Landsat Thematic Mapper Monitoring of Turbid Inland Water Quality

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ABSTRACT: This study reports on an investigation of water quality calibration algorithms under turbid inland water conditions using Landsat Thematic Mapper (TM) multispectral digital data. TM data and water quality observations (total suspended solids and Secchi disk depth) were obtained near-simultaneously and related using linear regression techniques. The relationships between reflectance and water quality for Green Bay and Lake Michigan were compared with results for Yellowstone and Jackson Lakes, Wyoming. Results show similarities in the water quality-reflectance relationships; however, the algorithms derived for Green Bay – Lake Michigan cannot be extrapolated to Yellowstone and Jackson Lake conditions.

INTRODUCTION

INLAND WATERS ARE OPTICALLY COMPLEX due to the presence of phytoplankton, dissolved organic material (DOM), and suspended sediment. Owing to the difficulty in modeling the optical complexity of inland waters, empirical calibration approaches have generally been employed, where near-simultaneously acquired reference observations are related to the radiances observed by satellite sensors using linear regression techniques. Suspended sediment (both inorganic and organic in origin) backscatters radiation strongly and, in moderate to high concentrations (e.g., defined here as turbid conditions), generally overwhelms the reflectance signal due to phytoplankton pigment or DOM absorption (Bukata *et al.*, 1985). Though the estimation of phytoplankton pigment concentrations (e.g., chlorophyll *a*) is problematic in turbid lake waters, the estimation of suspended sediment concentration and more general measures of water transparency (e.g., Secchi disk depth) are possible using the limited spectral resolution afforded by such relatively broad-band sensors as the Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), or SPOT High Resolution Visible (HRV) (Ritchie *et al.*, 1990; Lathrop and Lillesand, 1989; Curran and Novo, 1988).

Empirically derived calibration algorithms provide site-specific predictions with reasonable accuracy but are limited in their universal application (Whitlock *et al.*, 1982). There was a large effort by the Environmental Protection Agency and state agencies in the late 1970s to use Landsat MSS data to classify the trophic state of lakes on a regional basis using empirical relationships derived between MSS radiance and Secchi disk depth (Martin *et al.*, 1983; Witzig and Whitehurst, 1981; Boland, 1976). In general, the regression models developed were appropriate for lakes of similar type (e.g., phytoplankton dominated) within a broad geographic region but separate models were needed where suspended sediments or DOM were present in significant amounts. Interestingly, there has not been a concerted effort to update this inventory of lake trophic state in the 1980s with Landsat TM data.

In earlier work, Lathrop *et al.* (1991, 1986) demonstrated the utility of empirical calibration of Landsat TM digital data for mapping turbid inland water quality in Green Bay and Lake Michigan. These initial results prompted further research into examining the relationship between water quality and TM observed reflectance for other large lake systems. The objective of this study was to test whether the models for Secchi disk depth and total suspended solids derived for Green Bay and Lake Michigan were more universally applicable. Jackson and Yellowstone Lakes in northwestern Wyoming were selected for comparison as both are oligotrophic lakes affected by turbid river plumes, especially during the spring freshet period. This study is part of ongoing research into the effects of the extensive wildfires of 1988 on stream and lake water quality in the Greater Yellowstone Region.

METHODS

STUDY AREA

The Green Bay-Lake Michigan study area, hereafter referred to as simply the Green Bay study area, covers approximately the southern two-thirds of Green Bay and the adjacent waters of western Lake Michigan. Green Bay contains a gradient of trophic states from hypereutrophic conditions at its southern end to oligotrophic conditions at the northern end where it mixes with the adjacent waters of Lake Michigan. In the bay's southern end, high concentrations of suspended sediment, chlorophyll *a*, and DOM are present and positively covarying.

The Yellowstone lakes study area includes Jackson and Yellowstone Lakes in northwestern Wyoming. These large oligotrophic, high altitude lakes (2064 and 2357 metres, respectively) receive significant pulses of river-borne suspended sediment during the annual spring freshet (the months of May and June) and following severe summer storms.

DATA ACQUISITION

Concurrent surface reference and satellite sensor data sets were acquired on three separate dates: two dates for the Green Bay study area (18 July 1984, 9 June 1987) and one date for the Yellowstone lakes study area (7 June 1989). Additional acquisition dates were planned for the Yellowstone lakes but cloud cover hampered further acquisitions. The TM data were radiometrically and geometrically corrected. Sky conditions at the time of image acquisition for the Green Bay scenes were largely haze- and cloud-free; the Yellowstone image had scattered cumulus cloud cover.

