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Quantitative Analysis of Aircraft Multispectral-Scanner Data and Mapping of Water-Quality Parameters in the James River in Virginia

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SUMMARY

Statistical analysis techniques were applied to develop quantitative relationships between in situ river measurements and the remotely sensed data that were obtained over the James River in Virginia on May 28, 1974.

Two water-quality parameters, suspended-sediment and chlorophyll a concentrations, had significant regression equations with correlation coefficients of 0.899 and 0.961, respectively; these equations were applicable to remotely sensed data over the total experimental area. Based on a regression equation that used band 2 (0.440 to 0.490 μm) and band 6 (0.620 to 0.660 μm), suspended sediment was found to have a standard error of estimate of 5.23 mg/l over a range of 8.60 to 47.70 mg/l. By using a regression equation with band 2 (0.440 to 0.490 μm), band 6 (0.620 to 0.660 μm), and band 8 (0.700 to 0.740 μm), chlorophyll a was found to have a standard error of estimate of 1.75 mg/m^3 over a range of 1.61 to 19.5 mg/m^3. Five additional parameters (i.e., nitrite concentration, nitrate concentration, salinity, phosphate concentration, and Secchi disc depth) had significant correlations with remotely sensed data in one portion of the experimental area. Six other parameters (i.e., acidity (pH), carotenoids concentration, fluorescence, chlorophyll c concentration, dissolved oxygen concentration, and chlorophyll b concentration) did not have significant correlations with remotely sensed data.

Maps of the relative quantitative distributions of three water-quality parameters were developed to study the characteristics of a pollutant plume entering the turbid river system. From these maps, the pollutant plume was characterized by lower suspended-sediment and chlorophyll a concentrations, and higher nutrient loads.

For chlorophyll a and suspended sediment, an analysis made by reducing the remotely sensed data to three preselected bands (i.e., band 2 (0.440 to 0.490 μm), band 6 (0.620 to 0.660 μm), and band 8 (0.700 to 0.740 μm)) resulted in the same values for the standard error of estimate and correlation coefficient as those obtained from the 10-band analysis. This result indicates that scanners with a reduced number of preselected bands might be used to monitor some water-quality parameters.

An alternate nonlinear model that used a ratio of radiances was also used for the analysis of chlorophyll a. When compared with the results of the linear model, the nonlinear model results gave a comparable correlation coefficient and a degraded value for the standard error of estimate.

The stepwise regression analysis technique appears to have adequate sensitivity to correlate variations observed in multispectral-scanner data with variations measured for several water-quality parameters; however, more data sets are required in different environmental areas before it can be established that each of these water-quality parameters can be distinguished from all the others by remote sensing.

INTRODUCTION

Suspended-sediment and chlorophyll a concentrations are important environmental parameters for monitoring water quality, water movement, and land use in river watersheds. Uncontrolled sediment runoff reduces the depth of the photic zone and therefore reduces the volume of water in which photosynthesis (oxygen production) can take place. Suspended sediment has also been recognized as a natural tracer that may be used to measure flow and distributions in a water body in order to provide information on pollutant concentrations and dispersions. Differences in suspended-sediment loads between a pollutant plume and the receiving waters may be used to track plumes and measure dispersions. In addition, high suspended-sediment loads may be indicative of harmful erosion of nearby land areas and/or high filling rates in reservoir systems. Chlorophyll a concentrations can be an indicator of the current state of health of a water body. Other parameters such as nutrient concentrations provide valuable information about the water quality and may provide information on pollution-plume dispersion characteristics.

In references 1 and 2, Landsat multispectral-scanner data were analyzed and suspended-sediment concentration categories were mapped. A typical water category range had heavy sediment concentrations from 15 to 25 mg/l. Reference 3 extended results of lake studies to make quantitative determinations of water-quality parameters from remotely sensed data in the New York Bight. A statistical stepwise regression (continuous function) analysis was applied to Landsat multispectral-scanner data in reference 4 and to aircraft multispectral-scanner data in references 5 and 6 to calibrate remotely sensed data. The linear regression equations from these analyses were used to map suspended-sediment concentration distributions in the Potomac River in Maryland and James River in Virginia. In reference 7, the stepwise regression technique was applied to Landsat data and the relationships were obtained between remotely sensed data and 12 chemical and biological parameters in Saginaw Bay.

Reported herein are the results of applying the statistical stepwise regression analysis technique of references 5 and 6 by using a more restricted data set to evaluate quantitative relationships between remotely sensed aircraft multispectral-scanner data and additional water-quality parameters. The resulting linear regression equations are used to map synoptic distributions of several parameters in an area of the James River which is subject to sewage treatment plant and industrial pollution. In addition, results from the linear regression analysis (where bands of data in the regression equations are selected in the analysis procedure) are compared with a nonlinear equation and with a reduced subset of remotely sensed measurements (e.g., radiance measurements in a reduced number of bands) where the bands have been preselected.

EXPERIMENTAL METHOD

On May 28, 1974, remotely sensed data were collected over the James River in conjunction with sea-truth measurements. Sea-truth measurements used in this analysis were made from six boats at two sites, Norfolk (N) and Hopewell (H); three boats were used at each of the two sites. In situ measurements were made and water samples were taken at fixed stations at 20-min intervals from 0935 to 1115 hr. Subsequently, the boats (except boat 1 at Norfolk) moved to new stations. The maximum time span between the sea-truth measurement (or sample collection) and the remote sensor overpass was 2 hr. Sea-truth parameters are as follows:

Wind speed, knots
Wind direction, deg
Temperature, °C
Salinity, ppt
Dissolved O_2, mg/l
pH
Secchi disc depth, m
Chlorophyll *a*, mg/m^3
Chlorophyll *b*, mg/m^3
Chlorophyll *c*, mg/m^3
Inorganic PO_4, mg/l
Inorganic NO_2, mg/l
Inorganic NO_3, mg/l
Phaeophytins *a*, mg/m^3
Carotenoids, mg/m^3

Water depth, m
Current speed, knots
Current direction, deg
Transmittance, m
Total suspended solids, mg/l
Total inorganic suspended solids, mg/l
Tidal conditions after mean high water or mean low water, hr and min
Size fractions, particles/l, for bands of
  0.0 to 0.5 μm
  0.5 to 1.0 μm
  1.0 to 2.0 μm
  2.0 to 4.0 μm
  4.0 to 8.0 μm
  8.0 to 16.0 μm
0.200 to 0.900 μm scan
0.200 to 0.900 μm acetone extract scan

Remotely sensed data were collected by a multispectral scanner from about 1015 to 1135 hr from an aircraft platform at an altitude of 2.44 km (8000 ft). The flight lines are shown in figure 1. The bandwidths and wavelengths of the 11-band (10 bands in the visible and near-infrared regions plus one thermal band) Modular Multispectral Scanner

(Bendix M^2S) are given in table I, along with spatial coverage information at the flight altitude. Resolution is about 7 m (25 ft). Multispectral-scanner imagery in band 5 (0.580 to 0.620 μm) over the experiment area is shown in figure 2.

DATA ANALYSIS AND RESULTS

Data and Data Preprocessing

Results of a statistical regression analysis of suspended-sediment and chlorophyll a concentrations have previously been reported (ref. 5) for the data taken in this experiment. Those results used 54 and 51 sets of observations for suspended-sediment and chlorophyll a concentrations, respectively. In that analysis, the same spectral data were assigned to each of the sea-truth measurements made at a given station over a period of time. Since subsequent evaluation of the data indicated that more restrictive requirements should be used, redundant data were eliminated (sea-truth measurements that were closest timewise to the remote sensor overpass were used) and only sea-truth measurements with consistent sample-handling techniques were used. After applying these criteria, the data set for the analysis of water-quality parameters in this report has a maximum of 21 sets of observations that consisted of sea-truth measurements and corresponding remotely sensed data. For some water-quality parameters, the analysis was made with a lesser number of observations because of fewer sea-truth measurements. In addition, analyses were made with a subset of data at the Hopewell site to investigate clustering of data at the two primary sites, Hopewell and Norfolk.

The data set consists of measurements of water-quality parameters at the sampling stations and remotely sensed data collected over the same geographical location. Reference 8 gives sea-truth data for the mission. The specific set of sea-truth data analyzed in this study is given in table II; the stations, the water-quality-parameter values, and the time of the measurements are given.

Both the remotely sensed radiance values for the 10 scanner bands in the visible and near-infrared spectral range and the nominal time of measurement are listed in table III. The scanner band 11 (the thermal band) was not included in the analysis. Representative radiance values were used for each station. Representative values were determined from the calibrated mean count (the count is a scanner instrument output value that is proportional to radiance) over an 11 by 11 picture-element (pixel) field that was centered as nearly as possible at the sea-truth station. The 11 by 11 pixel field was determined empirically to be a suitable size that could adequately compensate for uncontrollable spectral noise and spatial inaccuracies. The mean count was multiplied by a band calibration factor to obtain average radiance values (mW/cm^2-sr-μm) over each band. Due to the near proximity of stations, in one case a few common pixels were used in determining the representative count for observations. In this case, there was one line (11 pixels of a total of 121) of overlap for samples N1D and N2D.

