M-11

QUANTITATIVE SUSPENDED SEDIMENT MAPPING USING AIRCRAFT REMOTELY SENSED MULTISPECTRAL DATA

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ABSTRACT

Suspended sediment is an important environmental parameter for monitoring water quality, water movement, and land use. Quantitative suspended sediment determinations have been made from analysis of aircraft remotely sensed multispectral digital data. A statistical analysis and derived regression equation were used to determine and plot quantitative suspended sediment concentration contours in the tidal James River, Virginia, on May 28, 1974. From the analysis, a single band, Band 8 (0.70-0.74 microns), was adequate for determining suspended sediment concentrations. A correlation coefficient of 0.89 was obtained with a mean inaccuracy of 23.5 percent for suspended sediment concentrations up to about 50 mg/ℓ. Other water quality parameters - secchi disc depth and chlorophyll - also had high correlations with the remotely sensed data. Particle size distributions had only a fair correlation with the remotely sensed data.

INTRODUCTION

Suspended sediment is an important environmental parameter for monitoring water quality, water movement, and land use in river water sheds and filling rates in reservoirs. Uncontrolled sediment runoff reduces the depth of the photic zone and therefore 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, thereby providing information on pollutant concentrations and dispersions. In addition, high sediment loads may be indicative of harmful erosion of nearby land areas and/or high filling rates in reservoir systems.

Williamson and Grabau (ref. 1) and Klemas, et al. (ref. 2) analyzed LANDSAT multispectral scanner data and determined suspended sediment concentration categories in the areas of water analyzed. A typical water category had sediment concentrations from 15 to 25 mg/ℓ. Johnson (ref. 3) applied a continuous function analysis to develop a regression equation to determine sediment concentrations for each pixel. By this latter procedure it was possible to determine and plot quantitative suspended sediment concentration contours as shown in figure 1, which is taken from reference 3.

It is the purpose of this investigation to apply the methodology of reference 3 to aircraft multispectral scanner data to quantitatively determine suspended sediment concentrations in a turbid tidal river system. In addition, other water quality parameters such as chlorophyll, secchi disc depth and particles will be investigated for correlations among themselves and with the digital multispectral scanner data.

EXPERIMENTAL METHOD

Remotely sensed data were collected in conjunction with ground truth measurements over the Norfolk and James River, Virginia, areas on May 28, 1974. Remotely sensed data were collected from about 1015 to 1135 hours e.d.t. by a Bendix Modular Multispectral Scanner (M2S) from a flight altitude of 8000 feet (2.4 km). Ground truth measurements were made from seven boats at three sites; Norfolk, Hopewell, and Hog Island. Three boats were located at each of the first two sites, Norfolk and Hopewell, and one boat was used at Hog Island. In situ measurements were made and water samples taken for subsequent laboratory determinations at 20-minute intervals from about 0935 to 1235 hours e.d.t. A wide range of water parameters were measured. This investigation will consider suspended sediment, secchi disc depth, chlorophyll, and particle size distributions.

Remotely sensed data were collected by an 11-band (10 bands in the visible and near IR and one thermal band) multispectral scanner (Bendix M2S). Bandwidths and frequencies are listed in table I, along with spatial coverage information at the flight altitude. Pixel size and resolution are about 25 feet (7 m). Multispectral scanner imagery in Band 5 (0.58-0.62μ) over the test areas is shown in figure 2.

Digital data in the visible and near IR frequencies were analyzed using statistical regression techniques to develop an equation for quantitatively determining suspended sediment concentrations. In the analysis, suspended sediment concentration (mg/ℓ) is the dependent variable and the 10 bands of remotely sensed data (mw/cm^2-ster) are the independent variables. Correlation among the M2S bands and with suspended sediment is generally high except for widely separated bands, as shown in the linear correlation matrix, table II. Individual band correlations with suspended sediment are high for Bands 4 through 9 which cover a frequency range from 0.54 to 0.86μ, with Band 8 (0.70-0.74μ) the highest with a correlation coefficient of 0.89.