Water quality reference data were collected near simultaneously with the satellite overpass (e.g., within several hours before or after) except for Jackson Lake which was collected one day prior. The number of sample stations varied, depending on the available resources (personnel and equipment). Water quality reference data consisted of measurements of total suspended solids (mg/l) and Secchi disk depth (m). Total suspended solids (TSS) were determined by filtering 1- litre grab samples (surface, to a depth of 0.3m) and weighing the filters after drying 24 hours at 50°C. At a minimum, duplicate measurements of TSS were made for each station and averaged. Secchi disk depth

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(SDD) was measured using either a 20-cm black-and-white or an entirely white disk.

TM Data Transformations

The TM data for the three visible bands (Bands 1 to 3, centered on 0.485 μm, 0.570 μm, and 0.660 μm, respectively) and one near infrared band (Band 4, centered on 0.830 μm) were extracted at each sample point. The digital number (DN) data for a 3- by 3-pixel window (88.5m) centered on the sample point was extracted and averaged for each sample point on a band-by-band basis as a method of reducing sensor noise (Whitlock *et al.*, 1982).

A dark-object subtraction technique proposed by Chavez (1989, 1988) was used as a first-order correction for atmospheric scattering. A starting haze value was used from Band 2 for both study areas. A clear atmosphere and a 1 percent dark-object reflectance was assumed for both the Green Bay and Yellowstone lakes study area. The same atmospheric model was used for both study areas because it was felt that the potentially increased atmospheric moisture content (as evidenced by scattered cumulus cloud cover) in the Yellowstone lakes scene was compensated for by the higher altitude. The multiplicative components (e.g., transmission coefficients) due to atmospheric absorption were assumed constant between band and not corrected. The corrected DN data were then converted to reflectance (a maximum of 1.0) using the sensor calibration information provided by Markham and Barker (1986). Solar zenith angle was taken from the imagery header information and Earth-sun distance from an astronomical handbook.

Data Analysis Techniques

Regression analysis was used to examine the relationship between the water quality parameters and selected bands and ratios of reflectance values. The two data sets were analyzed independently and the regression coefficients were then tested (Student's t test) to see if two separate regression models were needed. Several statistical parameters were used to indicate the significance of the regression models (Whitlock *et al.*, 1982). These included the coefficient of determination (R^2), the standard error of the mean Y estimate ($SE(\overline{Y})$), and the F value. The F value was expressed as a ratio of the observed F value to the critical F value at the 5 percent significance level. A ratio greater than 4.0 implies a significant prediction equation (Draper and Smith, 1981, Appendix 2C). Parsimonious regression models were stressed so as to aid in both their interpretation and their application by other potential users of the models. Due to potential problems of simple regression methods in calibrating remotely sensed data with ground reference data, a reduced major axis approach was employed in determining the actual calibration models as suggested by Curran and Hay (1986).

RESULTS

The TM reflectance and the surface reference data sets clearly show a difference in response between the two study areas. The relationship between SDD and Bands 1 to 4 reflectance will be considered first (Figures 1a to 1d). A power model was selected as an appropriate fit to the nonlinearity expressed in the SDD/reflectance relationship. In comparison to the Yellowstone lakes data set, the Green Bay data show a generally flat response between SDD and Band 1 reflectance. At higher SDD values (e.g., lower turbidity, thus greater water transparency), the Green Bay data set shows a comparatively higher response. The two data sets show quite similar relationships in Bands 2, 3, and 4. At high SDD values (> 8m) the two data sets show similar reflectance values, then diverge significantly at low SDD values (< 1m) with the Yellowstone lakes data set exhibiting a greatly elevated response. Band 4 reflectance (near IR) shows great scatter at high SDD levels (e.g., low turbidity waters) which is essentially noise and does not respond until turbidity reaches a sufficiently high level (SDD < approx. 2m).

In low turbidity waters with comparatively low reflectance values, the signal-to-noise ratio is such that signal noise becomes important. The bidirectional swathing pattern is evident with alternate scans displaying a shift of approximately 1 to 2 DN. This swathing pattern is especially evident in the Yellowstone lakes data due to either an aging sensor with decreasing sensitivity and/or adjacent land surfaces (e.g., snowfields, clouds) that affect differentially the sensor response on adjacent swaths.

The close correspondence in response between the Green Bay and Yellowstone lakes data sets in TM Bands 2 and 3 for SDD values > 2m may be real or may be an artifact of the atmospheric correction process. Due to the subtraction of the additive atmospheric haze component, each data set will shift vertically depending on the magnitude of initialization factors selected (e.g., the atmospheric type and reflectance of the dark-objects). For example, if a very clear atmosphere rather than a clear atmosphere is assumed for the Yellowstone lakes data set, the response in Band 1 is reduced by a factor of two.

