (Baalsrud et al, 1976).

These effects have been severe in the Adirondack region of New York both in extent and rapidity of development. "A recent survey found that 51% of mountain lakes (217 lakes at an elevation above 600m) have pH values below 5.0; 90% of these lakes contain no fish. In contrast, during the period 1929-1937, only 4% of these lakes had a pH under 5.0 or were devoid of fish" (Likens, 1976, p. 43).

This rapid change in environmental conditions creates an environmental monitoring problem. At one extreme, investigators have suggested that water chemistry measurements should be made in lakes 5-10 times each year and during periods of limnological change (Dochinger and Seliga, 1976). However, which lakes should be sampled, and how can we optimize such a costly program? Remotely sensed measurements may provide a cost-effective environmental monitoring tool to reduce the number of water samples required for a regional monitoring program. Such programs have been successful in the past for lake trophic classification (Witzig and Whitehurst, 1981), and it is possible that digital analysis techniques may be applicable to the monitoring acid rain effects as well.

THE CURRENT STUDY - SCOPE

This study represents the first of a series of experiments to determine if lake acidification could be detected directly by digital interpretation of multispectral scanner (MSS) data. Previous studies (Mace, 1982; Alfoldi and Munday, 1978) have indicated that regression-based techniques may be successfully used to map a variety of water quality parameters from MSS data. Therefore, this investigation used regression-based digital interpretation procedures to establish the relationship between airborne MSS data collected over Adirondack State Park, New York and a series of lake measurements.

The area studied consists of 40 lakes within a rectangle bounded on the east and west by Raquette Lake and Old Forge and on the north and south by Cranberry Lake and State Highway 8. Four adjacent north-south flight lines provided scanner coverage of the 97.5 by 25.0 km study area.

Automated analysis of the digital imagery was used to relate the concurrent water sample data (Secchi depth, pH, alkalinity, total suspended solids, chlorophyll a, phaeophyton, and dissolved organic carbon) to radiances detected by the airborne multispectral scanner.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

From the evidence produced by this study and a review of pertinent literature, it is concluded that:

- o Weak linear relationships exist between multispectral scanner data and lake pH and alkalinity.
- o Secchi depth and dissolved organic carbon are reasonably well-defined by linear combinations of the multispectral scanner data.
- o A non-linear multispectral model may yield a better fit for chlorophyll a, total suspended solids, and phaeophyton.
- o All of the regression models would be considerably improved by a greater range of measured values in the water quality variables.
- o Multispectral data from the ultraviolet-blue (scanner channels 1 and 2), red (scanner channels 6 and 7), and near infrared (scanner channels 9 and 10) provided the best linear estimates of the water quality parameters studied.
- o The Thematic Mapper on the Landsat D satellite has spectral channels similar to MSS channels 7 and 9, and may provide an excellent water quality monitoring tool.
- o ^{Although} ~~While~~ the results of this study do not establish the use of the MSS as an operational tool for monitoring lake pH, the correlations are sufficiently good to offer promise toward its eventual use. Continued development of the use of MSS toward the detection and monitoring of acid rain effects is warranted.

RECOMMENDATIONS

The analysis presented in this report yields the following recommendations:

- o More sophisticated models need to be developed relating MSS data to a variety of water quality parameters affected by acid precipitation.
- o An atmosphere/sun angle/scan angle correction needs to be developed to reduce the variance in the spectral data induced externally to the water column upwelling radiance. This is particularly important for multiple flight line studies or multi-date analysis.
- o Follow-on studies should attempt to conduct water sampling in areas with as much water quality variability as possible to achieve a better description of the relationships between MSS data and acid rain-related phenomena.
- o Follow-on studies should concentrate on seasons which would maximize the variability of possible indicators of lake acidification.
- o If possible, further study should include Thematic Mapper or Thematic Mapper Simulator data.
- o Water sampling should be conducted using a minimum of a three-replicate system and an error analysis should be provided with the data.

METHODOLOGY

DATA ACQUISITION

The multispectral data were acquired using a Daedalus DS-1260 multispectral scanner flown aboard an Aero Commander 680V aircraft from 0753 to 0919 EDT on September 25, 1981 and from 1253 to 1426 EDT on October 13, 1981. The flight altitude was approximately 6400 meters (21000 feet) above mean sea level (MSL). The average terrain level below the aircraft was approximately 600 meters (1970 feet) yielding a nadir ground resolution element of approximately 14.5 by 14.5 meters. More detailed information about the multispectral scanner may be found in Appendix A.

Additionally, simultaneous 9 by 9-inch aerial transparencies were collected using Kodak 2448 color film and a Wild RC-8 mapping camera with a 152-mm (6-inch) focal length lens and a haze-correcting antivignetting filter. This produced stereo coverage of the study area at a nominal scale of 1:38,000. The film transparencies and associated film wedge have been archived at the Environmental Monitoring Systems Laboratory, Las Vegas, for possible densitometric analysis.

All of the imagery from the September 25 mission was seriously degraded due to atmospheric attenuation. Therefore, only the data from the October 13 mission was analyzed.

PREPROCESSING OF MULTISPECTRAL SCANNER DATA

MSS channels 1 through 10 (see Appendix A) were decommutated to computer compatible tapes and converted to band interleaved-by-pixel format. Simultaneously, each scan line was corrected for tangential distortion, and scan-line overscan corrections were made.

Further, a correction for illuminant changes was attempted. Samples of 25 picture elements were extracted from the digital data in water areas from adjacent flight lines. The ratios between the radiances for the adjacent pairs were averaged, and a multiplicative normalization factor was applied in each spectral band to correct flight lines two and four to line three, and line one to the corrected line two. However, scan angle/sun angle/atmospheric interactions proved to be too complex to be modeled in this way, and this technique was abandoned during the final analysis.

DATA ANALYSIS

The general data analysis approach used in this study was to relate the multispectral scanner data to a variety of water quality parameters, one at a time, with a multiple linear regression technique. The multispectral data were treated as independent variables in a step-wise best subsets regression routine.

Lake Sampling

Water sampling in approximately 40 lakes was accomplished by Paul Smith's College, Ecology and Environmental Technology Division, and Mr. Frank Vertucci of Cornell University during the period from September 25 through September 28, 1981. Selected lakes were again sampled on October 17, 1981 to confirm no major changes in lake chemistry had occurred between the first and second overflights.

In situ measurements were made of temperature and Secchi depth. Alkalinity, pH, total suspended solids, chlorophyll a, and phaeophytⁱon were measured using standard laboratory techniques by Paul Smith's College. Dissolved organic carbon measurements were made by the EPA laboratory in Corvallis, Oregon. Usually, three locations were sampled within each lake, and two replicates were taken at each sample location. Appendix B contains the results of the laboratory analysis for the sites used by the regression analysis. Values are averages of the replicates.

Additionally, lake radiance measurements were collected simultaneously with the second scanner overflight. However, these measurements did not correspond to

the scanner radiance measurements and were not used in the subsequent analysis.

Multispectral Sampling and Transformations

The ground survey crew marked the location of each sampling station with a code number on USGS 1:62,500 scale topographic quadrangles. Channel 10 (infrared) of the multispectral scanner imagery was displayed on a COMTAL image display system and the location of each sample station was visually determined by reference to the display screen and the appropriate map. A cursor was placed over the sample location on the video screen and a 5 X 5 pixel matrix of data values was extracted from the 10 channel data set. This procedure was repeated for both the normalized and uncorrected data sets.

Mean values for each channel of the 25-pixel MSS data matrices were calculated and stored in a computer file on a Varian V-75 computer. Thus, each water sampling station had a corresponding matrix of 10 mean vectors representing the multispectral scanner data.

The mean vectors for each channel were then transformed to radiances using equation 1:

$$R = \frac{W (C - GB)}{G (A - B)} \quad (1)$$

Where: R = radiance (μ watt/cm² - nm - str) for a channel

C = mean vector for a channel

G = scanner gain setting

A, W, and B = scanner calibration values provided by
empirical measurements conducted by NASA at
a scanner gain setting of 1

These computed radiances formed the basis for all subsequent processing and analyses.

Best Subsets Multiple Linear Regression

The multispectral radiances and the water sampling data were combined into a single file (Appendix B) for use by the Biomedical Computer Programs for statistical analysis (Dixon, 1977). Program P9R (Best Subsets Multiple Linear Regression) was used to establish the relationship between the MSS data and each of the water quality parameters. Mallow's C_p was selected as the best subset criterion (as suggested by Whitlock, 1977). The decision rule for the regressions was to select MSS channels as independent variables such that the value of C_p was minimized.

It has been suggested in the literature that ratios of multispectral data may improve the relationship between the MSS data and concurrent water sample data (Alfoldi and Munday, 1978). Therefore, several ratio transformations of the multispectral radiances were included in the analysis.

Chromaticity ratios were calculated for each channel. The chromaticity ratio follows the form:

$$Ch_i / \Sigma Ch_i \quad (2)$$

Where: Ch_i = the radiance for a particular channel (i)

$$\Sigma Ch_i = Ch_1 + Ch_2 + Ch_3 + \dots + Ch_{10}$$

Physically, these ratios represent the percent reflectance for a channel relative to the total reflectance sensed by all channels. The chromaticity ratios for all channels were included on the regression analysis. Additionally, the albedo (ΣCh_i) was included as an additional variable. The only exception was that Ch_3 had to be dropped from the independent variable list, as it was a linear combination of other variables, producing a singular covariance matrix.

Also, adjacent-channel ratios of the form:

$$Ch_i / Ch_{(i + 1)} \quad (3)$$

were calculated and used on independent variables. The ratio Ch_5 / Ch_{10} was also included in this group. It was hypothesized that some of the MSS radiance

measurement error (due to atmospheric scattering) could be reduced in this manner.

The radiance data, chromaticity data, and band ratio data were analyzed as three distinct groups of independent variables. Both the normalized and untransformed data sets were treated in this manner.

