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Use of Landsat Data to Predict the Trophic State of Minnesota Lakes*

The Landsat data correlated well with Carlson Trophic State Index (TSI) values, although clouds, wind, poor image data, small lake size, and shallow lake depth caused some problems in lake TSI-prediction.

Abstract: *Near-concurrent Landsat Multispectral Scanner (MSS) and ground data were obtained for 60 lakes distributed in two Landsat scene areas. The ground data included measurement of secchi disk depth, chlorophyll-a, total phosphorous, turbidity, color, and total nitrogen, as well as Carlson Trophic State Index (TSI) values derived from the first three parameters. The Landsat data best correlated with the TSI values. Prediction models were developed to classify some 100 "test" lakes appearing in the two analysis scenes on the basis of TSI estimates. Clouds, wind, poor image data, small lake size, and shallow lake depth caused some problems in lake TSI prediction. Overall, however, the Landsat-predicted TSI estimates were judged to be very reliable for the secchi-derived TSI estimation, moderately reliable for prediction of the chlorophyll-a TSI, and unreliable for the phosphorous value. Numerous Landsat data extraction procedures were compared, and the success of the Landsat TSI prediction models was a strong function of the procedure employed.*

Considerations in implementing the Landsat approach on a statewide basis are presented.

Introduction

This paper summarizes a one year pilot project aimed at assessing if, and how, Landsat satellite data might assist the Minnesota Pollution Control Agency (MPCA) in complying with Section 314(a) of the Clean Water Act of 1977 (PL95-217). Section 314(a) mandates that each state identify and classify its public freshwater lakes according to their trophic condition. In Minnesota, this involves classifying some 3,000 to 4,000 lakes (depending upon the definition of "public lake"). The data collection and analysis necessary for such a classification entails numerous logistical problems and substantial costs. Faced with these problems, the MPCA contracted with the University of Minnesota Remote Sensing Laboratory (RSL) to perform the pilot project reported herein. The basic approach taken in the study was to compare MPCA-supplied ground data collected during 1980 on some 60 lakes to the digital multispectral image values measured by Landsat on the same lakes. Statistical models relating the two data sets were developed and they were subsequently used to estimate the trophic state of approximately 100 additional lakes on the basis of the Landsat data alone.

This paper summarizes the pilot project in the following manner. First, the geographical areas of investigation and the form of the Landsat and

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ground data made available for the study are discussed. Second, the methods used to develop and calibrate the trophic status estimation models are presented, along with a discussion of the overall statistical integrity of each model. Third, the methods used to classify the 104 "test" lakes with the Landsat data are discussed. Last, the conclusions and recommendations resulting from this effort are summarized.

It should be noted that it is not our intention in this paper to summarize the details of how MSS data have been used to estimate water quality in a multitude of previous studies. This subject is adequately treated elsewhere (Witzig and Whitehurst, 1981). Our intention here is to summarize the work performed in the pilot project and to comment on the apparent effectiveness of the Landsat approach.

Study Areas/Available Data

Figure 1 depicts the location of the lakes used to calibrate our trophic state estimation models. These lakes appear in two Landsat scene areas (path/row 29/29 and 31/28), one covering the Twin Cities metropolitan area and its surroundings, and the other covering the Ottertail Lakes region of West-Central Minnesota. These scene areas were chosen by MPCA as being typical of the range of lake conditions found throughout most of the state. In addition, the location of the study areas comparatively close to the Twin Cities enabled thorough field analysis within the limits of project funds.

Landsat Data

It was our original intention to analyze data from several dates within each scene area. Regrettably, adverse weather conditions and NASA data processing difficulties limited the availability of Landsat imagery to two dates in the Ottertail Lakes region (5 June and 18 August 1980) and one date in the metropolitan region (29 July 1980). One of these scenes, the 25 June Ottertail Lakes image, was omitted from full analysis due to insufficient concurrent ground data (only six lakes had been sampled). Thus, the analysis was per-