The general form of the relationship, a power model, between TSS and TM reflectance for the Green Bay and Yellowstone lakes data sets were similar (Figures 2a to 2d). As in the case of the SDD, the response in TM Band 1 was relatively flat in the Green Bay data set. In the other TM bands, both data sets show a similar response at low TSS levels but then diverge at approximately 2 to 3 mg/l. At high TSS levels, the Yellowstone lakes data set shows two outliers representing a significant lack of fit.

The ratio band combinations were found useful for both data sets (Figures 3 and 4). The reflectance in the longer wavelength Bands 2 and 3 increased faster than in Band 1. Thus, either the ratio of Band 2 or 3 to Band 1 is a useful indicator of SDD and TSS levels. The Band 2/1 ratio model was useful over the entire range of both data sets. A single Band 3/1 ratio model for the entire data range was not appropriate because of a shift in response at low TSS levels (e.g., TSS < 1.0 mg/l).

As expected, there is a nonlinear relationship between the reflectance and the selected water quality parameters. The general form of the relationship for the two data sets is similar, with a power model found to typify the data best, resulting in the expression

$$\mathrm{REF} = a\,\mathrm{WQ}^b$$

where REF is the selected band or band combination ratio of reflectances, WQ is the selected water quality parameter (e.g., SDD or TSS), and a and b are regression coefficients. A natural logarithmic transformation was required to linearize the data, such that

$$\ln \mathrm{REF} = \ln a + b \ln \mathrm{WQ}.$$

This simple model accounted for most of the nonlinearity in the reflectance-WQ relationship.

Two separate regression models are needed to adequately characterize the two data sets ($p < 0.0001$). In extremely turbid water (e.g., SDD < 0.5m or TSS > 15 mg/l), the Yellowstone lakes data show a comparatively higher reflectance response. Using the Band 2/1 and Band 3/1 ratio combinations, the fit for the separate models is quite good (Table 1). A reduced major axis approach was used to determine the actual calibration models to predict the SDD and TSS for the two different lake systems (Table 2). The 95 percent confidence interval around the mean SDD is generally less than ±10 percent for both the Green Bay and Yellowstone lakes study area. The 95 percent confidence interval for mean TSS is also approximately ±10 percent for the Green Bay study area but vastly greater for the Yellowstone

