Use of Thematic Mapper Data to Assess Water Quality in Green Bay and Central Lake Michigan

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ABSTRACT: The Thematic Mapper (TM) with its improved spatial, spectral, and radiometric resolution should greatly increase the accuracy of remotely sensed water quality determination. The major objective of this study was to assess the technical feasibility of using TM data to evaluate, both qualitatively and quantitatively, the general water quality of southern Green Bay and central Lake Michigan.

An empirical approach of relating TM data with simultaneously acquired "sea truth" data through multiple linear regression analysis was employed. Highly significant relationships were identified between TM data and secchi disk depth (m), chlorophyll *a* concentrations (μg/L), turbidity levels (NTU) , and surface temperatures (°C), allowing their quantitative assessment. A simple one-band power model, $y = ax^b$, and resulting transformation, $\ln y = \ln a + b \ln x$, was found to best typify the data. The following TM bands were identified for inclusion in the regression models: TM Band 2 (0.52 to 0.60 μm, green visible wavelengths) for secchi disk depth and chlorophyll *a*; and TM band 3 (0.63 to 0.69 μm, red visible wavelengths) for turbidity. TM Band 6 (10.40 to 12.50 μm), the sole thermal infrared channel, was used for surface temperature. Subsequently, the regression models were used to prepare digital cartographic products depicting the water quality and thermal distributions over the entire study area.

INTRODUCTION

SINCE THE LAUNCH of Landsat 1 in 1972, Multispectral Scanner (MSS) data have been used (with varying degrees of success) in a range of lake water quality assessment activities. The wealth of experience gained using MSS data for this purpose is well documented (Carpenter and Carpenter, 1983; Lillesand *et al.*, 1983; Lindell *et al.*, 1985; Moore, 1980; Scarpace *et al.*, 1979; Verdin, 1985; Witzig and Whitehurst, 1981). With the launch of Landsats 4 and 5 in 1982 and 1984, respectively, water resource managers now have access to Thematic Mapper (TM) in addition to MSS data. While the geographic area covered by both the MSS and TM sensors is virtually identical, the TM has greatly improved spatial, spectral, and radiometric resolution. From a user's perspective, the major design improvements of the TM over the MSS include

- 30-m versus 80-m ground resolution in its visible and reflected infrared bands;
- Seven bands of sensing versus four bands; among these are a new band in the blue wavelength region (TM1, 0.45 to 0.52 μm), two new middle infrared bands (TM5 and TM7), and a high resolution (120 m) thermal infrared band (TM6); and
- 8-bit versus 6-bit radiometric resolution affording data recording over a 256-level gray scale compared to a 64-level gray scale.

Because TM data have been collected only relatively recently, and because the TM has been operated primarily as a research instrument, comparatively little experience has been gained in the application of TM data in water quality assessment. The overall objective of this study was to assess the utility of TM data and water quality under conditions typical of the Great Lakes. To this end, near-simultaneously acquired TM data and water quality observations were obtained and related using linear regression techniques. The resulting regression models were then used as a basis for generating digital cartographic products to depict water quality distributions throughout the study area.

The following discussion of methods describes the study area, data acquisition, and data analysis procedures employed in this investigation. This is followed by sections treating the results obtained in the various analyses and the conclusions which we have drawn based on these results.

METHODS

STUDY SITE AND DATA ACQUISITION

Figure 1 shows the location of the study site used in this study. It consists of the southern half of Green Bay and the waters of west-central Lake Michigan that border the Wisconsin coast. The TM data cov-

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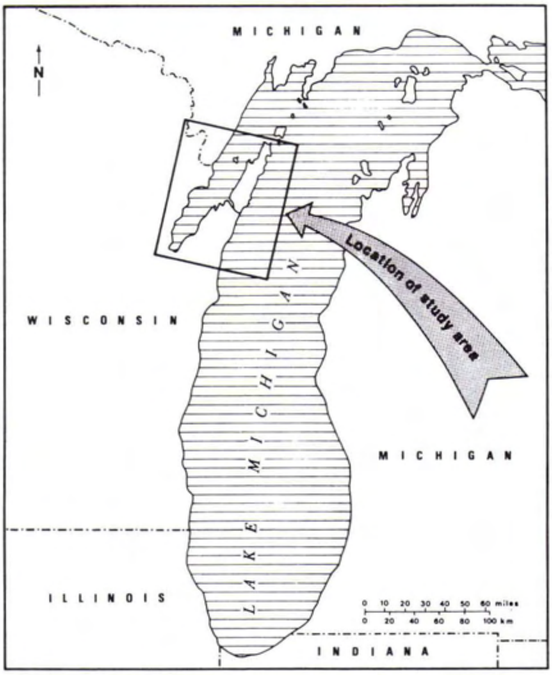

FIG.1. Outline of study site.