Multispectral Classification

The regression equation obtained for the "best subset" describing pH was then applied to each pixel of one of the multispectral data tapes (approximately 2,000 scan lines by 742 elements). This transformation is described by equation 4:

$$\begin{aligned} \text{pH} = & - 1.19501\text{Ch}_1 + 9.10103\text{Ch}_2 - 11.8644\text{Ch}_3 + 8.8001.8\text{Ch}_5 \\ & - 8.94497\text{Ch}_9 + 4.91758 \end{aligned} \quad (4)$$

Where: pH = estimated pH for a pixel

Ch_i = the radiance value for channels i = 1,2,3,5, and 9

The calculated pH for each pixel was then multiplied by 10 and rounded to the nearest 8-bit integer (0-255). Thus, a single channel of pH values was synthesized from the five multispectral channels suggested by the best subsets regression.

Channel 10 (infrared) of the corresponding data was copied along with the synthesized (transformed) pH channel to form a two-channel file. This permitted the classifier to operate separately on water and non-water pixels, as low values in channel 10 uniquely delineate water. It also permitted a useful grey level representation of the land pixels as the infrared channel is sensitive to forest cover differences.

A parallelepiped (box) classification was then performed on the two-channel data set, categorizing the pH values of water pixels into 0.5 pH increments and the land pixels into five levels of brightness based on infrared reflectance.

RESULTS

REGRESSION ANALYSIS

The results of the best subset regression analyses are presented in Table 1. The input data were radiances (not normalized), chromaticity ratios of radiances, and adjacent band ratios of radiances. Numbers 1-10 indicate MSS channels used with the following exceptions:

- 1) For chromaticity ratios, Σ is the sum of the radiances of all channels.
- 2) For adjacent band ratios, 10 indicates channel 5 radiance/channel 10 radiance.

R^2 is the coefficient of determination, and S is the standard error of the estimate. The order of predictors indicates the relative order of each independent variable using only one predictor. Although this indicates the relative importance of variables as predictors, it should be noted that no single channel was a good predictor. The measured range and measured mean refer to the 102 water sample measurements of the dependent variables.

TABLE 1. BEST SUBSET MULTIPLE LINEAR REGRESSION SUMMARY

	Secchi Depth (m)	pH	Alkalinity (μ eq/l)	Total Suspended Solids (ppm)	Chlorophyll a (mg/m ³)	Phaeophyton (mg/m ³)	Dissolved Organic Carbon (ppm)
R ²	0.796	0.383	0.309	0.494	0.424	0.502	0.807
S	1.436	0.593	39.738	0.935	1.649	0.820	0.824
Channels used	2,4,5, 6,10	1,2,3, 5,9	1,2,3,5, 6,9	2,7	2,7,10	1,5,7	1,2,4, 7,9
Order of predictors	7,6,8,5, 9,10,4, 2,1,3	9,10,6, 5,7,4,8, 2,3,1	10,9,6,5, 7,8,2,4, 3,1	7,8,6,9, 5,10,4,1, 3,2	7,6,8,5, 9,10,1, 4,3,2	7,8,6,9, 10,5,1, 4,3,2	7,6,5,2, 8,3,4, 10,1,9
R ²	0.801	0.390	0.321	0.510	0.409	0.504	0.793
S	1.434	0.593	39.404	0.920	1.661	0.814	0.854
Channels used	Σ ,1,2,4, 5,6,8	1,2,5,7, 8,10	1,2,5,6, 8,10	Σ ,7	Σ ,7	Σ ,7	Σ ,1,2, 7,9
Order of predictors	7,6,8,2, 5,1,4,9, Σ ,10	9,10,5, 6,8,7,2, 4, Σ ,1	10,9,5,2, 6,8,7,1, Σ ,4	7,6,8,1, 5,9,10, 2, Σ ,4	7,6,8,1, 5,9,2,10, Σ ,4	7,6,8,1, 9,5,10, 2, Σ ,4	7,6,4, Σ , 1,2,10, 8,9,5
R ²	0.786	0.394	0.306	0.574	0.393	0.448	0.788
S	1.489	0.585	38.432	0.884	3.001	0.877	0.896
Channels used	3,4,5	1,2,4,5, 7,8	1,2,4, 5,8	2,4,5,6, 9,10	2,4,6,8	1,4,5,6 9,10	1,2,3,4, 5,6,7,8,
Order of predictors	4,5,6,3, 1,2,8,7, 10,9	7,8,4, 10,9,3, 2,1,5,6	8,4,7,2, 10,9,1, 5,6,3	6,4,5,1, 2,9,10, 3,7,8	6,4,5,1, 3,2,8, 10,7,9	6,5,4,1, 2,8,7,3, 10,9	5,6,4,7, 2,3,1,8, 10,9
Measured Range	1.5-16.0	4.35-7.73	-39.000- 170.650	0.02-6.29	0-10.41	0-5.39	0-7.0
Measured Mean	5.0	5.74	27.397	1.667	1.867	1.076	3.314

Figures 1-7 are plots of the observed (measured) values for the dependent variables on the X-axes and the values predicted by the radiance regression models on the Y-axes. The straight line drawn on each plot indicates the line of perfect correlation. Points falling above this line indicate overestimation by the model, and points falling below the line indicate underestimation.

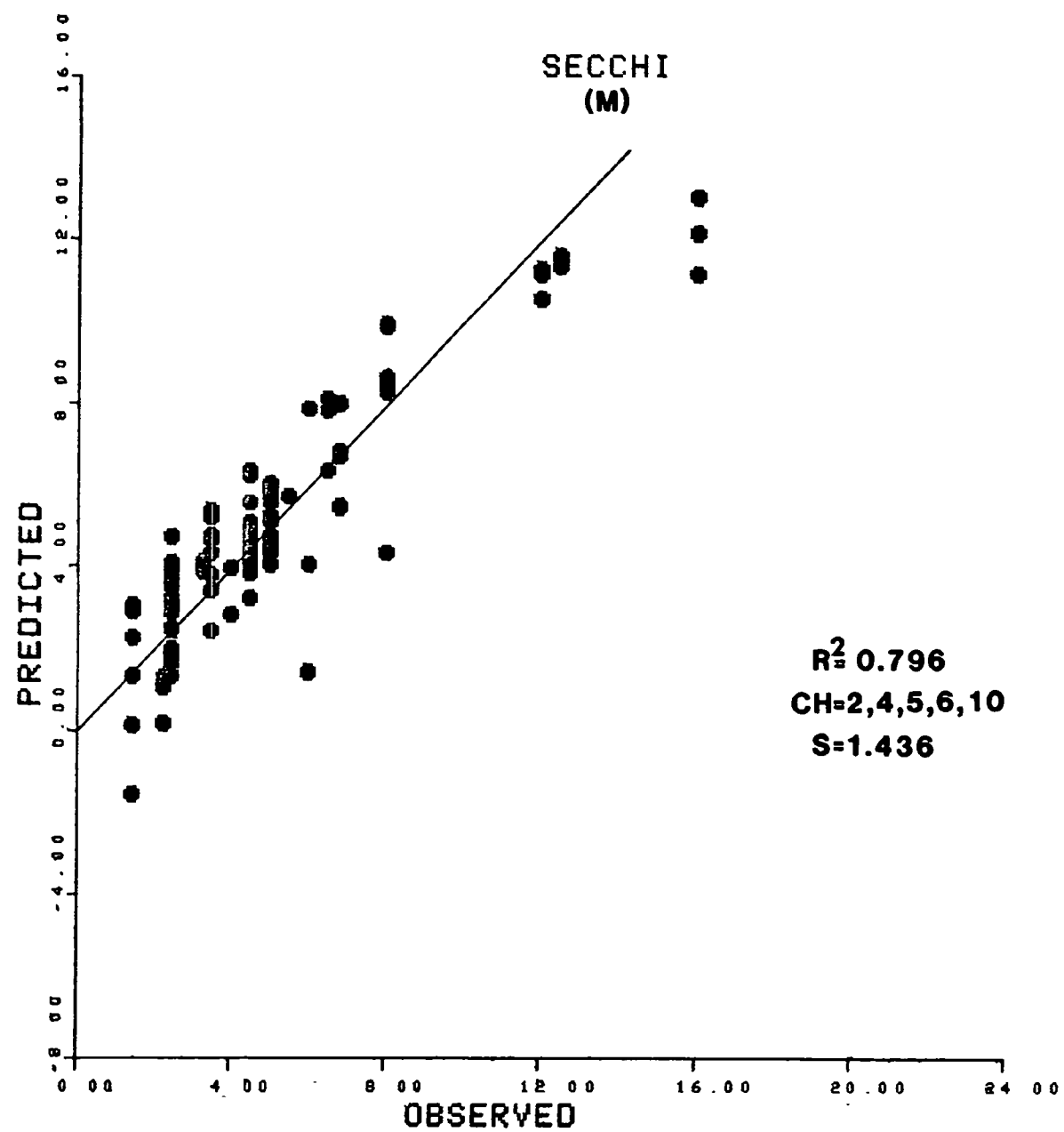


Figure 1. Predicted vs. observed Secchi depth (m).