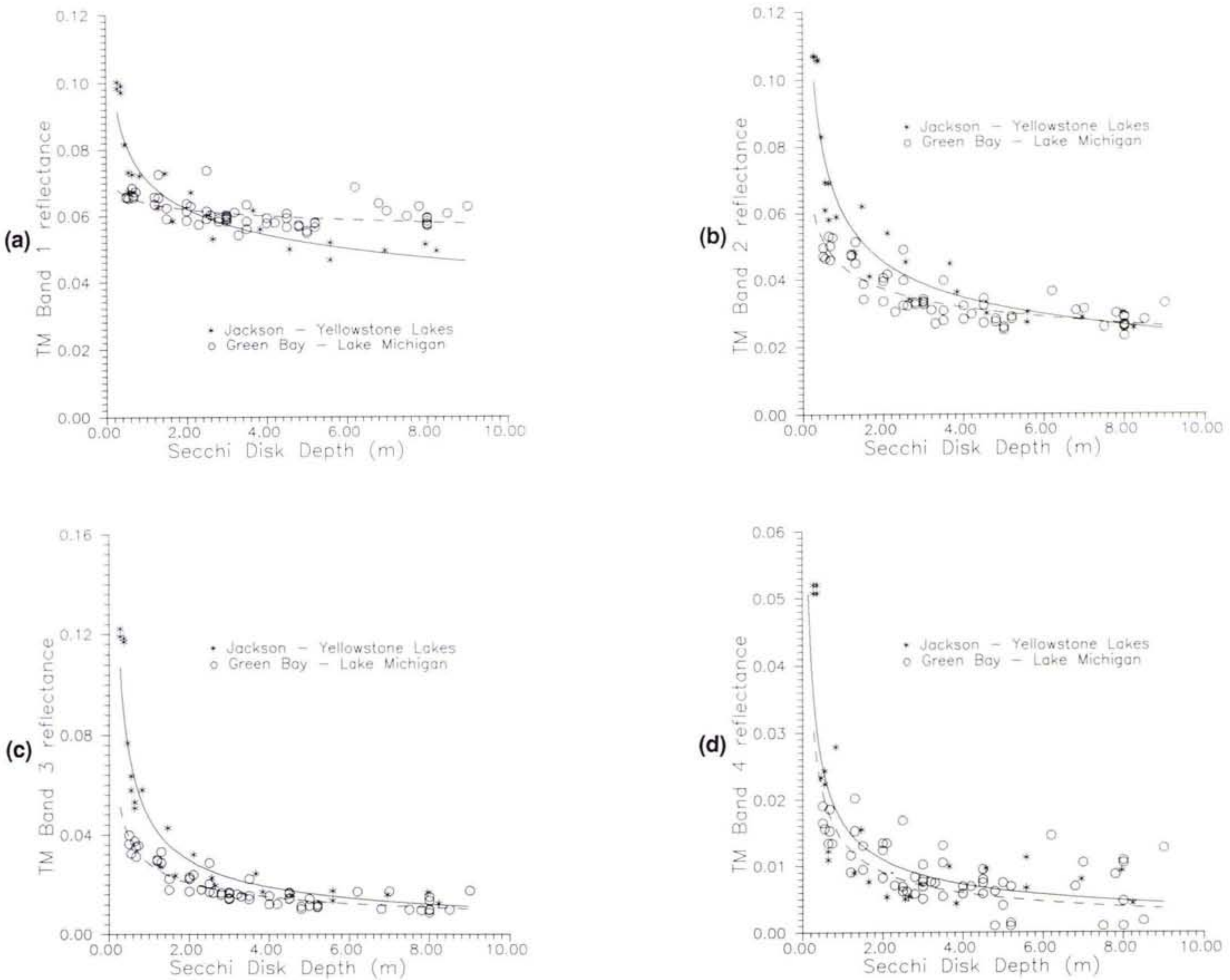

FIG. 1. Plot of TM Bands 1 to 4 Reflectance vs. Secchi Disk Depth for the Green Bay-Lake Michigan and Jackson-Yellowstone Lakes study areas. The regression line for a best fit power model is displayed (Green Bay: dashed line; Yellowstone: solid line). (a) Plot of Band 1 Reflectance vs. Secchi Disk Depth. (b) Plot of Band 2 Reflectance vs. Secchi Disk Depth. (c) Plot of Band 3 Reflectance vs. Secchi Disk Depth. (d) Plot of Band 4 Reflectance vs. Secchi Disk Depth.

lakes (e.g., varied from ±20 percent to 60 percent of the mean) due to the significant lack of fit at high TSS values.

CONCLUSIONS

The TM-observed reflectance shows a strong relationship with Secchi disk depth and total suspended solids. Calibration models consisting of a ratio of longer wavelength TM Bands 2 or 3 over shorter wavelength TM Band 1 provide a useful index of SDD and TSS. The reflectance in the longer red and near IR wavelengths increases faster than in the shorter blue and green wavelengths; thus, ratios of longer wave to shorter wave (e.g., red to blue) are positively related to turbidity levels (e.g., total suspended solids concentrations). The relationship between the water quality parameters and the individual band reflectances and the ratio band combinations is nonlinear, approximating the general form of a power model.

As is typical in empirical approaches, extrapolation of results to new situations is risky. As this and other studies have shown, separate calibration models must be developed for each lake type. For instance, one model was adequate for both Yellowstone and Jackson lakes which have similar water quality characteristics (e.g., generally low chlorophyll *a* and DOM levels, at least during the spring freshet period) and are dominated by suspended sediment. A separate model was needed for the Green Bay - Lake Michigan study area which is characterized by high levels of suspended sediment, chlorophyll *a*, and DOM (Lathrop *et al.*, 1991). Though suspended sediment generally dominates the volume reflectance, high levels of chlorophyll *a* and DOM appear to have a suppressing effect on the observed reflectance.

