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E7.6-10.124
CR-146057

COMPUTER MAPPING OF WATER QUALITY IN
SAGINAW BAY WITH LANDSAT DIGITAL DATA

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(E76-10124) COMPUTER MAPPING OF WATER
QUALITY IN SAGINAW BAY WITH LANDSAT DIGITAL
DATA Special Report (Bendix Corp.) 15 p
HC \$3.50

N76-16547

CSCL 08H

G3/43 Unclass
00124

January 1976
Special Report

Original photography may be purchased from
EROS Data Center
10th and Dakota Avenue
Sioux Falls, SD 57198

Prepared for:

GODDARD SPACE FLIGHT CENTER

Greenbelt, Maryland 20771

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Computer Mapping of Water Quality in Saginaw Bay with LANDSAT Digital Data		5. Report Date January 1976	
		6. Performing Organization Code	
7. Author(s) V. E. Smith, R. H. Rogers, N. J. Shah, J. B. McKeon		8. Performing Organization Report No. BSR 4213	
9. Performing Organization Name and Address Bendix Aerospace Systems Division 3621 South State Road Ann Arbor, Michigan 48107		10. Work Unit No.	
		11. Contract or Grant No. NAS 5-20942	
12. Sponsoring Agency Name and Address Goddard Space Flight Center Greenbelt, Maryland 20771		13. Type of Report and Period Covered Special Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract Computer techniques have been developed for mapping water quality parameters from LANDSAT data, using surface samples collected in an ongoing survey of water quality in Saginaw Bay (Lake Huron), Mi., sponsored by the US Environmental Protection Agency. Chemical and biological parameters were measured on 31 July 1975 at 16 bay stations in concert with the LANDSAT overflight. Application of stepwise linear regression to seven of these parameters and corresponding LANDSAT measurements resulted in regression correlation coefficients that varied from 0.94 for temperature to 0.71 for Secchi depth. Chloride, conductivity, total Kjeldahl nitrogen, total phosphorus, and chlorophyll \bar{a} were best correlated with the ratio of LANDSAT Band 4 to Band 5. Temperature and Secchi depth were best correlated to Band 5. Results of the regression analysis were used to map the water quality parameters over the entire bay.			
17. Key Words (Selected by Author(s)) LANDSAT, Computer Processing Regression Analysis, Water Quality, Ratio Imagery		18. Distribution Statement	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page)	21. No. of Pages 13	22. Price*

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ABSTRACT

Computer techniques have been developed for mapping water quality parameters from LANDSAT data, using surface samples collected in an ongoing survey of water quality in Saginaw Bay (Lake Huron), Michigan, sponsored by the US Environmental Protection Agency. Chemical and biological parameters were measured on 31 July 1975 at 16 bay stations in concert with the LANDSAT overflight. Application of stepwise linear regression to seven of these parameters and corresponding LANDSAT measurements resulted in regression correlation coefficients that varied from 0.94 for temperature to 0.71 for Secchi depth. Chloride, conductivity, total Kjeldahl nitrogen, total phosphorus,

and chlorophyll \bar{a} were best correlated with the ratio of LANDSAT Band 4 to Band 5. Temperature and Secchi depth were best correlated to Band 5. Results of the regression analysis were used to map the water quality parameters over the entire bay.

INTRODUCTION

In response to environmental requirements for large-area surveillance of water quality and watershed land use, NASA's LANDSAT-2 investigation is establishing the cost benefits of LANDSAT to the surveillance and control of lake eutrophication in the Great Lakes Basin. To accomplish this objective, LANDSAT data products are being generated to support the United States Environmental Protection Agency (EPA) modeling study of eutrophication in Saginaw Bay; the State of Michigan's survey of inland lakes and watersheds for the purpose of assessing the effects of watershed land use on lake water quality; and the State of Wisconsin's lake survey to determine eutrophication status, causes, effects, and control treatments. One goal of this work is to determine which water quality parameters best correlate with LANDSAT measurements. This paper reports on results directed toward this goal using water quality parameters and LANDSAT data acquired on 31 July 1975 in the Saginaw Bay test area.

Several institutions and federal agencies in the United States and Canada are conducting a comprehensive survey of water quality and circulation in Lakes Huron and Superior (the Upper Lakes Reference Study, a part of the United States/Canadian Great Lakes Water Quality Agreement of 1972). In Saginaw Bay (Lake Huron), EPA is sponsoring a 36-month modeling study of water quality. EPA's program will develop a deterministic model that will describe water quality changes within the bay and their relationships to enrichment and pollution caused by man. The resulting model will be used to evaluate various strategies to control nutrient flow into the bay. Important goals in this project are to describe, on a seasonal basis, the circulation and water quality in Saginaw Bay, to monitor inputs of nutrients from its watershed, and, ultimately, to develop and evaluate models for predicting water quality in the bay as a function of various control strategies.