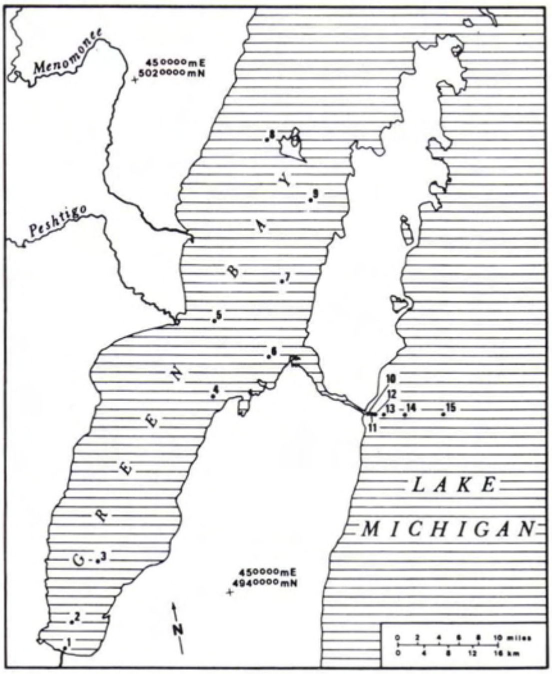

FIG.2. Map of study site showing sampling stations.

ering this area were obtained under NOAA's Special Acquisition Program on 18 July 1984 at approximately 1103 C.D.T. The resulting image (scene ID No. 400696013) is of generally excellent quality and is cloud-free over the entire study area. The image was fully processed through the standard EROS Data Center TIPS system (NASA, 1984). Sky conditions at the time of image acquisition were very clear, with winds from the northwest gusting up to 24 km/hr causing moderately wavy conditions.

Ground reference data consisting of secchi disk depth (m), chlorophyll *a* (μg/l), turbidity (NTU), suspended solids (mg/l), and surface temperature (°C) were acquired nearly coincident with the TM overpass. Nine stations in Green Bay and six in Lake Michigan were sampled by four boats within one and one half hours of satellite overpass, between 0930 and 1230 C.D.T. (see Figure 2). Surface (0.5 m) grab samples of chlorophyll *a*, turbidity, and suspended solids were taken in triplicate but not averaged at three stations. The total number of observations equalled 15 for secchi disk depth and water temperature and 21 for the chlorophyll *a*, turbidity, and suspended solids observations. All of the samples were analyzed in the same laboratory to ensure consistency. Turbidity was measured using a Hach turbidimeter; chlorophyll *a* was filtered through a glass fibermat and extracted with acetone; suspended solids were filtered at 0.45 μm, dried at 100°C for 24 hours, and weighed; temperature was measured by a thermistor; and secchi depth was measured using a 20-cm white disk.

DATA ANALYSIS

The locations of all sample stations were measured by a LORAN-C navigation system aboard each of the sampling boats. The resulting LORAN-C coordinates were plotted on an NOS nautical chart overprinted with a LORAN-C reference grid. The corresponding latitude/longitude coordinates were then determined from the chart. The typical accuracy of using LORAN-C in this mode is less than one quarter nautical mile (approx. 460 m) (U.S. Coast Guard, 1984). Three sample site locations that were identifiable because of their proximity to physical landmarks (e.g., mouth of Fox River) were used to check the accuracy of the LORAN-C positions and subsequent coordinate transformations. All three were well within the aforementioned 460-m accuracy of the navigation system, generally on the order of 100 to 150 m.

The TM data for all seven bands were extracted at each sample point using the following procedure. First, a second-order polynomial coordinate transformation was used to relate ground positions in the Universal Transverse Mercator (UTM) reference system to their equivalent row and column position in the TM scene. (A total of 14 control points was used for this purpose, and the resulting coordinate transformation had a root mean square (RMS) error of ±0.28 pixels.) Next, the sample site locations in latitude and longitude were transformed to the UTM system, and then to their corresponding TM row/column pixel addresses. A Stanford Technology Corporation (STC) Model 70 color graphics terminal (supported by a PDP 11/45 minicomputer) was then employed to interactively locate and review each sample point in the imagery.