SDD incorporates both the absorption and backscattering characteristics of the water body, and to a certain extent integrates the effects of suspended sediment, phytoplankton pigment, and DOM. The expectation that SDD calibration models developed for Green Bay would be applicable to the Yellowstone lakes was not borne out. A difference in TSS calibration

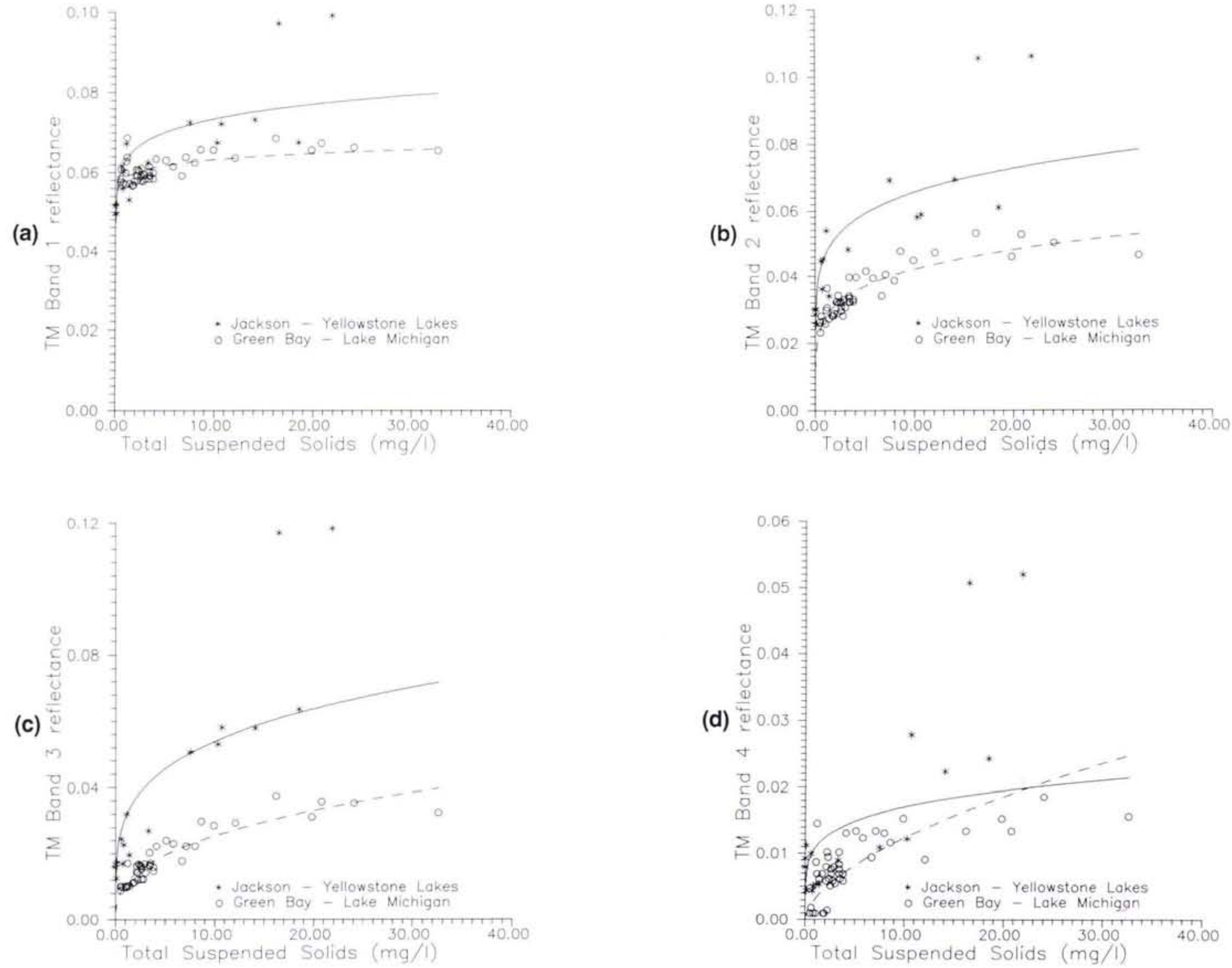

FIG. 2. Plot of TM Bands 1 to 4 Reflectance vs. Total Suspended Solids for the Green Bay-Lake Michigan and Jackson-Yellowstone Lakes study areas. The regression line for a best fit power model is displayed (Green Bay: dashed line; Yellowstone: solid line). (a) Plot of Band 1 Reflectance vs. Total Suspended Solids. (b) Plot of Band 2 Reflectance vs. Total Suspended Solids. (c) Plot of Band 3 Reflectance vs. Total Suspended Solids. (d) Plot of Band 4 Reflectance vs. Total Suspended Solids.

models was not unexpected due to potential differences in sediment grain size and differential effects on reflectance. The two study areas have vastly different geological and geomorphological regimes, and though not independently confirmed, are suspected of having different sediment grain sizes. At equal concentrations (mg/l), a sediment-laden water mass composed of smaller grain sizes would have a greater number of particles, greater surface area, and consequently stronger backscattering (Holyer, 1978). It is postulated that the general size fraction of Yellowstone sediment is smaller than that of Green Bay - Lake Michigan.