The scanner unit provides calibration values for each line of data collected. These changes were negligible compared with other factors in the analysis.

Table II gives a review of the sea-truth measurements and indicates that, within the experimental area, two geographically separated regions, Norfolk and Hopewell, have certain physical differences that may contribute to environmental differences (e.g., low salinity at Hopewell compared with that at Norfolk). Since one of the objectives of this analysis is to determine the extent of spectral similarity over the experimental area, the hypothesis that the data from the two areas are spectrally homogeneous was tested in two ways: first, by an evaluation of the analysis results and, second, by a comparison of the analysis results with the results of the analyses of a subset of data at Hopewell where there are maximum ranges for most of the parameters and there are minimum time intervals between the remotely sensed data collection and sea-truth measurements.

Stepwise Regression Analysis

Remotely sensed digital data in the visible and near-infrared wavelengths were analyzed by using the statistical stepwise regression analysis (SWRA) used in references 5 and 6. Suspended-sediment concentrations will be described as an example water-quality parameter; then the analysis will be extended to other parameters measured in the sea-truth program.

In the analysis, suspended-sediment concentration (mg/l) is the dependent variable and the 10 bands of multispectral-scanner radiances (mW/cm^2-sr-μm) are the independent variables. Correlations among the scanner bands and with suspended sediment are shown in the linear correlation matrix given in table IV. Correlations among the scanner bands are generally high.

In an SWRA, the program will determine the one independent variable (radiance) that has the highest correlation with the dependent variable (suspended-sediment concentration); then, in successive steps, it will continue to determine another variable to enter the equation until all the independent variables that make significant contributions to the regression equation are included. In each step, variables in the regression equation are tested for significance by an F test. Thus, when the program terminates, all significant variables are in the regression and the insignificant ones are outside the regression. (An independent variable may be significant and taken into the regression; then, because of the other variables added, it may become insignificant and must be removed.) In the analysis, a 95-percent confidence level is used to determine whether independent variables (scanner bands) should be included in the final regression equation (ref. 9, page 560). When referring to the linear correlation matrix for the grouped data (table IV), the first scanner band taken into the regression equation will be the one with the highest correlation coefficient (band 6 with a value of 0.853). Subsequent steps use the F value calculated in each step as the criterion. (For a detailed discussion, see ref. 10, page 171.)

Results of the SWRA with suspended-sediment concentrations are shown in the following table:

Step	Independent variable added	Regression variables	Standard error of estimate, mg/l	Range of measured values, mg/l	Regression correlation coefficient
1	R6	R6	6.07	8.60 to 47.6	0.853
2	R2	R2, R6	5.23	8.60 to 47.6	.899

where RN is the radiance (mW/cm^2-sr-μm) from the scanner in band N (i.e., R6 is the radiance in band 6); the standard error of estimate is the statistical standard deviation about the fitted regression line in mg/l; the range of measured values is taken from the sea-truth measurements; and the regression correlation coefficient with a maximum value of unity is a measure of the mutual relationship among variables.

For this particular data set, a two-parameter regression equation in scanner bands 2 and 6 meets the statistical criteria to determine suspended-sediment concentrations for each pixel in the remotely sensed scene. The resultant equation in mg/l is

$$\text{Suspended-sediment concentration} = 30.97 - 30.06R2 + 27.13R6$$

Remotely sensed and measured suspended-sediment concentrations for the 21 sets of observations are shown in figure 3; the 1:1 (perfect-fit) line is also shown. Deviations from the 1:1 line occur randomly; thus, the linear equation appears to be adequate. References 4 and 11 have previously indicated linear response of suspended-sediment concentrations with radiance in this range of values. Note that the continuous-function regression line adequately describes measurements taken at both the Norfolk and Hopewell sites (i.e., the grouped data).

Additional Water-Quality Parameters

Twelve additional parameters selected as measures or indicators of water quality and/or pollution effects were analyzed to determine if changes in their concentrations could be detected and measured by remote sensing. Results of the analysis, including suspended sediment, are given in table V. A primary result of the analyses of the grouped data set (1(a) to 13(a)) was the clustering of measured and/or remotely sensed values for some of the parameters that had high correlations with the remotely sensed data. Clustering was observed in some of the plots of remotely sensed values when compared with the measured values of the parameters. The comparisons for suspended-sediment concentration, chlorophyll a concentration, nitrite (NO_2) concentration (an example of the dissolved materials), and Secchi disc depth are shown in figures 3, 4, 5, and 6, respectively.

Because of the apparent clustering characteristic of the data set, a subset of the sea-truth and remotely sensed measurements at Hopewell was evaluated by SWRA. Results from this subset of data (1(b) to 13(b)) are also shown in table V for the 13 water-quality parameters. From observation of the plots and SWRA results from table V, it appears that only changes of suspended-sediment and chlorophyll a measurements may be combined in the SWRA to compute equations to represent a continuous-function equation for both the Hopewell and Norfolk sites. Even though neither the measured nor the remotely sensed values overlap, there are random distributions about the fitted linear-regression lines. In addition, comparison of the statistical results (e.g., bands, standard error of estimate, and correlation coefficients) indicates comparable results. Correlation among bands is more pronounced in the Hopewell subset, as seen in table VI. Lower correlation coefficients in the Hopewell subset analysis results are probably due to the decreased range of measurements with the same deviations.

Returning to the analysis results given in table V, variables (other than suspended sediment and chlorophyll a) have been given based on decreasing correlation coefficients for the Hopewell data subset. Five additional parameters (nitrite (NO_2) concentration, nitrate (NO_3) concentration, salinity, phosphate (PO_4) concentration, and Secchi disc depth) had correlation coefficients that met the 95-percent confidence level criterion for the number of observations. Six parameters (acidity, carotenoids concentration, fluorescence, chlorophyll c concentration, dissolved oxygen concentration, and chlorophyll b concentration) did not have significant correlation coefficients.

Four of the additional five parameters (other than suspended sediment and chlorophyll) with significant correlations are dissolved substances. The physical bases of these correlations are not fully understood at this time; however, possible reasons are that the uniquely shaped particles may be source specific or that there may be changes in the background water absorption or scattering characteristics. Secchi disc depth has been shown by other investigators (e.g., ref. 11) to vary with suspended-sediment concentrations and radiances.

From the results of the SWRA on this data set, the water-quality parameters may be grouped as follows:

I. Significant spectral response for the entire experimental area

  (a) Suspended sediment
  (b) Chlorophyll a

II. Significant spectral responses in the Hopewell subset of data

  (c) Nitrite (NO_2)
  (d) Nitrate (NO_3)
  (e) Salinity
  (f) Secchi disc depth
  (g) Phosphate (PO_4)

III. Nonsignificant spectral response in the Hopewell subset of data

  (h) Acidity
  (i) Carotenoids
  (j) Fluorescence
  (k) Chlorophyll c
  (l) Dissolved oxygen
  (m) Chlorophyll b

Mapping Water-Quality-Parameter Distributions

Remotely sensed data provide a means for mapping synoptic distributions of one or more water-quality parameters in the remotely sensed scene. One application of these mappings is to characterize and study pollution-plume dispersions in the receiving body of water.

Results of the quantitative analyses (regression equations) were used to determine distributions of several key water-quality parameters. For each water-quality parameter contoured, a field of data was developed. In this case, every fourth pixel on every eighth line (which gives reasonable ground spacing for the rectangular pixels) was used. This two-dimensional field of data was smoothed to reduce spectral and spatial noise (i.e., each value is replaced by the mean of it and the two adjacent values even though the edge values remain unchanged); then the resultant field of data was input to a computerized contour plot routine. In this data set, approximately five line and column smoothings were used for each of the parameters.

An area of particular interest in this experiment was the James River near Hopewell, which is an industrialized complex. (See fig. 7.) Bailey Creek is a source of industrial and sewage treatment plant effluent. In general, the dispersion of the plume may be seen by the dark water area in figure 7, which shows band 5 (0.580 to 0.620 μm) imagery over the area.

Three water-quality parameters analyzed in this experiment were selected to study plume-dispersion characteristics from Bailey Creek; suspended sediment and chlorophyll a were chosen because of their broad general interest and their broad spectral response over the experimental area, and nitrite was selected as an example of the dissolved materials that indicated spectral variations which correlated with concentration changes. Comparison of the remotely sensed values of nitrite with the measured values in the Hopewell subset of data is shown in figure 8. The regression equation for suspended sediment was previously presented; equations for chlorophyll a and nitrite in mg/m^3 and mg/l, respectively, are

$$\text{Chlorophyll } \underline{a} = 23.62 - 18.06R2 + 7.23R6 + 9.46R8$$

and

$$\text{Nitrite} = 5.79 - 2.55R3 + 3.76R8$$

Applying the regression equations to develop the fields of data and contour maps in this area, suspended-sediment, chlorophyll a, and nitrite concentration distributions are shown in figures 9, 10, and 11, respectively.