In order to assess the potential noise in the TM data on the one hand, and to assess the impact of potential errors in sample point location on the other, we evaluated the comparative response measured by the TM both of the central sample point pixel and over surrounding local windows which were 3 by 3, 5 by 5, 7 by 7, and 9 by 9 pixels in size. An analysis of the variance observed over these various measurement areas showed that a 3 by 3 window was adequate for characterizing the data at each station. Furthermore, the uniformity of response observed over these areas indicated that all the measurement stations were located in areas of relatively spatially uniform water quality conditions and that the residual errors in sample point locations were, accordingly, inconsequential in relating the boat and satellite data. Also, it should be noted that all data were collected in locations where potential bottom effects were avoided (water depth greater than twice the secchi depth.) The surface reference data and average TM digital number for each corresponding 3 by 3 pixel window are displayed in Table 1.

The average digital number for each 3 by 3 pixel window for each of the six reflected energy bands (TM1-5, 7) were converted to radiance (in $mW \cdot cm^{-2} \cdot sr^{-1}$) using the methods described in the TM Research Prospectus (NASA, 1984). This conversion was done to transform all six of the reflected energy bands onto the same scale, so as to facilitate direct comparisons among the bands (Table 2).

The TM and limnological reference data were analyzed using the Minitab Statistical Package on a Univac 1100 computer system. Data plots, correlation matrices, and stepwise linear regression were used to explore the relationships within the data. Linear regression was used to quantify the relationships between the various water quality parameters and selected bands of TM radiance values. The multiple correlation coefficient (R^2), the standard error of the mean Y estimate (SE(Y)), F-values, and the ratio of the C_p statistic to the number of regression parameters C_p/p) were used to establish the statistical significance of the regression models (Whitlock *et al.*, 1982). In the ideal case, R^2 should approach 100 percent and the standard error of the mean Y estimate should approach zero. Likewise, the F-value should be greater than four times the F criterion (F_{cr}) (which was set at 95 percent confidence level in this study) for the regression model to be deemed of good predictive value. The ratio of the C_p statistic to p (the number of parameters) was used as a measure of bias, where a C_p/p value of ≤ 1 is an indication of negligible bias.

As discussed in the next section of this paper, numerous regression models were evaluated, and the best model determined for each water quality parameter was then used to prepare a digital cartographic product depicting that parameter throughout the study area. To accomplish this the DN values were converted to radiances and the regression equations were used to translate the radiance values to the estimated level of the parameter of interest. Thus, we created a look-up table relating DNs to the various parameters. The DN values were then renumbered into the different class intervals of the chosen water quality parameter (level sliced).

RESULTS

Early in the data analysis, it became evident that the water masses in Green Bay and Lake Michigan had slightly different spectral characteristics and that they had to be treated separately in any regression analysis. The observed difference in the transparency of these two water bodies is supported by previous work (summarized by Bertrand *et al.* (1976) and appears to be attributable to a difference in water color due to the increased presence of dissolved humic substances in Green Bay. This difference in water color, as expected, affects the shorter green and blue wavelengths (TM1 and TM2) more than the longer red and near infrared (IR) wavelengths (TM3 and TM4). The differences had no bearing on the model used for temperature prediction.

It was also readily apparent that TM bands 1 to 4 were highly correlated with all the water quality parameters except suspended solids. The replicate samples for this parameter indicated variability sufficiently large to lead us to eliminate consideration of this parameter in our subsequent analysis. This variability was apparently attributable to the fact that the small sample volume (200 to 500 ml) used to measure this parameter was insufficient for reliable gravimetric determination under our sampling conditions.

Early data analysis also indicated that the middle infrared bands (TM5, 7) showed low correlations and basically random relationships with the water quality parameters. (This result was expected due to the low water depth penetration of middle infrared wavelengths.) Accordingly, these bands were dropped from further consideration.

Thus, our analysis was restricted to TM Bands 1 to 4 for secchi disk depth, chlorophyll *a*, and tur-

