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Use of Ocean Color Scanner Data in Water Quality Mapping

Suspended solids, chlorphyll, and turbidity could be detected in the San Francisco Bay Delta from OCS data but not from color or color-infrared photography.

ABSTRACT: *The objective of this investigation was to use remotely sensed data, combined with* in situ *data, for the assessment of water quality parameters within the San Francisco Bay-Delta. The water quality parameters of interest included suspended solids, chlorophyll, and turbidity. The remotely sensed data included Ocean Color Scanner (OCS) data and U-2 color and color-infrared photography.*

The approach consisted of simultaneous acquisition of (1) remotely sensed data as acquired from a NASA U-2 aircraft and (2) water quality samples as acquired from boats. Regression models were developed between each of the water quality parameter measurements and the OCS data. These regression models were then extended to the entire study area for mapping the water quality parameters.

The results included a series of color-coded maps, each pertaining to one of the water quality parameters, and the statistical analysis of the OCS data and regression models. Based on these results and the associated analyses of the imagery, the following conclusions were indicated: (1) concurrently collected OCS data and surface truth measurements proved highly useful in mapping the selected water quality parameters and locating areas having relatively high biological activity; and (2) it was virtually impossible, at least within this test site, to locate such areas on U-2 color and color-infrared photography.

INTRODUCTION

WATER DEMAND in the State of California is constantly increasing with the increase in population, improvement in the standard of living, and the expansion of industry. The San Francisco Bay and the associated delta that is formed by the confluence of the Sacramento and San Joaquin Rivers is one of California's most important aquatic resources. There are many conflicting proposals on how it might best be used, and because of this area's wealth of industrial, recreational and aesthetic resources, there are also conflicting opinions on the extent to which any given use might affect water quality throughout the area. Within this study area there is a "region of high biological activity" because physical forces cause an upwelling of the heavier salt water, which in turn stimulates a downwelling of fresh water and a consequent circulation of water currents and their associated nutrients.

Several government agencies, including the U.S. Fish and Wildlife Service, U.S. Geological Survey, U.S. Water and Power Resource Service, California Department of Fish and Game, California State Water Resources Control Board, and California Department of Water Resources, are attempting to gather extensive and detailed water quality data in order to monitor effectively the San Francisco Bay estuary. Remote sensing techniques are considered by these agencies as having the potential to provide a cost-effective method for gathering and processing water quality-related

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data. Such a system would benefit Federal, state, and local government agencies. However, there is a need for research to demonstrate the usefulness and applicability of remote sensing to water quality monitoring. Such a demonstration has not yet been made in California, according to State officials.

Water quality data collected by means of surface monitoring programs demonstrated that concentrations of phytoplankton, chlorophyll, particulate organic nitrogen and phosphate, turbidity, and inorganic suspended solids were significantly higher in the region of high biological activity than in adjacent upstream or downstream areas (Arthur, 1975; Ball, 1975; Peterson *et al.*, 1975). To some scientists this region has also become known as the "entrapment zone" (Arthur and Ball, 1979; Ball and Arthur, 1979; Orsi and Knutson, 1979; Siegfried *et al.*, 1979). The location of this region may thus have important effects upon the Delta fisheries, whose contribution to the economy of the area is officially estimated to exceed ten million dollars annually (Siegfried *et al.*, 1978). This "region of high biological activity" can be characterized by comparison of suspended solids, chlorophyll, turbidity, and conductivity determinations along the longitudinal axis of the estuary (Arthur, 1975, 1977).

