TRACE ELEMENT CYCLES IN THE SAN FRANCISCO BAY ESTUARY:

RESULTS FROM A PRELIMINARY STUDY IN 1989 - 1990

Final Report

to the

State Water Resources Control Board

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PREFACE

This report provides data on trace element concentrations in the San Francisco Bay estuary. The data were obtained with trace metal clean techniques, which have been extensively calibrated with certified reference materials. The analytical procedures utilized for this study have been published in peer reviewed scientific journals. They have also been tested in numerous national and international intercalibrations. This is in contrast with most previously published data on trace element concentrations in the estuary, which have been characterized as suspect in recent reviews by others.

These new data may be atypical, because they were collected during an atypical period. Unusually low flow conditions persisted throughout the sampling period. Comparisons with previous data from moderate and high flow conditions are questionable, because of recognized limitations of much of the earlier data. Therefore, additional data are required for a comprehensive understanding of elemental cycles within the estuary.

Still, we have tried to put these data in perspective with a variety of techniques. All of the techniques employed are based on widely accepted methods, which have been detailed in scientific journals. These include comparisons between trace element and nutrient concentrations, which are highly correlated in oceanic waters and predictive in estuarine waters. Those comparisons benefit from the relative wealth of published information on nutrient cycles in the San Francisco Bay estuary. However, factors controlling the cycling of nutrients in the estuary are still not fully understood, especially under the anomalous drought conditions encountered during our study.

Other comparative techniques included in this report are even more speculative. Criticisms that our box model calculations involve a "black box" are, by definition, appropriate. Criticisms of the limitations of extrapolations of trace element concentrations from high salinity to zero salinity are justified. Criticisms that one source or sink has been overemphasized may also be valid. There simply are insufficient data available for a definitive description of the cycling of trace elements in the estuary.

In summary, we acknowledge the strengths and limitations of both the data and associated calculations included in this report.

INTRODUCTION

Anthropogenic perturbations in an urban estuary

San Francisco Bay is a highly impacted urban estuary. Ninety-five percent of it's original tidal marsh area and 37% of its original water surface area have been lost due to hydraulic mining, diking and other filling operations (Conomos, 1979; Nichols et al., 1986). Fresh water diversions and other management practices have decreased fresh water inflows to the estuary to 40% of historic levels (Nichols et al., 1986). In addition, the estuary has continued to receive inputs of contaminants[1] from point sources, surface runoff, riverine inputs, dredging and dredged material disposal, atmospheric deposition and spills. The relative magnitude of those anthropogenic perturbations is most evident during low flow periods, when principal fresh water inputs are from contaminated urban runoff (3.9×10^{11} L year^{-1}), municipal waste water discharges (2.4×10^{11} L year^{-1}) and industrial waste water discharges (6.9×10^{9} L year^{-1}) (Gunther et al., 1987).

A considerable amount of research has been conducted to determine the consequences of historical and current anthropogenic activities on contaminant concentrations in sediments and biota in San Francisco Bay (Long et al., 1989; Davis et al., 1990; O'Conner et al., 1990). These indicate that the elements of greatest concern are silver, copper, cadmium, mercury and selenium (Luoma and Phillips, 1988). The bioavailability of copper to organisms in San Francisco Bay appears to be exceptionally high (Luoma and Phillips, 1988), in contrast to adjacent coastal waters where copper concentrations in intertidal organisms are relatively low (Goldberg et al., 1983).

Bioassays conducted with waters from San Francisco Bay and the Delta have indicated sublethal toxicities are pandemic. Recent studies have documented toxicities along 125 km stretches of the Sacramento and San Joaquin Rivers (Foe and Conner, unpublished data cited by Anderson et al., 1990) and throughout San Francisco Bay (Anderson et al., 1990). Other studies have indicated metal induced stress in the benthos in extremely contaminated regions of the estuary. Again, this is most evident in the South Bay, where silver and copper concentrations in sediments and benthic organisms are highest in comparison to other areas in the estuary (Luoma and Phillips, 1988).

Previous studies

While there is a substantial amount of evidence that sediments and biota in San Francisco Bay are being affected by anthropogenic inputs of some toxic trace elements, the relationships between those elements in sediments and biota to elemental concentrations in the water column are not well known. There have been relatively few published measurements of trace elements in the water column of San Francisco Bay, and most of those have been spatially limited. Moreover, many of those measurements are questionable (Davis et al., 1990), because they were not obtained with currently accepted "trace metal clean" techniques for sampling, storage and analysis (Patterson and Settle, 1976; Bruland et al., 1979).

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1. In this report, the word contamination is used to indicate the elevation of a constituent above natural concentrations by anthropogenic processes. It is not intended to represent terminology in local, state, national or international legislation.

Three notable studies utilized acceptable techniques to measure trace element concentrations in the northern (Gordon, 1980) and southern (Kuwabara et al., 1989) reaches of the estuary and selenium concentrations throughout the estuarine system (Cutter, 1989). Gordon (1980) found nonconservative excesses of dissolved cadmium, copper, iron, manganese, nickel and zinc relative to conservative mixing gradients over a range of salinities in the northern reach of the estuary. He tentatively attributed those excesses to remobilization from sediments. He also found relatively conservative distributions of those elements at higher salinities. Kuwabara et al. (1989) found that dissolved concentrations of copper and zinc were positively correlated with dissolved organic carbon concentrations in the South Bay, which they concluded was the result of organic complexation on the solution chemistry of those elements. Cutter (1989) observed a mid-estuary source of selenium in the northern reach of the estuary during periods of low flow, which appeared to originate from petroleum refinery effluents. He also observed a selenium source in the South Bay, which was attributed to effluents from sewage treatment plants.

This study

The present study was based on the hypothesis that natural cycles of many trace elements throughout the San Francisco Bay Sacramento-San Joaquin Delta estuary are perturbed by anthropogenic inputs. That hypothesis is substantiated by the following preliminary data, which delineate dissolved and total (dissolved and suspended particulate) trace element concentrations throughout the estuarine system. The elements measured were silver (Ag), arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), iron (Fe), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn). Subsequent studies are being initiated to corroborate these initial measurements, and to quantify natural and anthropogenic processes influencing the chemistry of those elements within the estuary.

DESCRIPTION OF THE STUDY AREA

The San Francisco Bay estuary (Figure 1) is a relatively large, shallow and well mixed system. It is one of the largest estuarine systems in the northeast Pacific, with a surface area of 1,240 km^2. It is also relatively shallow, with seventy percent of the estuary less than 10 m deep. The bay's shallow bathymetry, combined with a tidal prism of approximately 24% of its volume and a tidal excursion of approximately 10 km, results in a well mixed vertical water column over the majority of the estuary.

However, it is not a simple estuarine system. Conomos (1979) characterized it as a three component system, based on the distinctly different hydrographic and geographic features of each area. These regions consist of (1) the northern reach and (2) the southern reach (referred to as the South Bay), which are both connected to (3) the Central Bay. The latter region unites with the oceanic end-member at the Golden Gate. The northern reach includes the confluence of the Sacramento and San Joaquin rivers and a complex of interconnected waterways, which are referred to as the Delta. Two other bays in the northern reach, Suisun Bay and San Pablo Bay, are separated by a geographically narrow constriction, Carquinez Strait.

There are marked differences in circulation patterns within the regions of the estuary, which strongly influence the distribution of materials within those regions. In the northern reach low salinity surface currents flow seaward and higher salinity bottom currents flow landward. In contrast, the South Bay is essentially a lagoon during low flow periods, when wind driven circulation produces oscillatory currents within the well mixed system (Smith, 1987). As noted by Gunther et al (1987), urban runoff and waste water discharges now are the primary sources of fresh water inputs to the South Bay during low flow periods.

The pronounced differences in circulation patterns are reflected by prodigious differences in hydraulic residence times within the estuarine system. The estimated mean hydraulic residence times are 1.2 days during high flow (10^4 m^3s^{-1}) conditions and 60 days during low flow (10^2 m^3s^{-1}) conditions for the northern reach of the estuary, while they are 120 days during high flow conditions and 160 days during low flow conditions in the South Bay (Walters et al., 1985). Additionally, the low flow estimates may be conservatively skewed by the predominance of flow measurements in estuary channels, and there may be significantly greater residence times for water in shallow reaches of the estuary (Smith, 1987).

Considerable seasonal differences in freshwater discharges to the estuary occur during normal precipitation periods. The freshwater discharge is typically Mediterranean, with summer flows ranging from 100 to 400 m^3 s^{-1} and winter flows ranging from 1,000 to 10,000 m^3 s^{-1}. This produces a seasonal flushing of the entire estuarine system, including the South Bay, during normal winter flows (Peterson, 1985).

However, drought conditions developed in 1987 and persisted through 1990, which included the three sampling periods for this study. This anomalous condition was evidenced by monthly mean discharges, which are characterized by the Delta Outflow Index (DOI) for the period between October 1988 and September 1989 (California Department of Water Resources, 1990). Those DOI flows ranged from 130 to 330 m^3 s^{-1}, with the exception of one high flow period in March of 1989 (mean monthly DOI = 1100 m^3 s^{-1}).

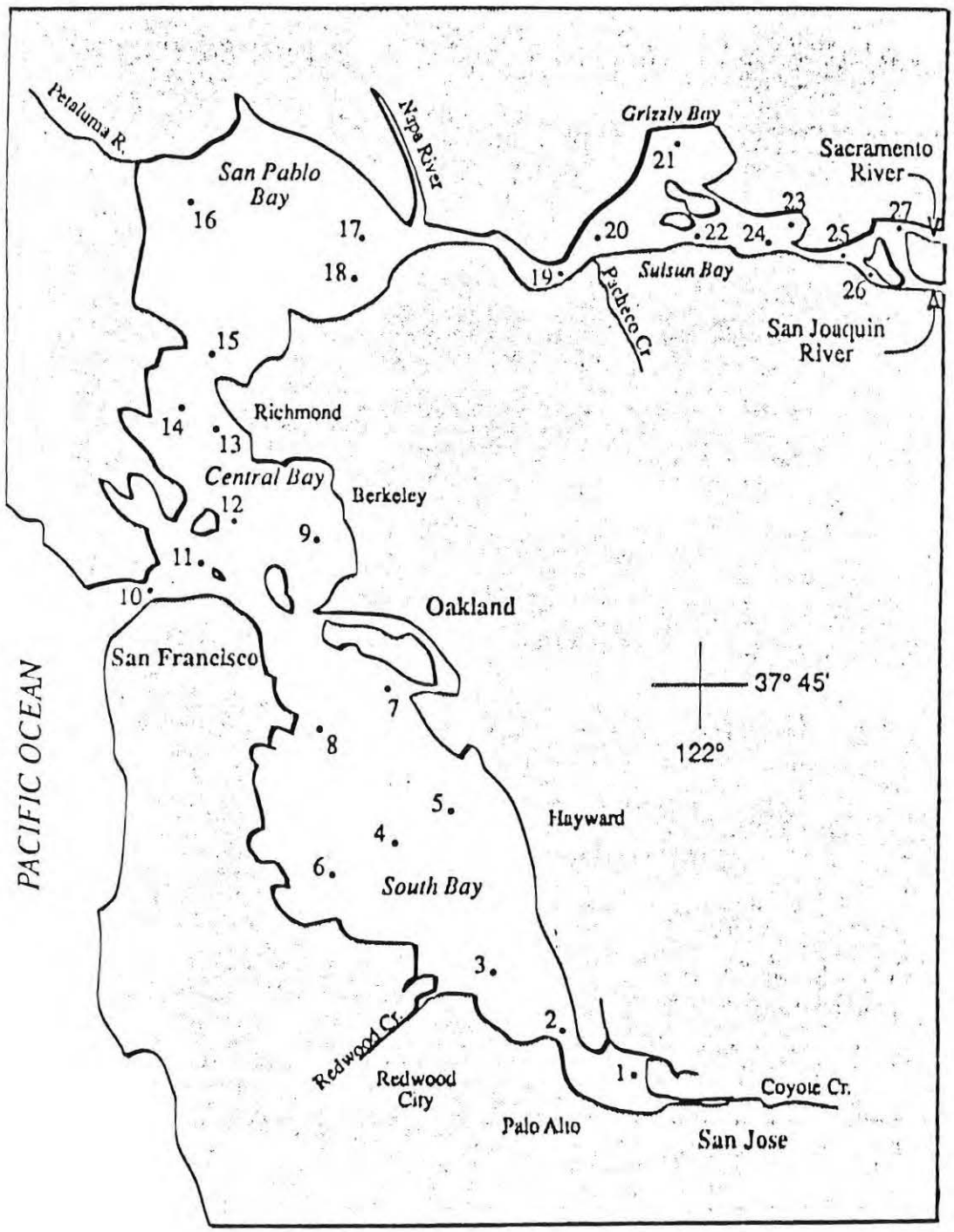


Figure 1. Index map of the San Francisco Bay estuary with water sampling stations. For the purposes of charrcterizing data in this report only, the northern reach includes Stations 9-27, which extend along a transect from the Sacramento-San Joaquin delta to the Golden Gate and the southern reach, or South Bay, includes Stations 1-8.