In this set of data, the Bailey Creek plume is characterized by lower suspended-sediment concentrations (fig. 9), lower chlorophyll a concentrations (fig. 10), and higher nitrite concentrations (fig. 11). These plume features may be due to relatively high resuspension of sediment in the river areas away from the plume and toxic and nutrient materials in the plume.

Analysis of Reduced Number of Bands

From the overall results listed in table V, band selections in three ranges (i.e., 0.380 to 0.535 μm, 0.580 to 0.700 μm, and 0.700 to 0.740 μm) consistently showed high correlations with water-quality parameters. Thus, it appears that less than 10 bands of data (in the visible and near-infrared regions) may provide acceptable results for some of the water-quality parameters that had significant correlations in the earlier analyses (e.g., suspended sediment, chlorophyll a, and one of the dissolved chemical parameters, nitrite). This basic approach has been suggested for instruments such as a thematic mapper in which fewer bands with improved spatial resolution are used. By experimentally selecting one scanner band in each of the spectral regions noted, the analysis was repeated. Where only data in scanner bands 2 (0.440 to 0.490 μm), 6 (0.620 to 0.660 μm), and 8 (0.700 to 0.740 μm) were used, the results of SWRA for the three water-quality parameters were as follows:

Water-quality parameter	Scanner bands in regression equation	Standard error of estimate	Correlation coefficient	Experimental area (a)	Number of observations
Suspended sediment	2, 6	5.23	0.899	H & N	21
Chlorophyll a	2, 6, 8	1.75	.961	H & N	21
Nitrite (NO_2)	2, 8	.22	.929	H	10

[a] Same areas as for quantitative mapping.

As may be seen from a comparison with table V, the results are the same for suspended sediment and chlorophyll a. Nitrite uses bands 2 and 8 (instead of 3 and 8) with some degradation of results.

Chlorophyll a Analysis by Nonlinear Equation

An analysis technique suggested in reference 3 was to use a ratio of radiances for relating remotely sensed data to chlorophyll a concentrations in relatively turbid or highly productive waters. The suggested equation format was

$$\log CH(RS) = a + bR(1)$$

where

log CH(RS)	logarithm (base 10) of chlorophyll a concentration, mg/m^3
a, b	experimental constants
R(1)	$\dfrac{\text{Radiance } (0.620\ \mu m \text{ to } 0.700\ \mu m) \text{ band}}{\text{Radiance } (0.420\ \mu m \text{ to } 0.480\ \mu m) \text{ band}}$

For the scanner, a good approximation of this ratio (see table I) is

$$R(1)' = \frac{(R6 + R7)}{(R2)}$$

where R2, R6, and R7 are radiances in scanner bands as previously defined. Spectral response in scanner bands 6 and 7 gives average radiance values in the range of 0.620 to 0.700 μm, as suggested for the numerator, and scanner band 2 (0.440 to 0.490 μm) approximates the range suggested for the denominator.

Results of the analysis of chlorophyll a for the grouped data (Hopewell and Norfolk) are shown in the following table:

Water-quality variable	Regression variable	Correlation coefficient	Standard error of estimate, mg/m^3	Range of measurement, mg/m^3
Chlorophyll a	R(1)'	0.95	2.28	1.61 to 19.5

where R(1)' is defined in the previous equation.

Comparison of these results with those from the linear equation in table V indicates that the nonlinear equation format gives a comparable correlation coefficient and a degraded value for the standard error of estimate for this set of data.

CONCLUDING REMARKS

Statistical analysis techniques were applied to develop quantitative relationships between in situ river measurements and remotely sensed data that were obtained over the James River in Virginia on May 28, 1974.

Two water-quality parameters, suspended sediment and chlorophyll a concentration, had significant regression equations with correlation coefficients of 0.899 and 0.961, respectively; these equations were applicable to remotely sensed data over the total experimental area. Based on a regression equation that used band 2 (0.440 to 0.490 μm) and band 6 (0.620 to 0.660 μm), suspended sediment was found to have a standard error of estimate of 5.23 mg/l over a range of 8.60 to 47.70 mg/l. By using a regression equation with band 2 (0.440 to 0.490 μm), band 6 (0.620 to 0.660 μm), and band 8 (0.700 to 0.740 μm), chlorophyll a was found to have a standard error of estimate of 1.75 mg/m^3 over a range of 1.61 to 19.5 mg/m^3. Five additional parameters (i.e., nitrite concentration, nitrate concentration, salinity, phosphate concentration, and Secchi disc depth) had significant correlations with remotely sensed data in one portion of the experimental area. Six other parameters (i.e., acidity (pH), carotenoids concentration, fluorescence, chlorophyll c concentration, dissolved oxygen concentration, and chlorophyll b concentration) did not have significant correlations with remotely sensed data.

Maps of the relative quantitative distributions of three water-quality parameters were developed to study the characteristics of a pollutant plume entering the turbid river system. From these maps, the pollutant plume was characterized by lower suspended-sediment and chlorophyll a concentrations, and higher nutrient loads.

For chlorophyll a and suspended sediment, an analysis made by reducing the remotely sensed data to three preselected bands (i.e., band 2 (0.440 to 0.490 μm), band 6 (0.620 to 0.660 μm), and band 8 (0.700 to 0.740 μm), resulted in the same values for the standard error of estimate and correlation coefficient as those obtained from the 10-band analysis. This result indicates that scanners with a reduced number of preselected bands might be used to monitor some water-quality parameters.

An alternate nonlinear model that used a ratio of radiances was also used for the analysis of chlorophyll a. When compared with the results of the linear model, the nonlinear model results gave a comparable correlation coefficient and a degraded value for the standard error of estimate.

The stepwise regression analysis technique appears to have adequate sensitivity to correlate variations observed in multispectral-scanner data with variations measured for several water-quality parameters; however, more data sets are required in different environmental areas before it can be established that each of these water-quality parameters can be distinguished from all the others by remote sensing.

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TABLE I.- MULTISPECTRAL-SCANNER BANDWIDTHS AND WAVELENGTHS, AND SPATIAL COVERAGE AT 2.4-km (8000-ft) ALTITUDE

Spectral range (including thermal band), μm	0.380 to 1.060 + thermal
Band range, μm, for –	
Band 1	0.380 to 0.440
Band 2	0.440 to 0.490
Band 3	0.495 to 0.535
Band 4	0.540 to 0.580
Band 5	0.580 to 0.620
Band 6	0.620 to 0.660
Band 7	0.660 to 0.700
Band 8	0.700 to 0.740
Band 9	0.760 to 0.860
Band 10	0.970 to 1.060
Thermal band	8.000 to 13.000
Spatial coverage for –	
Field-of-view width, m	6800
Field-of-view length, m	Continuous
Resolution, m	7

TABLE II.- SEA-TRUTH MEASURED VALUES OF WATER-QUALITY PARAMETERS

Sample (a)	Time of measurement, EDT	Suspended sediment, mg/l	Chlorophyll a, mg/m^3	Nitrite (NO_2), mg/l	Nitrate (NO_3), mg/l	Salinity, ppt	Phosphate (PO_4), mg/l (b)	Dissolved oxygen, mg/l	Acidity, pH (b)	Secchi disc depth, m	Carotenoids, mg/m^3 (b)	Fluorescence, mg/m^3 (b)	Chlorophyll b, mg/m^3	Chlorophyll c, mg/m^3
N1D	1035	10.520	1.820	0.012	0.126	17.620	0.092	6.100	7.530	0.900	0.040	0.000	0.020	3.250
N2D	1035	8.800	1.650	.009	.115	17.570	0.000	5.910	7.800	1.000	.060	0.000	.490	7.250
N2G	1115	10.120	2.680	.009	.190	17.720	0.000	6.540	7.740	1.100	.060	0.000	.160	3.030
N2H	1155	17.720	3.820	.006	.095	17.140	0.000	7.780	7.980	.790	.050	0.000	.120	6.120
N2I	1215	12.240	1.750	.007	.092	17.050	0.000	5.890	7.910	.890	.050	0.000	.030	3.400
N2J	1235	11.560	2.730	.006	.081	17.220	0.000	7.200	7.990	.820	.050	0.000	.120	3.970
N3D	1035	12.000	1.950	.011	.101	16.560	0.000	5.420	7.420	1.000	.080	0.000	.340	4.620
N3G	1135	8.600	2.970	.010	.158	17.610	0.000	6.370	7.610	1.300	.070	0.000	.110	3.730
N3H	1155	21.520	2.900	.008	.095	17.440	0.000	7.350	7.580	.930	.070	0.000	.110	3.270
N3I	1215	9.040	2.370	.011	.150	17.600	0.000	6.480	7.630	1.100	.080	0.000	.300	3.880
N3J	1235	10.960	2.680	.009	.140	17.650	.220	6.370	7.510	1.130	.070	0.000	.220	5.320
H1F	1115	28.200	17.460	2.860	21.730	.097	.070	5.890	5.500	.490	0.000	12.790	1.750	6.290
H1H	1155	31.600	15.780	3.080	22.030	.094	0.000	5.690	5.600	.370	0.000	10.630	4.090	.550
H1J	1235	47.600	19.500	3.120	23.180	.082	0.000	6.230	5.700	.410	0.000	14.310	.450	5.790
H2F	1115	28.600	12.050	2.870	21.050	.097	.070	5.250	0.000	.410	0.000	2.070	.600	2.640
H2H	1155	28.800	13.580	2.730	22.330	.099	.070	6.010	0.000	.500	0.000	10.630	3.360	9.440
H2I	1215	23.000	10.260	2.750	22.840	.097	.140	6.090	0.000	.390	0.000	8.100	.250	2.490
H2J	1235	40.800	11.510	2.280	23.750	.097	.040	5.990	0.000	.380	0.000	0.000	2.060	2.710
H3F	1115	24.400	9.190	2.280	21.510	.104	.220	5.750	0.000	.480	0.000	12.070	2.760	5.440
H3H	1155	26.800	6.560	1.840	18.470	.082	.260	6.610	0.000	.440	0.000	9.790	1.390	.230
H3I	1215	31.400	8.730	1.520	16.590	.080	.130	6.350	0.000	.500	0.000	10.300	1.880	3.900