To develop a better assessment of the data set, a stepwise regression analysis (SRA) technique was applied to the data. In an SRA the program will determine the one independent variable (radiance) that provides the best statistical correlation with the dependent variable (suspended sediment concentration), then in successive steps determines a second variable to be added that improves the multiple correlation and so on until all of the independent variables have been included in the correlation. The first step provides information on the best single band. Additional steps provide a measure of the improvement as successive information (bands) are added.

Results of the analysis are shown below.

Step	Independent variable added	Regression variables	Std. error of estimate mg/ℓ	Regression correlation coefficient
1	R8	R8	4.76	0.888
2	R1	R8, R1	4.68	.896
3	R6	R8, R1, R6	4.58	.903
		.		
		.		
		.		
10	R10	All	4.31	.927

where RN is radiance (mw/cm^2-ster) from the M2S in Band N (i.e., R8 is the radiance in Band 8). Standard error of estimate is the statistical standard deviation in mg/ℓ. Regression correlation coefficient is a measure of the relative responses of the variables with a maximum value of unity.

To test the assumed linear regression equation, residuals (deviations from the fitted regression line) were plotted as a function of sediment concentration, figure 3. Since the variation of residuals occurred approximately randomly the linear equation appears to be adequate. Johnson (ref. 3) and McCauley and Yarger (ref. 4) have previously indicated linear response of suspended sediment concentrations with radiance in this range of values.

A one-parameter (Band 8) regression equation was used for the determination of suspended sediment since the addition of other variables (M2S bands) does not make a significant improvement (based on reduction in sum of squares for 95-percent confidence level, e.g., p. 455, ref. 5) for this particular data set. The resultant equation for a single band regression is

Suspended sediment concentration (mg/ℓ) = -88.80 + 600.00R8

Estimated mean inaccuracy using the above equation is about 23.5 percent (standard error of estimate 4.76 mg/ℓ and an average sediment concentration of 20.22 mg/ℓ). Sediment concentrations range up to about 50 mg/ℓ. Suspended sediment concentrations, Band 8 response, and the fitted regression line are shown in figure 4.

Quantitative values of suspended sediment concentrations may be used to determine and plot contours of equal concentrations in the study area. Contours in the upper James River near Hopewell are shown in figure 5. Comparison with the same area in figure 2 indicates the same suspended sediment characteristics; however, the contour plots provide quantitative values of suspended sediment concentrations, rather than relative (or qualitative) measures.

In addition to suspended sediment concentrations, ground truth measurements included other water quality parameters: chlorophyll a, secchi disc, and particle size distributions. The latter were determined from the Langley computerized particulate counter (Millipore πMC). Correlations among these parameters are shown in a correlation matrix (table III). Poor correlations were obtained for very small particles (less than 1 micron). Relatively good correlations with suspended sediment were obtained for small to medium size (1.0 to 4.0μ) and for total particles. This correlation is not as good as might be expected under the good conditions for sediment resuspension - shallow water areas on each side of the channel, fresh water outflow combined with ebb tide over the data collection period, and a 15- to 20-knot wind blowing down the river. A high correlation (negative sign indicates inverse relationship) was obtained between secchi disc depth and suspended sediment concentration as expected. The high correlation between chlorophyll a and suspended sediment concentrations, in addition to the essentially parallel response to suspended sediment concentrations in the particle distributions, indicates that this may be a parallel correlation with particles; however, the analysis technique provides separation of chlorophyll in this particular set of data. Day-to-day correlations of chlorophyll that did not show a high correlation as grouped data have been previously observed by Bowker and Witte (ref. 6) in their analysis of LANDSAT data from the Chesapeake Bay.