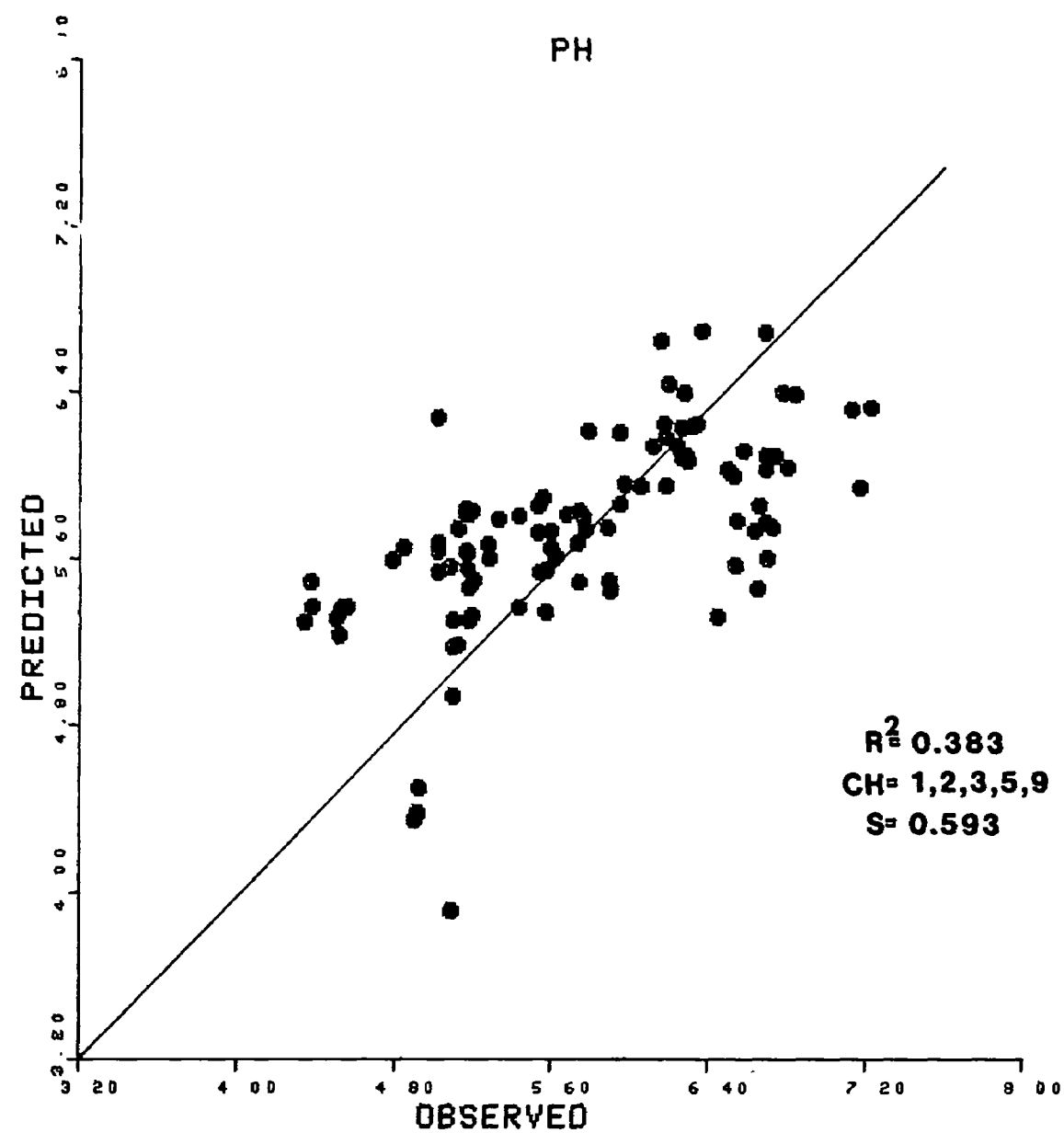


Figure 2. Predicted vs. observed pH.

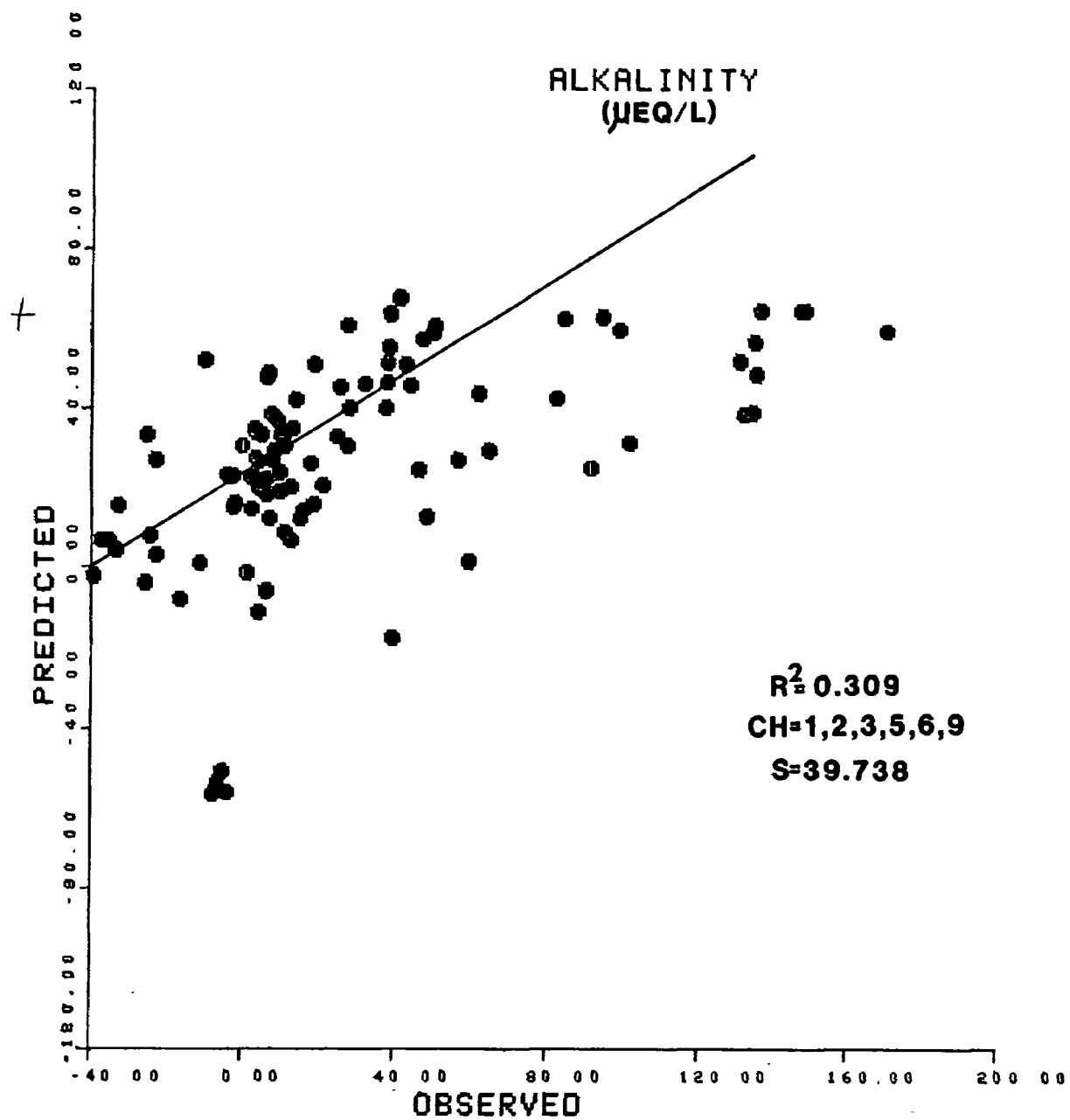


Figure 3. Predicted vs. observed alkalinity (μ eq/l).

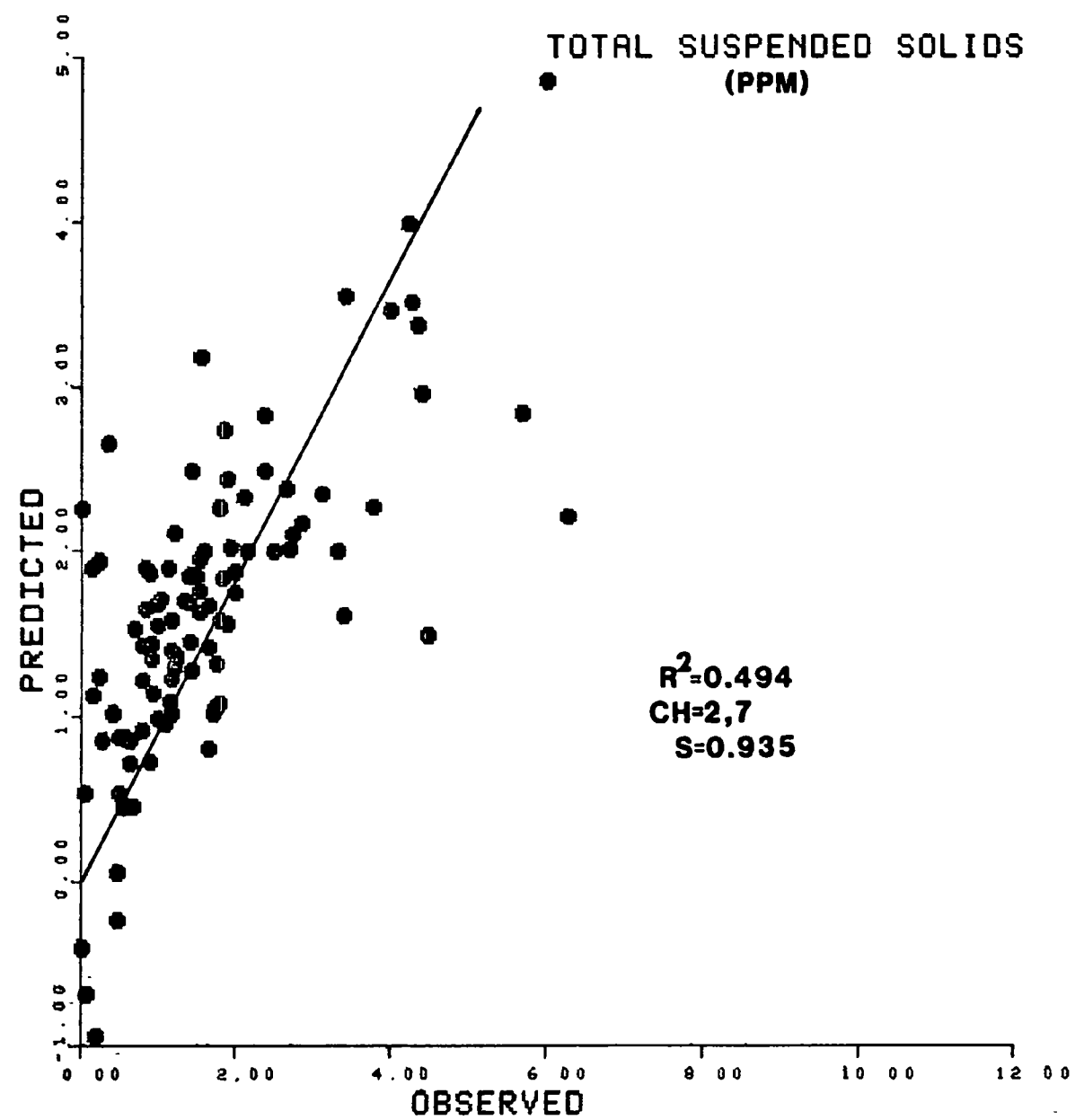


Figure 4. Predicted vs. observed total suspended solids (ppm).

