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Mapping of Chlorophyll *a* Distributions in Coastal Zones

Concurrently collected sea-truth measurements may be used to calibrate remotely sensed multispectral scanner data.

Abstract: *Chlorophyll "a" is an important environmental parameter for monitoring water quality, nutrient loads, and pollution effects in coastal zones. Remotely sensed data may be calibrated by concurrently measured sea truth. Regression equations from the analysis may be used to map quantitative distributions of chlorophyll "a" in coastal zone areas, thereby providing information that is not readily available from other sources. Results of experiments with aircraft multispectral scanners over the turbid James River, Virginia, and the New York Bight ocean area, indicate that statistically significant quantitative relationships exist between remotely sensed data and chlorophyll "a" measurements in these environmentally different areas. In a James River experiment on May 28, 1974, the linear regression equation used data in the 440-490 nm, 620-660 nm, and 700-740 nm spectral bands from a Modular Multispectral Scanner (M2S) flown at a 2.4 km altitude. The correlation coefficient was 0.96 with a standard error of estimate of 1.75 mg/m³ for a measured range of 1.61 to 19.5 mg/m³. In an April 13, 1975, New York Bight experiment, the linear regression equation used radiances in the 499-519 nm and 610-630 nm spectral bands of the Ocean Color Scanner (OCS) flown at a 19.7 km altitude. The correlation coefficient was 0.83 and the standard error of estimate was 3.87 mg/m³ for a measured range of 2.20 to 24.30 mg/m³. In both experiments, suspended sediments were a factor in interpreting results of the analyses. Quantitative maps of synoptic chlorophyll "a" distributions were made for both the James River and New York Bight.*

Introduction

Chlorophyll *a* is an important environmental parameter for monitoring water quality, nutrient loads, and pollution effects in coastal zones. High chlorophyll *a* concentrations occur in areas that have high nutrient inflows from sources such as sewage treatment plants and industrial wastes. High chlorophyll *a* levels and associated eutrophication of water bodies limit their usefulness for recreation, water supplies, and other purposes. High chlorophyll *a* levels, due to algal "blooms," and the resultant secondary pollution also deplete oxygen concentrations, leading to upsets of the ecological balance in water systems. In additon, low chlorophyll *a* concentrations may be due to the addition of toxic substances from industrial wastes or other sources. Thus, either abnormally high or low concentrations of chlorophyll *a* may indicate pollutant inputs and/or effects.

Remote sensing, with its wide area spatial coverage and synoptic view, provides an opportunity to assess distributions of water quality parameters, such as chlorophyll *a*, and thus provides information that is not readily available by other means. In addition, remote sensing, as a nonintrusive technique, may provide useful information for monitoring and enforcement of pollution practices.

Duntley and coworkers[1] indicated that spectral responses at different wavelengths could be related to changes in chlorophyll *a* concentrations. Taking advantage of the decrease in the blue reflectance and an increase in the red reflectance, a number of investigators have used ratio techniques with photographic[2] and electronic[3-6] sensors to detect and map chlorophyll *a* distributions. Johnson[7,8] applied a continuous function analysis technique, stepwise regression, to multispectral scanner digital data collected over the James River, Virginia. This latter approach identifies spectral bands for quantifying individual water quality parameters in a data set. The results indicated that changes in chlorophyll *a* concentrations give unique spectral responses compared to those for other water quality parameters. Calibrated regression equations from the analysis were used to map quantitative distributions of suspended sediment and other parameters of interest.

It is the purpose of this paper to present results of the chlorophyll *a* analysis and a quantitative mapping of the James River, Virginia, using the approach described by Johnson[8], and to apply the multiple regression analysis technique to a data set collected over the New York Bight, an environmentally different area of the coastal zone.

Experimental Method

Remotely sensed data were collected in conjunction with sea-truth measurments over two environmentally different areas of the Atlantic Coastal Zone. In both experiments sea-truth measurements were made within about two hours of the remote sensor overpass. These sea-truth measurements included chlorophyll *a* concentrations and other water quality parameters.