Many investigators have used remote sensing techniques for water quality mapping. Landsat and Skylab multispectral scanner imagery and conventional aerial photographs have been used for detecting water pollution plumes and mapping sediment distribution patterns (Strandberg, 1966; Welch, 1971; Klooster and Scherz, 1973; Scarpace *et al.*, 1974; Sherz *et al.*, 1975; Klemas *et al.*, 1976; Lo, 1976). A number of studies have shown correlations between remotely-sensed multispectral scanner data and such water quality parameters as suspended solids, Secchi disk extinction depth, and Jackson turbidity Units for inland waters and estuarine systems (Yarger *et al.*, 1973; Williamson and Garbeau, 1973; Bressette, 1974; Kritikos *et al.*, 1974; Klemas *et al.*, 1974; Brooks, 1975; Bowker *et al.*, 1975; Lillesand *et al.*, 1975; Rogers *et al.*, 1975; Johnson, 1975; Johnson and Bahn, 1977; Johnson *et al.*, 1977; Johnson and Harris, 1980). Multispectral scanner data collected by aircraft and Landsat satellites have been used by many investigators for mapping chlorophyll content of water for various aqueous environments (Clarke *et al.*, 1970; Duntley, 1971; Arveson *et al.*, 1971; Wezernak, 1974; Kattawar and Humphreys, 1976; Hovis and Leung, 1977; Johnson and Bahn, 1977; Vanselous *et al.*, 1978; Viollier *et al.*, 1978; Johnson, 1978; Johnson and Harris, 1980). This paper demonstrates, for this geographical area, the use of remote sensing for mapping the selected water quality parameters and locating the "area of high biological activity."

The objective of this investigation was to use remotely sensed data, combined with *in situ* data, for the assessment of water quality parameters and location of the region of high biological activity within the San Francisco Bay Delta. The water quality parameters included suspended solids, chlorophyll, and turbidity.

MATERIALS AND METHODS

The approach involved simultaneous (from 9:00 A.M. to 10:30 A.M. local times, corresponding to high tide in low flow season) acquisition of (1) the Ocean Color Scanner (OCS) data and color and color-infrared photography flown on a NASA U-2 aircraft and (2) water quality samples from boats. Regression models were then developed between data for each of the water quality parameters and the OCS data. These regression models were then extended to the entire study area for mapping the water quality parameters of interest. The methodology is divided into the following four sections:

COLLECTION AND LABORATORY ANALYSIS OF WATER QUALITY SAMPLES

On 14 September 1978, 29 samples of the three selected water quality parameters were collected at pre-determined sites in the San Francisco Bay-Delta Region. The parameters measured at all sites were turbidity and suspended solids. Chlorophyll concentration was measured at nine of the sites. The sample sites as shown in Figure 1 were distributed throughout the Delta. Because of the technical problems, the chlorophyll data were collected at the first nine sites (sample sites 1 through 9 in Figure 1) as the sample boats progressed from San Pablo Bay toward the Delta region.

Suspended solids water samples were collected by pumping from approximately 0.3 m below the water surface through a weighted hose. Samples were frozen in the field and taken to the laboratory for analysis. In the laboratory, suspended matters were collected by vacuum filtration on preweighed 0.45 μm filters, dried at 105°C (221°F), and reweighed on an analytical balance. Suspended matters included inorganic detritus, organic detritus, and plankton. Chlorophyll samples were collected by vacuum filtration on glass fiber filters, pre-treated with a $Mg\ CO_3$ suspension, and analyzed by the fluorometric method. Turbidity was determined *in situ* by a Hellige Turbidmeter, which compared the light scattering of surface samples to a silicon dioxide standard.

ACQUISITION AND ANALYSIS OF THE OCEAN COLOR SCANNER (OCS) DATA

The ocean color scanner is a ten-channel line scanning radiometer having a 90° total field-of-

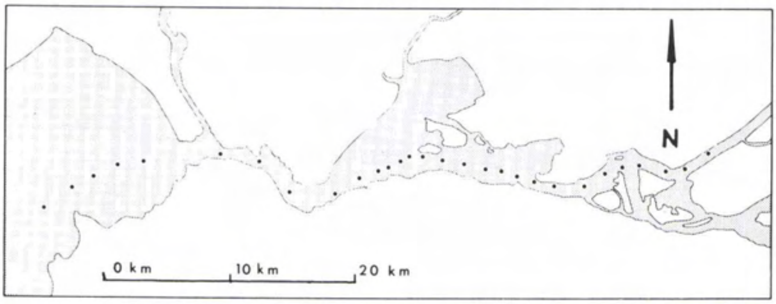

FIG. 1. Location of water quality sample sites on a map based on the mosaic of the study area taken by NASA's U-2 aircraft. The sites were numbered 1 to 29 from left to right. San Pablo Bay is on left.