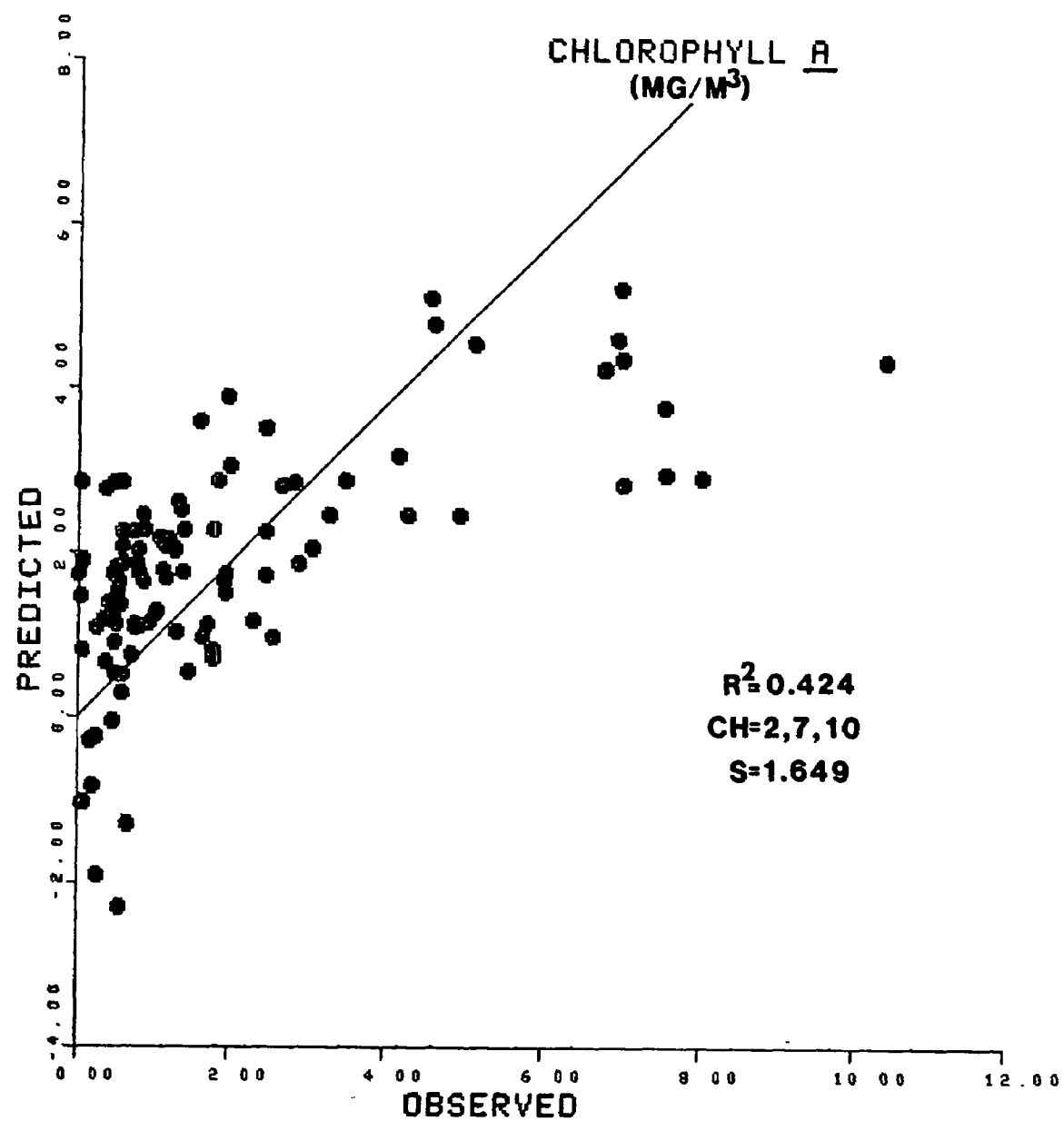


Figure 5. Predicted vs. observed chlorophyll a (mg/m³).

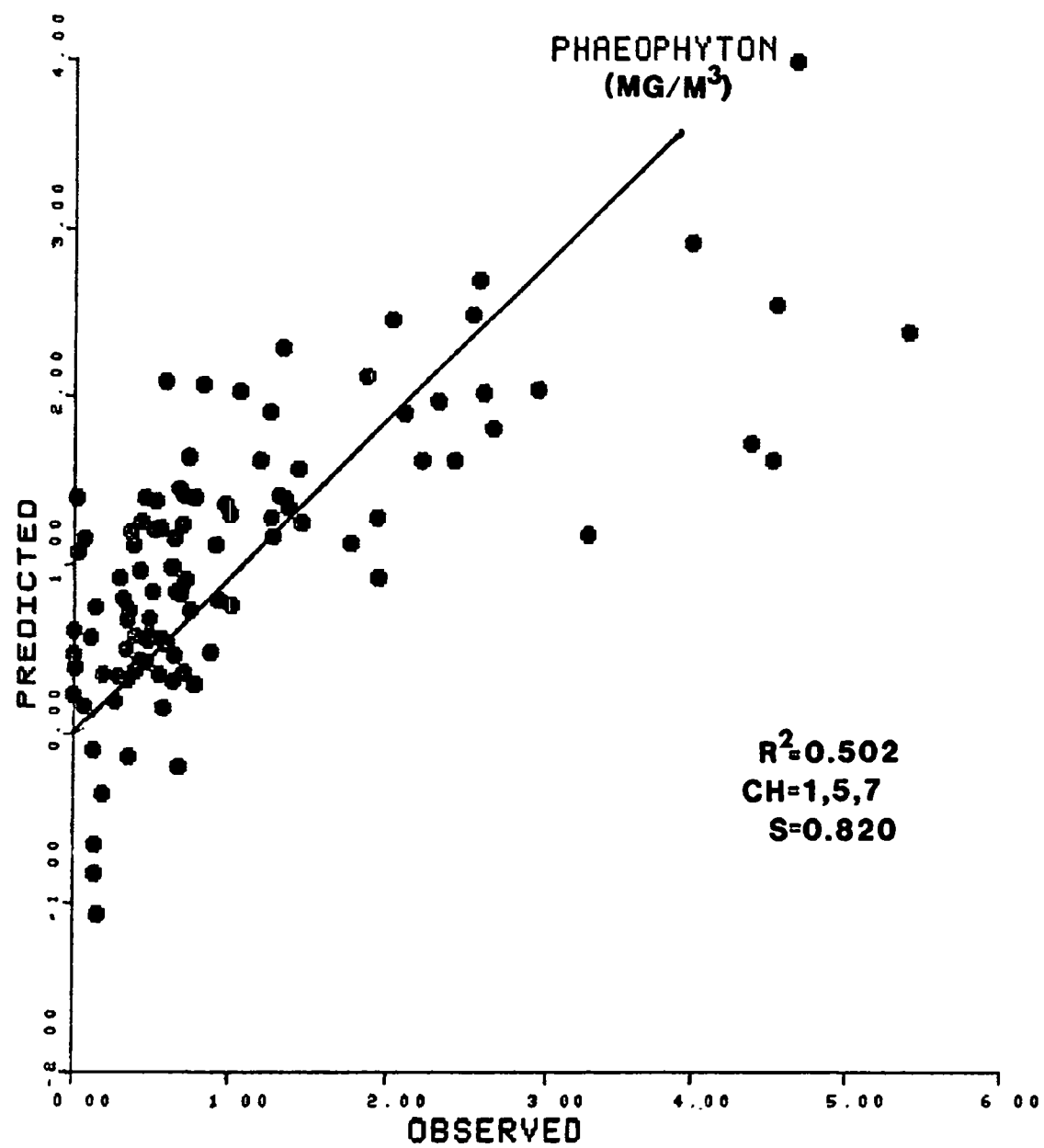


Figure 6. Predicted vs. observed phaeophyton (mg/m³).