TABLE 1. SURFACE REFERENCE DATA AND AVERAGE TM DIGITAL NUMBERS FOR EACH SAMPLE STATION

Station	Time (C.D.T.)	Temp (°C)	Secchi (m)	Turbidity (NTU)	Chlor A (μg/l)	Susp Solids (mg/l)	Average TM Digital Number Data for Each Band 1	2	3	4	5	6	7
Green Bay													
1	1040	23.9	0.5	10	48.6	24.4	83.8	31.4	30.0	14.9	6.0	134.3	3.6
2	1034	21.8	0.5	12	50.3	62.8	83.6	32.4	32.0	14.0	5.2	129.0	3.0
2	"	"	"	10	50.3	44.8	"	"	"	"	"	"	"
2	"	"	"	10	48.1	14.4	"	"	"	"	"	"	"
3	0946	20.2	2.3	1.6	7.9	2.88	76.8	24.7	21.2	10.9	5.2	127.0	2.9
4	1145	19.2	3.3	1.1	7.2	16.6	74.3	23.3	19.8	11.1	6.3	123.0	3.4
5	1105	19.6	3.5	0.97	5.6	8.18	75.7	23.7	20.0	12.0	8.1	125.0	4.4
5	"	"	"	0.93	5.1	2.2	"	"	"	"	"	"	"
5	"	"	"	0.95	5.2	17.6	"	"	"	"	"	"	"
6	0949	20.5	2.0	1.60	13.6	<1	77.9	26.0	20.9	11.3	7.2	126.8	3.7
7	1023	19.5	4.5	0.85	4.3	10.4	76.2	23.4	19.4	11.1	8.0	125.2	3.9
8	1105	18.0	5.0	0.75	4.4	17.4	75.2	22.6	18.0	10.0	6.6	121.3	3.3
9	1032	19.6	5.0	1.00	4.1	<1	74.7	22.9	19.4	11.0	6.7	126.0	3.2
Lake Michigan													
1	1019	16.5	1.3	7.9	4.9	48.0	89.4	33.1	28.7	15.2	9.7	119.8	4.4
2	1023	12.5	2.5	3.3	3.4	8.57	90.4	32.2	26.4	14.1	10.1	111.4	6.3
3	1029	13.5	7.0	0.95	1.5	<1	80.2	25.0	20.8	12.0	7.8	112.0	4.3
4	1036	13.8	9.0	0.75	1.5	5.83	81.4	25.7	21.0	12.8	9.4	111.7	5.8
5	1045	14.3	8.0	0.54	1.3	<1	78.4	24.0	19.7	12.2	8.0	113.0	3.9
5	"	"	"	0.62	1.0	23.0	"	"	"	"	"	"	"
5	"	"	"	0.90	1.1	24.1	"	"	"	"	"	"	"
6	1120	14.4	8.0	0.57	2.7	26.1	78.6	24.1	19.0	12.0	7.9	113.0	4.4

TABLE 2. TM RADIANCE DATA ($MW \cdot CM^{-2} \cdot SR^{-1}$)

Station	Band					
Green Bay	1	2	3	4	5	7
1	0.3427	0.2731	0.1379	0.1489	0.0050	0.0001
2	0.3418	0.2826	0.1475	0.1386	0.0034	< 0.0001
2	0.3418	0.2826	0.1475	0.1386	0.0034	< 0.0001
2	0.3418	0.2826	0.1475	0.1386	0.0034	< 0.0001
3	0.3133	0.2094	0.0949	0.1032	0.0034	< 0.0001
4	0.3029	0.1969	0.0884	0.1057	0.0058	< 0.0001
5	0.3086	0.2001	0.0895	0.1158	0.0094	0.0008
5	0.3086	0.2011	0.0895	0.1158	0.0094	0.0010
5	0.3086	0.2001	0.0895	0.1158	0.0094	0.0008
6	0.3179	0.2220	0.0938	0.1082	0.0076	0.0003
7	0.3109	0.1979	0.0869	0.1057	0.0094	0.0006
8	0.3067	0.1896	0.0799	0.0931	0.0062	< 0.0001
9	0.3044	0.1927	0.0869	0.1044	0.0064	< 0.0001
Lake Michigan						
1	0.3667	0.2888	0.1314	0.1526	0.0130	0.0015
2	0.3709	0.2805	0.1207	0.1399	0.0138	0.0044
3	0.3277	0.2126	0.0932	0.1158	0.0088	0.0013
4	0.3329	0.2189	0.0943	0.1247	0.0124	0.0035
5	0.3203	0.2032	0.0879	0.1183	0.0094	0.0006
5	0.3203	0.2032	0.0879	0.1183	0.0094	0.0006
5	0.3203	0.2032	0.0879	0.1183	0.0094	0.0006
6	0.3207	0.2042	0.0847	0.1158	0.0090	0.0015