On May 28, 1974, NASA and the Environmental Protection Agency (EPA) conducted a joint experiment over the James River, Virginia. Remotely sensed data were collected by a M2S onboard a Bendix Aerospace Systems Division aircraft at a flight altitude of 2.4 km (8,000 ft). The M2S has 11 bands in the visible, near IR, and thermal spectral ranges. This analysis only uses those data in the visible and near IR spectral ranges. Bandwidths and wavelengths are shown in Table 1, along with spatial coverage information at the flight altitude. Pixel size and resolution are about 7 m (25 ft). The experimental area and aircraft flight lines are shown in Figure 1. Sea-truth measurements were made from three boats at each of the two primary experiment sites, Norfolk and Hopewell. Sea-truth measurements of chlorophyll *a* and suspended sediment concentrations along with corresponding radiance values in the M2S bands for the 21 sets of observations analyzed in this report are shown in Table 2. Johnson *et al.*[9] provided a data report for the mission.

Table 1. Multispectral Scanner (M2S) Bandwidths and Frequencies, and Spatial Coverage at 2.4 Km (8,000 ft) Altitude.

Range Bands	Spectral 380 – 1060 nm + Thermal Band	Range
	1	380 – 440 nm
	2	440 – 490 nm
	3	495 – 535 nm
	4	540 – 580 nm
	5	580 – 620 nm
	6	620 – 660 nm
	7	660 – 700 nm
	8	700 – 740 nm
	9	760 – 860 nm
	10	970 – 1060 nm
	Thermal	8000 – 13 000 nm
	Spatial	
Field of View		
Width, M		6800
Length, M		Continuous
Resolution, M		7

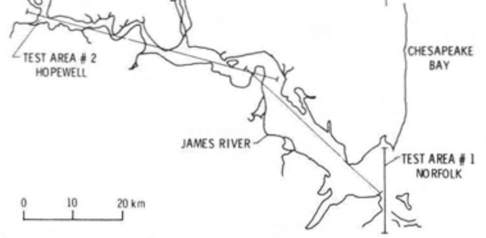

Fig. 1. Aircraft flight lines over James River, Virginia, from Norfolk to Hopewell on May 28, 1975 (M2S at 2.4 km altitude).

TABLE 2. SEA TRUTH AND RADIANCE MEASUREMENTS FOR THE JAMES RIVER EXPERIMENT ON MAY 28, 1974.

	Sea-Truth Measurements		Remotely Sensed Measurements									
			Average Radiance in M2S Bands, mw/cm²-ster-μm									
Samples	Chloro *a* mg/m³	Susp. Sed. mg/*l*	1	2	3	4	5	6	7	8	9	10
N 1D	1.820	10.520	2.023	2.558	3.590	3.104	2.670	2.122	1.715	0.891	0.532	0.445
N 2D	1.650	8.800	2.023	2.558	3.590	3.104	2.670	2.122	1.715	0.891	0.532	0.445
N 2G	2.680	10.120	2.121	2.558	3.590	3.104	2.670	2.122	1.715	1.071	0.532	0.445
N 2H	3.820	17.720	2.318	3.071	4.390	3.860	3.375	2.939	2.333	1.432	0.657	0.445
N 2I	1.750	12.240	2.121	2.729	3.890	3.356	2.811	2.286	1.869	1.252	0.532	0.445
N 2J	2.730	11.560	2.121	2.729	3.890	3.356	2.811	2.449	1.869	1.252	0.532	0.445
N 3D	1.950	12.000	2.023	2.558	3.590	3.104	2.670	2.122	1.715	1.071	0.532	0.242
N 3G	2.970	8.600	2.023	2.615	3.790	3.230	2.811	2.286	1.869	1.071	0.532	0.445
N 3H	2.900	21.520	2.023	2.501	3.490	2.978	2.529	1.959	1.560	0.891	0.532	0.242
N 3I	2.370	9.040	2.121	2.558	3.490	2.978	2.388	2.122	1.560	0.891	0.532	0.445
N 3J	2.680	10.960	2.121	2.501	3.490	2.978	2.388	1.959	1.560	1.071	0.532	0.242
H 1F	17.460	28.200	2.023	2.501	3.490	3.356	3.093	2.776	2.178	1.613	0.782	0.445
H 1H	15.780	31.600	2.220	2.900	4.190	3.987	3.798	3.429	2.952	2.154	1.157	0.855
H 1J	19.500	47.600	2.121	2.957	4.390	4.239	3.939	3.593	2.952	2.154	1.157	0.855
H 2F	12.050	28.600	2.121	2.729	3.790	3.608	3.375	3.103	2.488	1.793	1.032	0.651
H 2H	13.580	28.800	2.121	2.729	3.890	3.482	3.234	2.939	2.488	1.793	1.032	0.651
H 2I	10.260	23.000	2.220	2.786	3.890	3.482	3.375	2.939	2.488	1.793	1.032	0.855
H 2J	11.510	40.800	2.023	2.615	3.690	3.356	3.234	2.939	2.333	1.613	0.907	0.651
H 3F	9.190	24.400	2.023	2.615	3.490	3.356	3.093	2.776	2.178	1.432	0.657	0.445
H 3H	6.560	26.800	2.121	2.615	3.690	3.482	3.234	2.776	2.178	1.432	0.782	0.445
H 3I	8.730	31.400	2.318	2.843	3.990	3.734	3.375	2.939	2.178	1.613	0.782	0.445