Further analysis of the chlorophyll a data was obtained by taking chlorophyll as the dependent variable and multispectral responses as the independent variables, as was done for suspended sediment. Again, the stepwise regression approach was followed. Results of the analysis were

Step	Independent variable added	Regression variables	Std. error of estimate, mg/M^3	Regression correlation coefficient
1	R8	R8	2.64	0.89
2	R2	R8,R2	1.88	.95
3	R4	R8,R2,R4	1.70	.96
4	R9	R8,R2,R4,R9	1.62	.96
5	R5	R8,R2,R4,R9,R5	1.60	.97
		0		
		0		
		0		
10	R4	All	1.56	.97

where the statistical parameters are the same as previously defined.

The mean inaccuracy of chlorophyll determinations from the regression equation (for a mean chlorophyll concentration of 6.9 mg/M^3) varies from about 36 percent for a one-parameter equation to about 22 percent for a regression equation of three variables. It is interesting that the two most significant variables, R8 and R2, are essentially the same as for the sediment correlation (R8 and R1 for sediment), thus, it appears, as noted above, that the correlation of chlorophyll with multispectral response is related to the particle response.

CONCLUDING REMARKS

Multispectral scanner digital data have been analyzed to develop a regression equation for determining suspended sediment concentrations. A linear equation using one band, Band 8 (0.70-0.74μ), appears to be adequate for in-scene analysis for this particular data set although addition of other bands marginally improves the correlation coefficient and in most cases mean inaccuracy is less. Mean error associated with application of the regression equation to determining suspended sediment concentration contours is 23.5 percent for sediment concentrations up to about 50 mg/ℓ. Variations of equal or greater magnitude might be expected from measurement and spatial inaccuracies due to ground truth measurement and/or spectral inaccuracies due to particle composition and size distributions.

Analysis of additional water quality parameters - chlorophyll a, secchi disc depth, and particle size distributions - indicates the multispectral scanner data are "suspended sediment dominated," thus it is difficult to analyze for other materials. A high correlation was obtained between chlorophyll a and multispectral scanner data; this appears to be due to particles that contain chlorophyll, rather than chlorophyll per se and the specific relationship is probably limited to this set of data.

Additional remotely sensed data in conjunction with ground truth from a number of environmentally different areas will be required to further define the accuracy of and conditions under which regression equations for quantitative analysis of digital multispectral data may be applied.

REFERENCES

1. Williamson, A. N., and W. E. Grabau. Sediment Concentration Mapping in Tidal Estuaries. Third Earth Resources Technology Satellite-1 Symposium, Washington, D.C., December 10-14, 1973.

2. Klemas, V., M. Otley, W. Philpot, C. Wethe, and R. Rogers. Correlation of Coastal Water Turbidity and Circulation with ERTS-1 and Skylab Imagery. Presented at the Ninth International Symposium on Remote Sensing of Environment, Univ. of Michigan, Ann Arbor, Michigan, April 15-19, 1974.

3. Johnson, Robert W. Quantitative Sediment Mapping from Remotely Sensed Multispectral data. Presented at the Fourth Annual Remote Sensing of Earth Resources Conference, March 24-26, 1975, Tullahoma, Tennessee.

4. McCauley, James, and Harold Yarger. Kansas Water Quality Using ERTS-1. Presented at the Fourth Annual Remote Sensing of Earth Resources Conference, March 24-26, 1975, Tullahoma, Tennessee.

5. Snedecor, George W., and William G. Cochran. Statistical Methods. Sixth Edition, The Iowa State University Press, Ames, Iowa, 1967.

6. Bowker, David E., and William Witte. Evaluation of ERTS MSS Digital Data for Monitoring Water in the Lower Chesapeake Bay Area. Presented at the Fourth Annual Remote Sensing of Earth Resources Conference, March 24-26, 1975, Tullahoma, Tennessee.

Table I. Multispectral Scanner (M2S) Bandwidths and Frequencies, and Spatial Coverage at 8000-Foot (2.4 km) Altitude.

