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Development of Water Quality Models Applicable throughout the Entire San Francisco Bay and Delta

Landsat MSS-aided single models may be developed to be applicable to the entire San Francisco Bay and Delta for mapping salinity, turbidity, total suspended solids, and chlorophyll *a* concentrations.

Abstract: *The objective of this study was to explore whether Landsat-based models could be developed to map each of four water quality parameters in the entire San Francisco Bay and Delta for a given date during low runoff period.*

Landsat Multispectral Scanner (MSS) data were combined with in situ *data for developing such models. The water quality parameters of interest included salinity, turbidity, suspended solids, and chlorophyll* a *concentrations. Water quality samples were collected simultaneously with the Landsat overpass. Regression models were developed between each of the water quality parameter measurements and Landsat digital data for 50 sample sites. The performances of these models were evaluated based on the application of selected models to 23 remaining sites and comparison of observed and simulated values for these sites. These regression models were then extended to the entire study area for mapping the water quality parameters of interest. The results included a series of color-coded maps, each pertaining to one of the water quality parameters, statistical summaries, and accuracy assessment tables.*

Introduction

Because of temporal and spatial heterogeneity, mapping and effective monitoring of water quality in estuarine environments are very difficult. Many investigators have been limited by the inability to view the entire or even a large portion of San Francisco Bay and Delta estuary at one time. Relying upon a series of sampling stations distributed throughout the estuary, investigators have had to interpolate parameter values between stations, and have been forced to extrapolate in the large shallow bays where research boats cannot penetrate. The patchiness evidenced by the use of a continuous flow fluorometer illustrates the inaccuracy of such interpolation and extrapolation. Repetitive remotely-sensed data acquired from Landsat satellites may be considered as having the potential to provide the temporal and spatial data for mapping water quality in estuarine systems cost-effectively.

The usefulness of airborne multispectral data obtained from the Ocean Color Scanner (OCS) for water quality mapping in this region has already been documented (Khorram, 1981a), but the Landsat data are preferred to OCS airborne data because of repetitive coverage. The applicability of Landsat MSS data within the Delta portion of this study area has been documented (Khorram, 1981b). This paper deals with models applicable to the entire bay and delta for a given date during low runoff period.

Remotely-sensed data derived from multispectral scanners have been used for water quality mapping of inland and estuarine systems by many investigators (Clarke *et al.*, 1970; Duntley, 1971; Bressette, 1974; Johnson, 1975; Ritchie and Schiebe, 1979; Whitlock and LeCroy, 1982). Landsat data have been used to map concentrations of suspended sediments (Klemas *et al.*, 1973; Williamson and Garbeau, 1973; Kritikos *et al.*, 1974). Rogers *et al.* (1975), R. Johnson (1980), and Khorram (1981a) applied regression models based on remotely-sensed data for mapping chlorophyll and other water quality parameters in estuarine environments. The

Photogrammetric Engineering and Remote Sensing,
Vol. 51, No. 1, January 1985, pp. 53-62.
0099-1112/85/5101-0053$02.25/0

same technique has also been used for mapping turbidity and total suspended solids from Landsat digital data in estuaries (Brooks, 1975; Ritchie, 1976; Aranuvachapun and LeBlond, 1981; Khorram, 1981b). Several investigators have studied the applicability of Landsat data for determining and monitoring water quality in reservoirs, lakes, and estuarine systems (Smith *et al.*, 1977; Johnson and Harris, 1980; Lillisand *et al.*, 1983).

Surface water quality monitoring programs have demonstrated that concentrations of phytoplankton, chlorophyll, particulate organic nitrogen and phosphate, turbidity, and inorganic suspended solids are significantly higher in a region of high biological activity, also known as the "Entrapment Zone," within the Delta portion of the study area than in adjacent upstream or downstream areas (Arthur, 1975; Ball, 1975; Siegfried *et al.*, 1979). The entrapment zone can then be characterized by comparison of suspended solids, chlorophyll, and turbidity along with longitudinal axis of the estuary (Arthur, 1975). Applicability of Landsat data to map the parameters for locating the entrapment zone is discussed in this paper.