view and a 3.5 milliradian spatial resolution. This scanner collected that data at 70 m by 70 m (227.5 ft by 227.5 ft) resolution when flown on a NASA U-2 aircraft at an altitude of 19812 m (65,000 ft) over the study area on 14 September 1978. The calibrated computer compatible tapes of the OCS data were obtained from NASA Goddard Space Flight Center (GSFC). The following procedure was used in processing and analyzing the OCS data:

Data Reformatting. An algorithm was developed and applied for reformatting the OCS digital data from the GSFC format to the format of the Remote Sensing Research Program (RSRP), University of California at Berkeley, data processing system.

Bad Data Rectification. The OCS data contained a large number of bad data lines (referred to in this paper as "dropouts"). These dropouts resulted from the malfunctioning of the digitizer on the scanner at the time of data acquisition.

Two procedures were used for replacing the bad lines:

- Procedure One was used to replace data line dropouts not exceeding three consecutive lines. This procedure was based on a linear interpolation of the data from the reliable data of a line above and below the dropout region. In this procedure, the dropout lines were simply replaced, pixel by pixel, with the linearly interpolated values between the lines immediately above and below the dropouts.
- Procedure Two was used to eliminate dropout regions exceeding three consecutive lines. This situation occurred on the average of once per hundred scan lines in each band (approximately 5 percent of the data). Procedure Two utilized internally developed software to create data lines in the dropout regions. This replacement was accomplished as follows: For each band to be corrected (i.e., dropout regions replaced) called "Band A," an available band with a different dropout pattern (i.e., "Band B") was selected which was the most highly correlated with "Band A." The minimum correlation coefficient between bands A and B was R = 0.98. For each set of dropout regions in "Band A," the nearest scan lines above and below the dropout area which had reliable data in both "Band A" and "Band B" were located. On the basis of these two lines, a table containing the transformations from "Band B" to "Band A" was generated and used for filling the dropout region with the transforms of the corresponding lines in "Band B." None of the 29 sample sites corresponded to areas of large dropouts on the spectral channels.

OCS Channel Selection. The OCS data consisted of six usable channels. Channels 1, 2, 8, and 9 were not used. Because of the atmospheric turbidity, Channels 1 and 2 contained inappropriate data for water quality studies; Channel 8 was not acquired over the study area; and Channel 9 was designed to be most sensitive to terrestrial areas. A correlation matrix was examined to determine the dependency of the six available channels on each other. Based on this correlation matrix, there were very strong correlations between Channels 4 and 5 (R = 0.938) and Channels 6 and 7 (R = 0.965). Therefore, Channels 4 and 6 were eliminated and only four channels were chosen for analysis. These channels were 3, 5, 7, and 10. The peak wavelengths and wavelength ranges (based on Blaine *et al.*, 1977) for these channels are shown in Table 1.

Sample Site Location. The 29 water quality sampling sites were located in the OCS data coordinate system by applying a coordinate transformation equation between the Universal Transverse Mercator (UTM) coordinate system and the OCS scanner coordinate system. The transformation was based on a second-order linear regression equation between UTM coordinates for a

TABLE 1. PEAK WAVELENGTHS AND SPECTRAL RANGES FOR THE FOUR OCS CHANNELS ANALYZED

Channels	Peak λ, μm	Range λ, μm
3	0.506	0.494–0.518
5	0.586	0.574–0.598
7	0.667	0.655–0.679
10	0.778	0.766–0.790

number of ground points obtained from USGS maps and the corresponding scanner coordinates in the OCS system extracted from the OCS data. The regression equation then employed the UTM coordinates of the 29 sample sites (which were extracted from the USGS quadrangles) to calculate the coordinates for 29 sample sites in OCS coordinate system. In this way, OCS spectral data corresponding to the sample sites could be extracted from the disk file, and then related to the water quality parameters measured by the sample boats.

Spectral Data Extraction at Each Sample Site. To insure the correct correspondence (or registration) of the spectral data to the sample sites, the radiance values for a nine-pixels square surrounding each predicted sample site were extracted from OCS Channels 3, 5, 7, and 10.