While persistently low flows during this preliminary survey may have produced atypical constituent concentrations and distribution patterns within the estuarine system, those low flows may also serve to illustrate the effects of potential increases in water diversions. Current discharges to the system are substantially lower than historical discharges due to the diversion of fresh water from the system (≈ 7 km^3 yr^{-1}). These provide for approximately two-thirds of all the municipal, industrial and agricultural water consumption in California. Demands for additional exports are rapidly increasing in the state, which experienced unprecedented growth (6.2 million) in the past decade to a population of 29.8 million. The effect of protracted growth on fresh water diversions from the estuarine system is illustrated by the nearly three-fold increase in projected exports to the Central Valley Project for municipal and industrial water contracts from 381,204 acre feet in 1986 to 936,072 acre feet in 2010 (State Water Resources Control Board, 1990).

MATERIALS AND METHODS

Sample Collections

Samples were collected in April, August and December of 1989 from the R/V Scrutiny (owned and operated by the U.S. Bureau of Reclamation) at 27 stations covering the major geographic regions of San Francisco Bay (Figure 1). Stations 9-27 (hereafter referred to as the northern reach) formed a transect running from freshwaters at the confluence of the Sacramento and San Joaquin rivers (referred to as the Delta region), through the central Bay to the mouth of the Golden Gate. Stations 1-8 (hereafter referred to as the southern reach or South Bay) formed a transect extending from the Central Bay to the southernmost reaches of the South Bay. The station names, numbers and geographic coordinates are listed in Table 1.

Water samples were collected approximately one meter below the surface using a peristaltic pump system (Masterflex, Cole Parmer) equipped with C-Flex tubing in the pump head. Water was drawn in through Teflon tubing attached to an aluminum pole which was oriented upstream of the ship's drift. Sample aliquoting was conducted on deck on the windward side of the ship to minimize contamination from shipboard sources. The applicability of this sampling procedure has been demonstrated previously with intercalibrated analyses of water collected with the California Institute of Technology Deep Water Sampler and General Oceanics, Inc. trace metal clean Go-Flo's (Flegal and Stukas, 1987).

Both filtered and unfiltered water samples were collected, after flushing several liters of water through the system. Filtered water was obtained by placing an acid-cleaned polypropylene filter cartridge (Micron Separations, Inc. 0.45 μm pore size) on the outlet of the pumping system. Filtered and unfiltered water samples were then drawn directly into acid-cleaned polyethylene or Teflon bottles. Unfiltered water was pumped directly into the bottles. Bottles were rinsed three times before filling. Both sets of samples were acidified with sub-boiling quartz distilled (2x) acids in a trace element clean laboratory on a Class 100 clean-air bench.

Trace Element Determinations

Most trace element concentrations (Ag, Cd, Co, Cu, Fe, Ni, Pb and Zn) were analyzed by graphite furnace atomic absorption spectrometry preceded by sample preconcentration using the APDC/DDC organic extraction method described by Bruland et al. (1985). Mercury concentrations were measured by flameless atomic fluorescence spectrometry using the method described by Gill and Bruland (1990). Arsenic concentrations were measured by hydride generation atomic absorption spectrometry using the method described by Anderson and Bruland (1991).

The accuracy and precision of the elemental analyses were quantified by concurrent intercalibrations with internal and external standards and replicate analyses, respectively. Analytical detection limit values, blank signals, and recoveries for the Canadian reference sea water (CASS-1) standard reference material (Berman et al., 1983) are given in Table 2. Quality assurance procedures described by Patterson and Settle (1976), were established to assure the accuracy and precision of the trace element concentration measurements. Sampling units were prepared and samples were processed in a Class-100 trace metal clean

Table 1. Sampling station locations.

STATION NAME	LATITUDE	LONGITUDE	CODE
Extreme South Bay	37.29	122.05	1-XSB
Dumbarton Bridge	37.30	122.07	2-DB
Redwood Creek	37.33	122.11	3-RC
San Bruno Shoals (Central So. Bay)	37.37	122.17	4-SBS
Hayward Flats (aka Oakland E. Flats)	37.38	122.13	5-HF
S.F. Airport (aka S.F. W. Flats)	37.37	122.20	6-SFO
San Leandro Channel (aka Alameda)	37.45	122.18	7-SLC
Hunter Point	37.43	122.20	8-HP
Berkeley Flats	37.50	122.20	9-BF
Golden Gate	37.49	122.28	10-GG
Alcatraz	37.50	122.25	11-AZ
Angel Island / Treasure Island	37.50	122.23	12-AI
San Rafael Bridge Nearshore	37.55	122.24	13-SRBN
San Rafael Bridge Channel	37.55	122.26	14-SRBC
San Pedro Point	37.59	122.26	15-SPP
Petaluma River	38.02	122.24	16-PR
Pinole Shoal Channel	38.03	122.19	17-PSC
Pinole Shoal Nearshore	38.01	122.19	18-PSN
Benicia Bridge	38.02	122.08	19-BB
Pacheco Creek	38.02	122.05	20-PCK
Grizzly Bay	38.06	122.02	21-GB
Port Chicago	38.03	122.01	22-PTC
Honker Bay	38.04	121.56	23-HB
Stake Point (near Buoy #20)	38.03	121.57	24-SP
Chip's Island (near Buoy #20)	38.02	121.55	25-CI
New York Slough	38.01	121.51	26-NYS
Sacramento River	38.03	121.51	27-SR

laboratory, using double distilled, sub-boiling quartz distilled reagents. Each set of samples was analyzed in duplicate after a series of intercalibrations with Canadian reference sea water (CASS-1) and quantification of procedural blanks. These calibrations were then conducted concurrently with all sample analyses.

Ancillary Data

Additional samples were collected concurrently for measurements of ancillary parameters. Dissolved phosphate, silicate, and nitrate plus nitrite, were analyzed following the procedures described by Parsons et al. (1984). Total acid-hydrolyzable phosphorous was measured in unfiltered samples using the procedure detailed in Standard Methods (APHA, 1989). Salinity was determined using an inductive salinometer calibrated with IAPSO standard seawater. Chlorophyll-a was determined by a fluorometric technique using filtered material from 100 mL samples (Parsons et al., 1984). Temperature and conductivity were measured with a CTD meter (Seabird, Seacat Profiler), and pH was measured aboard the ship with a portable pH meter (Orion SA250).

Multivariate Statistical Analyses

Multivariate statistical analyses were used to identify the most important parameters contributing to variation in the dissolved ($<0.45\ \mu m$) data and to identify clustering of stations by heterogeneity in the data. Hierarchical clustering of the stations was performed using dendrograms (average linkage method) to quantify station heterogeneity. Factor analysis, which is a multivariate statistical technique that creates new independent variables (factors) that are linear combinations of the original variables (e.g. trace element concentrations), was used to identify principal component factors associated with trace element concentration variance.

The multivariate statistical analyses were performed with SYSTAT (Wilkinson, 1987). Raw data were logarithmically transformed and reduced using similarity indices (correlation coefficients). Varimax and Quartimax rotations were used to optimize the results of the factor analyses. Additional details of these types of analyses applied to trace element concentration data are described by Sañudo-Wilhelmy and Flegal (1991).

Table 2

Trace Metal Determinations:

Blanks, Detection Limit and Recoveries

			CASS-1 Reference Material	
Metal	Blank, ng (mean ± std)	Detection Limit (ug/kg)	Certified Value, ng/L (mean ± std)	Measured, ng/L, n=3 (mean ± std)
Copper	2.8 ± 1.1	0.013	291 ± 27	293 ± 6
Nickel	4.4 ± 2.3	0.028	290 ± 31	268 ± 5
Cadmium	0.03 ± 0.02	0.00030	26 ± 5	29 ± 1
Zinc	1.3 ± 0.4	0.0052		
Cobalt	0.26 ± 0.25	0.0030	23 ± 4	23 ± 1
Iron	10 ± 7.9	0.095		
Silver	0.13 ± 0.08	0.00096		
Lead	0.22 ± 0.12	0.0014		
Mercury	0.030 ± 0.004	0.00012		
Arsenic	0.29 ± 0.06	0.007	77.9 ± 0.3	71.9 ± 0.3

RESULTS

Trace element concentrations

Mean values for duplicate determinations of trace elements (Ag, As, Cd, Co, Cu, Fe, Hg, Ni, Pb and Zn) in filtered (0.45 μm) and unfiltered (total) water samples collected on the three cruises (April, August and December 1989) are listed in Appendix 1. The precision of those analyses was typically ± 5% .

Nutrient and salinity data

Dissolved nutrient (PO_4, NO_2 + NO_3, SiO_2) and salinity data for cruises 1 (April 1989), 2 (August 1989) and 3 (December 1989) are listed in Appendix 2. The precision of those analyses also was typically ± 5% .

Spatial and temporal variations

There were pronounced spatial variations in trace element concentrations within the estuary. These are illustrated in the following plots of dissolved and total trace element concentrations at each of the sampling locations during the three cruises in Figure 2 (a-j) and Figure 3 (a - j), respectively. These show consistent differences between stations that often persisted between different sampling periods, as indicated by the multivariate analyses. Variations at individual locations between different sampling periods were also evident.