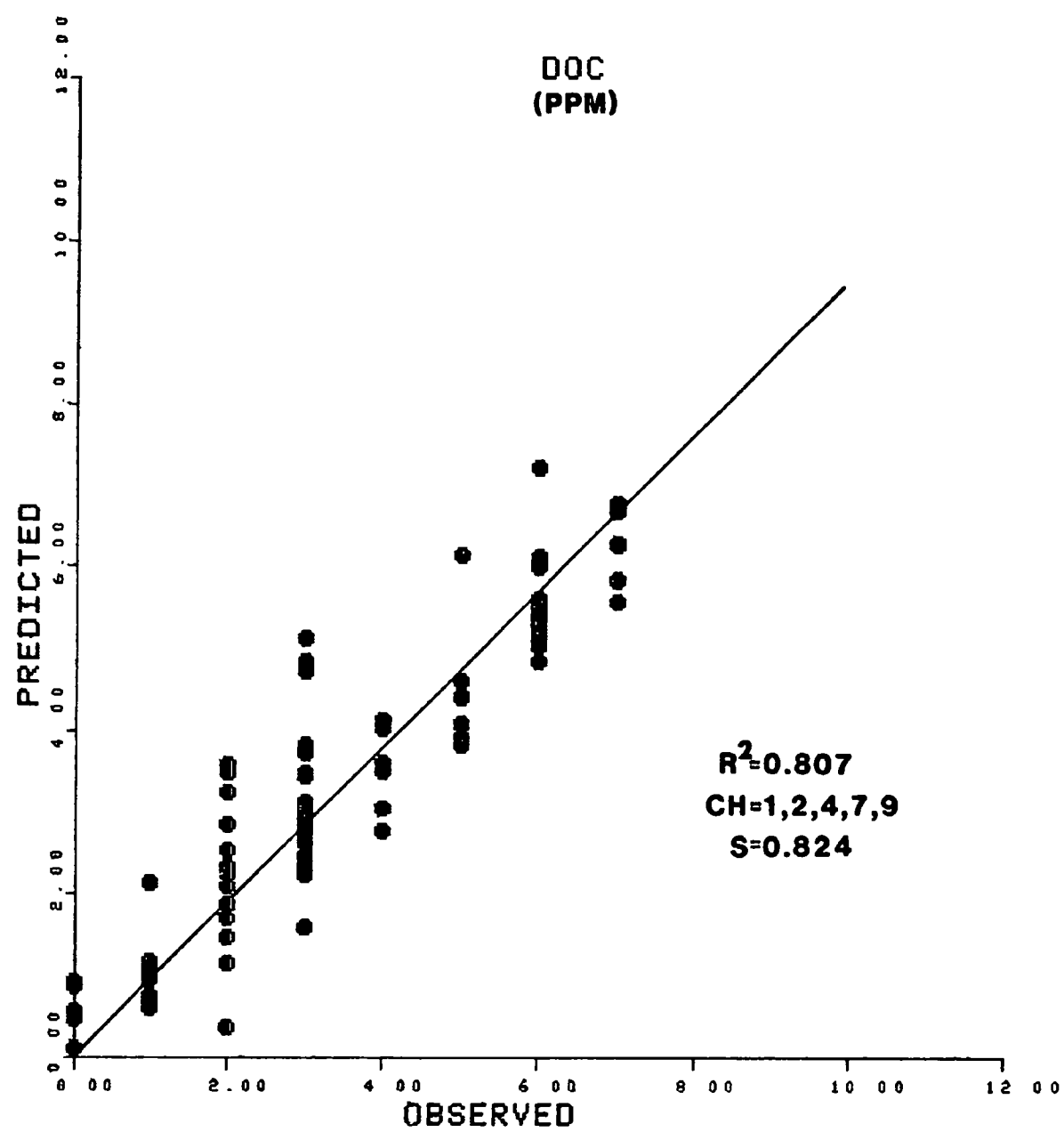


Figure 7. Predicted vs. observed dissolved organic carbon (ppm).

The spatial form of the model is depicted by Figure 8. The results of the multispectral classification are presented for pH in the area between Fourth and Big Moose Lakes. Colors represent modeled pH levels in the lakes and streams, and black-and-white tones represent various forest cover classes.

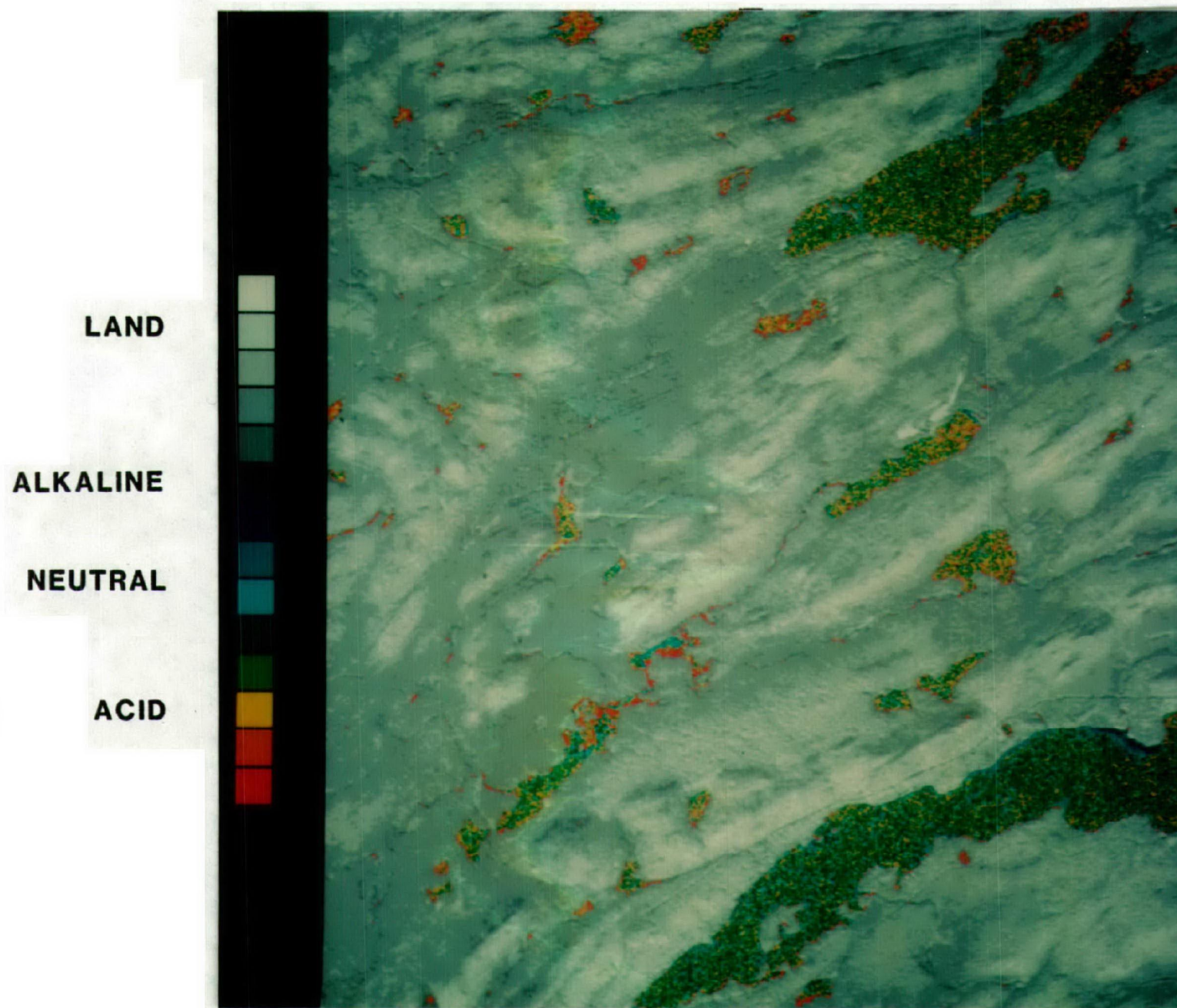


Figure 8. Multispectral Classification of Lake pH, Adirondack State Park, New York.

DISCUSSION

Multispectral Relationships

Review of Table 1 indicates that only Secchi depth and dissolved organic carbon provide reasonably good coefficients of determination (R^2) values. Alkalinity and pH provide the worst R^2 values. However, weak, positive relationships are present even for these variables, and the standard error of the estimate (S) for each of the dependent variables seems to be of an acceptable magnitude.

There seems to be no distinct advantage to the use of ratios rather than radiances directly. Although, slight increases in R^2 were noted in a few cases, no consistent pattern developed to justify the increased computational difficulty.

Although no single MSS channel was a good predictor of any of the water quality parameters, several MSS channels were consistently more useful. It was initially hypothesized that channel 1 (0.38-0.42 μm) would be a valuable predictor of at least dissolved organic carbon. Taken singly, this was not the case. However, either channel 1 or adjacent channel 2 was included in every best subset group.

The red channels (6 and 7, 0.60-0.65 and 0.65-0.70 μm), representing chlorophyll absorption bands, proved very useful for all but pH and alkalinity, while the infrared channels (9 and 10, 0.80-0.89 μm and 0.92-1.10 μm) were most influential in discriminating levels for the latter. This may provide a clue to the process of relating MSS data to acid rain effects. It may be that the chlorophyta (which are detected by channels 2, 7 and 10) are not the key to remote sensing of lake acidification effects. Nor are we likely to find a surrogate in the phaeophyta, as the chlorophyll absorption band is an important predictor as well. However, it is likely that some plant response, or combination of responses is responsible for the relative importance of the infrared channels in the best subsets regression. Infrared energy is absorbed within the top few centimeters of the water column. Therefore, some near-surface phenomenon must combine with phenomena throughout the water column to produce the relationship between MSS-detected spectral response and lake acidity. Measurements of chlorophyll a, b, and c will be made during the spring conditions

follow-on to this study and may provide further clues to the detectable phenomena related to lake acidity.

It is also encouraging that the Thematic Mapper aboard the new Landsat D and D' series satellites have MSS channels similar to the most useful channels of the aircraft MSS. Channels 3 and 4 of the Thematic Mapper describe energy within the 0.63-0.69 μm and 0.77-0.90 wavebands, respectively. These channels are approximated by the aircraft MSS channels 7 and 9 in this study. With its 30-meter spatial resolution, the Thematic Mapper should prove to be a very useful water quality assessment tool.

Scatter Plots

The scatter plots, represented by Figures 1-7, are visual representations of the regression results. Generally, they confirm the relatively poor R^2 values for the pH, alkalinity, chlorophyll a, total suspended solids, and phaeophyton regressions. They also indicate that the chlorophyll a, phaeophyton, and alkalinity regression values may be improved by some transformation (perhaps \ln) of the dependent variables.