Cell Mean Radiance Value Calculation. The average (mean) radiance value of the nine-pixel cell encompassing each sample site was computed. These average cell values were used as independent variables in the regression models described below.

DEVELOPMENT OF REGRESSION MODELS FOR ESTIMATING WATER QUALITY PARAMETERS FROM OCS DATA

A number of statistical models were examined for determining the best relationships between each water quality parameter and the mean radiance values computed from Channels 3, 5, 7, and 10, as well as their ratios and combinations. Based on the evaluation of (1) the significance levels of "F" values corresponding to each OCS channel in the regression equations; (2) significance levels of overall "F" values; (3) simple correlation coefficients; and (4) multiple correlation coefficients, the best fit for each one of the water quality parameters was determined. These models are presented and discussed under the Results section.

APPLICATIONS OF THE REGRESSION MODELS TO THE STUDY AREA

The regression models, developed between the water quality parameters and the mean radiance values of the OCS data for 29 sample sites, were extended to the entire study area for mapping the water quality parameters. The extension of these models to the study area was accomplished by using a simple linear discriminant function. By applying this function to each pixel in the study area and then grouping these continuous water quality variables into discrete classes, the classification was accomplished. A unique function for each water quality parameter was applied to the OCS data, producing three unique class maps. The results of these classifications are displayed as water quality maps under the Results section.

RESULTS

Based on the procedure discussed under "Bad Data Rectification," the bad data lines (dropouts) were replaced with new data. As an example, the data in Channel 10 before and after rectification of the dropouts are shown in Figures 2 and 3, respectively. The mean radiance values of four selected OCS channels for sample sites are shown in Table 2.

The results of the laboratory analysis for the 29 water quality sample sites are shown in Table 3.

Based on the results of the statistical analysis, the following models were selected to represent the relationship between the water quality measurements obtained from the sample sites and the mean radiance values of the OCS data corresponding to those sites.

Chlorophyll Model

$$y_{CH} = a + b/X_7 + cX_{10} + dX_{10}^2$$

where

y_{CH} = chlorophyll concentration expressed in mg/l,
X_7 = the mean radiance value in Channel 7,
X_{10} = the mean radiance value in Channel 10, and
$a = -0.2919$, $b = 0.8065$, $c = 0.0951$, and $d = -0.0093$.

Suspended Solids Model

$$y_{SS} = a + b/X_3 + c/X_7 + dX_3$$

where

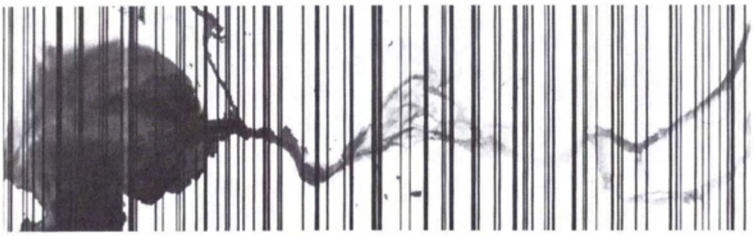

FIG. 2. Display of digital OCS data in Channel 10 prior to rectification of the dropout regions.

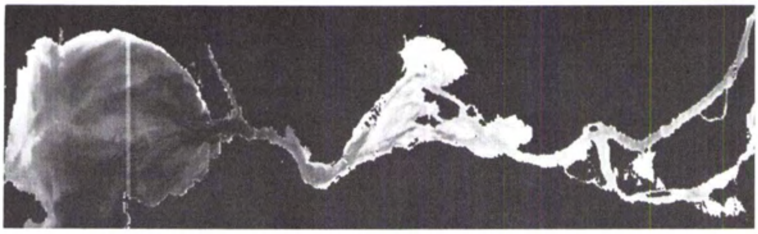

FIG. 3. Display of digital OCS data in Channel 10 after rectification of the dropout regions and masking.

y_{SS} = suspended solids, expressed in mg/l,
X_3 = the mean radiance value in Channel 3,
X_7 = the mean radiance value in Channel 7, and
$a = 564.1$, $b = 609.0$, $c = -1694$, and $d = -32.62$.

