PRODUCTION OF A WATER QUALITY MAP OF SAGINAW BAY BY COMPUTER PROCESSING OF LANDSAT-2 DATA

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ABSTRACT

Surface truth and LANDSAT measurements collected July 31, 1975 for Saginaw Bay are used to demonstrate a technique for producing a color coded water quality map. On this map, color is used as a code to quantify five discrete ranges in the following water quality parameters: temperature, Secchi depth, chloride, conductivity, total Kjeldahl nitrogen, total phosphorous, chlorophyll _a_, total solids and suspended solids.

The LANDSAT and water quality relationship is established through the use of a set of linear regression equations where the water quality parameters are the dependent variables and LANDSAT measurements are the independent variables.

Although the procedure is scene and surface truth dependent, it provides both a basis for extrapolating water quality parameters from point samples to unsampled areas and a synoptic view of water mass boundaries over the 3000 km^2 bay area made from one day's ship data that is superior, in many ways, to the traditional machine contoured maps made from three day's ship data.

1. INTRODUCTION

Since June of 1974 the Bendix Aerospace Systems Division has been conducting a research program in the surveillance from LANDSAT of eutrophication in Saginaw Bay, Michigan and in the inland lakes and watersheds of Michigan and Wisconsin. This paper addresses the development of one specific water quality map of Saginaw Bay.

The EPA-sponsored study of water quality in Saginaw Bay (Lake Huron) aims to describe, on a seasonal basis, the distribution of water quality factors in the Bay; to monitor inputs of nutrients from its watershed; and to develop and evaluate models for predicting water quality in the Bay as a function of various control strategies (Reference 1 and 2). A surface/subsurface measurement program has been underway since April 1974. From each of 59 stations distributed throughout Saginaw Bay, some 30 water quality parameters are determined on an 18-day cycle that coincides with the LANDSAT over-flights. During 1974 and 1975 32 cruises were made.

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 km^2 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 southwestern end and contributes approximately 90% of the pollutants found in the bay (Reference 3). This river and its tributaries drain a watershed of more than 21,000 km^2 that contains 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. In addition, the natural estuarine-like movement of pollutants from the bay into southern Lake Huron may reduce water quality throughout the lower Great Lakes.

The purpose of this and earlier efforts was twofold: 1) to use LANDSAT to produce a color map delineating water masses within the bay, and, more importantly, to relate the water masses so delineated to quantative levels of water quality. The first level of mapping requires no surface truth measurements and can be done with a minimal amount of computer processing. The second level of mapping, however, requires detailed surface truth and a number of computer processing steps but provides a significant increase in the information content and its effective presentation. The procedure reported here was determined to be the most efficient and productive of the approaches investigated.

2. TECHNIQUE

The data processing procedure used to produce the water quality map of Saginaw Bay can be described as a number of steps.

Step 1. Ship Data Collection. Three consecutive days are required to sample all the bay stations. For the maps produced in this study only those surface samples taken the same day as the overpass, from 16 of the 59 stations, were used (Figure 1 and Table 1).

Step 2. Geometric Correction. LANDSAT-2 computer compatible tapes for two consecutive scenes, acquired on 31 July 1975 (2190-15401 and 2190-15404), were processed on a Bendix MDAS (Multispectral Data Analysis System). The satellite data were first geometrically controlled by digitizing ground control points (GCPs) such as prominent coastal features, from a navigation chart. The latitude and longitude of each GCP was converted to LANDSAT coordinates using an interactive display routine on MDAS, and a geometric transformation matrix was established for the greater bay area. The 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).

Step 3. LANDSAT Data Sampling. The established geometric correction matrix and the MDAS TV monitor were used to display the single pixel best corresponding to the digitized location of each bay station. 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 2).