Objective

The objective of this study was to investigate the usefulness of Landsat Multispectral Scanner (MSS) digital data for (1) developing a series of models for mapping selected water quality parameters throughout the entire San Francisco Bay and Delta for a given date during low runoff period; and (2) locating the entrapment zone. The water quality parameters of interest included salinity, turbidity, suspended solids, and chlorophyll *a* concentrations. The selected date was 27 October 1980.

General Approach

The general approach involved (1) acquisition of water quality samples from predetermined sample sites simultaneously with the Landsat overpass; (2) laboratory analyses of water quality samples; (3) development of regression estimators for predicting water quality parameters from Landsat digital data; (4) application of regression-based functions for mapping the spatial distribution of water quality parameters within the entire study area; and (5) assessment of modeling accuracy.

Collection and Laboratory Analyses of Water Quality Samples

A total of 73 samples were collected from 11 boats from 9:30 to 10:30 A.M. local time on 27 October 1980. The locations of these sample sites are shown in Figures 1 and 2. Landsat overpass time was 10:05 A.M. local time.

Salinity was determined first by measuring electrical conductance with a conductivity bridge and then coverting the specific conductivity values to salinity in parts per thousand. Turbidity was measured with a Hatch Turbidometer in Nephelometric Turbidity Units. Suspended solids were collected by vacuum filtration on preweighed filters, dried, and reweighed on an analytical balance. Chlorophyll *a* concentrations were extracted with 95 percent acetone and analyzed fluorometrically.

FIG. 1. Location of 50 water quality samples, collected on 27 October 1980, and used for development of water quality models. Scale is approximately 1:500,000.

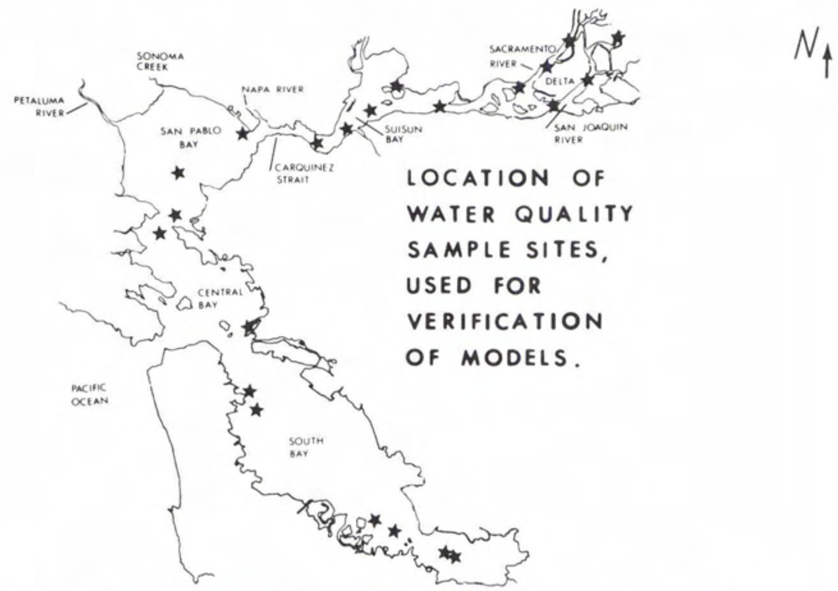

FIG. 2. Location of 23 water quality samples, collected on 27 October 1980, and used for verification of water quality models. Scale is approximately 1:500,000.

ACQUISITION AND ANALYSIS OF LANDSAT DATA

Landsat-2 Computer Compatible Tapes (CCT) were obtained from the Earth Resource Observation Systems (EROS) Data Center in Sioux Falls, South Dakota. The Landsat CCTs were reformatted to a format compatible with the Remote Sensing Research Program (RSRP), University of California at Berkeley, data processing system.

All of the water quality sample sites were located in the Landsat Coordinate System by applying a coordinate transformation equation between the Universal Transverse Mercator (UTM) Coordinate System and the Landsat Coordinate System. This transformation was based on a second order linear regression equation based on a number of control points with $R^2 > 0.98$. This regression model was then used to transfer the UTM-based coordinate system for the 73 water quality sample sites to the Landsat Coordinate System. The exact locations of these sample sites were also visually verified.