[a] Sample designation site: N-Norfolk; H-Hopewell; 1,2,3-Boat; letter designation indicates time (e.g., D = 1035).

[b] 0.000 indicates no measurement made.

TABLE III. - AVERAGE RADIANCE IN SCANNER BANDS OVER SEA-TRUTH STATIONS

[Measurement given per micrometer of bandwidth]

Sample (a)	Time of measurement, EDT	Average radiance, mW/cm^2-sr-μm, in –									
		Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10
N1D	1035	2.023	2.558	3.590	3.104	2.670	2.122	1.715	0.891	0.532	0.447
N2D		2.023	2.558	3.590	3.104	2.670	2.122	1.715	.891	.532	.447
N2G		2.121	2.558	3.590	3.104	2.670	2.122	1.715	1.071	.532	.447
N2H		2.318	3.071	4.390	3.860	3.375	2.939	2.333	1.432	.657	.447
N2I		2.121	2.729	3.890	3.356	2.811	2.286	1.869	1.252	.532	.447
N2J		2.121	2.729	3.890	3.356	2.811	2.449	1.869	1.252	.532	.447
N3D		2.023	2.558	3.590	3.104	2.670	2.122	1.715	1.071	.532	.242
N3G		2.023	2.615	3.790	3.230	2.811	2.286	1.869	1.071	.532	.447
N3H		2.023	2.501	3.490	2.978	2.529	1.959	1.560	.891	.532	.242
N3I		2.121	2.558	3.490	2.978	2.388	2.122	1.560	.891	.532	.447
N3J		2.121	2.501	3.490	2.978	2.388	1.959	1.560	1.071	.532	.242
H1F	1115	2.023	2.501	3.490	3.356	3.093	2.776	2.178	1.613	.782	.447
H1H		2.220	2.900	4.190	3.987	3.798	3.429	2.952	2.154	1.157	.855
H1J		2.121	2.957	4.390	4.239	3.939	3.593	2.952	2.154	1.157	.855
H2F		2.121	2.729	3.790	3.608	3.375	3.103	2.488	1.793	1.032	.651
H2H		2.121	2.729	3.890	3.482	3.234	2.939	2.488	1.793	1.032	.651
H2I		2.220	2.786	3.890	3.482	3.375	2.939	2.488	1.793	1.032	.855
H2J		2.023	2.615	3.690	3.356	3.234	2.939	2.333	1.613	.907	.651
H3F		2.023	2.615	3.490	3.356	3.093	2.776	2.178	1.432	.657	.447
H3H		2.121	2.615	3.690	3.482	3.234	2.776	2.178	1.432	.782	.447
H3I		2.318	2.843	3.990	3.734	3.375	2.939	2.178	1.613	.782	.447

[a]Sample designation site: N-Norfolk; H-Hopewell; 1,2,3-Boat; letter designation indicates time (e.g., D = 1035).

TABLE IV. - CORRELATION MATRIX FOR GROUPED DATA

[Suspended sediment and average responses in scanner bands]

		Suspended sediment	Scanner bands									
			1	2	3	4	5	6	7	8	9	10
Suspended sediment		1.000	0.188	0.446	0.450	0.727	0.828	0.853	0.819	0.843	0.846	0.641
Scanner bands	1		1.000	.777	.691	.595	.483	.459	.419	.439	.346	.327
	2			1.000	.969	.892	.781	.744	.734	.673	.563	.600
	3				1.000	.892	.771	.717	.727	.662	.561	.607
	4					1.000	.954	.929	.912	.875	.776	.718
	5						1.000	.981	.977	.943	.889	.808
	6							1.000	.981	.963	.913	.820
	7								1.000	.972	.941	.870
	8									1.000	.949	.829
	9										1.000	.881
	10											1.000

TABLE V.- RESULTS OF SWRA OF SELECTED WATER-QUALITY PARAMETERS AND REMOTELY SENSED DATA MEASURED FOR JAMES RIVER ON MAY 28, 1974

Water-quality parameter	Scanner bands in regression equation	Standard error of estimate	Range of measured values	Regression correlation coefficient	Number of observations
1(a) Suspended sediments, mg/l	2, 6	5.23	8.60 to 47.6	0.899	21 (N & H)
1(b) Suspended sediments, mg/l	6	5.93	23.00 to 47.6	.674	10 (H)
2(a) Chlorophyll a, mg/m^3	2, 6, 8	1.75	1.61 to 19.5	0.961	21 (N & H)
2(b) Chlorophyll a, mg/m^3	2, 8	2.21	6.56 to 19.5	.881	10 (H)
3(a) Inorganic NO_2, mg/l	3, 6, 8, 9	0.18	0.01 to 3.12	0.993	21 (N & H)
3(b) Inorganic NO_2, mg/l	3, 8	.13	1.52 to 3.12	.978	10 (H)
4(a) Inorganic NO_3, mg/l	3, 6, 9	2.32	0.08 to 23.75	0.981	21 (N & H)
4(b) Inorganic NO_3, mg/l	1, 10	.71	16.59 to 23.75	.959	10 (H)
5(a) Salinity, ppt	3, 6, 9	2.46	0.08 to 17.72	0.966	21 (N & H)
5(b) Salinity, ppt	4, 7	.005	0.08 to 0.10	.857	10 (H)
6(a) Secchi disc depth, m	3, 6	0.12	0.37 to 1.31	0.928	21 (N & H)
6(b) Secchi disc depth, m	10	.04	0.37 to 0.50	.744	10 (H)
7(a) Inorganic PO_4, mg/l	8, 10	0.06	0.05 to 0.26	0.619	14 (N & H)
7(b) Inorganic PO_4, mg/l	9	.06	0.07 to 0.26	.740	9 (H)
8(a) Acidity, pH	2, 6, 9, 10	0.13	5.40 to 7.99	0.993	14 (N & H)
8(b) Acidity, pH	[a]9	.02	5.40 to 5.70	.993	3 (H)
9(a) Carotenoids, mg/m^3					
9(b) Carotenoids, mg/m^3	[a]10	0.01	0.04 to 0.08	0.557	[b]11 (N)
10(a) Chlorophyll c, mg/m^3	[a]10	2.17	0.23 to 9.44	0.148	21 (N & H)
10(b) Chlorophyll c, mg/m^3	[a]1	2.86	0.23 to 9.44	.298	10 (H)
11(a) Fluorescence, mg/m^3					
11(b) Fluorescence, mg/m^3	[a]4	3.64	2.07 to 14.31	0.230	9 (H)
12(a) Dissolved oxygen, mg/l	3, 9	0.51	5.25 to 7.78	0.612	21 (H & N)
12(b) Dissolved oxygen, mg/l	[a]1	.39	5.75 to 6.61	.255	10 (H)
13(a) Chlorophyll b, mg/m^3	8	0.99	0.02 to 4.09	0.602	21 (N & H)
13(b) Chlorophyll b, mg/m^3	[a]10	1.34	0.02 to 4.09	.113	10 (H)

[a] No significant correlation with scanner remotely sensed data (95-percent confidence level), band with highest individual response indicated.

[b] Data collected only at Norfolk.