MAY 28, 1974

	SPECTRAL	
RANGE	380 - 1060 nm + THERMAL	
BANDS	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

Table II. Linear Correlation Matrix of Suspended Sediment (mg/ℓ) and Multispectral Scanner Response (mw/cm^2-ster).

	SEDIMENT	M2S BANDS									
		1	2	3	4	5	6	7	8	9	10
SEDIMENT	1.000	0.464	0.546	0.503	0.788	0.860	0.878	0.849	0.888	0.857	0.639
1		1.000	.889	.855	.786	.691	.659	.664	.632	.630	.558
2			1.000	.961	.906	.822	.782	.811	.707	.712	.654
3				1.000	.877	.778	.728	.779	.654	.679	.600
4					1.000	.975	.959	.966	.908	.876	.704
5						1.000	.987	.989	.954	.924	.747
6							1.000	.988	.968	.926	.737
7								1.000	.956	.933	.753
8									1.000	.946	.720
9										1.000	.840
10											1.000

Table III. Linear Correlation Matrix of In Situ Water Quality Parameters on May 28, 1974, in James River, Virginia.

	SEDIMENT	CHLOR a	SECCHI DISC	PARTICLES 0-0.5μ	PARTICLES 0.5-1μ	PARTICLES 1-2μ	PARTICLES 2-4μ	PARTICLES 4-8μ	PARTICLES 8-16μ	PARTICLES TOTAL
SUSPENDED SEDIMENT	1.000	0.824	-0.879	-0.306	-0.407	0.635	0.461	0.413	0.138	0.543
CHLOR a		1.000	-.810	-.285	-.355	.668	.516	.447	.033	.565
SECCHI DISC			1.000	.315	.435	-.747	-.502	-.426	-.071	-.589
PARTICLES 0-0.5μ				1.000	.542	-.067	-.109	-.091	-.094	-.105
PARTICLES 0.5-1μ					1.000	-.130	-.031	-.054	-.103	-.077
PARTICLES 1-2μ						1.000	.854	.722	.023	.896
PARTICLES 2-4μ							1.000	.929	.051	.961
PARTICLES 4-8μ								1.000	.042	.889
PARTICLES 8-16μ									1.000	.271
TOTAL PARTICLES										1.000

