MULTIDATE ANALYSIS OF REMOTELY-SENSED ESTUARINE WATER QUALITY PARAMETERS USING LANDSAT MSS

by

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ABSTRACT

PELKEY, PATRICK D. Multidate Analysis of Remotely-sensed Estuarine Water Quality Parameters Using Landsat MSS. (Under the direction of Siamak Khorram)

Predictive multidate water quality models based on Landsat MSS reflectance values were developed for 1980 and 1983 turbidity (TURB), total suspended solids (TSS), and salinity (SAL) concentrations in the San Francisco Bay and Delta, California. These models were tested for statistical significance, goodness of fit, and structural consistency to determine if generalized models could characterize both dates, given differences in Delta flow conditions, tide phases, satellite sensors, and sun elevations.

Water quality data covering the Bay/Delta were collected within one hour before and after overpasses of Landsat 2 (1980) and Landsat 4 (1983) under near-slack and flood tides, respectively. The 1980 Delta flow conditions were normal for the season while 1983 flow was extremely high and similar to spring runoff. Literature sources and preliminary analysis suggested that the Bay and Delta were hydrologically distinct and that Landsat MSS could detect differences in hydrodynamic conditions.

Tests of models representing the entire area indicated that different models were required for each date. Comparison of regional models suggested that generalized TURB and TSS functions could explain conditions for both dates, only within the Delta. Delta models were applied to their respective MSS data and color-coded maps identifying

discreet concentration levels were generated. The imagery was checked against water quality sample data indicating Entrapment Zone characteristics, and locations of both Entrapment Zones were compared.

BIOGRAPHY

Patrick Daniel Pelkey was born and raised in Millinocket, Maine. After graduating from Stearns High School, he enlisted in the Air Force where he served four years as a firefighter. He was awarded the Air Force Commendation Medal for outstanding service and was honorably discharged in 1979.

Upon completion of his enlistment, Pat enrolled in the School of Forestry at the University of Maine, Orono. He graduated with distinction in 1983 with a Bachelor of Science degree in Forestry. In August, 1983, he entered a Master of Science degree program in Forestry under Dr. Siamak Khorram at North Carolina State University. His research and course of study has emphasized remote sensing, digital image processing, and development of water quality predictive models.

Pat married his wife, Lynn, in 1976. They have three children, twin daughters and a son. Pat has many interests, but considers his family his most important priority.

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My deepest thanks are for Heather Cheshire and Jim Vose. I spent many hours with Heather discussing and learning about the spectral properties of water quality parameters and Jim gave me a tremendous amount of support and guidance in my analysis of the data. Heather was also my image processing mentor. Learning and applying this technology was the most enjoyable part of this project. I have a great amount of respect for these people and I appreciate their friendship.

Another friend whom I want to thank is my typist and editor, Kim Moss. This paper was professionalized by her skill and efforts and I am very grateful.

Finally, I want to thank you, Lynn, Becky, Stephanie, and Kevin. You give my life meaning. There is nothing more important than you.

TABLE OF CONTENTS

INTRODUCTION

The San Francisco Bay/Delta is an urban estuary supporting major fish and wildlife populations and wetland resources which are threatened by domestic encroachment and anthropogenic pollution from industrial and agricultural sources. In response to environmental concerns, Federal and State legislation has mandated that long-term management plans be formulated and implemented to protect this region. Despite extensive and detailed data collection by a number of government agencies, hydrodynamic processes in the estuary remain unclear. Conomos et al. (1979) contend that a better understanding of the transport and mixing of the water masses is necessary because these factors largely determine the biological processes in the Bay. They (Conomos et al. 1979) prescribe further study and support maintenance of a long-term database to distinguish yearly and short-term variations and trends.

An important factor contributing to the inadequate representation of spatially heterogeneous water quality parameters has been the discreet sampling techniques used to collect these data. Investigators have had to rely on point sampling methods which have required interpolation between stations and can be exorbitant in terms of expense and labor. Remote sensing with Landsat satellites has been considered as a means of monitoring water quality. The advantages of this method are that it is possible to attain repetitive (every 16 to 18 days depending upon the satellite), synoptic, and a reasonably accurate representation of the variation between and beyond sampling stations at a modest expense.

The Landsat Multispectral Scanner (MSS) detects reflected wavelengths in the green (0.5 - 0.6 um), red (0.6 - 0.7 um), and infrared (0.7 - 0.8 um and 0.8 to 1.1 um) portions of the electromagentic spectrum. The wavelength intervals were labeled as bands 4 through 7 in early Landsat versions, but have been renamed to bands 1 through 4 in Landsats 4 and 5. For simplicity, Landsat-2 and Landsat-4 MSS bands are referred to as 1 through 4 as they are compared throughout this report. Each band has an array of six sensors which scan a 185 km-wide path in an oscillating motion. Each sensor records reflected spectral energy from a minimum detectable area referred to as a pixel. The nominal pixel size for Landsat MSS data is generally considered to be 79 m x 79 m. The analog voltage signals from each sensor are averaged then converted to unitless digital values. After ground-based processing, the possible digital scale or radiometric resolution is 0 - 127 for bands 1 through 3 and is 0 - 63 for band 4.

The objectives of my research were to: (1) formulate and test multidate water quality models for statistical significance, goodness of fit, and consistent relationships between water quality parameters and their associated spectral values under two different flow conditions; and (2) to analyze the predicted distributions of water quality parameters for flow condition effects on the location of the Entrapment Zone. These models were intended to predict the distributions of chlorophyll a, suspended solids, turbidity, and salinity during high spring flow and low autumn flow conditions using Landsat MSS data.

Water quality data and Landsat 4 MSS digital data were collected on September 13, 1983, and successfully analyzed. Landsat 5 MSS data were also collected coincident with water quality data on May 24, 1984, but were found to have an anomalous striping effect which rendered the spectral data unsatisfactory. In order to maintain my objective of a multidate analysis, an available Landsat 2 scene and accompanying water quality data for October 27, 1980, were selected as an alternative data source. This is the data set which was used by Khorram (1985) to develop water quality models for turbidity, total suspended solids, chlorophyll a, and salinity for the entire San Francisco Bay/Delta.

Although both data collections occurred in the autumn, there were distinct differences in the flow conditions between the data sets. The September, 1983 Delta outflow was extremely high with measured velocities of 850 $m^3 \cdot sec^{-1}$, whereas the October, 1980 Delta outflow was recorded at approximately 170 $m^3 \cdot sec^{-1}$ which is near the seasonal norm (Harlan Proctor, California Department of Water Resources, personal communication). In comparing the 1983 fall outflow with others measured by Conomos et al. (1979) it is apparent that this outflow was more like spring runoff conditions (Figure 1). Because of the differences in the outflows model behavior and entrapment zone characteristics could still be examined within each flow condition.

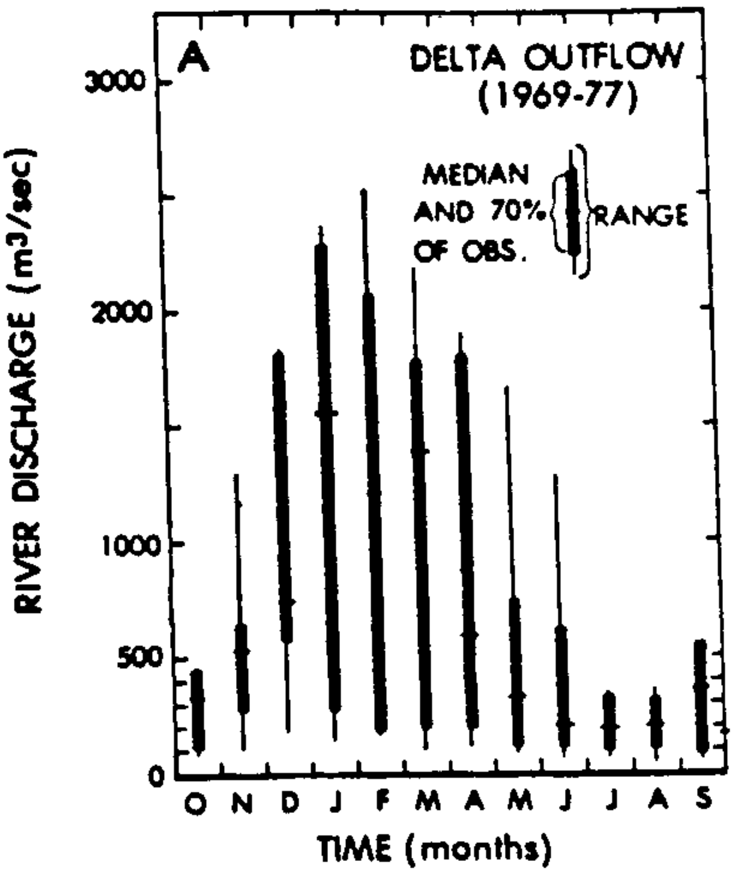


Fig. 1. Monthly means of Delta river outflow from 1969-1977. (Adapted from Conomos et al. 1979)

LITERATURE REVIEW

Numerous researchers have shown that some surface measurements of water quality parameters (such as turbidity, suspended solids, and chlorophyll) collected near-simultaneously with multispectral data are correlated with the multispectral values and that predictive models can be developed based on these relationships. It is more difficult to relate spectral data with water quality parameters in estuaries as compared to oceans or clear lakes because of the hydrodynamic properties and the greater abundance of organic and inorganic constituents present in these ecosystems.

Because of the scattering and attenuation of visible wavelengths in the water column and the absorption of long-wave infrared, the detected spectral signature of a given water quality parameter is generally considered as a measure of the near-surface distributions only. The remote sensing measurements may approximate the actual concentrations of a parameter within a water column; however, it remains to be determined how surface measurements actually correspond with vertical distributions and the effects of advective and diffusive processes throughout the column. Platt and Herman (1983) have investigated remotely-sensed ocean surface chlorophyll data as an estimate of its vertical distribution using the Coastal Zone Color Scanner. Their findings indicate that the remotely-sensed data detect only a small, yet consistent, fraction of total phytoplankton biomass in the water column and that they could not detect the peaks in the vertical profile of biomass or chlorophyll production. These authors point out, however, that there is potential for predicting chlorophyll distributions and estimating primary productivity, particularly for areas with excessive spatio-temporal variability providing that a modest surface-truthing program is also carried out. Further studies are needed to investigate the correlation between surface measurements and the vertical profiles for suspended solids, turbidity, and salinity.

Considerations in the Selection of Landsat MSS Spectral Bands Used for Modeling

Multiple band analysis is necessary in order to accurately measure different types of phytoplankton and suspended materials because the spectral signature of one component can mask others and proportional changes in two or more parameters can have an invariant effect on the overall reflectance (Munday and Zubkoff 1981). Johnson and Harris (1980) point out that Landsat satellite data correlate with surface truth measurements of chlorophyll *a* but spectral discrimination is difficult when there is a mixture of particles. Munday and Zubkoff also mention that a multispectral technique must be spectrally very selective to resolve the restricted absorption and reflectance regions of some parameters.

Chlorophyll *a*. Chlorophyll measurements are generally used in interpreting phytoplankton biomass and primary productivity estimates. Phytoplankton tend to be more spatially variant than inorganic material. Their spectral properties tend to have restricted ranges of absorption and reflectance and can vary depending upon age, vitality, and concentration as well as taxonomic distinction (Wilson and Kiefer 1979; Uno et al. 1980; Yentsch 1983). All algae have absorption peaks in the 430 nm and 670 to 680 nm regions of the spectrum due to the presence of chlorophyll a. As chlorophyll a concentrations increase, wavelengths < 500 nm and approximately 670 nm are increasingly absorbed while wavelengths in the 550-600 nm range and those > 750 nm are increasingly reflected (Uno et al. 1980; Aranuvachapun and Perry 1981; Yentsch 1983; Catts et al. 1985). Landsat MSS does not sample in the blue absorption region characteristic of chlorophyll and its broad band intervals are not efficient in taking advantage of other narrow absorption and reflectance peaks, particularly at low concentrations.

Chlorophyll-bearing materials are considerably darker (weak backscattering) than inorganic sediment across the visible spectrum and typically occur in lower concentrations. These two characteristics make such stringent demands on radiometric sensitivity that the signal-to-noise characteristics of the sensing device become a limitation (Alfoldi 1982). Given the radiometric, spatial, and spectral demands chlorophyll measurements place on the resolving factors of a remote sensing system, it seems likely that Landsat MSS would be restricted in its ability to accurately detect this parameter.

Salinity. Laboratory studies have shown that salinity has no effect on waters' visible and near infrared spectral characteristics (Scherz et al. 1969). Predictive models for salinity developed from remote sensing data, however, have been able to account for a significant portion of the variability in this data (Cheshire et al. 1986; Khorram 1984 and

1982; Khorram and Cheshire 1983). It is believed that spectral detection is actually the result of reflection from some surrogate parameter. Moore (1980) suggests that the correlation of spectral signals with colorless chemical constituents is probably influenced by the distribution of ions absorbed on suspended particles or constituents used in the growth processes of phytoplankton. Sholkovitz et al. (1978) describe the colloidal flocculation of dissolved humic acids at salinity levels of 0 to 5 ppt. Cheshire et al. (1986) have hypothesized that salinity interactions with dissolved humic acids in a North Carolina estuary produce water color changes which are spectrally detectable. They have developed a predictive model for salinity using Landsat Thematic Mapper data which accounts for 82% of the variability in the water quality data.

The interaction of salinity with a surrogate parameter which is spectrally detectable is not well understood in the San Francisco Bay estuary. Salinity may be causing inorganics to flocculate, reducing turbidity in the Delta and Bay. Arthur and Ball (1979) mention that laboratory studies have demonstrated that flocculation of suspended inorganic particles [primarily in the 2 to 10 u size range] can occur at salinity concentration of 0.6 ppt. Khorram's work (1982, 1985) indicates that salinity can be indirectly quantified from spectral measurements. Unfortunately, a generalized model form was not established to address both scenes. These results could be a function of changes in the surrogate parameter such as size, type, or concentration differences.

Total Suspended Solids. Alfoldi (1982) mentions that there are two characteristics in the spectral relationship with total suspended solids: (1) reflectance increases with increasing suspended solids concentration; and (2) peak reflectance shifts to longer wavelengths with increasing concentrations. The measured signal at any wavelength interval is also dependent on particle size and may be dependent on the absorption (reflectance) and refraction characteristics of the suspended material (Moore 1980).

Many investigators have independently established a positive correlation between suspended solids concentration and reflectance in the visible and near-infrared wavelengths. Ritchie et al. (1976) determined that linear regression best described the fit between the near-infrared (700-800 nm) equivalent to Landsat band 3 and measured total suspended solids which were for the most part less than 200 mg/l. They found that the wavelength interval of 600 to 700 nm was most sensitive in detecting changes in reflected radiation from water surfaces but more variation was associated with this range. Other studies have been able to successfully correlate Landsat band 2 (600-700 nm) with suspended solids concentrations (Klemas et al. 1973; Kritikos et al. 1974; Aranuvachapun and LeBlond 1981).

Munday and Alfoldi (1979) found that for small ranges of suspended solids concentrations (2-100 mg/l) linear and nonlinear regressions were equally satisfactory, whereas large ranges of suspended solids were best described with a nonlinear function. The TSS measurements for this study were all less than 100 mg/l.

The modeling of total suspended solids has raised questions concerning the variances attributable to organic and inorganic substances. The percentage of organic matter generally varies from 25 to 35 percent of the total suspended solids and has a wide variety of differing shapes, sizes, and surface textures compared to inorganics (Muralikrishna 1983). The interaction of reflectances specific to these two components has been given little attention. There is a possibility of improved accuracy in predicting suspended material if these components are modeled separately, but no research has been conducted to test this hypothesis.

Turbidity. Turbidity is a measure of the optical transparency or opacity of a water body. Changes in turbidity of many reservoirs and estuaries are caused almost entirely by changes in concentrations of suspended silt or clay (Moore 1980; Alfoldi 1982). Moore (1980) discusses the fact that quantitative remote sensing of turbidity is possible under some conditions but a thorough understanding of the effects of all variables is necessary to interpret the remotely-sensed signal. Water quality modeling efforts have shown a correlation of spectral data with concentrations of suspended sediments and chlorophyll, but these water quality constituents may or may not correlate with turbidity. In mixed sizes of suspended material, colloidal particles contribute an amount of backscattered light flux that is out of proportion to their concentration. Thus, differences in colloidal content may be a problem in secondary correlations, such as optical turbidity with sediment content or plankton biomass.

Multidate Satellite-based Water Quality Model Applications

There are very few studies which discuss multidate satellite-based techniques for estimating water quality parameters. Most models are validated with data withheld from a larger set which was used to construct the model and was collected at a single sample period. The applicability of these models to other circumstances cannot be assumed and until they are validated under different conditions, they have limited usefulness.

Carpenter and Carpenter (1983) developed date-independent models for turbidity and algal pigment using Landsat multispectral data and water quality samples from a lake in Southeast Australia. The data were collected over six different occasions and were pooled to construct generalized models. These models also included sun elevation and time of sample collection to account for further variation in the water quality data. The generalized date-independent models were validated using new data from the original lake and for two other lakes on three occasions. In all cases the turbidity model was accurate in estimating the parameter while the algal pigment model was more variable in it's prediction accuracy.

Scarpace et al. (1979) developed a multidate model to predict trophic conditions for inland lakes throughout Wisconsin. Their regression parameters incorporated atmospherically-corrected Landsat data and the results revealed considerable accuracy in predicting conditions for 27 lakes in two sets of Landsat scenes. Verdin (1985) used several Landsat data sets corrected for sun angle and atmospheric effects and concurrently collected surface truth data to estimate reservoir trophic condition as a function of Secchi depth and chlorophyll a concentrations. The methods Verdin (1985) employed for removal of atmospheric effects involved simplified assumptions concerning complex atmospheric processes and was also based on the assumption that these effects were occurring under uniform atmospheric conditions. Despite the empirical nature of his models, Verdin (1985) has shown through hypothetical examples that failure to account for atmospheric effects when working with multidate imagery can potentially lead to erroneous assessments of water quality data.

For the purposes of this study, atmospheric conditions were assumed to be constant for each date and virtually cloud-free conditions existed over the Bay and Delta during both overpasses. The 1983 MSS imagery has some cloud cover but it is restricted to the Golden Gate entrance and a small part of the central Bay area.

Previous Water Quality Models Developed for the San Francisco Bay/Delta from Spectral Data

Mathematical models of water quality parameters derived from remotely-sensed data for the San Francisco Bay/Delta have been under investigation since 1978. Khorram (1981a) examined the potential for predicting suspended solids, chlorophyll a, and turbidity for flood tide conditions in a low flow season using airborne Ocean Color Scanner (OCS) multispectral data collected along with water quality data from 29 sites located in the northern reaches of the Bay and Delta. Four of ten OCS channels were selected as independent variables. The spectral range of these channels were narrower than the large band widths associated with Landsat MSS; however, the total spectral region sampled was comparable to the first three bands of the Landsat data. Predictive models for turbidity and suspended solids (Khorram, 1981b) and salinity (Khorram, 1982) were also developed using Landsat 2 MSS data collected at the same time as the OCS data. Turbidity and suspended solids models derived from both OCS and MSS data had similar correlation coefficients in comparing their predicted values versus observed; however, the OCS models had a less complicated structure and for the most part emphasized different independent variables. Catts et al. (1985) examined the applicability of airborne Daedalus MSS data for mapping surface distributions of chlorophyll a under ebb and flood tidal conditions in the northern reaches of the Bay. They defined consistent relationships between chlorophyll sampled at ±10 minutes from the overflight and four narrow bands of multispectral data for both tidal flows. They also determined that predicted horizontal distributions of chlorophyll a were consistent with gross horizontal distributions inferred from boat sampling. Model verification using samples withheld from the original data set indicated robust equations.

Predictive models for the entire San Francisco Bay and Delta were developed by Khorram (1985) for a low runoff period. Chlorophyll a, suspended solids, turbidity, and salinity were modeled using Landsat 2 MSS data collected on October 27, 1980. The 1980 model structures were simpler than those developed earlier, but verification of the total suspended solids, salinity, and chorophyll a models using 23 sample sites reserved from the original 73 was only marginal.

Every remote sensing investigation of the estuary has revealed an area in the upper reaches of the Bay where high spectral values corresponded with maximum concentrations of suspended solids, chlorophyll _a_, and turbidity values. Water resources scientists and fisheries biologists have defined this area as an entrapment zone which is largely maintained by the salinity-controlled density differences between river and ocean waters (Arthur and Ball, 1979 and 1980; Cloern, 1979; Conomos et al., 1979; Krone, 1979; Orsi and Knutson, 1979; Kelley et al., 1982). Tidal influences cause dense saline water to flow upstream along the bottom while freshwater river flow travels seaward along the surface. The position of this entrapment zone is largely modulated by the timing and magnitude of the highly seasonal river flow (Conomos, 1979). The estuarine circulation cell that results from the convergence of these two currents is characterized by an abundance of suspended sediments and a maximum of turbidity values on the order of 2 to 30 times the upstream and downstream levels. Arthur and Ball (1979) theorize that suspended inorganics flocculate at specific salinity concentration of 1 to 6 ppt and that there is high biological activity present at all levels of the food chain. Maximum concentrations of particulate organic nitrogen and phosphorus, phytoplankton, certain zooplankton, and juvenile striped bass (young of the year) are all associated with the maximum suspended solids concentrations and the specific ranges of salinity.

The entrapment zone is a sensitive ecological component of the Bay/Delta environment and can easily be disrupted by changes in Delta outflow regimes. Frequent surveillance of this zone could yield important insight into the understanding of primary productivity and aquatic fauna relationships for this estuary.

MATERIALS AND METHODS

Study Area

The San Francisco Bay estuarine system (Figure 2) consists of several interconnected embayments which cover an area of approximately 1.04×10^6 km^2 at mean lower low water (MLLW) (Conomos, 1979). The Delta is described as the region associated with the confluence of the Sacramento and San Joaquin rivers. The Sacramento River supplies about 80 percent of the fresh water entering the bays while the San Joaquin River and surrounding smaller streams yield another 15 percent.

The San Francisco Bay/Delta is described as two geographic and hydrodynamically distinct estuaries (Cole and Cloern, 1982; Conomos et al., 1979). The northern reach (Suisun, San Pablo, and North San Francisco bays) is a partially- to well-mixed estuary in which transport processes are dominated by flow from the delta rivers whereas the southern reach (South San Francisco Bay) is a semi-enclosed coastal embayment in which transport processes are controlled by tidal mixing. The water masses from these two regions generally have unique characteristics because they respond differently to seasonal changes in the rates of physical and biological processes. However, according to Conomos et al. (1979), some transport of water between the northern and southern reaches occurs because of tidal phase differences and large tidal excursions.

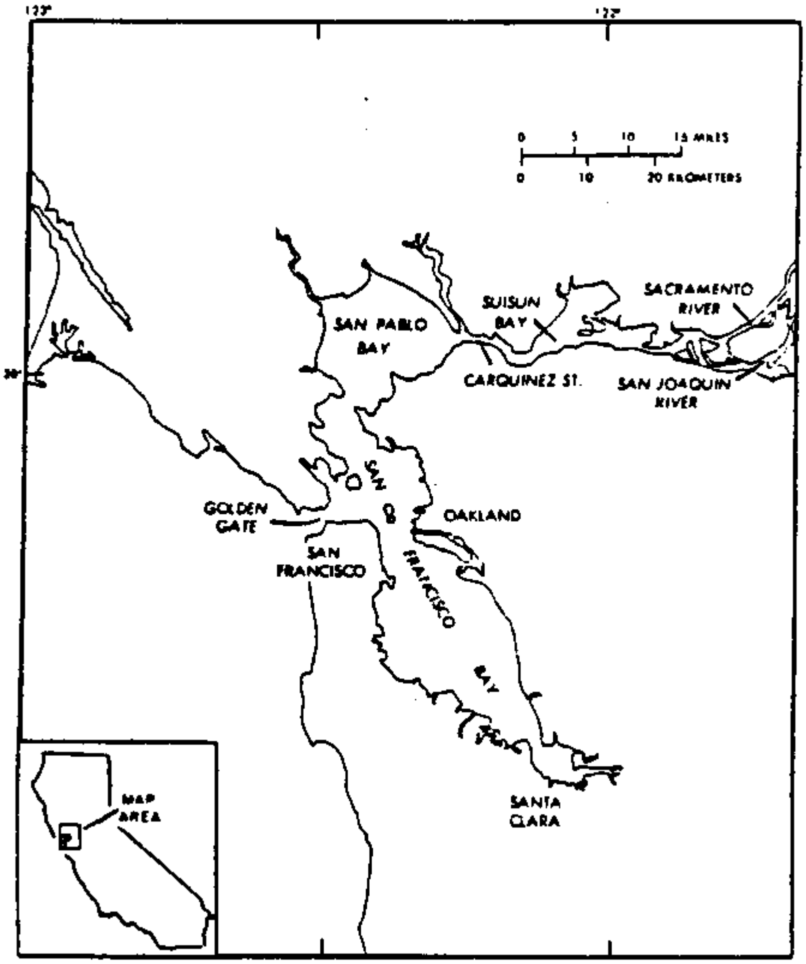


Fig. 2. San Francisco Bay and Delta.

Data Collection

The 1983 water quality data were collected from boats between 10:30 a.m. and 12:43 p.m. Pacific Daylight Time (PDT) under low tide conditions. The Landsat-4 overpass occurred at 11:15 a.m. PDT. A total of 76 sites were sampled and at each sample point 1-liter volume aliquots were collected from the upper 30 cm of water and iced for later laboratory analysis of chlorophyll a (CHLA), turbidity (TURB), and total suspended solids (TSS). Salinity (SAL) was measured as parts per thousand (ppt) in situ using a conductivity bridge. CHLA was determined fluorimetrically (Yentsch and Lengel 1963) from water samples which were extracted in 95% acetone. Trees et al. (1985) suggest that there may be a considerable amount of error introduced by the standard fluorimetric process. They have demonstrated that this method generally underestimates CHLA by an average of 39%. CHLA concentrations were measured in micrograms per liter (ug/l). TSS was recorded in milligrams per liter (mg/l) using standard gravimetric methods. Suspended matter were collected by vacuum filtration on preweighed 0.45 u filters dried at 105 C and reweighed on an analytical balance. TURB was measured in nephalometric turbidity units (NTUs) using a nephlometric turbidometer.

The water quality sample stations were for the most part located in the deep water navigable channels. These regions tend to differ from the shoal regions in their water quality characteristics. Conomos et al. (1979) emphasize the importance of wave-induced resuspension creating higher turbidity in the shoals while Cloern (1979) reports that the shallow embayments of the northern reach accumulate an abundance of phytoplankton because of resuspension processes. The mean photic depth (the depth to which one percent of the surface light penetrates) increases longitudinally for both the deep water channel and the shoals from north to south, but for all areas the channel generally exhibits a greater mean photic depth indicative of clearer water conditions. (Dr. James E. Cloern, U.S. Geological Survey, Menlo Park, CA, personal communication).

The Landsat 4 MSS data were acquired from the Earth Resources Observation System Data Center at Sioux Falls, SD. The data were received as computer compatible tapes and were reformatted to meet the specifications of HACKSAT, the current image processing applications system used at Computer Graphics Center, North Carolina State University. A subscene containing the study area was delineated and five 1 x 1 (every pixel) image files were created for further intensive spatial, spectral, and radiometric analysis at maximum resolution. Additional resampled image files were created to cover the entire study area at lower resolution.

A network of 142 control points was established for geographically referencing the Landsat data. The water quality sample sites were located on the imagery by local transformations to the control point coordinate system based on a fifth-order polynomial regression equation. Radiometric count values were then extracted for a 3 x 3 pixel block surrounding each site. Count values were averaged for each block for 57 of the 76 sites over each of the four bands of the 1983 MSS image. Extraction of mean block values is a method used to ensure that the actual sample site is encompassed in the area. Five sites were excluded because they could not be accurately located and the other fourteen sites near the Golden Gate entrance were dropped because of cloud interference.

The 1980 data consisted of measurements from 73 sample sites which were distributed in nearly the same pattern as the 1983 points. The water quality data were collected between 8:27 a.m. and 10:28 a.m. PDT under high tide conditions while the overpass of Landsat 2 MSS occurred at 10:05 a.m. PDT. These data were analyzed in a similar fashion as the 1983 data. For both dates the sampled points were numbered such that the first points were located at the southern tip of the San Francisco Bay and increased progressively to the Delta. The 1980 data had a higher concentration of sites within the Sacramento and San Joaquin rivers and several stations were located in northern San Pablo Bay (Figure 3).

Preliminary Data Analysis

Initial inspection of the 1983 water quality and spectral (Table 1) data indicated that there were differences between the Delta region consisting of Honker Bay, Suisun Bay, and Carquinez Strait, and the Bay region comprised of San Pablo Bay and San Francisco Bay. Count values of each of the four MSS bands were, for the most part, consistently higher in the Delta region and had a broader range. Turbidity abruptly shifted from low NTUs in the Bay region to high values in the Delta region with only a small transition zone existing between San Pablo Bay and Carquinez Strait. Salinity had the same break between the two geographic areas, but the concentration distributions were the reverse of the turbidity distributions. Low salinity values were measured in the freshwater Delta

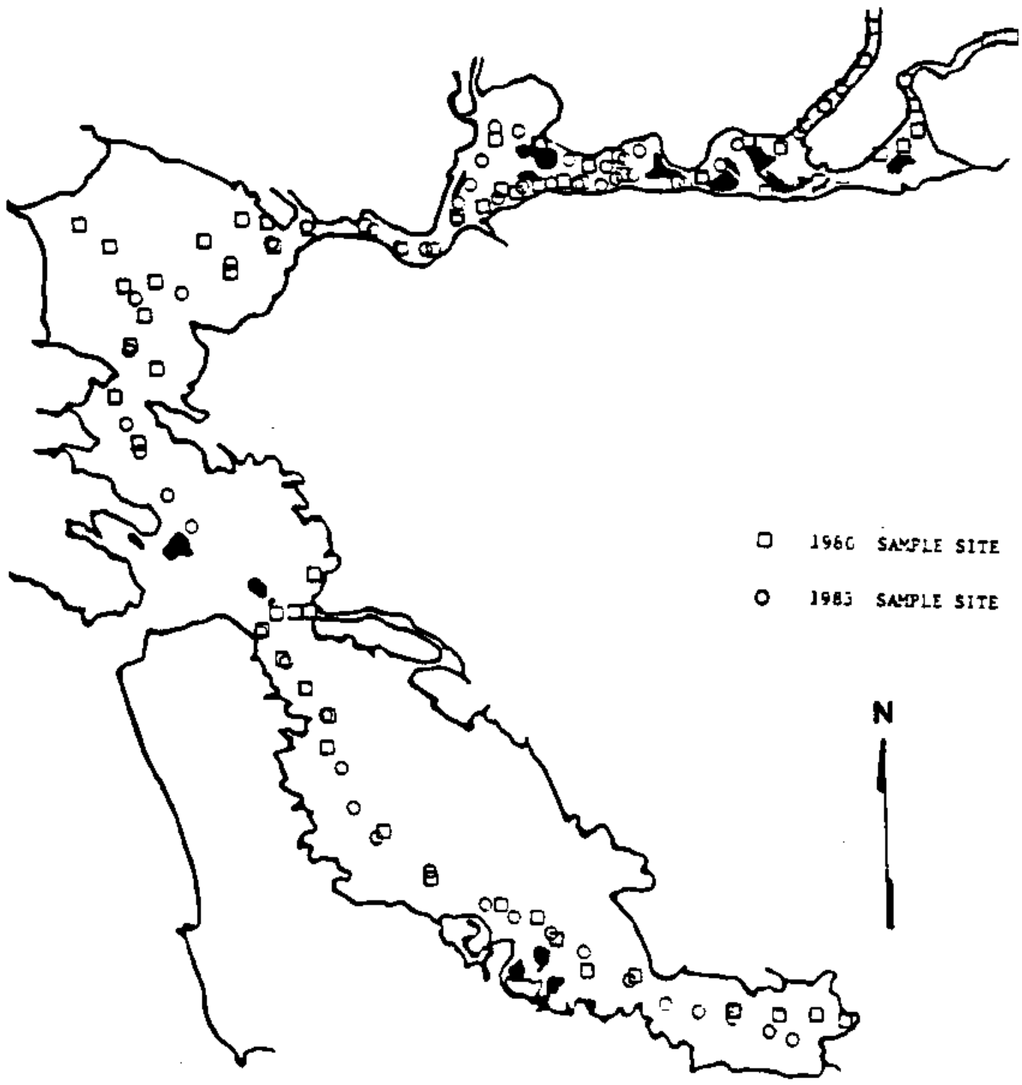


Fig. 3. The 1980 and 1983 water quality sample sites.

Table 1. Water quality and Landsat 4 MSS data from sample sites in the San Francisco Bay/Delta for September 13, 1983.

Bay

STA	TURB	TSS	CHLA	SAL	BAND1	BAND2	BAND3	BAND4
1	9.5	49.2	11.42	18.5	21.6667	19.7778	8.5556	3.1111
2	11.1	40.9	4.36	21.2	22.4444	18.1111	8.2222	4.2222
3	6.8	41.3	8.31	20.2	21.8889	17.3333	7.7778	3.2222
4	6.8	34.5	5.09	20.0	21.5556	16.4444	7.1111	2.8889
5	4.7	32.8	3.22	20.5	20.0000	15.8889	6.6667	2.6667
6	5.5	39.6	3.55	20.6	20.1111	14.6667	6.6667	1.3556
7	3.0	21.6	3.22	22.6	20.4444	15.0000	6.4444	2.5556
8	3.0	42.4	3.18	23.4	20.4444	14.4444	5.8889	2.0000
9	2.1	32.6	0.55	23.8	20.0000	13.8889	5.0000	2.4444
10	1.8	32.4	2.38	23.9	19.3333	13.5556	4.6667	2.1111
11	1.6	26.8	4.17	24.3	19.3333	13.3333	4.3333	2.1111
12	1.0	31.4	3.44	25.0	17.7778	11.4444	4.1111	2.4444
13	0.7	34.9	3.92	25.3	17.8889	11.1111	4.4444	2.0000
14	1.0	29.5	5.38	24.3	19.1111	12.5556	5.5556	1.2222
15	1.5	29.1	5.49	23.7	20.2222	13.7778	5.7778	2.4444
16	1.9	19.8	5.34	23.6	20.1111	13.8889	4.7778	2.0000
17	2.0	33.4	5.27	24.5	19.3333	13.8889	5.8889	2.3333
18	1.9	38.6	3.18	23.8	20.4445	14.2222	5.5556	1.3333
33	5.0	20.7	15.43	16.6	19.0000	12.4444	3.8889	2.2222
34	2.0	37.4	3.44	16.5	20.0000	15.4444	6.2222	3.1111
35	3.9	28.7	6.30	15.5	19.6667	13.6667	5.1111	2.1111
36	2.5	44.9	3.77	18.1	21.1111	16.0000	5.0000	1.5556
37	3.1	20.2	5.64	12.8	17.6667	14.3333	4.6667	1.7778
38	2.9	26.5	13.54	15.8	18.8889	14.5556	3.1111	2.0000
39	2.9	19.4	7.50	10.1	19.5556	12.8889	4.1111	2.3333
40	4.4	14.7	10.25	9.0	19.7778	15.2222	4.8889	2.0000
41	5.5	15.1	5.16	7.5	19.7778	15.2222	5.5556	2.3556

Delta

STA	TURB	TSS	CHLA	SAL	BAND1	BAND2	BAND3	BAND4
42	8.8	20.4	4.61	6.3	23.1111	19.0000	7.6667	3.0000
43	8.0	17.7	8.02	5.2	23.8889	20.5556	8.6667	3.4444
44	9.2	23.4	3.99	4.9	23.4444	20.8889	8.5556	4.5556
45	18.6	39.9	3.15	2.7	25.8889	26.1111	10.6667	4.5556
46	14.9	26.8	3.48	2.8	26.2222	25.6667	10.7778	3.7778
47	27.9	45.9	2.96	1.3	25.0000	25.6667	11.4444	4.3333
48	27.7	43.3	2.78	1.0	26.1111	26.0000	11.3333	3.8889
49	20.5	30.2	2.64	1.1	25.1111	25.0000	10.0000	4.6667
50	15.2	21.1	2.05	0.1	24.6667	23.6667	9.4444	4.1111
51	16.7	19.9	1.90	0.2	22.4444	20.7778	9.0000	4.1111
52	13.5	14.6	2.05	0.1	23.0000	22.0000	9.3333	4.2222
53	9.2	12.1	2.09	0.1	22.5556	20.2222	9.0000	3.8889
54	11.0	12.9	3.04	0.1	23.3333	21.3333	9.1111	4.4444
55	9.4	12.4	2.09	0.1	23.2222	20.6667	9.5556	4.5556
56	9.1	12.0	1.46	0.1	22.3333	20.5556	8.4444	4.1111
57	11.0	23.3	3.99	4.0	25.1111	25.2222	10.0000	3.7778
58	21.3	32.1	3.15	2.4	25.2222	11.4444	11.2222	4.2222
59	28.8	46.0	3.00	2.0	25.6667	28.4444	14.3333	5.5556
60	28.4	43.6	3.95	2.9	29.2222	27.4444	12.6667	4.3333
61	33.5	38.5	3.40	5.8	25.5556	26.6667	12.7778	4.3333
62	22.2	31.1	3.44	6.0	25.7778	25.2222	12.0000	3.8889
63	19.4	26.9	3.37	3.1	24.8889	24.2222	9.8889	3.0000
64	13.1	18.8	3.81	2.3	24.3333	23.4444	10.1111	4.3333
65	11.7	15.4	3.18	0.1	23.7778	21.7778	9.1111	2.6667
66	18.1	29.4	5.97	0.1	23.5556	22.5556	9.6667	4.2222
67	9.7	13.4	3.48	0.1	22.3333	20.1111	9.0000	3.7778
68	8.4	12.8	2.20	0.1	22.4444	20.6667	5.6667	4.1111
69	8.1	11.0	3.00	0.1	23.1111	18.6667	8.5556	3.7778
70	7.5	9.5	2.09	0.1	22.5556	20.1111	8.6667	4.1111
71	6.5	9.9	1.68	0.1	22.2222	21.6667	12.6667	6.6667

whereas values approaching ocean concentrations were recorded for points throughout the central and southern parts of San Francisco Bay. CHLA appeared to be fairly uniform throughout the Bay and Delta, but there were several points within the Bay region which were approximately three times that of other points within either region. Bay region TSS measurements were, for the most part, larger than the Delta region but there was an area within the Delta where TSS concentrations were as high as the Bay region. This same site also exhibited higher TURB and SAL quantities indicative of entrapment zone conditions.