Mechanistic understanding of the relationship between water constituent concentrations, water volume reflectance, and satellite sensor-observed radiance through radiative transfer modeling provides the most rigorous basis for calibrating water quality estimation algorithms. This mechanistic approach requires a complete spectral characterization of the absorption and backscattering properties of water and its constituents, as well as modeling radiative transfer across the air/water interface and the intervening atmosphere (Bukata *et al.*, 1988). Until mechanistic models are developed that can be inverted to predict water quality from remotely sensed data, empirical approaches are necessary. Though conceptually site independent, even mechanistic approaches will require adequate reference data collection to initialize the model as to unique site conditions (e.g., high or low DOM concentrations). The empirical approach, though not conceptually elegant, does permit operational mapping of water quality on a lake or even region wide basis to support limnological and water resources study.

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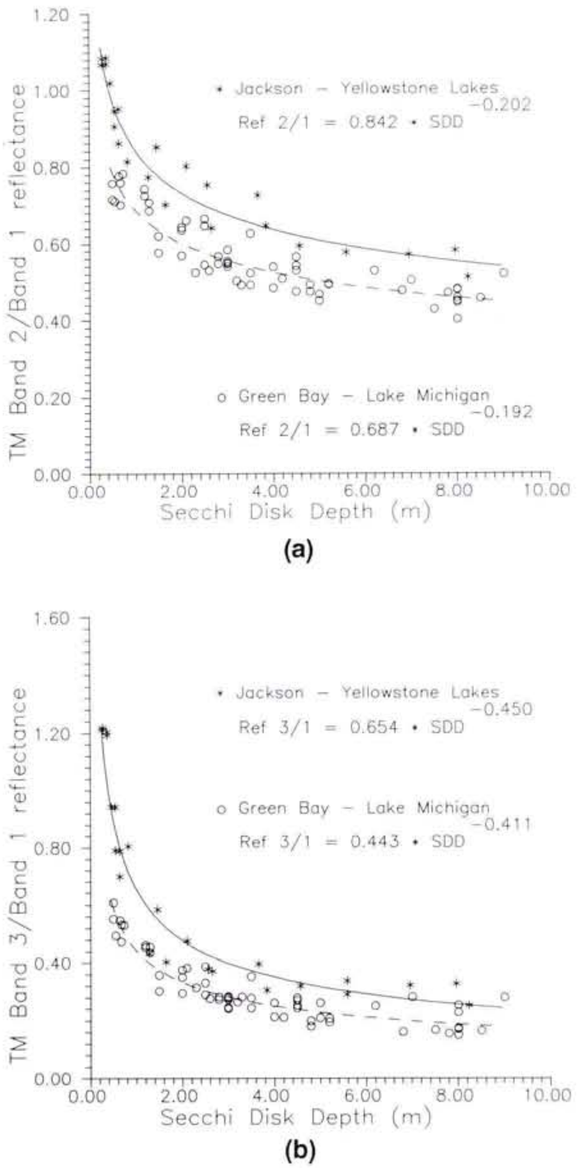

FIG. 3. Plot of TM Band Reflectance Ratios vs. Secchi Disk Depth for the Green Bay-Lake Michigan and Jackson-Yellowstone Lakes study areas. The regression model and line for a best fit power model is displayed (Green Bay: dashed line; Yellowstone: solid line). (a) Plot of TM Bands 2/1 Reflectance Ratio vs. Secchi Disk Depth. (b) Plot of TM Bands 3/1 Reflectance Ratio vs. Secchi Disk Depth.