Deviations in the plotted data from the correlation line represent errors in the regression-based predictive model. These errors may be induced by mensuration errors in radiometry as well as water chemistry. During at least one previous study, the model estimated error was within standard laboratory measurement limits for N-NO_3 , total phosphorous, total suspended solids, and conductivity (Mace, 1982). This probably was due to relatively wide ranges in the water sample data. The present study, however, dealt with relatively low concentrations of chlorophyll a, suspended solids, organic carbon, and phaeophyton. Multispectral analysis techniques may not be sensitive to extremely low levels of some materials in water. Even the laboratory measurements revealed some sample replicates differing from each other by a factor of 10. Since only two replicates were taken, spurious values could not be eliminated. Also, no quality assurance analyses were provided for the laboratory data. Future studies should attempt to reduce the variance due to water chemistry measurement differences by at least a three-replicate procedure, and a quality assurance program should be instituted.

Variances induced by errors in radiometry are most probably caused by a sun

angle/scan angle/atmospheric interaction. Corrections for these effects are not straightforward, and more research needs to be performed before reliable corrections can be made to the MSS data.

Multispectral Classification

The multispectral classification enclosed in this report represents a small portion of the imaged area. Moreover, the relationship between lake spectral response and pH was not strong. However, Figure 8 is included in this report as an example, in image form, of the eventual application of this technology. Clearly, the model must be improved before an operational monitoring technique is developed. The image does, however, illustrate general differences in acidity between lakes and may serve as a qualitative tool. For example, the mix of yellow and green mapping levels in Fourth Lake (lower right) favor more neutral conditions, while the mix of colors in Big Moose Lake (upper right) favor more acidic conditions. The speckled nature of the classification reflects the statistical observation that the variance in the estimate (Figure 2) approaches the range of observed values. Nevertheless, a weak, positive relationship is expressed in the image as well as the statistical data.

General Considerations

Considering the magnitude of the problem, and the benefits to be gained by the development of an operational monitoring technique, the monitoring of lake acidification by remote means provides sufficient promise of success to be worth additional study. Overflight timing may be the critical element. Levels of the various water quality parameters examined in this study were relatively low during the fall sampling for this study. A spring follow-on to this study will be undertaken, but some of the concentrations of the surrogates to lake acidity may again be low. The experiment should be repeated at least once more - during mid-late summer. This would permit the temporal variable to be examined, as well as full development of plant responses to the lake pH values. The cost of such a continuation of this study is relatively low compared to the cost of developing an extensive water-sample-based system. If appropriate models and timing can be found, tremendous savings can be made in the establishment of an operational monitoring program.

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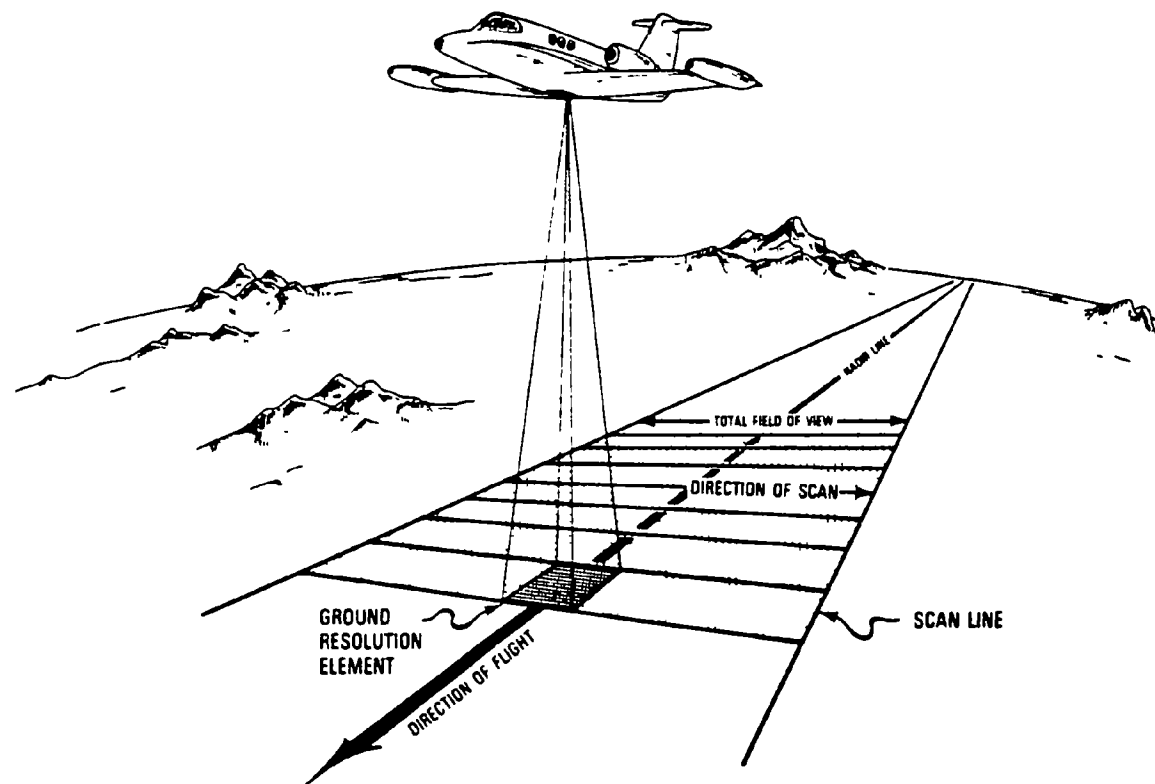
APPENDIX A

MULTISPECTRAL SCANNER
AND
ANALYSIS SYSTEM CHARACTERISTICS

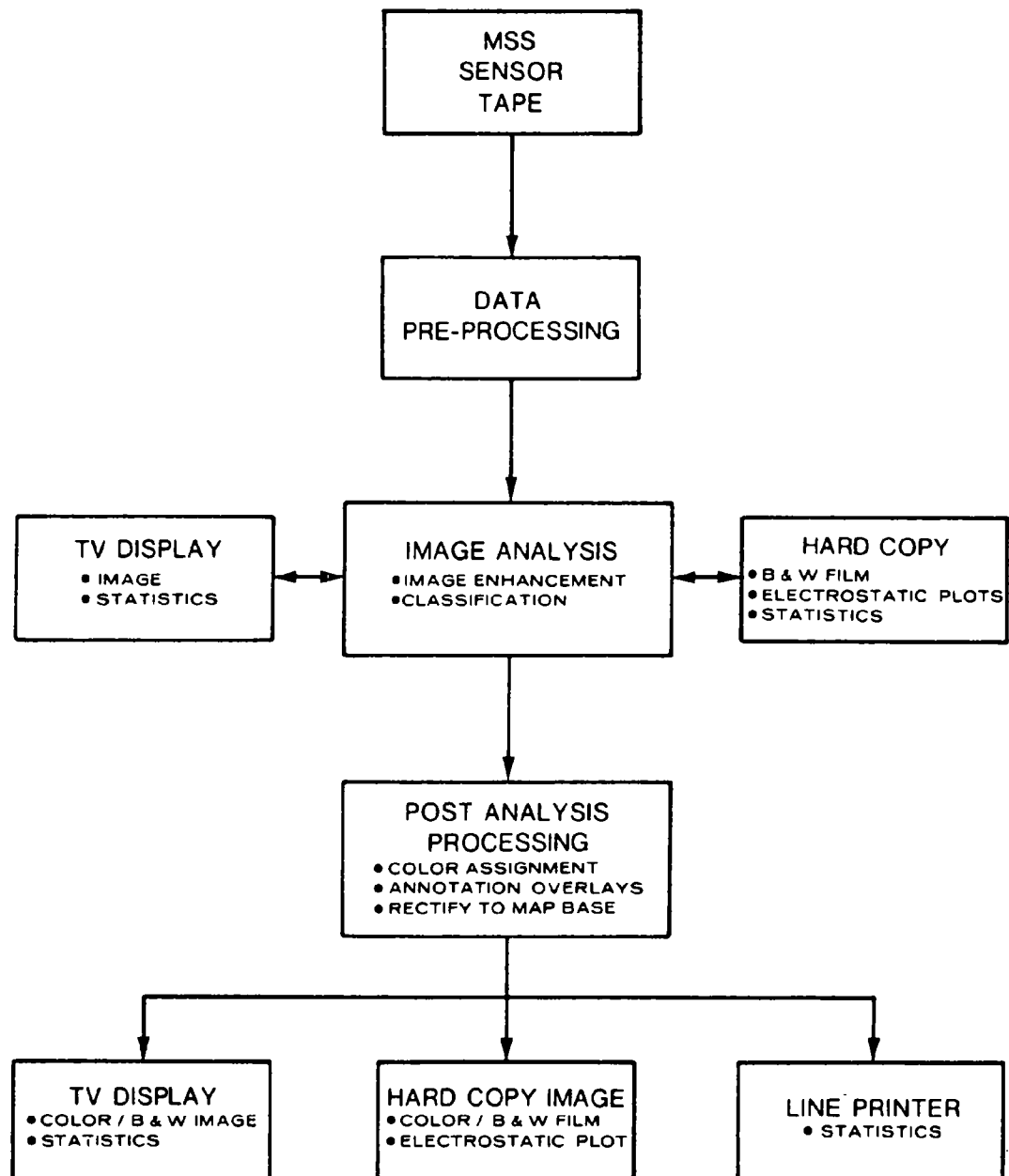
MSS WAVELENGTH BANDS

<u>Channel</u>	<u>Wavelength Band</u>	<u>Color/Spectrum</u>
1	0.38-0.42 μ m	Near Ultraviolet
2	0.42-0.45 μ m	Blue
3	0.45-0.50 μ m	Blue
4	0.50-0.55 μ m	Green
5	0.55-0.60 μ m	Green
6	0.60-0.65 μ m	Red
7	0.65-0.70 μ m	Red
8	0.70-0.79 μ m	Near Infrared
9	0.80-0.89 μ m	Near Infrared
10	0.92-1.10 μ m	Near Infrared
11	8.00-14.00 μ m	Thermal Infrared