Examination of the 1980 water quality and spectral data (Table 2) also revealed an abrupt transition for all parameters and the break again occurred between San Pablo Bay and Carquinez Strait. Statistics generated for each of the parameters showed that the Delta region had higher concentrations of TURB, CHLA, and TSS while the Bay region had higher SAL values. Count values for all four 1980 Landsat 2 MSS bands were greater for the Delta as were the 1983 Landsat 4 MSS bands.

Based on the apparent regional differences for both dates, Students' t-tests were performed to test the equality of regional means of each water quality parameter and MSS band. A ratio of the form $t = \frac{\bar{x}_1 - \bar{x}_2}{S\bar{x}_1 - \bar{x}_2}$ was compared with the 100 $(1 - \alpha)$ % point of the t distribution. If the calculated t values were greater than the specified value at $\alpha = .05$ then the regional means were assumed to be from two different populations. The t-test is based on the assumption that the variances of the two groups are equal, therefore an F statistic of the form $F = \frac{\text{the larger } s^2}{\text{the smaller } s^2}$ was computed to test variance equality. For those instances where the variances proved to be significantly

Table 2. Water quality and Landsat 2 MSS data from sample sites in the San Francisco Bay/Delta for October 27, 1980.

Bay

STA	TURB	TSS	CHLA	SAL	BAND1	BAND2	BAND3	BAND4
1	10	15.5	1.8	20.0	15.7	13.1	4.9	0.9
2	10	14.8	2.3	23.6	14.9	13.2	5.0	0.3
3	9	14.5	2.6	25.6	15.7	13.3	6.6	0.0
4	11	14.6	3.9	26.7	14.9	12.6	4.8	0.6
6	5	12.1	1.8	27.2	14.9	11.4	4.0	0.4
7	7	9.5	2.8	28.6	16.2	11.7	4.7	0.1
8	5	8.5	2.8	28.9	15.3	11.9	4.2	0.1
9	4	5.9	2.3	30.3	15.7	11.1	4.8	0.2
10	4	9.0	1.3	30.0	15.0	11.2	3.9	0.0
11	6	10.7	1.5	30.0	15.1	10.8	3.8	0.0
23	6	16.3	1.5	30.0	15.9	10.8	3.9	0.0
24	4	9.7	1.3	30.0	15.3	11.0	4.1	0.2
25	3	6.9	1.3	30.0	15.2	10.7	3.9	0.0
26	3	2.1	1.3	30.0	15.3	11.2	2.9	0.4
27	4	15.7	1.5	30.0	15.9	11.9	4.7	0.2
28	5	16.1	1.0	30.3	15.6	11.2	4.6	0.4
29	4	4.9	1.8	30.0	15.2	10.8	4.7	0.3
30	4	2.2	1.5	30.0	15.7	10.4	4.6	0.1
31	2	10.3	2.1	30.0	14.8	11.3	3.3	0.0
32	2	12.5	3.9	29.4	14.3	9.8	4.7	0.2
46	6	23.0	0.5	24.2	16.6	12.1	4.3	0.0
47	6	8.3	1.0	23.3	17.2	12.7	5.0	0.7
48	12	15.6	2.8	22.6	18.2	14.1	6.0	0.1
49	6	11.1	4.1	21.3	17.8	14.3	6.2	0.0
50	10	9.6	5.9	21.4	18.4	15.1	6.8	0.3
51	10	11.0	2.6	22.9	17.9	13.5	5.4	0.3
52	5	2.1	1.3	20.3	18.4	15.7	7.1	0.8
53	8	14.8	2.1	19.1	18.7	16.0	6.3	0.7
54	7	11.1	1.5	16.9	18.3	14.1	6.2	0.0
55	4	11.8	1.8	26.7	15.1	10.9	3.8	0.0
56	4	8.0	2.1	25.2	16.7	12.2	3.9	0.0
57	5	7.5	2.1	21.3	17.0	12.4	4.1	0.2
58	4	8.8	1.3	22.8	16.9	12.3	4.7	0.0
59	4	5.5	0.8	16.9	16.4	12.5	5.0	0.1
60	6	16.1	2.1	16.2	17.4	13.0	4.9	0.2
61	6	7.8	2.1	16.5	16.2	12.6	4.7	0.9

Delta

STA	TURB	TSS	CHLA	SAL	BAND1	BAND2	BAND3	BAND4
62	13	21.7	4.1	13.5	18.0	15.2	7.8	0.4
63	16	32.5	7.7	10.8	18.1	15.8	7.9	0.0
64	18	35.4	12.3	9.7	17.6	15.9	8.2	1.4
65	14	24.8	8.5	9.4	18.0	17.2	8.7	1.0
66	20	45.9	16.2	7.9	18.8	18.6	9.7	1.1
67	24	49.1	11.3	8.5	19.1	18.3	10.7	1.7
68	31	54.3	20.6	6.7	18.9	19.6	11.1	2.8
69	23	36.9	22.1	5.9	19.6	19.1	10.6	1.4
70	21	44.5	18.8	5.6	19.7	19.2	10.4	2.4
71	25	41.1	16.8	3.7	19.4	19.7	11.1	2.2
72	29	48.3	14.1	2.7	20.1	20.7	12.6	3.3
74	35	46.7	10.7	1.8	20.3	21.9	12.7	3.1
75	33	48.1	6.7	1.3	21.1	22.6	13.2	3.2
77	18	35.3	16.8	9.3	18.8	17.9	9.6	1.3
78	24	49.4	24.1	8.1	18.9	17.9	9.1	1.8
79	25	49.6	30.9	6.4	18.1	17.6	9.9	1.2
83	17	28.1	18.1	6.2	19.4	19.1	11.1	3.0
85	28	51.1	18.1	3.6	19.8	20.6	12.3	2.6
86	25	40.5	12.1	3.4	22.1	21.0	12.3	3.2
92	12	9.3	5.1	0.1	20.4	19.4	11.6	3.4
93	17	37.8	6.2	0.1	19.6	19.8	11.2	2.6
94	25	25.5	4.4	0.4	22.0	21.8	13.3	3.1
95	28	36.3	4.9	0.6	23.3	24.4	15.0	5.0
96	29	45.4	5.1	0.7	22.8	22.7	14.6	3.7
97	40	66.4	5.7	0.9	23.1	23.2	14.4	4.8
98	37	62.0	6.7	1.1	22.1	23.0	13.8	3.3
99	17	12.1	4.9	0.1	19.9	17.1	9.7	2.4
100	17	14.1	4.9	0.1	19.8	18.9	10.0	2.4
103	15	18.9	9.5	0.1	18.9	17.6	10.6	2.1
104	14	20.2	13.9	0.1	19.4	18.6	11.6	3.8
105	15	16.9	6.7	0.1	21.0	22.2	12.6	5.0
106	16	18.5	12.9	0.2	22.8	21.0	13.8	5.0
107	18	23.2	11.1	0.3	23.2	23.6	15.3	5.8
108	25	30.0	9.3	0.5	24.0	24.3	15.8	6.0
109	20	19.6	7.2	0.5	23.0	22.2	14.8	5.7
110	30	49.5	6.9	0.5	21.2	21.3	12.6	3.2
111	31	47.8	5.9	0.8	21.6	21.3	12.7	2.7

different an approximate t was calculated using a computed estimate for the degrees of freedom (Steel and Torrie, 1980). A significance level of .05 was also used for t and F-tests.

The results of the t-tests show that there are significant differences between the Bay and Delta regions for all water quality parameters and spectral bands for each date (Tables 3.1 and 3.2). These differences support the concept that the San Francisco Bay and Delta are hydrodynamically distinct and emphasize that Landsat MSS is sensitive enough to detect different spectral responses from the two regions comprising this estuarine ecosystem.

Other preliminary data analysis included plots of each water quality parameter vs. each MSS band for a given date (see Appendix). The plots of the 1980 TSS and TURB data for the Delta region revealed a wide dispersion among spectral values associated with low and moderate measurements of these water quality parameters. A check of the map positions of each point confirmed that the majority of these points were located in the Sacramento and San Joaquin rivers and that each point was found to be between 130 m and 250 m from a river bank or 1 to 2 m of shallow water. Since the nominal pixel width of MSS data is equivalent to 79 m and the count values used in this analysis were derived by averaging a 3 x 3 pixel block encompassing a given sample site, it is possible that the count values associated with these points were influenced by the high spectral response from pixels containing land or shallow water with bottom reflectance.

Table 3.1. T-test results comparing 1983 mean differences among water quality parameters and spectral data for the Delta (1) and Bay (2) regions.

$n_1 = n_2 = 30$

Variable	Mean	(Variance)
TURB (1)	15.59	(59.14)**a/
TURB (2)	3.45	(6.30)
CHLA (1)	3.20	(1.74)a/
CHLA (2)	5.71	(14.06)**
TSS (1)	23.81	(139.00)b/
TSS (2)	32.95	(113.42)**
SAL (1)	1.78	(3.92)a/
SAL (2)	20.11	(25.70)**
Band 1 (1)	24.20	(2.59)b/**
Band 1 (2)	20.15	(1.77)
Band 2 (1)	22.53	(11.63)a/**
Band 2 (2)	14.59	(3.35)
Band 3 (1)	9.98	(3.13)b/**
Band 3 (2)	5.59	(1.61)
Band 4 (1)	4.15	(0.53)b/**
Band 4 (2)	2.38	(0.45)

** significant difference at = .01

a/ Data analyzed by approximate t-test.

b/ Data analyzed by parametric t-test.

Table 3.2. T-test results comparing 1980 mean differences among water quality parameters and spectral data for the Delta (1) and Bay (2) regions.

$n_1 = 37$
$n_2 = 36$

Variable	Mean	(Variance)
TURB (1)	22.84	(52.71)**a/
TURB (2)	5.86	(6.71)
CHLA (1)	11.39	(42.12)**a/
CHLA (2)	2.07	(1.12)
TSS (1)	36.12	(214.33)**a/
TSS (2)	10.66	(21.34)
SAL (1)	3.56	(15.13)b/
SAL (2)	25.23	(22.47)**
Band 1 (1)	20.38	(3.20)**b/
Band 1 (2)	16.22	(1.56)
Band 2 (1)	20.01	(5.90)**b/
Band 2 (2)	12.30	(2.25)
Band 3 (1)	11.71	(4.58)**a/
Band 3 (2)	4.79	(0.98)
Band 4 (1)	2.89	(2.25)**a/
Band 4 (2)	0.24	(0.07)

** significant difference at = .01.

a/ Data analyzed by approximate t-test.

b/ Data analyzed by parametric t-test.

Because of the suspected bias associated with reflectance values of these points, tests of group differences were made between points $\leq$ 250 m from a high reflectance source (group 1) and points greater than this distance (group 2). A SAS general linear model procedure was used to test for equal slopes and intercepts among groups for each water quality parameter and MSS band. If a computed F value was significantly different from a point estimate from the F distribution at $\alpha = .05$ for either of the two tests, it was assumed that group differences were intrinsic and that the points close to land or shallow water were biased. In other words, a statistically significant difference indicated that the relationships between a water quality parameter and MSS band were different for the two sites. After completing the analysis, group 1 was found to be significantly different from group 2 for all water quality parameter/band combinations, except for TURB (Table 4). Based on these results, the 20 points which were suspected as being biased, were eliminated from further analysis within the 1980 data set.

The nonsignificant results of the group effect for TURB vs. Band 1, Band 2, and Band 3 were affected by an influential point which was likely the result of a local effect. This point had the highest concentration of turbidity as well as a high spectral measurement and was included among the sample stations close to sources of high reflectance. Plots of TURB vs. these three independent variables (see Appendix) show that the influential point has a large variance and tends to be isolated from the rest of its group. If this point is not considered in the analysis, the F-statistics are significant at the .05 level for the partitioned TURB

Table 4. Test of equal slopes and intercepts for October 17, 1980 Delta water quality parameters and band values.

	SLOPE			INTERCEPT		
	Group 1	Group 2	PR > F	Group 1	Group 2	PR > F
DEPENDENT VARIABLE: TURB						
Band 1	3.85	2.02	0.179	-50.69	-21.14	0.235
Band 2	2.76	1.74	0.189	-28.48	-14.40	0.174
Band 3	3.39	1.74	0.094	-11.80	- 0.29	0.191
Band 4	5.78	0.48	0.004**	12.72	19.97	0.160
DEPENDENT VARIABLE: TSS						
Band 1	4.26	1.98	0.403	-40.04	- 7.28	0.007**
Band 2	3.26	2.32	0.604	-19.36	-17.80	0.004**
Band 3	3.96	1.95	0.374	0.84	5.80	0.005**
Band 4	6.95	-1.09	0.034*	29.04	34.49	0.006**
DEPENDENT VARIABLE: CHLA						
Band 1	-1.17	-0.80	0.774	37.48	25.45	0.003**
Band 2	-0.25	-0.49	0.778	19.42	18.79	0.003**
Band 3	-0.25	-0.43	0.870	17.41	13.94	0.003**
Band 4	-0.18	-0.19	0.995	15.09	9.24	0.003**
DEPENDENT VARIABLE: SAL						
Band 1	-2.23	-0.52	0.0008**	49.57	12.16	0.0003**
Band 2	-1.47	-0.30	0.0001**	34.39	7.38	0.0001**
Band 3	-1.80	-0.37	0.0001**	25.37	6.11	0.0001**
Band 4	-3.01	-0.66	0.0001**	12.24	3.64	0.0001**

* significant difference at = .05
** significant difference at = 0.01.

models containing bands 2 and 3. These results indicate that this point has an influential effect on the statistics which define turbidity/band relationships for the points closest to features with high reflectance.

Although a "cause and effect" relationship cannot be substantiated in explaining the high reflectances of points close to land or shallow water, the significant differences between groups were accepted as being a reasonable justification for dropping those points. It was also assumed that any points which were $\leq$ 250 m from these features in the other data sets could have similar problems; therefore, they were also eliminated. After checking all questionable points, four stations were dropped from the 1980 Bay data, four points were disregarded in the 1983 Delta data, and three points were eliminated from the 1983 Bay data.

Plots of 1980 TURB, TSS, and SAL vs each MSS band (see Appendix) reveal a linear trend in most instances for those points > 250 m from land or shallow waters. Although the Bay data are restricted in both the X and Y dimensions compared to the Delta, the graphs suggest that a single linear Bay/Delta predictive model could be used. The Delta data appear to offer the most information in fitting a regression whereas the Bay data have a limited dispersion and are likely to have a poor relationship with the spectral data by themselves. This limited range for Bay water quality values may be an artifact of the location of the sample sites in the deep water channel. Measurements outside this channel might result in more diverse conditions. Despite the characteristics of the Bay data, their position along a hypothetical line with the Delta data suggested that Bay water quality values could be predicted with a minimum of error using a model which incorporated both regions.

Plots of 1980 CHLA vs. the spectral bands suggest a curvilinear relationship which again may be described with one model. After eliminating those points which were close to high reflectance sources, the shape of the curve seems to indicate that Landsat MSS data may exhibit a threshold response with CHLA. The inability of MSS to respond, particularly to higher values of chlorophyll within the measured range, is probably related to limitations of the scanner or confounded by the spectral response of other suspended material as mentioned earlier.

The 1983 plots of TURB vs. the MSS bands have much the same behavior as the 1980 graphs, while plots of SAL indicate a fit by a single model or possibly two regional models. The TSS graphs emphasize the need for separate Bay and Delta models and CHLA data seem to have no apparent relationship with any of the spectral variables.

Since some of the plots of water quality parameters vs. the MSS bands indicated that full Bay/Delta models could be used and others showed a definite need for regional models, both types of models were developed. The model design, measures of goodness of fit, and statistical significance were analyzed to determine whether regional models might give better predicted results as compared to the full Bay/Delta models, particularly since the Delta data seemed to be offering the most information in the context of full model development.

An assumption in including the Bay data in a full model is that the behavior of larger values of Bay water quality data will follow the same distribution pattern as the Delta. This assumption seems to be violated in comparing the 1980 and 1983 plots of Bay TSS (see Appendix). The components comprising TSS were not accounted for in these data and different constituents will change the spectral response associated with the TSS measurements. Sampling indicated larger amounts of chlorophyll a measured in the Bay region in 1983 indicating a greater abundance of phytoplankton. Phytoplankton and detritus may be contributing to the TSS measurement and influencing its spectral response. Conomos et al. (1979) also mention that suspended material in the Bay can be influenced by sewage effluent disposal from the numerous urban areas around the Bay. The size, type, and/or concentration of the TSS constituents can have a dramatic effect on the spectral response associated with this parameter.

Design differences in the Landsat satellites' optics, filters, and detectors may cause a constant source of reflected energy to register as different digital values. Markov and Barker (1983) discuss the variability between Landsat 2 and Landsat 4 MSS sensors and describe the differences in count values which result from calibration differences.

The digital count values are a measure of the intensity of reflected radiant energy and are produced from a linear model which calibrates the data to a range of 128 levels for bands 1 through 3 and 64 levels for band 4. Within a given band, the digital values are internally consistent; however, Robinove (1982) states that direct comparisons of count values between satellites or bands within a satellite cannot be made because of calibration differences. He mentions that ratioing bands within a single scene can yield quantitatively incorrect results because the calibration of each band within a satellite is different. To compare data from different sensors at different times, Robinove says that digital values should be corrected to radiance ($mW \cdot cm^{-2} \cdot sr^{-1}$) or reflectance values (unitless) if there is a difference in sun angles. There was a 15 degree difference in sun elevation between 1980 and 1983. The 1980 MSS data were collected at a sun elevation of 33 degrees while the sun elevation associated with the 1983 MSS data was 48 degrees.

Since Robinove's transformation criteria were applicable to the conditions of this study, the MSS data were converted to the physical values by the following calculations.

$$L_{rad} = \frac{DC}{DC_{max}} (L_{max} - L_{min}) + L_{min}$$

where L_{rad} is the radiance sensed by Landsat in a given spectral band, DC is the digital count value for a given pixel, DC_{max} is the maximum digital number that is recorded in each of the four spectral bands, L_{max} is the radiance saturation for a sensor, and L_{min} is the minimum threshold level detected by a sensor. Values for L_{max} and L_{min} for Landsats 2 and 4 are presented in Table 5.

$$L_{ref} = \frac{L_{rad}}{E \sin (A)}$$

where L_{ref} is a measure of the percentage of light reflected from a given target, E is the solar constant for a given band at the top of the atmosphere and A is the solar elevation measured from the horizontal in

Table 5. Maximum and minimum radiance values ($mW \cdot cm^{-2} \cdot sr^{-1}$) for low gain mode operation of Landsat 2 after July 16, 1975, and Landsat 4 after April 1, 1983, taken from Verdin (1985).

BAND	Landsat 2 L_{min}	Landsat 2 L_{max}	Landsat 4 L_{min}	Landsat 4 L_{max}
1	0.08	2.63	0.04	2.38
2	0.06	1.76	0.04	1.64
3	0.06	1.52	0.05	1.42
4	0.11	3.91	0.12	3.49

degrees. Values for E are given in $mW \cdot cm^{-2} \cdot sr^{-1}$ and are as follows (Nelson 1985).

Band 1	17.70
Band 2	15.15
Band 3	12.37
Band 4	24.91

Following an example by Nelson (1985), coefficients of variation (CV) were calculated for count values and transformations of each band/date/area combination to determine which data processing method effectively reduced between scene variability. CV's (standard deviation/mean) were compared so that scaling differences between transformations could not affect the comparison (Table 6). Nelson contends that the transformation which most consistently produced the lowest CV would be the most effective preprocessing step for correcting between-scene variations.

There were reductions in the CV's for both dates and areas from the count values in all bands to the radiance and reflectance transformations but the most appreciable reductions were noted in bands 3 and 4. Transformation of band 3 count values to either radiance or reflectance measurements resulted in a reduction of scene variability of approximately 35%. Similarly, transformation of band 4 resulted in about a 45% reduction in scene variability. The transformation process had little effect on the correlation structure of the data. Therefore, the

Table 6. The coefficient of variation calculated for each transformation by band for each study area.

	1980 Delta	1980 Bay	1983 Delta	1983 Bay
Count Value				
Band 1	.072	.073	.066	.049
Band 2	.124	.118	.121	.096
Band 3	.184	.202	.180	.191
Band 4	.551	1.162	.147	.219
Radiance Value				
Band 1	.059	.059	.060	.044
Band 2	.101	.087	.106	.078
Band 3	.123	.095	.123	.101
Band 4	.286	.128	.094	.107
Reflectance Value				
Band 1	.059	.059	.060	.044
Band 2	.101	.087	.106	.078
Band 3	.123	.095	.123	.101
Band 4	.286	.128	.094	.107

reduction of band 4 variability may be meaningless since the only data set where band 4 had significant correlation with the water quality parameters was in the 1980 Delta and then it was one of several highly correlated variables. Band 3 appears to have an important association with Delta TSS and TURB for both dates and also 1980 Delta SAL, thus a transformation of these count values may be beneficial.

The results of Table 6 also show that there is no difference between radiance and reflectance transformations. A lack of difference between CV's of these transformations seems to indicate that the difference in sun elevations between the two data sets was not a critical factor. Nelson's findings (1985) indicated that the reflectance transformation consistently produced the smallest CV's for a given band/area test and Verdin (1985) indicated that a similar reflectance transformation was necessary to model reservoir trophic conditions, therefore this methodology was adopted as a prerequisite to developing predictive models for the water quality parameters. Converted reflectance values for 1980 and 1983 data are listed in Table 7.

Correlation matrices were constructed for each date/area combination and the coefficients summarize the relationships between water quality parameters and reflectance variables (REF) (Tables 8.1 through 8.4).

The Delta region's TURB and TSS data are highly correlated with the spectral measurements for all reflectance terms in 1980 and REF 1 through REF 3 in 1983. SAL data shows high correlation for all bands for 1980 but has no measure of significant association with the 1983 reflectances. The Delta CHLA data show no apparent relationship with any of the reflectance terms for either date.

Table 7. Landsat 2 (1980) and Landsat 4 (1983) reflectance values.

STA	REF1	REF2	REF3	REF4
3	0.12880	0.09063	0.06336	0.02547
4	0.12357	0.08706	0.05371	0.03385
6	0.12357	0.08098	0.04942	0.03106
7	0.13207	0.08247	0.05317	0.02687
8	0.12619	0.08349	0.05049	0.02687
9	0.12889	0.07942	0.05371	0.02827
10	0.12422	0.07993	0.04889	0.02547
11	0.12489	0.07789	0.04835	0.02547
23	0.13011	0.07789	0.04899	0.02547
24	0.12619	0.07891	0.04996	0.02827
25	0.12553	0.07738	0.04889	0.02547
26	0.12619	0.07993	0.04352	0.03106
27	0.13011	0.08349	0.05317	0.02827
28	0.12815	0.07993	0.05264	0.03106
29	0.12553	0.07789	0.05317	0.02966
30	0.12880	0.07585	0.05264	0.02687
31	0.12291	0.08044	0.04567	0.02547
32	0.11964	0.07279	0.05317	0.02827
46	0.13469	0.08451	0.05103	0.02547
47	0.13862	0.08757	0.05478	0.03525
48	0.14516	0.09471	0.06014	0.02687
49	0.14254	0.09572	0.06121	0.02547
51	0.14320	0.09165	0.05693	0.02966
52	0.14647	0.10286	0.06604	0.03665
53	0.14843	0.10439	0.06175	0.03525
55	0.12488	0.07840	0.04835	0.02547
56	0.13535	0.08502	0.04889	0.02547
57	0.13731	0.08604	0.04996	0.02827
58	0.13665	0.08553	0.05317	0.02547
59	0.13333	0.08655	0.05478	0.02687
60	0.13993	0.08910	0.05425	0.02827
61	0.13207	0.08706	0.05317	0.03804
62	0.14385	0.10031	0.06979	0.03106
63	0.14451	0.10337	0.07033	0.02547
64	0.14124	0.10388	0.07194	0.04503
65	0.14385	0.11050	0.07462	0.03944
66	0.14909	0.11764	0.07998	0.04084
68	0.14974	0.12274	0.08748	0.06458
69	0.15432	0.12019	0.08480	0.04503
70	0.15493	0.12070	0.08373	0.05899
72	0.15759	0.12834	0.09552	0.07156
74	0.15890	0.13486	0.09606	0.06877
75	0.16810	0.13803	0.09874	0.07017
77	0.14909	0.11407	0.07944	0.04363
78	0.14974	0.11407	0.07676	0.05061
79	0.14451	0.11254	0.08105	0.04223
85	0.15563	0.12885	0.09392	0.06179
86	0.17063	0.12987	0.09392	0.07017
88	0.17063	0.14006	0.10196	0.07156

STA	REF1	REF2	REF3	REF4
4	0.10441	0.06897	0.04130	0.04659
5	0.09757	0.06702	0.04166	0.04457
6	0.09806	0.06272	0.04166	0.03267
7	0.09952	0.06389	0.04085	0.04356
8	0.09952	0.06194	0.03880	0.03852
9	0.09757	0.05999	0.03552	0.04256
10	0.09463	0.05882	0.03429	0.03953
11	0.09463	0.05803	0.03306	0.03953
12	0.08779	0.05139	0.03224	0.04256
13	0.08828	0.05022	0.03347	0.03852
14	0.09365	0.05530	0.03757	0.03146
15	0.09854	0.05960	0.03839	0.04256
16	0.09806	0.05999	0.03470	0.03852
17	0.09463	0.05999	0.03880	0.04155
18	0.09952	0.06116	0.03757	0.03247
33	0.09317	0.05491	0.03142	0.04054
34	0.09757	0.06546	0.04003	0.04861
35	0.09610	0.05921	0.03593	0.03953
36	0.10246	0.06741	0.03552	0.03449
37	0.08730	0.06155	0.03429	0.03650
38	0.09260	0.06233	0.02856	0.03852
39	0.09561	0.05647	0.03224	0.04155
40	0.09659	0.06467	0.03511	0.03852
41	0.09659	0.06467	0.03757	0.04175
42	0.11126	0.07796	0.04535	0.04760
43	0.11463	0.08382	0.04904	0.05163
44	0.11272	0.08460	0.04963	0.06172
45	0.12301	0.10295	0.05641	0.06172
46	0.12495	0.10139	0.05682	0.05466
47	0.11957	0.10139	0.05978	0.05970
48	0.12446	0.10256	0.05887	0.05567
49	0.12006	0.09905	0.05395	0.06273
50	0.11810	0.09436	0.05191	0.05769
52	0.11077	0.08850	0.05150	0.05869
53	0.10881	0.08225	0.05027	0.05567
54	0.11224	0.08616	0.05068	0.06071
55	0.11175	0.08381	0.05232	0.06172
56	0.10783	0.08347	0.04827	0.05769
57	0.12006	0.09983	0.05395	0.05466
59	0.12250	0.11116	0.06997	0.07080
60	0.13815	0.10764	0.06378	0.05970
61	0.12201	0.10491	0.06419	0.05970
62	0.12299	0.09983	0.06133	0.05567
63	0.11903	0.09631	0.05354	0.04760
64	0.11664	0.09358	0.05436	0.05970
65	0.11419	0.08772	0.05060	0.04457
66	0.11321	0.09045	0.05272	0.05869
67	0.10783	0.08186	0.05027	0.05466
68	0.10832	0.08381	0.03799	0.05769
69	0.11126	0.07678	0.04863	0.05466

The variability in the 1980 SAL data for the Bay region is directly related to the variability in REF 1 and REF 2 and somewhat associated with REF 3 and REF 4. The 1983 Bay SAL data are not significantly correlated with any of the reflectances. The TURB data have a marginal relationship with REF 1 through REF 3 in 1980 and REF 1 and REF 2 in 1983. The 1980 TSS and CHLA data and the 1983 TSS data show no significant correlations and the 1983 CHLA data are only slightly correlated with REF 3.

Collinearity is apparent among the first three reflectance terms of all the date/region data sets. The 1980 Delta REF 4 values also express redundant information. If the independent variables are highly correlated, the regression coefficients have the potential to be altered by slight changes in the independent variables when using standard regression models. However, if the correlation pattern is generally consistent collinearity will not affect the predictive capabilities of the models.

<u>Entire Bay/Delta Model Development</u>

Stepwise regression was used to select reflectance variables which would explain a significant portion of the variance in the water quality parameters for the entire Bay/Delta and separate regions by date. The intent of the model development for both dates was to compare independent parameters and their coefficients to determine if a single area water quality model could be used to predict for both occasions given different tide and flow conditions. The stepwise regression technique evaluates all the variables in the model for significance when a new parameter is

Table 8.1. Correlation coefficients for 1980 Landsat 2 MSS reflectance values and water quality parameters from the Delta region.

CORRELATION COEFFICIENTS/PROB > |R| under Ho:RHo = 0/n = 17

	REF 1	REF 2	REF 3	REF 4	TURB	TSS	CHLA	SAL
REF 1	1.0000 0.0000	0.9015 0.0001	0.8920 0.0001	0.8274 0.0001	0.7357 0.0008	0.5601 0.0194	-0.2255 0.3842	-0.8542 0.0001
REF 2		1.0000 0.0000	0.9843 0.0001	0.9112 0.0001	0.9000 0.0001	0.7311 0.0009	-0.0807 0.7580	-0.9647 0.0001
REF 3			1.0000 0.0000	0.9216 0.0001	0.9080 0.0001	0.7288 0.0009	-0.0681 0.7953	-0.9676 0.0001
REF 4				1.0000 0.0000	0.8639 0.0001	0.7148 0.0013	-0.0270 0.9181	-0.9033 0.0001
TURB					1.0000 0.0000	0.8642 0.0001	0.0669 0.7986	-0.9006 0.0001
TSS						1.0000 0.0000	0.3602 0.1555	-0.7498 0.0005
CHLA							1.0000 0.0000	-0.0271 0.9178
SAL								1.0000 0.0000

Table 8.2. Correlation coefficients of 1980 Landsat 2 MSS reflectance values and water quality parameters from the Bay region.

CORRELATION COEFFICIENTS/PROB > |R| under Ho:RHo = 0/n = 32

	REF 1	REF 2	REF 3	REF 4	TURB	TSS	CHLA	SAL
REF 1	1.0000	0.8658	0.6801	0.2833	0.4789	0.0809	0.0104	-0.7377
	0.0000	0.0001	0.0001	0.1157	0.0056	0.6600	0.9550	0.0001
REF 2		1.0000	0.7930	0.4339	0.5780	0.1173	0.1801	-0.7370
		0.0000	0.0001	0.0131	0.0005	0.5223	0.3238	0.0001
REF 3			1.0000	0.3372	0.5462	0.1002	0.3030	-0.5347
			0.0000	0.0591	0.0012	0.5858	0.0917	0.0016
REF 4				1.0000	0.2199	-0.1753	-0.0060	-0.3770
				0.0000	0.2261	0.3373	0.9743	0.0334
TURB					1.0000	0.4346	0.3789	-0.3528
					0.0000	0.0129	0.0325	0.0477
TSS						1.0000	0.1221	-0.0657
						0.0000	0.5057	0.7211
CHLA							1.0000	-0.0499
							0.0000	0.7861
SAL								1.0000
								0.0000

Table 8.3. Correlation coefficients for 1983 Landsat 4 MSS reflectance values and water quality parameters from the Delta region.

CORRELATION COEFFICIENTS/PROB > |R| under Ho:RHo = 0/n = 26

	REF 1	REF 2	REF 3	REF 4	TURB	TSS	CHLA	SAL
REF 1	1.0000 0.0000	0.8725 0.0001	0.7752 0.0001	0.2044 0.3162	0.7583 0.0001	0.8112 0.0001	0.1220 0.5529	0.3649 0.0668
REF 2		1.0000 0.0000	0.8660 0.0001	0.4126 0.0362	0.8692 0.0001	0.8787 0.0001	-0.0493 0.8109	0.2416 0.2346
REF 3			1.0000 0.0000	0.4399 0.0245	0.8609 0.0001	0.8100 0.0001	0.0044 0.9822	0.2397 0.2378
REF 4				1.0000 0.0000	0.3676 0.0646	0.3780 0.0568	-0.2597 0.2006	-0.1577 0.4420
TURB					1.0000 0.0000	0.9107 0.0001	-0.0511 0.8044	0.2095 0.3044
TSS						1.0000 0.0000	0.1135 0.5809	0.3435 0.0858
CHLA							1.0000 0.0000	0.5546 0.0033
SAL								1.0000 0.0000

Table 8.4. Correlation coefficients for 1983 Landsat 4 MSS reflectance values and water quality parameters for the Bay region.

CORRELATION COEFFICIENTS/PROB > |R| under Ho:RHo = 0/n = 24

	REF 1	REF 2	REF 3	REF 4	TURB	TSS	CHLA	SAL
REF 1	1.0000	0.7260	0.6296	0.1383	0.4049	0.3122	-0.1900	0.0151
	0.0000	0.0001	0.0010	0.5195	0.0498	0.1376	0.3717	0.9435
REF 2		1.0000	0.5868	0.2160	0.5885	0.1248	-0.0400	-0.3440
		0.0000	0.0026	0.3103	0.0025	0.5619	0.8534	0.0996
REF 3			1.0000	0.2216	0.3825	0.3657	-0.4698	0.1755
			0.0000	0.2978	0.0648	0.0788	0.0205	0.4122
REF 4				1.0000	0.1871	-0.1476	-0.0705	-0.0971
				0.0000	0.3809	0.4909	0.7436	0.6515
TURB					1.0000	-0.1967	0.3217	-0.5541
					0.0000	0.3569	0.1253	0.0050
TSS						1.0000	-0.5586	0.5633
						0.0000	0.0046	0.0042
CHLA							1.0000	-0.5573
							0.0000	0.0047
SAL								1.0000
								0.0000

entered and any non-significant variables are subsequently dropped. The criteria for selecting a parameter for entry into the model was based on a significance level of 0.05.

Concurrent with the work done using stepwise regression, each of the independent variables were compared with the spectral characteristics of the water quality parameter as described in the literature. They were also evaluated using support information such as correlation coefficients and plots of bands vs. the water quality parameters.

RESULTS AND DISCUSSION

Water Quality Parameters

After dividing the study area into two regions based on their specific water quality and spectral properties and eliminating those points which were close to sources of high reflectance, the final version of the data used in regional model development is summarized in Table 9. It should be noted that the 1980 water quality data for the Delta region exhibited higher measurements of salinity and chlorophyll a compared to 1983 values. This probably was the result of high freshwater inflow conditions in 1983. Total suspended solids and turbidity were also higher under lower flow conditions, yet other studies have found high concentrations of suspended material and increases in turbidity with higher outflows (Conomos et al. 1979; Arthur and Ball 1979). This could have been caused, as Conomos et al. explain, by greater volumes of resuspended sediment transported landward by wind and the near-bottom nontidal currents and by the greater production of organic matter

Table 9. Statistical description of 1980 and 1983 water quality and spectral parameters for the Bay and Delta regions.