Step 4.Regression Analysis. A variety of regression analyses were made. In all cases a linear regression was used and LANDSAT radiance measurements in the four bands were treated as the independent variable while the surface truth data were treated as the dependent variables. Earlier work showed that with stepwise multiple regression analysis: 1) the use of a ratio of bands does not improve the strength of the correlation over the use of single bands, and 2) bands 4 and 5 provide more information than bands 6 and 7. Accordingly, in this effort only data from bands 4 and 5 were entered into the analysis. The regression equations are shown in Table 3 and parameter range correlation coefficients and standard error of estimate are shown in Table 4

Step 5. Review of LANDSAT Data. This important step provides the basis for applying the relationship derived in step 4 back to the LANDSAT data for the entire bay. The bay was screened in both false color and single channel levels slice mode on MDAS to determine how many distinct water masses or zones were present. Five such levels of water quality were identified. The mean radiance of training sets for each of these five areas (categories) was computed by MDAS. A color code was assigned to each category at this time (Table 5). The parameter value associated for each color (Table 6) was calculated by putting the appropriate training set means back into the equations derived in Step 4 (Table 3).

Step 6. Processing and Filming. With training sets identified in Step 5 the entire bay was categorized and the result was output on the MDAS drum film recorder. Geometric corrections were automatically applied during filming.

3. DISCUSSION

The results of this technique have been evaluated by inspection of graphs and tabular data, by inspection of map features and by comparison with another technique.

Figure 2 is a representative plot of many that were constructed to graphically summarize the performance of the regression analysis. In this example, chlorophyll a, it shows that all but 3 of the 16 predicted sample values fall within one standard deviation of their measured value.

Table 7 was prepared to aid in the explanation of the physical relationship between the LANDSAT data and the water quality values. 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; chlorophyll a, suspended solids, turbidity, and Secchi depth, 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 (Table 7).

Analysis of the final map (Figure 3) has confirmed some known features of circulation and water quality in Saginaw Bay. Previous surveys of the bay (Reference 1 and 3) 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 resuspended.

The Saginaw River enters Saginaw Bay at its extreme southwestern end and contributes the majority of pollutants found in the Bay. The magenta color, which represents levels of water quality that are beyond the range of the sample data used in the regression program, enhances the plume of turbid water that enters the Bay from the Saginaw River and extends in a southeast direction. In the shallow near-shore zone (less than about ten feet deep) of the lower bay, the magneta denotes areas where there is significant local resuspension of sediment.

A lobe of relatively clean Lake Huron water (blue) appears to enter the mouth of the Bay between a central island (Charity Is.) and a coastal point (Lookout Pt) and flow up the Bay (south) along its deepest channel. The boundary of the lobe and the Bay water (green) is very pronounced and not gradational as is the case with the remaining three water mass boundaries.

A third feature is the spiral of water masses just northeast of the "thumb" of Michigan. This is an apparent mixing zone of turbid water that has been transported from the Bay into Lake Huron. The transporting current may have been set up by the counterclockwise deflection of southward moving Lake Huron water, along the shallow area between Charity Island and the eastern shore of the Bay mouth (Oak Pt.). Thus one mass of Lake Huron water enters the Bay along its western shore while another mass is prevented from entering but helps transport turbid bay water into Lake Huron. The apparent increase in turbidity at the top right corner of the map is due to the presence of an atmospheric haze associated with clouds, about 25 km northeast of the right corner of the map, but within the full scene.

The nine water quality parameters were mapped as one map. If separate maps were required for each parameter the breaks between color levels could be relocated so as to better proportion the levels. For example, the map shown here indicates that chlorophyll a is low in the outer bay and central portion of the inner bay but extremely high in the near shore zone of the inner bay. A separate map, made with different training areas, could be made for each parameter. In the case of chlorophyll a this would permit perhaps one color code for the areas of low concentration and four colors for the areas of high concentration as opposed to three and two respectively.