From April 7 to 17, 1975, a joint experiment was conducted by NASA, the National Oceanic and Atmospheric Administration (NOAA), and EPA in the New York Bight to study marine processes and pollution effects. On April 13, 1975, remotely sensed data were collected by a 10 band OCS aboard a NASA Ames Research Center (ARC) U-2 aircraft which flew at an altitude of 19.7 km (65,000 ft) over the New York Bight.[10] The OCS has 10 bands in the visible and near IR spectal ranges, with center wavelengths from 433 nm to 772 nm for the nominally 20 nm wide bands. Bandwidths and wavelengths along with spatial coverage information are shown in Table 3. Sea-truth measurements for this experiment were collected by NOAA personnel onboard a Coast

TABLE 3. OCEAN COLOR SCANNER SPECTRAL AND SPATIAL CHARACTERISTICS AT 19.7 Km (65,000 ft) ALTITUDE.

Range Bands	Spectral 423 – 782 Nanometers (nm) Band	Range
	1	433 nm ± 10 nm
	2	471 nm ± 10 nm
	3	509 nm ± 10 nm
	4	547 nm ± 10 nm
	5	583 nm ± 10 nm
	6	620 nm ± 10 nm
	7	662 nm ± 10 nm
	8	698 nm ± 10 nm
	9*	733 nm ± 10 nm
	10*	772 nm ± 10 nm
	* Bands Not in Analysis	
	Spatial	
Field of View		
Width, M		25 000
Length, M		Continuous
Resolution, M		75

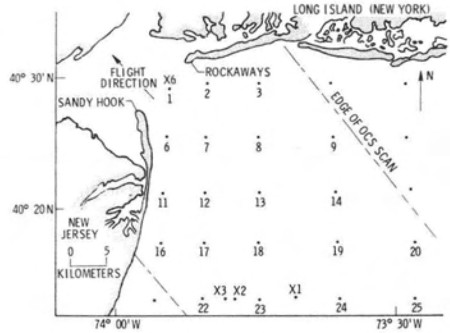

FIG. 2. Location of sea-truth stations in the New York Bight apex on April 13, 1975 (OCS at 19.7 km altitude).

Guard helicopter over stations in the New York Bight apex. Sample locations and the OCS scan line are shown in Figure 2. Sea-truth measurements of chlorophyll *a* and suspended sediment concentrations along with corresponding radiance values in the OCS bands are listed in Table 4. Only bands 1 through 8 of data were available for the analysis. Eighteen sets of observations were useable in the chlorophyll *a* analysis and 22 for suspended sediment.