	MEAN	STD DEV	MIN	MAX
1980 Bay Region (n = 32)				
TURB (NTU)	5.44	2.38	2.00	12.00
CHLA (ug/l)	1.97	0.88	0.50	4.10
TSS (mg/l)	10.40	4.77	2.10	23.00
SAL (ppt)	25.82	4.62	16.20	30.30
REF 1	0.1317	0.0077	0.1196	0.1484
REF 2	0.0845	0.0074	0.0728	0.1044
REF 3	0.0530	0.0051	0.0435	0.0660
REF 4	0.0286	0.0037	0.0255	0.0380
1980 Delta Region (n = 17)				
TURB	24.12	7.27	13.00	37.00
CHLA	14.74	7.21	4.10	30.90
TSS	42.74	10.57	21.70	62.00
SAL	6.31	3.62	1.10	13.50
REF 1	0.1531	0.0091	0.1412	0.1707
REF 2	0.1200	0.0121	0.1003	0.1401
REF 3	0.0847	0.0104	0.0698	0.1020
REF 4	0.0530	0.0152	0.0255	0.0716
1983 Bay Region (n = 24)				
TURB	2.95	1.63	0.70	6.80
CHLA	5.60	3.95	0.55	16.25
TSS	29.46	8.34	14.70	44.90
SAL	19.63	5.47	7.50	25.30
REF 1	0.0960	0.0042	0.0873	0.1044
REF 2	0.0607	0.0048	0.0502	0.0690
REF 3	0.0364	0.0037	0.0286	0.0433
REF 4	0.0398	0.0043	0.0315	0.0486
1983 Delta Region (n = 26)				
TURB	15.59	7.83	8.00	33.50
CHLA	3.20	1.33	1.46	8.02
TSS	23.81	11.84	11.00	46.00
SAL	1.78	2.05	0.10	6.30
REF 1	0.1168	0.0070	0.1078	0.1382
REF 2	0.0925	0.0098	0.0768	0.1112
REF 3	0.0536	0.0066	0.0380	0.0699
REF 4	0.0571	0.0054	0.0446	0.0708

(phytoplankton) in the Entrapment Zone. The 1980 Bay region has higher measures of salinity as expected compared with the 1983 data. It also had a higher average TURB, whereas the 1983 Bay region had greater average measures of TSS and CHLA.

In examining the 1983 data for the Delta region, there were 14 points which fell within Arthur and Ball's (1979) specified 1 to 6 ppt salinity concentration range. These points stretched from Suisun Bay to Carquinez Strait. There were three points in the Strait which were in the salinity range but their TURB and TSS values were less than those in Suisun Bay which were two to three times higher than those upstream or downstream. The 1980 data for the Delta region had all but five points within the salinity range. These points extended from the middle of Suisun Bay to the confluence of the rivers.

The sample size of the 1980 Bay/Delta data was reduced by more than 30% after points close to sources of high reflectance (see Preliminary Data Analysis section) were removed. These points were among the most variable and their removal resulted in having to redevelop the models of Khorram (1985). The new models described linear relationships with first order terms for TSS, TURB, and SAL compared to quadratic and logrithimic terms which were used in the previous 1980 models. The 1980 CHLA model was redefined from a quadratic function which included all the spectral terms as a two term model which estimated CHLA as a function of e^x. The R^2 values for the new TSS, TURB, and SAL models were comparable with the earlier ones (Khorram 1985), but the new models had fewer terms. The goodness of fit of the new log CHLA could not be compared with the previous model since the error term is multiplicative in this function. The exponential design of the CHLA model suggested that it is fitting some threshold response and that there may be a spurious relationship between the water quality parameter and the Landsat MSS reflectance variables.

The results of all the models are listed in Table 10 and the plots of their goodness of fit are given in Figures 4 - 9. Predicted water quality values from each model were regressed onto their observed values and the results of these exercises were graphed. The regression lines which were fit through these plots can be interpreted as a measure of the deviation of the predicted values from the observed since an ideal fit would result in an intercept of 0 and a slope of 1. The plots of residuals vs. predicted values where residuals were generated from the difference between observed and predicted is another method by which model performance was measured. Ideally the graph should resemble a "horizontal band" where the distribution has a mean of 0 and a constant variance. If there is a deviation from this pattern the model is interpreted to be incorrect (Draper and Smith 1981).

SAL and TURB were the only parameters which could be compared between dates. The structural differences between these models for the two dates indicated that general models could not describe both data sets because the 1980 SAL and TURB models had linear terms, whereas the 1983 models had curvilinear expressions.

Table 10. Statistical summary of entire Bay/Delta models.

Model	R^2	F/PROB>F	RMSE	Model Coefficients	Coefficient Standard Error	T/PROB>T
1980 (n = 49)						
TURB = $b_0 + b_1$ (REF 3) $+ b_2$ (REF 4)	.93	324.5/.0001	7.044	b_0 = -22.78	1.79	-12.78/.0001
				b_1 = 456.85	57.22	7.98/.0001
				b_2 = 146.83	64.68	2.27/.028
TSS = $b_0 + b_1$ (REF 3)	.84	248.3/.0001	47.756	b_0 = 38.01	3.91	-9.72/.0001
				b_1 = 931.42	59.11	15.76/.0001
SAL = $b_0 + b_1$ (REF 2)	.91	476.6/.001	9.739	b_0 = 68.28	2.30	29.71/.0001
				b_1 = -508.34	23.28	-21.83/.0001
Log (CHLA) = $b_0 + b_1$ (REF 1) $+ b_2$ (REF 3)	.71	57.6/.0001	0.342	b_0 = 1.27	1.52	0.84/.407
				b_1 = -35.96	15.85	-2.27/.028
				b_2 = 78.04	12.31	6.34/.0001
1983 (n = 50)						
TURB = $b_0 + b_1$ (REF 2) $+ b_2$ (REF 2^2) $+ b_3$ (REF 3^2)	.91	146.86/.0001		b_0 = 20.89	10.05	2.08/.043
				b_1 = -773.32	261.93	-2.95/.005
				b_2 = 6601.61	1799.56	3.67/.001
				b_3 = 3304.69	1417.12	2.33/.024
SAL = $b_0 + b_1$ (1/REF 2) $+ b_2$ (1/REF 3) $+ b_3$ (1/REF 4)	.80	60.39/.0001		b_0 = -28.27	3.23	-8.77/.0001
				b_1 = 3.02	0.61	4.99/.0001
				b_2 = -0.73	0.33	-2.21/.032
				b_3 = 0.67	0.26	2.58/.013

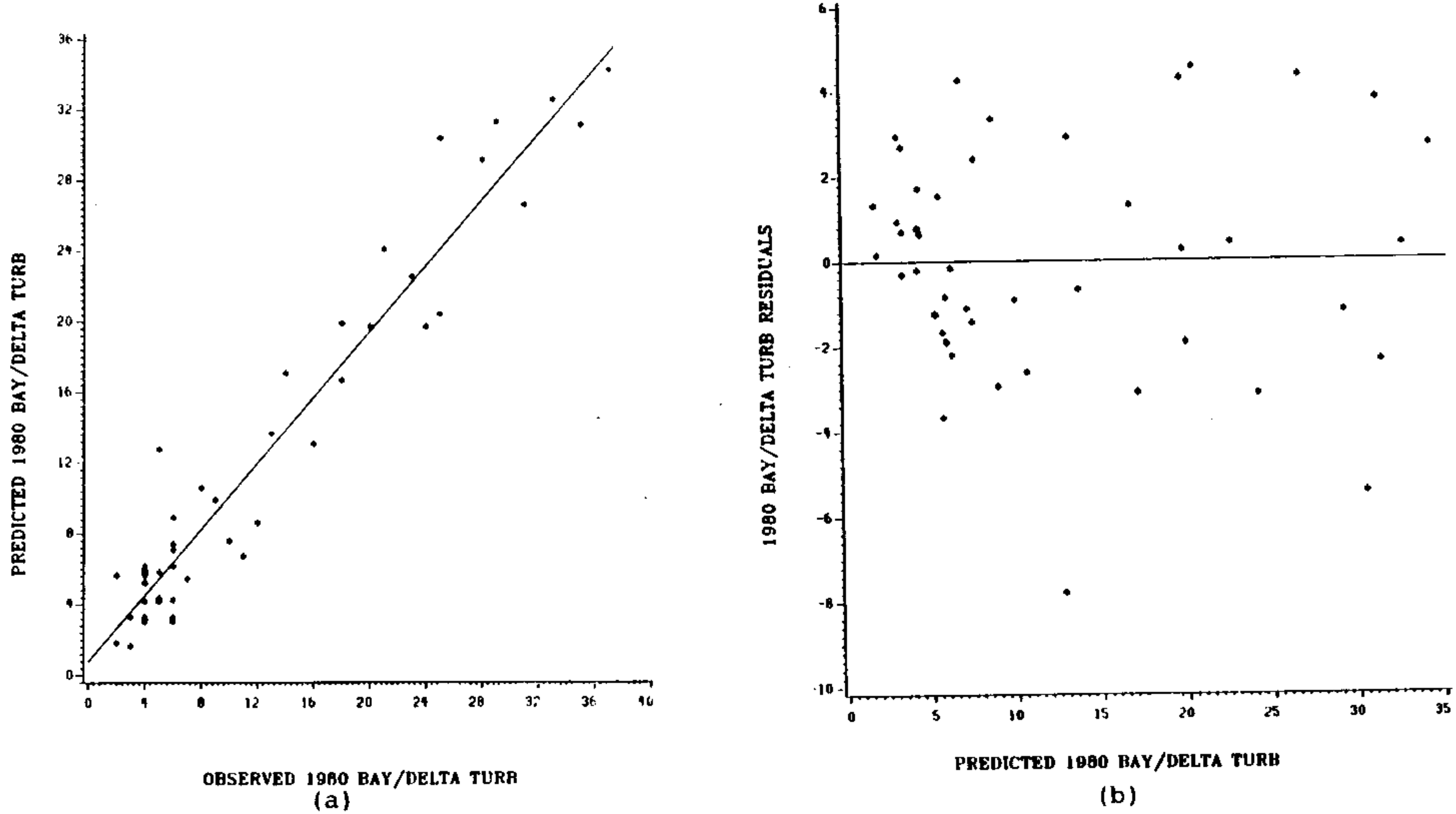


Fig. 4. Bay/Delta 1980 turbidity model performance (a) predicted vs. observed turbidity (NTU), (b) residuals vs. predicted.

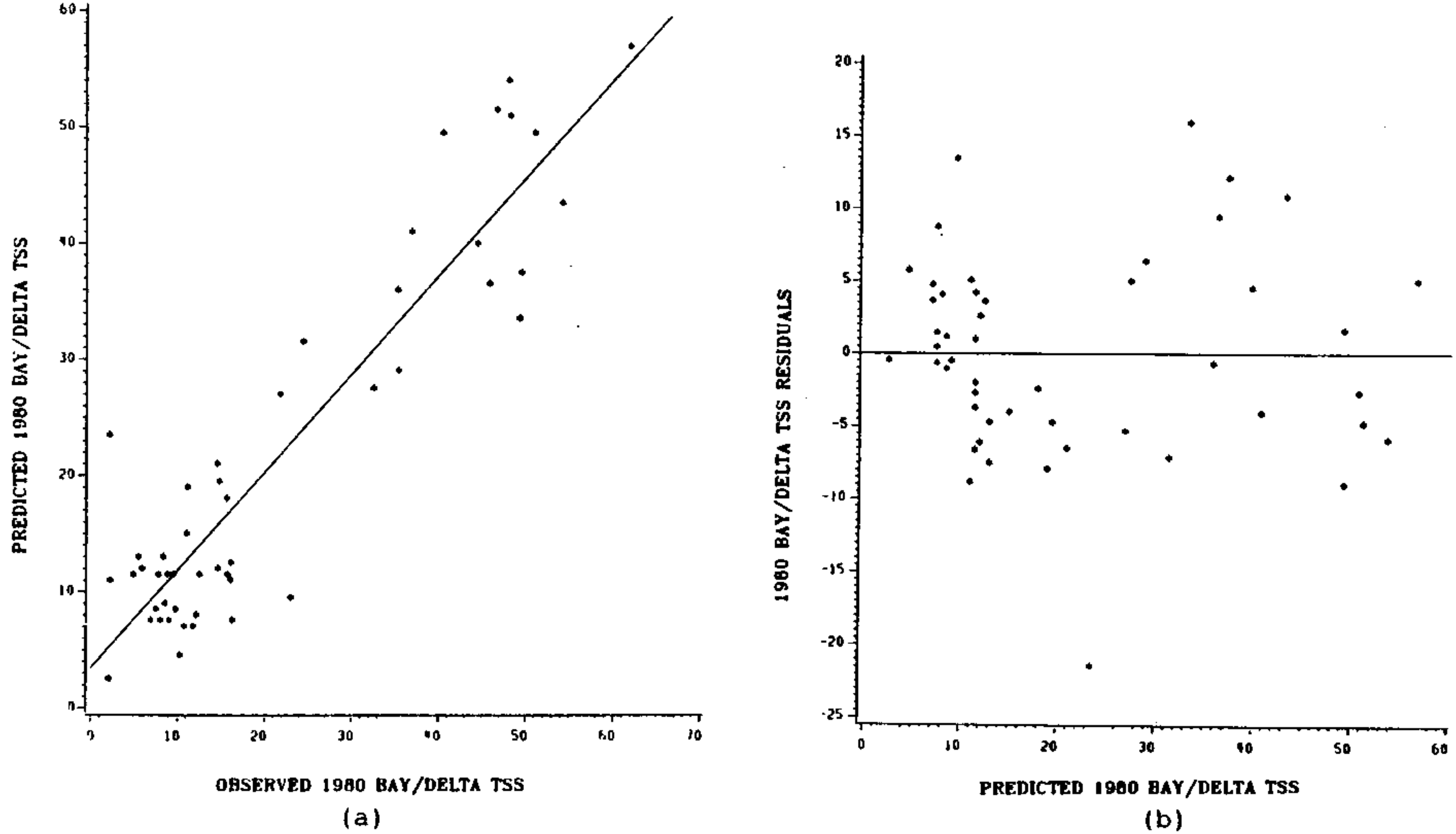


Fig. 5. Bay/Delta 1980 total suspended solids model performance, (a) predicted vs. observed total suspended solids (mg/l), (b) residuals vs. predicted.

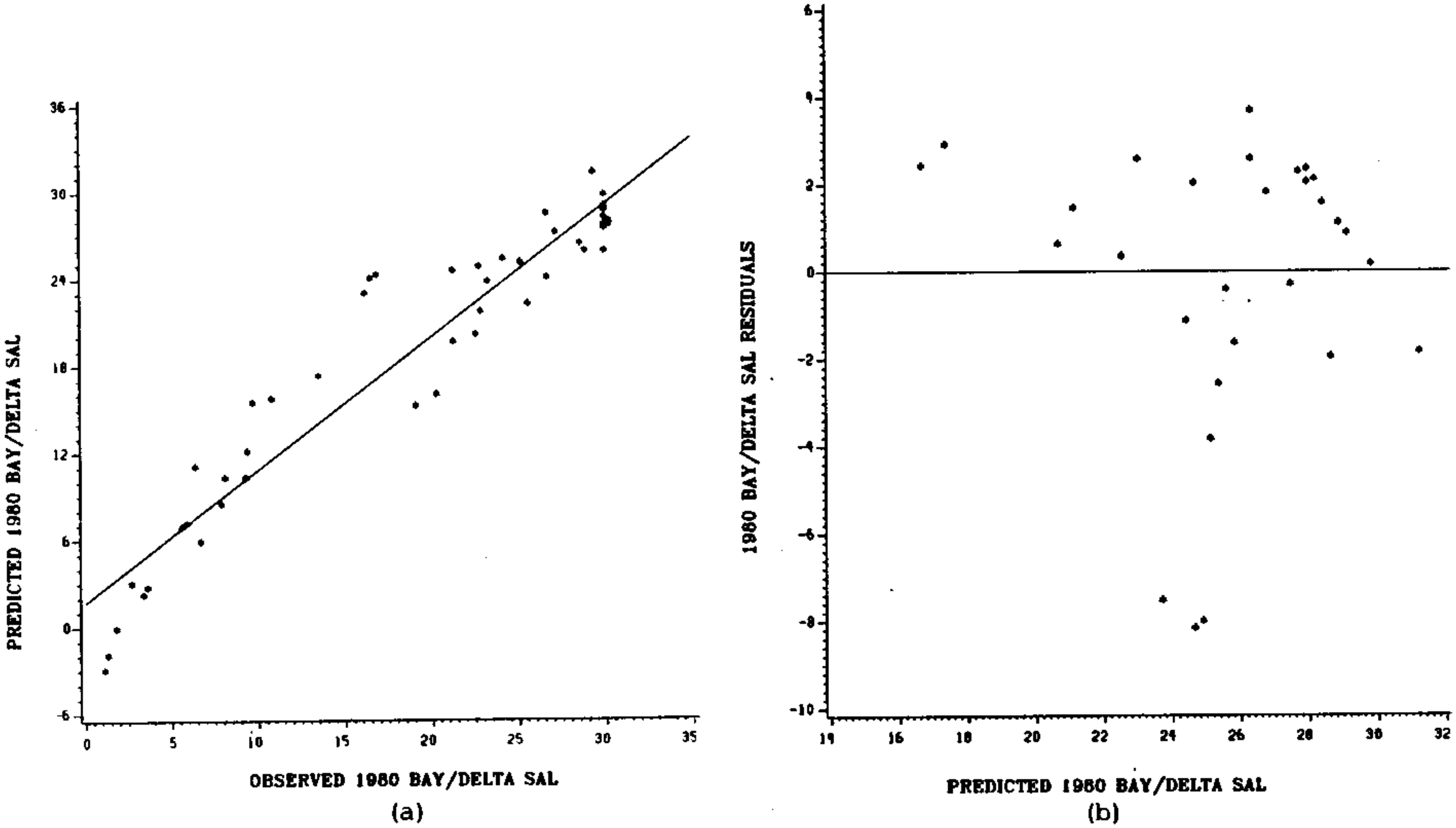
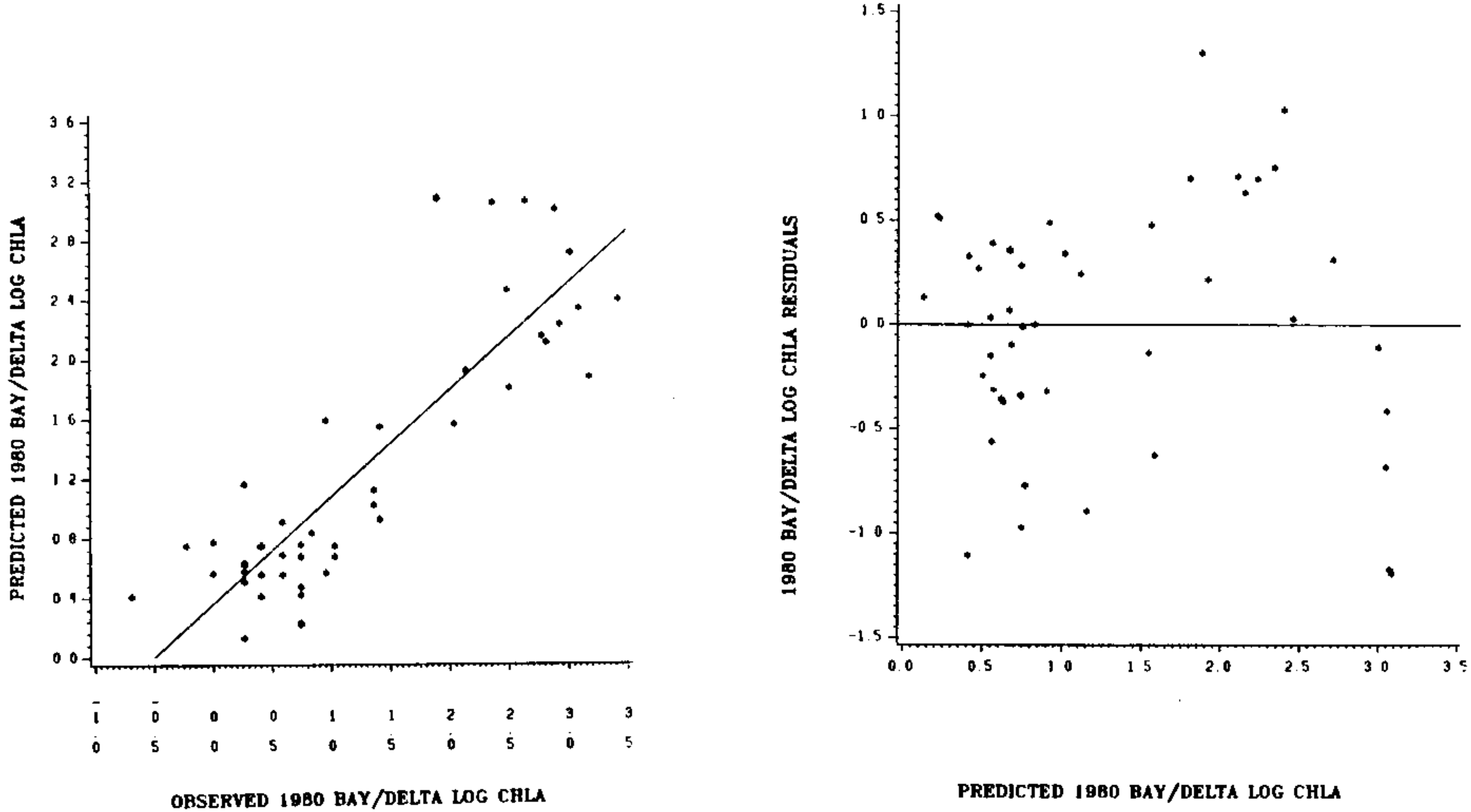


Fig. 6. Bay/Delta 1980 salinity model performance, (a) predicted vs. observed salinity (ppt), (b) residuals vs. predicted.



(a) (b)

Fig. 7. Bay/Delta 1980 chlorophyll a log model performance, (a) predicted vs. observed log chlorophyll a (ug/l), (b) residuals vs. predicted.

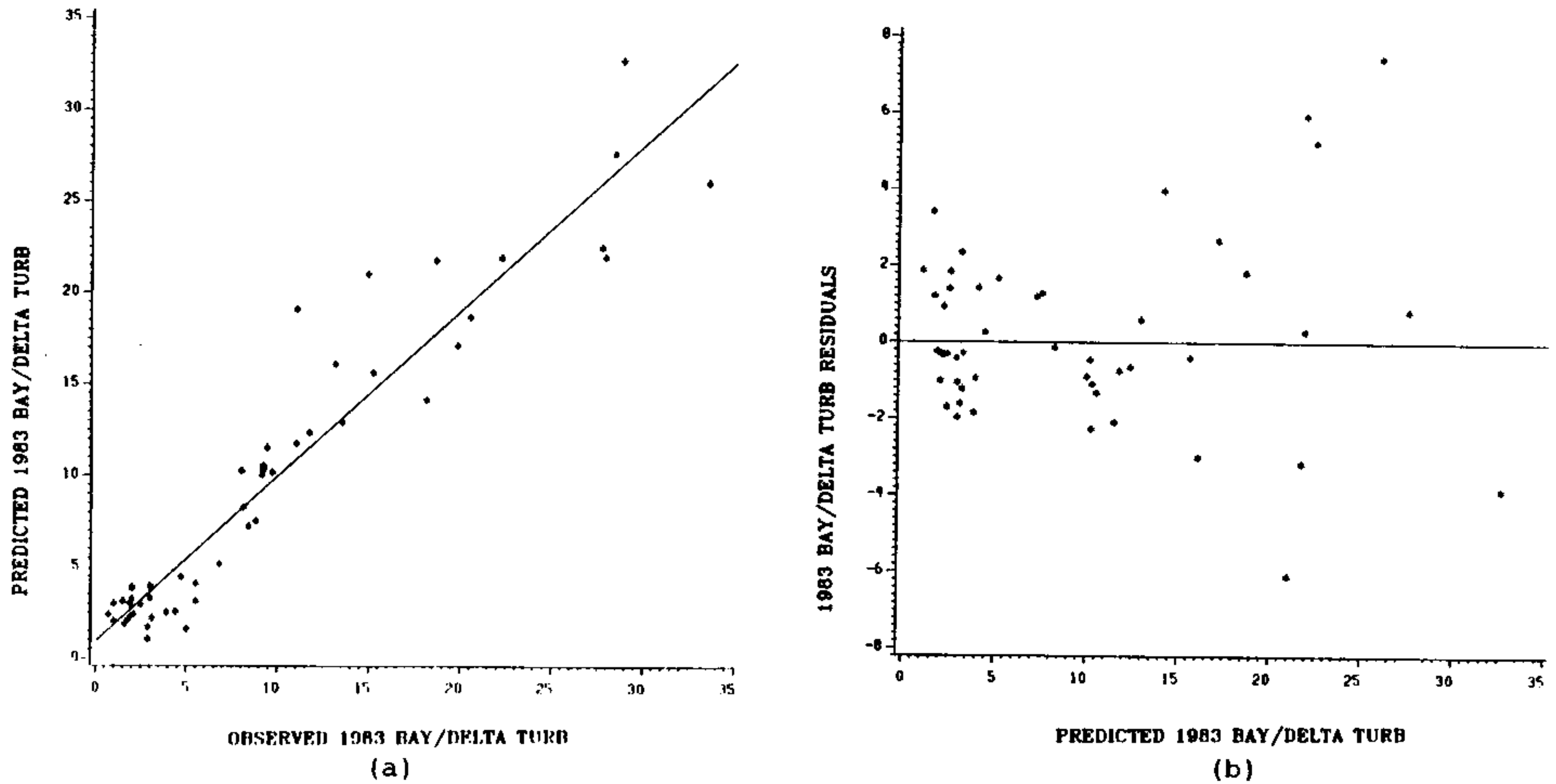


Fig. 8. Bay/Delta 1983 turbidity model performance, (a) predicted vs. observed turbidity (NTU), (b) residuals vs. predicted.

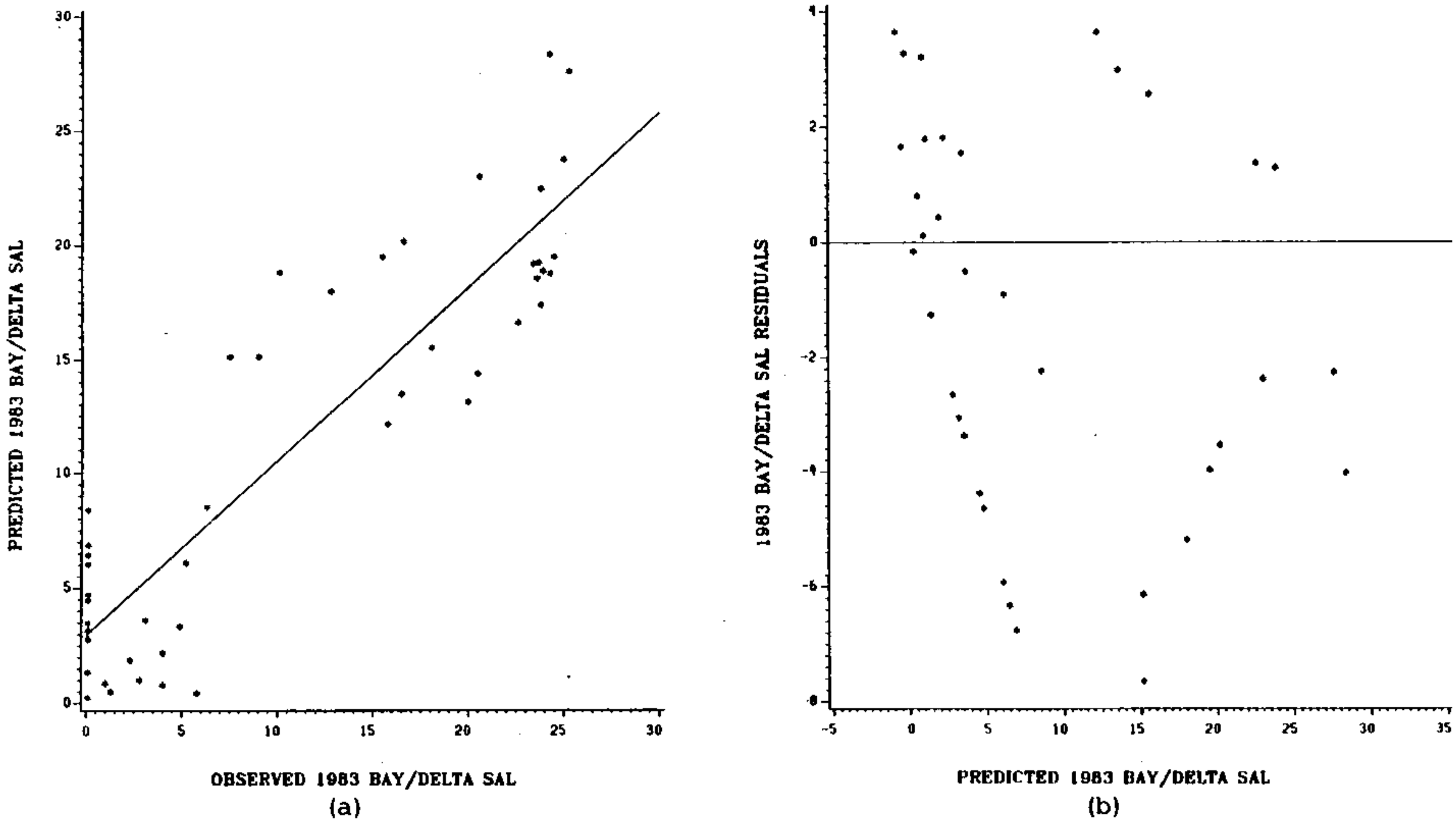


Fig. 9. Bay/Delta 1983 salinity model performance, (a) predicted vs. observed salinity (ppt), (b) residuals vs. predicted.

Regional Model Development

Regional water quality models were developed for those parameters which expressed a relationship with the reflectance values. The results of these models are discussed separately by date and area, and a statistical summary is given in Table 11.

Chlorophyll *a*. Attempts to find a simple model based on known spectral responses of chlorophyll were very unsuccessful. Stepwise regression methods determined that there were no significant reflectance parameters which explained the variability within the Delta for either date. There was also no predictive relationship associated with the 1980 Bay chlorophyll data and reflectance variables. A model was selected by stepwise regression for the 1983 Bay data which incorporated REF 3 but its R^2 was only 0.23 and plots of model performance (Fig. 10a, b) suggest that the regression is being directed by two influential points. Based on the results, the 1983 Bay CHLA model was not considered as a useful predictive equation. Correlation coefficients for chlorophyll and reflectance variables were all nonsignificant at the 0.05 level and plots by region show no relationship between the spectral values and this water quality parameter.

The difficulty in modeling chlorophyll is likely the result of errors in the fluorimetric measurement technique, satellite limitations, and biological and physical characteristics associated with phytoplankton. Catts et al. (1985) mention that phytoplankton can be transported considerable distances over a short time in the San Francisco Bay/Delta currents and that their findings indicate that surface

Table 11. Statistical summary of regional models.

Model	R^2	F/PROB>F	RMSE	Model Coefficients	Coefficient Standard Error	T/PROB>T
1980 DELTA (n = 17)						
TURB = $b_0 + b_1$ (REF 3)	.82	70.4/.0001	9.900	b_0 = -29.51	6.44	-4.59/.0004
				b_1 = 633.14	75.44	8.39/.0001
TSS = $b_0 + b_1$ (REF 2)	.53	17.2/.0009	55.448	b_0 = -33.97	18.57	-1.83/.087
				b_1 = 639.36	154.07	4.15/.0009
SAL = $b_0 + b_1$ (REF 3)	.94	220.1/.0001	0.892	b_0 = 34.77	1.93	18.00/.0001
				b_1 = -336.06	22.65	-14.84/.0001
1983 DELTA (n = 26)						
TURB = $b_0 + b_1$ (REF 2)	.80	46.6/.0001	13.165	b_0 = -48.10	6.88	-6.99/.0001
$+ b_2$ (REF 3)				b_1 = 394.30	147.89	2.67/.014
				b_2 = 514.78	220.67	2.33/.029
TSS = $b_0 + b_1$ (REF 2)	.77	81.3/.0001	33.291	b_0 = -73.37	10.94	-6.71/.0001
				b_1 = 1060.18	117.59	9.02/.0001

Table 11. continued

Model	R^2	F/PROB>F	RMSE	Model Coefficients	Coefficient Standard Error	T/PROB>T
1980 BAY (n = 32)						
TURB = $b_0 + b_1$ (REF 2)	.33	15.05/.0005	3.904	b_0 = -10.33	4.08	-2.53/.017
				b_1 = 186.51	48.08	3.88/.0005
SAL = $b_0 + b_1$ (REF 1)	.54	35.81/.0001	10.047	b_0 = 84.06	9.75	8.62/.0001
				b_1 = -442.23	73.90	-5.98/.0001
1983 BAY (n = 24)						
TURB = $b_0 + b_1$ (REF 2)	.35	11.65/.0025	1.81	b_0 = -9.28	3.59	-2.58/.017
				b_1 = 201.60	59.05	3.41/.003
SAL = $b_0 + b_1$ (REF 2)	.33	5.30/.014	21.81	b_0 = 36.12	12.79	2.82/.010
+ b_2 (REF 3)				b_1 = -785.00	253.03	-3.10/.005
				b_2 = 856.13	326.88	2.62/.016
CHLA = $b_0 + b_1$ (REF 3)	.22	6.23/.021	12.70	b_0 = 23.93	7.38	3.24/.004
				b_1 = -504.19	201.98	-2.50/.021

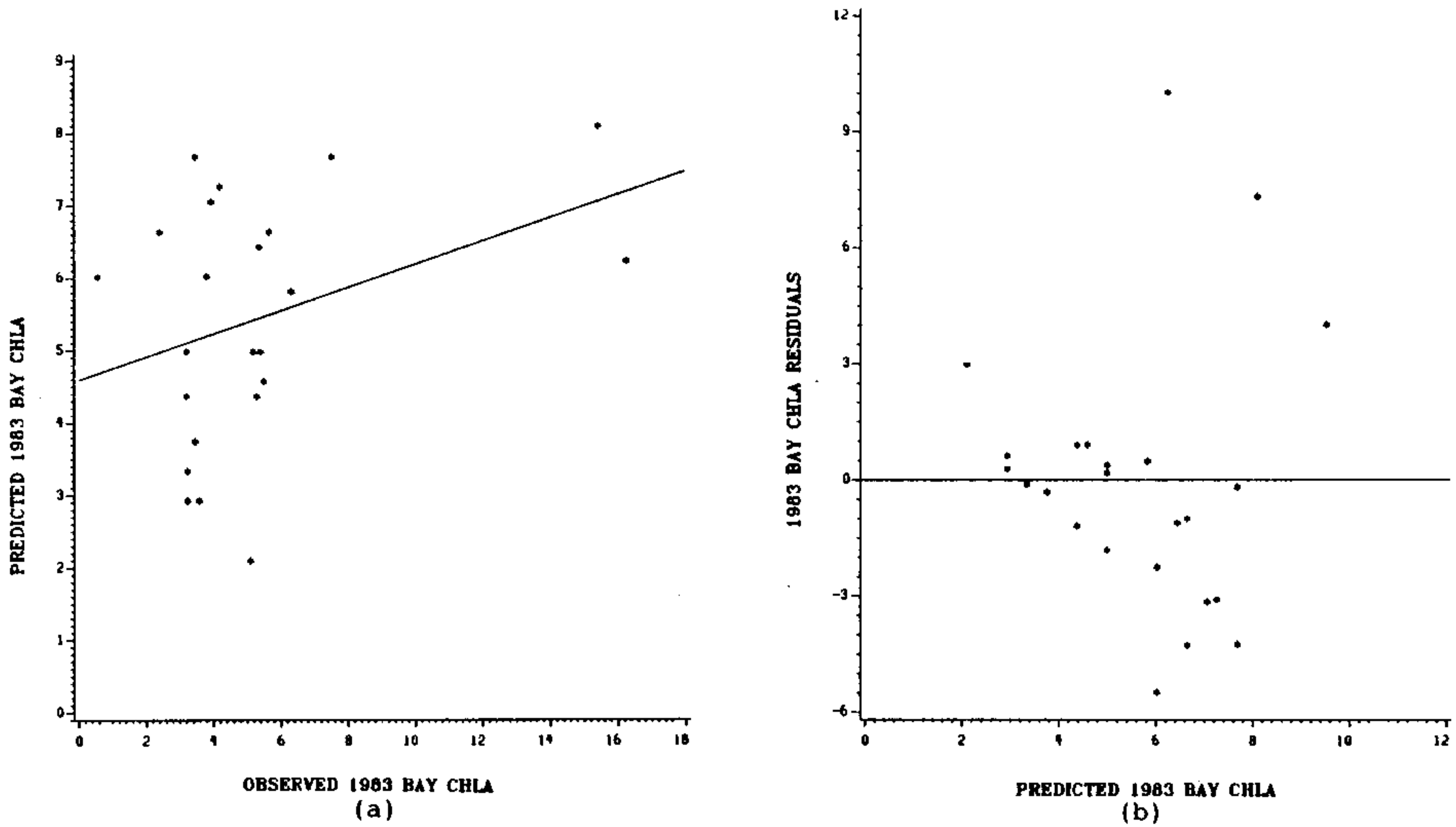


Fig. 10. Bay 1983 chlorophyll a model performance, (a) predicted vs. observed chlorophyll a concentrations (ug/l), (b) residuals vs. predicted.

surface measurements of chlorophyll _a_ collected within 10 minutes of a scanner overflight should be analyzed for a more reliable assessment. This analysis was not possible for either data set in this study because of the limited number of samples collected at the time of satellite overpass.