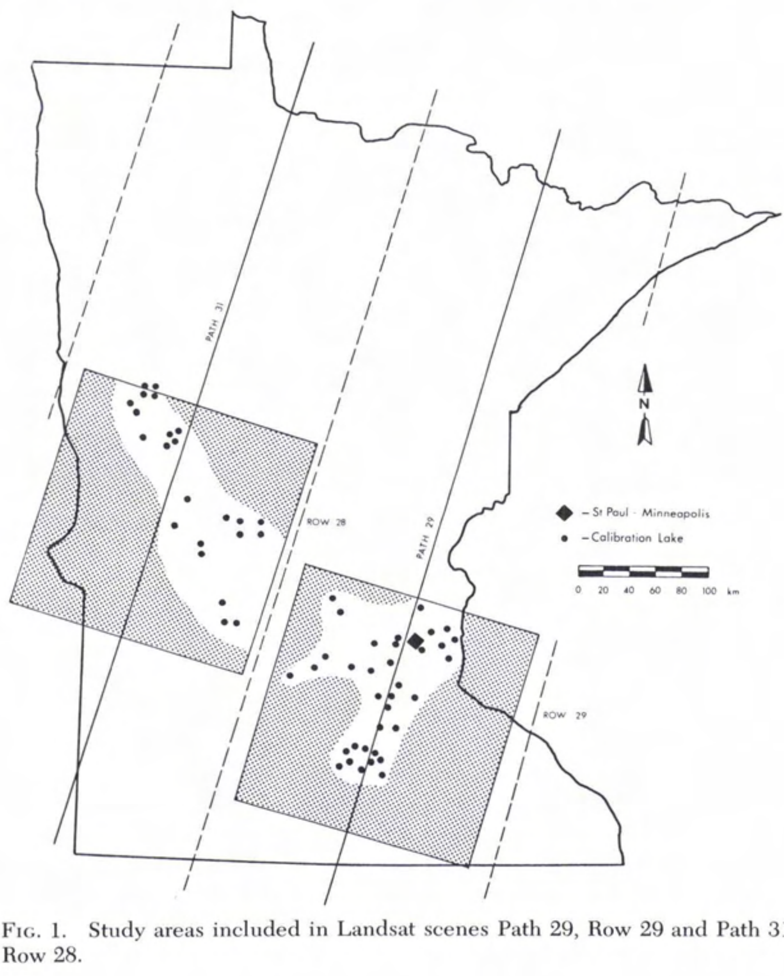


Fig. 1. Study areas included in Landsat scenes Path 29, Row 29 and Path 31, Row 28.

formed on one date within each area and no atmospheric normalization between scenes was necessary.

Figures 2 and 3 are full-scene photographic prints of the Landsat scenes which were analyzed. Figure 2 shows the image covering the Ottertail Lakes region on 18 August 1980. The quality of this image was very good except for the presence of clouds which obscured a number of the study lakes. Figure 3 shows the Twin Cities Metropolitan area in the top center portion of scene 29/29. This scene was of marginal quality, and included some cloud cover (center of left edge) and numerous bad data lines. Whereas the Ottertail Lakes image had been fully processed by NASA (including geometric correction and full-scene photographic generation), the Metropolitan area scene had been lost in the NASA processing stream. Fortunately, a pre-correction computer compatible tape of this scene was obtained, from which the full-scene print shown in Figure 3 was generated by the RSL on a Dicomed image recorder. Although this image was not geometrically corrected, it was still fully usable for the study.

GROUND DATA

The ground data supplied for each of the two study areas were of two forms. The first was MPCA-collected observations of secchi disk depth (in metres), chlorophyll-a concentration (μg/l), total phosphorous (μg/l), turbidity (FTU), color (Pt-Co), and total nitrogen (μg/l). These samples were taken by means of a float plane within 1-1/2 days of the Landsat overpass.

The second source of ground data was the Citizen Lake Monitoring Program (CLMP), coordinated by MPCA. The CLMP set contained data only for secchi disk depth and limited observations for total phosphorous and color. Because variations in sampling error between observers was anticipated, the CLMP data were not used in the modeling process, but were used as supplementary data to evaluate the model results. All model development was done using the MPCA-collected data only.

In the case of the Ottertail Lakes scene, ground data from a total of 32 sample points located on 25 "calibration" lakes were made available for mod-

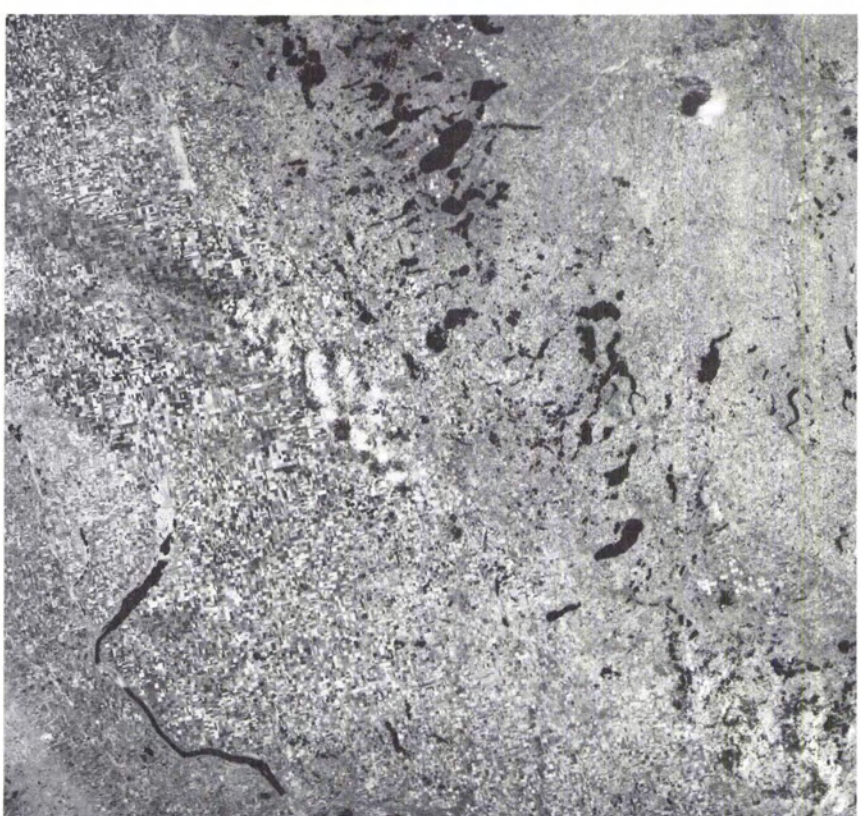


FIG. 2. 18 August 1980 Landsat MSS Band 7 image of Ottertail Lakes study area (Path 31, Row 28).