TABLE VI. - CORRELATION MATRIX FOR HOPEWELL DATA SUBSET

[Suspended sediment and average responses in scanner bands]

		Suspended sediment	Scanner bands									
			1	2	3	4	5	6	7	8	9	10
Suspended sediment		1.000	-0.105	0.429	0.584	0.615	0.614	0.674	0.517	0.507	0.434	0.378
Scanner bands	1		1.000	.704	.598	.474	.447	.293	.247	.339	.304	.268
	2			1.000	.959	.891	.897	.842	.787	.802	.720	.700
	3				1.000	.935	.947	.901	.850	.867	.796	.733
	4					1.000	.966	.934	.823	.831	.674	.592
	5						1.000	.971	.913	.901	.795	.761
	6							1.000	.948	.936	.833	.777
	7								1.000	.970	.923	.893
	8									1.000	.930	.868
	9										1.000	.926
	10											1.000

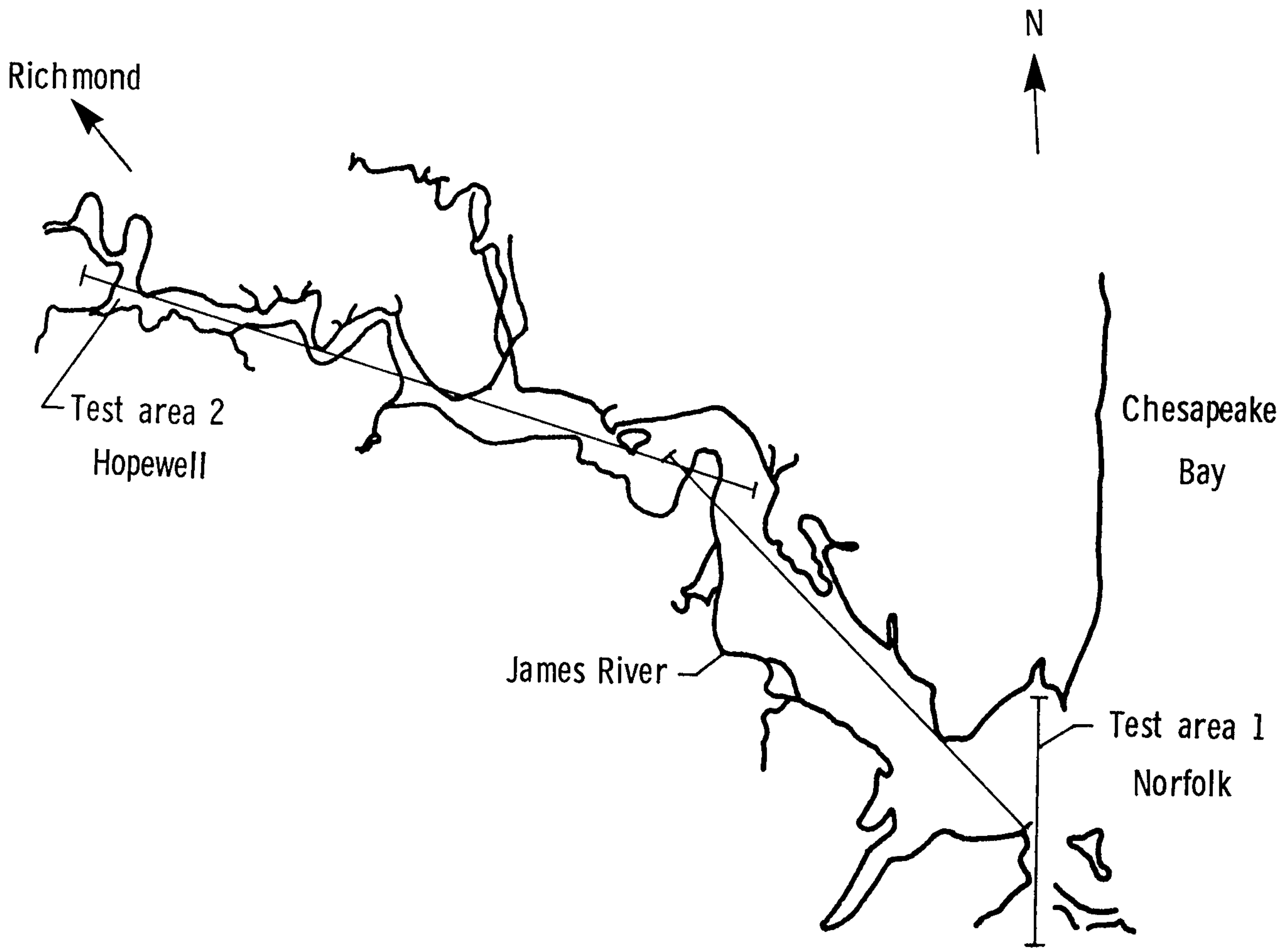
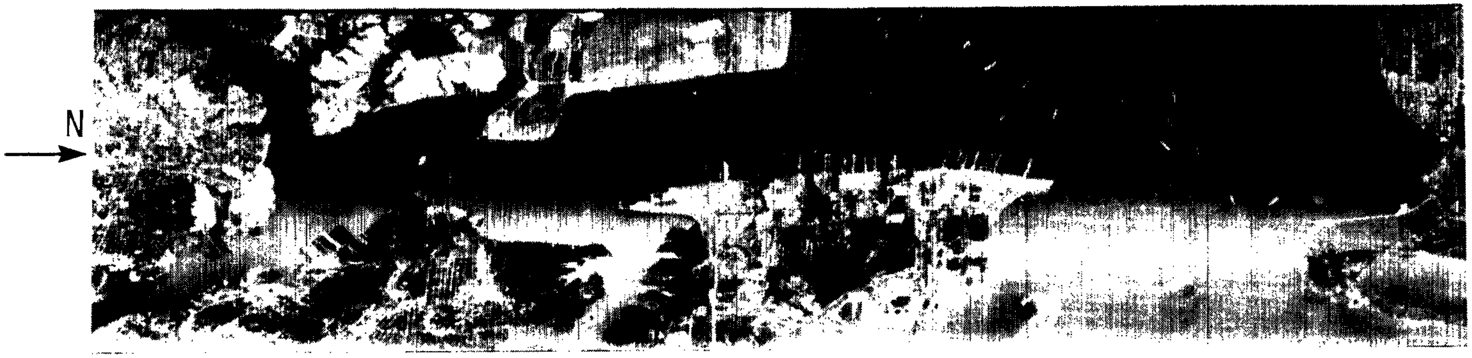


Figure 1.- Aircraft flight lines over James River from Norfolk to Hopewell on May 28, 1974.



Test site 1, Norfolk

Test site 2, Hopewell

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Figure 2.- Scanner imagery of test sites on May 28, 1974, in band 5 (0.58 to 0.62 μm).

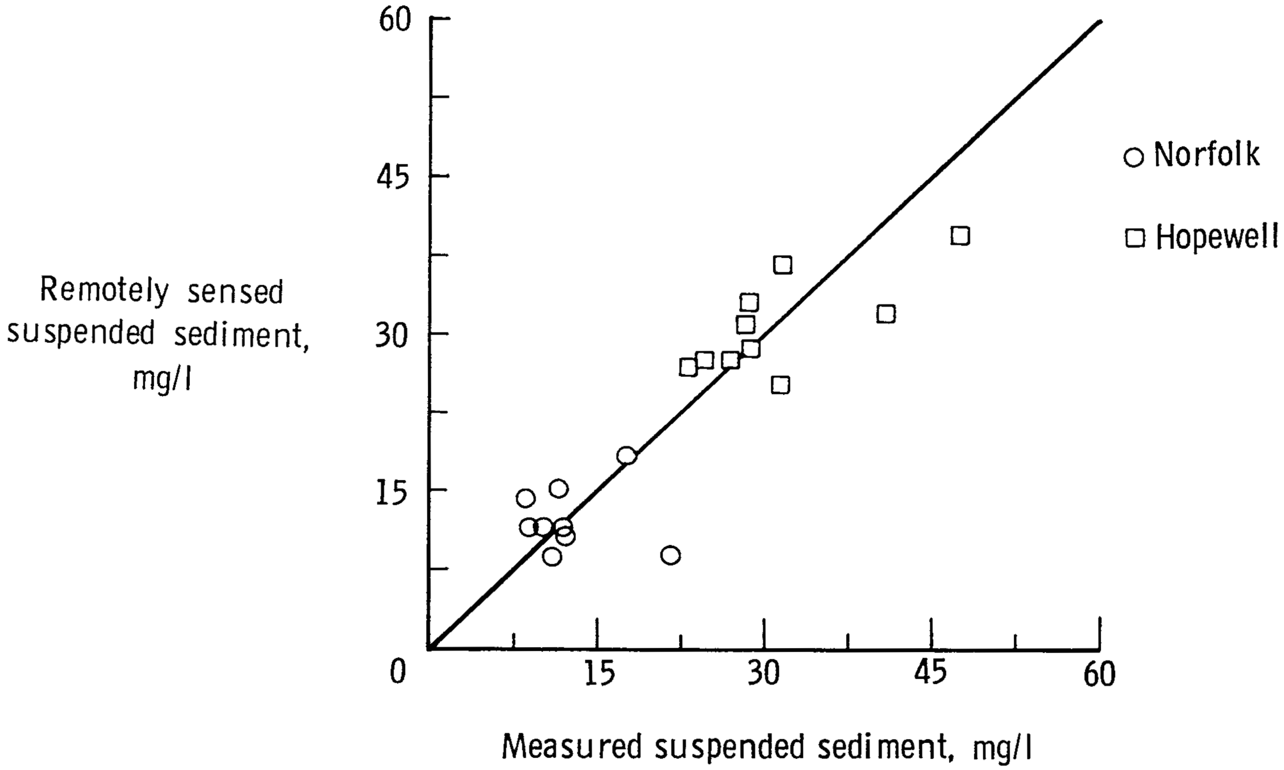

Figure 3.- Remotely sensed and measured values of suspended sediment in James River on May 28, 1974.