A comparison between the LANDSAT derived water quality map and those produced by another technique, but for the same surface truth measurements, provides for further evaluation of this technique. The EPA commonly makes machine plotted contour maps for areas such as Saginaw Bay from station data that is filed in the EPA-STORET system. Figure 4 is a copy of one such map for Chloride and shows the 16 stations, the parameter values at each station, and the computed contour lines. Figure 5 is a copy of the Chloride map for 3 days of ship data with shading to reflect the same levels of water quality that are shown in Figure 3. The boundary values of the shaded areas correspond to mid range values as determined from Table 6. A comparison of Figure 4 with Figure 5 shows that plotter maps of one day's data do not provide an accurate synoptic portrayal of bay water quality. Figure 3 compares very favorably with Figure 5 but the LANDSAT technique provides a much more detailed portrayal that is more realistic in pattern than that provided by the machine plotter technique. Figure 6 is shown to provide further comparison with one additional water quality parameter Secchi depth. One conclusion of this comparison of techniques is that a water quality map derived from the computer processing of LANDSAT data and one day's surface truth provides as much, if not more, detail than a water quality map made from the machine contouring of three days surface truth. If the LANDSAT derived map meets the standards and needs set up by the water quality researcher then in subsequent studies the three day ship survey cruise could be shortened to one day at a significant cost savings.

It should be emphasized that the equations used to relate the water quality measurements with the LANDSAT data are scene and surface truth dependent. Atmospheric conditions can be extremely variable with time over the bay region and, in addition, the relationship of water quality to radiance may vary. Thus, this technique would have to be repeated from processing LANDSAT data of a different date.

4. ACKNOWLEDGEMENTS

Many individuals contributed to this project, while space does not permit identifying each the efforts of William L. Richardson of the U.S. EPA Large Lakes Research Station, in providing the contour maps, and Navin J. Shah, of Bendix for developing special software and facilitating data handling are acknowledged.

5. SUMMARY

Computer processed LANDSAT data can be color keyed to water quality parameters by a procedure using linear regression equations and surface truth measurements. Although the procedure is scene and surface truth dependent it establishes a relationship with a predictable accuracy. The resulting color-keyed map shows the concentration and distribution of water quality parameters throughout Saginaw Bay. The parameters need not be directly detectable by LANDSAT, provided their concentration is correlated with some water characteristic that is detectable. LANDSAT when used in conjunction with 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.

Application of non-linear regression analysis and techniques for correcting LANDSAT data for atmospheric effects should decrease the standard error of estimate in predicting water quality parameters and result in the possible further reduction of surface sampling. These steps and work with data of different dates may help to further the goals of the EPA in their effort to study the circulation of water masses and model the water quality of Saginaw Bay.

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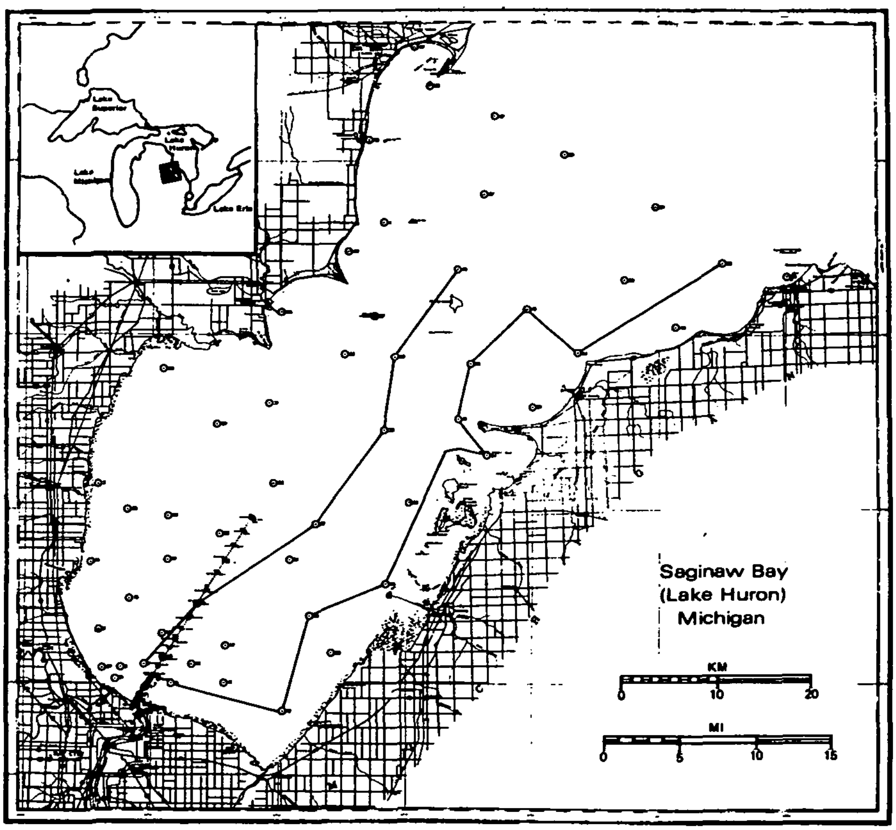