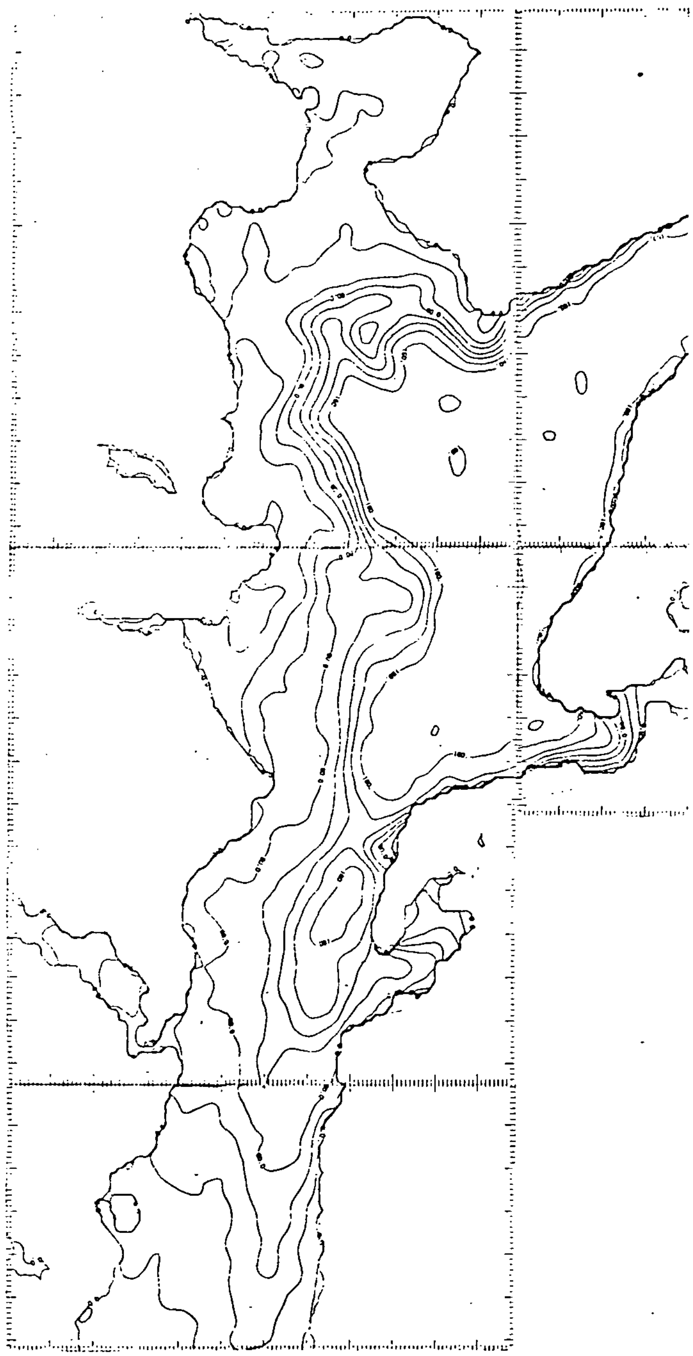
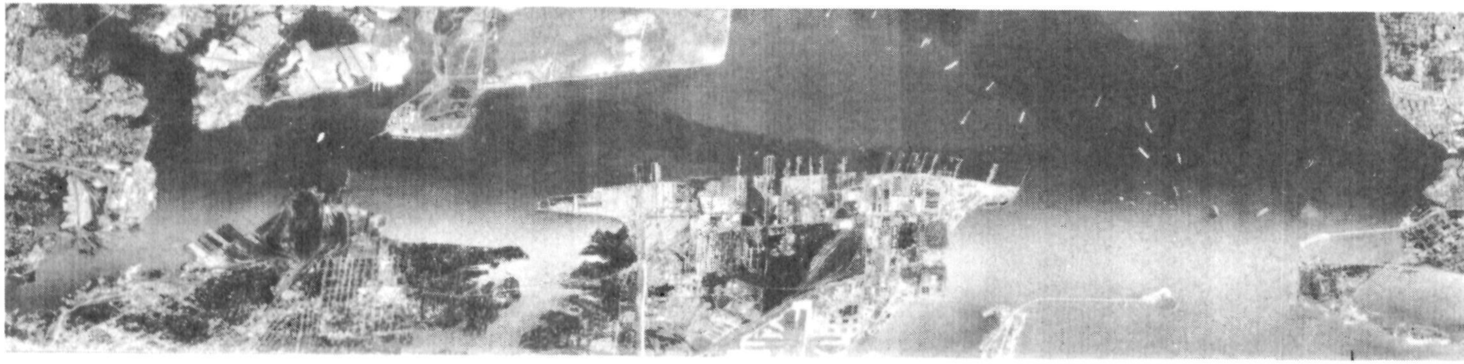
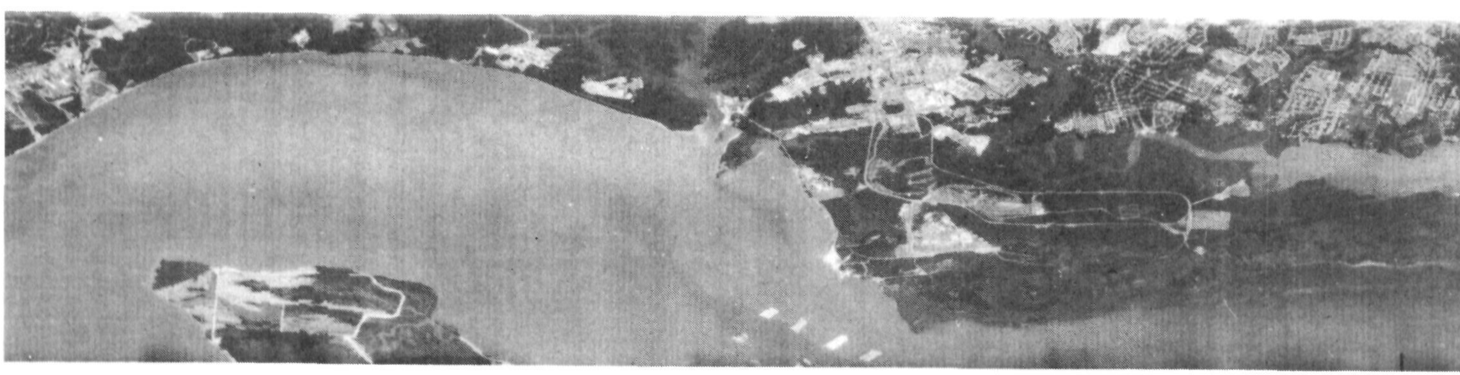