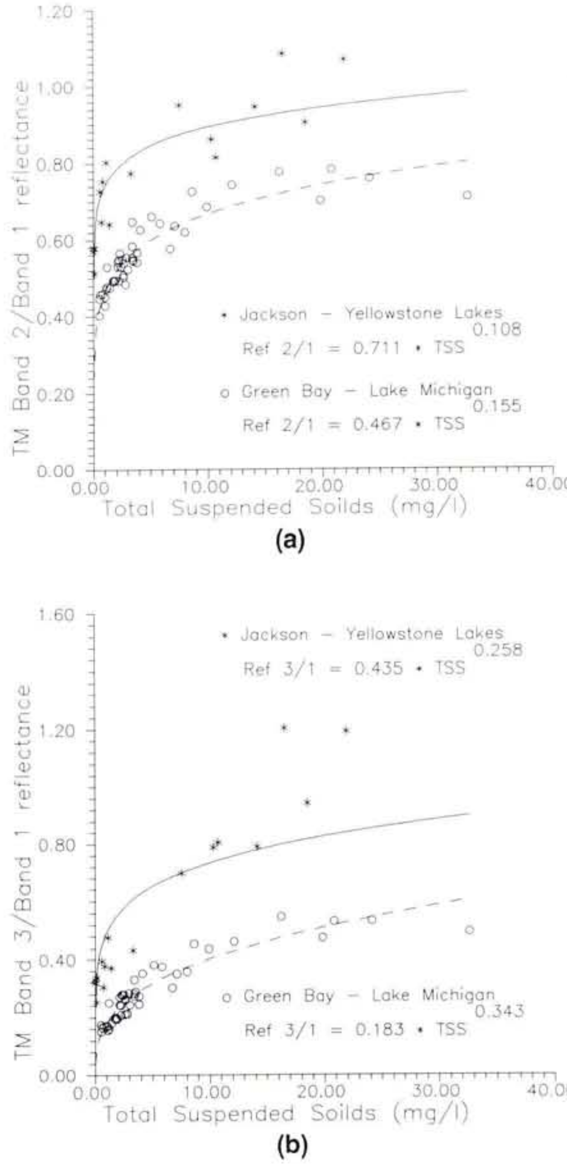

FIG. 4. Plot of TM Band Reflectance Ratios vs. Total Suspended Solids for the Green Bay-Lake Michigan and Jackson-Yellowstone Lakes study areas. The regression model and line for a best fit power model is displayed (Green Bay: dashed line; Yellowstone; solid line). (a) Plot of TM Bands 2/1 Reflectance Ratio vs. Total Suspended Solids. (b) Plot of TM Bands 3/1 Reflectance Ratio vs. Total Suspended Solids

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REFERENCES

Boland, D. H. P., 1976. *Trophic Classification of Lakes Using Landsat-1 (ERTS-1) Multispectral Scanner Data*. USEPA Report EPA-600/3-76-037, Corvallis, Oregon, 245p.

Bukata, R. P., J. E. Bruton, and J. H. Jerome, 1985. *Application of Direct Measurements to the Estimation of Lake Water Quality Indicators*. NWR IWD Scientific Series No. 140, Burlington, Ontario, 35p.

Bukata, R. P., J. H. Jerome, and J. E. Bruton, 1988. Particulate concen-

TABLE 1. BAND REFLECTANCE RATIO REGRESSION RESULTS.

Secchi Disk Depth (SDD)			
Green Bay			
REF 2/1 = 0.687 • $SDD^{-0.192}$			
$SE(\overline{Y})$ = 0.0717	R^2 = 0.82	n = 62	F/F_{cr} = 68.3
REF 3/1 = 0.443 • $SDD^{-0.411}$			
$SE(\overline{Y})$ = 0.0328	R^2 = 0.83	n = 62	F/F_{cr} = 71.5
Yellowstone lakes			
REF 2/1 = 0.842 • $SDD^{-0.202}$			
$SE(\overline{Y})$ = 0.0607	R^2 = 0.94	n = 24	F/F_{cr} = 77.3
REF 3/1 = 0.654 • $SDD^{-0.450}$			
$SE(\overline{Y})$ = 0.139	R^2 = 0.94	n = 24	F/F_{cr} = 73.9
Total Suspended Solids (TSS)			
Green Bay			
REF 2/1 = 0.467 • $TSS^{0.155}$			
$SE(\overline{Y})$ = 0.0608	R^2 = 0.87	n = 47	F/F_{cr} = 73.4
REF 3/1 = 0.183 • $TSS^{0.343}$			
$SE(\overline{Y})$ = 0.125	R^2 = 0.88	n = 47	F/F_{cr} = 85.0
Yellowstone lakes			
REF 2/1 = 0.711 • $TSS^{0.108}$			
$SE(\overline{Y})$ = 0.0907	R^2 = 0.84	n = 15	F/F_{cr} = 16.7
REF 3/1 = 0.435 • $TSS^{0.258}$			
$SE(\overline{Y})$ = 0.196	R^2 = 0.87	n = 15	F/F_{cr} = 17.5