The mean radiance values in all four bands of Landsat MSS data for the nine pixel block (3 by 3 pixels) encompassing each sample site were computed. These mean block values were used as independent variables in the regression model described below.

DEVELOPMENT OF WATER QUALITY MODELS BASED ON SAMPLE SITES

A series of statistical models (based on a stepwise regression method) were examined for determining the best relationships between each water quality parameter measurement at 50 sample sites and the mean count values computed from Landsat bands 4, 5, 6, and 7, as well as band ratios and combinations. Based on the evaluation of the coefficients of determination (R^2), the "F" values, the significance levels of these "F" values, the residual values, and the range for residual values, the best regression fit for each one of the selected water quality parameters was determined. The Results section includes these models.

EXTENSION OF WATER QUALITY MODELS TO THE ENTIRE STUDY AREA

The regression models developed between the water quality measurements for 50 sample sites and their corresponding mean count values were extended to the entire study area for mapping the selected water quality parameters. This extension was accomplished by using a simple linear discriminant function. By applying this function to each pixel in the study area and then grouping each continuous water quality variable into discrete classes, the classification was accomplished. These discriminant functions were applied to Landsat MSS data to produce the classified outputs representing water quality. These classified maps were then renumbered to the final maps.

ACCURACY ASSESSMENTS FOR STATISTICAL MODELS

The selected statistical models for water quality estimation were based on 50 of 73 sample sites. These selected models were applied to the 23 remaining sample sites for verification. The simulated values and the actual water quality measurements from boats for these 23 sample sites were used for evaluating the performance of models.

RESULTS

The results were composed of (1) a series of mathematical models for predicting each water quality parameter along with their statistical summaries and accuracy assessment tables; (2) measured values of water quality parameters for all sample sites; and (3) a series of color-coded maps of the entire study area, each pertaining to a water quality parameter of interest.

Based on the statistical analyses, the following models were selected to represent the best relationship between the water quality measurements for sample sites obtained from boats and the corresponding mean count values of Landsat data:

SALINITY MODEL

$Y_{EC} = 91.8 - 19.7 (\ln X_5) - 11.8 (\ln X_6)$, where
Y_{EC} = salinity expressed in parts per thousand.

TURBIDITY MODEL

$Y_T = 3.70 - 0.04 (X_4)^2 + 0.08 (X_5)^2 + 0.09 (X_6)^2 - 0.57 (X_7)^2$, where
Y_T = turbidity expressed as Nephelometric Turbidity Units.

SUSPENDED SOLIDS MODEL

$Y_{SS} = -79.25 + 24.24 (\ln X_5) + 0.34 (\ln X_7)$, where
Y_{SS} = total suspended solids expressed in mg/l.

CHLOROPHYLL MODEL

$Y_{CH} = -40.99 + 2.73 (X_4) - 2.62 (X_5) + 1.93 (X_6) + 4.14 (X_7) - 0.07 (X_4)^2 + 0.30 (X_5)^2 - 0.25 (X_6)^2 - 0.19 (X_7)^2$, where
Y_{CH} = chlorophyll concentration expressed in μg/l.
In all of the above models,
X_4 = the mean count value in band 4 of Landsat data,
X_5 = the mean count value in band 5 of Landsat data,
X_6 = the mean count value in band 6 of Landsat data, and
X_7 = the mean count value in band 7 of Landsat data.

The coefficients of determination (R^2) for water quality models (developed based on 50 sample sites) and the correlation coefficients (R) values for verification of models based on 23 remaining sites are shown in Table 1. All of the "F" values were statistically significant at least at 0.01 level. The determination and correlation coefficients are measures of the closeness with which the regression models fit the water quality measurements. The significant "F" values indicate that variations in spectral response account for a significant portion of the variations in water quality parameters.

The distribution of the observed values and the predicted values for salinity, turbidity, suspended solids, and chlorophyll *a* models are shown in Figures 3, 4, 5, and 6, respectively.