Figure 1. Suspended sediment weight contours for Potomac River, October 11, 1972. (Taken from ref. 3.)



Test site 1, Norfolk.

Test site 2, Hopewell.



Test site 3, Hog Island.

Figure 2. Multispectral scanner (Bendix M2S) imagery of test sites on May 28, 1974. Band 5 (0.58 - 0.62μ) shown.

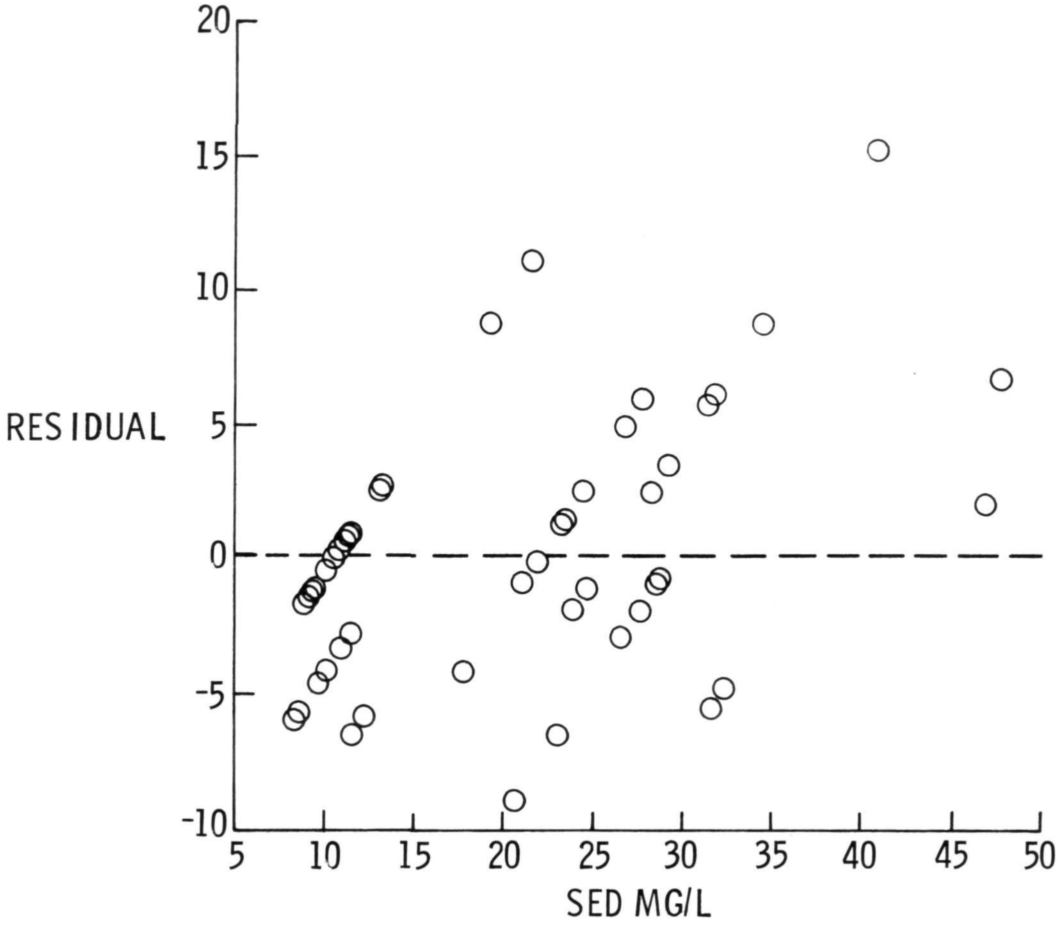


Figure 3. Regression equation residuals (deviations from fitted regression line) as a function of sediment concentration.

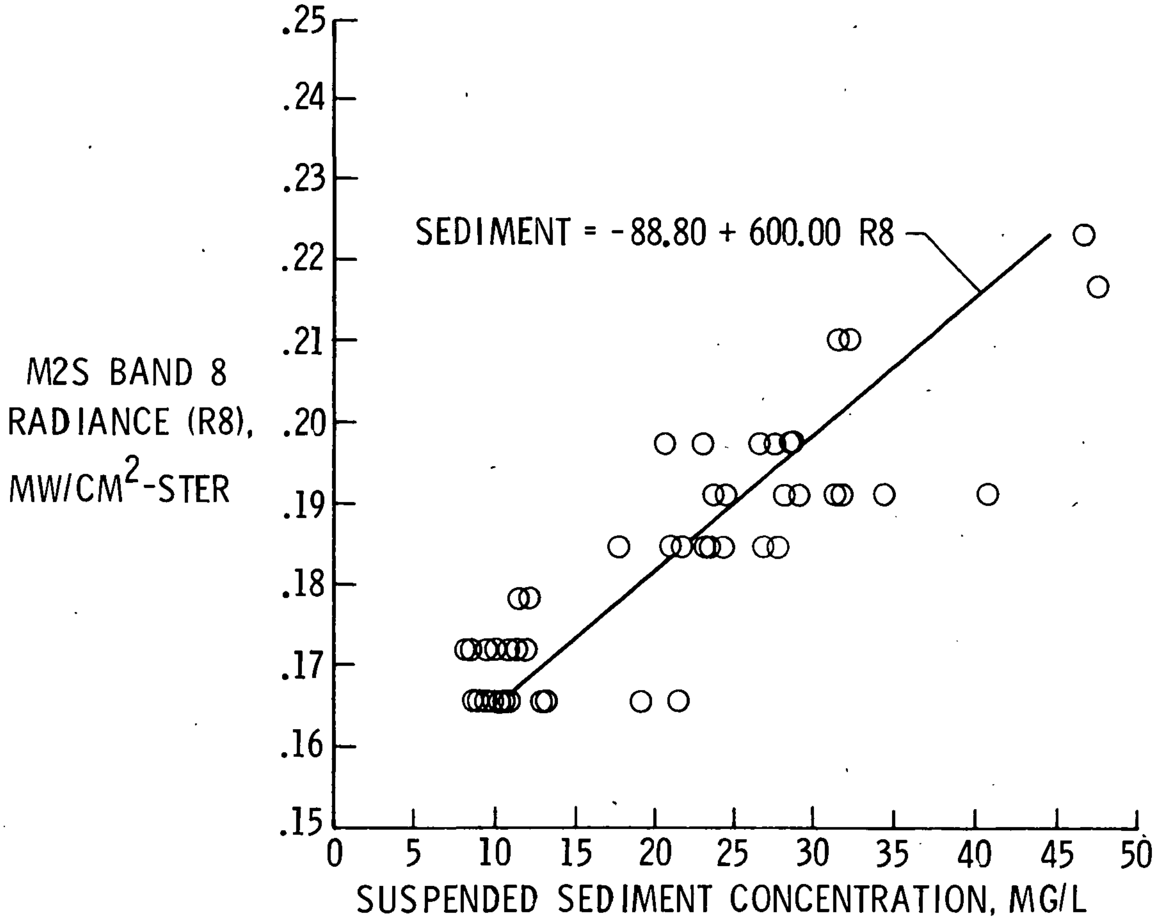


Figure 4. Suspended sediment concentrations, M2S Band 8 radiances and fitted single band regression line.