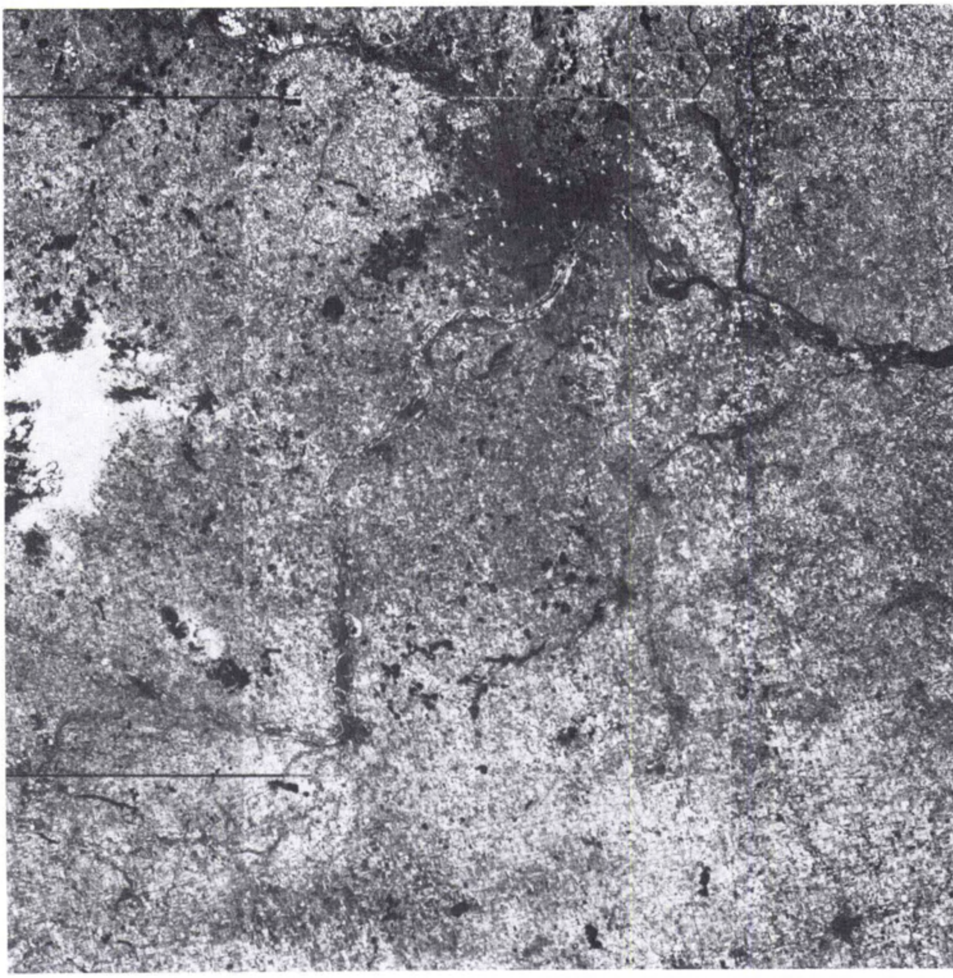


FIG. 3. 29 July 1980 Landsat MSS Band 7 image of Twin Cities metropolitan study area (Path 29, Row 29).

eling. (Multiple samples were acquired on lakes manifesting within-lake variability in trophic state.) Wind problems precluded the collection of secchi disk data at eight of these sampling points and clouds obscured the Landsat image of seven of the lakes. For the Metropolitan scene, data on 31 sample points located on 28 calibration lakes were used in the modeling process.

SUPPLEMENTAL AERIAL PHOTOGRAPHS/BATHYMETRIC CHARTS

To assist in analyzing the Landsat data, the RSL acquired aerial photographs of all calibration lakes within hours of Landsat overflight. These images were recorded on color and color infrared film, at a scale of 1:65,000, using a motor-driven 35-mm Nikon F2 camera system. Enlargements of the infrared photographs were assembled into mosaics depicting each calibration lake at a scale of 1:18,000. The resulting mosaics were valuable in documenting lake conditions in much finer detail than that available from the Landsat data and aiding the image analysis in interpreting the digital portrayal of the lakes. Such features as aquatic vegetation, bottom effects, algae blooms, sediment plumes, etc. could be clearly seen on the aerial imagery.

The aerial photographs were referenced in conjunction with MPCA-supplied bathymetric charts for each lake. In addition to the depth contours, the approximate locations of all sampling points were indicated on these charts.

CALIBRATION OF MODELS RELATING LANDSAT AND WATER QUALITY DATA

PARAMETERS MODELED

Certainly one of the most important, and probably one of the most difficult, issues to be addressed in any lake classification program is the selection of an index (or set of indices) upon which to base trophic assessment. This question can only be answered after the objectives of the classification have been established, and these can range from being highly quantitative and scientific, to very qualitative and practical. Likewise, the objective of the classification may be quite general or specific. Similarly, the resources available to accomplish the task at hand may be quite adequate or very limited. All of these issues must be faced before the appropriate role for remote sensing in the classification process can be defined.

Previous work has shown that remote sensing data cannot only be used to predict certain individual water quality parameters, these data can also be related to composite trophic indices developed from multiple parameters. For example, multispectral data have been related to indices formulated using the multivariate statistical technique of principal component analysis (Wezernak *et al.*, 1976). Other investigators have very successfully related Landsat data to subjective trophic indices, (Scarpace *et al.*, 1979). Given the objectives of our study, we adopted the Carlson Trophic State Index (TSI) (Carlson, 1977) as the variable to be predicted from the Landsat data. This index not only met the intent of the federal lake classification program, it was cited by the MPCA as having general acceptance and value in various other ongoing lake management programs in Minnesota. While no trophic index is ideal for all applications or geographical regions, the Carlson TSI became the logical descriptor of trophic state for our study.