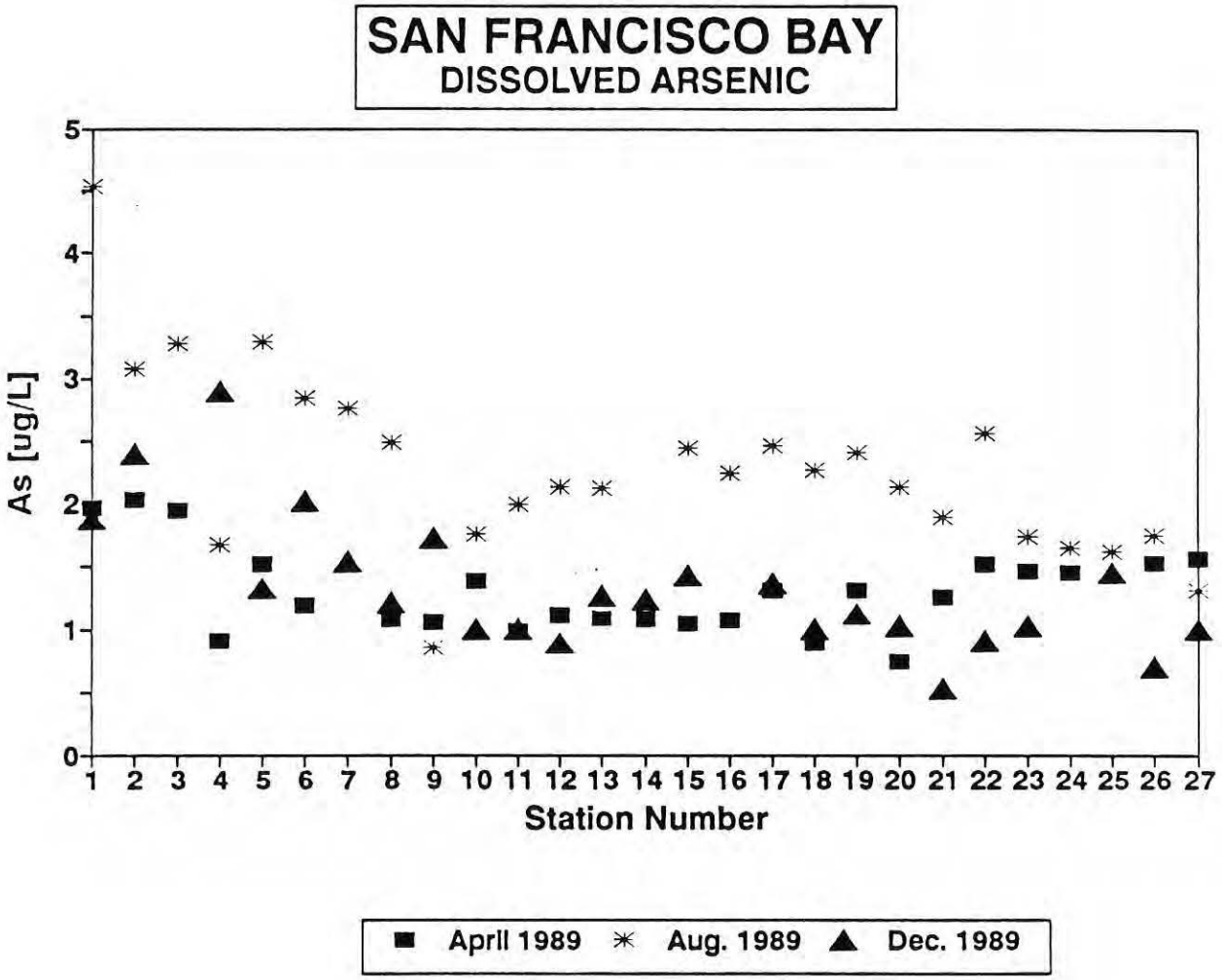
Multivariate analyses

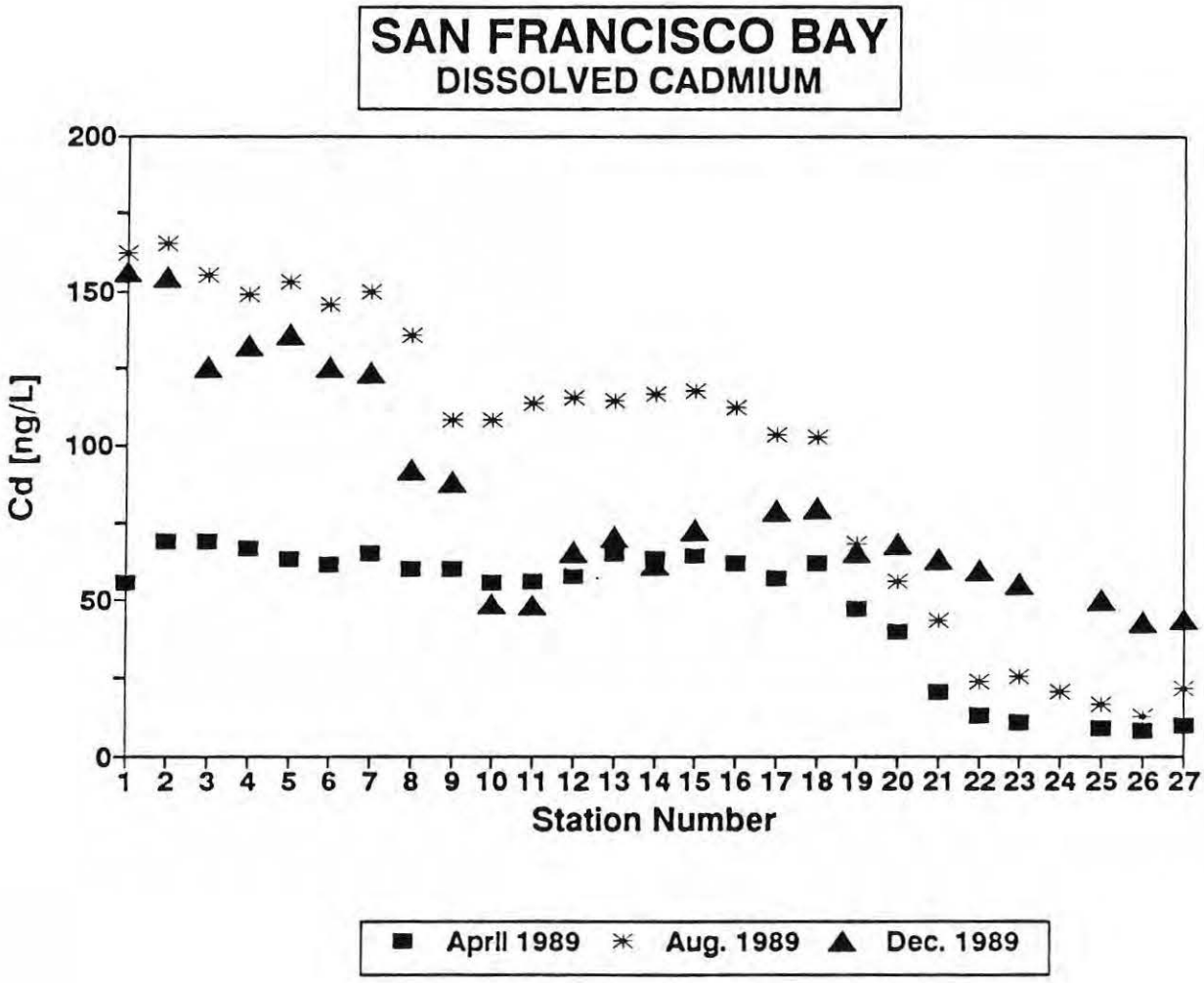
Tables of multivariate statistical analyses of some of the trace metal, nutrient and ancillary data are listed in Appendix 3. Factor analyses of rotated loadings of some of the dissolved trace element concentrations and associated data provide a quantification of the relationships among those parameters and the variance explained by the principal factors. The factor analyses have been grouped by stations derived from dendrograms, because the data for the estuarine system clustered into discrete geographical components. This corroborated the pronounced geographic differences indicated by trace element concentration gradients. A discussion of the application of multivariate analyses of trace element concentrations in sea water is provided in a report by Sañudo-Wilhelmy and Flegal (1991).

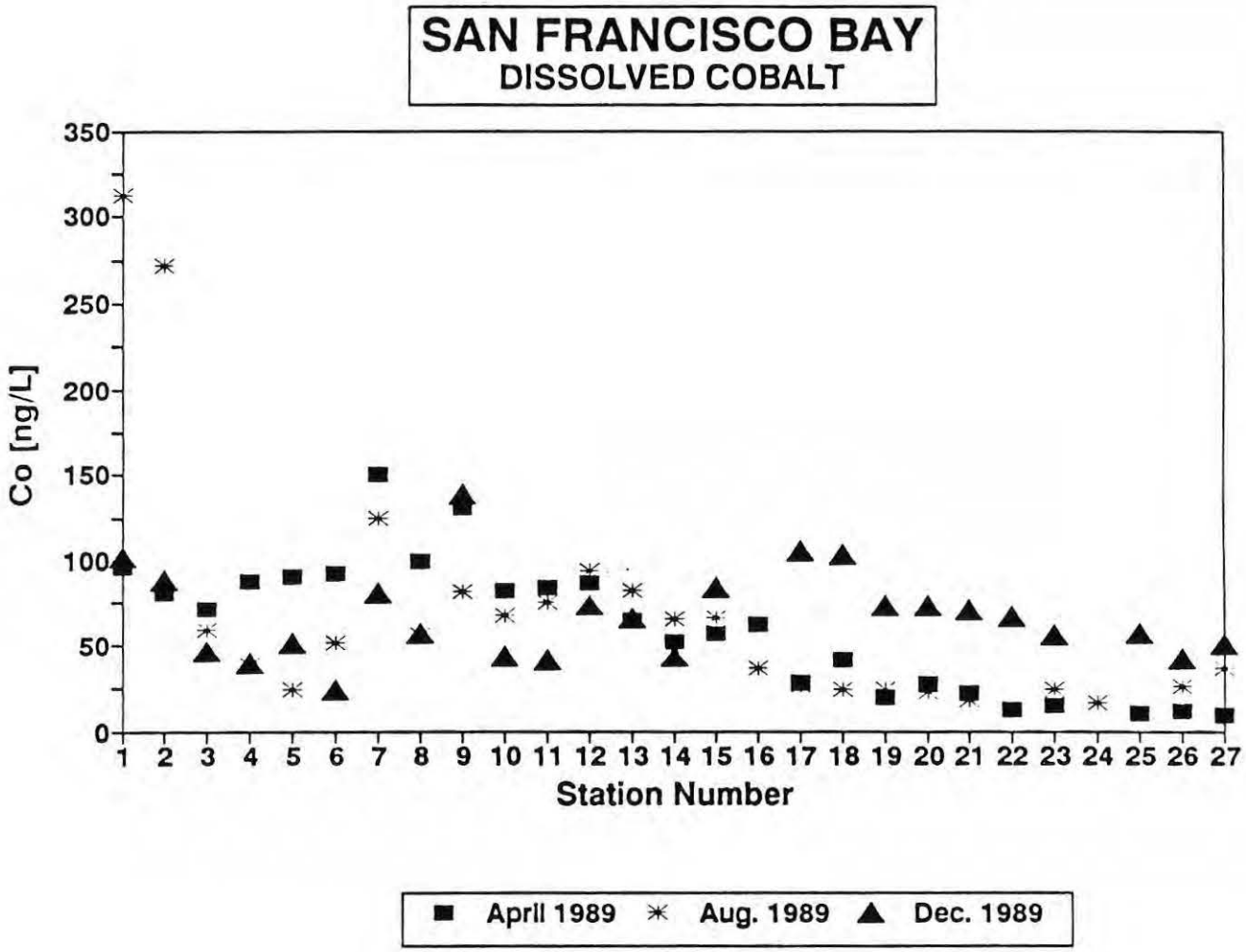
The primary factor associated with geographic variability in the multivariate analyses is salinity. It is highly correlated with geographic gradients in trace element concentrations within the estuary, as well as with temporal gradients at individual locations. This correlation is characteristic of estuaries, and is the focus of the following discussion.