TABLE 2. CALIBRATION MODEL RESULTS USING REDUCED MAJOR AXIS METHOD

Secchi Disk Depth (SDD)	
Green Bay	
SDD = 0.189 • REF $2/1^{-4.70}$	
$SE(\overline{Y})$ = 0.254	95% C.I. $\overline{Y}$ = (2.8, 3.2)
SDD = 0.183 • REF $3/1^{-2.21}$	
$SE(\overline{Y})$ = 0.117	95% C.I. $\overline{Y}$ = (2.9, 3.1)
Yellowstone lakes	
SDD = 0.444 • REF $2/1^{-4.80}$	
$SE(\overline{Y})$ = 0.244	95% C.I. $\overline{Y}$ = (1.4, 1.7)
SDD = 0.408 • REF $3/1^{-2.15}$	
$SE(\overline{Y})$ = 0.112	95% C.I. $\overline{Y}$ = (1.4, 1.6)
Total Suspended Solids (TSS)	
Green Bay	
TSS = 105 • REF $2/1^{6.00}$	
$SE(\overline{Y})$ = 0.317	95% C.I. $\overline{Y}$ = (2.9, 3.5)
TSS = 113 • REF $3/1^{2.74}$	
$SE(\overline{Y})$ = 0.136	95% C.I. $\overline{Y}$ = (3.0, 3.3)
Yellowstone lakes	
TSS = 19.3 • REF $2/1^{8.44}$	
$SE(\overline{Y})$ = 0.874	95% C.I. $\overline{Y}$ = (1.6, 4.2)
TSS = 21.6 • REF $3/1^{3.61}$	
$SE(\overline{Y})$ = 0.345	95% C.I. $\overline{Y}$ = (2.1, 3.1)

trations in Lake St. Clair as recorded by a shipborne multispectral optical monitoring system. *Remote Sensing of Environment*, Vol. 25, pp. 201–229.

Chavez, P. S., Jr., 1988. An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data. *Remote Sensing of Environment*, Vol. 24, pp. 459–479.

———, 1989. Radiometric calibration of Landsat Thematic Mapper multispectral images. *Photogrammetric Engineering & Remote Sensing*, Vol. 55, pp. 1285–1294.

Curran, P. J., and A. M. Hay, 1986. The importance of measurement error for certain procedures in remote sensing at optical wavelengths. *Photogrammetric Engineering & Remote Sensing*, Vol. 52, pp. 229–241.

Curran, P.J., and E. M. M. Novo, 1988. The relationship between suspended sediment concentration and remotely sensed spectral radiance: a review. *Journal of Coastal Research*, Vol. 4, pp. 351–368.

Draper, N. R., and H. Smith, 1981. *Applied Regression Analysis*. J. Wiley & Sons, New York, N.Y., 709 p.

Holyer, R. J., 1978. Toward universal multispectral suspended sediment algorithms. *Remote Sensing of Environment*, Vol. 7, pp. 323–338.

Lathrop, R. G., Jr., and T. M. Lillesand, 1986. Utility of Thematic Mapper data to assess water quality in southern Green Bay and west-central Lake Michigan. *Photogrammetric Engineering & Remote Sensing*, Vol. 52, pp. 671–680.

———, 1989. Monitoring water quality and river plume transport in Green Bay, Lake Michigan with SPOT-1 imagery. *Photogrammetric Engineering & Remote Sensing*, Vol. 55, pp. 349–354.

Lathrop, R. G., Jr., T. M. Lillesand, and B. S. Yandell, 1991. Testing the utility of simple multi-date Thematic Mapper calibration algorithms for monitoring turbid inland waters. *International Journal of Remote Sensing* (in press).

Markham, B. L., and J. L. Barker, 1986. Landsat MSS and TM post-calibration dynamic ranges, exoatmospheric reflectances and at-satellite temperatures. *EOSAT Landsat Tech. Notes*, Vol. 1, pp. 3–8.

Martin, R. H., E. O. Boebel, R. C. Dunst, O. D. Williams, M. V. Olsen, R. W. Merideth, Jr., and F. L. Scarpace, 1983. *Wisconsin's Lakes - A Trophic Assessment Using Landsat Digital Data*. WI DNR Report S00536601, Madison, Wisconsin, 124 p.

Ritchie, J. C., C. M. Cooper, and F. R. Schiebe, 1990. The relationship of MSS and TM digital data with suspended sediments, chlorophyll, and temperature in Moon Lake, Mississippi. *Remote Sensing of Environment*, Vol. 33, pp. 137–148.

Whitlock, C. H., C. Y. Kuo, and S. R. LeCroy, 1982. Criteria for the use of regression analysis for remote sensing of sediment and pollutants. *Remote Sensing of Environment*, Vol. 12, pp. 151–168.

Witzig, A. S., and C. A. Whitehurst, 1981. Current use and technology of Landsat MSS data for lake trophic classification. *Water Resources Bulletin*, Vol. 17, pp. 962–970.

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