TABLE 3. DATA CORRELATION MATRICES

3A. DATA CORRELATION MATRIX FOR GREEN BAY LN RADIANCE AND LN SURFACE REFERENCE DATA

	LNB1	LNB2	LNB3	LNB4	LNSS	LNCH	LNTB
LNB2	0.991						
LNB3	0.978	0.991					
LNB4	0.895	0.904	0.922				
LNSS	0.516	0.506	0.544	0.519			
LNCH	0.975	0.990	0.975	0.880	0.499		
LNTB	0.980	0.992	0.994	0.895	0.527	0.986	
LNSD	−0.969	−0.991	−0.979	−0.910	−0.454	−0.993	−0.987

3B. DATA CORRELATION MATRIX FOR LAKE MICHIGAN LN RADIANCE AND LN SURFACE REFERENCE DATA

	LNB1	LNB2	LNB3	LNB4	LNSS	LNCH	LNTB
LNB2	0.994						
LNB3	0.978	0.992					
LNB4	0.943	0.967	0.975				
LNSS	0.266	0.309	0.281	0.407			
LNCH	0.964	0.982	0.990	0.958	0.367		
LNTB	0.932	0.961	0.977	0.955	0.375	0.809	
LNSD	−0.916	−0.955	−0.964	−0.946	−0.570	−0.975	−0.984

LNSS = LN Suspended Solids
LNCH = LN Chlorophyll A
LNTB = LN Turbidity
LNSD = LN Secchi Depth

bidity, and TM6 for surface temperature. Within this range of TM bands, the formulation of the regression models was not constrained by any *a priori* restriction on the inclusion of particular bands in any given model. Also, it should be noted that the TM Band 1-4 data, as well as the optically related water quality parameters, were highly intercorrelated in our particular data set (see Table 3).

Examination of the original data plots, as well as plots of standardized residuals versus the predicted dependent variable (as determined by regression analysis), revealed the nonlinear character of the data and the consequent desirability of applying some sort of nonlinear transformation to the data set. The simple power model, $y = ax^b$, and resulting transformation, $\ln y = \ln a + b\ln x$, was found to best typify the data. Stepwise linear regression and correlation matrix analyses were used to identify the significant TM bands in each relationship. Subsequent regression analyses were then performed to confirm the appropriateness of those bands identified by the stepwise regression procedure. The same band relationships were found to hold for each water quality parameter, allowing the application of the same general model (but with different intercepts and slopes) for the two different water masses. We attribute the parsimonious one-band character of the regression models to the high intercorrelation of the TM bands observed under our study conditions. Extra bands did not add statistically significant information to any of our models.

The final regression model for *secchi disk depth* is
Green Bay $\ln SD = -8.38 - 6.00 \ln \text{TM2}$ $n = 9$
$R^2 = 98.2\%$ $SE(\bar{Y}) = 1.05$ m $F/F_{cr} = 66.98$ $C_p/p = 0.26$
Lake Michigan $\ln SD = -5.36 - 4.75 \ln \text{TM2}$ $n = 6$
$R^2 = 91.2\%$ $SE(\bar{Y}) = 1.12$ m $F/F_{cr} = 5.39$ $C_p/p = 6.74$

The final regression model for *chlorophyll a* is
Green Bay $\ln \text{Chla} = 12.05 + 6.40 \ln \text{TM2}$ $n = 13$
$R^2 = 98.0\%$ $SE(\bar{Y}) = 1.04$ μg/l $F/F_{cr} = 115.0$ $C_p/p = 1.79$
Lake Michigan $\ln \text{Chla} = 6.18 + 3.79 \ln \text{TM2}$ $n = 7$
$R^2 = 96.4\%$ $SE(\bar{Y}) = 1.05$ μg/l $F/F_{cr} = 20.11$ $C_p/p = 0.73$

The final regression model for *turbidity* is
Green Bay $\ln \text{Turb} = 11.59 + 4.75 \ln \text{TM3}$ $n = 13$
$R^2 = 98.8\%$ $SE(\bar{Y}) = 1.04$ NTU $F/F_{cr} = 179.4$ $C_p/p = 1.87$
Lake Michigan $\ln \text{Turb} = 13.53 + 5.74 \ln\text{TM3}$ $n = 8$
$R^2 = 95.5\%$ $SE(\bar{Y}) = 1.08$ NTU $F/F_{cr} = 21.40$ $C_p/p = 1.06$

The regression models are all highly significant with high R^2, low standard deviations of the mean Y estimate, and relatively low bias (except for the Lake Michigan secchi depth model with $C_p/p = 6.74$). Figures 3 through 5 show the transformed data with the regression line plotted for secchi depth, chlorophyll *a*, and turbidity, respectively. Plates 1 through 3 show the distribution of each of these parameters throughout the study area.