Salinity. Salinity may be causing inorganics to flocculate reducing turbidity in the estuary. Suspended particles of silt and clay can cause turbid conditions within the water column yet may not correlate well with the mass per unit volume measurement of TSS. The 1980 Bay and Delta and 1983 Bay salinity parameters were all negatively correlated with turbidity although to a lesser extent for the Bay parameters. This might suggest that water clarity is proportionally related to salinity which would be in agreement with Cloern's description (Personal communication) of increasing mean photic depth in the Bay where higher saline concentrations occur.

The 1983 Delta salinity had extremely low measured values which were likely the result of denser saline water being forced seaward by high freshwater runoff. These data were not significantly correlated with any water quality parameter at the 0.05 significance level except chlorophyll.

The 1980 Delta data had negative correlations for SAL vs. TURB and TSS. There was also a high positive correlation between TSS and TURB indicating that suspended sediments may be contributing to turbid conditions and that salinity is reducing the effects of turbidity. The 1980 Bay SAL data had no relationship with TSS, and TSS and TURB had a weak association. Krone (1979) points out that a majority of the larger suspended inorganics settle out by the time they reach San Pablo Bay. As a result, Bay salinity may be reacting with silts and clays which would scatter light in the water but may not impact the TSS measurements.

The 1983 Bay SAL data was negatively correlated with TURB to a greater degree than the 1980 Bay data. SAL also had a positive association with TSS, but TSS and TURB were poorly correlated. The negative relationship between SAL and TURB may be the result of a similar interaction hypothesized for the 1983 Bay data but the particle sizes may be larger given the high velocity Delta outflow which could transport such material. Flocculation of larger particles could result in a measurable increase of TSS; however, the lack of correlation between TURB and TSS suggests that other factors may be involved. More detailed information about the constituents that comprise TSS needs to be collected in the future to determine the types of interactions that may be occurring.

A salinity model for 1980 Delta conditions exhibited a high R^2 (.94) with a single independent variable (REF 3). Plots of this model are given in Figure 11 a and b. The model design for 1980 Delta salinity differed from the three parameter model Khorram (1982) developed for 1978 Delta conditions even though the salinity and spectral values were in the same general ranges for both dates. This might be the result of interactions occurring between salinity and surrogate parameters, thus it is uncertain whether a single general predictive model can explain Delta salinity.

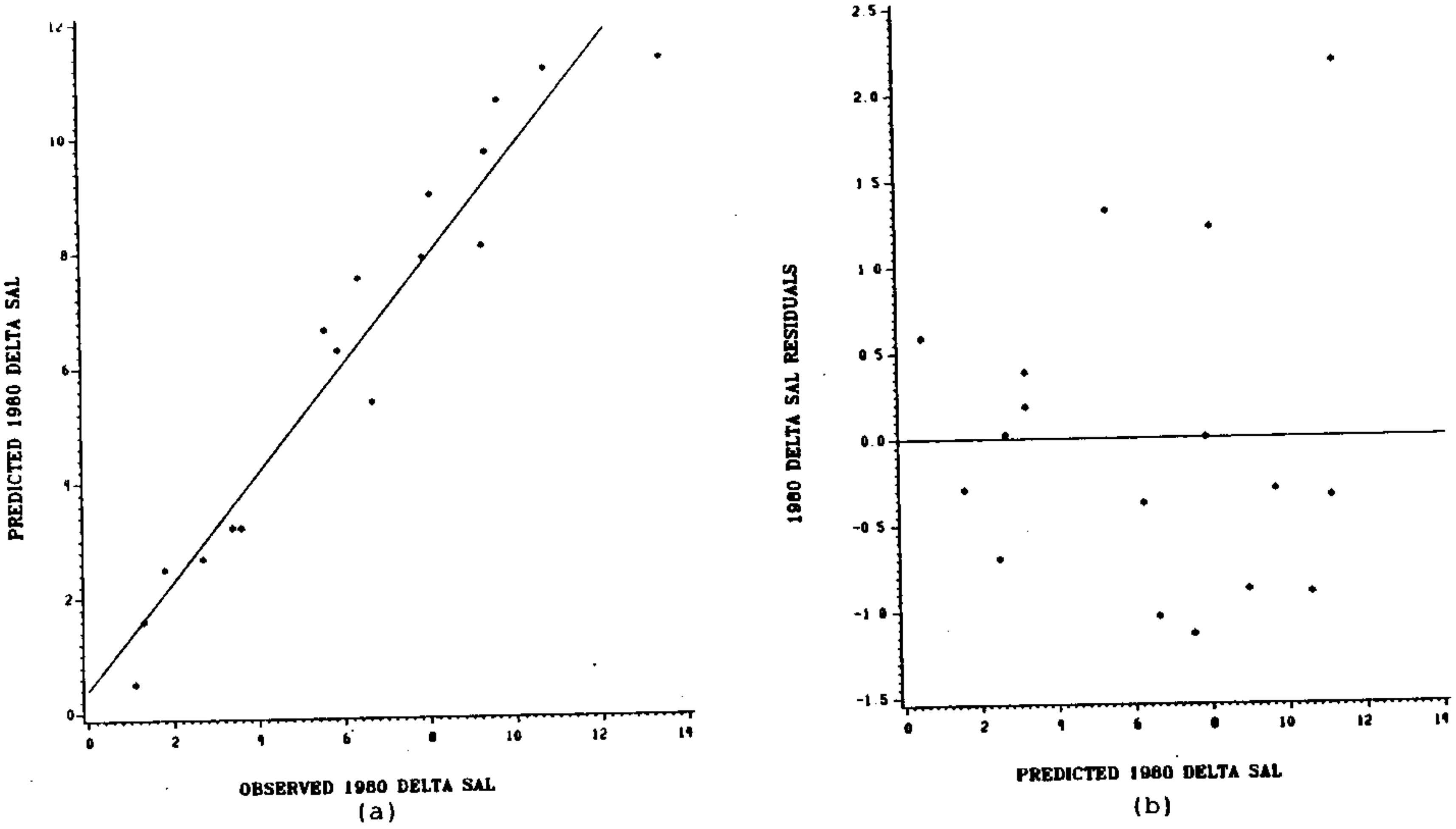


Fig. 11. Delta 1980 salinity model performance, (a) predicted vs. observed salinity (ppt), (b) residuals vs. predicted.

Each Bay salinity model emphasized different spectral terms and their coefficients of determination indicated that there was a lot of variability in the salinity data which was unaccounted for. The performances of these models are seen in Fig. 12 a-b and Fig. 13 a-b. A difference in concentration, size, or type of suspended material which salinity might be reacting with would account for the difference in the spectral variables between the two models. An increase in the size of suspended particles would cause a shift to longer wavelengths and this might be the relationship the 1983 model is based upon.

Plots of the 1983 Bay salinity data versus each of the reflectance values (Fig. 14) revealed a higher measure of salinity and an apparent linear trend associated with those points (n = 15) below the Golden Gate outlet, while salinity measurements in San Pablo Bay and northern San Francisco Bay were lower and seemed to have no relationship with the spectral variables. Conomos (1979) explains that changes in the southern reach salinity structure depends on the magnitude of the peak Delta outflow and that the flushing of this area may take several weeks. The linear trend in the southern Bay suggests that the salinity structure has not been affected by the freshwater Delta outflow yet, while the behavior of the points in the upper Bay is probably the result of a transition zone where Delta outflow is encountering higher salinity concentrations and creating a source of high variability. This example shows that further research is needed to understand and account for the variability of hydrodynamic conditions in the San Francisco Bay estuary.

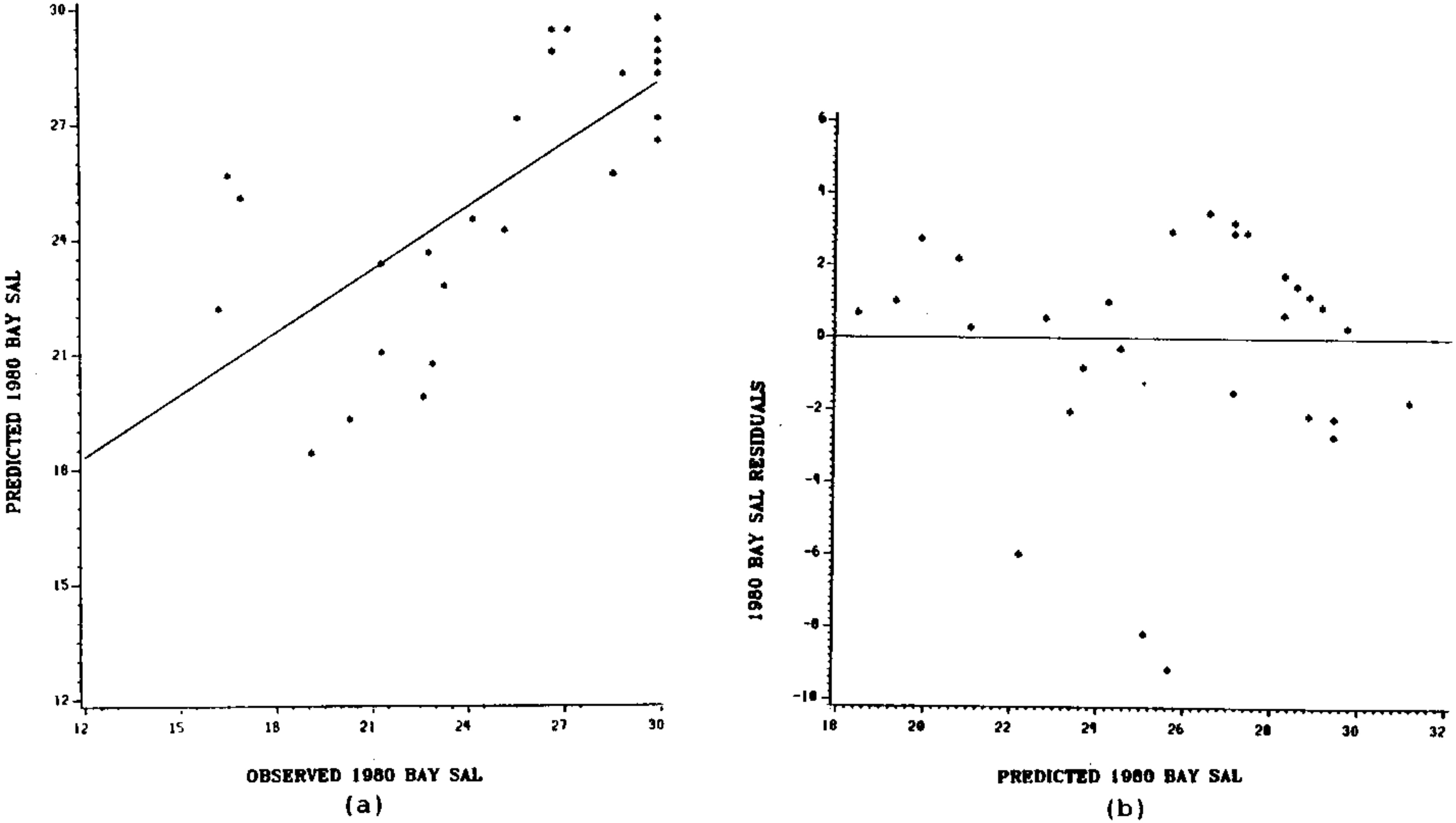
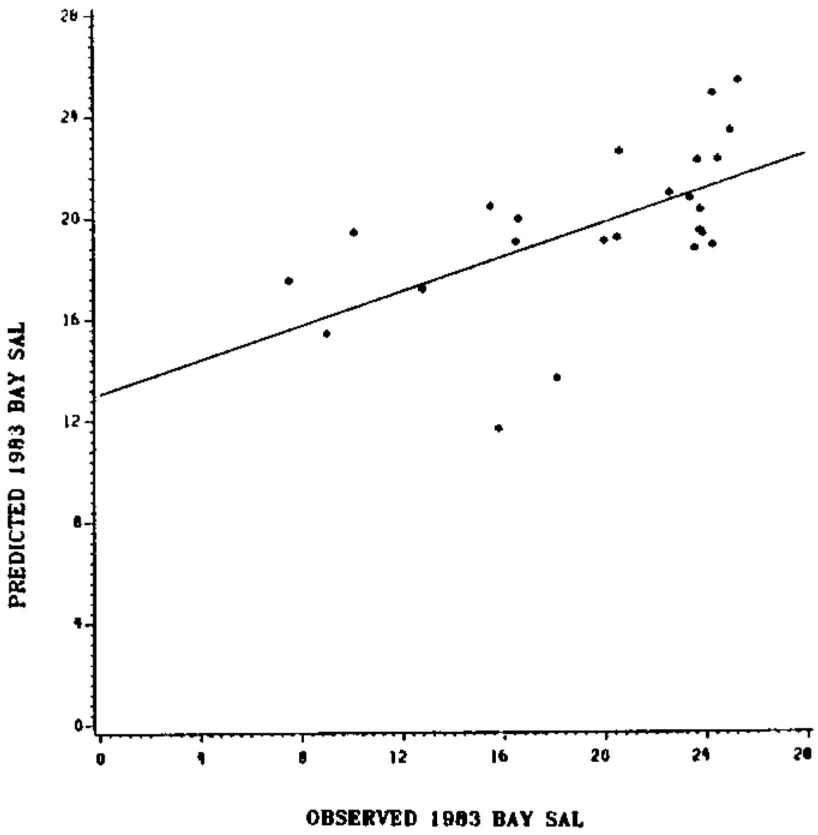
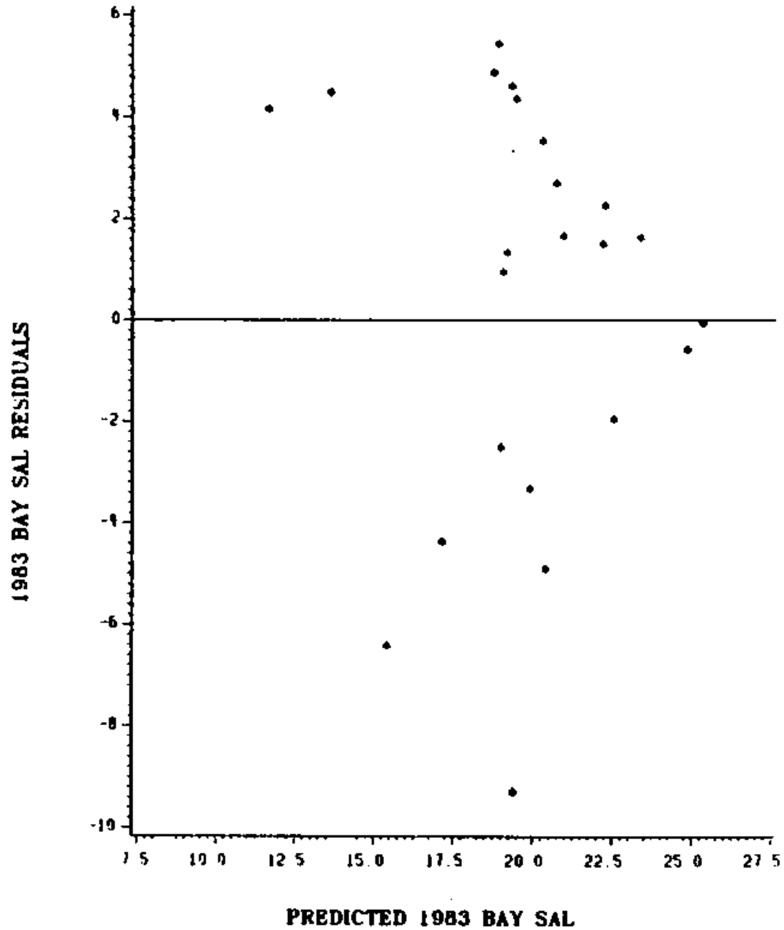


Fig. 12. Bay 1980 salinity model performance, (a) predicted vs. observed salinity (ppt), (b) residuals vs. predicted.



(a)



(b)

Fig. 13. Bay 1983 salinity model performance, (a) predicted vs. observed salinity (ppt), (b) residuals vs. predicted.

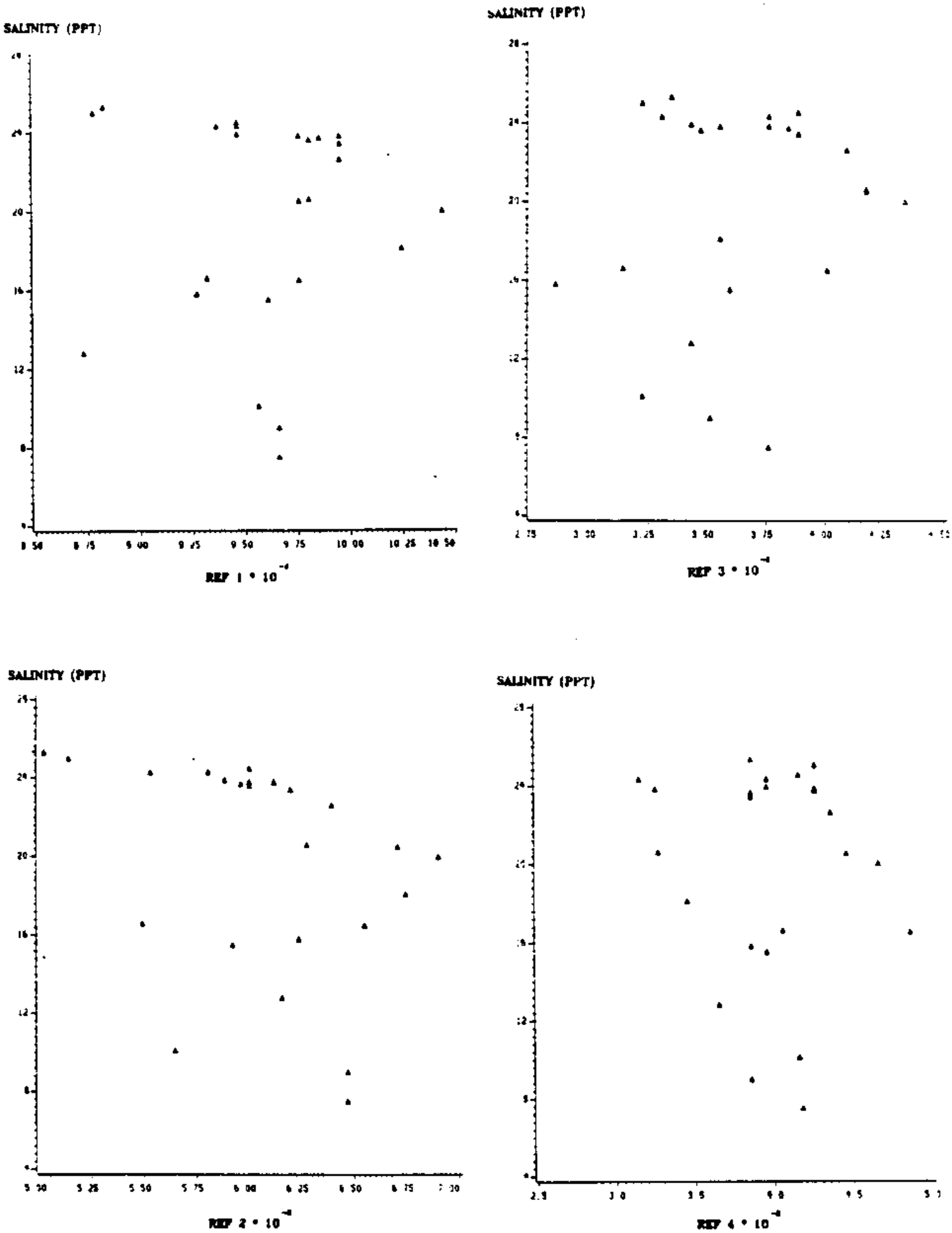


Fig. 14. Bay 1983 salinity values vs. Landsat 4 band reflectance values. Filled triangles represent points in the region from San Pablo Bay to the Golden Gate Bridge and unfilled triangles represent those points in the lower San Francisco Bay.

Turbidity. Turbidity models explained at least 80% of the variability in the Delta data (Fig. 15 a-b and Fig. 16 a-b) and about 34% in the Bay data (Fig. 17 a-b and Fig. 18 a-b) for both dates. The poor fits for Bay turbidity are probably due to clearer water condtions resulting from flocculation and settling of suspended material as well as dilution of Bay water from low-turbid ocean water (Arthur and Ball 1979).

The 1983 Delta model included REF 2 and REF 3 as independent terms whereas the 1980 Delta model was a function of only REF 3. The high correlation between the spectral variables within the two data sets suggests that there are interactions between the independent variables; therefore, intercepts and slopes for the two models could not be directly compared. The fact that REF 2 and REF 3 have a correlation coefficient of 0.98 in the 1980 Delta data indicates that the two terms are nearly interchangeable and is probably why the 1980 model only included one of these terms.

To determine if the models were the same, the 1983 Delta TURB model was fit to the 1980 Delta TURB data then the resulting predicted values were regressed against the 1980 observed values. If the models were the same the expected response in fitting $TURB_{80-83}$ predicted values to the 1980 observed values would be an intercept (b_0) of 0 and a slope (b_1) equal to 1. Confidence intervals of the form

$$b_i = \pm\, t\ (n-2,\ 1- \ /2)\ s_{b_i}$$

where = .05

were constructed on the regression coefficients to test for model similarity. The 1980 Delta TURB function was also applied to the 1983

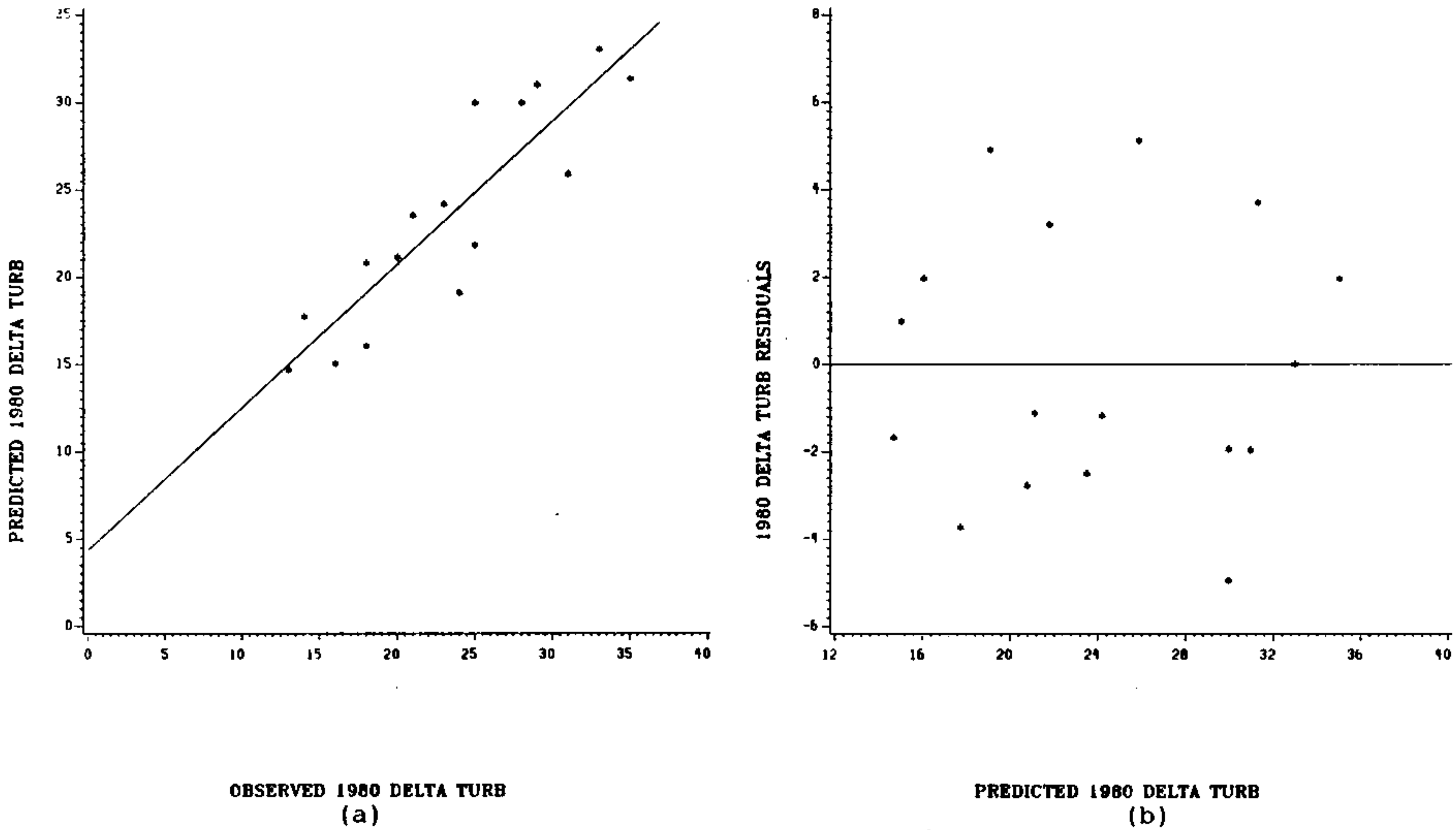
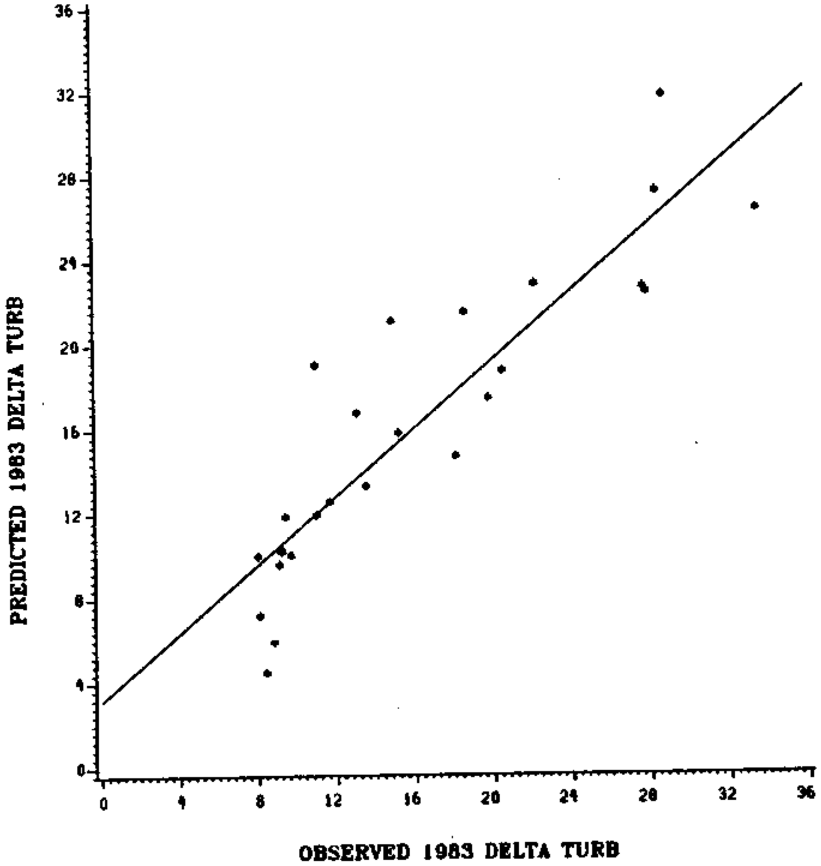
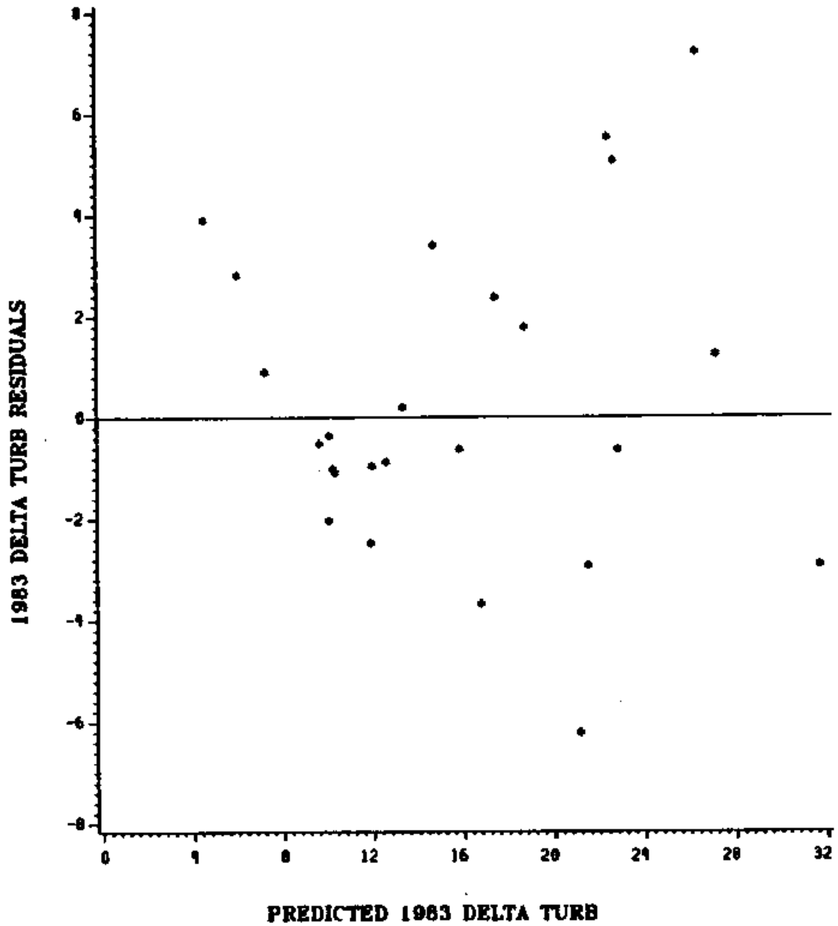


Fig. 15. Delta 1980 turbidity model performance, (a) predicted vs. observed turbidity (NTU), (b) residuals vs. predicted.



(a)



(b)

Fig. 16. Delta 1983 turbidity model performance, (a) predicted vs. observed turbidity (NTU), (b) residuals vs. predicted.

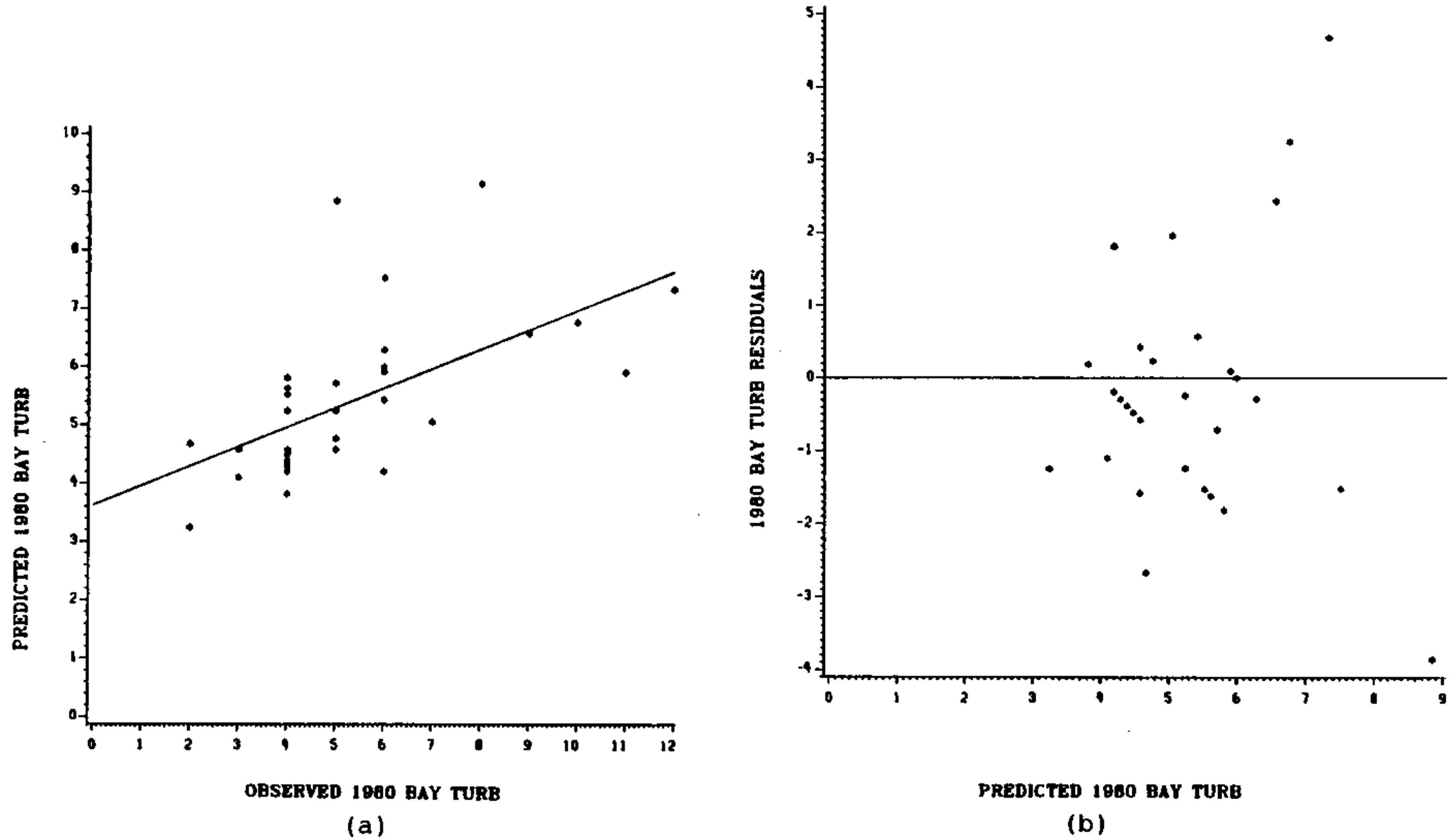


Fig. 17. Bay 1980 turbidity model performance, (a) predicted vs. observed turbidity (NTU), (b) residuals vs. predicted.