A number of investigators have reported on the feasibility of determining various water quality parameters from LANDSAT data. Klemas (Ref 1)* has used Secchi depth and suspended sediment measurements as correlated with Band 5 image radiance to map turbidity and circulation patterns in Delaware Bay. Yarger (Ref 2) has processed multirate digital data for reservoirs in Kansas to study the effects of sun angle change, and has studied the 5/4, 6/4, and 7/4 band ratios to predict suspended solids (ppm) at unsampled areas from ground truth samples. Johnson (Ref 3) has applied the equations for predicting suspended sediment derived from stepwise regression analysis of ground truth data from Delaware Bay to image data for Chesapeake Bay and has found reasonable agreement with ground truth measurements for Chesapeake Bay.

*References are located at the end of this paper.

This LANDSAT-2 investigation has produced two previous reports (Refs 4 and 5). The first discusses the applications of a supervised computer processing technique to a 3 June 1974 LANDSAT scene (1680-15455) to produce a geometrically-corrected color-coded image of Saginaw Bay which shows nine discrete categories of turbidity, as indicated by nine Secchi depths between 0.3 and 3.3 meters. This first effort was limited to the consideration of the Secchi depth parameter as an indicator of turbidity and the application of the supervised processing technique to correlate the Secchi depth parameter to the LANDSAT measurements. More recently (Ref 5), this investigation reprocessed the same June 1974 scene to develop relationships between 12 of the water quality parameters and the LANDSAT measurements by a stepwise linear regression program (Ref 6). This first application of the regression technique only evaluated the four LANDSAT bands as the independent variables and concluded that Band 6 alone was sufficient and the most important band for predicting values of most of the water quality parameters. This paper extends this analysis by using the ten independent variables; the LANDSAT bands individually (Bands 4, 5, 6, and 7); and the six non-redundant ratios (Bands 4/5, 4/6, 4/7, 5/6, 5/7, and 6/7) in the regression program to process the 3 June 1974 scene and a 31 July 1975 scene (2190-15404). This analysis shows that a ratio of bands is more strongly correlated to most water quality parameters.

Mapping specific ranges of a water quality parameter by a supervised technique requires subdividing the parameter of interest into discrete categories, locating and editing LANDSAT measurements corresponding to each category, and applying the training measurements to categorize other LANDSAT picture elements ("pixels"). This technique is well established and is by far the most efficient procedure for mapping land-cover categories, i.e., urban, grassland, bare soil, water, etc., in which the spectral characteristics of the categories are very different (uncorrelated). The application of this same processing technique to mapping the amount or concentration of a continuous water quality parameter, i.e., Secchi depth, chlorophyll concentration, etc., may not be justified as better estimates of the parameter may be obtained with less effort by a simpler technique. If a continuous equation can be established between the parameter and LANDSAT, e.g., the equation of a straight line with one independent and one dependent variable, its solution would provide many more estimates of the desired parameter than would be practical by the supervised technique, which requires a training set for each discrete value of the parameter. This paper investigates this possibility by applying a stepwise linear regression program to seven water quality parameters and LANDSAT measurements observed on 31 July 1975 at 16 stations in Saginaw Bay (Table 1).

TEST AREA

Saginaw Bay is a shallow extension of Lake Huron and is bounded by five counties of southeastern Michigan (Figure 1). The bay has an area of some 2,960 km² and a maximum length and width of 82 km and 42 km, respectively. The mean depths are 4.6 m for the inner bay and 14.6 m for the outer bay. The Saginaw River enters the bay at its extreme

Table 1. Water Quality and LANDSAT Data for Saginaw Bay on 31 July 1975.
Measurements Were Made at Water Depths of One Meter