DATA ANALYSIS AND RESULTS

DATA PREPROCESSING

Representative radiance values corresponding to the sea-truth measurements were determined in both experiments by locating the sampling station as nearly as possible, then taking the average of an 11 by 11 pixel field centered at that location to obtain the representative value. This field size was empirically determined as the area to compensate for uncontrollable spectral and spatial noise or uncertainty. Inflight calibrations were used to determine average radiance (mw/cm^2-ster-μm) values in each of the M2S and OCS bands.

QUANTITATIVE DATA ANALYSIS

Stepwise Regression Analysis (SWRA) was used to determine regression equations for quantitatively relating sea-truth measurements to remotely sensed data, as employed by Johnson.[7,8] In an SWRA, the program selects the independent variable (radiance in one scanner band) that has the highest correlation with the dependent variable (chlorophyll *a*). A number of variables are then selected consecutively until all of the independent variables that make a significant contribution to determining the dependent variable are in the regression equation and the others are "outside" of the regression. Limiting the regression equation to significant variables reduces the analysis time and improves the accuracy of the results. The criterion for inclusion of variables is a 95 percent confidence level (90 percent for the OCS data, due to apparently higher "noise") as determined by the statistical "F" test (see Draper and Smith,[11] p. 171, for a discussion of the SWRA).

QUANTITATIVE ANALYSIS RESULTS

James River Experiment, May 28, 1974. Sea-truth values and corresponding remotely sensed radiance values for the 21 sets of observations analyzed for the James River Experiment are listed in Table 2. Results of the SWRA applied to chlorophyll *a* and subsequently to suspended sediment[12] are given in Table 4 where M2SRN is the radiance in M2S band N (i.e., M2SR2 is radiance in band 2); standard error of estimate is a measure of the scatter about the fitted regression line; correlation coefficient is a measure of the relative change among variables; correlation coefficient to suspended sediment is the linear correlation coefficient of chlorophyll *a* to suspended sediment; and range of sea-truth measurements are for the water quality parameter being analyzed. The regression equation for chlorophyll *a* is

TABLE 4. RESULTS OF STEPWISE REGRESSION ANALYSIS APPLIED TO CHLOROPHYLL *a* AND TO SUSPENDED SEDIMENT FOR THE JAMES RIVER EXPERIMENT.

Water Quality Para.	M2S Bands in Regr. Equation	Standard Error of Estimate	Correl. Coef.	Correlation Coefficient to Suspended Sediment	Range of Sea-Truth Measurements
Chlorophyll *a*	M2SR2, M2SR6, M2SR8	1.75 mg/m^3	0.96	0.88	1.61 – 19.5 mg/m^3
Suspend. Sediment	M2SR2, M2SR6	2.23 mg/*l*	0.90	—	8.60 – 47.60 mg/*l*

$$\text{Chloro } a, \text{ mg/m}^3 = 25.62 - 18.06 \text{ M2SR2} + 7.23 \text{ M2SR6} + 9.46 \text{ M2SR8}.$$

Comparison of the remotely sensed values (calculated from the regression equation) and the measured sea-truth values for chlorophyll *a* (and, subsequently, suspended sediment) indicated approximately random distribution about the fitted regression lines for these parameters. The comparison for chlorophyll *a* is shown in Figure 3. Thus, the linear model appears adequate for this set of data.

New York Bight Experiment, April 13, 1975. Sea-truth measurements (eighteen stations for chlorophyll *a* and 22 stations for suspended sediment[13]) and radiance values in the OCS bands are listed in Table 5. The results of the SWRA as applied to chlorophyll *a* and subsequently to suspended sediment are given in Table 6 where OCSR6 is radiance in OCS band 6, etc.; and the other symbols are as defined previously. A comparison of remotely sensed and measured values of chlorophyll *a* is shown in Figure 4. The regression equation for chlorophyll *a* is