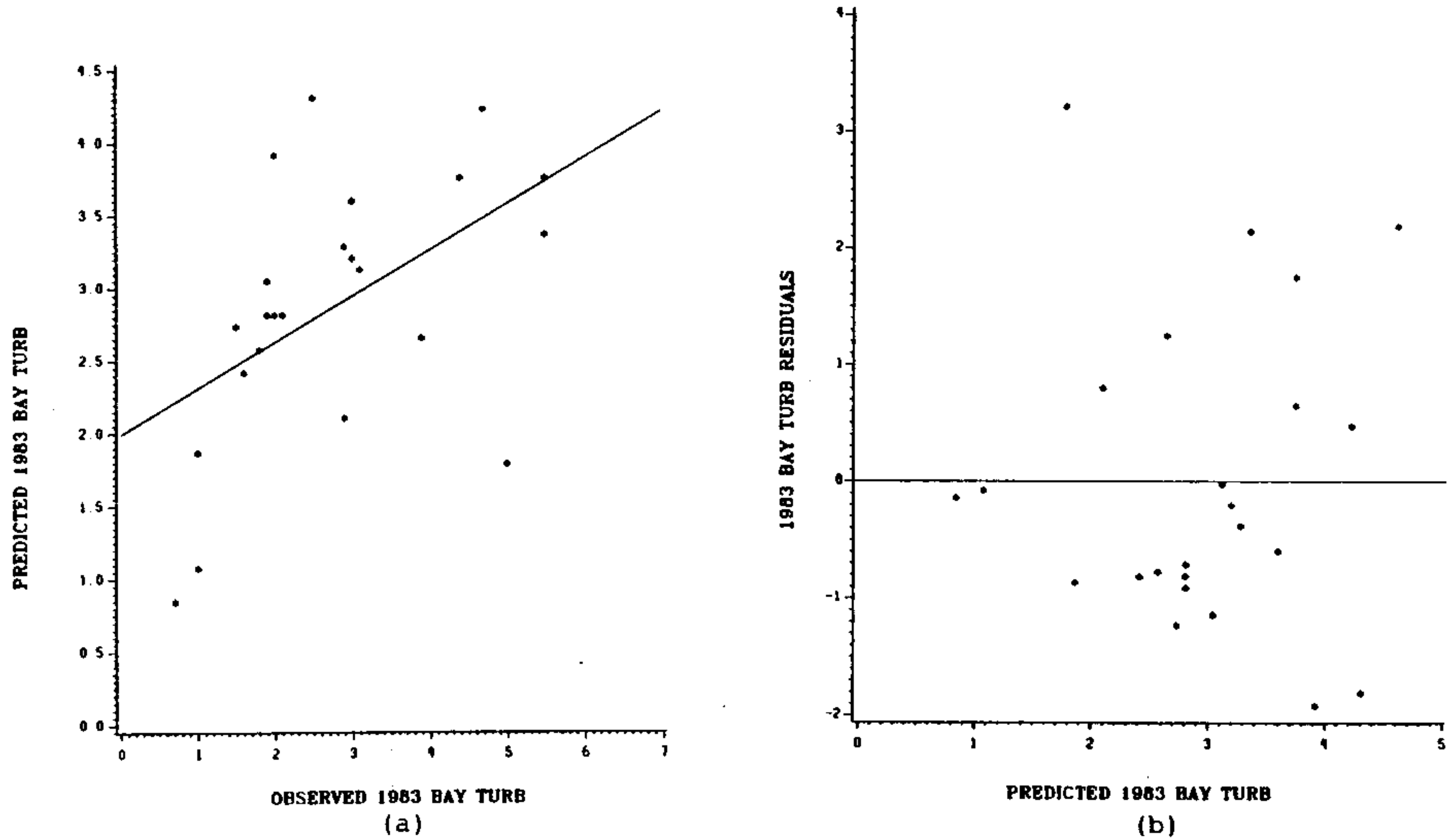


Fig. 18. Bay 1983 turbidity model performance, (a) predicted vs. observed turibdity (NTU), (b) residuals vs. predicted.

data. The TURB 83-80 predicted values were regressed against the 1983 observed values and confidence regions were developed for these regression coefficients as well.

The 1980 one-term (REF 3) model and a two-term (REF 2 and REF 3) version similar to the 1983 TURB model were applied to the 1983 Delta data to determine which one would best fit the 1983 data. If a 1980 two term model could accurately fit the 1983 data, then a single general model could be used to describe Delta TURB conditions for both dates. There was an extremely high correlation (R = .98) between REF 2 and REF 3 in the 1980 Delta data, therefore including both terms in the 1980 model would result in collinearity problems. Both 1980 models yielded essentially the same predictive results among their own data, but the two-term model resulted in unstable estimates of the regression coefficients. The standard errors associated with the coefficients nearly equaled or exceeded the parameter estimates because of collinearity; however, this problem does not effect predictions within the limits of the independent variables and both dates had nearly the same range of spectral values for REF 2 and REF 3.

The regression of 1983 predicted values derived from the 1980 two-term model revealed that the coefficients were nearly the same as the model with predicteds from the 1980 one-term model, but the R^2 associated with the two-term model was slightly better. Since the two-term model behaved the same as the one-term function, this model was used to test model similarity between dates.

The Delta TURB models are not the same based on the confidence interval results (Table 12). The 1983 model appears to be more robust in fitting the 1980 data than is the opposite arrangement. There is a difference in intercepts in the regression of $TURB_{80-83}$ predicteds onto 1980 observed values, but the slope of this model falls within the confidence range which implies that the 1983 model can describe 1980 conditions. The 1980 model was designed to fit a tighter distribution; therefore, it was not flexible enough to describe the more variable 1983 data. This suggests that a general two-term Delta model may have an overall better fit based on correlation coefficients and tests of the regression coefficients.

The same test was constructed for the Bay TURB models. Both models included the same reflectance term; therefore, confidence intervals were calculated for the regression coefficients of the two models. The confidence ranges are

$b_{0_{80}} = (-18.65, -2.01)$ $\qquad b_{0_{83}} = (-16.70, 1.87)$

$b_{1_{80}} = (88.43, 284.59)$ $\qquad b_{1_{83}} = (79.71, 323.49)$

where $t_{80} = 2.040$, and $t_{83} = 2.064$.

The confidence intervals overlap suggesting that the models are the same, but the R^2 values for both models were only about .35, indicating that the model similarity is really a description of the lack of fit which both models share in describing Bay turbidity conditions.

Table 12. Regression coefficient confidence intervals based on the model of predicted vs. observed values where predicted values were generated as a result of the application of 1980 and 1983 Delta TURB models to the data of the alternate year.

Model	n	R^2	Model Coefficients	Coefficient Standard Error	$t_{.05}$	C.I.
$TURB_{80-83} = b_0 + b_1\ TURB_{80}$	17	.82	$b_0 = 12.43$	3.78	2.056	4.37, 20.48
			$b_1 = 1.26$	0.15		0.94, 1.58
$TURB_{83-80} = b_0 + b_1\ TURB_{83}$	26	.79	$b_0 = -2.43$	0.93	2.110	-4.34, -0.52
			$b_1 = 0.49$	0.05		0.38, 0.60

<u>Total Suspended Solids</u>. The 1980 and 1983 TSS models would only be defined for Delta conditions (Fig. 19 a-b and Fig. 20 a-b). The 1980 Bay TSS had an extremely low range for both the water quality parameter and corresponding spectral values with no apparent relationship between the dependent and independent parameters. The 1983 Bay TSS had a distribution which was nearly equivalent to the 1983 Delta but there was minimal correlation bewteen Bay TSS and any of the spectral variables. This suggested that different types of TSS are being detected and the spectral response is registering accordingly.

Both Delta models included REF 2 as their only independent variable; therefore, confidence intervals were constructed on the intercepts and slopes of the two models to determine if they were describing the same relationship. The results are as follows:

$b_{0_{80}}$ (-73.52, 5.58) $\qquad$ $b_{0_{83}}$ (-95.91, -50.83)

$b_{1_{80}}$ (311.19, 967.53) $\qquad$ $b_{1_{83}}$ (817.94, 1302.42)

where $t_{80} = 2.040$, and $t_{83} = 2.064$.

Since the confidence intervals overlapped in both instances, the models were interpreted to be the same. This means that a generalized model can predict Delta TSS as a function of REF 2 under normal runoff and flood conditions, whereas attempts to develop a generalized model for the Bay or entire Bay/Delta were unsuccessful.

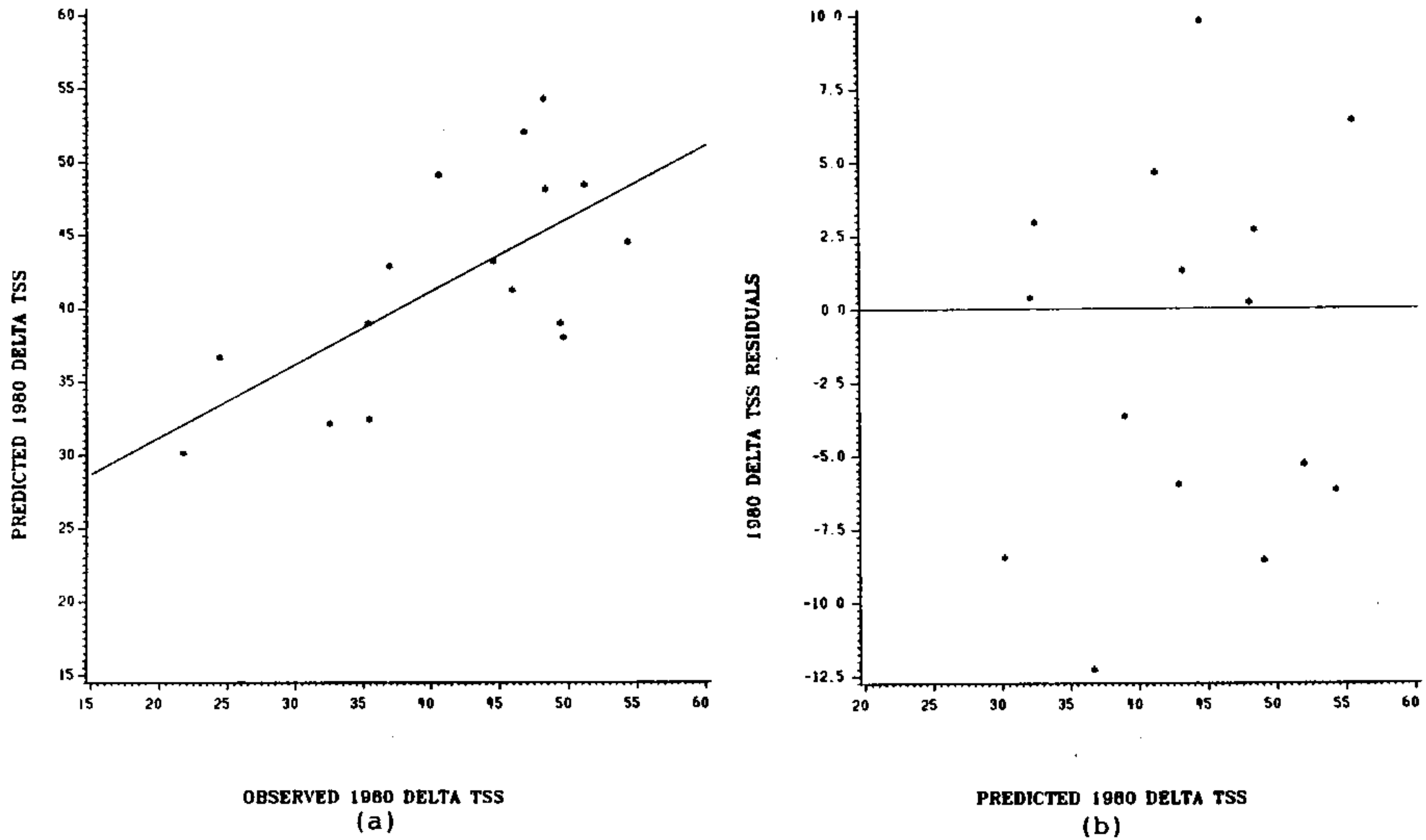


Fig. 19. Delta 1980 total suspended solids model performance, (a) predicted vs. observed total suspended solids (mg/l), (b) residuals vs. predicted.

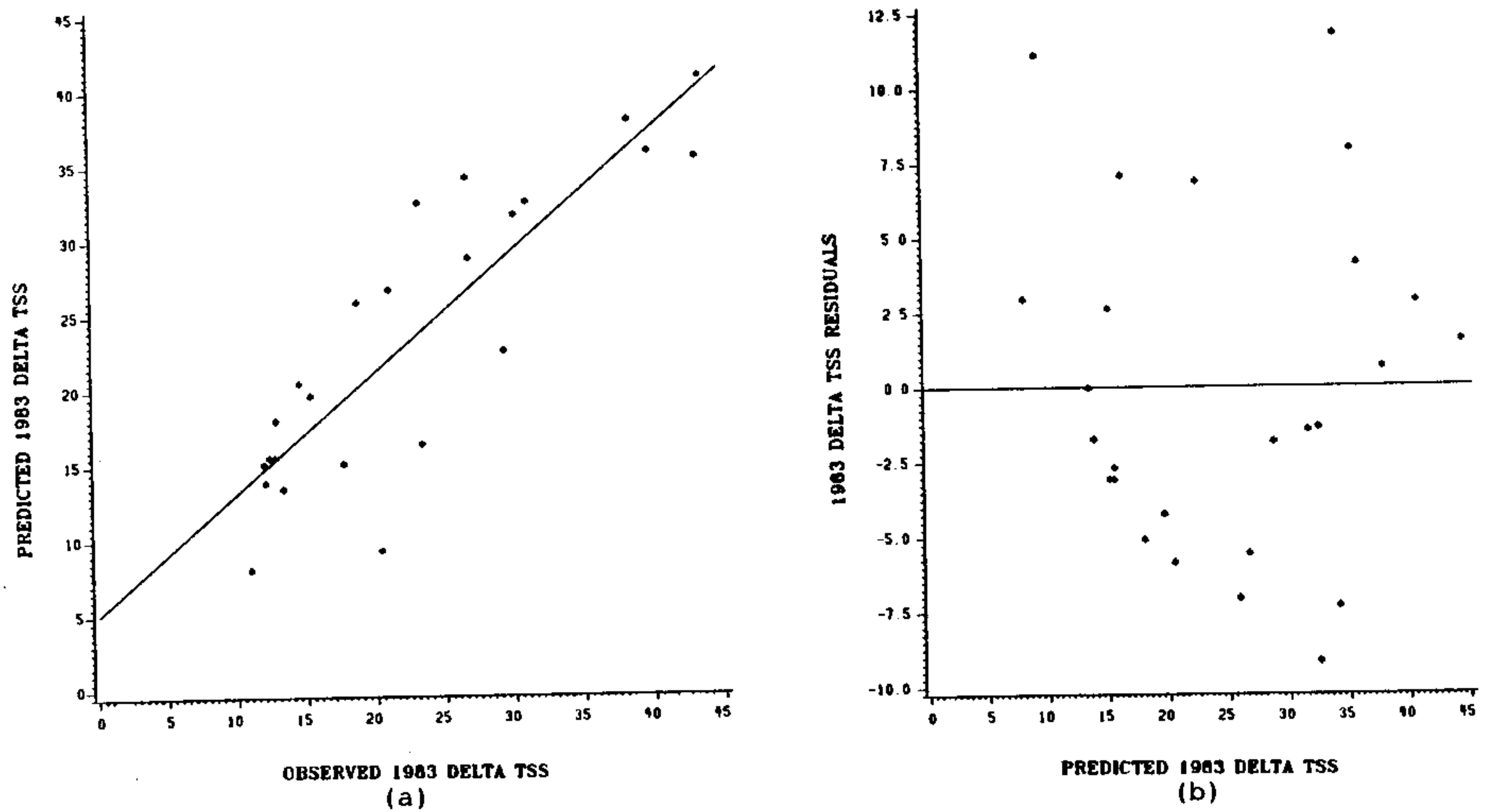


Fig. 20. Delta 1983 total suspended solids model performance, (a) predicted vs. observed total suspended solids (mg/l), (b) residuals vs. predicted.

Model Applications

Delta 1980 and 1983 models were applied to the entire MSS data covering their respective regions. Color-coded distribution maps of water quality parameter concentrations were produced and Entrapment Zone features were compared (Figs. 21 - 25).

Although water quality sample data were collected from only the deep water channels, the predictive models were applied to the entire Delta to assess their overall behavior. An examination of the 1983 range of pixel values throughout the Delta showed that the 1983 range of band 2 spectral values used in model development represented 93% of the entire range and MSS band 3 sample data represented 80% of the entire range of its data. The full range of band 2 and 3 values for the 1980 MSS data included 63% and 84%, respectively, of their sample data. Since all the models except 1980 TSS had large R^2 values and the range of the sample spectral values of bands 2 and 3 used in all the models represented a large portion of the entire MSS data, the application of the models to the entire Delta seemed reasonable.

Color maps of the 1983 TURB and TSS Delta models reveal an area of highest concentration extending from Suisun Bay to the entrance of Carquinez Strait. This area corresponds with the location of 1983 sample points which were indicative of an entrapment zone based on salinity concentrations described by Arthur and Ball (1979), and high measured values of TSS and TURB. The 1980 color maps show the highest concentrations to be located further upstream extending from the confluence of the Sacramento and San Joaquin Rivers to Honker Bay and the upper reach of Suisun Bay. This region also corresponds with sample

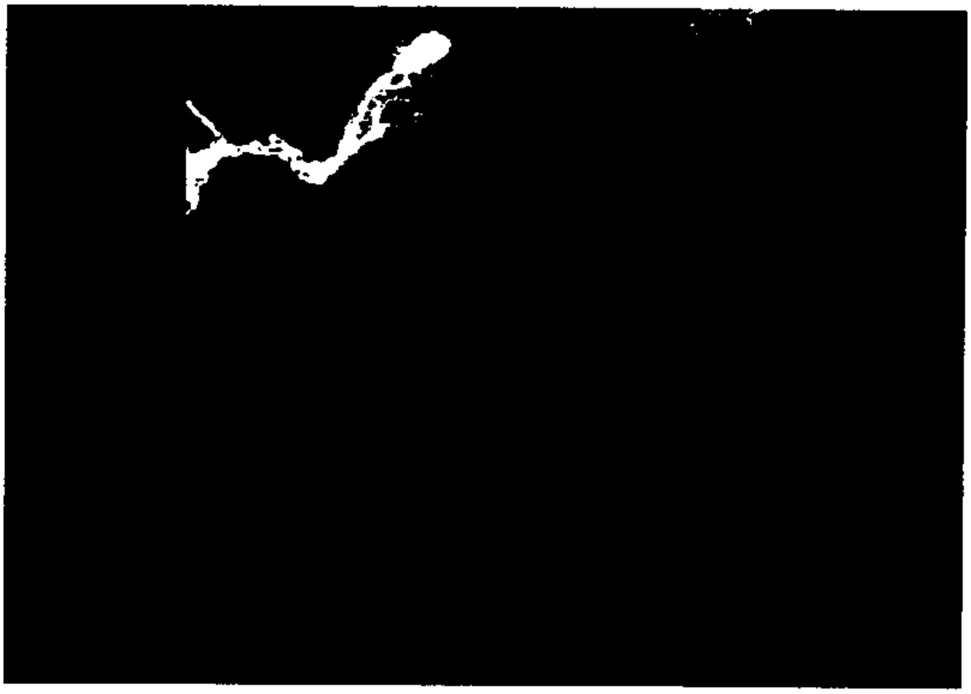


Fig. 21. Distribution of 1980 predicted Delta turbidity (NTU) as derived from Landsat 2 MSS data.

Blue	Less than 5 NTU
Cyan	5.1 - 10
Green	10.1 - 15
Yellow	15.1 - 20
Orange	20.1 - 25
Red	25.1 - 30
Brown	Greater than 30

Fig. 22. Distribution of 1980 predicted total suspended solids (mg/l) as derived from Landsat 2 MSS data.

Cyan	10 - 20 mg/l
Green	20.1 - 30
Yellow	30.1 - 40
Orange	40.1 - 50
Red	50.1 - 60
Brown	Greater than 60

Fig. 23. Distribution of 1980 predicted Delta salinity (ppt) as derived from Landsat 2 MSS data.

Blue	0 - 5 ppt
Cyan	5.1 - 10
Green	10.1 - 15
Orange	Greater than 15 ppt

Fig. 24. Distribution of 1983 predicted Delta turbidity (NTU) as derived from Landsat 4 MSS data.

Blue	Less than 5 NTU
Cyan	5.1 - 10
Green	10.1 - 15
Yellow	15.1 - 20
Orange	20.1 - 25
Red	Greater than 25

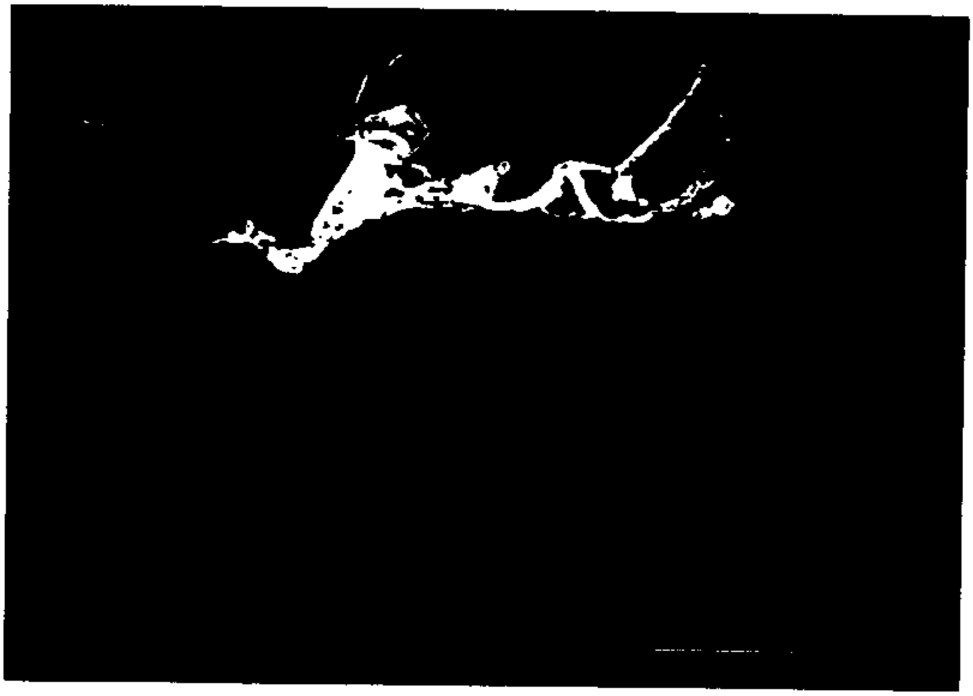


Fig. 25. Distribution of 1983 predicted Delta total suspended solids (mg/l) as derived from Landsat 4 MSS data.

Blue	Less than 10 mg/l
Cyan	10.1 - 20
Green	20.1 - 30
Yellow	30.1 - 40
Orange	Greater than 40

points which characterized entrapment zone conditions. The difference in the location of the two entrapment zones is believed to be related to the difference in Delta flow conditions between the two dates.

CONCLUSION

The results of this study indicate that Landsat MSS can detect differences in hydrodynamic conditions between the San Francisco Bay and Delta for October 27, 1980, and September 13, 1983. Water quality models based on Landsat MSS reflectance values were successful (R-squares >.75) in predicting distributions of 1980 and 1983 Delta turbidity, 1983 Delta total suspended solids, and 1980 Delta salinity. Marginal results were associated with the 1980 Delta total suspended solids and 1980 and 1983 Bay turbidity and salinity models.

The Delta total suspended solids models were the only functions which could be expressed in a generalized form where one model could describe both dates despite differences in Delta flow conditions, tide phases, satellite sensors, and sun elevation. Both 1980 and 1983 Delta turbidity models contained the same independent variables but confidence intervals constructed on the regression coefficients indicated that the coefficients were not the same for the two models. Tests of regression coefficients for the Bay turbidity indicated that a generalized model could describe both dates but the models were not predicting accurately based on the interpretation of the low coefficients of determination (R-squares = .33).

The Delta salinity models were not compared because the 1983 version could not be established. The 1980 Delta salinity model was compared with an earlier function developed for similar flow conditions (Khorram 1978) but the earlier algorithm emphasized different independent variables suggesting that a generalized model may not be applicable for this parameter.

Attempts to model chlorophyll a in this study were unsuccessful. Earlier modeling efforts by Khorram (1980 had suggested a relationship between 1980 chlorophyll a concentrations covering the entire Bay and Delta and MSS band values although examination of this data on a regional basis revealed no relationship. These results indicate that the earlier regression of the entire Bay and Delta data may have been fitting a curve to the regional means. The lack of fit of the chlorphyll data for both dates was probably influenced by satellite limitations and measurement errors associated with the fluorimetric process as well as patchy distributions characteristic of phytoplankton and differences in the time between the collection of water quality data and the satellite overflight.

Several distributions of 1980 and 1983 Bay and Delta water quality parameters plotted against MSS bands suggested that models could describe conditions for the entire Bay and Delta. Inspection of these distributions show, however, that the Delta data are contributing the most information in describing the relationship between water quality parameters and spectral terms. Attempts to define generalized functions which describe the variability in the water quality data over the entire Bay and Delta were unsuccessful.

The restricted applicability of regional generalized models may have been limited because there were only two data sets used for comparison. These results were also probably affected by the differences between 1980 and 1983 conditions and that generalized models for Delta turbidity and salinity may be feasible under more uniform conditions. Generalized models for Bay parameters might also be readily defined under similar conditions; however, the inability of current models to accurately predict for either date suggests that Landsat MSS values may not be sensitive enough to detect the smaller concentration of turbidity and total suspended solids typically found in the Bay.

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APPENDIX

Key:

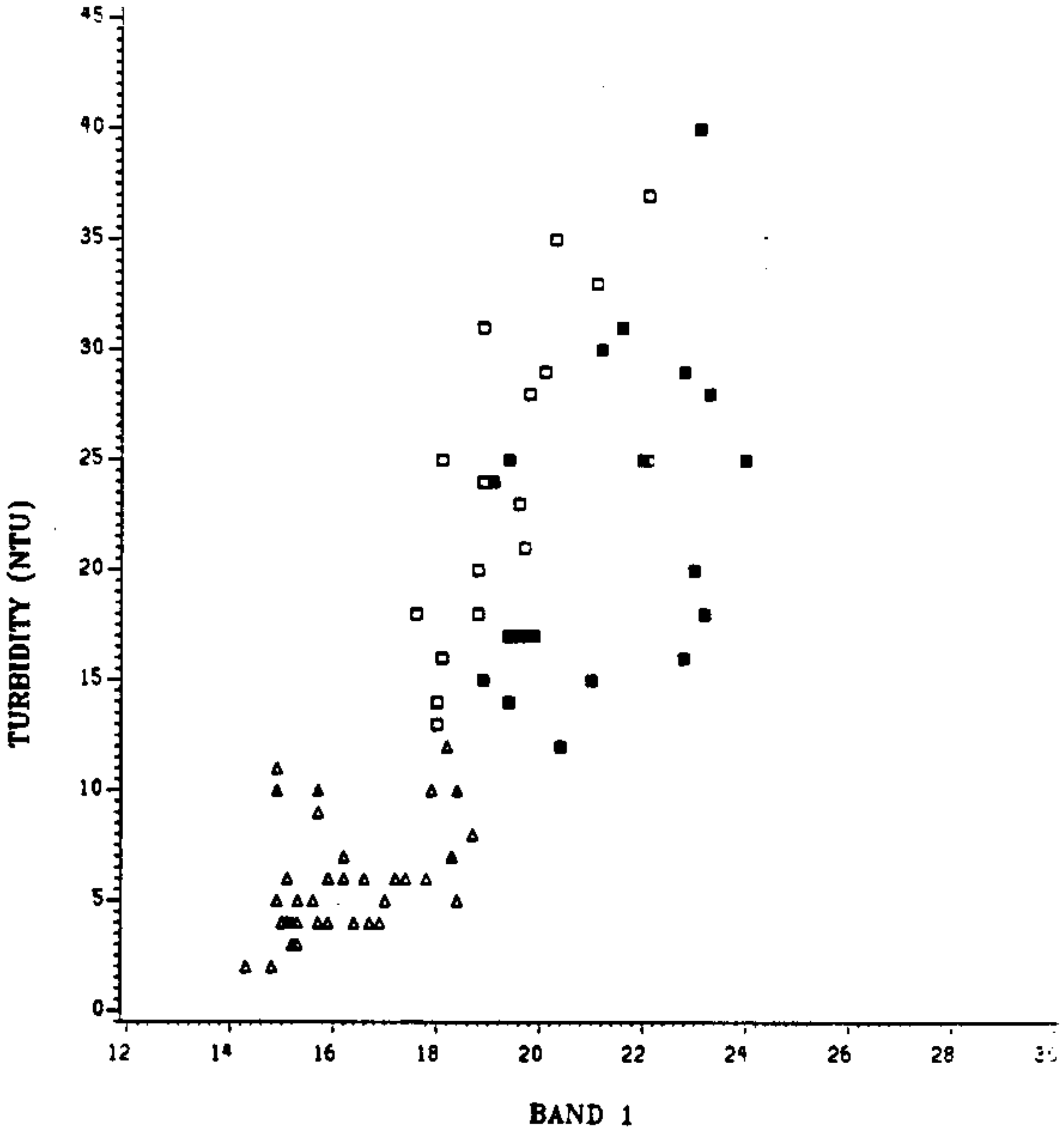
DELTA: filled squares = $\leq$ 250 m from shoreline

empty squares = > 250 m from shoreline

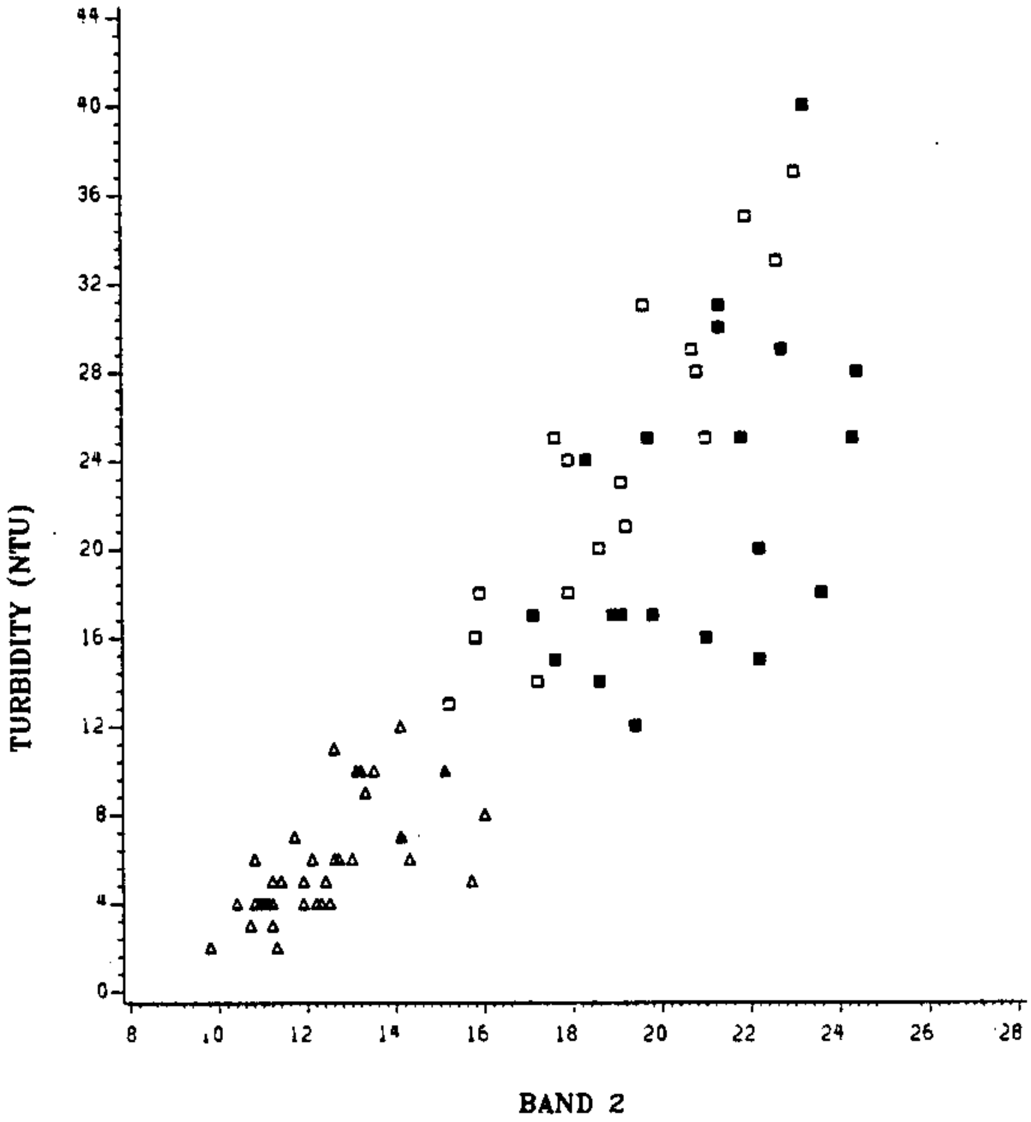
BAY: filled triangles = $\leq$ 250 m from shoreline