Figure 1. Map of Saginaw Bay, Showing the 61 Water Quality Stations by the Symbol ⊙. The Cruise Tracks of the Two Vessels and the 16 Stations Sampled on the Day of the LANDSAT Overpass (31 July 1975) are also Shown.

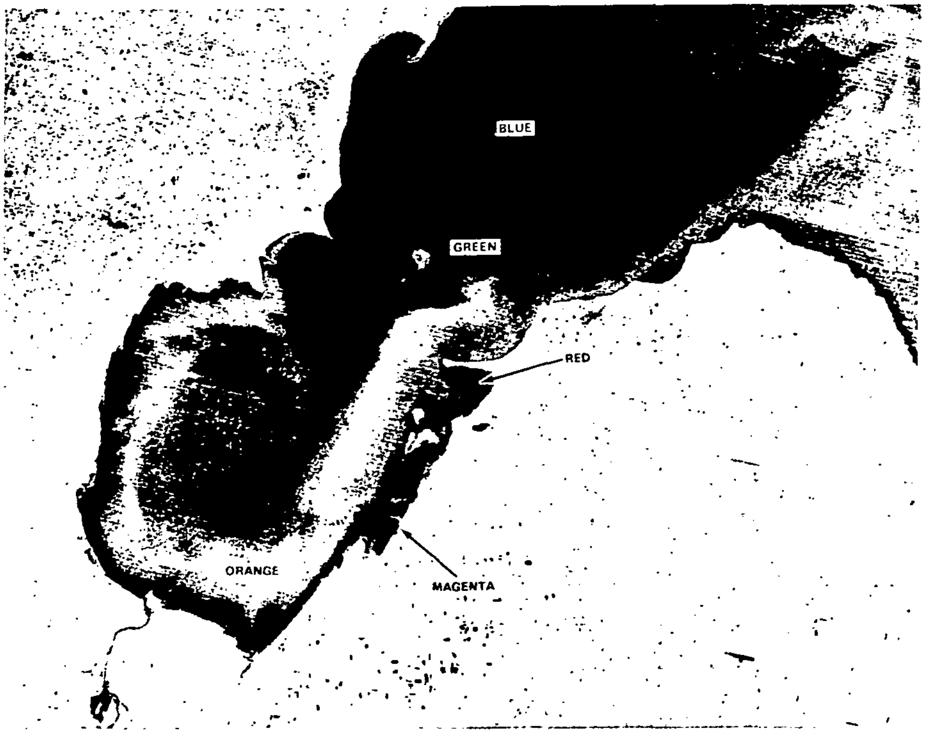

Figure 3 Water Quality Map Made From LANDSAT and Ship Data From 16 Stations, July 31, 1975