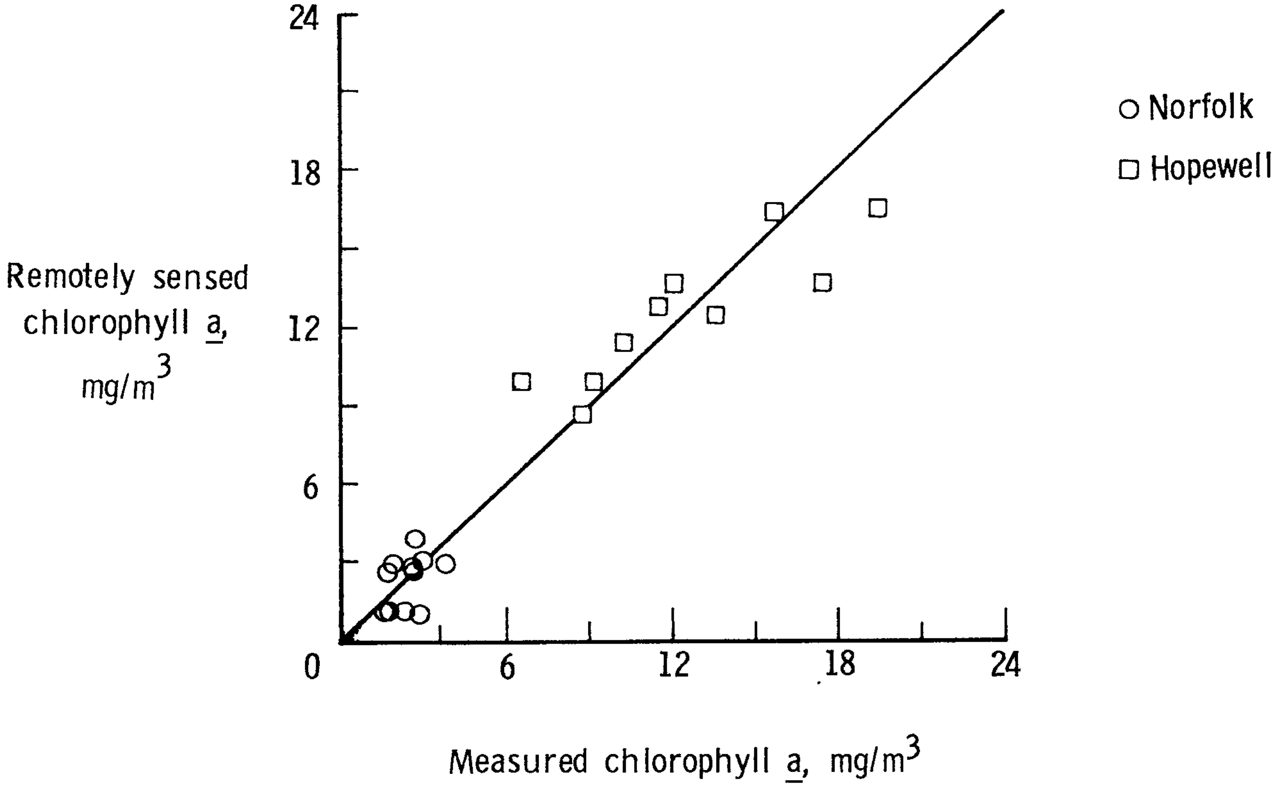

Figure 4.- Remotely sensed and measured values of chlorophyll a in James River on May 28, 1974.

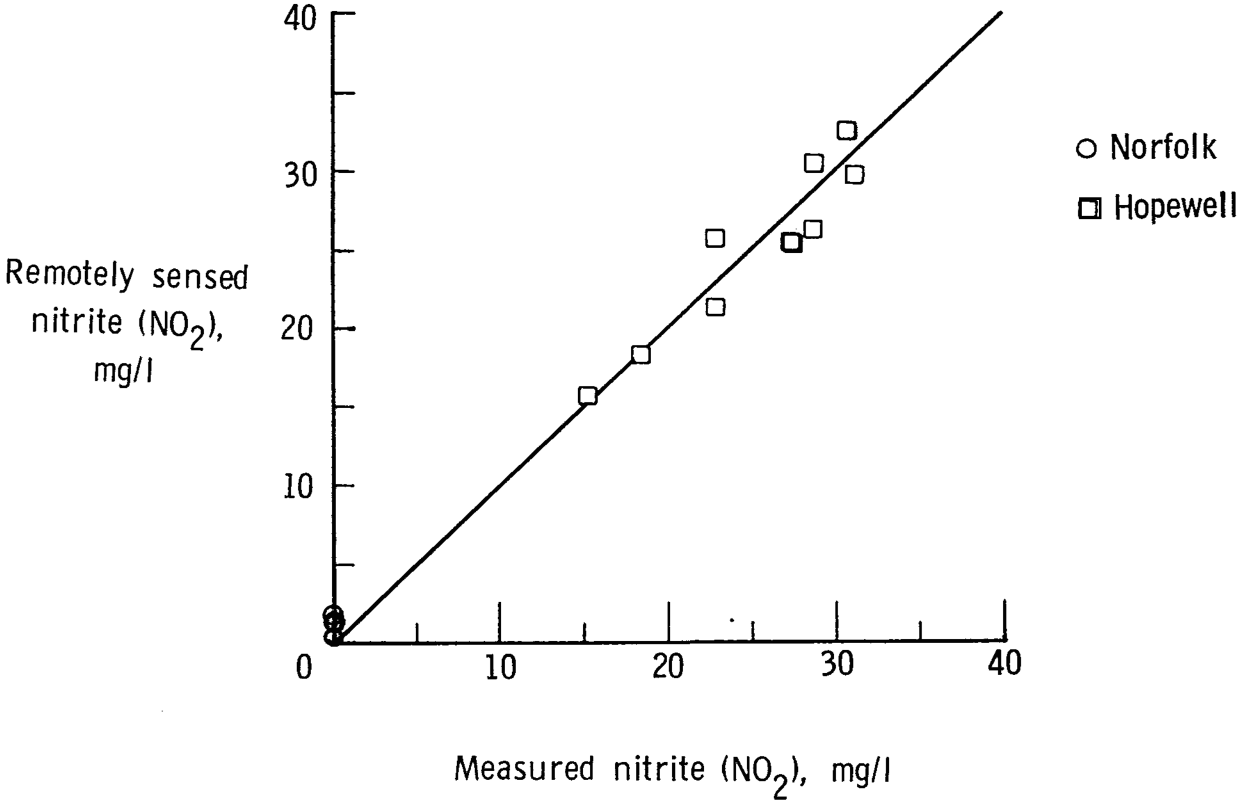

Figure 5.- Remotely sensed and measured values of nitrite (NO_2) in experimental area.