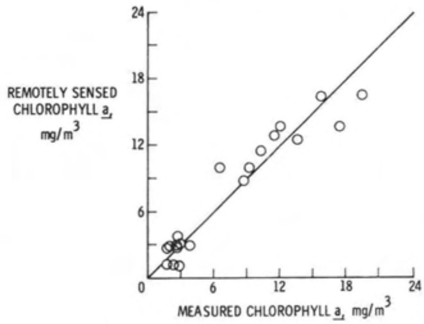

FIG. 3. Remotely sensed (calculated from regression equation) and measured values of chlorophyll *a* in the James River on May 28, 1974.

$$\text{Chloro } a, \text{ mg/m}^3 = -4.51 - 4.96 \text{ OCSR3} + 11.44 \text{ OCSR6}.$$

COMPARISON AND INTERPRETATION OF ANALYSIS RESULTS

Comparison of the analysis results from the two experiments indicates several interesting features. First, the most significant spectral regions are similar, from

TABLE 5. SEA-TRUTH AND RADIANCE MEASUREMENTS FOR THE NEW YORK BIGHT EXPERIMENT ON ARIL 13, 1975, (ONLY DATA IN OCS SCAN SHOWN).

	Sea-Truth Measurements		Remotely Sensed Measurements							
			Average Radiance in OCS Bands, mw/cm²-ster-μm							
Station	Chloro. *a* mg/m³	Susp. Sed. mg/l	1	2	3	4	5	6	7	8
1	15.000	6.140	13.37	10.99	12.97	11.72	9.16	6.66	5.00	3.00
2	4.600	3.210	13.61	11.37	13.29	12.09	9.36	7.01	5.26	3.37
3	5.300	1.700	13.26	11.14	13.11	12.07	9.61	7.04	5.08	3.09
6	24.300	8.380	13.28	10.98	12.96	12.04	10.49	7.98	5.90	4.00
7	6.400	2.710	13.15	10.96	12.87	11.98	9.82	7.00	5.00	3.00
8	6.600	2.310	12.89	10.43	12.01	11.00	8.88	6.00	4.17	3.00
9	5.000	1.100	13.15	11.01	12.98	11.08	9.00	6.19	5.00	3.00
11	15.300	6.290	12.93	10.55	12.12	11.46	10.00	7.00	5.00	3.10
12	14.000	2.550	13.11	10.82	12.45	11.28	9.01	6.60	5.00	3.00
13	4.600	1.930	13.08	10.87	12.50	11.12	9.00	6.12	5.00	3.00
14	3.800	1.060	12.79	10.27	11.97	10.38	8.00	6.00	4.00	2.94
16	17.800	3.600	12.83	10.80	12.72	11.45	9.88	7.07	5.07	3.30
17	2.700	0.460	12.54	10.10	11.89	10.72	8.17	5.98	4.00	2.98
19	2.400	0.680	12.75	10.33	12.03	10.93	8.12	6.00	4.17	3.00
20	2.200	0.560	12.71	10.57	12.01	10.02	8.00	6.00	4.00	3.00
22	4.200	0.710	12.46	10.08	12.07	10.41	8.12	6.00	4.06	3.00
24	3.300	1.360	12.88	10.42	12.01	10.47	8.02	6.01	5.01	3.00
25	2.700	0.690	12.69	10.02	11.12	9.50	7.03	5.41	4.00	2.81
X1	—	1.730	12.88	10.50	12.13	11.15	8.58	6.02	4.84	3.00
X2	—	0.790	12.36	10.14	12.44	11.81	9.23	6.00	4.61	3.00
X3	—	0.580	12.40	10.12	12.37	11.51	8.89	6.00	4.47	3.00
X6	—	5.100	13.26	10.99	12.92	11.41	9.04	6.38	5.00	3.00

TABLE 6. RESULTS OF STEPWISE REGRESSION ANALYSIS APPLIED TO CHLOROPHYLL *a* AND TO SUSPENDED SEDIMENT FOR THE NEW YORK BIGHT EXPERIMENT.