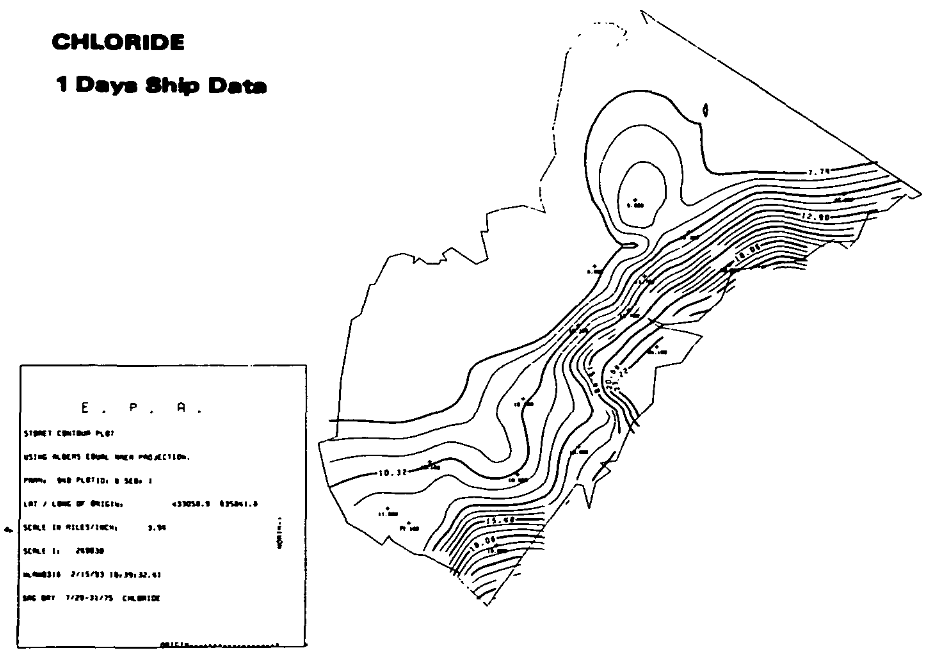

Figure 4 Machine Contoured Chloride Data, 16 Stations, July 31, 1975

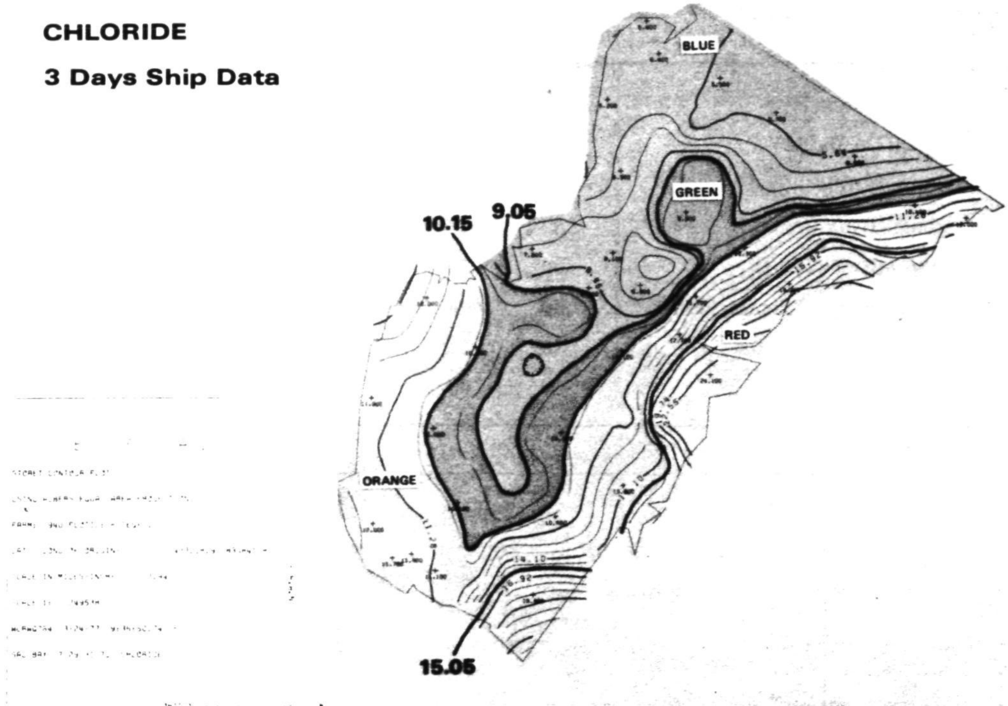

Figure 5 Machine Contoured Chloride Data, 33 Stations, July 29-31, 1975

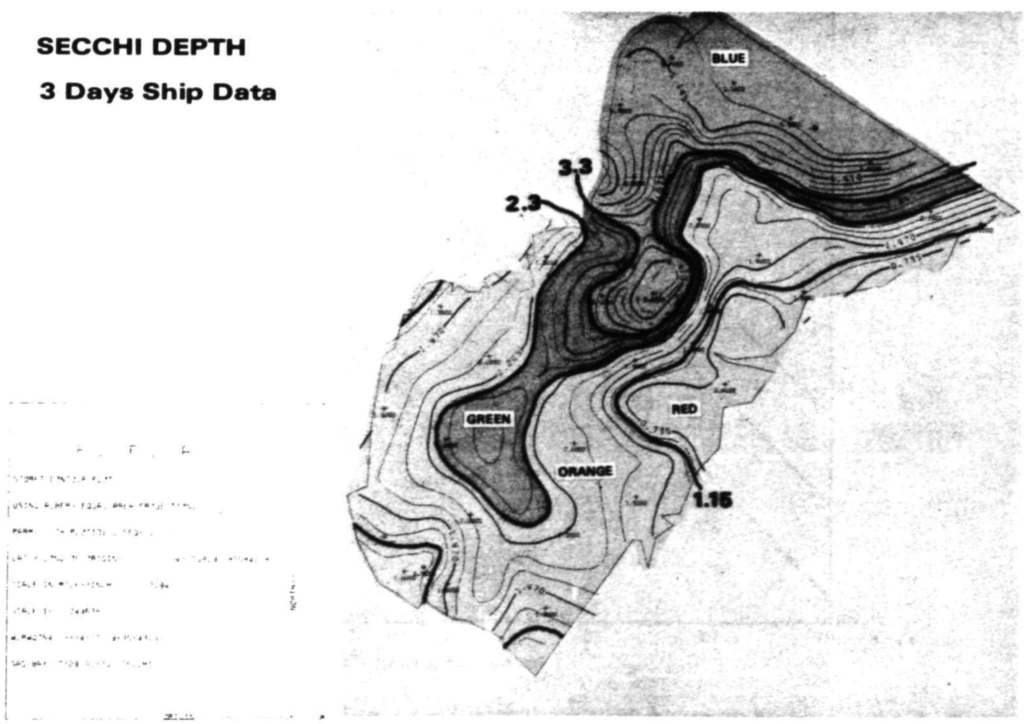

Figure 6 Machine Contoured Secchi Depth Data, 33 Stations, July 29-31, 1975

Table 7

Correlation Coefficient Matrix (59 Stations)

Cruise 25
July 29 - 31, 1975

	T	SD	Cl	Con	Ch a	TKN	TP
Temperature (T)	1.00						
Secchi Depth (SD)	-.76	1.00					
Chloride (Cl)	.48	-.54	1.00				
Conductivity (Con)	.47	-.54	.99	1.00			
Chlorophyll a (Ch a)	.54	-.67	.41	.37	1.00		
Total Kjeldahl Nitrogen (TKN)	.59	-.66	.94	.92	.61	1.00	
Total Phosphorus (TP)	.39	-.50	.98	.98	.39	.91	1.00