Turbidity Model

$$y_T = a + bX_3 + c/X_3 + dX_{10} + e/X_{10}$$

where

y_T = turbidity, expressed in mg/l SiO_2,
X_3 = the mean radiance value in Channel 3,
X_{10} = the mean radiance value in Channel 10, and
$a = 1357$, $b = -59.33$, $c = -7008$, $d = 3.417$, and $e = -163.9$.

The correlation coefficients, (R), (measures of the closeness with which the regression models fit the water quality measurements) and the overall "F" values are shown in Table 3. The multiple correlation coefficients were observed to be high for chlorophyll and medium for turbidity and suspended solids. All of the "F" values corresponding to the individual OCS channels in the regression equations and the overall "F" values were significant at the 0.01 level of significance. The

TABLE 2. MEAN RADIANCE VALUES OF FOUR SELECTED OCEAN COLOR SCANNER CHANNELS IN mw/cm²-st-μm FOR SAMPLE SITES

Sample Site #	OCS Ch. 3	OCS Ch. 5	OCS Ch. 7	OCS Ch. 10
1	11.27	8.58	7.47	2.60
2	11.39	8.80	8.08	2.83
3	11.45	8.32	8.89	3.18
4	11.68	9.20	9.08	3.29
5	11.65	9.27	8.85	3.08
6	11.12	8.47	7.10	2.83
7	11.75	9.41	8.77	3.86
8	11.39	9.27	8.78	3.92
9	10.35	9.54	7.91	4.91
10	11.35	9.46	9.21	4.87
11	11.28	9.36	9.04	4.82
12	11.23	9.34	9.03	4.77
13	11.35	9.44	9.01	4.88
14	11.36	9.49	9.00	4.81
15	11.41	9.40	9.11	4.56
16	11.93	9.89	9.88	4.98
17	12.31	10.28	10.80	5.54
18	12.60	10.63	11.10	5.22
19	12.71	10.65	11.28	5.35
20	12.82	10.92	11.47	5.44
21	12.87	10.82	11.62	6.43
22	12.92	10.91	11.67	6.84
23	13.44	11.41	11.77	6.12
24	13.11	11.00	11.60	5.59
25	13.02	10.95	11.59	5.40
26	12.90	10.55	11.56	6.80
27	12.91	10.70	10.79	4.92
28	12.84	10.52	10.47	4.79
29	12.99	10.57	10.41	5.20

TABLE 3. THE RESULTS OF LABORATORY ANALYSIS FOR WATER QUALITY SAMPLES COLLECTED ON 14 SEPTEMBER 1978

Sample Site #	Suspended Solids (mg/l)	Turbidity, (mg/l SiO_2)	Chlorophyll, (mg/l)
1	29.8	13.0	0.0038
2	37.4	23.0	0.0044
3	39.4	20.0	0.0040
4	36.2	18.0	0.0051
5	44.4	14.0	0.0062
6	28.9	21.0	0.0138
7	47.1	43.0	0.0201
8	—	44.0	0.0451
9	65.4	41.0	0.0520
10	69.8	58.0	
11	67.9	41.0	
12	73.0	53.0	
13	64.9	50.0	
14	69.3	50.0	
15	75.6	47.0	
16	74.5	50.0	
17	43.1	41.0	
18	69.2	47.0	
19	56.4	41.0	
20	53.5	37.0	
21	24.5	41.0	
22	80.0	53.0	
23	46.2	52.0	
24	46.0	45.0	
25	45.0	37.0	
26	21.8	31.0	
27	29.9	23.0	
28	19.7	18.0	
29	8.1	16.0	