Water Quality Para.	OCS Band in Regr. Equation	Standard Error of Estimate	Correlation Coefficient	Correlation to Suspended Sediment	Range of Sea-Truth Measurements
Chlorophyll *a*	OCSR3, OCSR6	3.87	0.83	0.90	2.20 – 24.30 mg/m^3
Suspend. Sediment	OCSR6	1.39	0.79	—	0.46 – 8.38 mg/*l*

about 450 to 750 nm, for the two scanners which were flown at different altitudes. However, specific equation coefficients are different due to the number of bands in the regression equations, their specific wavelengths, and the generally higher radiance levels in the New York Bight experimental area. Second, the M2S indicates higher correlations between remotely sensed data and sea-truth measurements for both chlorophyll *a* and suspended sediment. A number of factors, such as spectral and spatial resolution and environmental factors, make interpretation of this effect difficult. Finally, correlations among sea-truth and remotely sensed measurements will be discussed in the section on quantitative mapping, which follows.

QUANTITATIVE MAPPING OF CHLOROPHYLL *a* DISTRIBUTIONS

Quantitative mapping of water quality parameter concentration distributions may be determined from the regression equations. For each water quality parameter, concentrations are determined for each picture element (pixel) (or equal spacings of pixels on lines and columns), this field of data is typically smoothed to remove local spectral and spatial noise features, and then a contour map is developed by a computerized plotting routine. The smoothing used in these analyses is an averaging on a line-by-line and column-by-column basis in the data field where the middle value is replaced by the arithmetic mean of it and the two adjacent pixels. Edge values remain the same. In the James River data set, the data field used every fourth pixel in each eighth line with five smoothing passes; and in the New York Bight data set, each pixel was used in every third line with two smoothing passes. The actual spacing and smoothing were determined empirically for each set of data.

Quantitative distributions of chlorophyll *a* in the James River near Hopewell and for the New York Bight apex are shown in Figures 5 and 6, respectively. Sea-truth measurement locations are also indicated.

A feature of particular interest in the James River experimental area is Bailey Creek, located in the lower left corner of the map (Figure 5). Bailey Creek is a source of sewage treatment plant and industrial effluent. Its plume indicates lower chlorophyll *a* concentrations. In the New York Bight experiment, Figure 6, high chlorophyll *a* concentrations are indicated in the near-shore areas. The Hudson River

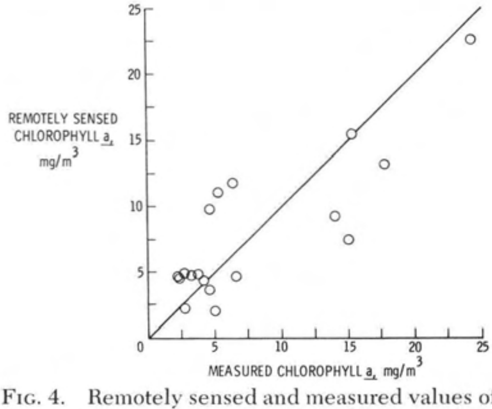

FIG. 4. Remotely sensed and measured values of chlorophyll *a* in the New York Bight on April 13, 1975.

FIG. 5. Quantitative distribution of chlorophyll *a* in the James River near Hopewell on May 28, 1974. (Also see Cover Photo.)

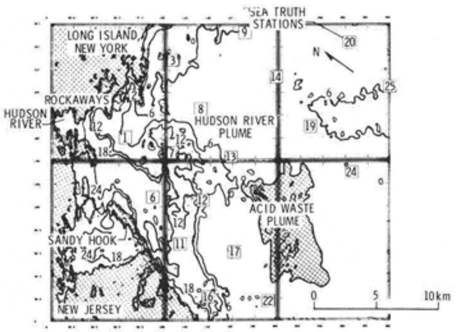

FIG. 6. Quantitative distribution of chlorophyll *a* in the New York Bight apex on April 13, 1975.

plume is also characterized by higher chlorophyll *a* concentrations as it flows into the New York Bight. Another feature of interest in this scene is the acid waste plume (which contains different materials[13]) that is qualitatively mapped in the lower center of Figure 6.