TABLE 1. COEFFICIENTS OF DETERMINATION FOR WATER QUALITY MODELS AND CORRELATION COEFFICIENTS FOR THEIR VERIFICATIONS

Water Quality Parameter	R^2 for best fit models based on 50 samples	"R" for verifications of models based on 23 remaining samples
Salinity	0.910	0.64
Turbidity	0.903	0.88
Susp. Solids	0.810	0.62
Chlorophyll *a*	0.760	0.60

All of the "F" values were significant at the 0.01 level indicating that the variation in Landsat MSS data account for a significant portion of the variations in water quality parameters.

The coefficients of determination were observed to be high for salinity and turbidity, relatively high for suspended solids, and relatively low for chlorophyll *a* concentrations. The low R^2 values for chlorophyll *a* may be due to an inadequate number of sample sites to represent the wide range of existing conditions within the study area in general and in the Delta region in particular. The fact that the physical, chemical, and biological properties of water are different for the Delta Region, the San Francisco Bay, and the Pacific Ocean suggests that the models must be based on the sample sites representing the entire range of possible values. Because the reflection in the visible and near-infrared part of the electromagnetic spectrum due to chlorophyll *a* concentrations is highly selective (Uno, 1980), we believe that the broad range of Landsat bands is partly responsible for low R^2 values in chlorophyll *a* model. The chlorophyll *a* model produced some negative values where the very low concentrations were expected. This indicates low sensitivity of the model for low values of chlorophyll *a*. This may also be due to the broad range of frequency in Landsat bands. Use of either airborne scanners with narrower ranges of frequencies for each channel or Landsat Thematic Mapper data may be expected to produce better results.

The tabulated results of laboratory analyses and the locations of the 50 water quality samples used for the development of models and the 23 water quality samples used for verification of models are shown in Table 2 and Figures 1 and 2.

The color-coded water quality maps for salinity, turbidity, suspended solids, and chlorophyll *a* concentrations are shown in Plates 1, 2, 3, and 4, respectively. In these figures, the values of water quality parameters increase with color changes from blue to green to yellow to orange and to red. That is, blue represents the lowest value and red represents the highest value.

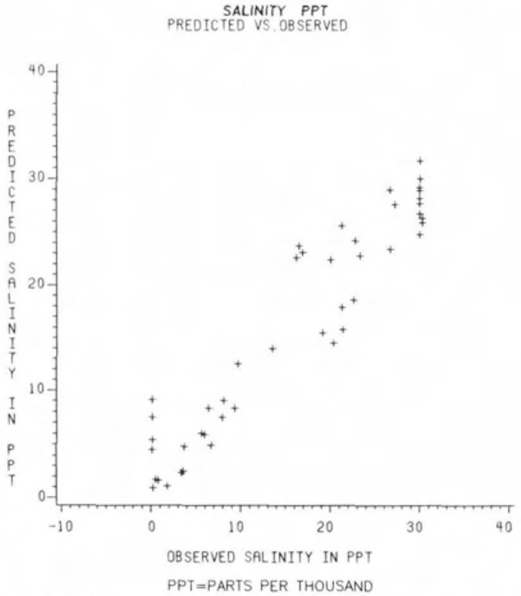

FIG. 3. Observed values versus predicted values based on salinity model.

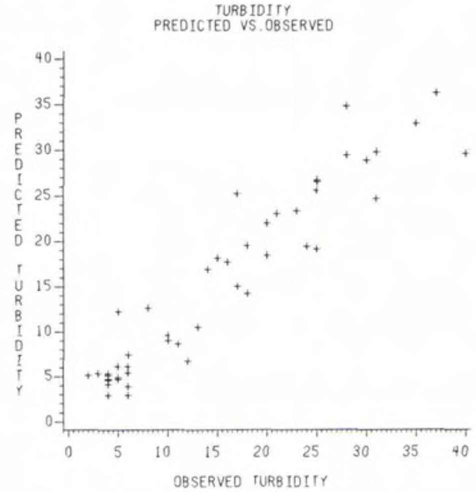

FIG. 4. Observed values versus predicted values based on turbidity model.