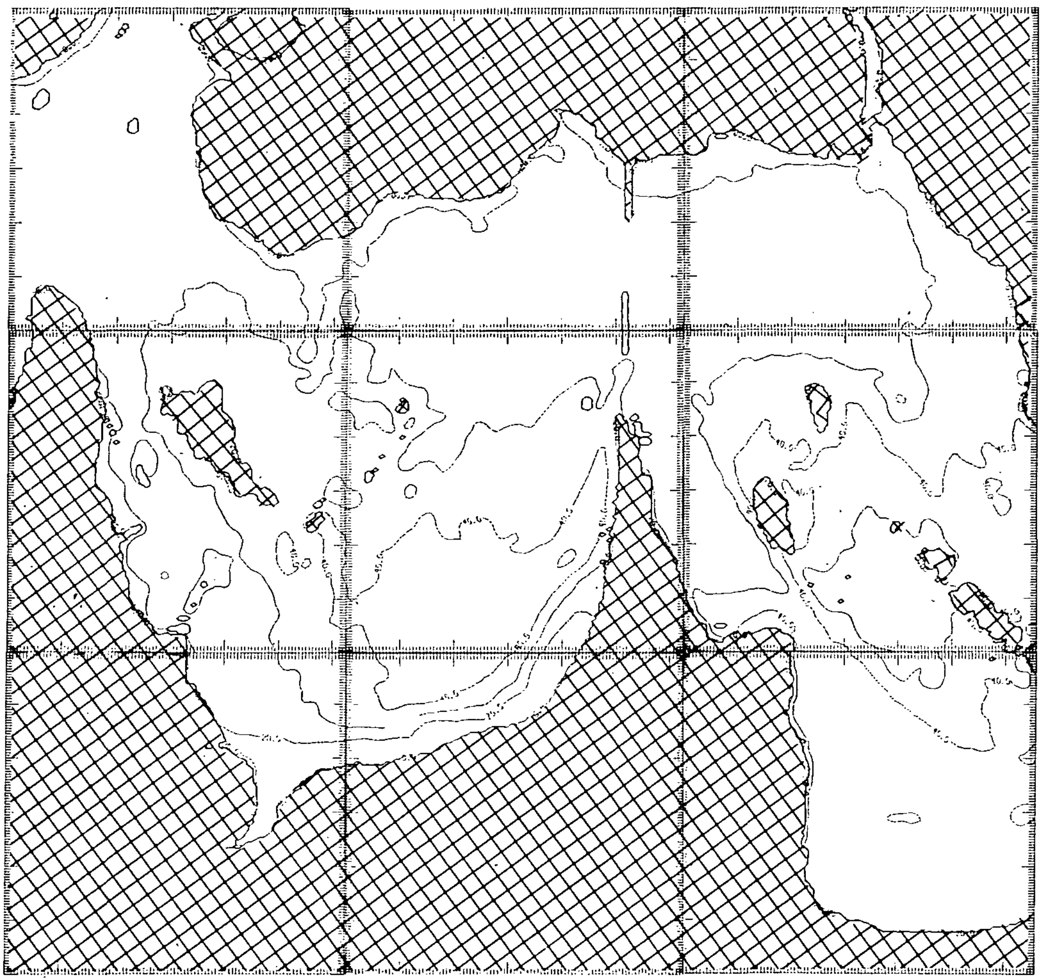


Figure 5. Quantitative suspended sediment contours in the upper James River near Hopewell, May 28, 1974.