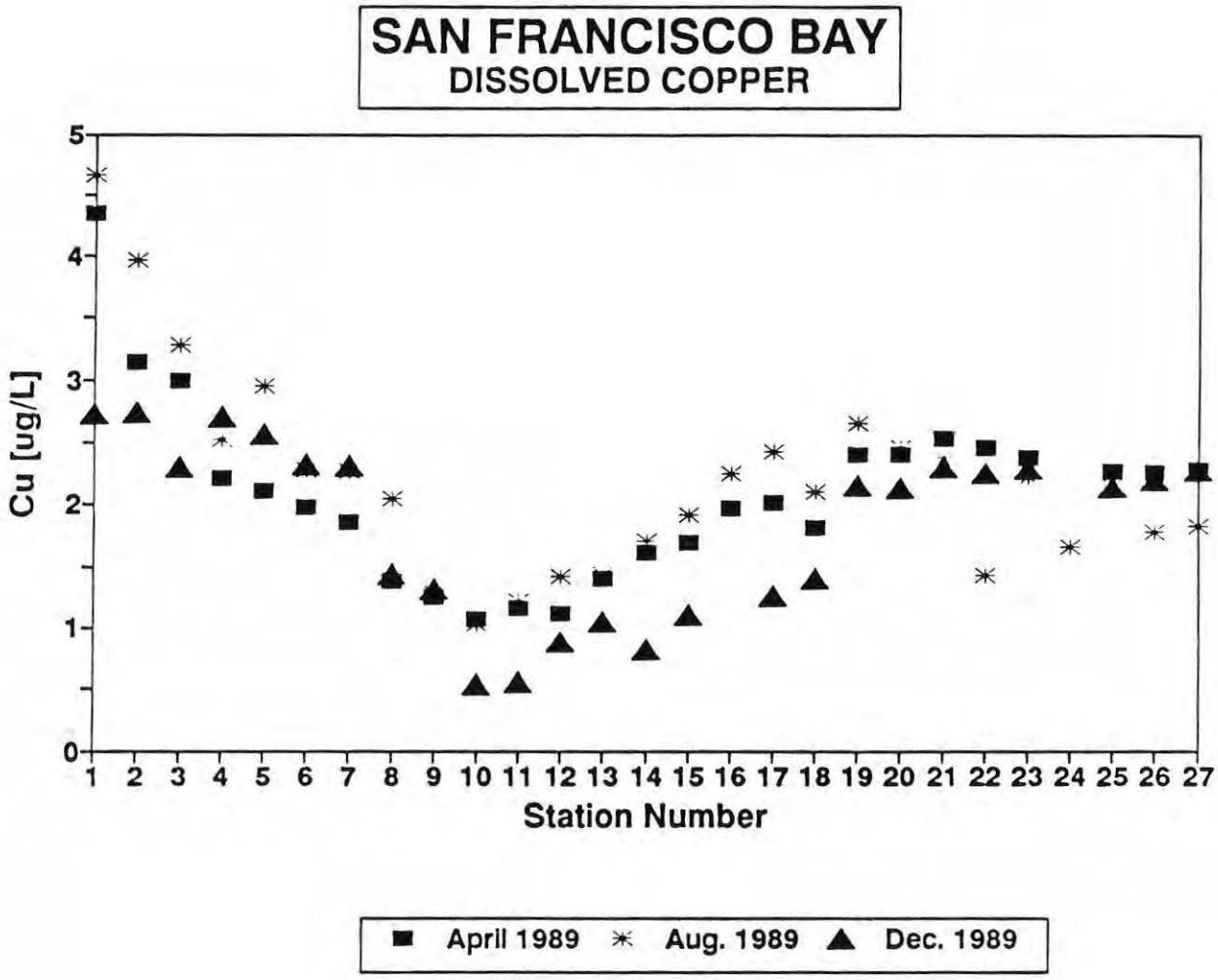
The discussion is limited to a brief description of the biogeochemical cycles of trace elements in the estuary. Only a few dissolved trace element concentration distributions are discussed, because the data are preliminary and there are insufficient complementary data for rigorous quantification. Additional data are now being acquired for a more comprehensive analysis, which will be presented in a subsequent report.

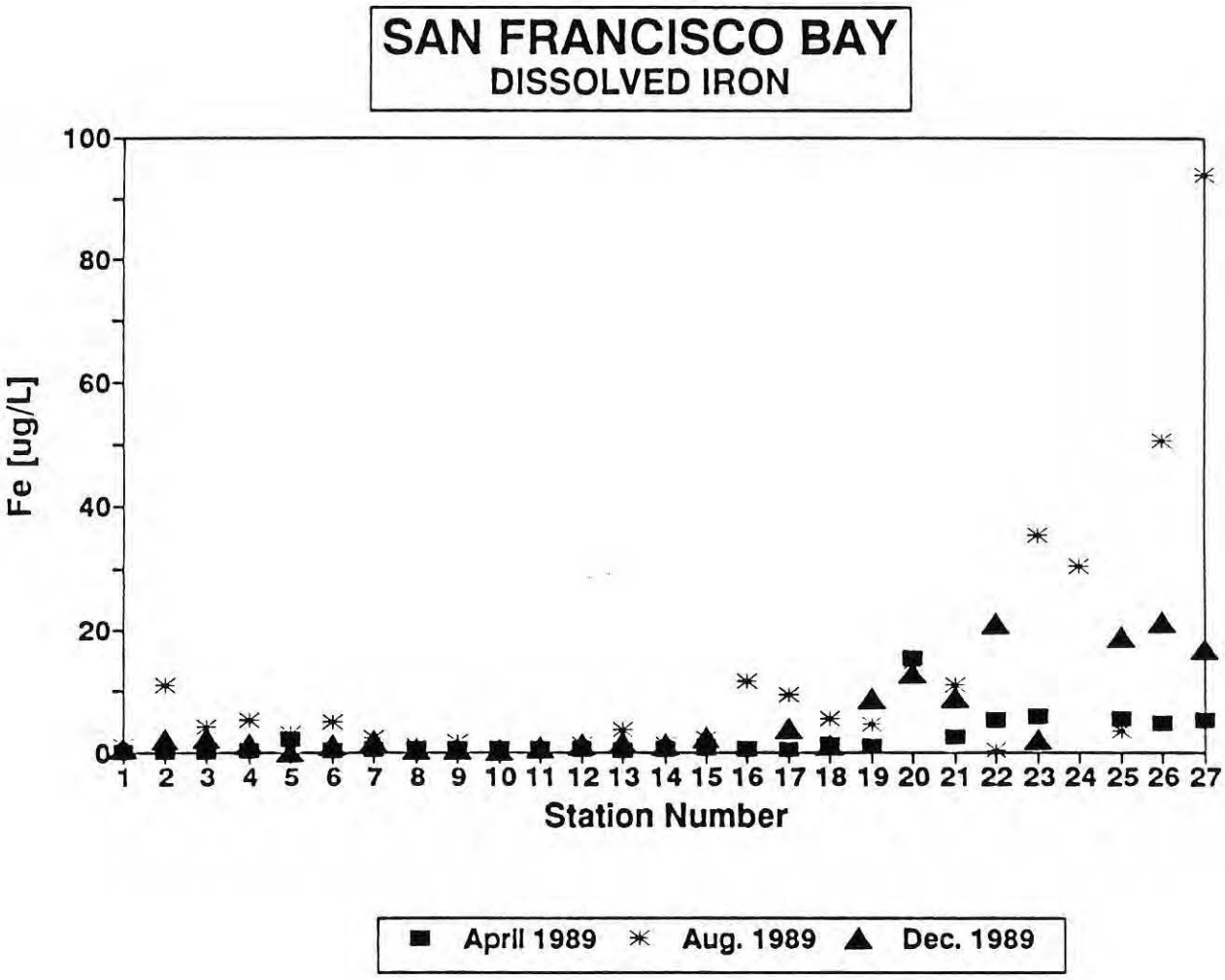
Figure 2 (a - j). Dissolved (< 0.45 μm) trace element concentrations at stations in the San Francisco Bay estuary sampled in cruise I (April), II (August) and III (December) 1989.

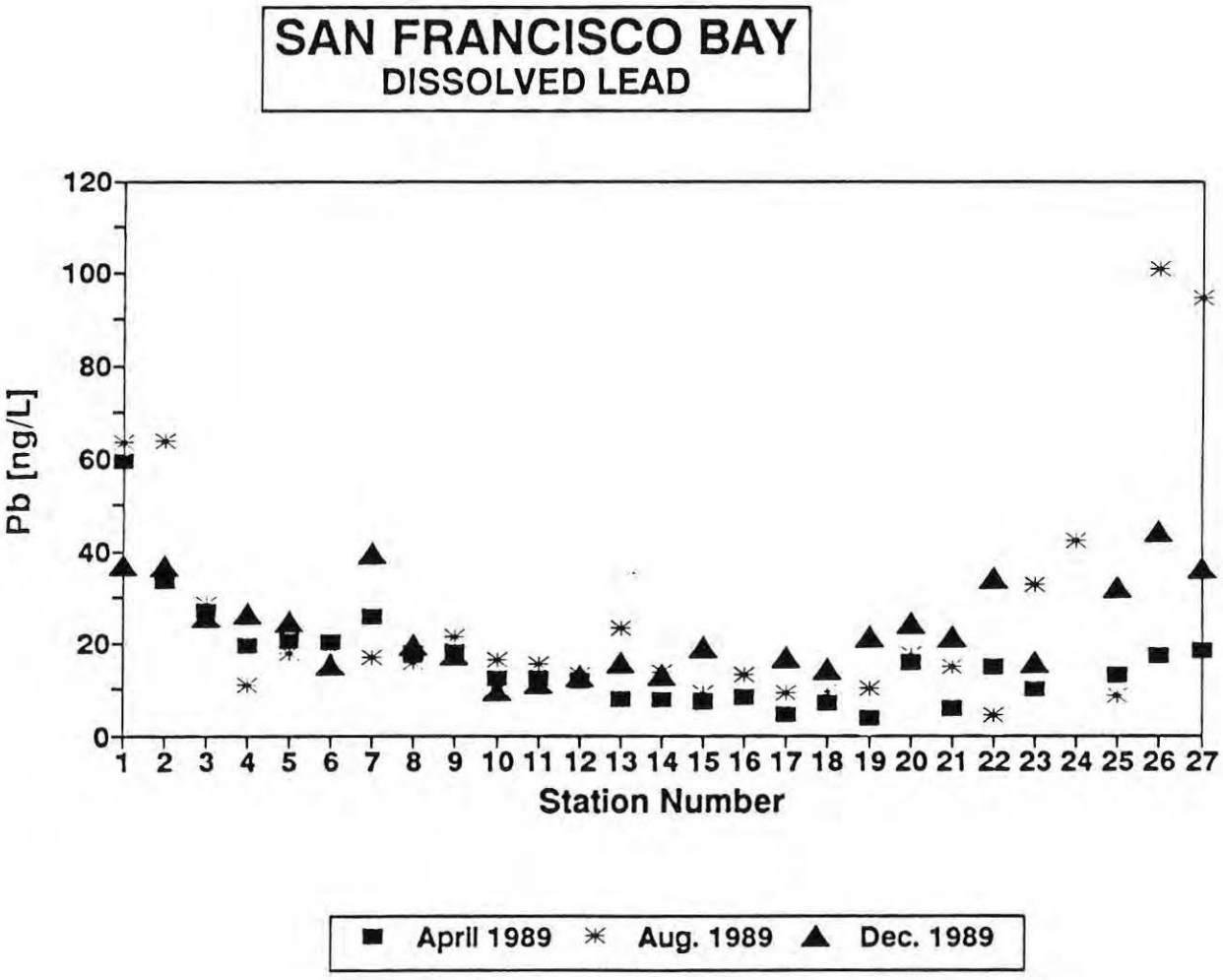

SAN FRANCISCO BAY
DISSOLVED ARSENIC
As [ug/L]
0
1
2
3
4
5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989