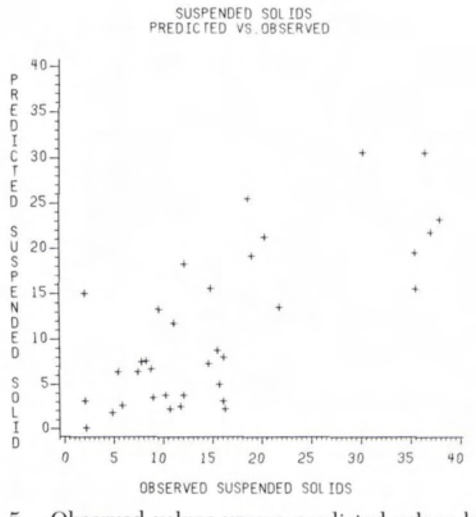

FIG. 5. Observed values versus predicted values based on suspended solids model.

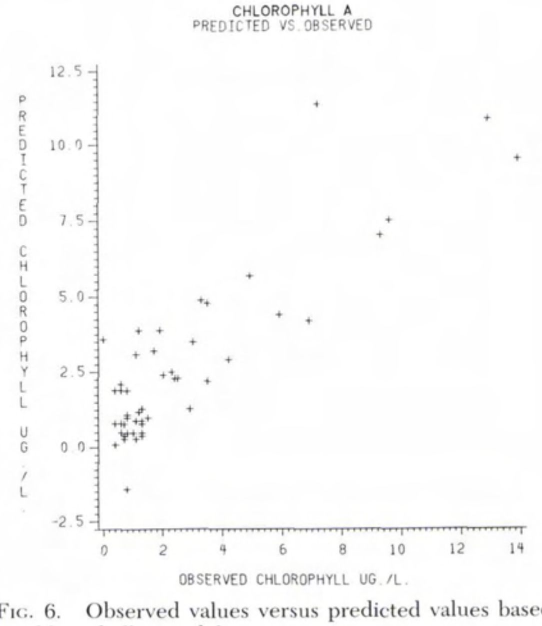

FIG. 6. Observed values versus predicted values based on chlorophyll *a* model.

The lower salinity values in the upper left part of San Pablo Bay are due to freshwater inflow from Petaluma and Sonoma Creeks. At the entrance of the Napa River into Carquinez Strait low salinity values are indicated. As expected, the higher suspended solids, turbidity, and chlorophyll *a* concentrations were observed at the entrance of Petaluma and Sonoma Creeks into San Pablo Bay. These higher values were in agreement with the surface measurements. In case of salinity, it is our opinion that we may be sensing one or more surrogate parameters because we have not found a strong difference in the reflectance characteristics of saline water and freshwater in the literature. These surrogate parameters may be turbidity because freshwater in this geographic region is much more turbid than saline water. The other factor contributing to this thought is the strong correlation between turbidity and salinity in our input dataset.

The analysis of chlorophyll *a*, suspended solids, and turbidity maps indicates the existence of a region with high biological activity in the Delta re-