correlation coefficients among the water quality parameters indicate high correlation between suspended solids and turbidity and low correlation between chlorophyll and turbidity or suspended solids. These correlation coefficients are shown in Table 4. The specific reason for low correlation between chlorophyll and other water quality parameters may be partly due to the insufficient sample size in chlorophyll measurements (surface-truth) and partly due to the diverse environmental conditions. All of the results may have been affected by the fact that OCS data were obtained through two complex turbid media, atmosphere and water, each with different properties. The factors affecting the spectral response of a diverse estuarine environment such as ours include intensity and spectral distribution of direct and diffused solar radiation, atmospheric turbidity, surface reflection, volume reflection, sensing device, bottom reflection in shallow waters, and the error associated with partial malfunctioning of image acquisition devices (where applied) and the techniques used for image analysis. Other investigators have also experienced this type of problem associated with mapping water quality from spectral data (Thoreson *et al.*, 1975; Lillesand *et al.*, 1975; Ritchie *et al.*, 1976; Bartolucci *et al.*, 1977; Johnson, 1978; Moore, 1978).

To prepare the maps of estimated water quality parameters, the relationships established between the water quality measurements and the OCS data by means of the regression models were extended to the entire study area using a simple linear discriminant function. This function was applied to the OCS data, resulting in a map which was color-coded to represent the three water quality parameters. The color-coded maps were converted to black-and-white illustrations by the Cartographic Section of the School of Geoscience of Louisiana State University at Baton Rouge. The maps for chlorophyll, suspended solids, and turbidity are shown in Figures 4a, 4b, and 4c, respectively. The distributions of water quality parameters are in agreement with the reported values in the literature for this time of year in this geographic area (Canomos and Peterson, 1974; Arthur and Ball, 1979; Ball and Arthur, 1979; Orsi and Knutson, 1979; Khorram, 1979; Siegfried *et al.*, 1979).

The analysis of the chlorophyll, suspended solids, and turbidity maps indicates the existence of a region with high chlorphyll content, high suspended solids, and high turbidity. This region is referred to as a "region of high biological activity" in this paper. Through the use of conventional ground survey techniques, the location of a "region of high biological activity" or "entrapment zone" in the main estuary of our study area and its adjacent environment has also been reported by other investigators (Conomos and Peterson, 1974; Peterson *et al.*, 1975; Arthur, 1975; Ball, 1977; Arthur and Ball, 1978; Ball and Arthur, 1979; and Siegfried *et al.*, 1979). The water quality maps of the same area, based on Landsat Multispectral Scanner data, also indicated a region of high biological activity (Khorram, 1979).

Consistent with our findings, the region of high turbidity and high suspended solids appears to be a common feature of moderately stratified estuaries. A region of maximum turbidity was measured as early as 1893 in the Gironde—Garonde Estuary of France (Glandeaud, 1939). Recently, several investigators through the use of conventional ground survey techniques have reported a region of maximum turbidity in many estuaries of northern Europe, British Guiana, and the United States (Postma, 1967; Schubel, 1968; Meade, 1968; Meade, 1972; Arthur, 1975; Arthur, 1977). Other investigators have noted a region of greatest suspended sediment accumulation in Thames Estuary (Inglis and Allen, 1957). Peterson *et al.* (1975) have suggested that the water column in the non-tidal current null zone in northern San Francisco Bay experiences the longest advective replacement time relative to other portions of the estuary, which may affect the planktonic community.

As it was discussed earlier, remote sensing data derived from multispectral scanners has been successfully used for the purpose of water quality mapping by many investigators. It is believed, however, that this study constitutes the first instance in which there has been an effort to use

TABLE 4. RESULTS OF REGRESSION MODELS BASED ON OCS DATA AND CORRELATION COEFFICIENTS FOR THE THREE WATER QUALITY PARAMETERS

Water Quality Parameter	OCS Data		Corr. Coeffs. for Surface Truth Data		
	Corr. Coeff.	F*	Chloro.	Susp. Solids	Turbidity
Chlorophyll	0.934	11.4	—	−0.236	0.144
Suspended Solids	0.609	4.9	—	—	0.752
Turbidity	0.791	10.0	—	—	—

* All of the "F" values are significant at the 0.01 level of significance.