The Carlson index can be computed from any or all of three water quality parameters: secchi disk depth, total phosphorus measurement, and chlorophyll-a concentration. The TSI is basically a logarithmic transformation of these original measurements. Relative to secchi disk transparency, the TSI is expressed as follows:

$$TSI_{(SD)} = 10(6 - \log_2 SD) \qquad (1)$$

where secchi disk transparency is in metres. Thus, a lake with transparency of 64 m has a TSI of 0 which is at the low end of the trophic scale. The other end of the scale is left open but does not extend much above 100. An increase of 10 TSI units relates to a halving of transparency.

Computation of the index from field measurement of total phosphorus (TP) or chlorophyll-a (CHL) is possible from

$$TSI_{(TP)} = 10(6 - \log_2 65\frac{1}{TP}) \qquad (2)$$

and

$$TSI_{(CHL)} = 10(6 - \log_2 7.7\ \frac{1}{CHL^{0.68}}) \qquad (3)$$

where total phosphorus and chlorophyll-a are in μg/l. These equations were developed by empirically relating total phosphorus and chlorophyll-a to transparency over a range of Minnesota lakes.

Note that the ability to independently compute the TSI value from the three water quality parameters suggests that it tends to synthesize various components of the underlying trophic condition. Yet the univariate nature of each individual formula makes the TSI values more interpretable, and hence acceptable, to the field limnologists. Other advantages of the Carlson TSI which have been cited (Shapiro, 1975) are

- The index uses easily obtained data.
- It is simple in form, being reported simply as a number.
- It is narrow enough in scope to be meaningful, i.e., it describes the "trophic" conditions in the open water and does not attempt to infer health, aesthetic, or other characteristics.
- It is purely objective. No value judgments are used and no names are suggested for different ranges of TSI.
- The TSI values are absolute and, having been derived from a wide variety of Minnesota lakes, are generally applicable.
- The relationships used are valid, i.e., transparency is not treated as linear but cognizance is taken of the parabolic shape of the transparency/biomass relationship.
- The index does not lose information by mixing up unrelated or even related parameters.
- The originally measured data can be retrieved from the index.
- The form of the index allows for an intuitive grasp of it in much the same fashion as the Richter earthquake scale does.
- The index has sufficient categories for fine discrimination between lakes.

For modeling purposes, MPCA supplied four Carlson TSI values in addition to the six raw measurements for each calibration lake. The first three TSI values were computed from the secchi, chlorophyll-a, and total phosphorous readings, and the fourth was the average of the first three. Suspecting great variability in the phosphorous-derived TSI value, MPCA expressed an interest in modeling a fifth TSI value, which was the average of the TSI's computed from the secchi disk and chlorophyll-a parameters only. While the several types of TSI measurements were analyzed separately, it should be remembered that in theory they are all estimates of a single true TSI value for each lake. Because real data are not absolutely consistent, the separate analyses were intended to show which TSI measurements were most useful. Models for predicting the six raw water quality measurements were also investigated for comparison purposes. Thus, 11 parameters (five TSI's and six raw values) were modeled during the study.

LANDSAT DATA EXTRACTION PROCEDURES

An interactive color display system was used to facilitate the process of extracting the Landsat data for each calibration lake. Multiple "windows" of data were segmented from the full scenes and recorded on floppy disks for subsequent display.

The histogram for each window was used to perform a contrast enhancement of the original data during the recording process. Also, thresholds were identified to automatically mask out land features in each window. Some 37 image segments were analyzed in the Ottertail Lakes scene, and 46 in the Metropolitan scene. Each segment contained 240 rows and 240 columns of picture elements (pixels). Pixels in the Ottertail Lakes area were nominally 60-m square at ground level. Those in the Metropolitan scene were 60 m by 80 m in size.

Five different sampling methods were used to collect the Landsat data on each calibration lake, enabling a comparison between techniques. Each of these methods is outlined below:

- *single point:* the single Landsat pixel corresponding visually to the water sample location marked on the bathymetric chart for the lake was sampled. The sample position was located on the display by viewing the bathymetric chart for the lake under analysis. This type of sample avoids the potential problem of variation in the lake water condition away from the sample point.
- *3 by 3 and 5 by 5 neighborhoods:* the computer also automatically sampled squares of 3 by 3 and 5 by 5 pixels surrounding the single point. Because the Landsat data contain a slight amount of electronic noise, these methods were intended to smooth out the spurious variations which may have occurred at the single pixel. Thus, the averaged value may be a more accurate indication of the ground radiance at the water sample point. When sampling very small or narrow lakes, the neighborhoods occasionally included some land pixels. These values were detected by their high variances and omitted from any subsequent analysis.
- *interior sample:* observing the bathymetric chart and aerial photographs, the analyst outlined a deep water region of depth greater than twice the secchi disk measurement for each calibration lake. This insured the avoidance of bottom effects, where the scanner views the lake bottom as well as the water. The analyst also avoided weedbeds, marinas, clouds, cloud shadows, and other anomalies observed either on the enhanced Landsat display or on the low altitude photography. This sampling approach further extends the "data smoothing" concept of the neighborhood samples, at the expense of possibly integrating over a variety of water quality zones within a lake.
- *exterior sample:* this approach involved outlining the entire lake, taking care not to include any other lakes within the outline. After collecting all of the Landsat data within the outline, a Band 7 threshold was used to discard all non-lake pixels. This approach provides no analyst intervention to avoid problems such as bottom effects. However, it is considerably more convenient operationally.