TABLE 2. RESULTS OF LABORATORY ANALYSES OF WATER QUALITY SAMPLES COLLECTED ON 27 OCTOBER 1980

Sample Site No.	Salinity PPT	Turbidity NTU	Susp. Solids mg/l	Chlorophyll *a* μg/l
BT1*	20.0	10	15.5	1.8
BT4*	26.7	11	14.6	3.9
BT6*	27.2	5	12.1	1.8
BT9*	30.3	4	5.9	2.3
BT10*	30.0	4	9.0	1.3
BT11*	30.0	6	10.7	1.5
BT23*	30.0	6	16.3	1.5
BT26*	30.0	3	2.1	1.3
BT27*	30.0	4	15.7	1.5
BT28*	30.3	5	16.1	1.0
BT29*	30.0	4	4.9	1.8
BT30*	30.0	4	2.2	1.5
BT31*	30.0	2	10.3	2.1
BT47*	23.3	6	8.3	1.0
BT49*	21.3	6	11.1	.1
BT50*	21.4	10	9.6	5.9
BT52*	20.3	5	2.1	1.3
BT53*	19.1	8	14.8	2.1
BT55*	26.7	4	11.8	1.8
BT57*	21.3	5	7.5	2.1
BT58*	22.8	4	8.8	0.3
BT59*	16.9	4	5.5	0.8
BT109*	0.5	20	19.6	7.2
BT110*	0.5	30	49.5	6.9
BT111*	0.8	31	47.8	5.9
BT2**	23.6	10	14.8	2.3
BT3**	25.6	9	14.5	2.6
BT7**	28.6	7	9.5	2.8
BT8**	28.9	5	8.5	2.8
BT24**	30.0	4	9.7	1.3
BT25**	30.0	3	6.9	1.3
BT32**	29.4	2	12.5	3.9
BT46**	24.2	6	23.0	0.5
BT51**	22.9	10	11.0	2.6
BT54**	16.9	7	11.1	1.5
BT56**	25.2	4	8.0	2.1
BT63**	10.8	16	32.5	7.7
BT65**	9.4	14	24.4	9.5
BT67**	8.5	24	49.1	11.3
BT72**	2.7	29	48.3	14.1
BT79**	6.4	25	49.6	39.9
BT83**	6.2	17	28.1	18.1
BT92**	0.1	12	9.3	4.1
BT94**	0.4	25	25.5	4.4
BT96**	0.7	29	45.4	5.1
BT100**	0.1	17	14.1	4.9
BT105**	0.1	15	16.9	6.7
BT107**	0.3	18	23.2	11.1
BT60*	16.2	6	16.1	2.1
BT61*	16.5	6	7.8	2.1
BT62*	13.5	13	21.7	4.1
BT64*	9.7	18	35.4	12.3
BT66*	7.9	20	45.9	16.2
BT68*	6.7	31	54.3	20.6
BT69*	5.9	23	36.9	22.1
BT70*	5.6	21	44.5	18.8
BT71*	3.7	25	41.1	16.8
BT74*	1.8	35	46.7	16.7
BT75*	1.3	33	48.1	6.7
BT77*	9.3	18	35.3	16.8
BT78*	8.1	24	49.4	24.1

TABLE 2. (Continued)

Sample Site No.	Salinity PPT	Turbidity NTU	Susp. Solids mg/l	Chlorophyll *a* μg/l
BT85*	3.6	28	51.1	18.1
BT86*	3.4	25	40.5	12.1
BT93*	0.1	17	37.8	6.2
BT95*	0.6	28	36.3	4.9
BT97*	0.9	40	66.4	5.7
BT98*	1.1	37	62.0	6.7
BT99*	0.1	17	12.1	4.9
BT103*	0.1	15	18.9	9.5
BT104*	0.1	14	20.2	13.9
BT106*	0.2	16	18.5	12.9
BT108*	0.5	25	30.0	9.3

* Used for modeling.
** Used for verification.

gion. To some scientists this area is known as the "Entrapment Zone." The location of this zone is in agreement with the results of other investigations (Ball, 1975; Arthur and Ball, 1979; Khorram, 1981a, b). This region is shown in red and brown colors in Plates 1, 2, and 3.

The distribution of salinity, turbidity, suspended solids, and chlorophyll *a* values throughout the Bay and the Delta regions was in general agreement with the expected values of these parameters and the values reported in the literature (Conomos and Peterson, 1974; Arthur and Ball, 1979; Cloern, 1979; Orsi and Knutson, 1979; Khorram, 1981a, b).

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 the study area and its adjacent environment has also been reported by other investigators (Conomos and Peterson, 1974; Peterson *et al.*, 1975; Arthur, 1975; Siegfried *et al.*, 1979).

Consistent with the results of this investigation, the region of high turbidity and high suspended solids appears to be a persistent feature of moderately stratified estuaries (Meade 1972). 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 high turbidity in many estuaries of northern Europe, British Guyana, and the United States (Postma, 1967; Schubel, 1968; Arthur, 1975).

The water quality maps of the same area based on the Ocean Color Scanner data also indicated the existence of this region of high biological activity (Khorram, 1981a).