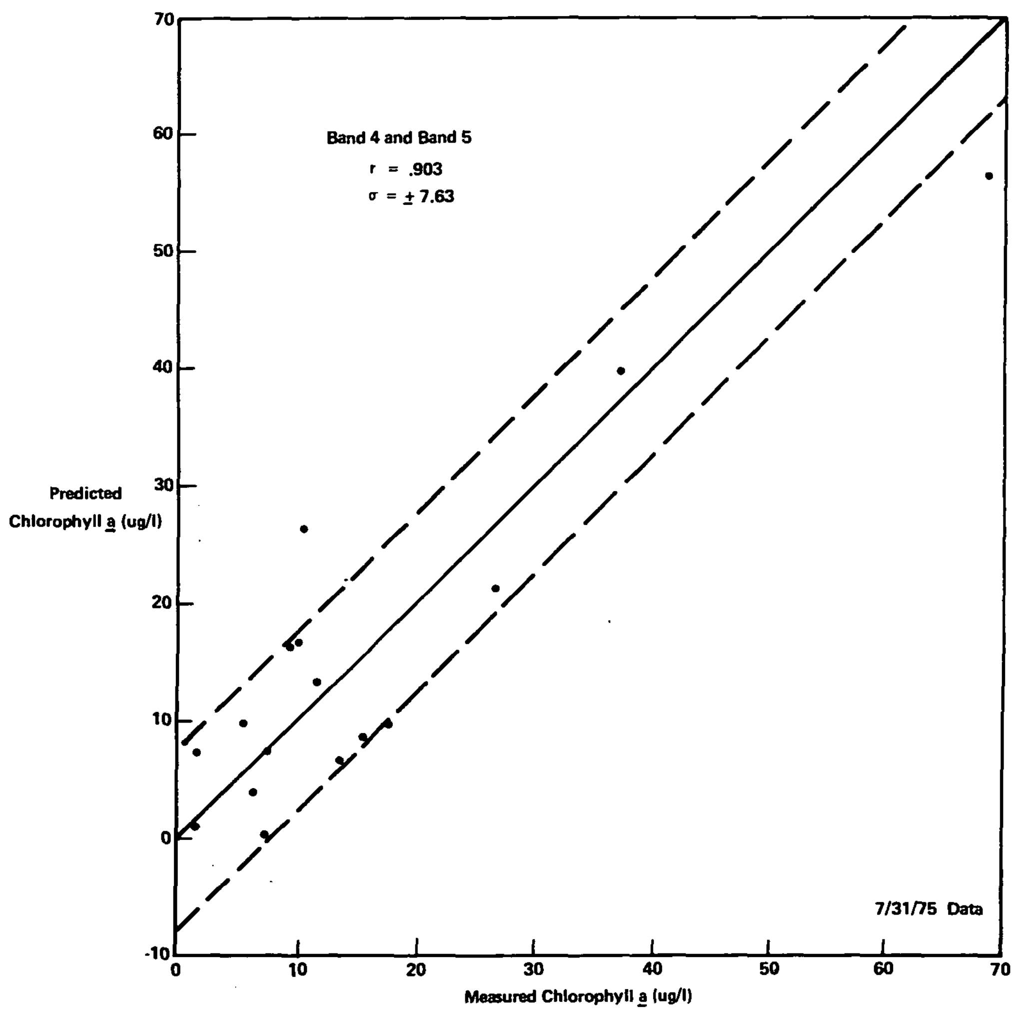

Figure 2 Predicted Versus Measured Chlorophyll a

Table 1

EPA Water Quality Data For Saginaw Bay, 31 July 1975.
Measurements were Made At Water Depth Of One Meter

Station	Temperature (°C)	Secchi Depth (m)	Chloride (mg/l)	Conductivity (micromhos)	Total Kjeldahl Nitrogen (mg/l)	Total Phosphorus (mg/l)	Chlorophyll a (µg/l)
7	26.1	1.9	10.9	243.	0.37	0.012	20.70
8	26.7	1.6	11.1	258.	0.41	0.017	9.38
12	26.8	1.3	18.8	277.	0.65	0.027	10.70
18	23.6	2.0	9.8	237.	0.38	0.012	5.61
26	26.0	1.6	13.8	251.	0.35	0.018	11.60
27	23.7	2.0	10.1	239.	0.29	0.012	7.38
32	24.8	1.8	10.1	235.	0.33	0.010	7.38
34	26.9	10.6	24.1	294.	1.00	0.039	68.50
38	25.1	1.4	11.7	244.	0.29	0.014	13.60
42	20.4	5.5	6.6	211.	0.14	0.002	1.84
43	23.5	1.5	12.1	246.	0.42	0.013	15.60
44	24.4	1.0	20.1	281.	0.72	0.027	37.10
52	21.5	2.1	10.4	238.	0.33	0.009	10.00
56	23.7	2.2	10.6	244.	0.26	0.014	6.58
60	22.5	5.0	6.9	215.	0.17	0.004	1.84
61	25.7	1.2	12.7	252.	0.42	0.020	18.00
Mean	24.46	2.0	12.5	247.8	0.41	0.016	15.36
Std. Dev.	1.92	1.3	4.7	21.8	0.22	0.009	16.53