Water temperature was treated differently from the other parameters in that no transformations or division of the data into two separate sets were necessary. The TM6 original data (DN) were regressed against surface temperature (°C), resulting in the following model:

$\text{Temp} = -38.33 + 0.463\ \text{TM6}$ $n = 15$
$R^2 = 98.7\%$ $SE(Y) = 0.11°$ $F/F_{cr} = 205.9$ $C_p/p = 1.01$

This regression model is also highly significant with good predictive value and low bias. Figure 6 shows the temperature data with the resulting regression line plotted. Plate 4 shows the predicted temperature values throughout the study area.

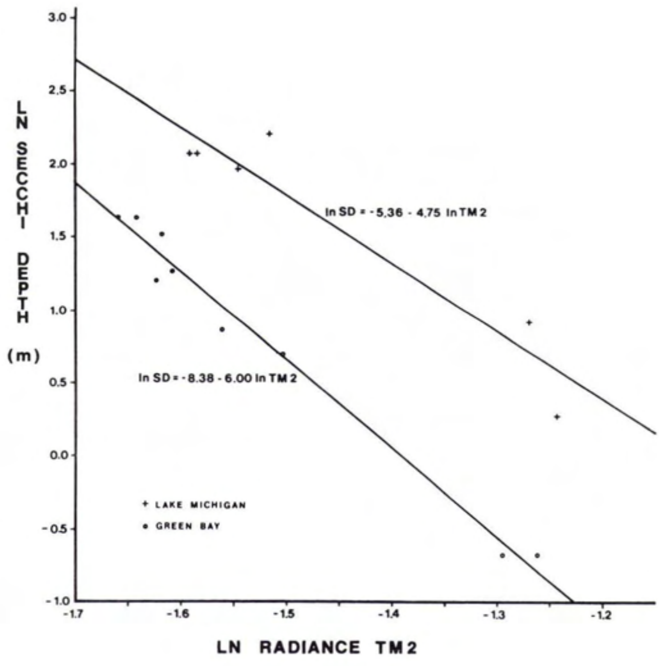

FIG.3. Plot of ln secchi depth versus ln radiance TM2.

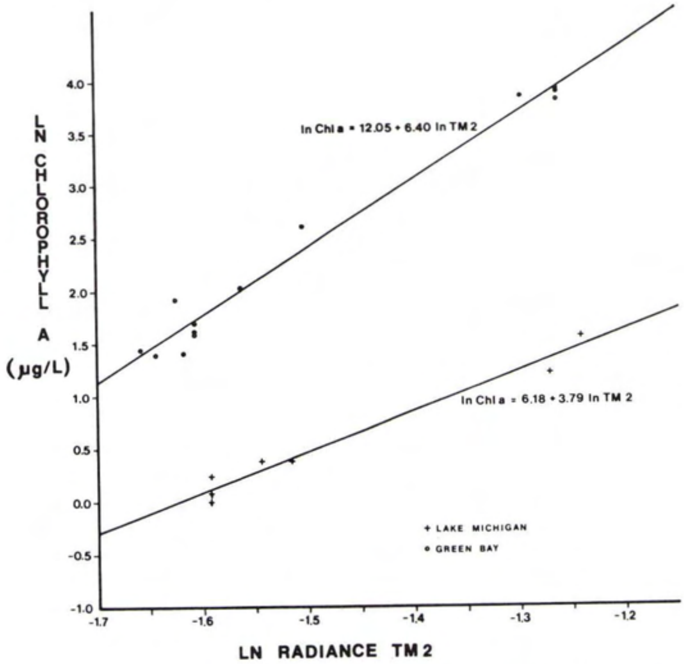

FIG.4. Plot of ln chlorophyll *a* versus ln radiance TM2.