empty triangles = > 250 m from shoreline

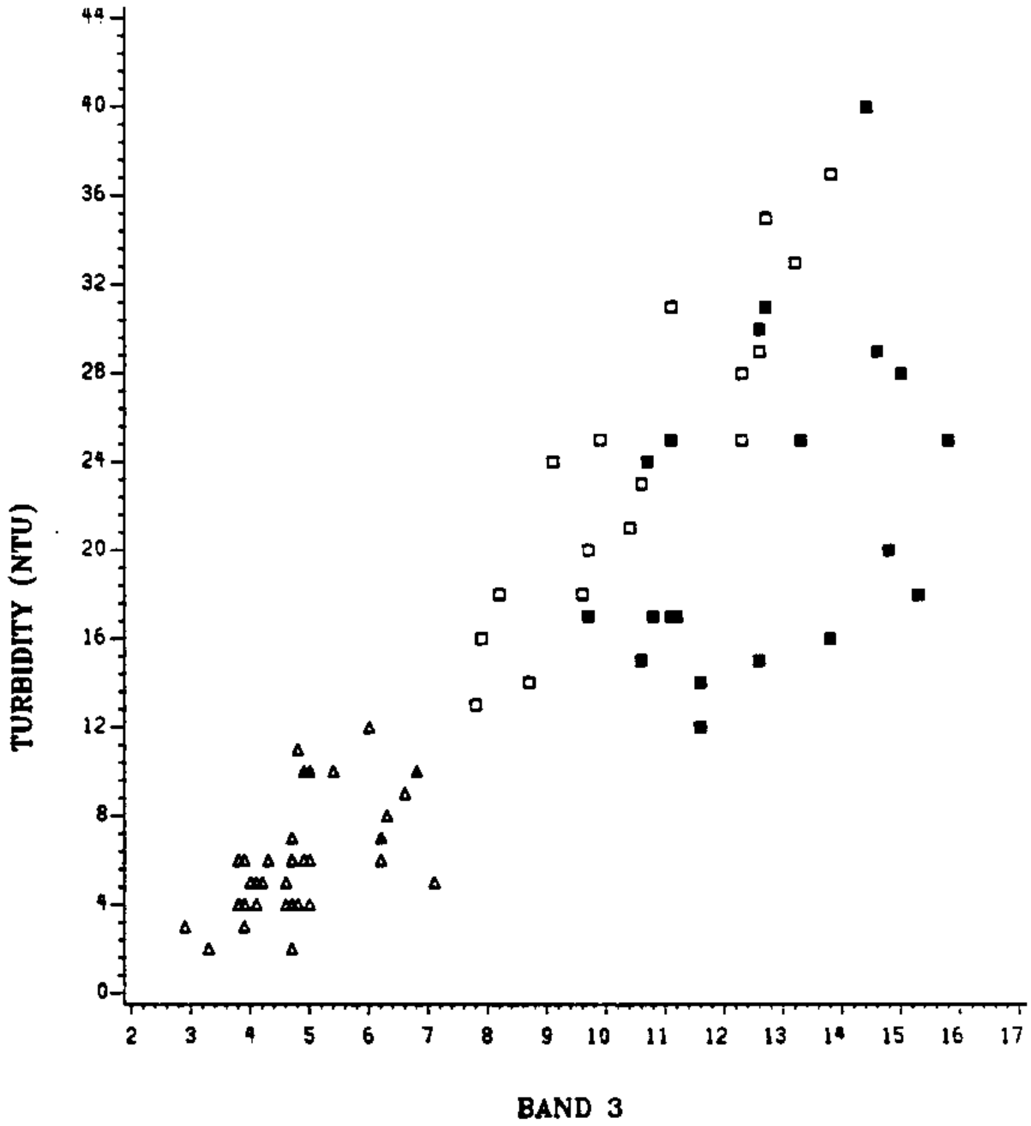
1980 PLOTS



TURBIDITY (NTU)
45
40
35
30
25
20
15
10
5
0
12
14
16
18
20
22
24
26
28
BAND 1



TURBIDITY (NTU)
0
4
8
12
16
20
24
28
32
36
40
44
8
10
12
14
16
18
20
22
24
26
28
BAND 2


TURBIDITY (NTU)
44
40
36
32
28
24
20
16
12
8
4
0
2
3
4
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8
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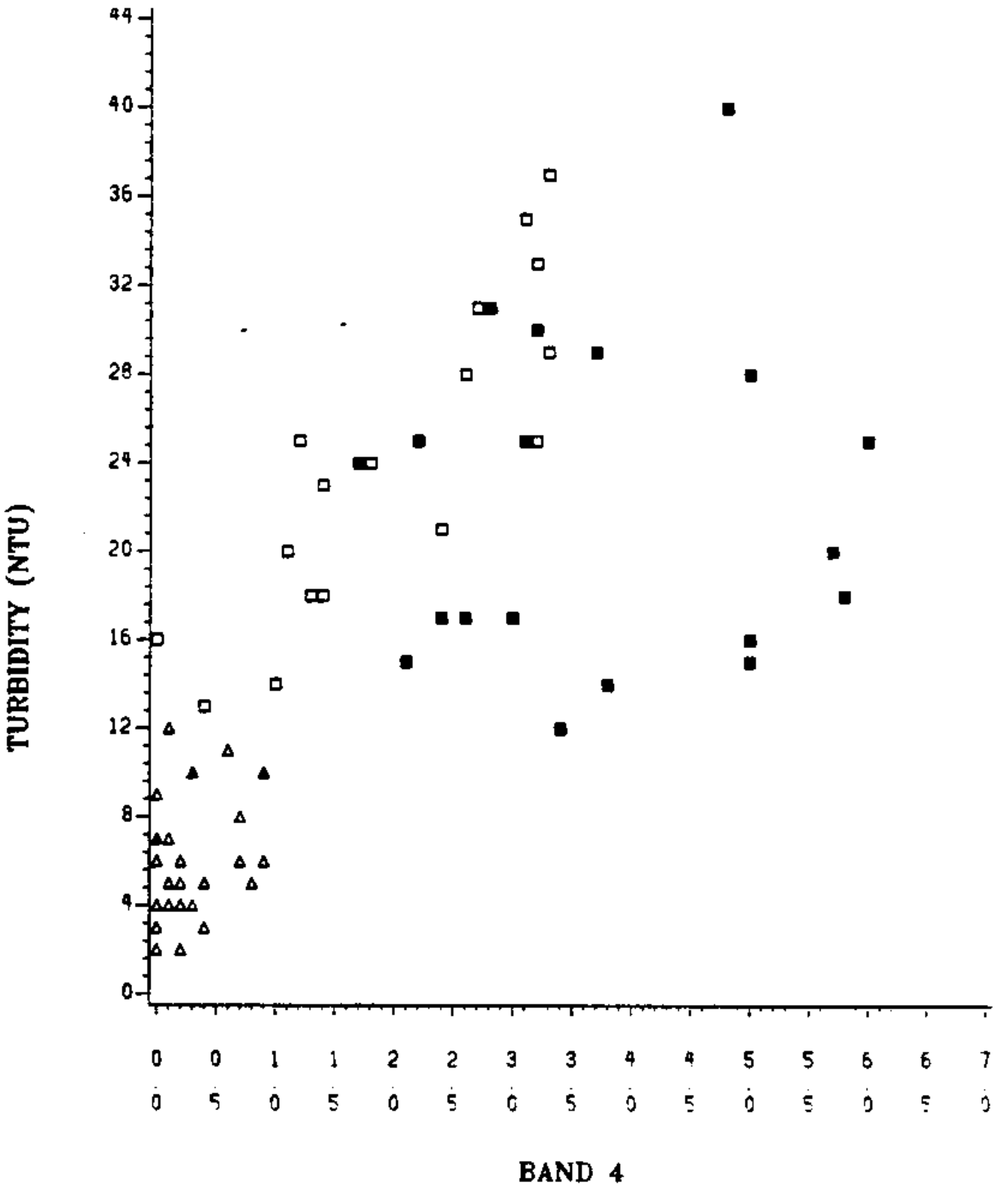
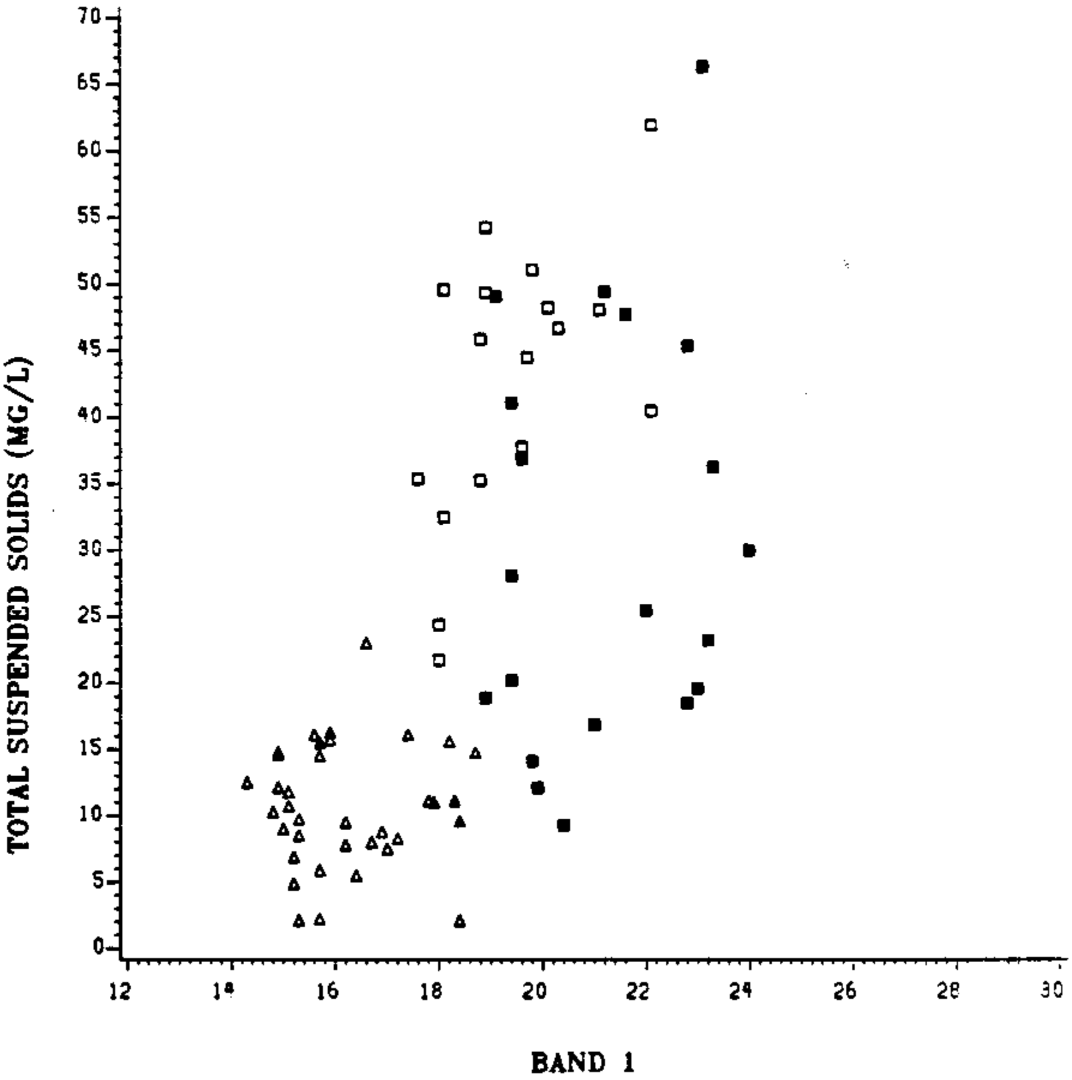
14
15
16
17
BAND 3



TURBIDITY (NTU)
44
40
36
32
28
24
20
16
12
8
4
0
BAND 4


TOTAL SUSPENDED SOLIDS (MG/L)
70
65
60
55
50
45
40
35
30
25
20
15
10
5
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12
14
16
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20
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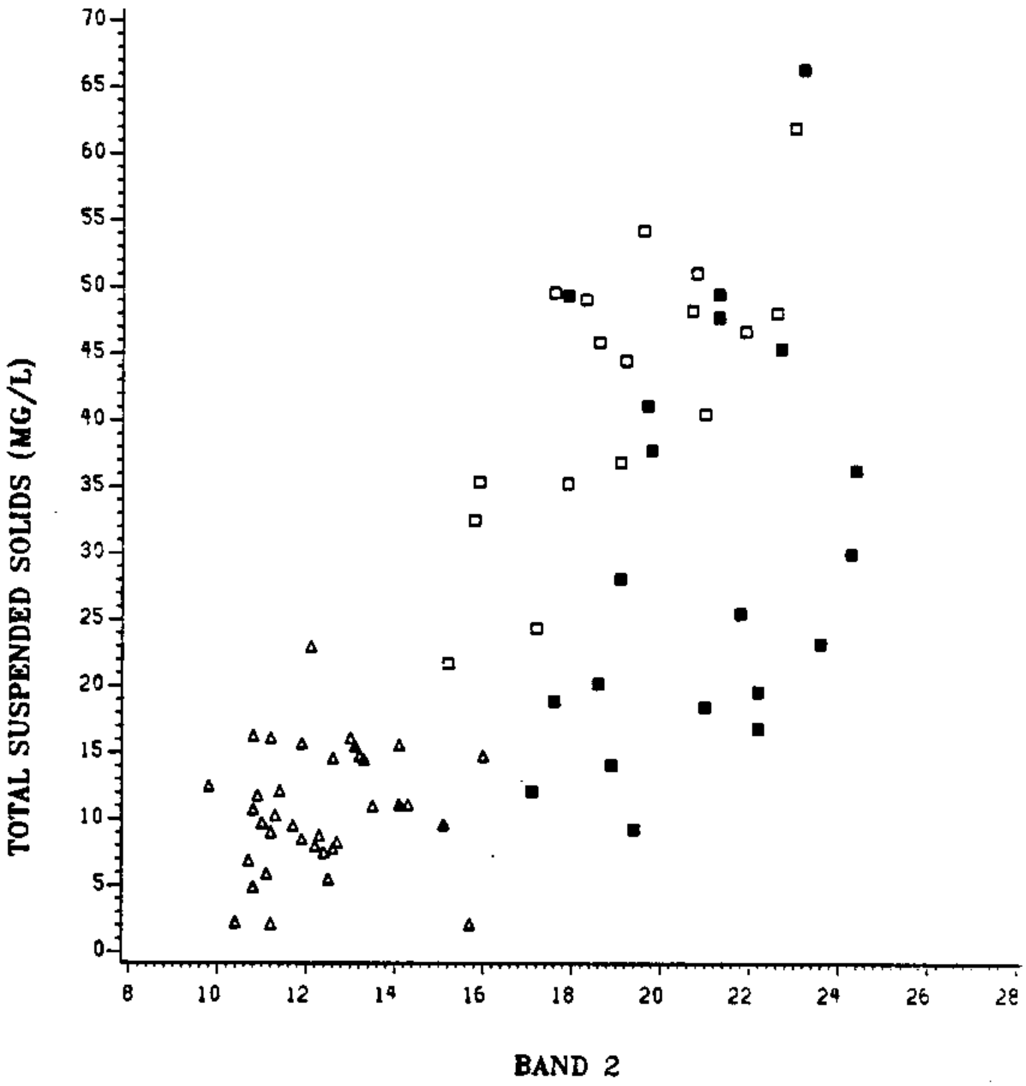
24
26
28
30
BAND 1


TOTAL SUSPENDED SOLIDS (MG/L)
70
65
60
55
50
45
40
35
30
25
20
15
10
5
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10
12
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18
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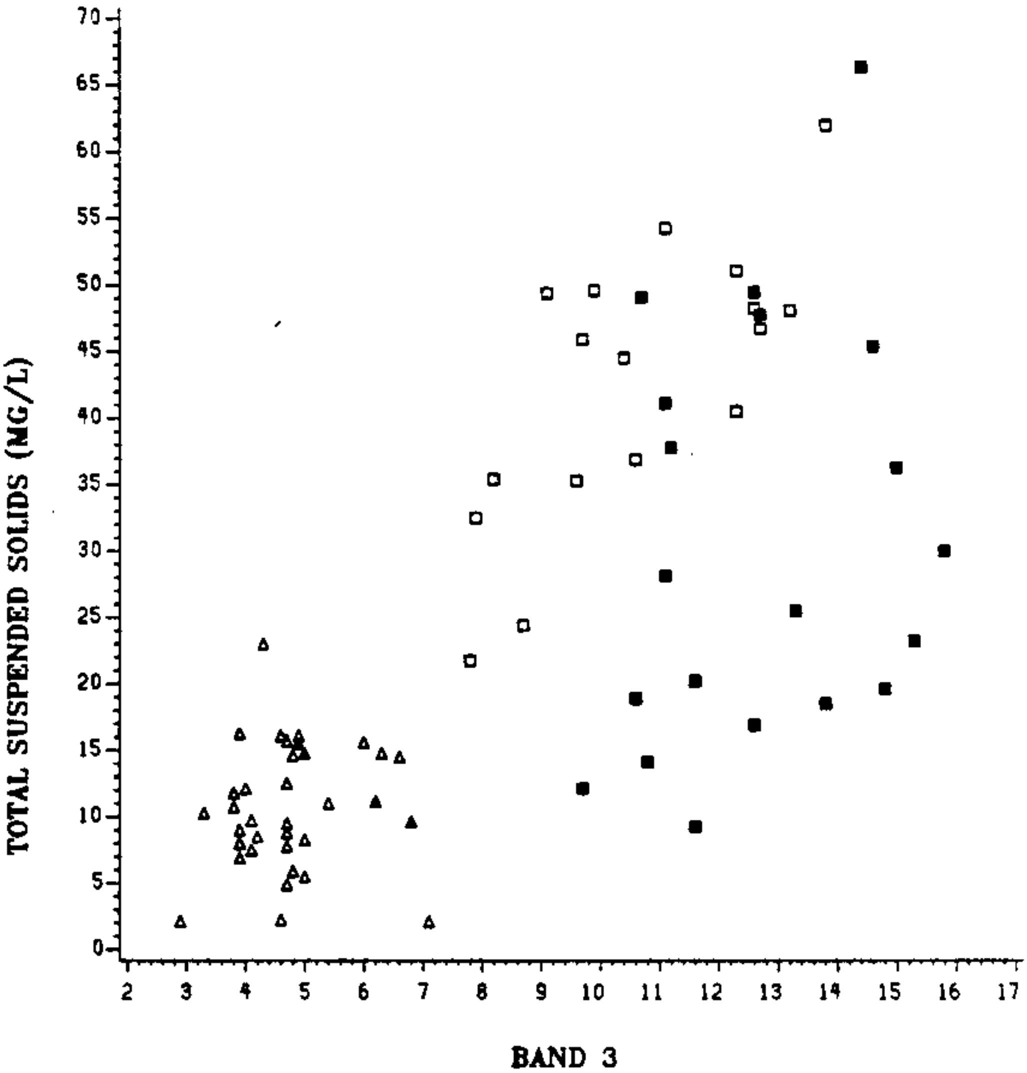
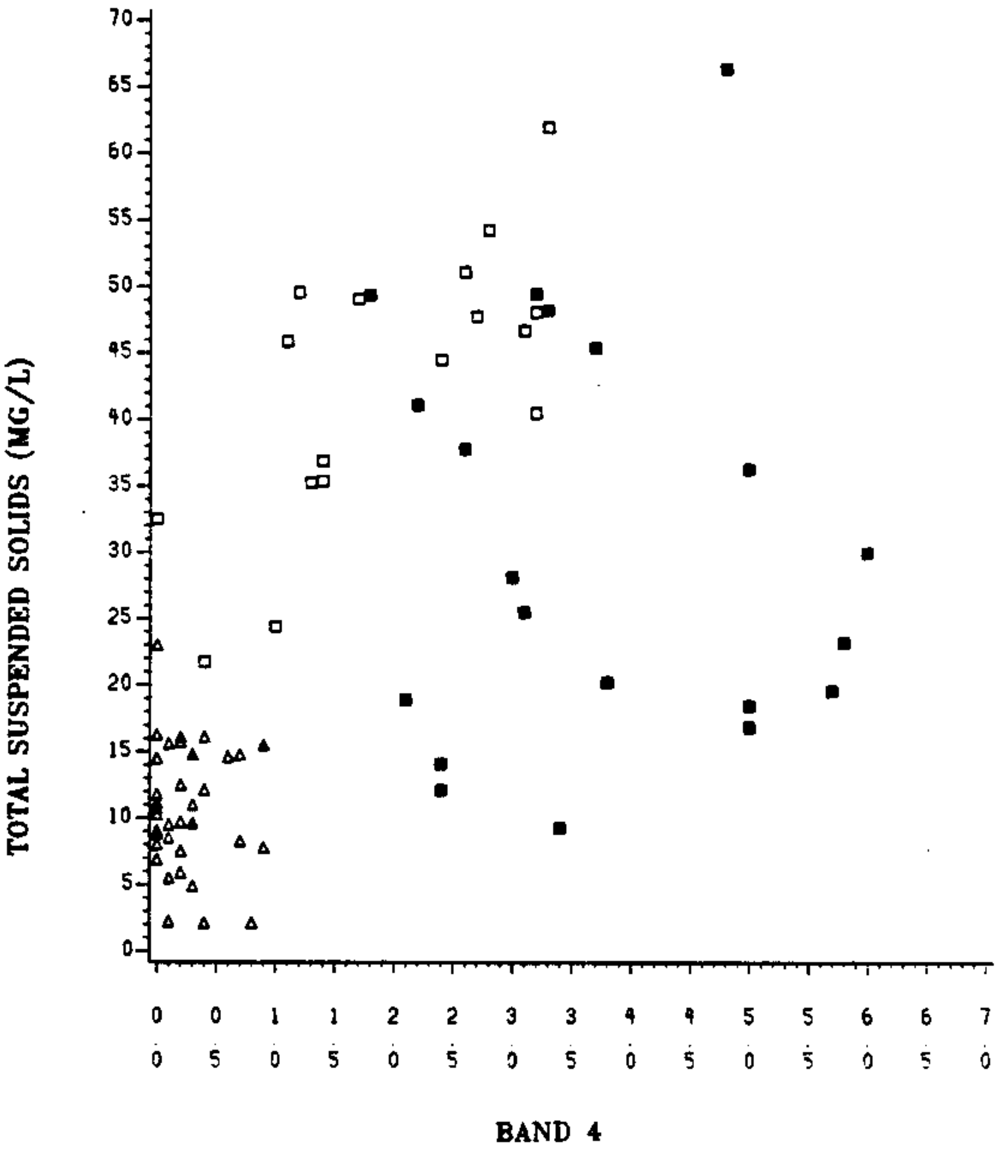
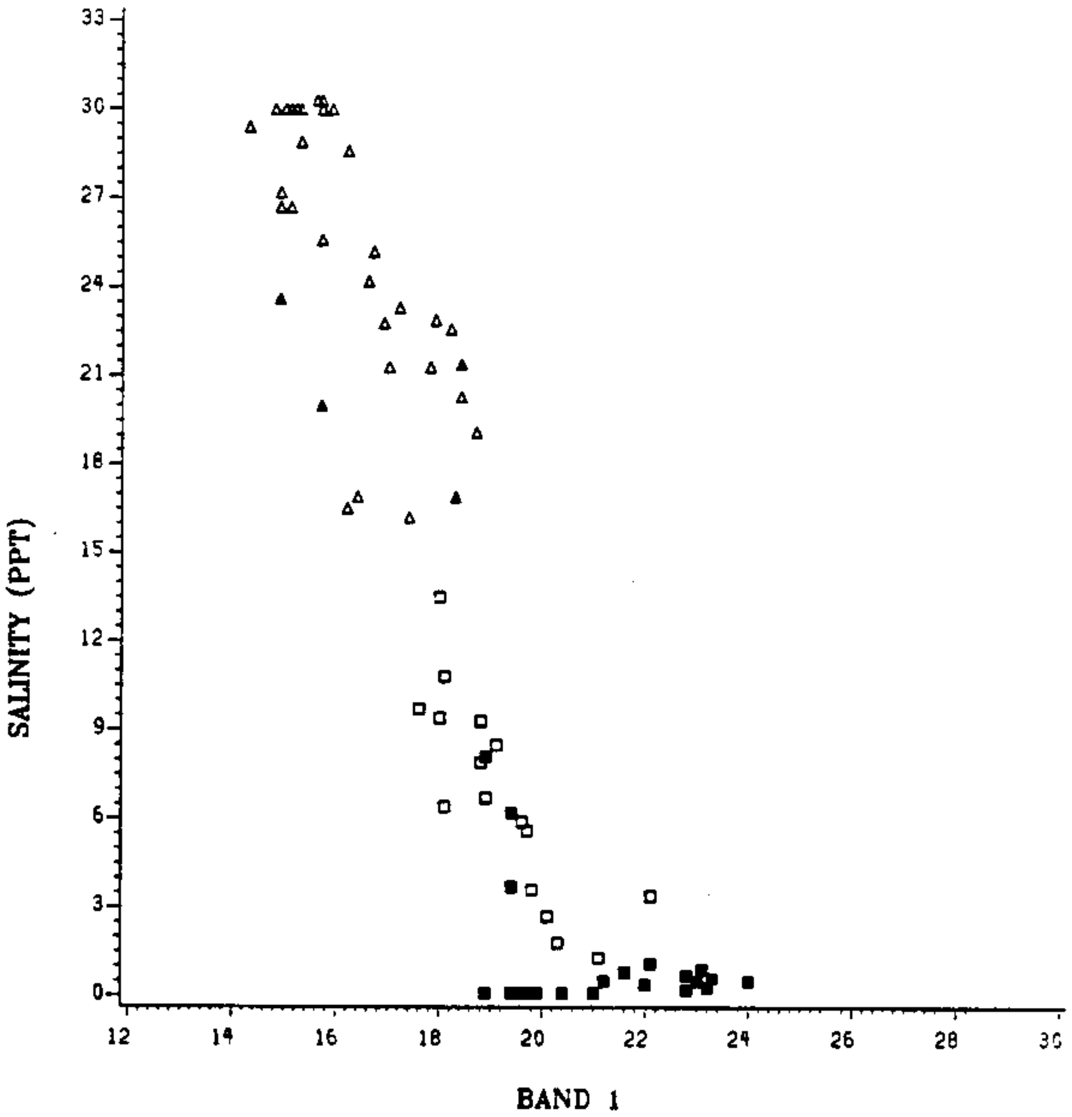
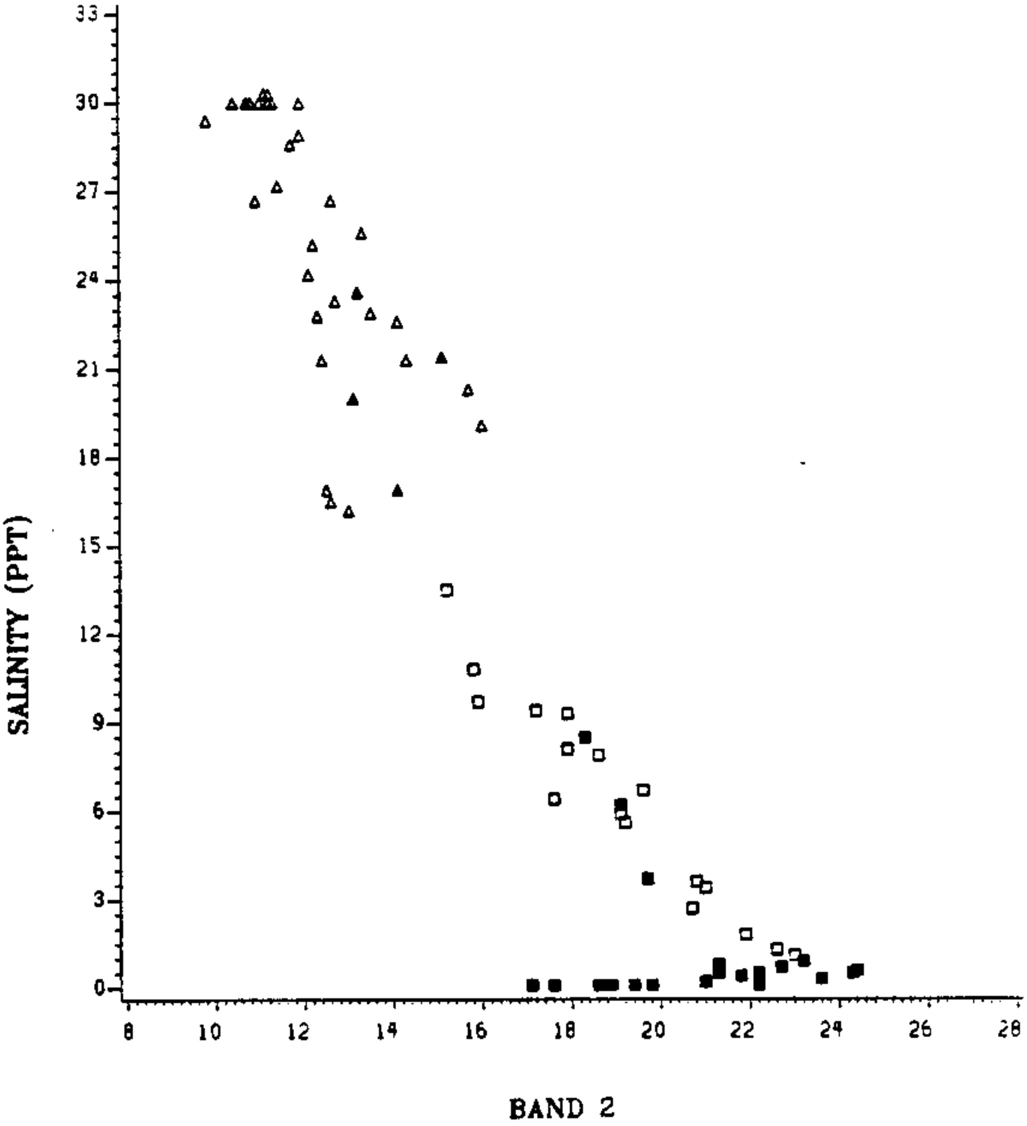
22
24
26
28
BAND 2

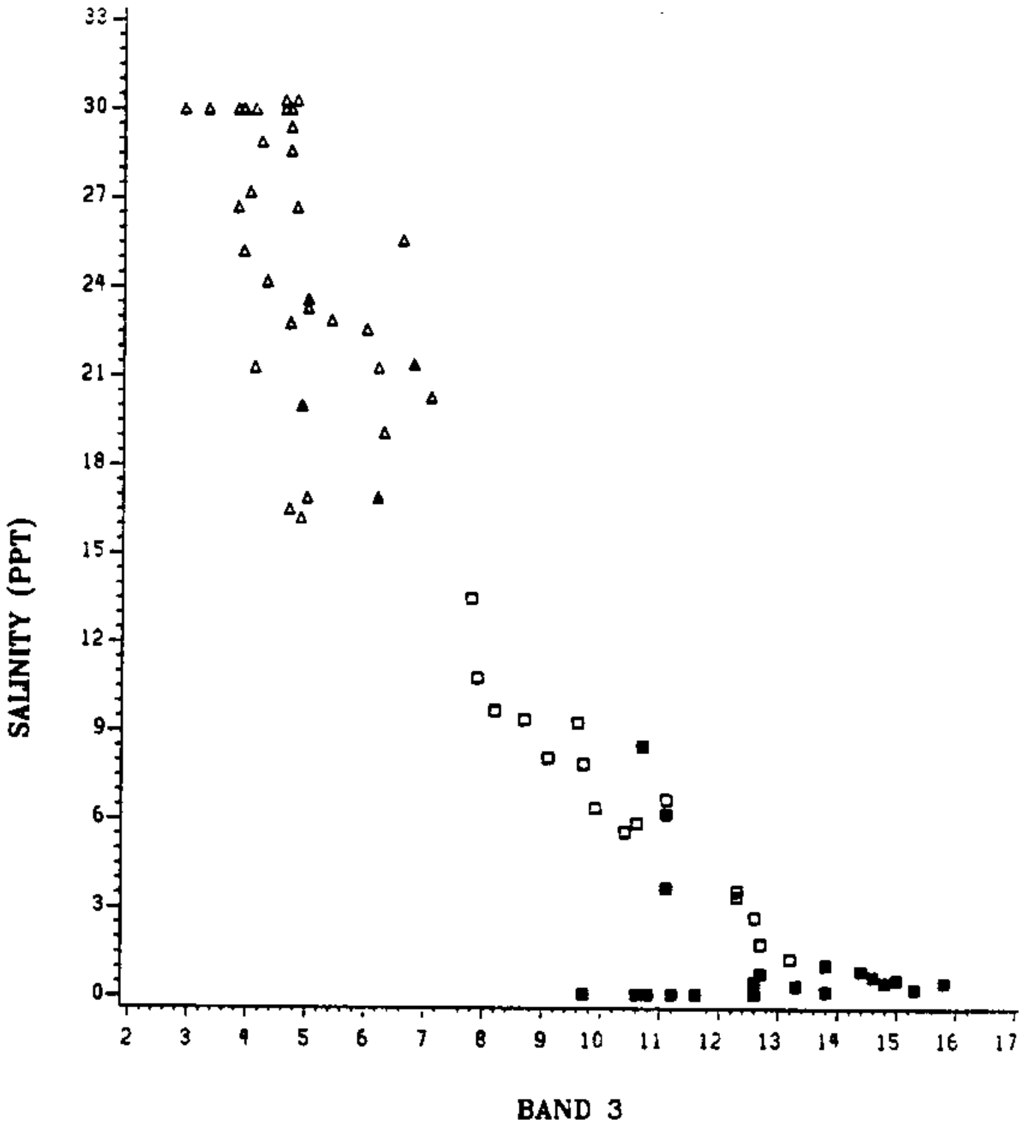


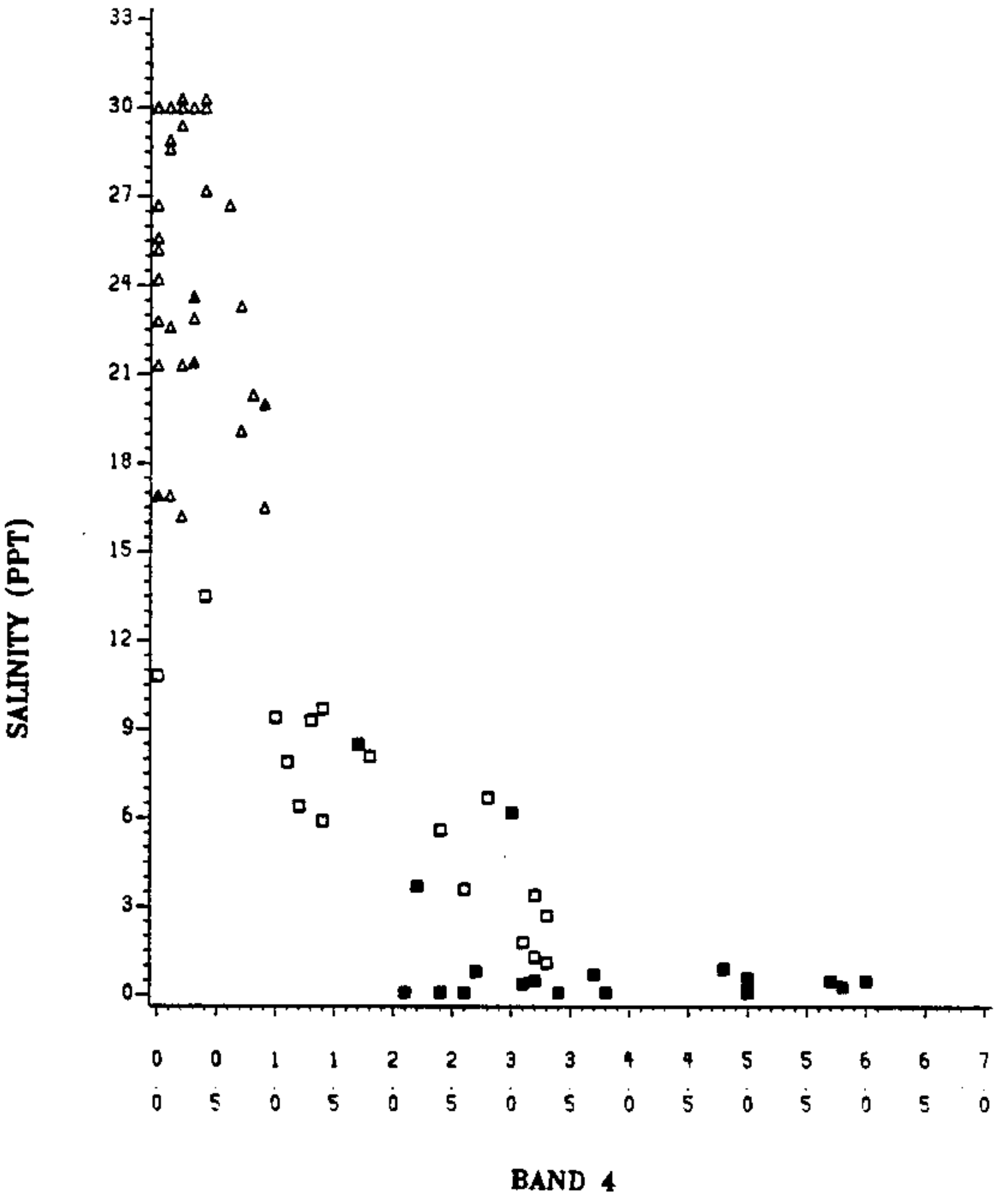
TOTAL SUSPENDED SOLIDS (MG/L)
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
BAND 3


TOTAL SUSPENDED SOLIDS (MG/L)
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
BAND 4

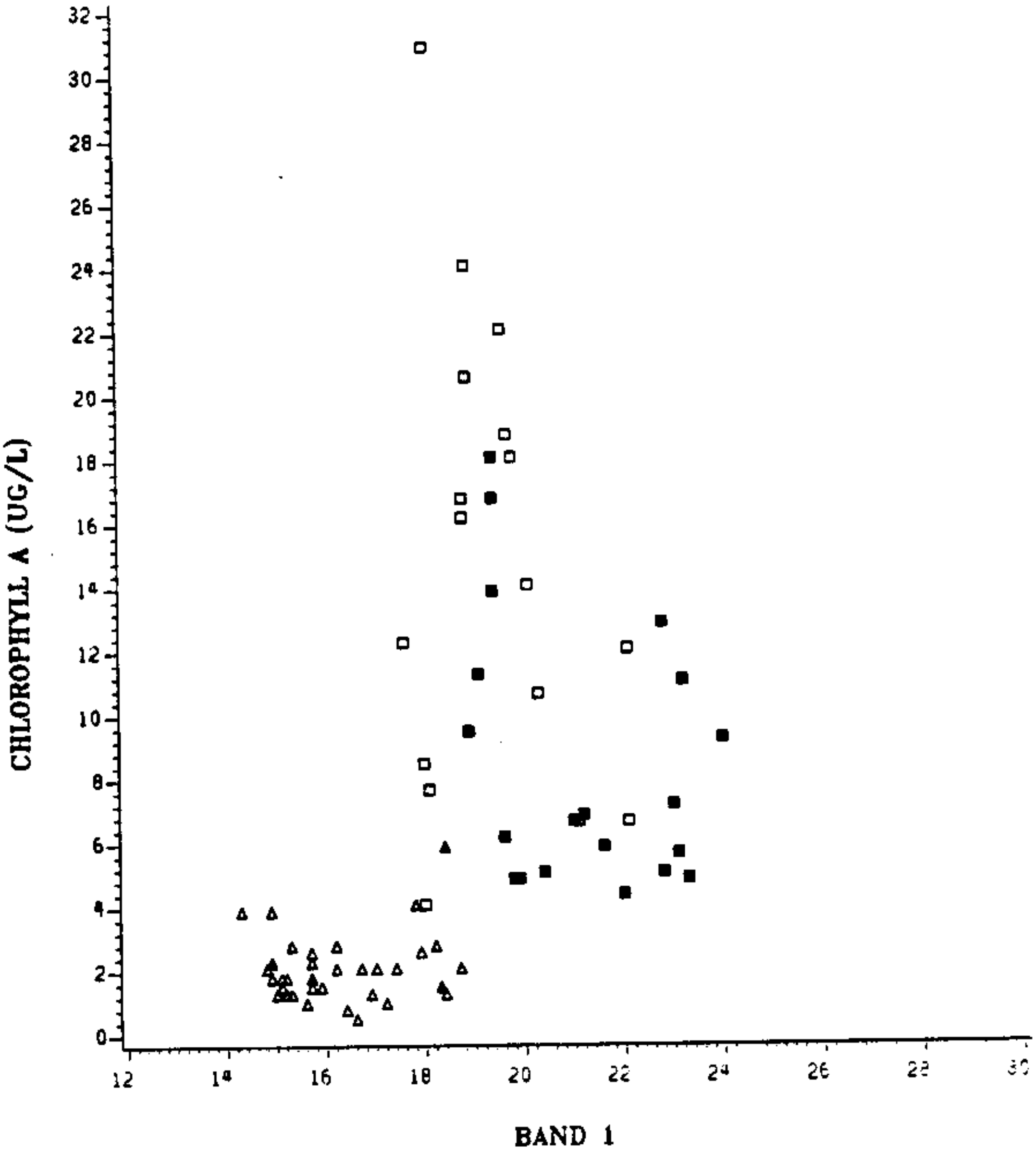

SALINITY (PPT)
33
30
27
24
21
18
15
12
9
6
3
0
12
14
16
18
20
22
24
26
28
30
BAND 1


33
30
27
24
21
18
15
12
9
6
3
0
SALINITY (PPT)
8
10
12
14
16
18
20
22
24
26
28
BAND 2


SALINITY (PPT)
33
30
27
24
21
18
15
12
9
6
3
0
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
BAND 3