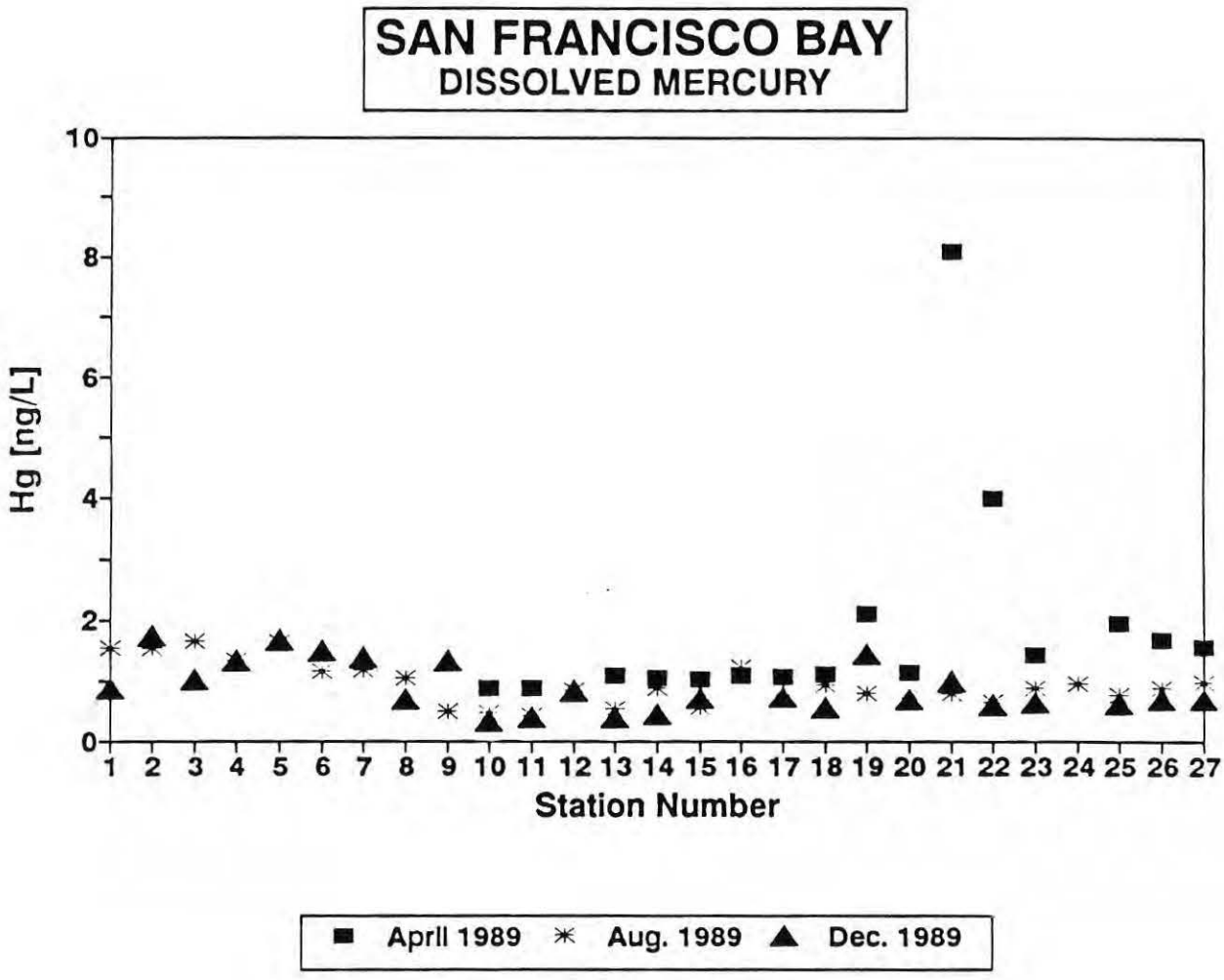

SAN FRANCISCO BAY
DISSOLVED CADMIUM
Cd [ng/L]
200
150
100
50
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989

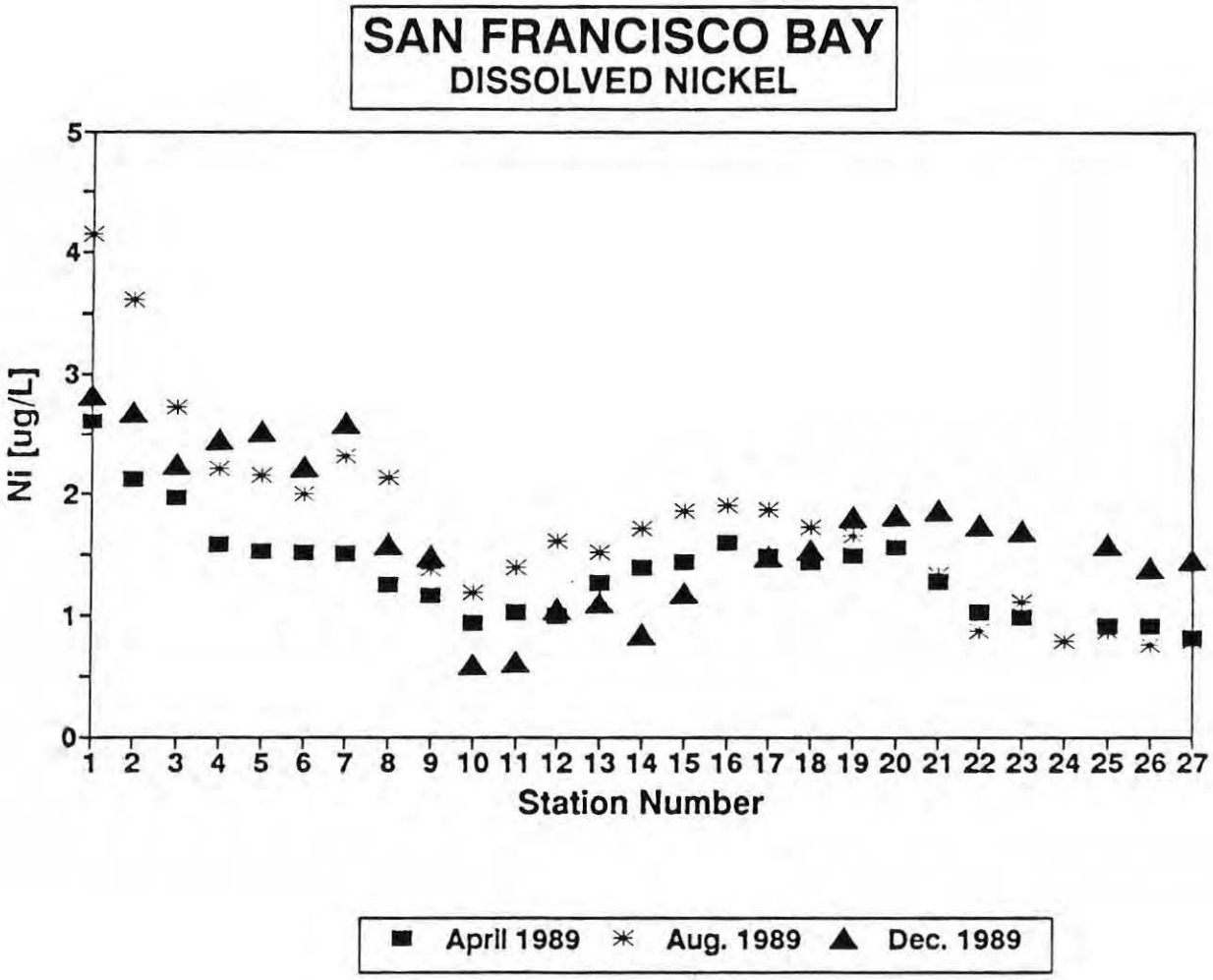

SAN FRANCISCO BAY
DISSOLVED COBALT
Co [ng/L]
350
300
250
200
150
100
50
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989

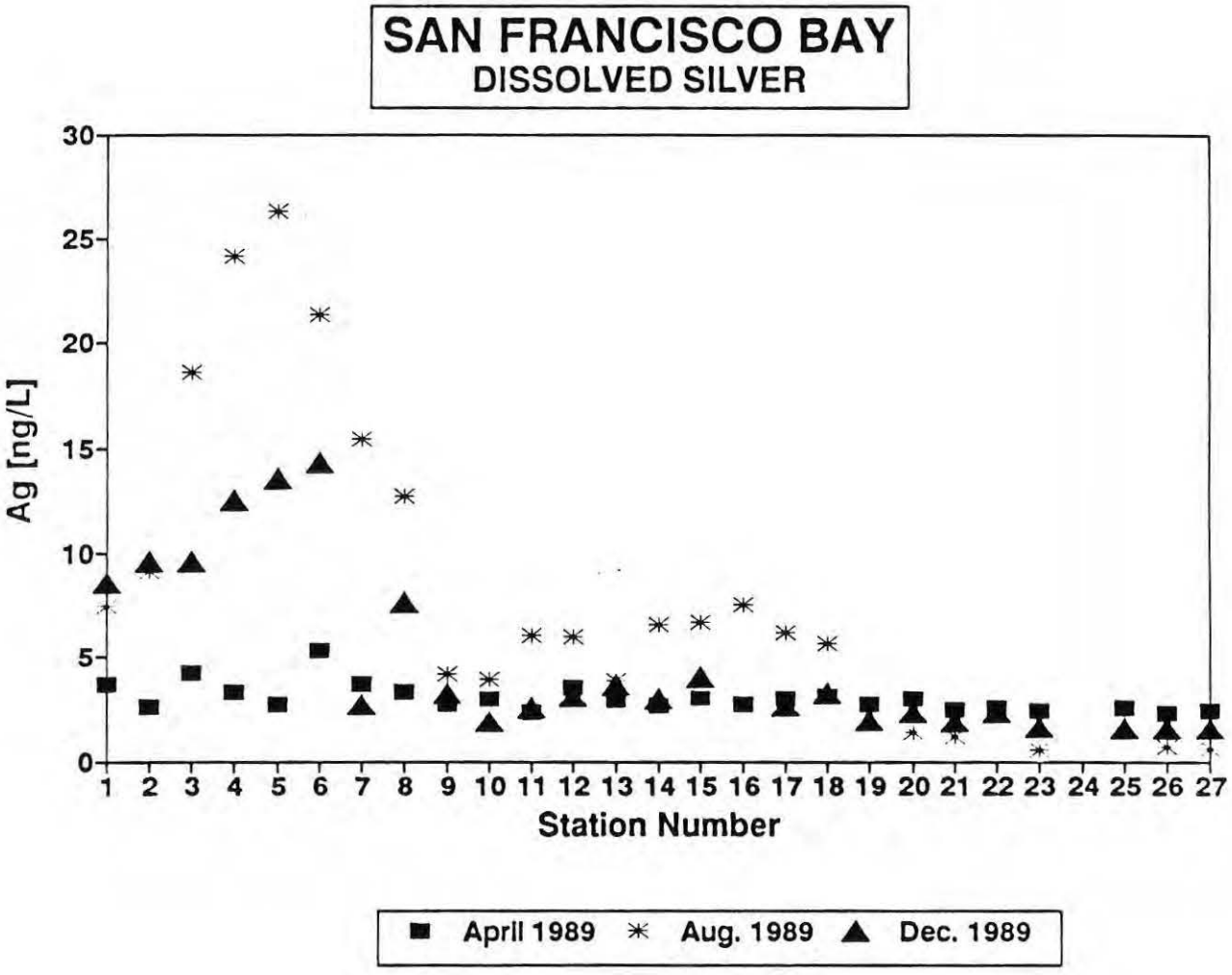

SAN FRANCISCO BAY
DISSOLVED COPPER
Cu [ug/L]
0
1
2
3
4
5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989


SAN FRANCISCO BAY
DISSOLVED IRON
Fe [ug/L]
100
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989


SAN FRANCISCO BAY
DISSOLVED LEAD
Pb [ng/L]
120
100
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989


SAN FRANCISCO BAY
DISSOLVED MERCURY
Hg [ng/L]
0
2
4
6
8
10
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989