MULTISPECTRAL SCANNER IMAGING CHARACTERISTICS (SIMPLIFIED)



MSS DATA PROCESSING (SIMPLIFIED)



APPENDIX B

MULTISPECTRAL RADIANCES

AND

WATER SAMPLE DATA

APPENDIX B

MULTISPECTRAL RADIANCES AND WATER SAMPLE DATA

LAKE/SAMPLE	CH 1	CH 2	CH 3	CH 4	CH 5	CH 6	CH 7	CH 8	CH 9	CH 10	SECCHI (M)	PH	ALKALINITY (µeq/l)	TOTAL SUSPENDED SOLIDS (ppm)	CHLOROPHYLL a (mg/ m ³)	PHAEOPHYTON (mg/ m ³)	DISSOLVED ORGANIC CARBON (ppm)
BEAK1	2.792	2.115	2.002	1.591	1.005	0.240	0.511	0.313	0.121	0.047	4.5	4.39	-32.80	1.54	1.160	1.010	3.0
BEAK2	2.770	2.012	1.866	1.494	0.912	0.190	0.482	0.313	0.122	0.047	4.5	4.39	-39.00	1.47	1.100	0.630	3.0
BEAK3	2.498	1.977	1.817	1.475	0.273	0.087	0.482	0.303	0.120	0.075	1.5	4.38	32.68	1.00	1.380	0.660	3.0
BEAV1	2.336	2.319	2.162	1.551	1.078	1.035	0.600	0.363	0.124	0.047	2.5	5.93	29.08	4.43	1.260	2.570	7.0
BEAV2	2.324	2.363	2.212	1.674	1.093	1.042	0.575	0.351	0.110	0.046	2.5	5.93	27.79	1.86	1.480	1.330	7.0
BEAV3	2.404	2.442	2.268	1.701	1.123	1.050	0.588	0.312	0.111	0.048	1.5	5.93	27.72	1.44	2.000	1.920	7.0
BMO510	3.077	2.396	2.137	1.563	1.078	0.253	0.530	0.315	0.095	0.048	4.5	5.74	12.10	1.77	0.240	0.380	2.0
BMO520	2.886	2.277	2.040	1.664	0.297	0.273	0.462	0.254	0.090	0.046	5.5	5.03	2.10	0.50	0.050	0.170	3.0
BMO530	2.528	2.029	1.857	1.255	0.281	0.251	0.250	0.264	0.093	0.046	5.0	5.03	9.55	0.37	0.040	0.050	3.0
BMO540	3.349	2.532	2.281	1.511	1.075	0.253	0.513	0.374	0.081	0.044	3.5	5.03	-3.13	0.50	0.180	0.130	4.0
BOCK1	1.377	1.291	1.357	1.3	0.716	0.253	0.463	0.350	0.071	0.042	4.5	5.03	10.04	0.75	0.500	0.360	4.0
BOCK2	2.285	1.974	1.813	1.376	0.202	0.031	0.444	0.254	0.061	0.046	4.5	5.03	8.84	1.20	0.700	0.110	4.0
BOCK3	1.291	1.337	1.287	1.37	0.205	0.036	0.431	0.254	0.094	0.048	4.5	5.03	8.77	1.20	0.560	0.370	4.0
BOCK4	1.182	1.082	1.063	1.04	1.069	1.043	0.597	0.313	0.081	0.031	1.5	6.16	50.62	3.23	0.920	4.530	6.0
BOCK5	2.098	1.707	1.573	1.360	0.905	0.889	0.628	0.254	0.072	0.036	1.5	6.29	3.707	0.29	2.510	4.370	6.0
BOCK6	2.117	1.833	1.713	1.723	0.254	0.940	0.520	0.254	0.050	0.015	1.5	6.37	39.10	5.71	10.410	2.650	5.0
BRAND1	2.336	2.319	2.212	1.674	1.093	1.042	0.575	0.351	0.090	0.046	12.0	5.93	5.45	0.08	0.260	0.160	1.0
BRAND2	2.700	2.150	1.987	1.406	0.889	0.772	0.391	0.196	0.047	0.022	12.0	5.93	5.45	0.08	0.260	0.160	1.0
BRAND3	2.589	2.086	1.916	1.406	0.891	0.774	0.385	0.226	0.063	0.013	12.0	5.93	6.58	0.02	0.660	0.140	1.0
CANAL1	1.871	1.822	1.750	1.335	0.912	0.816	0.425	0.254	0.081	0.022	7.0	5.77	13.59	1.17	2.300	0.610	2.0
CANAL2	1.511	1.804	1.743	1.337	0.707	0.291	0.412	0.252	0.065	0.009	6.0	5.75	2.42	1.67	1.640	0.160	1.0
CANAL3	1.911	1.832	1.753	1.391	0.912	0.835	0.422	0.254	0.083	0.046	6.0	5.78	11.10	1.73	1.780	0.650	1.0
CASO1	2.376	1.873	1.765	1.330	0.708	0.849	0.467	0.262	0.081	0.047	5.0	6.34	46.48	0.70	0.540	0.970	7.0
CASO2	2.191	1.859	1.745	1.333	0.703	0.832	0.463	0.254	0.091	0.047	5.0	6.67	65.15	0.05	0.620	0.770	3.0
CASO3	2.171	1.846	1.727	1.328	0.914	0.371	0.412	0.310	0.115	0.064	5.0	6.65	48.69	0.90	1.280	0.030	3.0
CLER1	1.842	1.906	1.850	1.471	0.864	0.774	0.421	0.254	0.106	0.046	12.5	5.11	16.08	0.90	0.580	0.000	0.0
CLER2	1.870	1.975	1.890	1.413	0.858	0.775	0.422	0.254	0.084	0.046	12.5	5.11	12.81	0.07	0.460	0.000	0.0
CLER3	2.494	1.925	1.791	1.354	0.887	0.831	0.441	0.221	0.041	0.000	3.5	6.30	38.26	0.30	0.750	0.190	5.0
CLER4	2.572	2.029	1.878	1.357	0.908	0.875	0.456	0.247	0.041	0.000	3.5	6.27	38.08	1.00	1.030	0.130	5.0
CLER5	2.005	2.128	1.908	1.450	0.946	0.887	0.474	0.254	0.041	0.000	3.5	6.35	38.41	0.43	1.070	0.300	5.0
DOCK1	2.796	2.014	2.077	1.555	1.010	0.747	0.508	0.315	0.122	0.046	4.5	5.19	7.76	1.42	0.440	0.350	3.0
DOCK2	2.575	2.111	1.934	1.495	0.990	0.715	0.482	0.262	0.097	0.046	4.5	5.20	6.18	1.25	0.460	0.400	3.0
DOCK3	2.418	1.923	1.862	1.443	0.945	0.884	0.472	0.262	0.104	0.046	4.5	5.21	7.21	1.20	0.400	0.490	3.0
FOUR1	2.389	1.927	1.845	1.337	0.943	0.830	0.467	0.264	0.071	0.041	5.0	7.17	132.14	1.45	1.920	0.480	3.0
FOUR2	2.697	2.097	1.920	1.493	0.988	0.895	0.470	0.254	0.041	0.018	5.0	7.13	135.00	1.75	1.790	0.580	3.0
FOUR3	2.172	1.839	1.715	1.363	0.906	0.827	0.431	0.242	0.041	0.000	5.0	7.23	170.65	1.80	1.940	0.350	3.0
HONN1	2.395	2.076	1.926	1.490	0.708	0.820	0.472	0.254	0.114	0.046	16.0	4.91	-5.76	0.57	0.240	0.000	0.0
HONN2	2.800	2.226	2.161	1.507	0.953	0.829	0.451	0.254	0.081	0.046	16.0	4.92	-7.46	0.48	0.080	0.680	0.0
HONN3	2.155	2.094	1.930	1.461	0.876	0.776	0.405	0.244	0.057	0.016	16.0	4.93	6.30	0.48	0.060	0.190	0.0
IND1	2.238	2.160	2.020	1.576	1.090	0.957	0.557	0.331	0.122	0.071	2.5	5.17	10.17	2.38	0.600	0.600	6.0
IND2	2.244	2.234	2.071	1.553	1.014	0.972	0.555	0.318	0.122	0.072	2.5	5.19	14.13	2.13	0.480	0.830	6.0
IND3	2.264	2.185	2.041	1.534	0.997	0.951	0.549	0.324	0.122	0.058	2.5	5.18	5.03	3.12	0.360	1.060	6.0
NANT1	1.862	1.941	1.847	1.419	0.750	0.835	0.535	0.335	0.138	0.053	2.5	5.09	-1.92	2.40	2.570	5.790	3.0
NANT2	1.927	1.955	1.864	1.431	1.010	1.019	0.639	0.549	0.364	0.262	2.5	5.10	-4.86	6.00	6.970	4.670	3.0
NANT3	1.915	1.969	1.875	1.446	0.969	0.968	0.571	0.359	0.169	0.089	2.5	5.11	-11.13	4.00	6.970	3.980	3.0
LILA1	2.342	2.378	2.147	1.610	1.040	0.995	0.559	0.318	0.073	0.046	2.5	6.40	50.14	1.73	0.860	1.270	6.0
LILA2	2.116	2.047	1.875	1.414	0.915	0.883	0.484	0.254	0.042	0.005	2.5	6.28	41.45	4.50	1.180	0.970	6.0
LILA3	2.244	2.195	2.044	1.514	0.990	0.937	0.513	0.364	0.065	0.007	2.5	6.27	44.16	3.40	1.000	1.350	6.0
LIMEK1	2.168	1.918	1.870	1.564	1.064	0.974	0.573	0.387	0.083	0.046	8.0	5.80	11.80	0.36	1.600	1.450	2.0
LIMEK2	2.146	1.910	1.842	1.487	0.945	0.879	0.431	0.254	0.047	0.036	8.0	5.68	6.41	0.60	0.360	0.070	2.0
LIMEK3	2.103	1.907	1.847	1.451	0.952	0.837	0.444	0.254	0.081	0.046	8.0	5.75	11.44	0.16	0.560	0.010	2.0