Analysis results, presented previously, may be used to evaluate whether the distributions shown in Figures 5 and 6 are unique to chlorophyll *a*.

One approach to evaluation is by comparison of correlation coefficients (recall that the correlation coefficient is a measure of the relative changes among variables) as shown in Table 7.

For both experiments correlation of sea truth to sea-truth measurements (chlorophyll *a* to suspended sediment) is about the same. However, correlations between sea-truth measurements and remotely sensed data are higher in the James River experiment than for the New York Bight. The higher correlation of chlorophyll *a* to remotely sensed data in the James River experiment indicates different spectral characteristics of chlorophyll *a* (compared to suspended sediment in the same experiment), while the lower correlation coefficient values of both chlorophyll *a* and suspended sediment to remotely sensed data in the New York Bight indicates a combined response where neither parameter may be unambiguously separated. The specific reason for this difference in the analysis results for the two experiments cannot be identified; however, it is probably related to combined environment (e.g., atmospheric and/or pollutant mixtures in the water) and instrument (e.g., spectral and spatial resolution) effects.

CONCLUDING REMARKS

The results of experiments conducted in the James River, Virginia, and the New York Bight indicate that concurrently collected sea-truth measurements may be used to calibrate remotely sensed multispectral scanner data collected over each of these environmentally different scenes. The same calibration technique (statistical stepwise regression analysis) was used in both experiments to identify and incorporate significant bands of multispectral scanner data into regression equations that quantitatively relate remotely sensed data to water quality parameters, such as chlorophyll *a* and suspended sediment. These regression equations were used to quantitatively map synoptic distributions of chlorophyll *a* in the remotely sensed scenes.

In the May 28, 1974, experiment conducted over the James River, Virginia, correlations were higher between chlorophyll *a* and remotely sensed data than between sea-truth measurements of the two water quality parameters, indicating a possible different quantitative mapping of chlorophyll *a*. On the other hand, in the New York Bight experiment in April 1975, higher correlations were obtained between chlorophyll *a* and suspended sediment sea-truth measurements than between sea-truth measurements and remotely sensed data, indicating that chlorophyll *a* and suspended sediment vary in the same manner in that experiment. The resultant mapping in the New York Bight is a combined response of these two parameters.

Quantitative regression equations for chlorophyll *a* and suspended sediment included radiance values in the same spectral range, from 450 to 750 nm. The statis-

TABLE 7. COMPARISON OF CORRELATION COEFFICIENTS.

Correlation Coefficients	James River Experiment	New York Bight Experiment
Chlorophyll *a* to Suspended Sediment	0.88	0.90
Chlorophyll *a* to Remotely Sensed Data	0.96	0.83
Suspended Sediment to Remotely Sensed Data	0.90	0.79

tical analyses results indicated higher correlations and improved accuracy for the M2S than for the OCS; however, there were many spectral, spatial, and environmental parameter variations that were not evaluated in the experiments.

The stepwise regression analysis is one technique for quantitatively relating remotely sensed data to chlorophyll *a* and suspended sediment in experimental data sets. In addition, statistical parameters from the analysis technique indicate the accuracy of the fitted multiple regression models. More data sets are required in different environmental areas, with and without industrial effluents, to establish more accurately the role of quantitative analysis in determining the distribution of water quality parameters. Further, techniques should be investigated that will allow transfer of information from one remotely sensed scene to another.

Acknowledgments

In any experimental program, a number of people make significant contributions. For the results reported here at least the following individuals should be recognized: Messrs. Gilbert S. Bahn and Robert M. Glasgow of the Vought Corporation for computerized data handling and development of contour plots; Dr. Warren Hovis, NESS/NOAA (previously at Goddard Space Flight Center, NASA), for the OCS data collection and reduction for the New York Bight experiment; and Mr. Terry Nelsen, Atlantic Oceanographic and Meteorological Laboratories/NOAA, for the sea-truth data measurements in the New York Bight experiment.

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