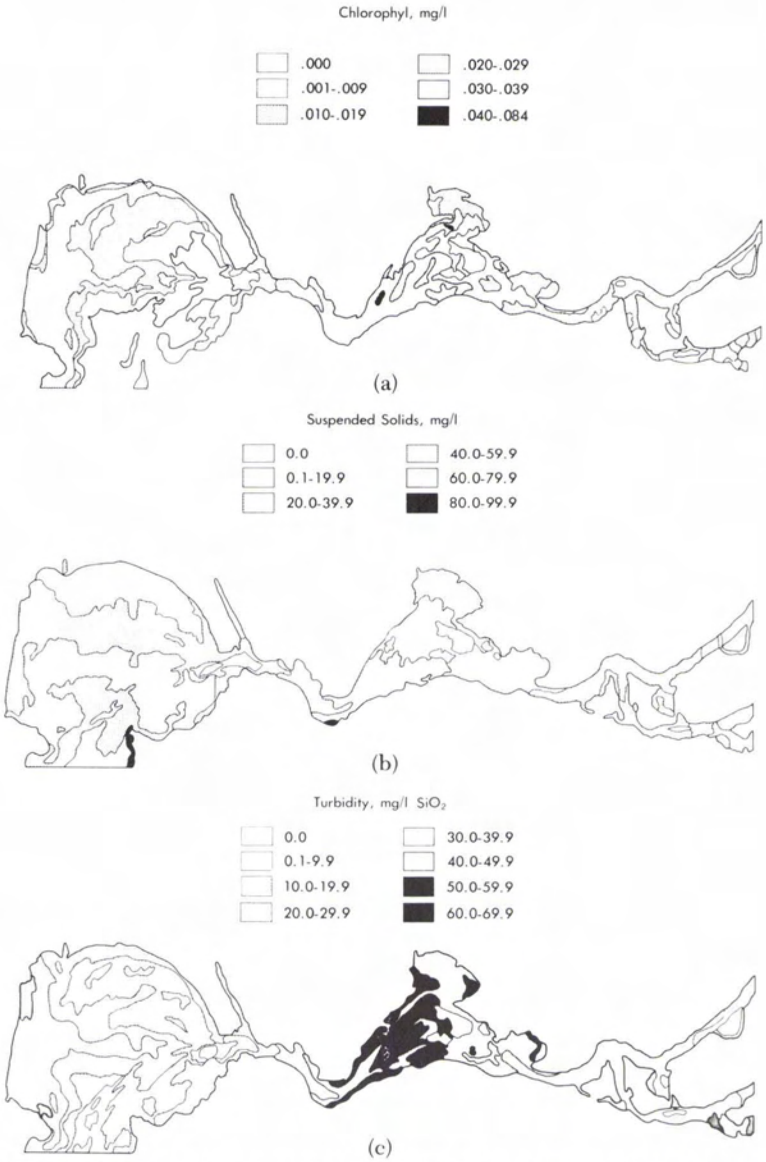

FIG. 4. Chlorophyll (a), suspended solids (b), and turbidity (c) distribution as derived from OCS data for the study area. San Pablo Bay is on the left.

remote sensing to locate the region of high biological activity and map the associated water quality parameters in the San Francisco Bay Delta.

CONCLUSIONS

Based on the results and the associated analyses that were made of the various kinds of imagery, the following conclusions were indicated:

(1) Areas having relatively high chlorophyll concentration were clearly discernible on suitably enhanced imagery made from OCS data. This area was also characterized by high turbidity and high suspended solids concentration.

(2) It was difficult, in this test site, to locate such areas on aerial photography of the highest quality that has been taken with either conventional color or infrared-sensitive color films.

(3) A number of investigators from different parts of the world, consistent with our findings, through the use of conventional ground survey techniques, have reported the region of high tur-

bidity and high suspended solids to be a common feature of moderately stratified estuaries.

(4) Remote sensing data derived from multispectral scanners has been successfully used for the purpose of water quality mapping by many investigators.

(5) It is believed, however, that the present study constitutes the first concerted effort to use remote sensing to locate the region of high biological activity in the San Francisco Bay Delta and map such associated parameters as turbidity, suspended solids, and chlorophyll concentration.

(6) Concurrently collected Ocean Color Scanner data and surface truth measurements in this study proved highly useful in mapping water quality parameters associated with the "region of high biological activity" in the San Francisco Bay and its associated Delta.

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