Each of the above techniques was employed on all of the calibration lakes by two image analysts working independently. This provided a means of cross-comparing variability between operators and methods, as well as providing checks on all data used in model development. The various sampling techniques were compared by computing correlation coefficients between the Landsat MSS and the TSI variables. The correlation coefficients for the Ottertail Lakes data consistently showed the interior samples to best fit all TSI's. This indicates that the smoothing effect of the larger sample was more important than the localized attribute of the point and neighborhood samples. Further supporting this finding were the exterior data, which also provided significantly higher correlation coefficients than the point or neighborhood data. The Metropolitan scene data exhibited a much smaller range in correlation values but the sampling techniques were ranked in the same order as with the Ottertail data. Also, significant differences between operators were observed for the point, 3 by 3 pixel, and 5 by 5 pixel methods. Differences between operators were insignificant for the interior and exterior sampling methods. Based on these results, the modeling effort was focused on the interior and exterior Landsat samples only.

MODELING RESULTS

The product of the data extraction process was a series of tables listing for each of the calibration lakes the mean digital number and variance in each of the four Landsat MSS channels and the corresponding eleven MPCA water quality measurements. A separate table was generated for each of the two scene areas and two Landsat sampling techniques (interior and exterior).

All model development was performed using standard regression techniques as implemented in the Multreg Statistical Analysis Package developed at the University of Minnesota. A series of regression models was derived, each estimating one of the 11 water quality variables using the Landsat data. In addition to the original Landsat variables, several transformed values were used. These included digital number squared and various ratios of two channels. A variable screening algorithm in Multreg was used to select the most effective combination of variables for each model. Several models were developed for each water quality variable. The statistical criteria used to select the "best" model for each parameter were many and varied. Suffice it to say here, the models chosen were those thought to have the best overall predictive accuracy when applied to the range of lakes to be classified in the two scenes. The interior models proved to be superior to the exterior models in this regard. Hence, we will provide additional details only on this final set of models.

TSI MODELS

The form of the regression models is shown in Table 1, which lists the Landsat variables used in

TABLE 1. SUMMARY OF PREDICTION MODELS FOR CARLSON TSI VALUES

Ottertail Lakes Area (18 August 1980) Variables (MSS bands)	r^2	rms	rms/mean (%)
Secchi (a)			
5, 6, 7, 5^2	0.94	1.93	3.9
Chlor (b)			
5, 6, 7, 5^2	0.84	3.88	7.0
TP (c)			
6, 7, 4/5	0.43	8.25	15
Ave (a, b, c)			
6, 7^2, 4/5	0.87	3.51	6.4
Ave (a, b)			
6, 7, 4/5	0.92	2.72	5.1
Metropolitan Twin Cities Area (29 July 1980) Variables (MSS bands)	**r^2**	**rms**	**rms/mean (%)**
Secchi (a)			
4, 5, 6^2, 7^2, 4/5	0.88	4.13	7.5
Chlor (b)			
4, 5, 6, 7, 4/5	0.84	6.38	10
TP (c)			
6, 4^2, 5^2, 7^2, 4/5	0.69	8.79	14
Ave (a, b, c)			
4, 5, 6, 7^2, 4/5	0.87	4.82	8.0
Ave (a, b)			
4, 5, 6, 7, 4/5	0.90	4.35	7.5

each of the final models for estimating the Carlson TSI values. The numbers 4 through 7 refer to the Landsat MSS channels. The squared terms refer to the channel variables squared, and the 4/5 refers to the ratio computed between band 4 and 5 values. Table 1 also lists the regression correlation coefficients (r^2), the standard errors of estimate (rms residuals), and the coefficient of variance, a measure of percent inaccuracy for each model. The regression correlation coefficient is a measure of the fit of the regression equation to the data with a maximum possible value of 1.0. The more variables included in a model, the higher r^2 will be, so direct comparisons between models using this statistic can be made only when the models under analysis have equal numbers of variables. The standard error of estimate has the same units as the predicted quantity, and is the standard deviation. Approximately 68 percent of the measurements are expected to be within one standard deviation. The coefficient of variation is simply the ratio (expressed as a percentage) of the standard error to the mean of the observed values used to develop the model.

The results shown in Table 1 indicate that the total phosphorus variable could not be accurately fitted. This had been anticipated by MPCA personnel, due to the inherent variability in this parameter. In addition, Table 1 shows that a higher overall level of success was realized with the Ottertail Lakes area data. This was also anticipated by the MPCA personnel, due primarily to a much larger range of lake conditions across the Metropolitan scene. The number of variables required to obtain a suitable model was higher for the Metropolitan scene data, indicating the greater complexity in the Metropolitan data. As expressed by the rms residuals (a measure of the average error found when applying the model to the calibration lakes), the TSI estimates for the Ottertail Lakes area data was generally accurate to ±4 TSI units, whereas the Metropolitan scene accuracy ranged ±6 units (excluding the total phosphorous TSI variable).

MODELS FOR "RAW" DATA

The results of modeling the raw data from the Landsat values are summarized in Table 2. Among other things, this table illustrates the generally poor performance of the raw data models in comparison to their TSI counterparts (in terms of the higher rms/mean values). In short, the transformation into TSI values generally improves the predictive ability of the models. At the same time, the TSI transformation makes for less complex model forms. In general, the raw values were not modeled well enough to use them as a basis for subsequent classification of the test lakes. Accordingly, classification was undertaken using the five TSI parameters only.