Station	Number of Pixels to Station Area	Temperature (°C)	Secchi Depth (m)	Chloride (mg/l)	Conductivity (micromhos)	Total Kjeldahl Nitrogen (mg/l)	Total Phosphorus (mg/l)	Chlorophyll \bar{a} ($\mu\text{g/l}$)	Mean Reflectance of Station Area				Ratio of Station Area Means Band Ratio					
									Band				4/5	4/6	4/7	5/6	5/7	6/7
									4 254*	5 254*	6 254*	7 252*						
7	56	26.1	1.9	10.9	243.	0.37	0.012	20.70	40.6	27.5	14.8	1.4	1.48	2.74	29.00	1.86	19.64	10.57
8	63	26.7	1.6	11.1	258.	0.41	0.017	9.38	44.0	29.5	16.3	1.5	1.49	2.70	29.33	1.81	19.67	10.87
12	72	26.8	1.3	18.8	277.	0.65	0.027	10.70	42.8	29.5	16.2	1.7	1.45	2.64	25.18	1.82	17.35	9.53
18	72	23.6	2.0	9.8	237.	0.38	0.012	5.61	38.1	24.7	13.8	0.5	1.54	2.76	76.20	1.79	49.40	27.60
26	64	26.0	1.6	13.8	251.	0.35	0.018	11.60	42.7	28.3	14.7	0.4	1.51	2.90	106.75	1.93	70.75	36.75
27	90	23.7	2.0	10.1	239.	0.29	0.012	7.38	38.1	24.5	12.2	0.3	1.56	3.12	127.00	2.01	81.67	40.67
32	100	24.8	1.8	10.1	235.	0.33	0.010	7.38	37.2	23.2	11.7	0.1	1.60	3.18	372.00	1.98	232.00	117.00
34	100	26.9	10.6	24.1	294.	1.00	0.039	68.50	38.6	29.1	16.4	0.9	1.33	2.35	42.89	1.77	32.33	18.22
38	121	25.1	1.4	11.7	244.	0.29	0.014	13.60	40.4	26.1	12.3	0.1	1.55	3.28	404.00	2.12	261.00	123.00
42	72	20.4	5.5	6.6	211.	0.14	0.002	1.84	32.3	20.3	9.8	0.3	1.59	3.30	107.67	2.07	67.67	32.67
43	72	23.5	1.5	12.1	246.	0.42	0.013	15.60	36.0	23.1	10.9	0.2	1.56	3.30	180.00	2.12	115.50	54.50
44	72	24.4	1.0	20.1	281.	0.72	0.027	37.10	35.6	25.5	14.5	0.8	1.40	2.46	44.50	1.76	31.88	18.13
52	72	21.5	2.1	10.4	238.	0.33	0.009	10.00	32.3	21.1	11.0	0.4	1.53	2.94	80.75	1.92	52.75	27.50
56	72	23.7	2.2	10.6	244.	0.26	0.014	6.58	39.5	25.2	12.8	0.6	1.57	3.09	65.83	1.97	42.00	21.33
60	110	22.5	5.0	6.9	215.	0.17	0.004	1.84	34.0	21.0	10.1	0.1	1.52	3.37	340.00	2.08	210.00	101.00
61	99	25.7	1.2	12.7	252.	0.42	0.020	18.00	43.7	28.7	14.1	0.6	1.52	3.10	72.83	2.04	47.83	23.50
Mean	81.7	24.46	2.0	12.5	247.8	0.41	0.016	15.36	38.5	25.4	13.2	0.6	1.52	2.95	131.50	1.94	84.47	42.05
Std. Dev.		1.92	1.3	4.7	21.8	0.22	0.009	16.53	3.8	3.1	2.2	0.5	0.08	0.32	126.54	0.13	79.12	37.66

*Maximum pixel count.