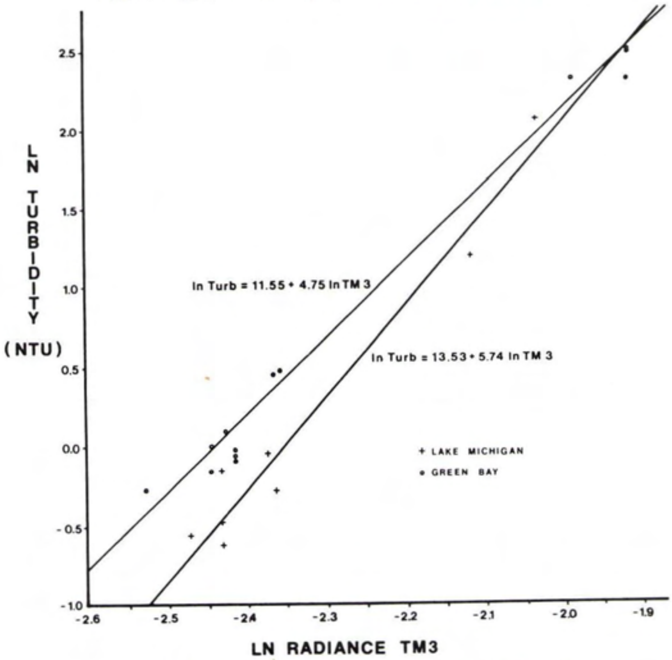

FIG.5. Plot of ln turbidity versus ln radiance TM3.

CONCLUSIONS

The following general conclusions are indicated with respect to the applicability of TM data to water quality assessment:

- *Overall, TM data appear to be a very effective means of assessing water quality.* In this study, highly significant relationships were identified between TM spectral radiances and secchi disk readings, chlorophyll *a* concentrations, turbidity levels, and temperature.

PLATE 1. Map of secchi disk depth (m).
Dark > 10.0
5.0 - 9.9
2.0 - 4.9
Light < 2.0
(Note: The slight banding observable in some regions of the maps is due to a brightness level shift related to the forward and reverse scans not corrected by the TIPS system at the time these data were processed.)

PLATE 3. Map of turbidity distribution (NTU).
Dark < 2.0
2.0 - 3.9
4.0 - 6.9
7.0 - 9.9
Light > 10.0

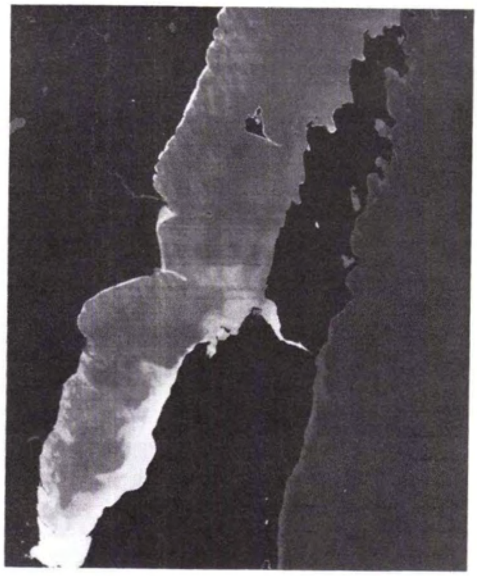

PLATE 2. Map of chlorophyll *a* distribution (μg/l).
Dark < 2.0
2.0 - 4.9
5.0 - 9.9
10.0 - 19.9
20.0 - 39.9
Light > 40.0

PLATE 4. Map of surface temperature (°C) distribution.
Dark < 12.0
12.0 - 13.9
14.0 - 15.9
16.0 - 17.9
18.0 - 19.9
Light > 20.0

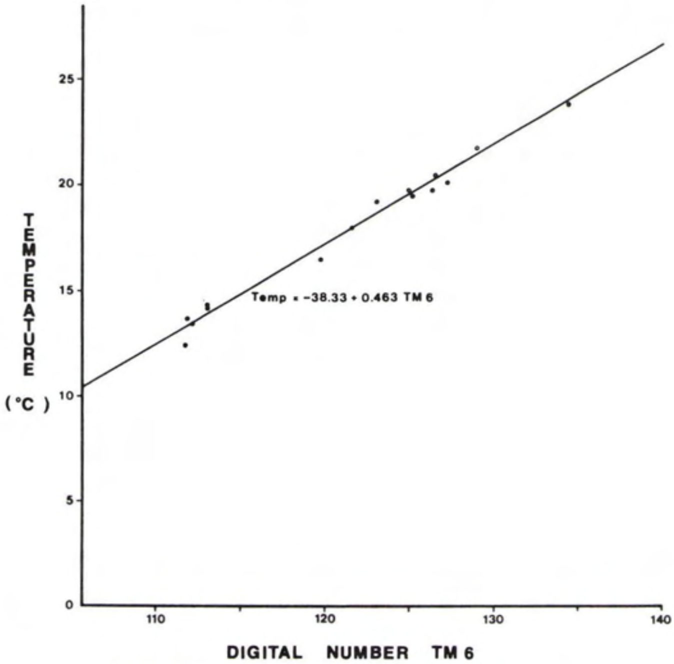

FIG.6. Plot of temperature vs. digital number TM6.