LAKE CLASSIFICATION

DATA EXTRACTION

The aforementioned models were used to predict the Carlson TSI values for a total of 32 lakes in the Ottertail scene and 72 in the Metropolitan scene. The data extraction procedure used to collect the Landsat values for these lakes varied only slightly from that used to develop the interior models. In the modeling effort, the secchi disk reading for each lake was available and it was used to define the sampling area to be used in the model. That is, the analyst avoided any areas of the lake having a depth less than twice the secchi reading. In the classification process, the secchi depth reading was not known. Accordingly, Landsat pixel values were generally extracted from all areas of a lake having depths greater than 5 m. It was felt that this criterion would minimize data degradation from such influences as bottom effect and submerged vegetation. In collecting the data, the image analyst again avoided any apparent extraneous scene elements such as algae blooms. Any unique tonal qualities or other characteristics of the lakes were noted on a lake-by-lake basis.

When lakes contained several geographically distinct lobes or bays, and/or apparently distinct trophic zones, separate samples were taken in each sub-area. Where possible, lakes having multiple samples were divided geographically according to MPCA's bay identification system. In all cases, the sub-areas used were delineated on the bathymetric chart for the lakes.

TABLE 2. SUMMARY OF PREDICTION MODELS FOR "RAW" WATER QUALITY PARAMETERS

Variables (MSS bands)	r^2	rms	rms/mean (%)
Ottertail Lakes Area (18 August 1980)			
Secchi			
5, 6, 7, 5^2, 6^2, 7^2, 4/5	0.98	0.16	6.4
Chlor			
4, 5, 6, 4^2, 5^2, 6^2, 7^2, 4/5	0.95	5.90	31
TP			
4, 5, 7, 4^2, 5^2, 4/5	0.73	20.2	47
Turbidity			
4, 5, 7, 4^2, 5^2, 4/5	0.87	0.89	37
Color			
4, 6, 7, 4^2, 6^2	0.75	4.76	33
Nitrogen			
4, 5, 7, 4^2, 5^2, 7^2, 4/5	0.79	186	19
Metropolitan Twin Cities Area (29 July 1980)			
Variables (MSS bands)	r^2	rms	rms/mean (%)
Secchi			
4, 6, 5^2, 6^2, 7^2, 4/5	0.91	0.57	30
Chlor			
6^2, 7^2	0.77	38.2	67
TP			
5, 6, 5^2, 7^2	0.69	76.4	67
Turbidity			
6, 6^2, 7	0.90	2.27	37
Color			
4, 5, 6, 7, 5^2, 6^2	0.83	4.85	25
Nitrogen			
4, 5^2, 6^2, 7^2, 4/5	0.90	326	20

Lakes with depth less than 5 m were visually evaluated and samples were taken only if bottom effects were not evident to the analyst. In such cases, the sampling was performed within the confines of the 3 m contour. In a limited number of cases, depths of less than 3 m were sampled if bottom effects were not evident in the Landsat data. Again, notes were taken to document the particulars of the sampling process employed on each lake.

Regrettably, not all of the test lakes could be easily classified, for various reasons. Some lakes were cloud covered in the Landsat image, or they simply were located outside the scene area. Some lakes were located in areas of noisy image data. Others were so shallow that bottom effects clearly precluded accurate model prediction. Others were so small that fewer than 20 pixels of reliable lake data could be collected. In such cases, there was great variation between the data obtained by the two image analysts, indicating inadequate sample size and extraneous pixel values.

Also deleted from the classification analysis were lakes that manifested dramatic tonal anomalies on the interactive display. Algae

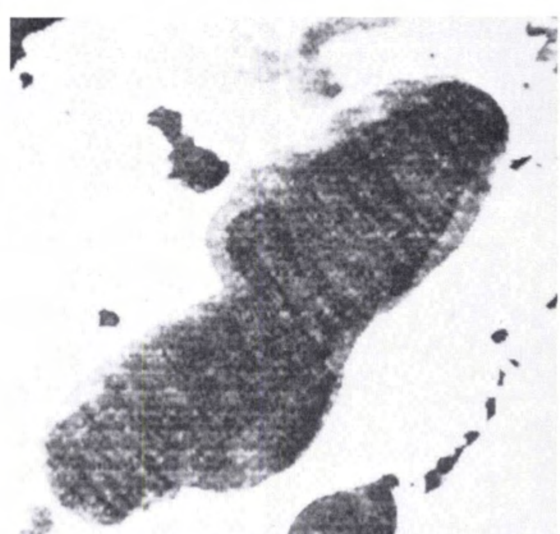


FIG. 4. Typical wind streaking pattern observed on several lakes appearing in the Ottertail Lakes Landsat scene. Note the lines on the display trending from upper left to lower right.

blooms, bottom effects, extensive weedbeds, among other things, could have been responsible for these anomalies. Reliable TSI predictions could not be made under these conditions. Another major factor present in the Ottertail Lakes scene was wind, which caused severe streaking of many of the larger lakes of interest. This phenomenon is illustrated in Figure 4.

Overall, approximately 85 percent of the lakes in the Ottertail scene and 60 percent of the lakes in the Metropolitan scene were classified. A number of lakes contained sub-areas in distinct trophic states.