SALINITY (PPT)
33
30
27
24
21
18
15
12
9
6
3
0
0 0 1 1 2 2 3 3 4 4 5 5 6 6 7
0 5 0 5 0 5 0 5 0 5 0 5 0 5 0
BAND 4



CHLOROPHYLL A (UG/L)
32
30
28
26
24
22
20
18
16
14
12
10
8
6
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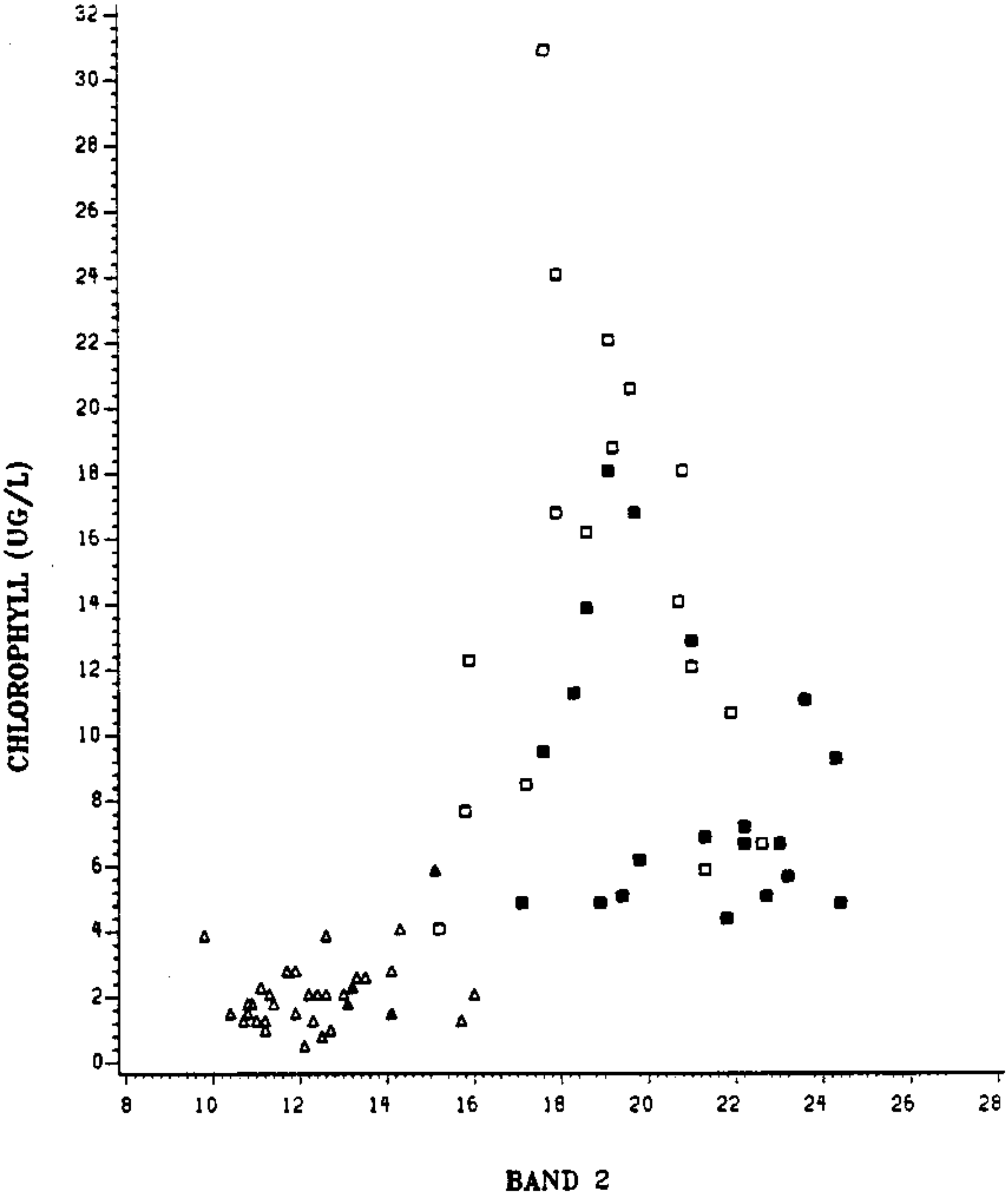
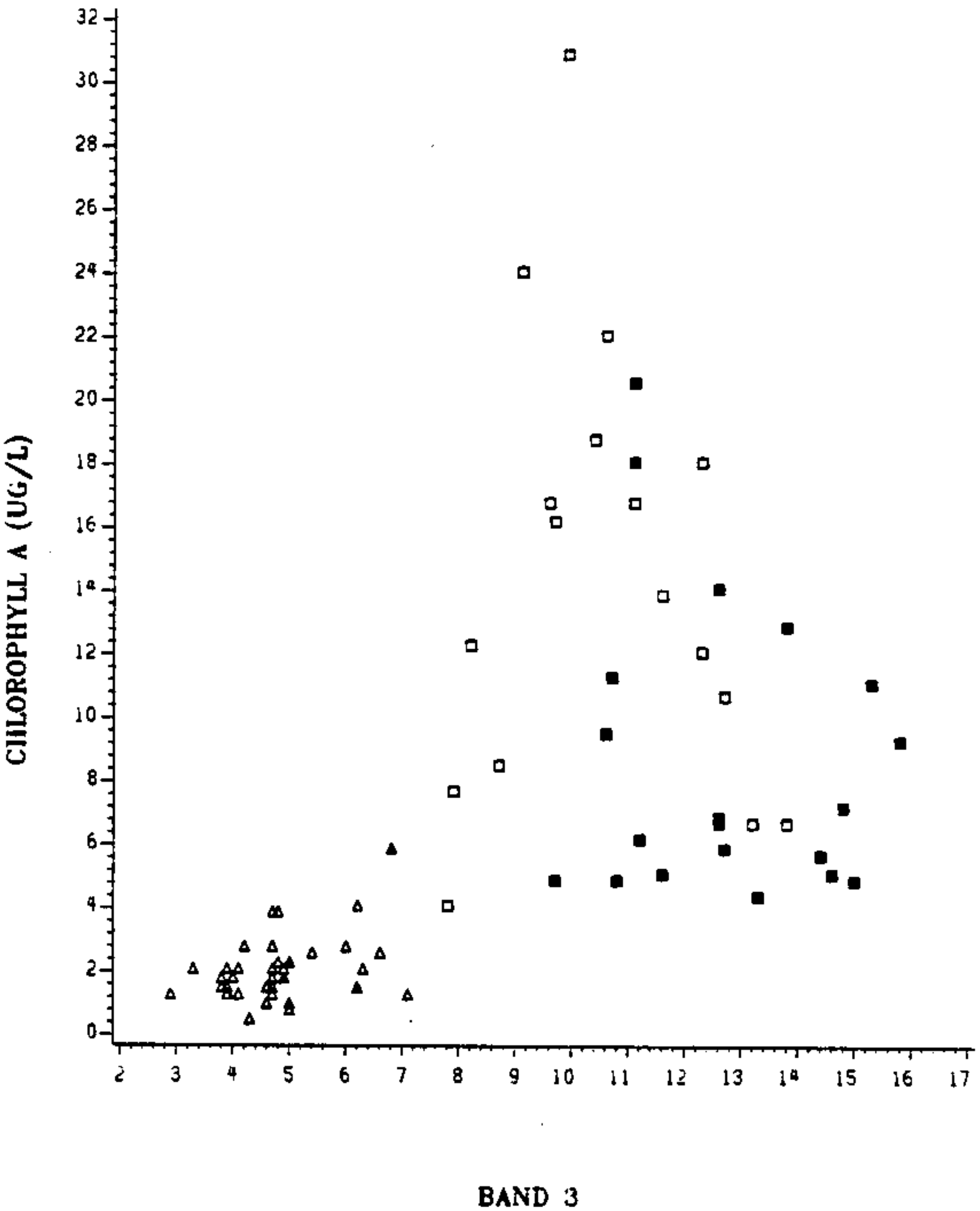
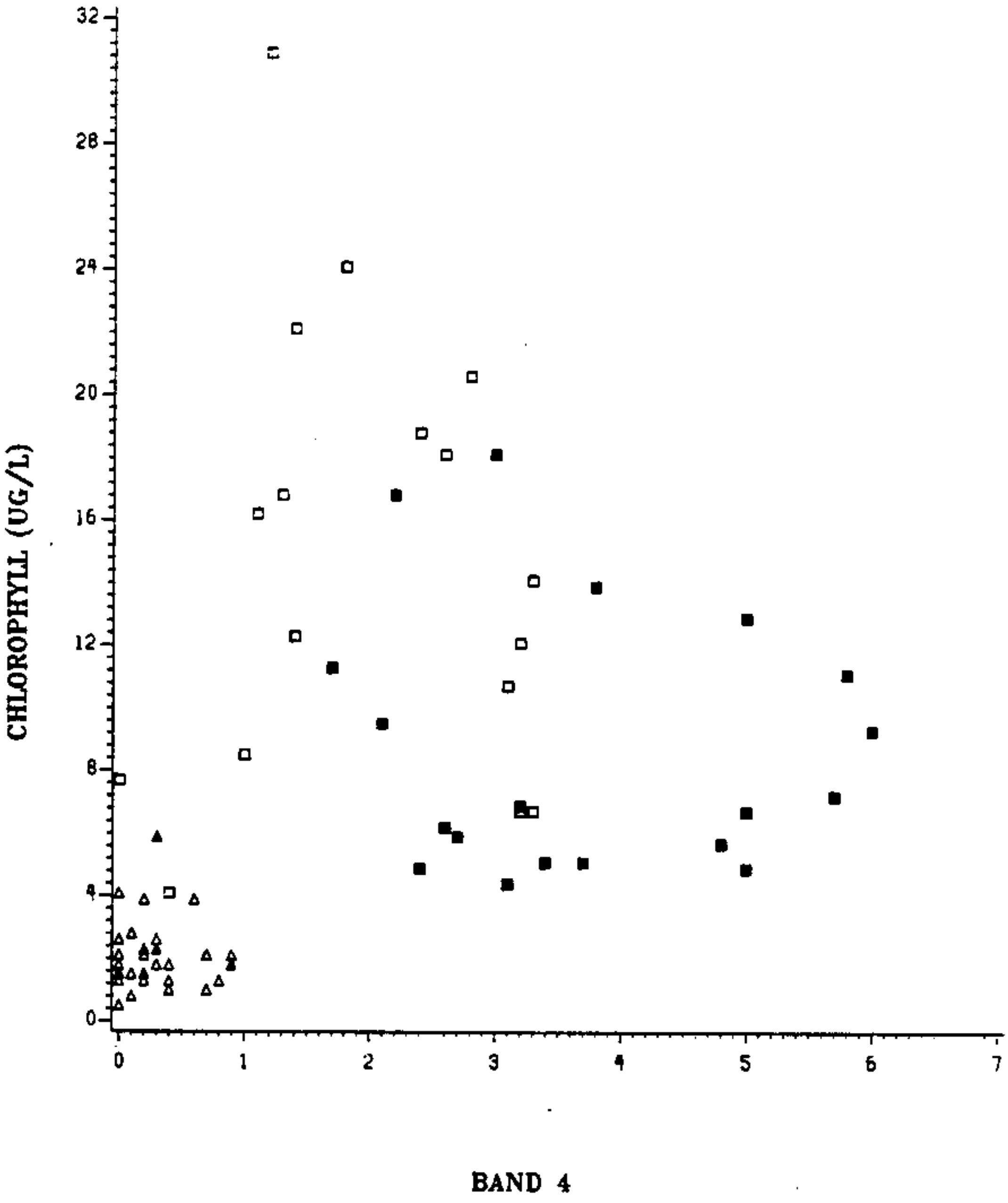
24
26
28
30
BAND 1

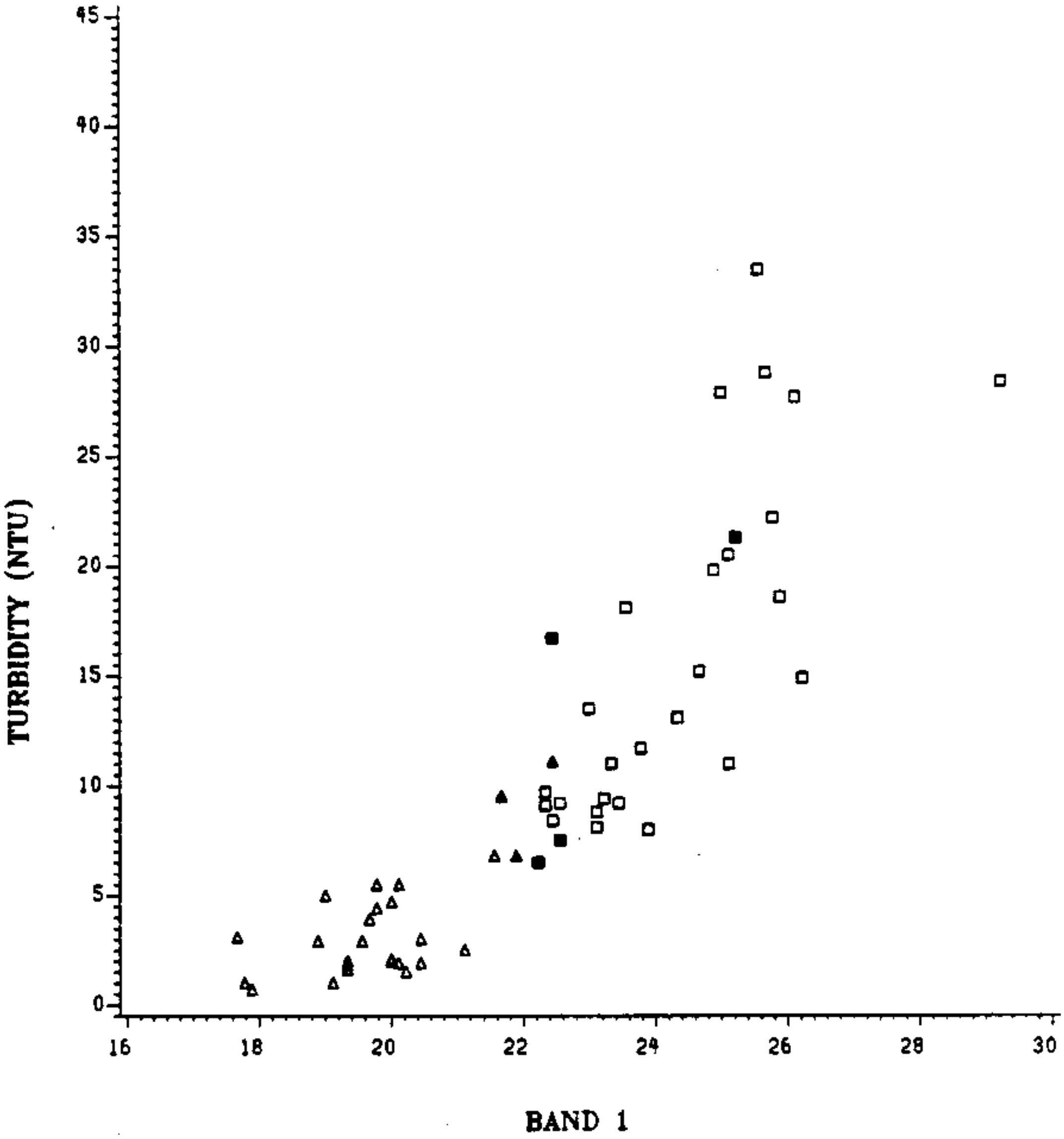

CHLOROPHYLL (UG/L)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
8
10
12
14
16
18
20
22
24
26
28
BAND 2


CHLOROPHYLL A (UG/L)
BAND 3

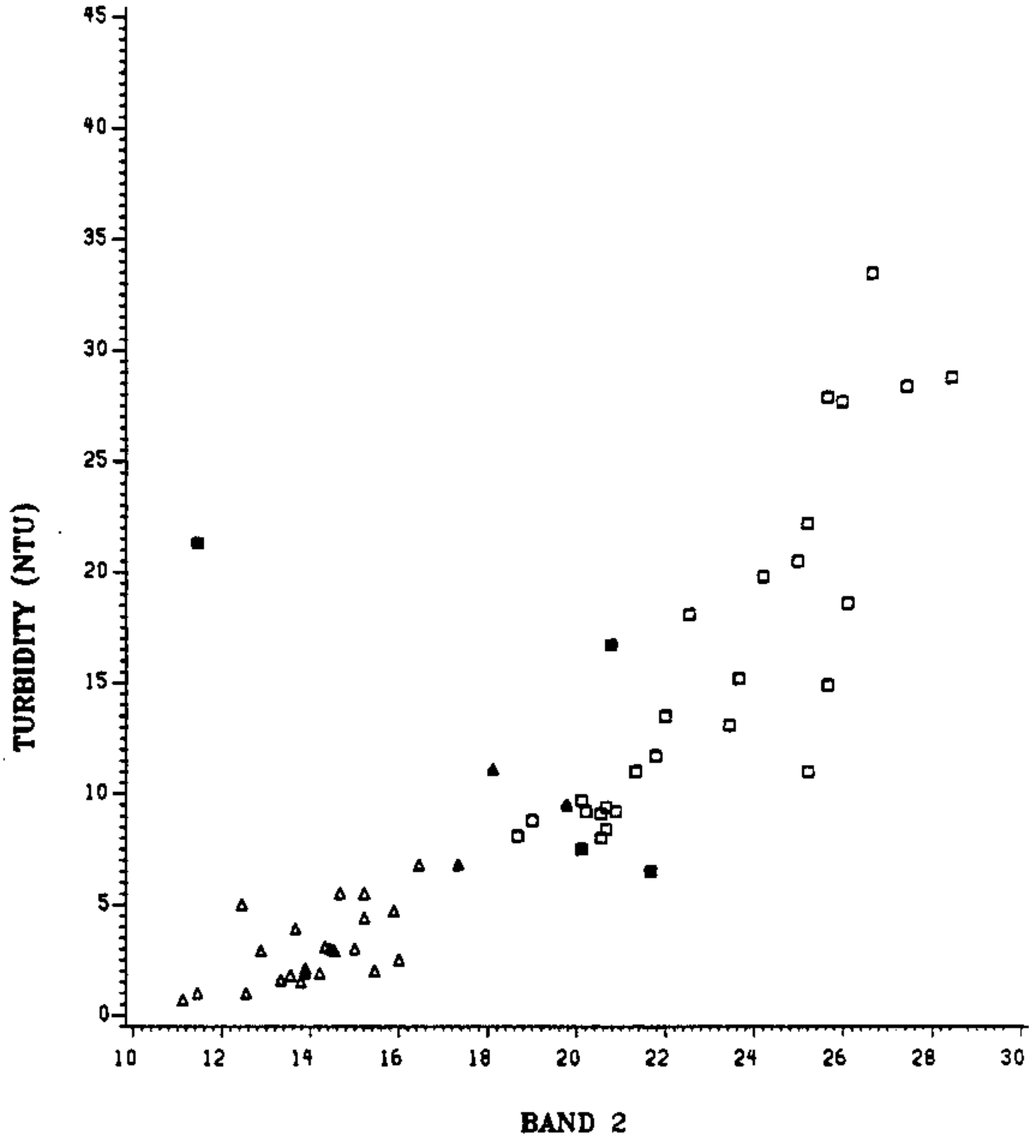


CHLOROPHYLL (UG/L)
32
28
24
20
16
12
8
4
0
0
1
2
3
4
5
6
7
BAND 4

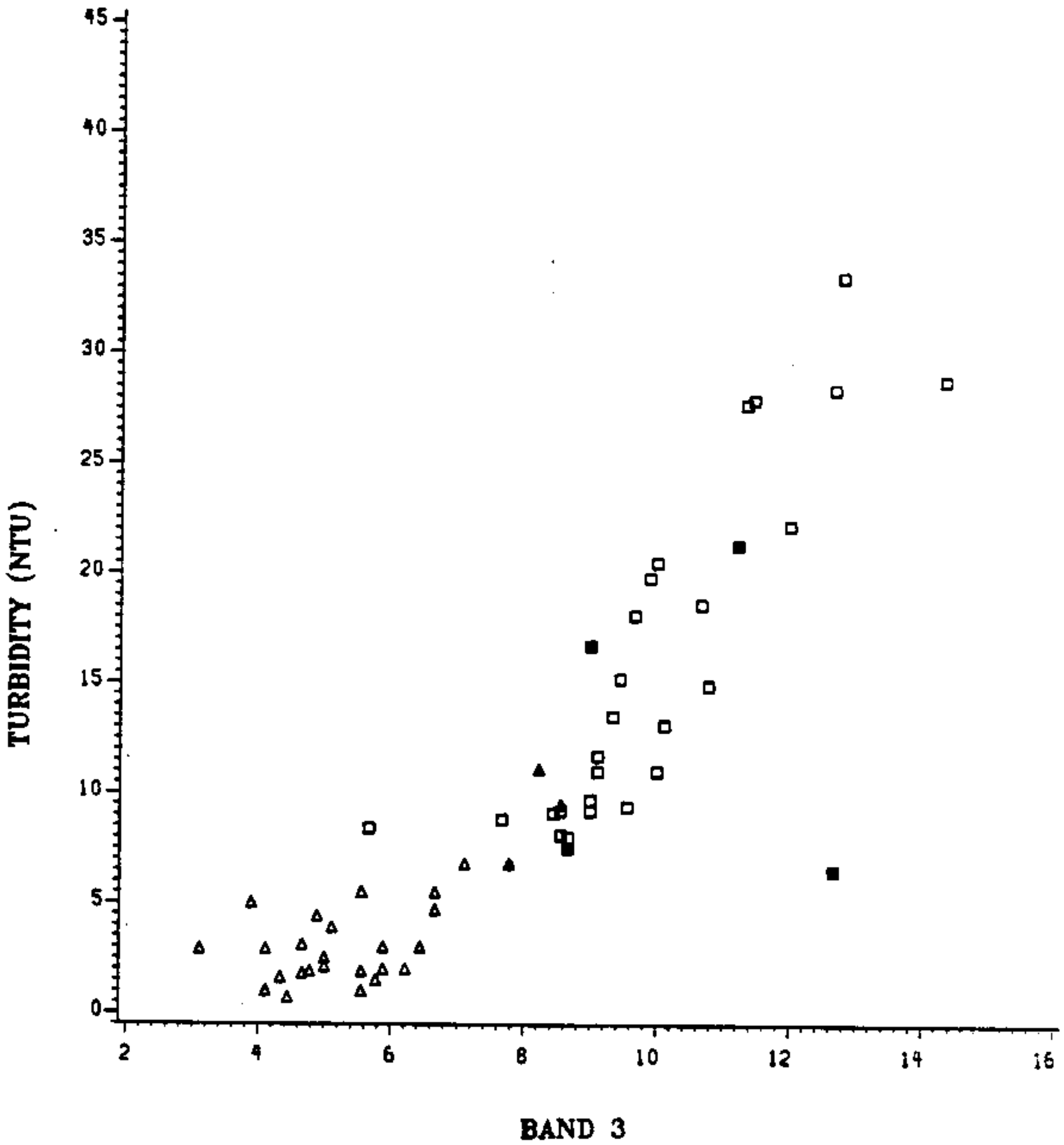
1983 PLOTS

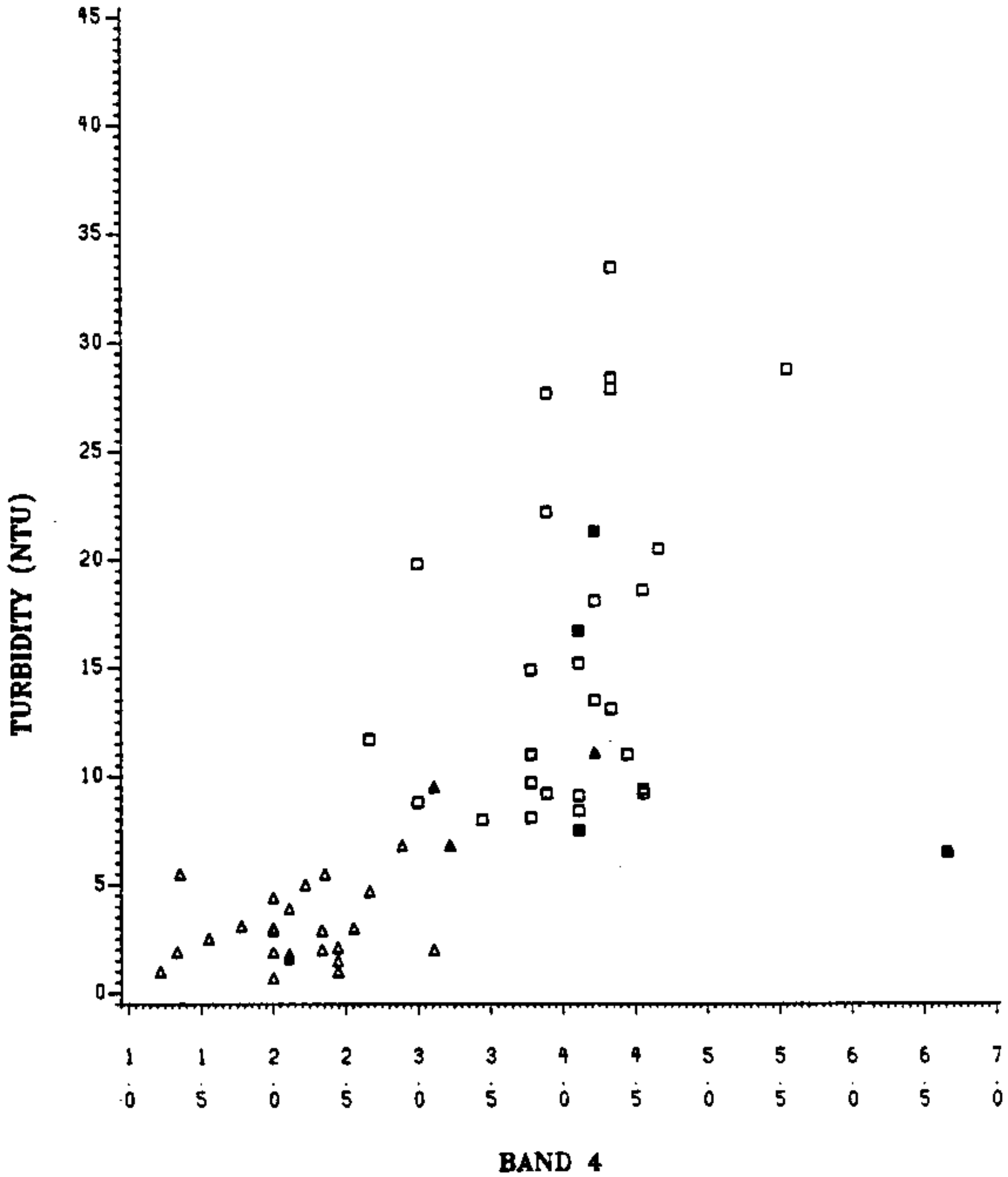


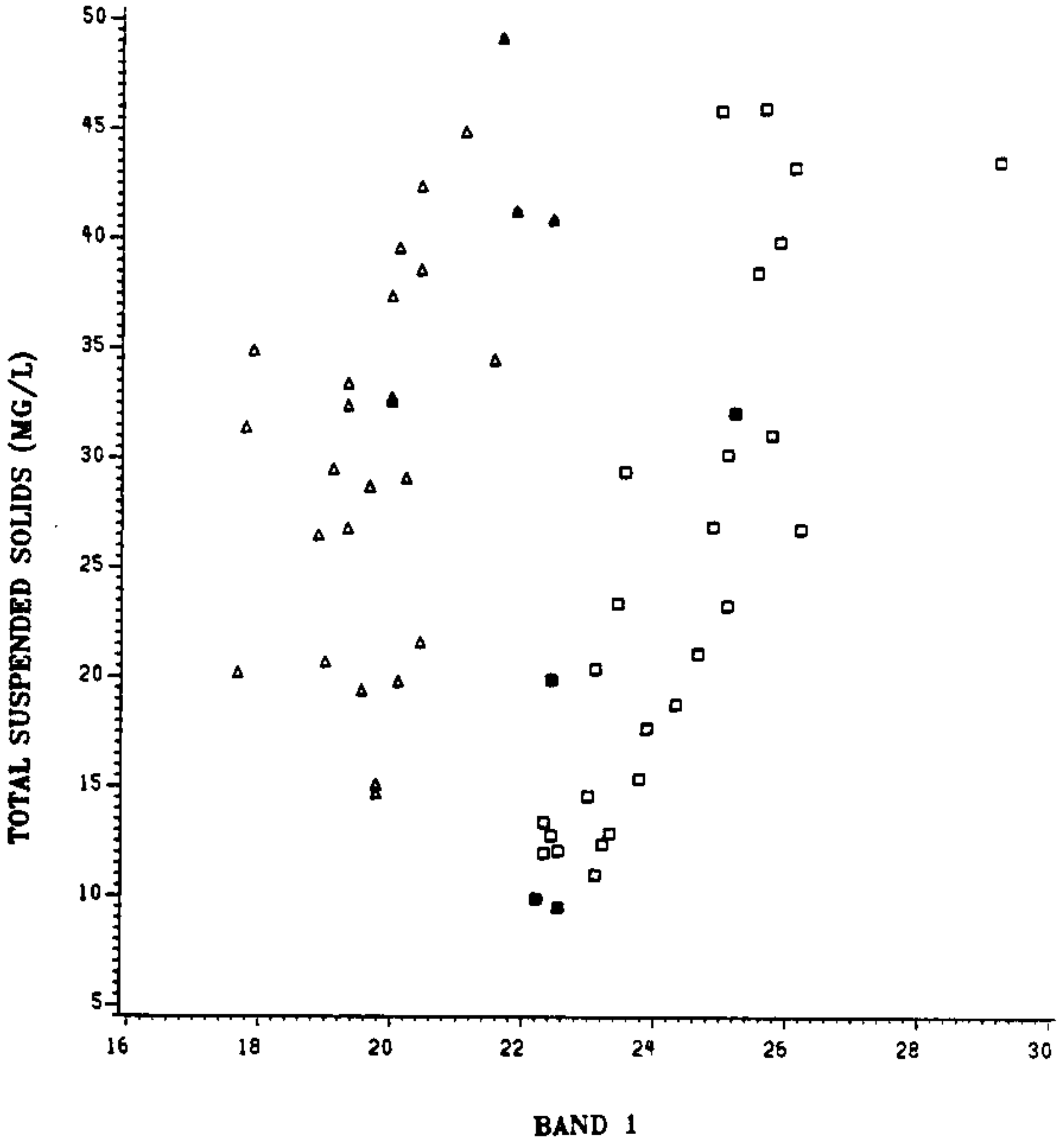
TURBIDITY (NTU)
45
40
35
30
25
20
15
10
5
0
16
18
20
22
24
26
28
30
BAND 1

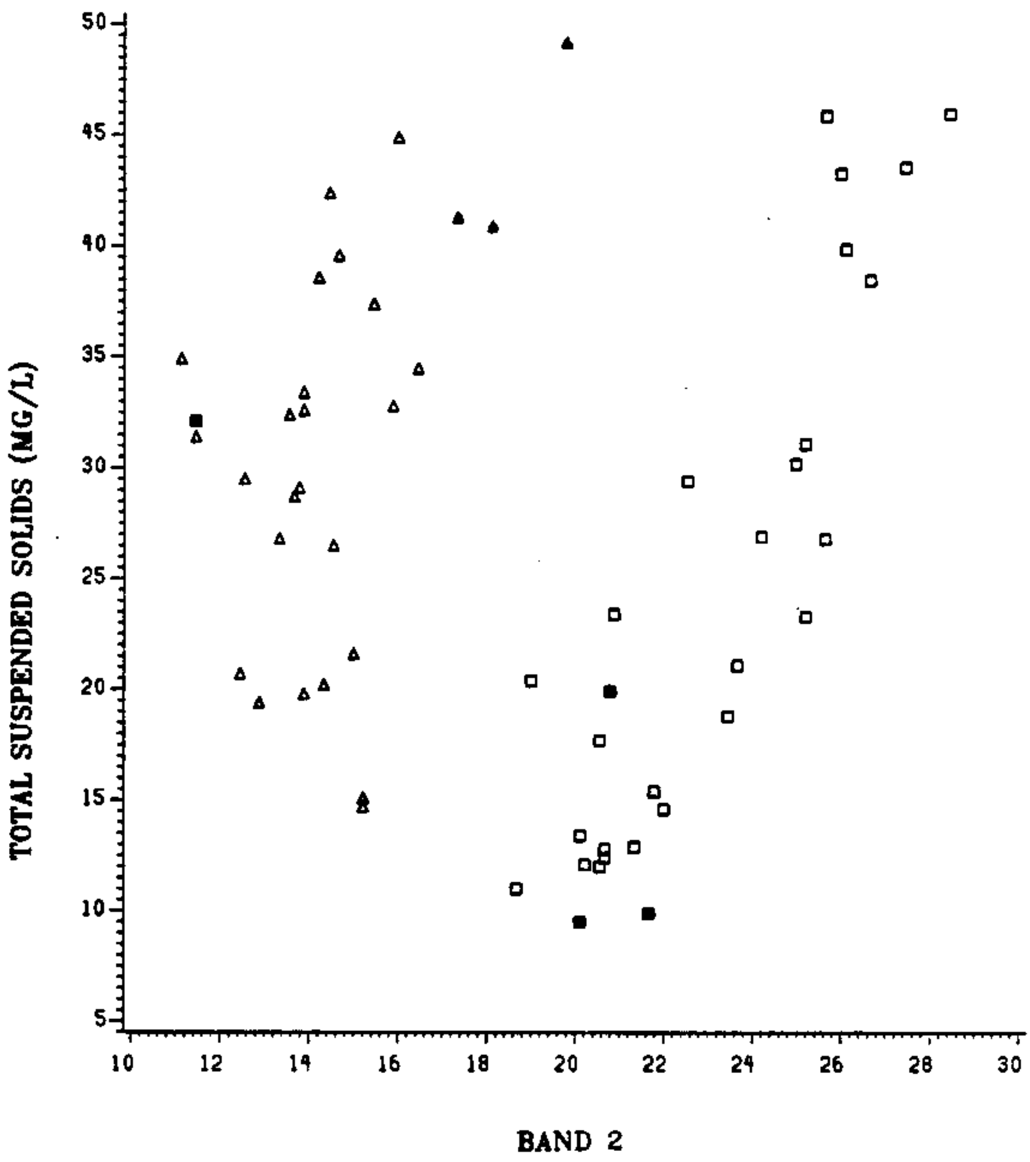


TURBIDITY (NTU)
45
40
35
30
25
20
15
10
5
0
10
12
14
16
18
20
22
24
26
28
30
BAND 2


45
40
35
30
25
20
15
10
5
0
TURBIDITY (NTU)
2
4
6
8
10
12
14
16
BAND 3


TURBIDITY (NTU)
45
40
35
30
25
20
15
10
5
0
10
15
20
25
30
35
40
45
50
55
60
65
70
BAND 4


TOTAL SUSPENDED SOLIDS (MG/L)
50
45
40
35
30
25
20
15
10
5
16
18
20
22
24
26
28
30
BAND 1


TOTAL SUSPENDED SOLIDS (MG/L)
50
45
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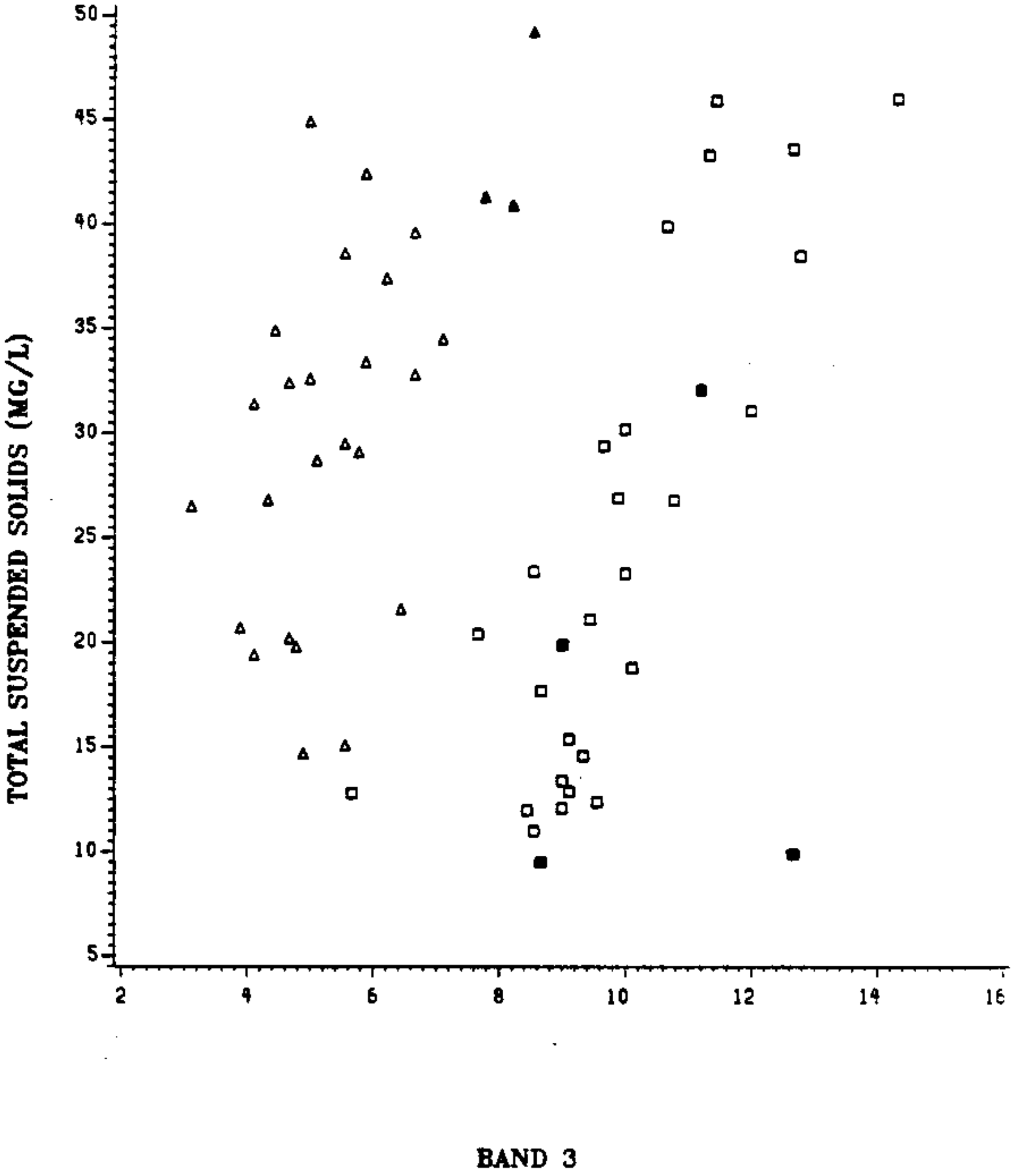
30
BAND 2