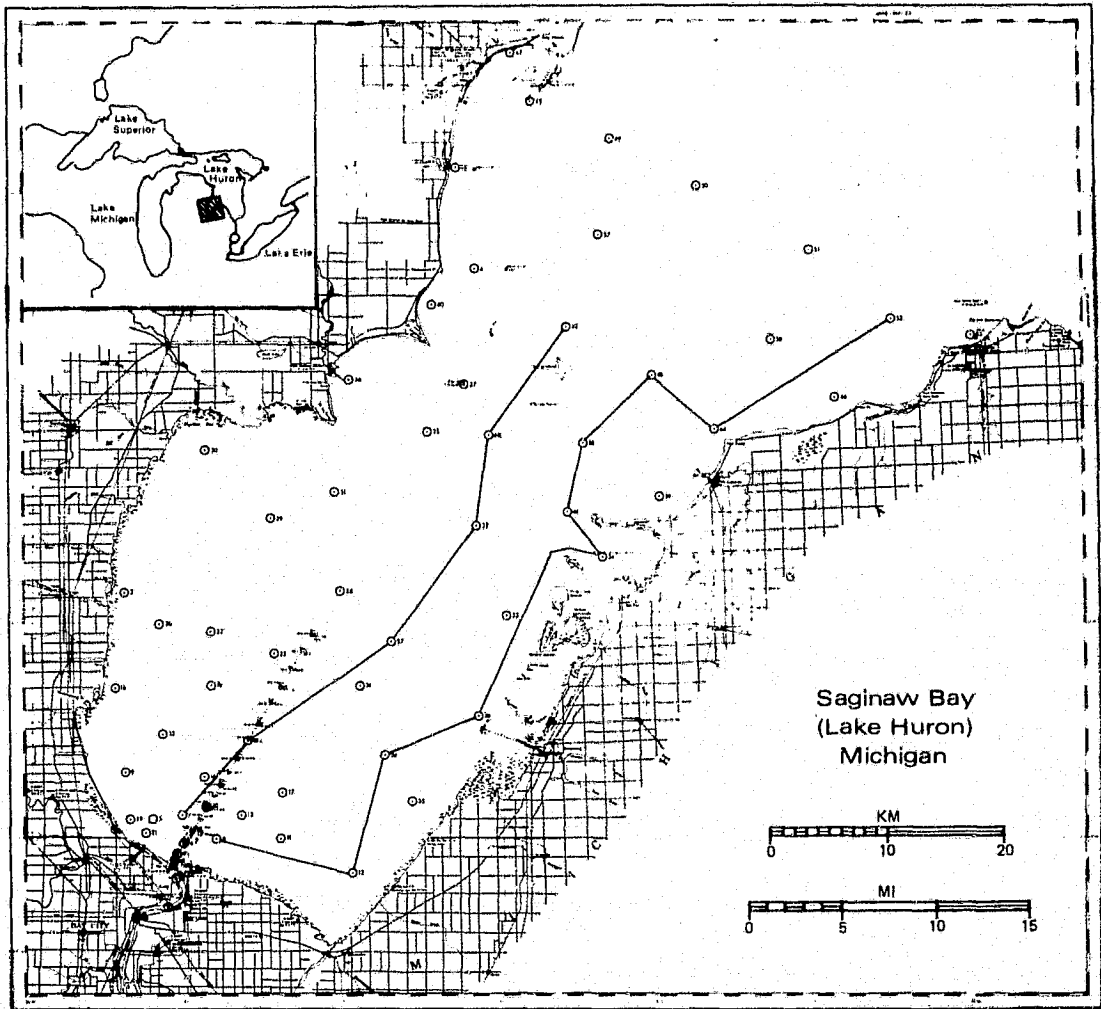


Figure 1. Map of Saginaw Bay, Showing the 61 Water Quality Stations by the Symbol \odot . The Cruise Tracks of the Two Vessels and the 16 Stations Sampled on the Day of the LANDSAT Overpass (31 July 1975) are also Shown.

southwestern end and contributes approximately 90% of the pollutants found in the bay (Ref 7). This river and its tributaries drain a watershed of more than 16,060 km² and contain four major cities and much agricultural land. Consequently, inputs of salts, nutrients, and pollutants to the bay have been increasing for many years. Levels of turbidity and algal production are consistently high, especially within the inner bay. Major declines in commercial fish yields, wildfowl populations, and esthetic values have resulted from this eutrophication. The natural estuarine-like movement of pollutants from the bay into southern Lake Huron may also reduce water quality throughout the lower Great Lakes. While circulation within the bay is highly wind-dependent, the pattern is generally counterclockwise. Clear Lake Huron water enters mainly along the western shore; turbid bay water exists along the eastern shore. Significant but unknown quantities of sediment are re-suspended regularly by wave action. The lower two-thirds of Saginaw Bay usually freezes over during January and February. These and other characteristics of Saginaw Bay have been documented by Freedman (Ref 7).

WATER SAMPLE PROGRAM

The EPA measurement program in Saginaw Bay is creating a data bank of water quality information that is being used to develop and test models of circulation, nutrient loadings, and algal productivity. Since April of 1974, surface and subsurface measurements have been obtained at the 61 bay stations shown in Figure 1, at 18-day intervals coinciding with LANDSAT overflights. Normally, three consecutive days are required to sample all stations. For this study, only measurements from stations sampled the day of the LANDSAT overpass were processed. These 16 stations are shown in Figure 1 linked by solid lines indicating the tracks of the two sample boats. The sampling began about three hours before and ended about eight hours after the satellite overpass.

On-site measurements at each bay station include temperature, pH, dissolved oxygen, conductivity, alkalinity, and water clarity. Clarity is indicated by Secchi depth and percent transmittance measurements. Variables measured in the laboratory include soluble nutrients (nitrate-nitrite, orthophosphate, sulfate, silicate, and ammonia), organic materials (nitrogen, phosphorus, carbon, and chlorophylls), chloride and metals (sodium, potassium, calcium, magnesium, and six trace metals), and total suspended solids. Enumerations of phytoplankton and zooplankton are also made. Coordinated studies of current patterns, nutrient inputs, and bottom fauna are also underway by EPA.

COMPUTER PROCESSING OF LANDSAT DATA

The LANDSAT computer-compatible tapes (CCTs) for this investigation were processed on the Bendix Multispectral Data Analysis System (MDAS) (Ref 4). Four major processing steps were involved; (1) transforming the locations of the bay stations from navigation charts to LANDSAT CCT coordinates, (2) extracting the LANDSAT digital measurements from the CCTs for each of the 16 bay station areas, (3) applying stepwise regression to the water quality parameters and LANDSAT measurements derived from each bay station area, and (4) producing a ratio image of the regression results on the film recorder.