The visible and near-infrared bands appear to be well suited for prediction of optically related parameters, and the thermal band affords a very reliable surface temperature measurement capability.

- *Relative to the MSS, the TM's improvements in spatial and radiometric resolution contribute to a substantial increase in the accuracy and specificity with which water quality parameters can be predicted and mapped.* The TM's improvements in spatial resolution permit observation of very detailed patterns in water quality conditions. The smaller ground pixel reduces the effect of mixed-pixel response in water bodies such as Green Bay (where there is high spatial variation in water quality), resulting in a good predictive fit for the regression models. The overall quality of the statistical relationships developed in this study appeared to be improved by the enhanced dynamic range present in the TM data.
- *In terms of the comparative utility of the various TM bands of sensing, TM1-4 data were all found to be correlated with the optically related parameters measured in this study.* At the same time, the responses in these bands were found to be highly intercorrelated under our study conditions. Hence, we were able to use very simple (one band, logarithmic) statistical models to predict the various parameters. TM2, which coincides with a minor chlorophyll reflectance peak in the green wavelength region, was particularly sensitive to chlorophyll *a* levels. Secchi disk depth, a water transparency measure highly correlated with both chlorophyll and turbidity, was also best fit by TM2. TM3 was highly responsive to variation in turbidity. This finding basically corresponds with MSS results for inland lakes, where MSS band 5 digital values correlated best with turbidity measurements (Moore, 1980). The high correlations of turbidity and secchi depth with chlorophyll *a* levels presumably reflect an organic origin (algae blooms) to variations in these parameters. Unfortunately, our suspended solids data were invalid, so we could not distinguish between organic and inorganic origins to the mapped turbidity levels with certainty.

  The comparative weakness of TM1 data in our observed correlations may be due, in part, to the nature of our surface data collection. That is, TM1 data appear to integrate volume reflectance over a greater depth than the other bands, while the reference data only typified near surface conditions. Greater atmospheric interference in TM1 data may also have played a role. The middle infrared bands (TM5, 7) did not contribute to the significance of any of the models developed in this study.
- *Once the appropriate regression models for predicting the various water quality parameters are established, a wide range of geometrically accurate digital cartographic products depicting the distribution of these parameters can be produced.* Both black-and-white and color maps of the various parameters were produced. Likewise, a variety of display options was investigated (e.g., mapping each parameter at various class intervals). All products were found to have high geometric fidelity, with observed TM data versus ground UTM position registration on the order of ± 0.5 pixels.

  Extrapolating the models to predict water quality parameters outside of the immediate study area must be done with caution. The potential problems are demonstrated in Figures 6 and 7, where a discontinuity exists between the Green Bay and Lake Michigan models. The boundary between Green Bay and Lake Michigan for mapping purposes was arbitrarily drawn at the tip of the Door Peninsula separating the two water bodies. Discontinuity of the two models at this junction is presumably due to the mixing of the two water bodies creating an intermediate response. This discontinuity exists in the models based on TM2 (i.e., secchi depth and chlorophyll *a*), where there is a big difference in the response between the Green Bay and Lake Michigan water bodies. The turbidity model based on TM3, does not show a large difference in response between the two water bodies and does not show any discontinuity (see Figure 7). Unfortunately, no surface reference data were available to verify the regression models in this locale.

Mapping of the water quality parameters in shallow-water zones can be subject to errors due to bottom reflectance. Bottom effects in this area tend to elevate the signal response, biasing the water quality estimation. Further research into the depth penetration capability of TM is being conducted which will hopefully clarify the extent to which bottom reflectance affects the water quality mapping process.

- *Further study of the utility of TM data over a range of water quality conditions should be conducted.* The aforementioned conclusions have been based on only one observation situation. Additional research is needed to quantify the utility of TM data under different conditions. (We are currently in the process of testing the geographic extendability of the surface temperature model presented herein by applying it to TM data acquired over southern Lake Michigan.)
- *The development of a standard methodological framework for satellite-based water quality modeling should be undertaken.* It is believed that the advantages afforded by the TM will heighten interest in the general application of satellite data to water quality assessment. At the same time, there are no explicit guidelines available to ensure that future studies with such data will be comparable. We echo the philosophy presented by others (e.g., Whitlock *et al.*, 1982) that establishment of at least a common approach to the statistical modeling aspects of such studies should be developed and adopted (e.g., standardized regression techniques, measures of variation, etc.). Such standardization is not only desirable to facilitate comparison between various investigations scientifically, it is also a prerequisite to the development of future operational monitoring systems.

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