APPENDIX B

MULTISPECTRAL RADIANCES AND WATER SAMPLE DATA

LAKE/SAMPLE	CH 1	CH 2	CH 3	CH 4	CH 5	CH 6	CH 7	CH 8	CH 9	CH 10	SECCHI (M)	PH	ALKALINITY (µeq/l)	TOTAL SUSPENDED SOLIDS (ppm)	CHLOROPHYLL a (mg/m³)	PHAEOPHYTON (mg/m³)	DISSOLVED ORGANIC CARBON (ppm)
LYON1	2.572	2.008	1.842	1.418	0.925	0.882	0.49	0.317	0.122	0.077	1.5	4.53	29.37	1.40	0.800	0.600	2.0
LYON2	2.572	2.008	1.842	1.418	0.925	0.882	0.501	0.318	0.122	0.080	4.5	4.51	-29.36	1.35	0.780	0.520	2.0
LYON3	2.580	2.004	1.845	1.418	0.925	0.889	0.504	0.318	0.122	0.077	4.5	4.52	-29.33	1.95	0.800	0.440	2.0
MET3	3.562	2.642	2.351	1.775	1.090	0.960	0.575	0.318	0.122	0.071	5.0	5.19	3.25	0.68	0.200	0.360	1.0
ROSS1	3.188	2.455	2.101	1.600	1.066	0.944	0.520	0.310	0.081	0.046	4.5	6.53	62.12	0.93	0.940	0.340	4.0
ROSS2	2.991	2.349	2.020	1.509	0.988	0.910	0.508	0.287	0.131	0.044	4.5	6.55	53.96	1.23	0.820	0.490	4.0
ROSS3	3.056	2.261	2.064	1.56	1.021	0.927	0.528	0.313	0.086	0.046	4.5	6.54	59.61	1.35	1.120	0.150	4.0
NEGRO1	2.133	1.851	1.756	1.400	0.729	0.823	0.468	0.390	0.170	0.046	3.5	5.90	16.03	2.00	2.030	0.660	2.0
NEGRO2	2.215	1.916	1.792	1.414	0.733	0.880	0.462	0.257	0.106	0.046	3.5	5.39	8.67	1.80	2.460	0.690	2.0
NEGRO3	2.350	1.969	1.847	1.453	0.750	0.834	0.483	0.225	0.110	0.049	3.5	5.91	15.57	1.40	2.820	0.510	2.0
NORTH1	2.000	1.833	1.728	1.333	0.808	0.856	0.470	0.354	0.075	0.046	2.5	5.13	2.46	2.00	1.400	1.370	5.0
NORTH2	2.072	1.933	1.841	1.405	0.911	0.889	0.452	0.315	0.170	0.046	2.5	5.13	4.45	2.75	1.300	1.700	4.0
NORTH3	2.132	2.024	1.939	1.423	0.950	0.909	0.511	0.318	0.122	0.047	2.5	5.03	2.72	0.25	0.880	0.710	5.0
QUEL1	2.129	1.844	1.717	1.350	0.867	0.780	0.476	0.264	0.021	0.046	5.0	4.70	-22.36	1.10	1.780	0.470	2.0
QUEL2	2.188	1.848	1.715	1.350	0.865	0.783	0.422	0.204	0.081	0.046	6.0	4.85	-24.99	0.60	1.460	0.710	2.0
QUEL3R	2.114	1.836	1.717	1.358	0.883	0.821	0.434	0.254	0.031	0.046	5.0	5.33	3.62	0.95	1.300	0.570	2.0
RONO1	1.905	1.808	1.723	1.362	0.838	0.825	0.474	0.354	0.041	0.046	5.0	5.60	18.24	1.20	0.740	0.750	3.0
RONO2	1.916	1.831	1.743	1.366	0.85	0.857	0.416	0.253	0.033	0.046	5.0	5.54	3.14	0.93	0.520	0.430	3.0
RONO3	1.863	1.846	1.757	1.373	0.902	0.828	0.416	0.254	0.081	0.044	5.0	5.54	2.64	1.00	0.460	0.390	3.0
SALM1	1.981	1.754	1.662	1.287	0.828	0.825	0.453	0.254	0.058	0.038	3.0	5.44	6.75	1.85	1.780	0.370	4.0
SALM2	1.977	1.723	1.667	1.291	0.848	0.825	0.448	0.254	0.033	0.046	3.0	5.44	10.16	1.90	1.950	0.070	3.0
SEV1	2.245	2.221	2.066	1.537	1.003	0.940	0.508	0.255	0.081	0.023	6.0	6.69	135.37	0.80	0.860	0.560	4.0
SEV2	2.369	2.392	2.239	1.683	1.006	0.995	0.549	0.313	0.081	0.040	6.0	6.58	130.93	1.05	0.720	0.680	3.0
SEV3	2.176	2.089	1.954	1.499	0.950	0.887	0.477	0.267	0.081	0.040	6.0	6.66	134.77	0.90	0.740	0.310	4.0
SHALO1	2.238	2.211	2.046	1.514	1.001	0.925	0.512	0.318	0.031	0.042	1.5	6.12	43.01	3.78	2.010	2.590	2.0
SHALO2	2.367	2.336	2.154	1.605	1.009	0.952	0.572	0.318	0.082	0.043	1.5	6.18	47.44	2.67	3.010	2.930	2.0
SHALO3	1.411	2.410	2.368	1.703	1.104	1.081	0.577	0.381	0.127	0.046	1.5	6.06	24.84	1.57	3.760	2.560	2.0
SIX12	2.060	1.965	1.815	1.427	0.945	0.884	0.492	0.318	0.114	0.047	6.0	6.69	135.52	1.15	0.600	0.780	3.0
SIX2	2.060	1.965	1.815	1.427	0.945	0.884	0.492	0.318	0.114	0.047	6.0	6.74	148.69	0.15	2.460	0.460	3.0
SIX3	2.060	1.965	1.815	1.427	0.945	0.884	0.492	0.318	0.114	0.047	5.0	6.71	147.60	0.85	0.710	0.020	3.0
SOUTH1	1.907	1.883	1.809	1.331	0.910	0.870	0.470	0.353	0.081	0.022	8.0	5.3	4.73	0.64	0.480	0.780	0.0
SOUTH2	2.022	1.934	1.780	1.310	0.923	0.814	0.474	0.254	0.051	0.076	9.0	5.90	1.44	0.80	0.480	0.400	1.0
SOUTH3	2.129	1.909	1.801	1.329	0.908	0.835	0.431	0.253	0.081	0.046	8.0	5.18	-2.72	0.64	0.580	0.550	1.0
SQUAW1	2.452	2.456	2.428	1.560	1.370	1.133	0.742	0.381	0.122	0.046	2.5	6.13	21.44	4.30	4.610	2.310	3.0
SQUAW2	2.444	2.480	2.424	1.562	1.333	1.120	0.648	0.381	0.122	0.046	2.5	6.10	16.85	4.37	5.170	2.100	3.0
SQUAW3	2.501	2.545	2.503	1.616	1.366	1.225	0.681	0.381	0.152	0.032	2.5	6.19	19.03	4.25	4.560	2.020	2.0
STILL1	1.971	2.117	1.972	1.491	0.984	0.912	0.521	0.255	0.041	0.013	2.5	6.50	27.67	2.70	2.660	1.430	6.0
STILL2	1.998	1.959	1.952	1.557	0.953	0.939	0.480	0.254	0.054	0.046	2.5	6.45	39.60	2.86	1.340	1.310	5.0
STILL3	2.069	2.020	1.899	1.573	0.936	0.94	0.505	0.253	0.081	0.044	2.5	6.12	5.92	1.50	1.210	1.940	5.0
TAJA	1.977	1.932	1.845	1.417	0.917	0.884	0.492	0.318	0.122	0.036	1.5	4.56	-35.23	2.17	4.950	4.510	2.0
TAJA2	1.977	1.932	1.845	1.417	0.927	0.884	0.492	0.318	0.122	0.047	3.5	4.54	37.00	3.33	4.380	2.410	2.0
TAJA3	1.977	1.932	1.845	1.417	0.917	0.884	0.492	0.318	0.122	0.046	3.5	4.54	-35.16	2.30	3.240	2.210	2.0
THAY1	2.594	2.002	1.832	1.343	0.934	0.940	0.520	0.255	0.051	0.046	2.5	6.78	24.40	1.60	2.830	0.700	6.0
THAY2	2.518	1.976	1.727	1.311	0.962	0.937	0.511	0.254	0.081	0.046	2.5	6.84	38.93	1.70	4.160	0.710	6.0
THAY3	2.654	2.007	1.861	1.453	0.938	0.944	0.520	0.254	0.081	0.046	2.5	6.82	101.74	1.80	3.490	3.270	6.0
TWIT1	2.185	1.887	1.762	1.375	0.908	0.869	0.474	0.253	0.043	0.046	4.0	5.17	5.72	1.95	0.630	0.910	3.0
TWIT2	2.137	1.877	1.733	1.346	0.907	0.833	0.473	0.254	0.021	0.046	3.5	5.17	0.36	1.45	0.620	1.770	3.0
TWIT3	2.023	1.804	1.657	1.338	0.933	0.867	0.472	0.255	0.120	0.046	4.0	5.09	4.74	1.60	1.350	1.000	3.0
WEST1	1.872	1.876	1.880	1.375	0.910	0.867	0.462	0.300	0.117	0.046	5.0	6.20	71.70	1.67	0.600	1.930	3.0
WLS1	1.949	1.950	1.779	1.367	0.907	0.838	0.456	0.255	0.110	0.046	5.0	6.22	82.73	1.67	0.940	1.760	4.0
WLS13	1.844	1.824	1.768	1.364	0.908	0.833	0.455	0.254	0.104	0.046	5.0	6.62	84.48	1.70	0.000	1.260	3.0