SAN FRANCISCO BAY
DISSOLVED NICKEL
Ni [ug/L]
0
1
2
3
4
5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989


SAN FRANCISCO BAY
DISSOLVED SILVER
Ag [ng/L]
30
25
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989

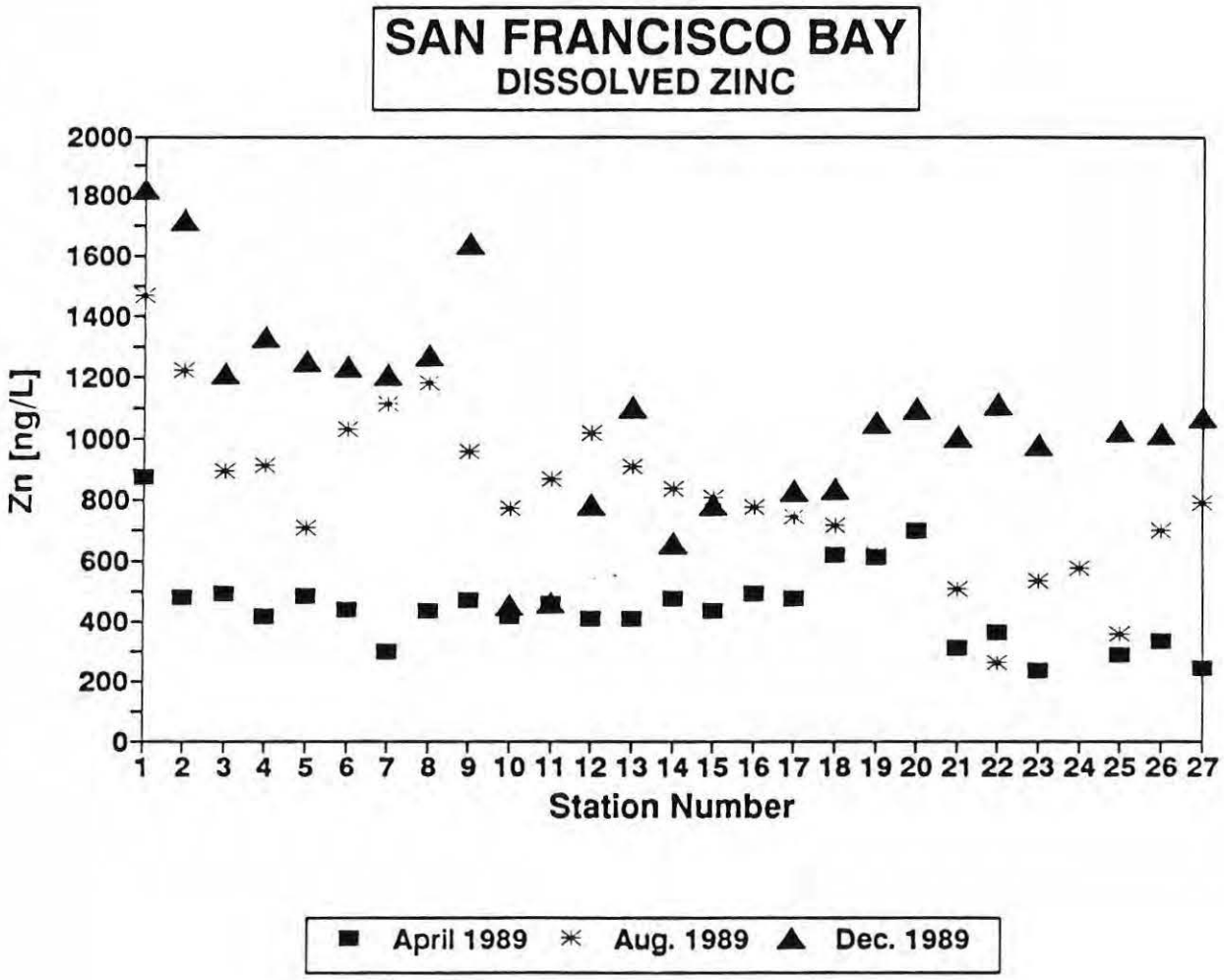
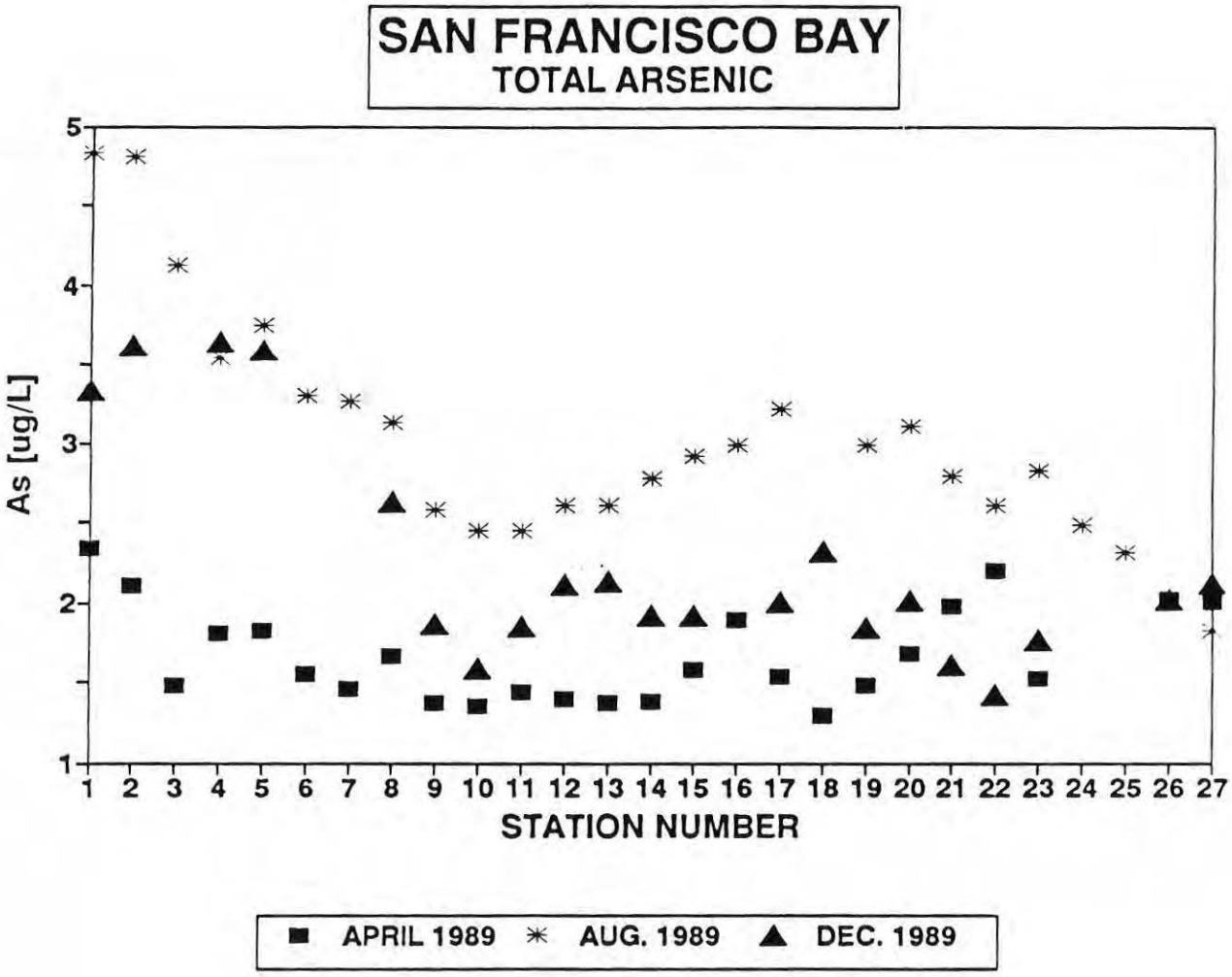
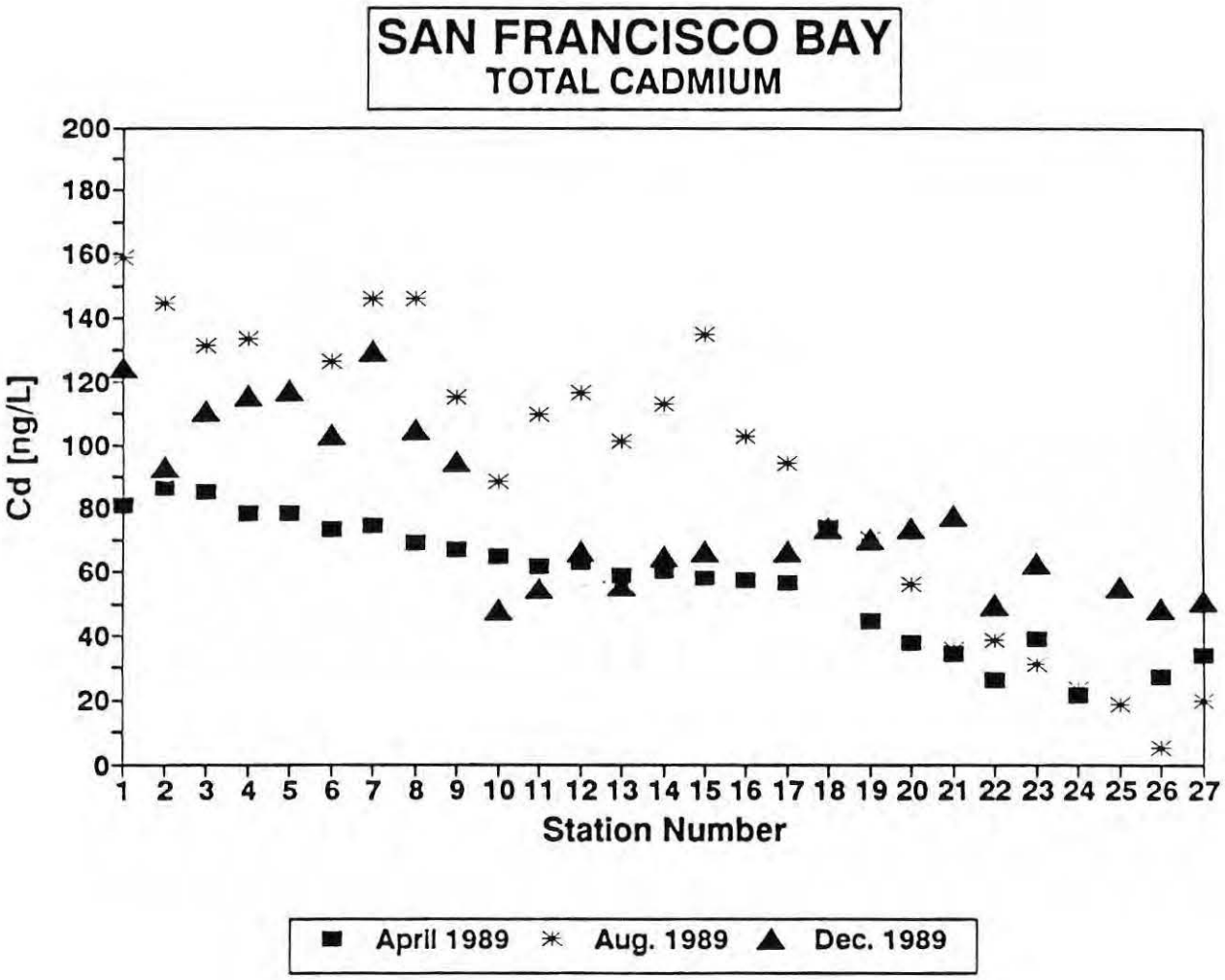
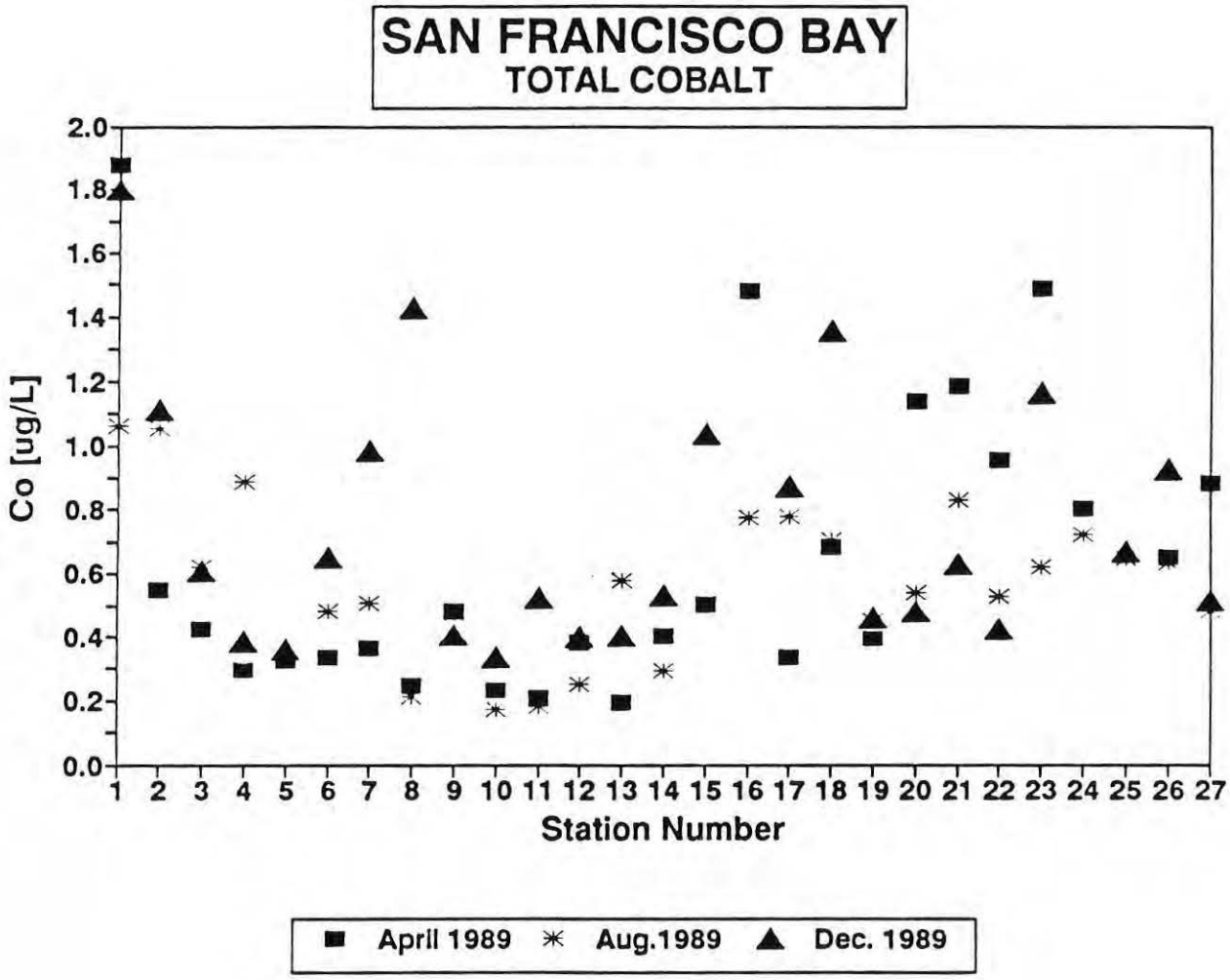
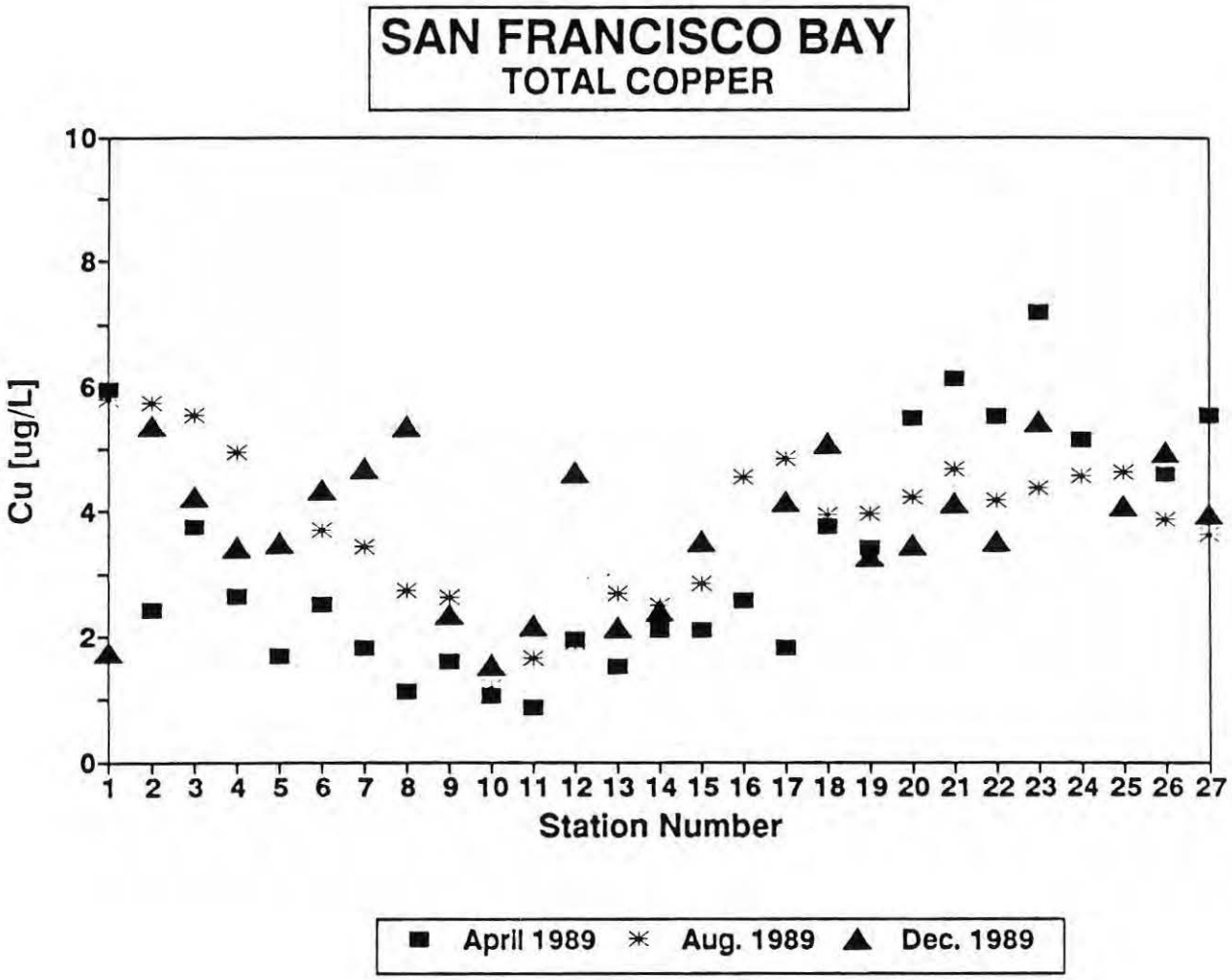