Earth-to-LANDSAT coordinate transformation

Three basic steps were involved in the automatic referencing of ground coordinates to LANDSAT coordinates. The first step consisted of automatically retrieving the latitude and longitude of carefully selected ground control points (GCPs) from a map through a digitizing process. The criteria for selecting these GCPs is that they can be easily and accurately identified on LANDSAT imagery. The second step consisted of converting the latitude and longitude of these GCPs to LANDSAT coordinates by using a theoretical transformation derived from known and assumed spacecraft parameters, including heading, scan rate, altitude, and a knowledge of earth rotation parameters. The LANDSAT coordinates and transformation matrices thus obtained are approximate, based on the use of the nominal spacecraft parameters. The approximately-derived LANDSAT coordinates and transformation are used, however,

to identify the actual LANDSAT coordinates associated with the GCPs. To accomplish this, the coordinates of a GCP are input to the Bendix MDAS. The approximate transformation computes the LANDSAT coordinates and displays the area on the TV monitor. Positional errors of the GCPs displayed to the operator are designated by a cursor to the computer, which uses the error measurement to derive an improved set of coefficients for the transformation matrix. This procedure is repeated on additional GCPs until the desired geometric accuracy is achieved. This investigation used 20 GCPs within the LANDSAT scene. The resulting bay station coordinates were transformed to LANDSAT coordinates with an error of less than one picture element (pixel). A LANDSAT pixel corresponds to an area of 57 by 79 m (0.44 hectares).

LANDSAT measurements from station areas

The MDAS TV monitor was used to display the single pixel best corresponding to each bay station location. A cursor was then positioned, expanded, and shaped by the operator about each station site to designate a station area of 60 to 100 pixels in size. Once the station areas were designated, the MDAS computer extracted the measurements from all pixels defined by the cursor and calculated the mean digital count in each band (Table 1). For the table shown, the digital counts from the standard LANDSAT CCT have been multiplied by two in Bands 4, 5, and 6 and by four in Band 7. The six non-redundant ratios of the four LANDSAT bands were calculated from the station area means. The mean values of the digital counts in each LANDSAT band and the ratios of the means for each bay station were then stored in a disk file for use in the regression analysis.

Stepwise regression analysis

The LANDSAT measurements stored on the disk file were used in a stepwise linear regression program (Ref 6) to investigate relationships between the LANDSAT measurements and each of seven water quality parameters. The stepwise regression procedure first determined which single independent variable (one of the four LANDSAT bands or the six ratios) provided the best statistical correlation with the dependent variable (one of the water quality parameters). In successive steps, a second independent variable was added, if necessary, to improve the multiple correlation.

Filming water quality parameters

MDAS was used to produce a color-coded image of the ratio of Band 4 to Band 5, which was determined by the regression procedure to be the single best variable for mapping five of the seven water quality parameters. The ratio image was viewed with 24 color levels on the MDAS TV display. These levels were grouped to seven final levels. The ratio image, produced on an Optronics film recorder, was used with the regression equations to interpret the various water quality parameters over the bay.

STATISTICAL RESULTS

The results of applying the regression program to the 31 July 1975 scene are summarized in Table 2. The results for only the first step of the regression are reported since, in every case, the correlation coefficient was not significantly improved by adding other independent variables. The constants, coefficients, and most significant band or ratio of bands listed in the table may be used to predict the dependent variable. For example:

$$\text{Chloride (mg/l)} = 99.27 - 57.138 (\text{Band 4/Band 5})$$

The regression correlation coefficient noted in the table provides a measure of the fit of the regression equation to the data and has a maximum value of unity. The standard error of estimate has the same units as the dependent variable and is the statistical standard deviation. Approximately 68% of the measurements are expected to be within one standard deviation of the mean.

Table 2. Regression Results for Saginaw Bay on 31 July 1975
(16 Stations)

Dependent Variable (Units)	Equation Constant	Equation Coefficient	Independent Variable (LANDSAT Band or Band Ratio)	Regression Correlation Coefficient (r)	Standard Error of Estimate
Temperature (°C)	9.688	+ 0.5304	Band 5	0.944 **	0.6560
Secchi Depth (m)	9.707	- 0.3010	Band 5	0.711 *	0.9650
Chloride (mg/l)	99.27	- 57.138	Band 4 to Band 5	0.922 **	1.891
Conductivity (micromhos)	650.0	- 264.82	Band 4 to Band 5	0.920 **	8.876
Total Kjeldahl Nitrogen (mg/l)	4.455	- 2.664	Band 4 to Band 5	0.934 **	0.0799
Total Phosphorus (mg/l)	0.1846	- 0.1112	Band 4 to Band 5	0.914 **	0.0039
Chlorophyll \bar{a} (ug/l)	303.1	- 189.4	Band 4 to Band 5	0.869 **	8.455

* Significant at P < 0.01 (r = 0.606)

** Significant at P < 0.001 (r = 0.725)

Figure 2 shows the correlation between one of the seven water quality parameters (dependent variable) and the LANDSAT Band 4 to Band 5 ratio (independent variable). The figure shows the 16 sample points, the regression line and equation, the standard estimate of error (dashed lines), and the regression correlation coefficient (Table 2).