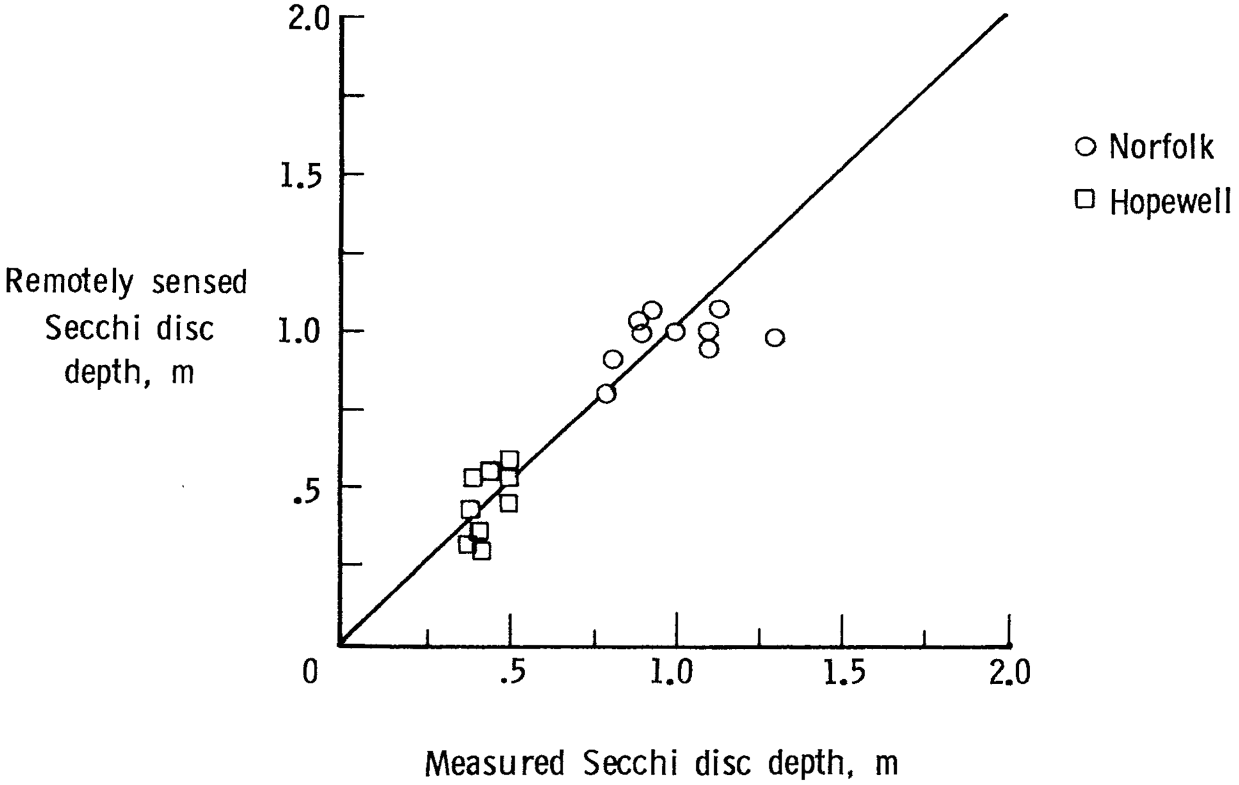

Figure 6.- Remotely sensed and measured values of Secchi disc depth in James River on May 28, 1974.

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Figure 7.- James River at Hopewell on May 28, 1974. Scanner band 5 (0.58 to 0.62 μm) imagery is given. (Note Bailey Creek at lower left.)

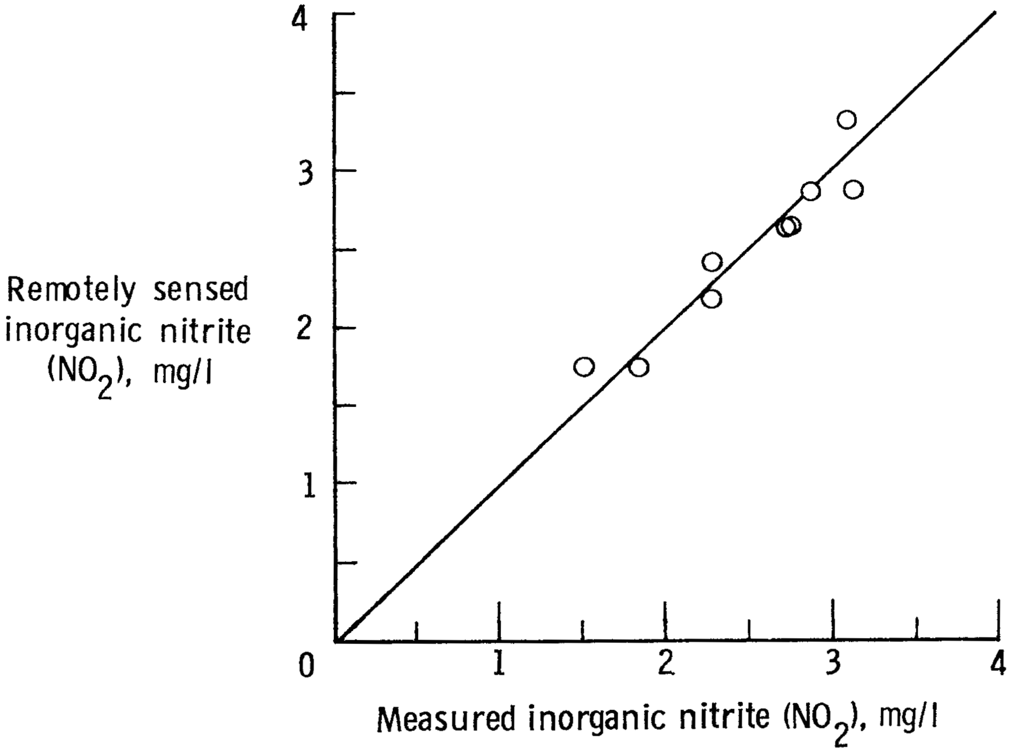

Figure 8.- Remotely sensed and measured values of nitrite (NO_2) at Hopewell.

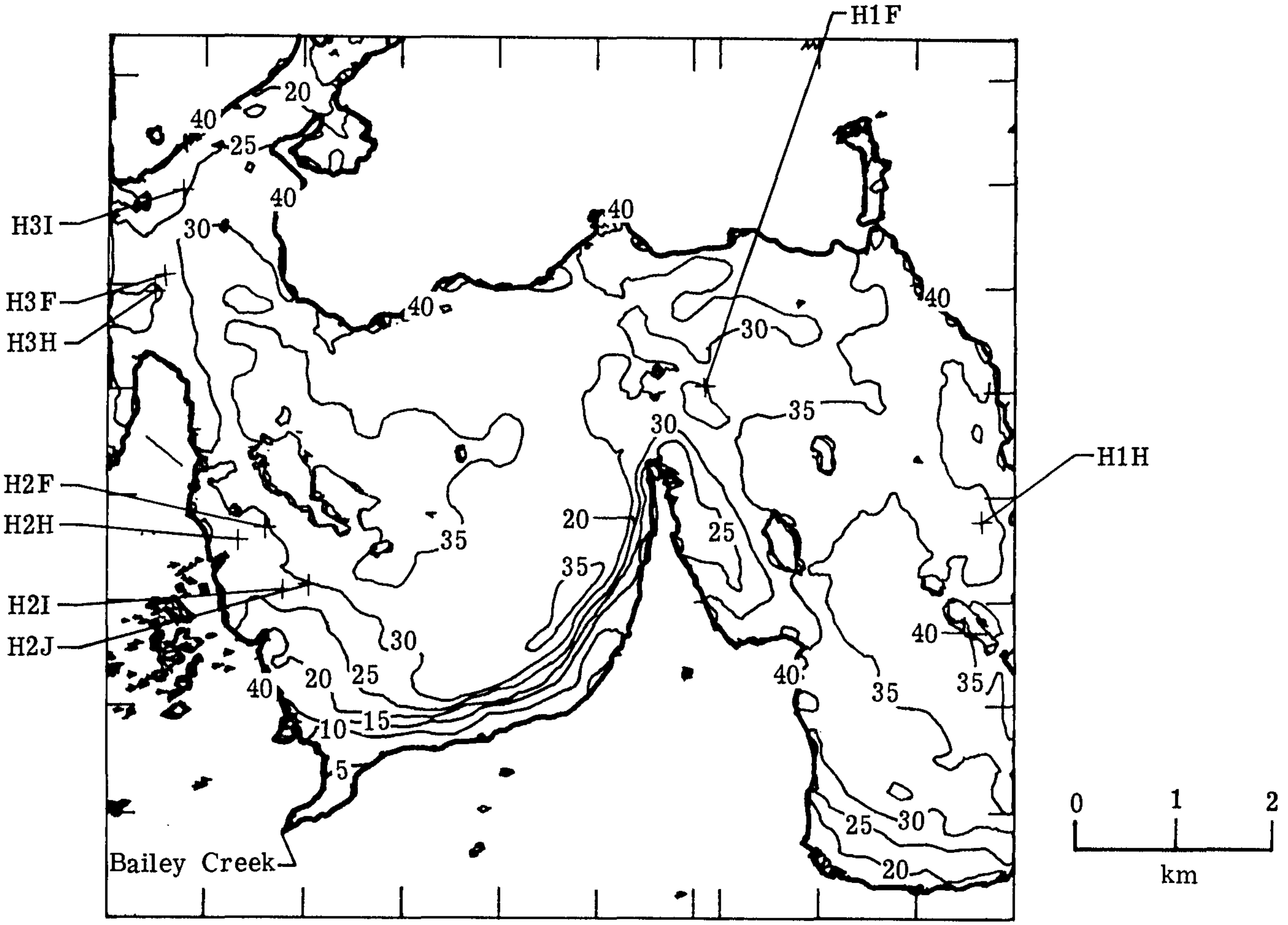

Figure 9.- Quantitative distribution of suspended sediment in James River near Hopewell on May 28, 1974. Sea-truth range, 8.60 to 47.60 mg/l; standard error, 5.23 mg/l; correlation coefficient, 0.899; scanner bands, band 2 (0.440 to 0.490 µm) and band 6 (0.620 to 0.660 µm); resolution, 7 m. (See table II for an explanation of the symbols.)