SAN FRANCISCO BAY
DISSOLVED ZINC
Zn [ng/L]
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989

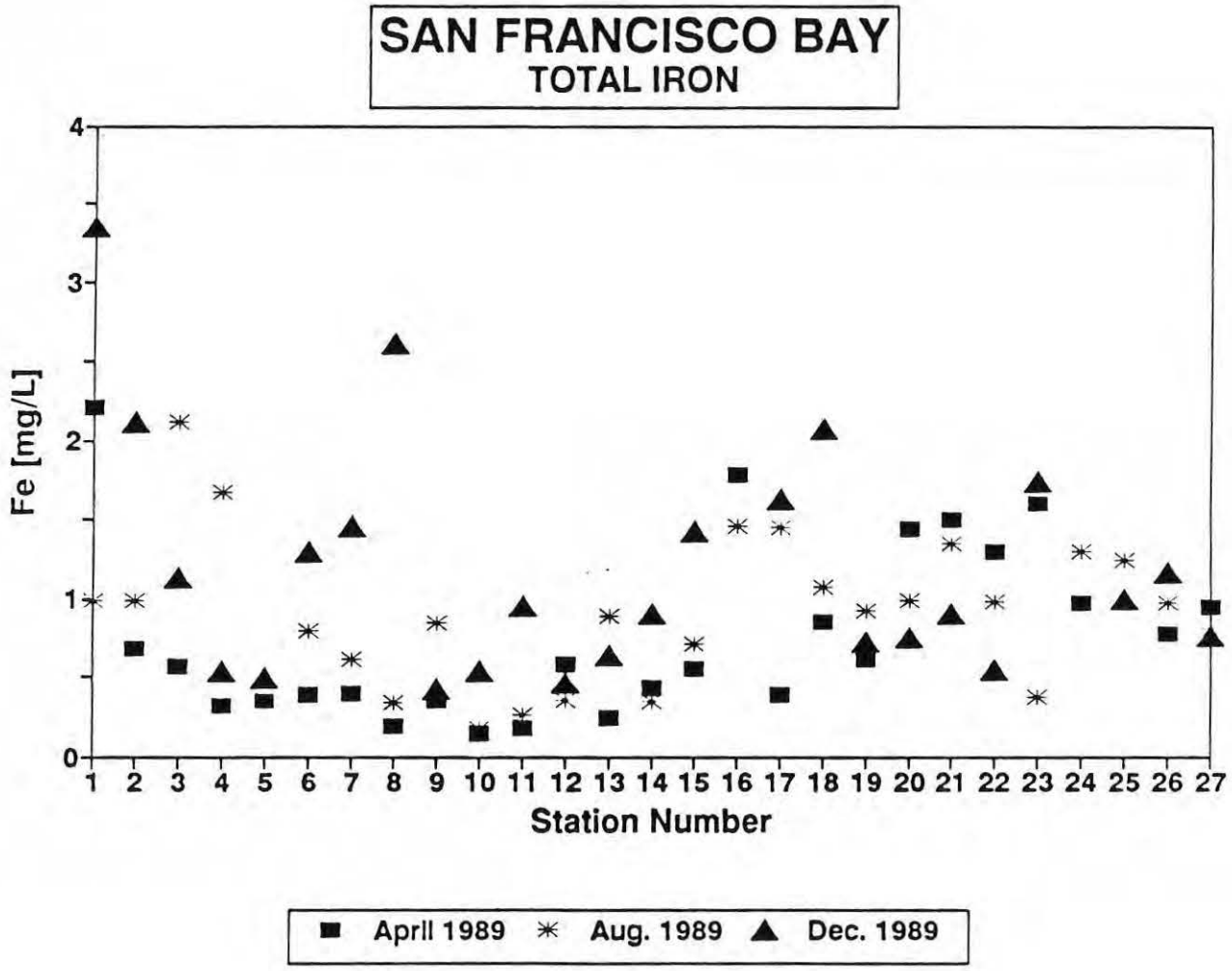
Figure 3 (a - j). Total (dissolved and suspended particulate) trace element concentrations at stations in the San Francisco Bay estuary sampled in cruise I (April), II (August) and III (December) 1989.