Figure 3 provides a visual evaluation of the overall fit of the regression equation for one of the seven water quality parameters. The regression equation and the appropriate independent variable values (Band 4 to Band 5 ratios) shown in Table 1, were used to arrive at predicted values of each water quality parameter. These predicted values, were, in turn, plotted against the measured values. If the regression equation resulted in a perfect correlation, all points would fall on a straight line having unity slope. The standard error of estimate is shown in Figure 3 as the dashed lines.

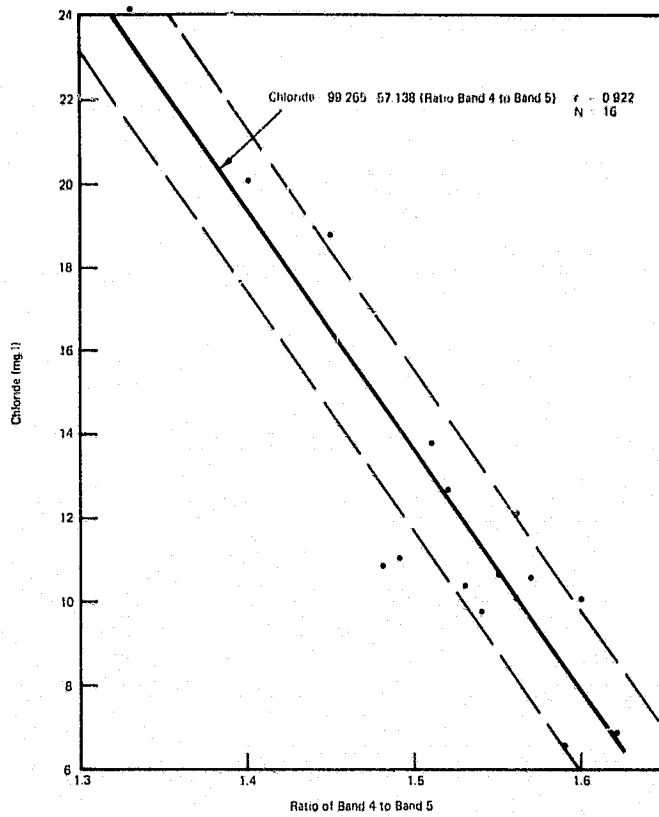


Figure 2. Chloride versus the Ratio of LANDSAT Band 4 to Band 5

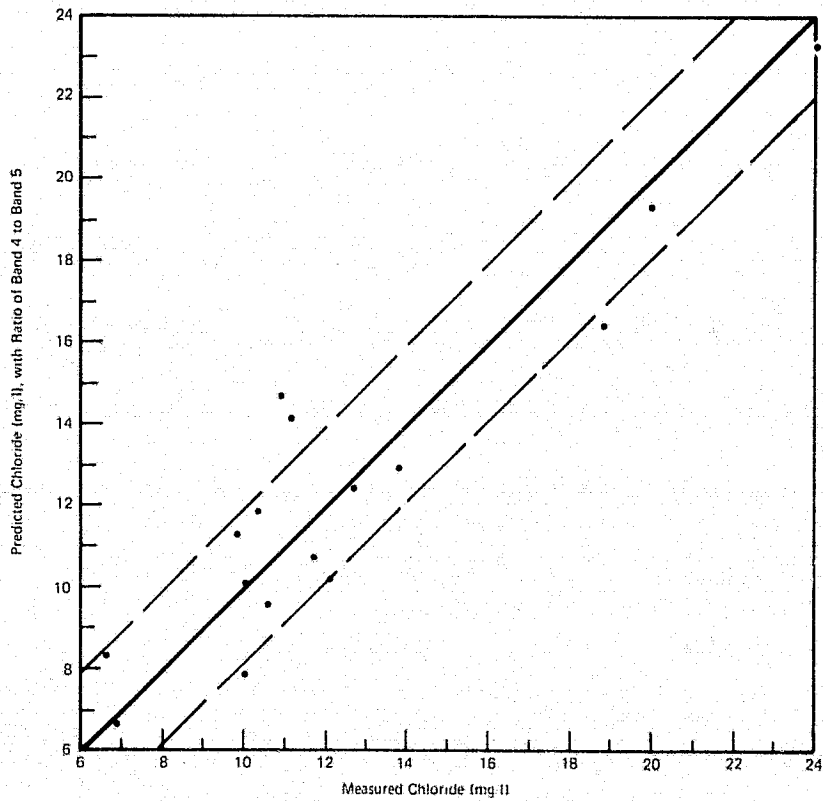


Figure 3. Predicted versus Measured Chloride

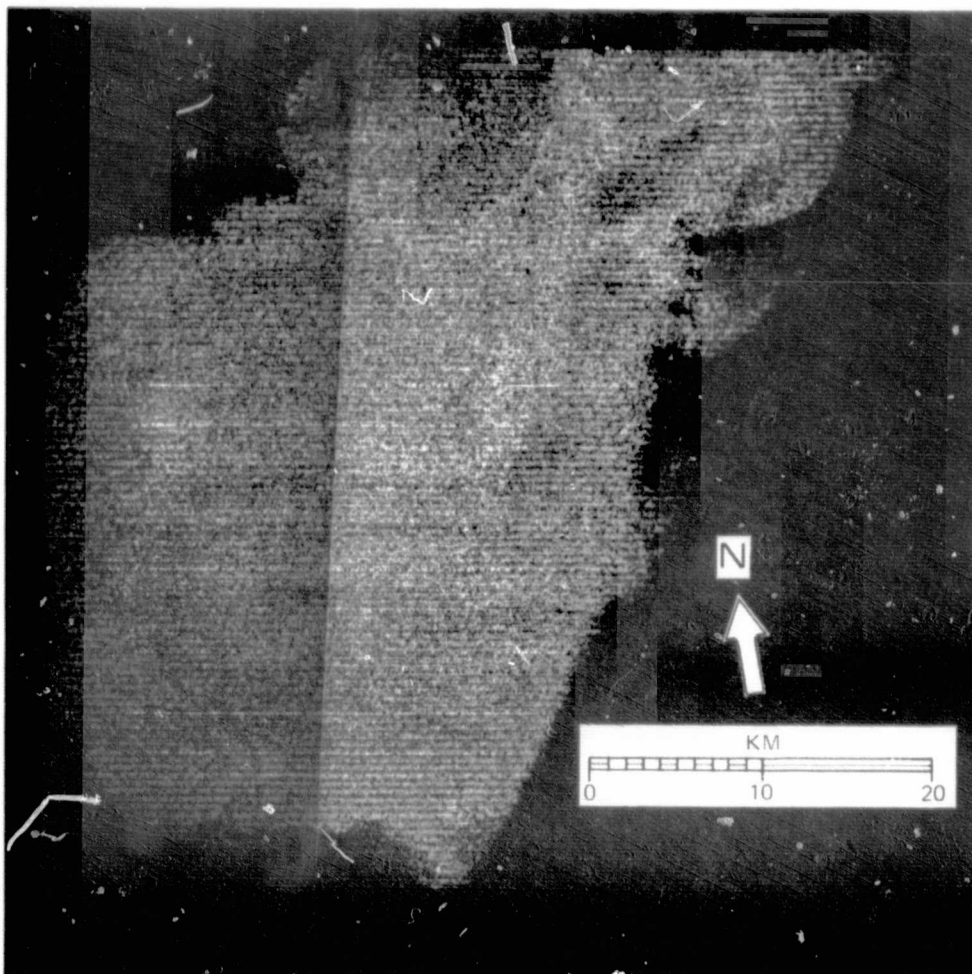
DISCUSSION

As reported previously (Ref 5), when the regression program was applied to the 3 June 1974 scene with the four LANDSAT bands as the independent variables, Band 6 alone was chosen by the regression procedure as providing the best correlation with most water quality parameters. Both Yarger (Ref 2) and Johnson (Ref 3) also found this to be true in Kansas reservoirs and in Chesapeake Bay, respectively. It was suggested (Ref 5) that the selection of Band 6, in the stepwise regression analysis, may have been caused by the noticeable atmospheric haze which causes non-uniform measurements of scene radiance and degrades the correlations in the two visible bands, Bands 4 and 5. When the four LANDSAT bands and the ratio of bands were applied as independent variables to the 3 June 1974 scene, a ratio of bands was chosen by the regression program as providing the best correlation with most water quality parameters. The fact that a ratio is a best choice for mapping water quality parameters was again verified by using bands and the ratios of bands in regression processing the 31 July 1975 scene, the results of which are observed in Table 2 and the figures of this paper. Table 2 shows that the ratio of Band 4 to Band 5 is sufficient to map the concentrations and distribution of chloride, conductivity, total Kjeldahl nitrogen, total phosphorus, and chlorophyll \bar{a} with a correlation coefficient of 0.869 or more. Temperature and Secchi depth preferred Band 5 alone.

It should be emphasized that LANDSAT measures color or volume reflectance of the water and does not, for example, measure temperature, chloride, conductivity, etc. directly. Only a few water quality parameters; chlorophylls, algal populations, and particulate carbon; have a direct influence on the color or volume reflectivity of Saginaw Bay water. However, the other water quality parameters do correlate secondarily with color or volume reflectance to the extent that they all characterize the same water masses.