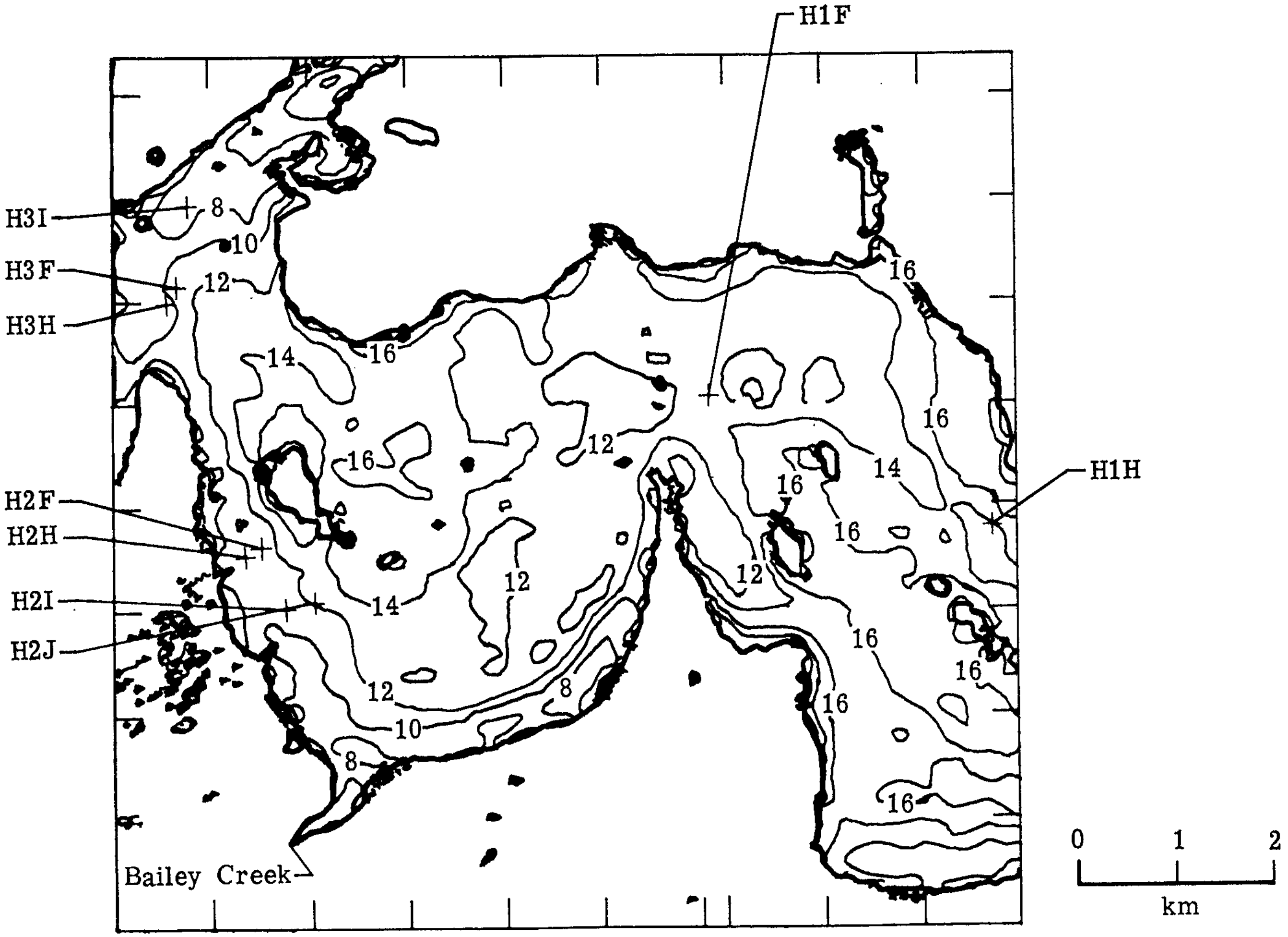

Figure 10.- Quantitative distribution of chlorophyll a in James River near Hopewell on May 28, 1974. Sea-truth range, 1.61 to 19.5 mg/m^3; standard error, 1.75 mg/m^3; correlation coefficient 0.961; scanner bands, band 2 (0.440 to 0.490 μm), band 6 (0.620 to 0.660 μm), and band 8 (0.700 to 0.740 μm); resolution, 7 m. (See table II for an explanation of the symbols.)

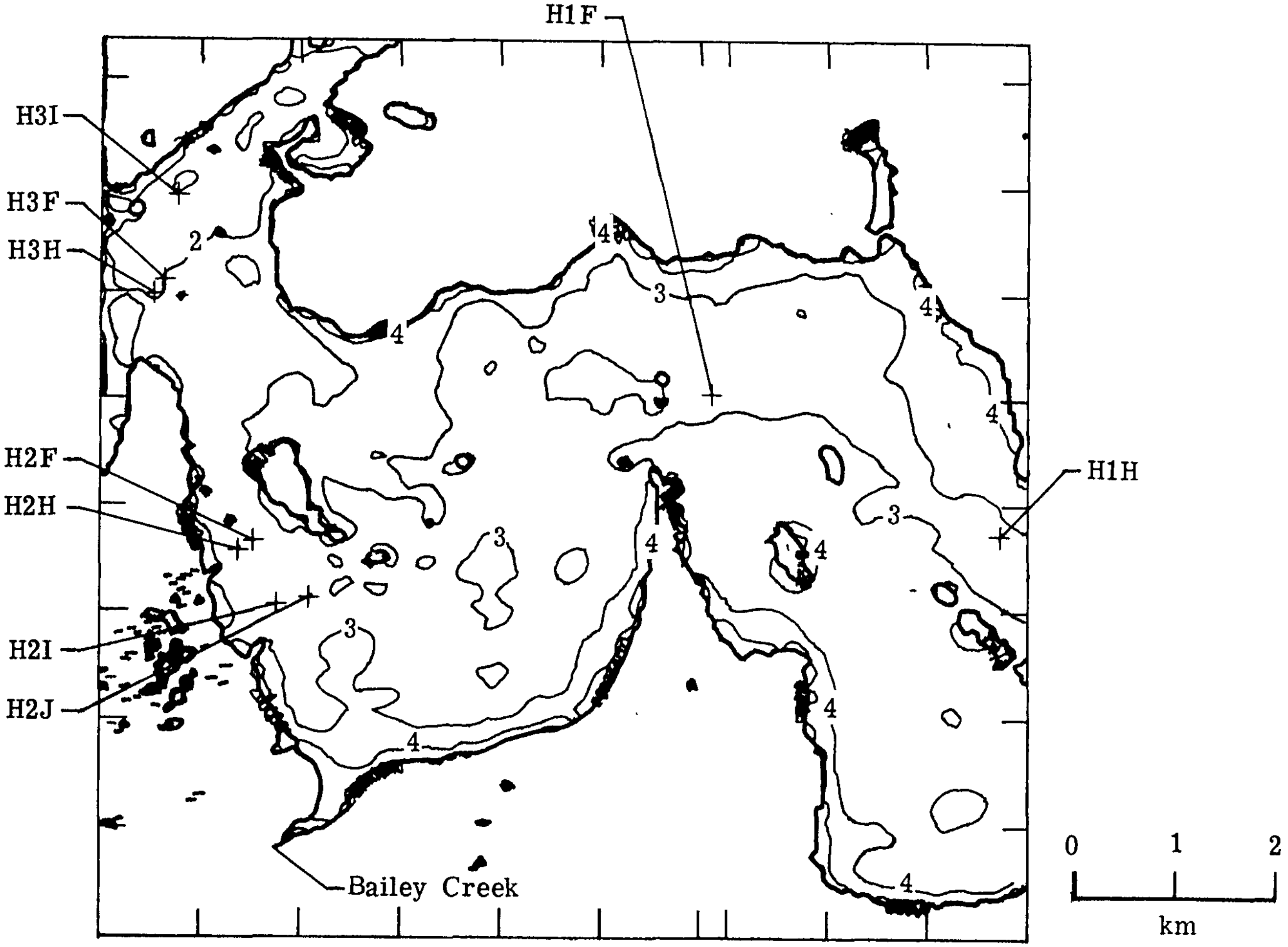

Figure 11.- Quantitative distribution of nitrite (NO_2) in James River near Hopewell on May 28, 1974. Sea-truth range, 1.52 to 3.12 mg/l; standard error, 0.13 mg/l; correlation coefficient, 0.978; scanner bands, band 3 (0.495 to 0.535 μm) and band 8 (0.700 to 0.740 μm); resolution, 7 m. (See table II for an explanation of the symbols.)