CONCLUSIONS

Based on the results of this investigation, the following conclusions were indicated:

- Areas having relatively high biological activity were clearly discernible on digitally-enhanced Landsat data. This area is characterized by high turbidity, high suspended solids, and high chlorophyll *a* concentrations.
- Consistent with our findings, many investigators from different parts of the world, through the use of conventional ground survey techniques, have reported a region of high turbidity and high suspended solids to be a common feature of moderately stratified estuaries.
- The coefficients of determination (R^2) were observed to be high for salinity and turbidity, relatively high for suspended solids, and low for chlorophyll *a* concentrations. In the case of salinity, we may be sensing one or more surrogate parameters. One of these parameters may be turbidity. Two reasons contribute to this thought: one is the less turbid nature of saline water as compared to freshwater in this geographic region and the other is the strong correlation between salinity and turbidity in our input dataset.
- The broad range of frequencies in Landsat MSS bands may be partially responsible for low R^2 values with respect to the chlorophyll *a* model. The use of the Thematic Mapper data, which has a narrower range of frequencies per band, is expected to produce better results.
- We were able to develop a single model for estimating the diverse range of each water quality parameter throughout the entire San Francisco Bay and Delta during a low runoff period based on the combination of Landsat and *in situ* data representing the existing physical, chemical, and biological conditions.
- Landsat MSS data have been successfully used for the purpose of water quality mapping by many investigators. It is believed, however, that the present study constitutes the first concerted effort to use remote sensing to map selected water quality parameters throughout the entire San Francisco Bay and Delta.
- Further research is needed to confirm these models or develop new models under different

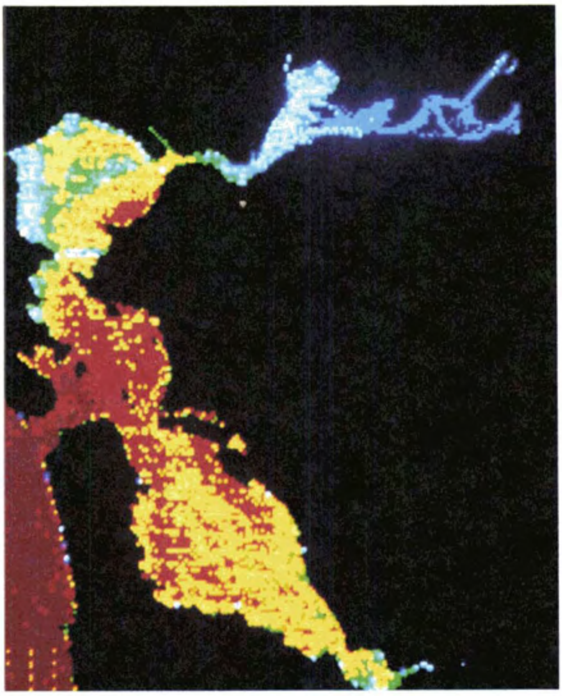

PLATE 1. Salinity map of the study area, derived from Landsat digital data.

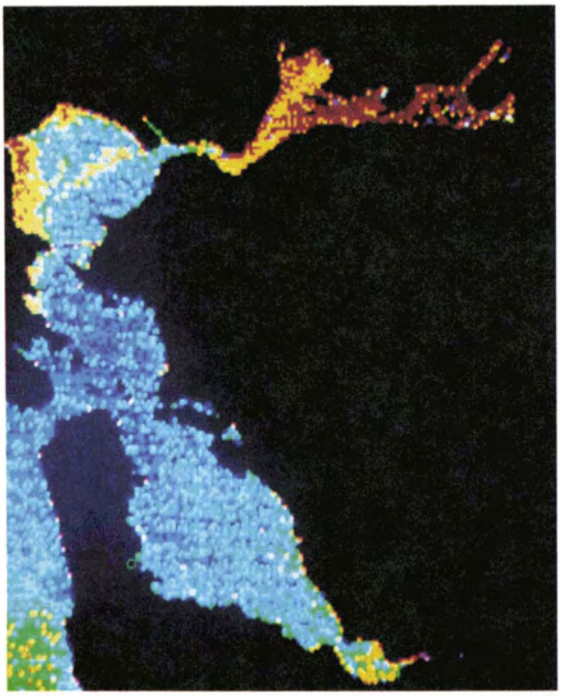

PLATE 2. Turbidity map of the study area, derived from Landsat digital data.