Figure 4 shows an image of the ratio of Band 4 to Band 5. The concentration and distribution of five water quality parameters can be interpreted directly from this image. The ratio values are indicated next to the appropriate breaks in the gray scale. The corresponding values for each of the water quality parameters have been calculated from either the equations shown in Table 2 or from plots of each variable, such as those shown in Figure 2. It should be emphasized that these values are accurate only within the ranges of standard error indicated in Table 2.

Analysis of the ratio image has confirmed some known features of circulation and water quality in Saginaw Bay. Previous surveys of the bay (Ref 7) have indicated that the predominant flow of Saginaw River water is northward along the eastern shore of the bay. Less turbid Lake Huron water dominates the outer bay and enters the inner bay chiefly along the western shore. Zones of mixing and local circulation are apparent on the map, as are shoal areas where sediment evidently has been re-suspended.



Saginaw Bay on 31 July 1975
Part of LANDSAT Scene 2190-15404

LANDSAT Band 4/5 Ratio	Gray Level	Chloride (mg/l)	Conductivity (micromhos)	Total Kjeldahl Nitrogen (mg/l)	Total Phosphorus (mg/l)	Chlorophyll \bar{a} ($\mu\text{g/l}$)
1.32	Black	23.8	300	0.939	0.038	53.1
1.36	Dark Gray	21.6	290	0.832	0.033	45.5
1.40	Medium-Dark Gray	19.3	279	0.725	0.029	37.9
1.48	Medium Gray	14.7	258	0.512	0.020	22.8
1.56	Light Gray	10.1	237	0.299	0.011	7.6
1.64	White	5.6	216	0.086	0.002	-

Figure 4. Ratio Image and Predicted Water Quality of Saginaw Bay (Seven Gray Levels)

A number of prominent water mass patterns can be identified from Figure 4. A lobe-shaped body of relatively clean Lake Huron water is located near the north edge of the ratio image. More turbid water enters the bay from the Saginaw River and flows counterclockwise along the shore. Also present are a few seemingly isolated areas of clean water within the bay. For example, note the area northwest of the most prominent point of land along the eastern shore.

The ratio image has been keyed to five of the 30 water quality parameters. The concentration and distribution of other water quality parameters may be obtained by their correlation with the five parameters mapped here. For example, sodium is highly correlated with conductivity and, if the relationship between sodium and conductivity is used, the conductivity map (ratio image) can also be transformed into a map showing the concentration of sodium over the bay. Similarly, the distribution of four major metals can be interpreted by their correlation with the chloride map.

The significance to water quality of each parameter measured in Saginaw Bay varies with the location and season. In general terms, however, the following applies to the July 1975 data. Temperature (also chemical and biological) gradients in the bay during the spring reflect the mixing of eutrophic Saginaw River water with oligotrophic (and cooler) Lake Huron water. Thus, temperature may be used coincidentally to discriminate between waters of markedly different quality. Secchi depth estimates are used to approximate water transparency as affected by suspended particles and solutes. Chlorophyll \bar{a} is also an approximate indicator of living algal biomasses. Conductivity, which varies directly with the concentration of dissolved ions, is generally high in eutrophic or polluted waters. Similarly, chloride is used here as a conservative tracer of enriched Saginaw River water.

CONCLUSIONS

LANDSAT digital data and ground truth measurements for Saginaw Bay (Lake Huron), Michigan, for 31 July 1975 can be correlated by stepwise linear regression and the resulting equations used to estimate "invisible" water quality parameters in nonsampled areas. The correlation of these parameters with one another indicates that the transport of Saginaw River water can now be traced by a number of water quality parameters, one or more of which are directly detected by LANDSAT. Chloride, conductivity, total Kjeldahl nitrogen, total phosphorus, and chlorophyll \bar{a} are best correlated with the ratio of LANDSAT Band 4 to Band 5. Temperature and Secchi depth correlate best with Band 5.

Water quality parameters mapped from the linear regression equations will indicate which water quality parameter(s) is most reliable as a tracer to identify Saginaw River water as it circulates throughout the bay and is diluted by Lake Huron water. The resulting regression equations can be used to map the concentration and distribution of water quality parameters throughout the bay, given the appropriate LANDSAT measurements. These parameters need not be directly detectable by

LANDSAT, provided their concentration is correlated with some water characteristic that is detectable. The predicted values for each water quality parameter can be displayed on a TV monitor and color-coded and mapped onto film. Thus, LANDSAT monitoring, as an adjunct to conventional point-sampling, provides an economical basis for extrapolating water quality parameters from point samples to unsampled areas and provides a synoptic view of water mass boundaries that no amount of point sampling could provide.

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