50
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40
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10
5
TOTAL SUSPENDED SOLIDS (MG/L)
2
4
6
8
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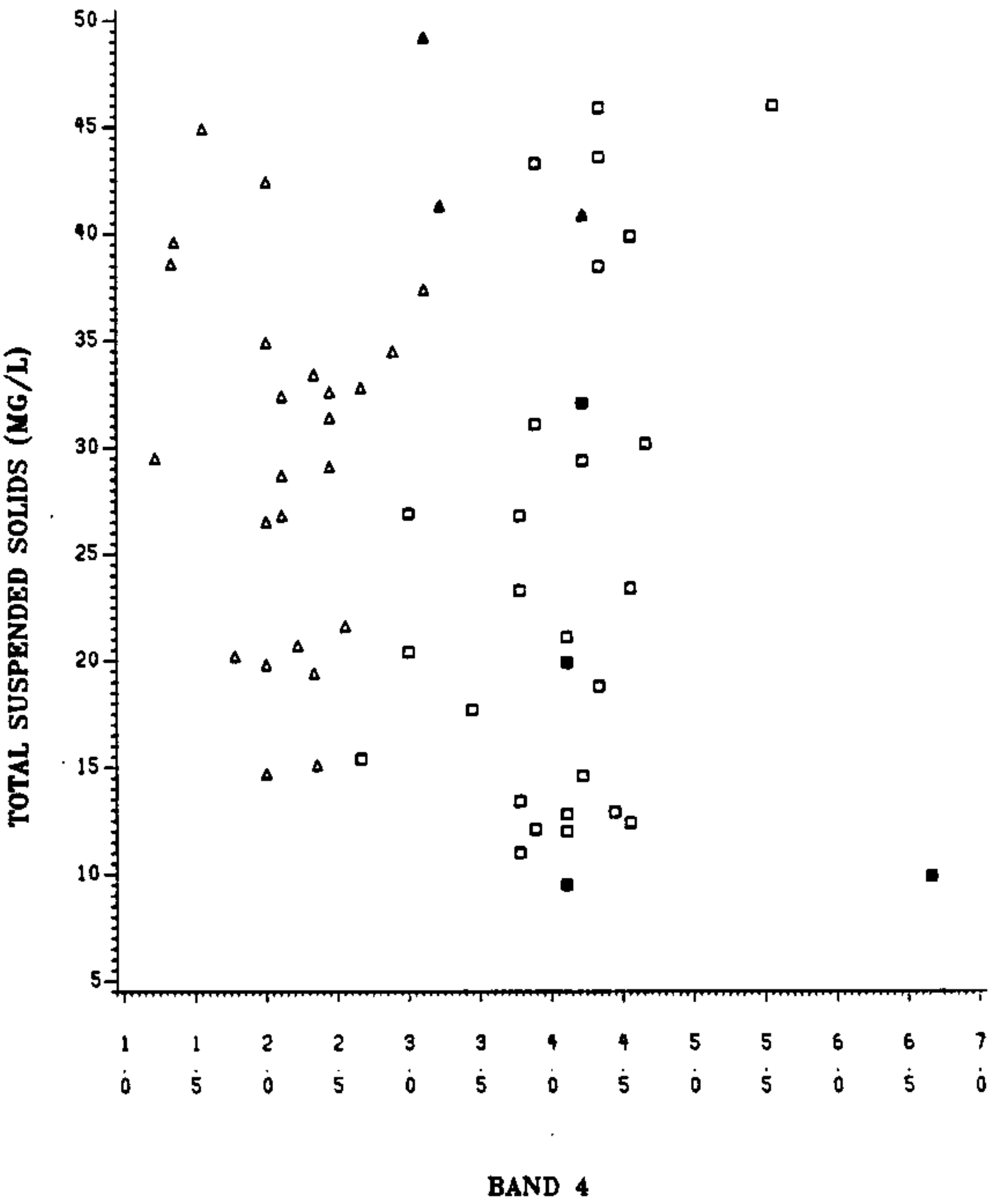
14
16
BAND 3


TOTAL SUSPENDED SOLIDS (MG/L)
50
45
40
35
30
25
20
15
10
5
1.0
1.5
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2.5
3.0
3.5
4.0
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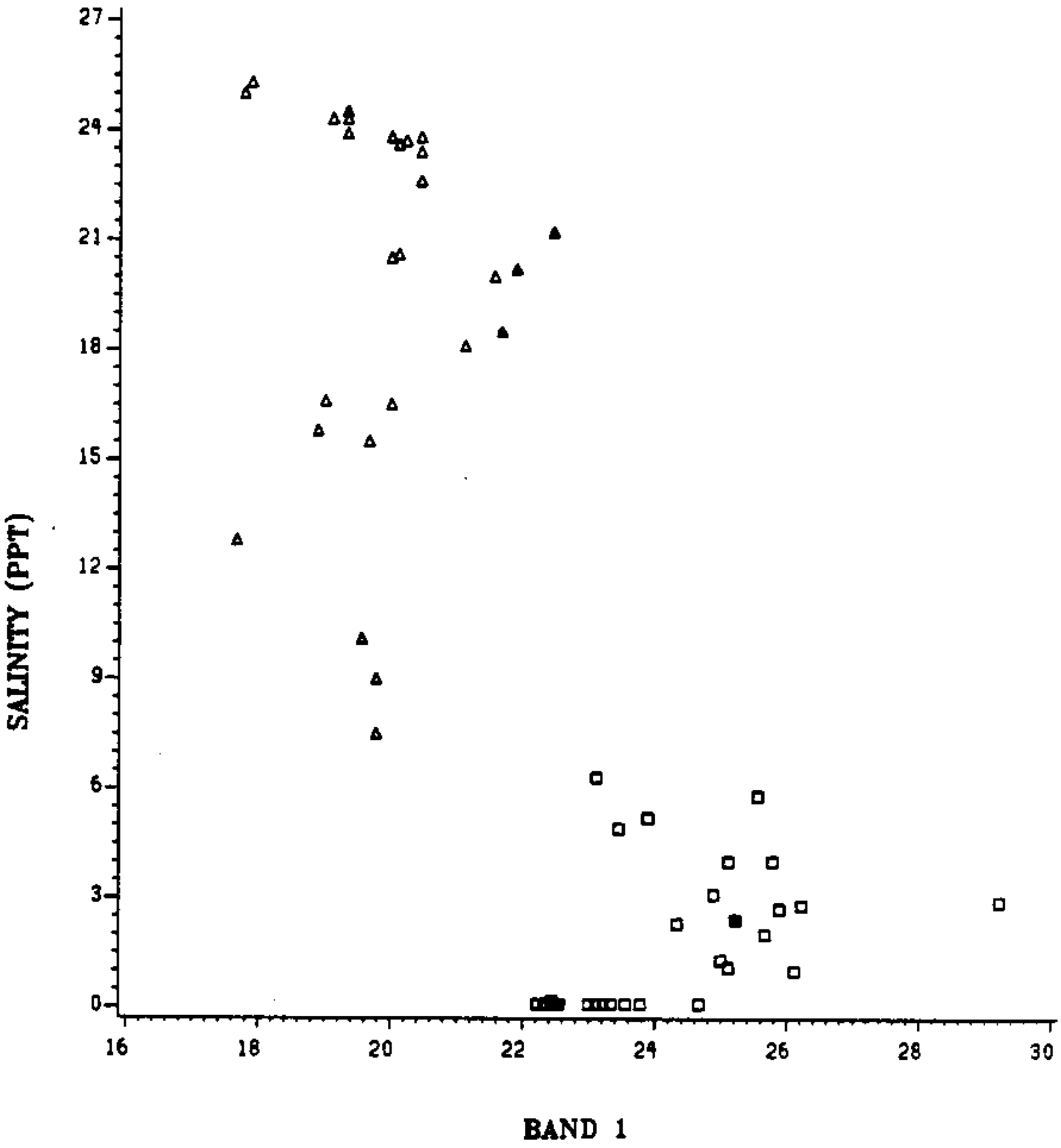
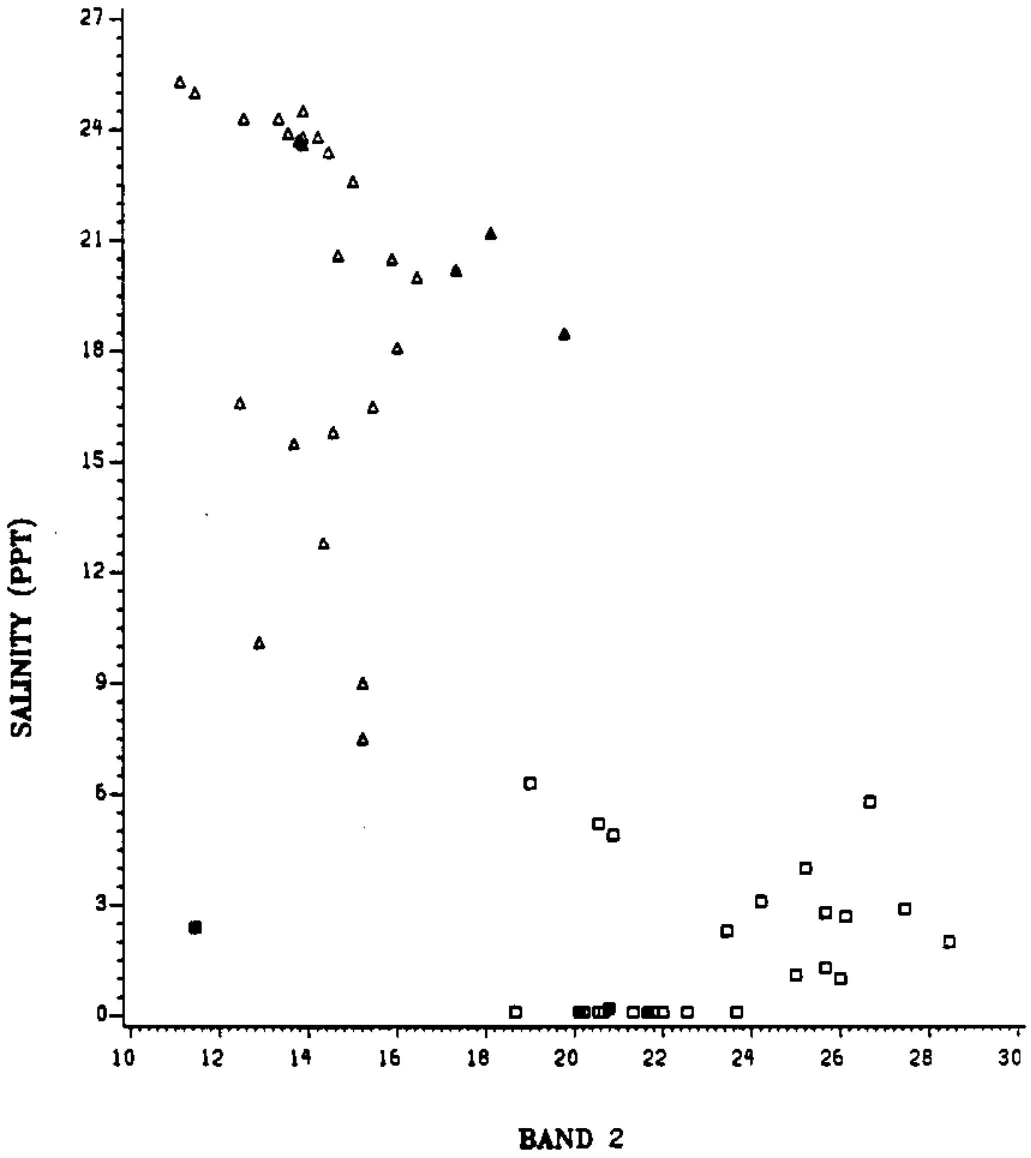
6.5
7.0
BAND 4



SALINITY (PPT)
27
24
21
18
15
12
9
6
3
0
16
18
20
22
24
26
28
30
BAND 1


27
24
21
18
15
12
9
6
3
0
SALINITY (PPT)
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12
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16
18
20
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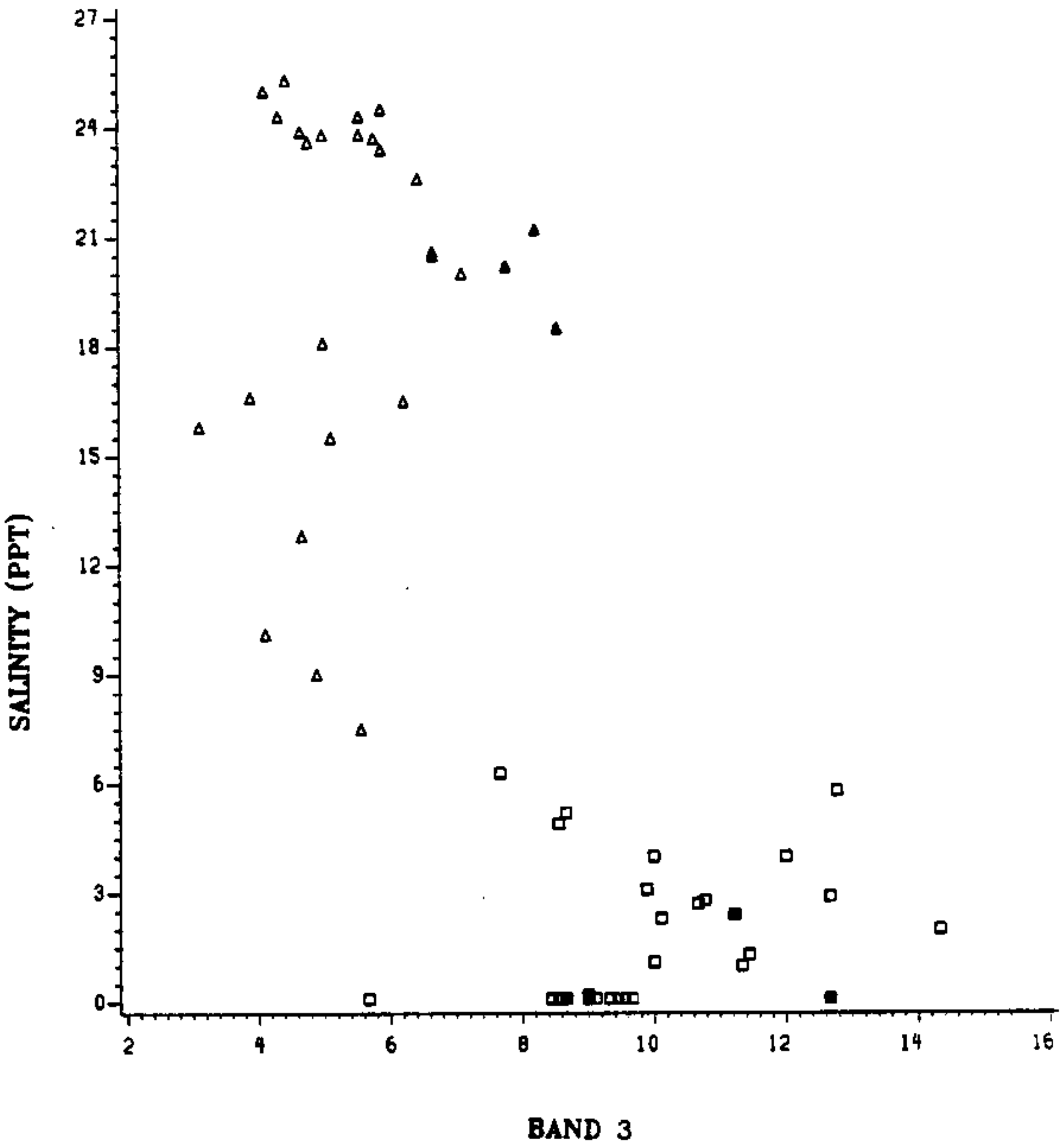
24
26
28
30
BAND 2


SALINITY (PPT)
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24
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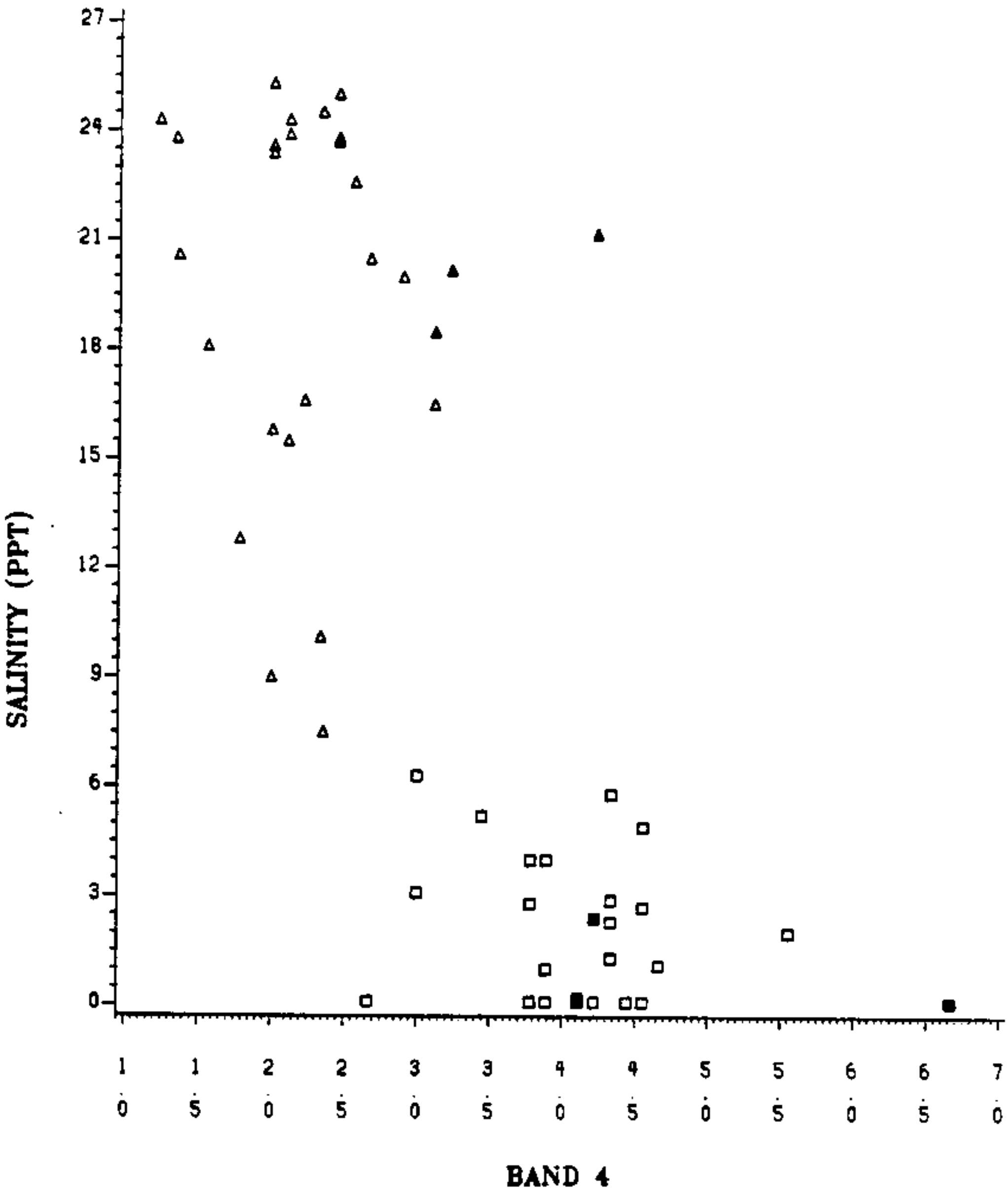
16
BAND 3



SALINITY (PPT)
27
24
21
18
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45
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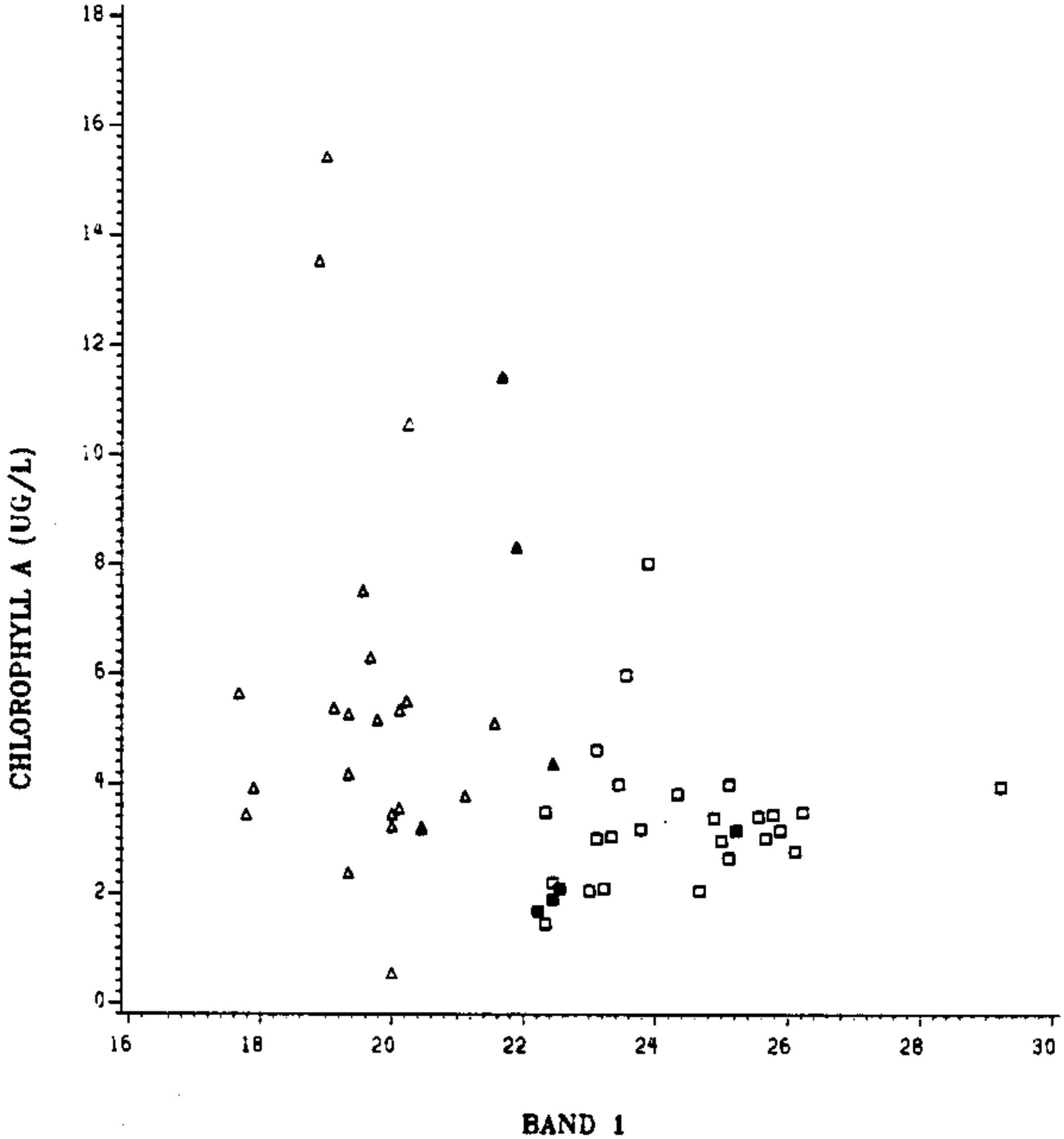
65
70
BAND 4


CHLOROPHYLL A (UG/L)
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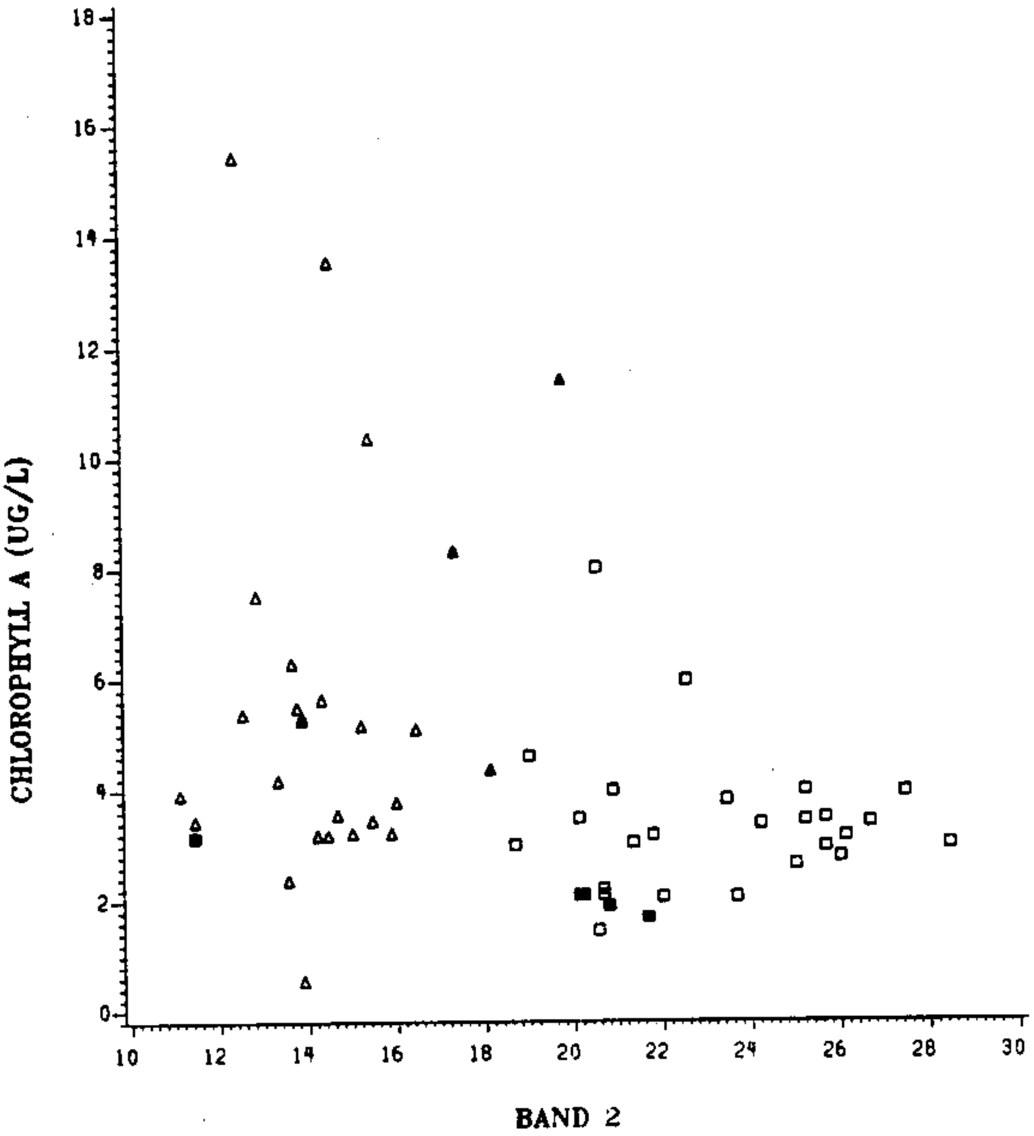
BAND 1


CHLOROPHYLL A (UG/L)
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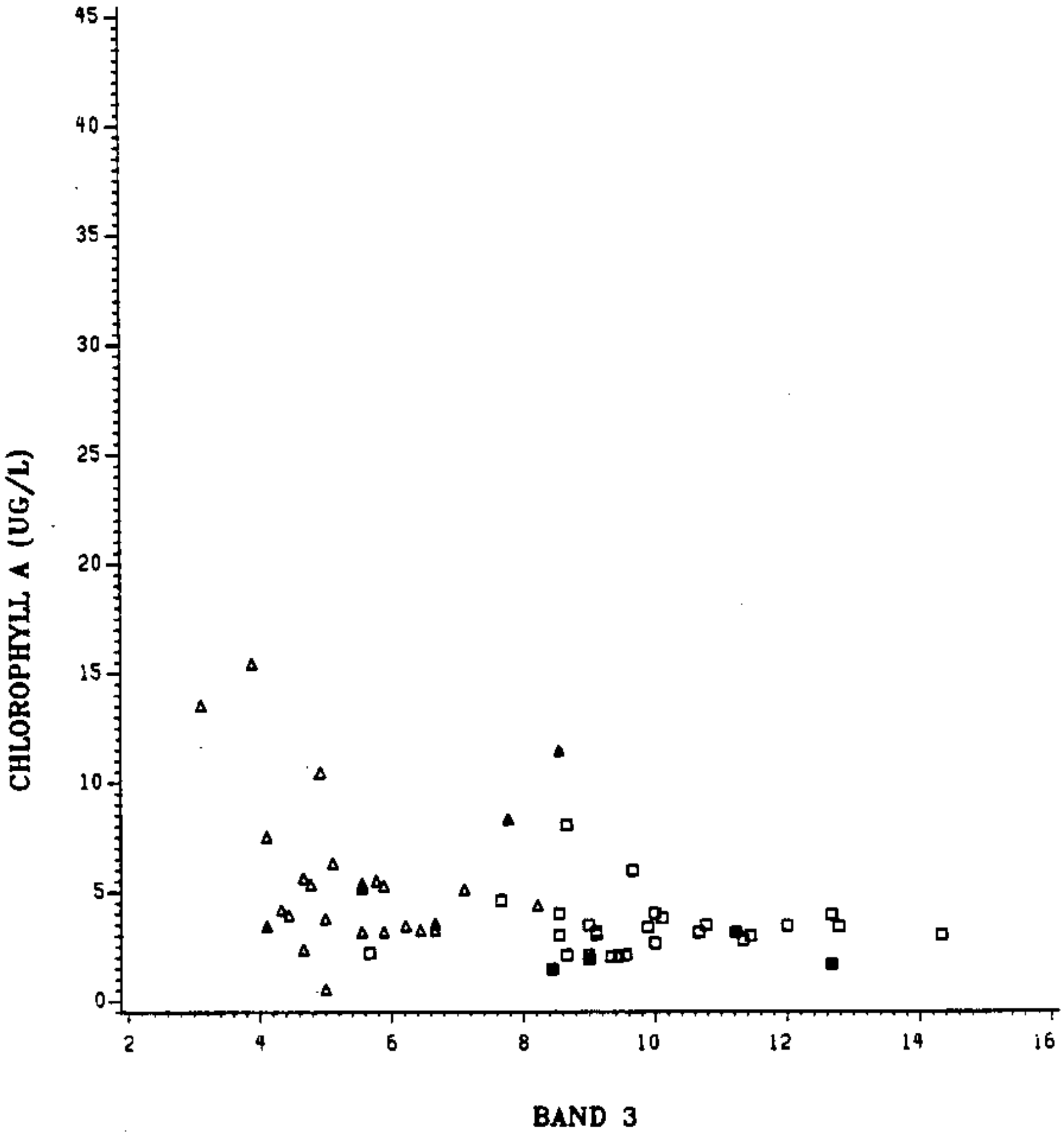
BAND 2



CHLOROPHYLL A (UG/L)
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40
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30
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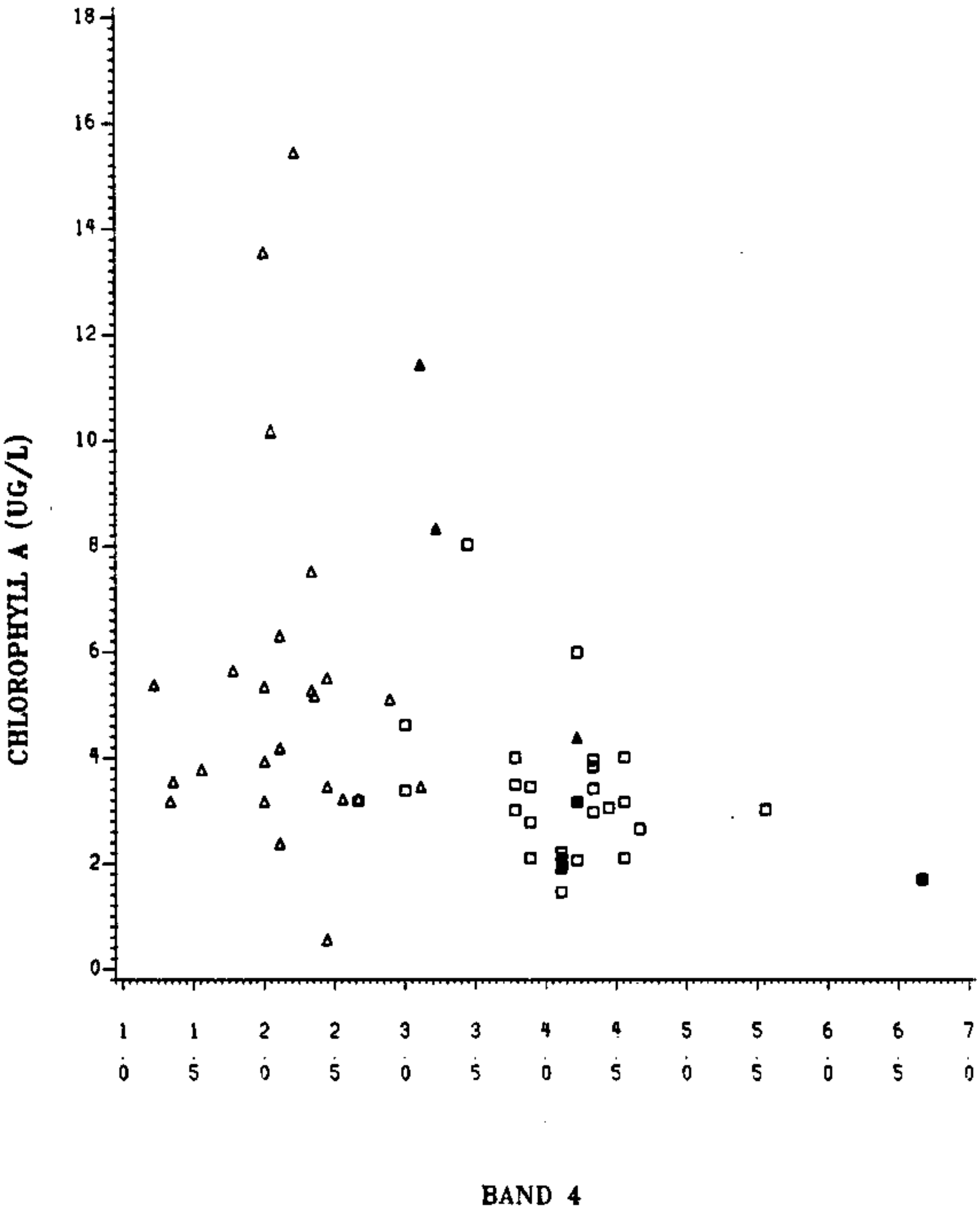
16
BAND 3


CHLOROPHYLL A (UG/L)
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12
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4
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0
10
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20
25
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35
40
45
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55
60
65
70
BAND 4