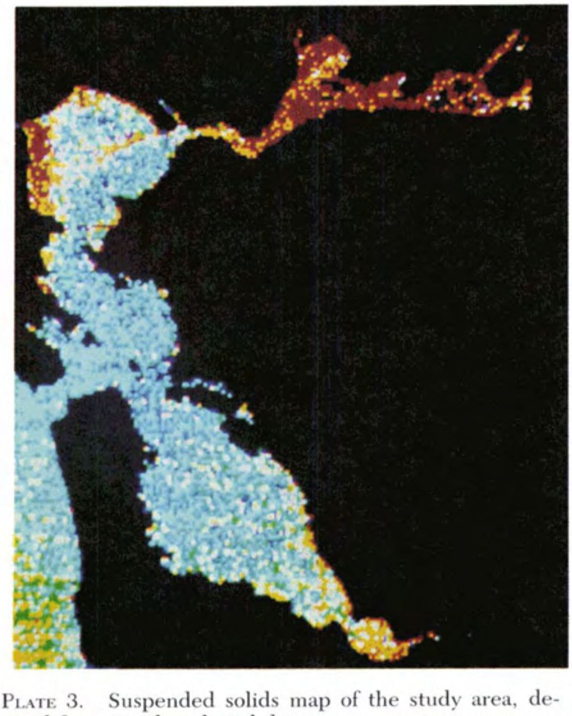

PLATE 3. Suspended solids map of the study area, derived from Landsat digital data.

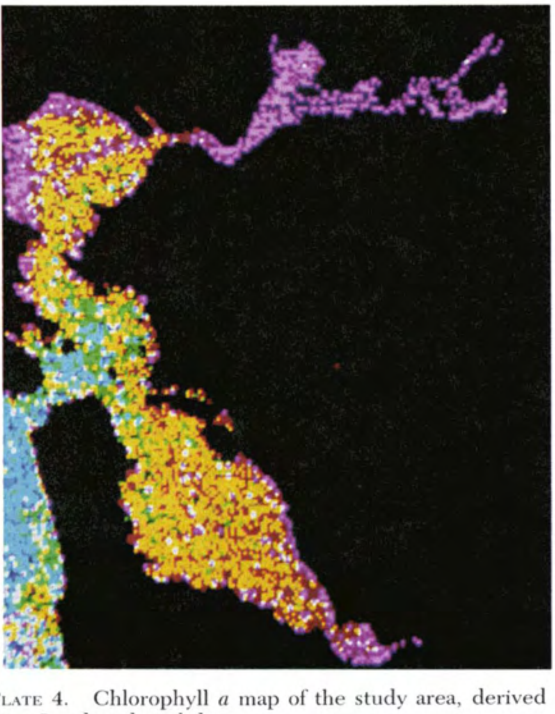

PLATE 4. Chlorophyll *a* map of the study area, derived from Landsat digital data.

freshwater inflow conditions and, possibly, develop a series of generalized models applicable all year round for this geographic region.

ACKNOWLEDGMENTS

The research leading to this manuscript was performed by the author at the Space Sciences Laboratory, University of California at Berkeley and was supported by the California Space Institute, U. C. San Diego, under the Coastwatch Program (CSI-RS80-1).

The author would like to thank Robert N. Colwell of U. C. Berkeley for his guidance and advice on this project, and Allen Knight and his staff of U. C. Davis for their assistance in coordinating, collecting, and analyzing water quality samples. The writer also thanks Steve DeGloria, Agnis Kaugers, Nikki Nedeff, and Sheri Woo of the Remote Sensing Research Program, U. C. Berkeley, for their assistance in digital processing of Landsat data.

Thanks are also extended to the following individuals for their assistance in collecting water quality samples: Jim Cloern and John Conomos and staff from the U.S. Geological Survey; Jim Arthur and staff from the U.S. Bureau of Reclamation; Maxwell Eldridge and staff of the National Marine Fisheries Service at Tiburon; Harlan Proctor of the California Department of Water Resources; and Marty Kjelson of the California Department of Fish and Game. I also thank Heather Cheshire, Paul Bolstad, and Glenn Catts of North Carolina State University for their assistance in the preparation of this manuscript.

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(Received 29 October 1983; revised and accepted 30 August 1984)

ACSG/CIS 85
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Edmonton, Alberta, Canada
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