RELIABILITY OF CLASSIFICATION

Ideally, one could assess the reliability of the Landsat classification by comparing the Landsat versus the MPCA data for a large random sample of the classified lakes. Regrettably, logistics and monetary constraints did not permit concurrent MPCA data collection for this purpose. Hence, historical MPCA data were used to assess the overall reliability of the Landsat classification. However, it is possible to make some a priori judgements of classification comparative reliability for the various models by other means. Figures 5 and 6 are included for this purpose. They show graphs of the

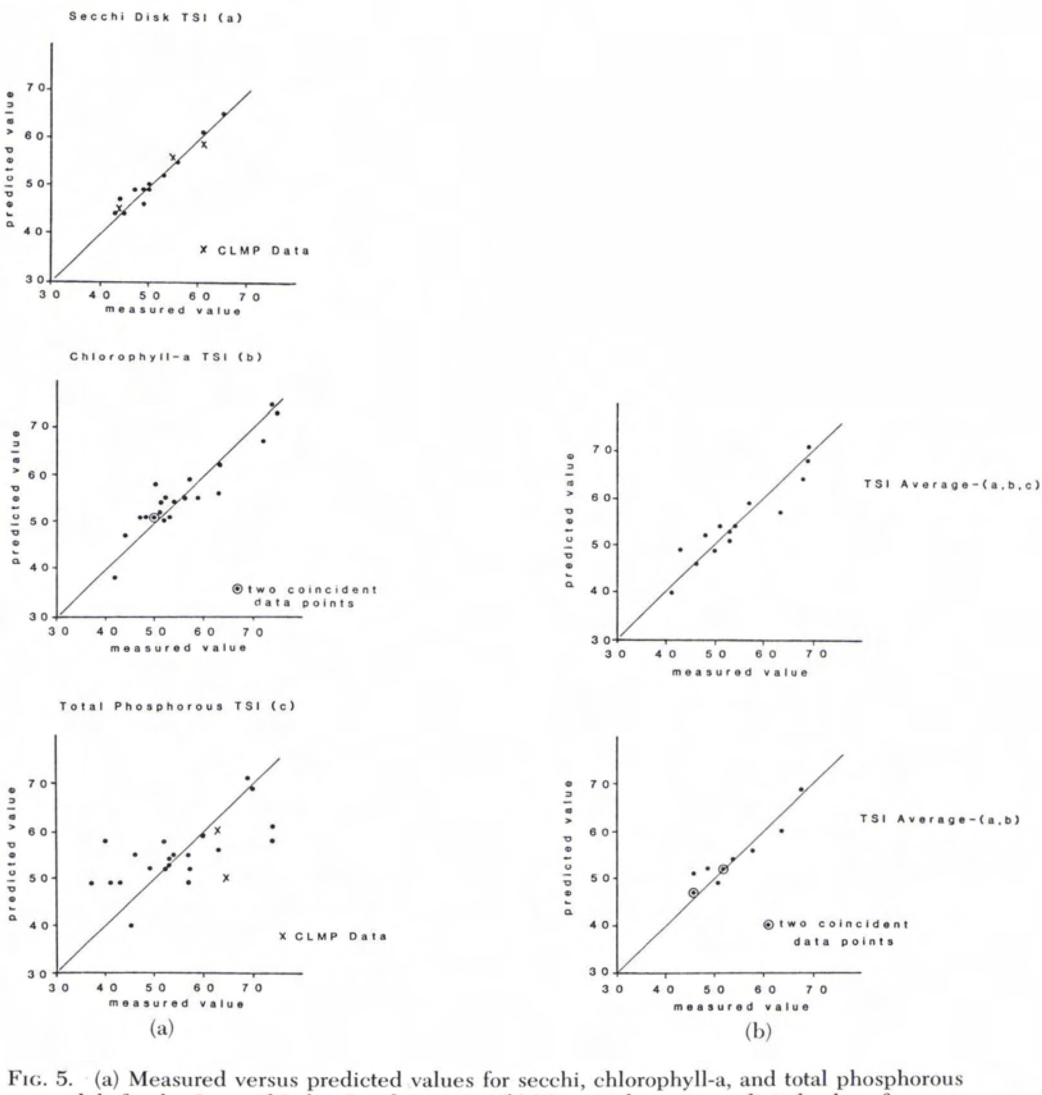
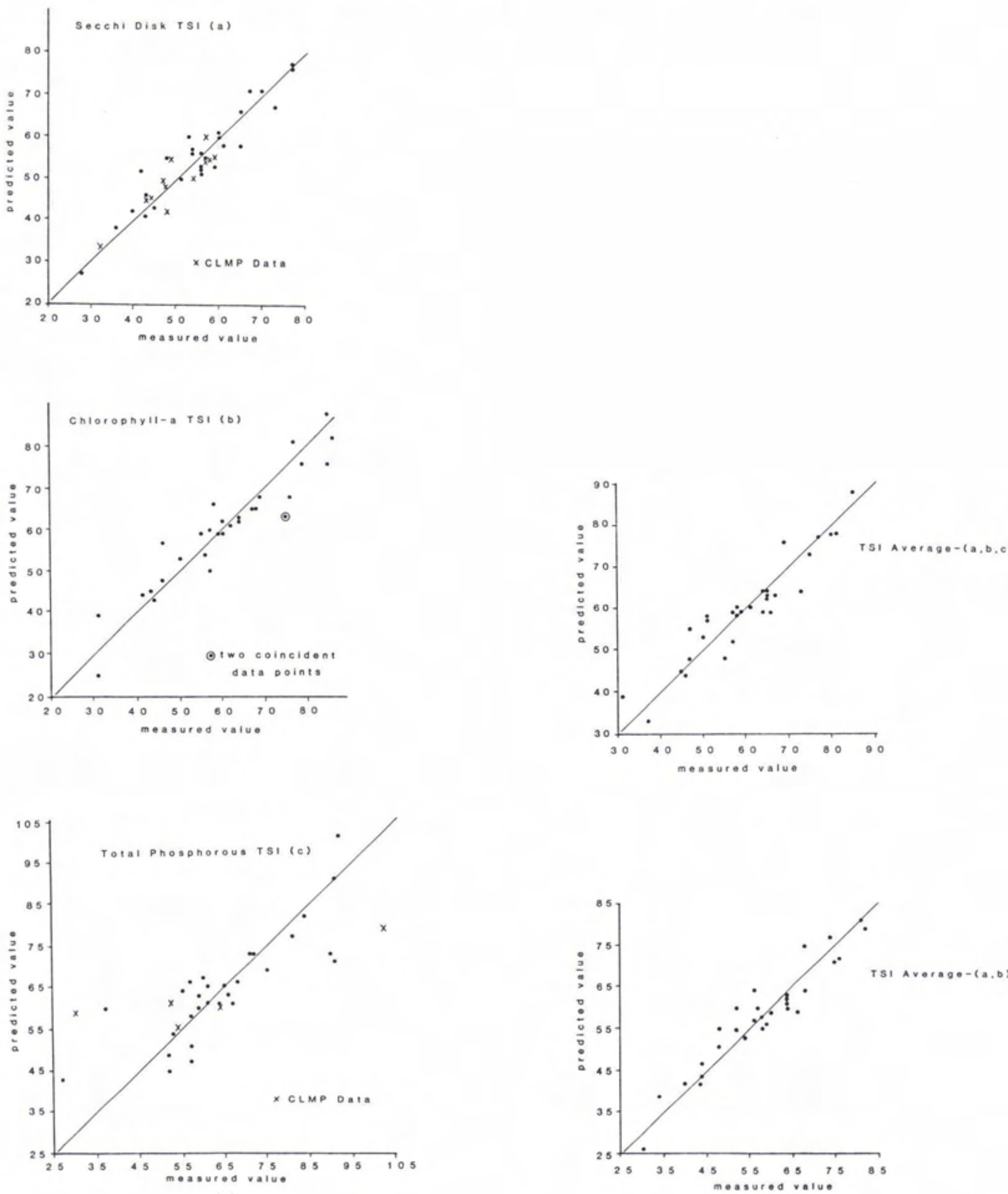