Table 2

LANDSAT Data For Saginaw Bay, 31 July 1975

Station	Number of Pixels to Station Area	Mean Reflectance of Station Area Band 4 254*	5 254*	6 254*	7 252*
7	56	40.6	27.5	14.8	1.4
8	63	44.0	29.5	16.3	1.5
12	72	42.8	29.5	16.2	1.7
18	72	38.1	24.7	13.8	0.5
26	64	42.7	28.3	14.7	0.4
27	90	38.1	24.5	12.2	0.3
32	100	37.2	23.2	11.7	0.1
34	100	38.6	29.1	16.4	0.9
38	121	40.4	26.1	12.3	0.1
42	72	32.3	20.3	9.8	0.3
43	72	36.0	23.1	10.9	0.2
44	72	35.6	25.5	14.5	0.8
52	72	32.3	21.1	11.0	0.4
56	72	39.5	25.2	12.8	0.6
60	110	34.0	21.0	10.1	0.1
61	99	43.7	28.7	14.1	0.6
Mean	81.7	38.5	25.4	13.2	0.6
Std. Dev.		3.8	3.1	2.2	0.5

*Maximum pixel count.

Table 3

Regression Equations For
Saginaw Bay 7/31/75 (16 Samples)

Temperature (°C)	= 9.61 + 0.007 (Band 4) + 0.572 (Band 5)
Secchi Depth (m)	= 8.24 + 0.142 (Band 4) - 0.458 (Band 5)
Chloride (mg/l)	= 9.489 - 2.040 (Band 4) + 3.202 (Band 5)
Conductivity (micromhos)	= 194.2 - 7.72 (Band 4) + 13.79 (Band 5)
Total Kjeldahl Nitrogen (mg/l)	= 0.419 - 0.102 (Band 4) + 0.153 (Band 5)
Total Phosphorus (mg/l)	= -0.0069 - 0.0033 (Band 4) + 0.0059 (Band 5)
Chlorophyll a (ug/l)	= 41.04 - 8.32 (Band 4) + 11.57 (Band 5)
Total Solids (mg/l)	= 154.1 - 7.73 (Band 4) + 12.93 (Band 5)
Suspended Solids (mg/l)	= 0.908 - 1.02 (Band 4) + 1.67 (Band 5)

Table 4

Regression Results For Saginaw Bay 7/31/75 (16 Samples)

Water Quality Parameter and Range	Regression Correlation Coefficient	Standard Error of Estimate
Temperature (20 - 27°C)	.94	0.68
Secchi Depth (0.6 - 5.5 m)	.73	0.97
Chloride (6 - 24 mg/l)	.92	1.9
Conductivity (211 - 294 micromhos)	.93	8.6
Total Kjeldahl Nitrogen (0.1 - 1.0 mg/l)	.94	.08
Total Phosphorus (0.002 - 0.039 mg/l)	.94	.0035
Chlorophyll a (1.8 - 68.5 ug/l)	.90	7.6
Total Solids (150 - 244 mg/l)	.79	15.
Suspended Solids (1 - 13 mg/l)	.74	2.3

Table 5

LANDSAT Training Set Means

Color	4	5	6	7
Blue	30.3	18.9	9.5	0.2
Green	36.7	23.5	11.6	0.2
Orange	41.6	26.8	14.2	1.2
Red	42.7	30.4	17.2	3.1
Magenta	45.6	37.8	25.1	6.8

Table 6

Explanation Block For The Water Quality Map (Figure 3)

	Blue	Green	Orange	Red	Magenta	Standard Error of Estimate
Temperature (°C)	20.6	23.3	25.2	27.3	31.6*	1.6
Secchi Depth (m)	3.9	2.7	1.9	0.4	< 0.4*	1.1
Chloride (mg/l)	8.2	9.9	10.4	19.7	37.5*	1.9
Conductivity (micromhos)	221	235	243	284	363*	8.9
Total Keldahl Nitrogen (mg/l)	.22	.27	.28	.71	1.55*	.08
Total Phosphorus (mg/l)	.005	.012	.014	.032	.066*	.004
Chlorophyll a (ug/l)	7.6	7.6	5.0	37.5	99.1*	8.5
Total Solids (mg/l)	164	174	179	217	290*	15
Suspended Solids (mg/l)	1.6	2.7	3.2	8.1	17.6*	2.2

*These values are beyond the range of the sample data.