FIG. 5. (a) Measured versus predicted values for secchi, chlorophyll-a, and total phosphorous TSI models for the Ottertail Lakes Landsat scene. (b) Measured versus predicted values for average TSI models for the Ottertail Lakes Landsat scene.



(a) (b)

FIG. 6. (a) Measured versus predicted values for secchi, chlorophyll-a, and total phosphorous TSI models for the Metropolitan Lakes Landsat scene. (b) Measured versus predicted values for average TSI models for the Metropolitan Lakes Landsat scene.

relative performance of the final prediction models for each scene. Plotted on these graphs are the model-predicted versus ground-observed measurements for the calibration lakes. Where available, model-predicted versus CLMP-supplied values (the Citizen Lake Monitoring Program data not used in model development) have also been plotted on these graphs, with a separate symbol (x). These graphs permit a visual evaluation of the overall fit of the regression equations. If a given equation resulted in perfect correlation between the predicted and measured quantities, then all points would fall on the 1:1 line. (The reader is cautioned that a good statistical fit doesn't guarantee a model which will give a good prediction, because the fit considers only the set of data used to derive the relationship).

Considered in concert with the statistics in Tables 1 and 2, Figures 5 and 6 illustrate the comparatively high reliability of the Landsat-predicted TSI values (except the phosphorous predictions). The overall average discrepancy observed between the Landsat-predicted values and the available CLMP values was only 2.6 TSI units for the secchi measurements (3 Ottertail lakes and 12 Metropolitan lakes). The comparable value for total phosphorous was 10.4 TSI units (2 Ottertail lakes and 7 Metropolitan lakes).

Conclusions

Though of limited scope and duration, this one-year pilot project has indicated the following:

- Landsat data appear to have great utility in assessing the trophic state of Minnesota lakes. In this study, Landsat MSS data were found to be particularly reliable predictors of secchi-derived Carlson TSI values, moderately reliable predictors of chlorophyll-derived values, and comparatively poor predictors of phosphorous-derived values. The Landsat models were also found to be reasonably reliable predictors of average TSI values.
- The overall practical utility of the Landsat approach to trophic state prediction is a strong function of the quality of the Landsat data available, the range of lake conditions appearing in any given scene, and the manner in which the Landsat data are extracted. In this study, weather conditions, logistics, and NASA data processing problems precluded multitemporal analysis of the study lakes. Clouds and data of inferior quality caused problems in the single-date analyses performed in this study. Also, the entire methodology appears to be much more applicable to the Ottertail Lakes region than to the Metropolitan region. The principal problem in the Metropolitan scene was the comparatively small size of the lakes to be classified.

Recommendations

- The procedures developed in this study should be tested in other geographical locations of the state, and the utility of the forthcoming Thematic Mapper data should be investigated.
- Further application of the Landsat methodology should be done on a scene-by-scene calibration basis and separate models should be investigated for different lake types, time of year, etc. Chromaticity analysis and in-situ radiometry should also be investigated as means of atmospheric normalization. Preliminary attempts to use such features as airport runways to perform between-scene atmospheric normalization were unsuccessful in the present study. Such features were nonexistent in some scenes, too small in others, and their absolute reflectance varied over time.
- The Landsat methodology should not be employed on extremely shallow lakes (circa 2 m), nor small lakes (fewer than 12 hectares of open water having a depth of more than 3 m).
- Research should be initiated to define manners in which the Landsat classification methodology might be implemented on a more automated basis and on microprocessor-based hardware. The underlying object of these efforts should be the development of an operational monitoring procedure which MPCA could employ on a long-term, in-house basis.

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