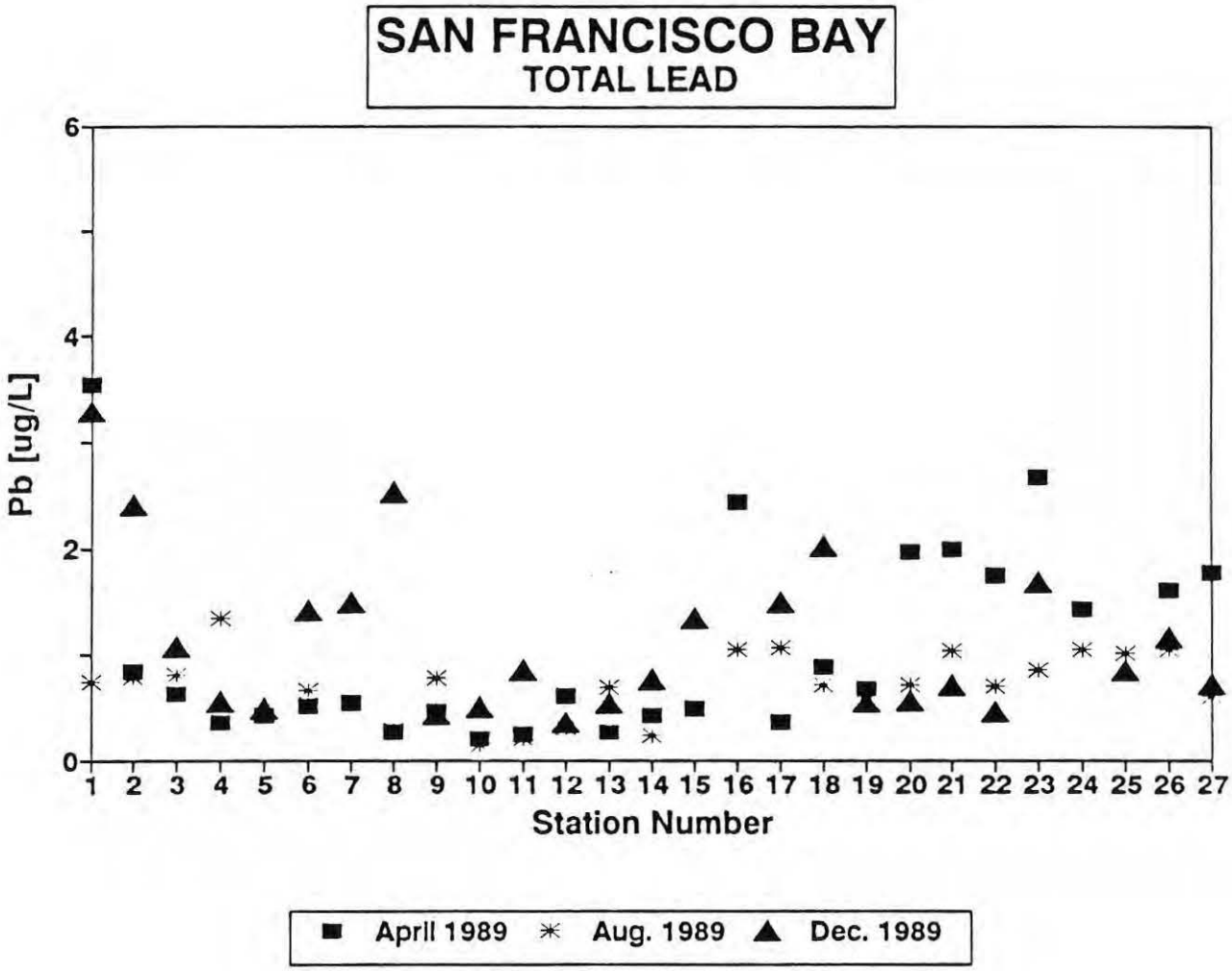

SAN FRANCISCO BAY
TOTAL ARSENIC
As [ug/L]
5
4
3
2
1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
STATION NUMBER
APRIL 1989
AUG. 1989
DEC. 1989

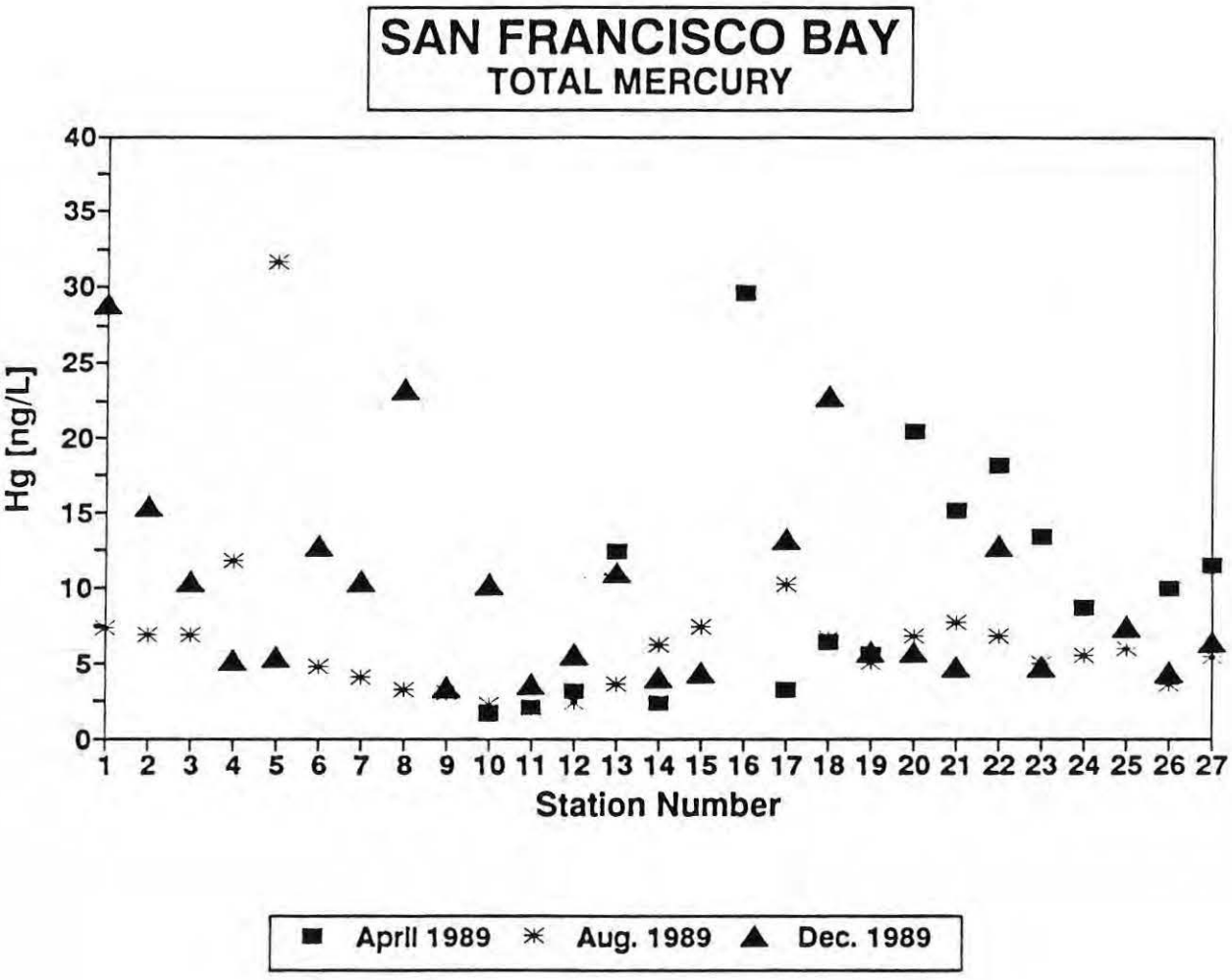

SAN FRANCISCO BAY
TOTAL CADMIUM
Cd [ng/L]
200
180
160
140
120
100
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989

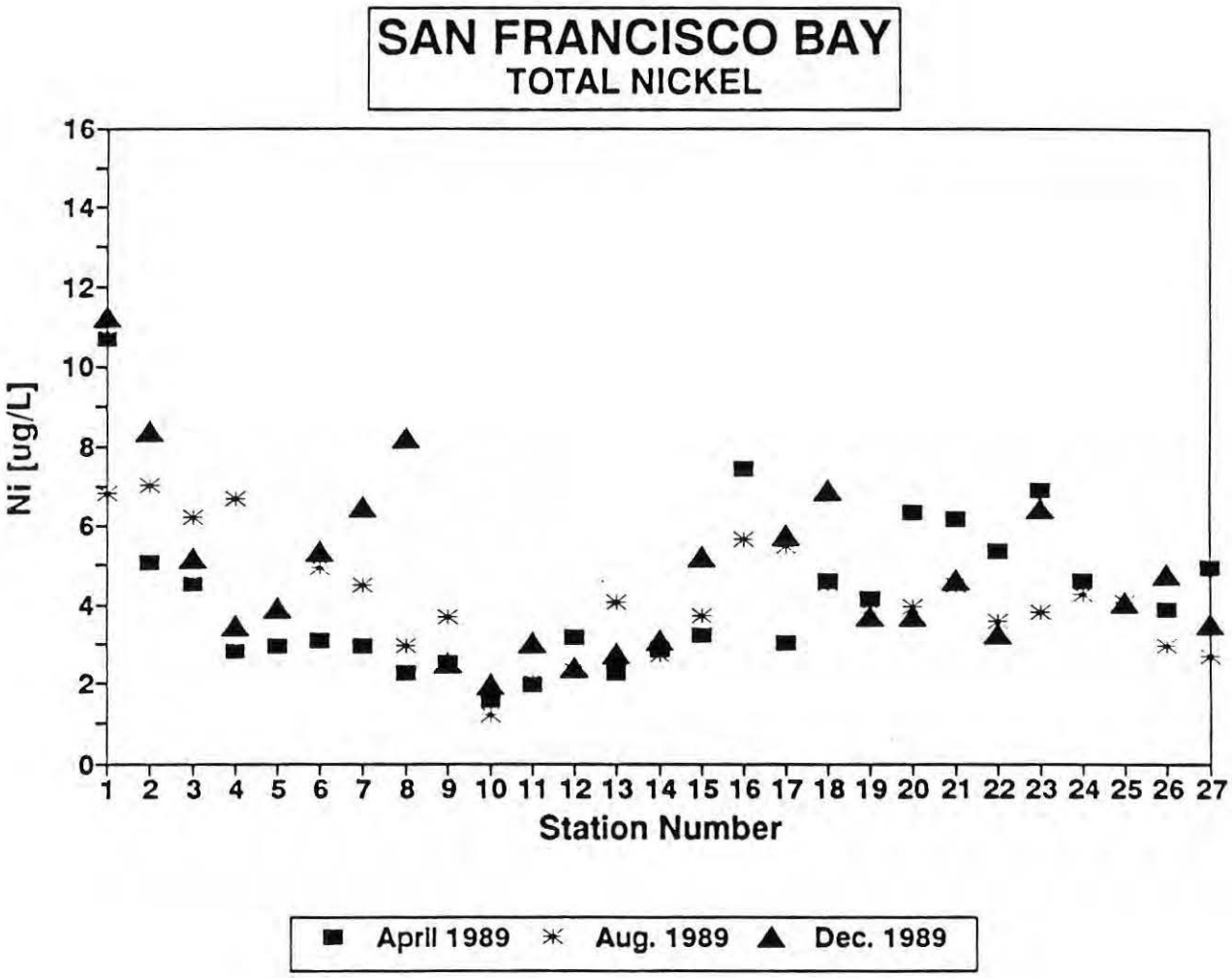

SAN FRANCISCO BAY
TOTAL COBALT
Co [ug/L]
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug.1989
Dec. 1989

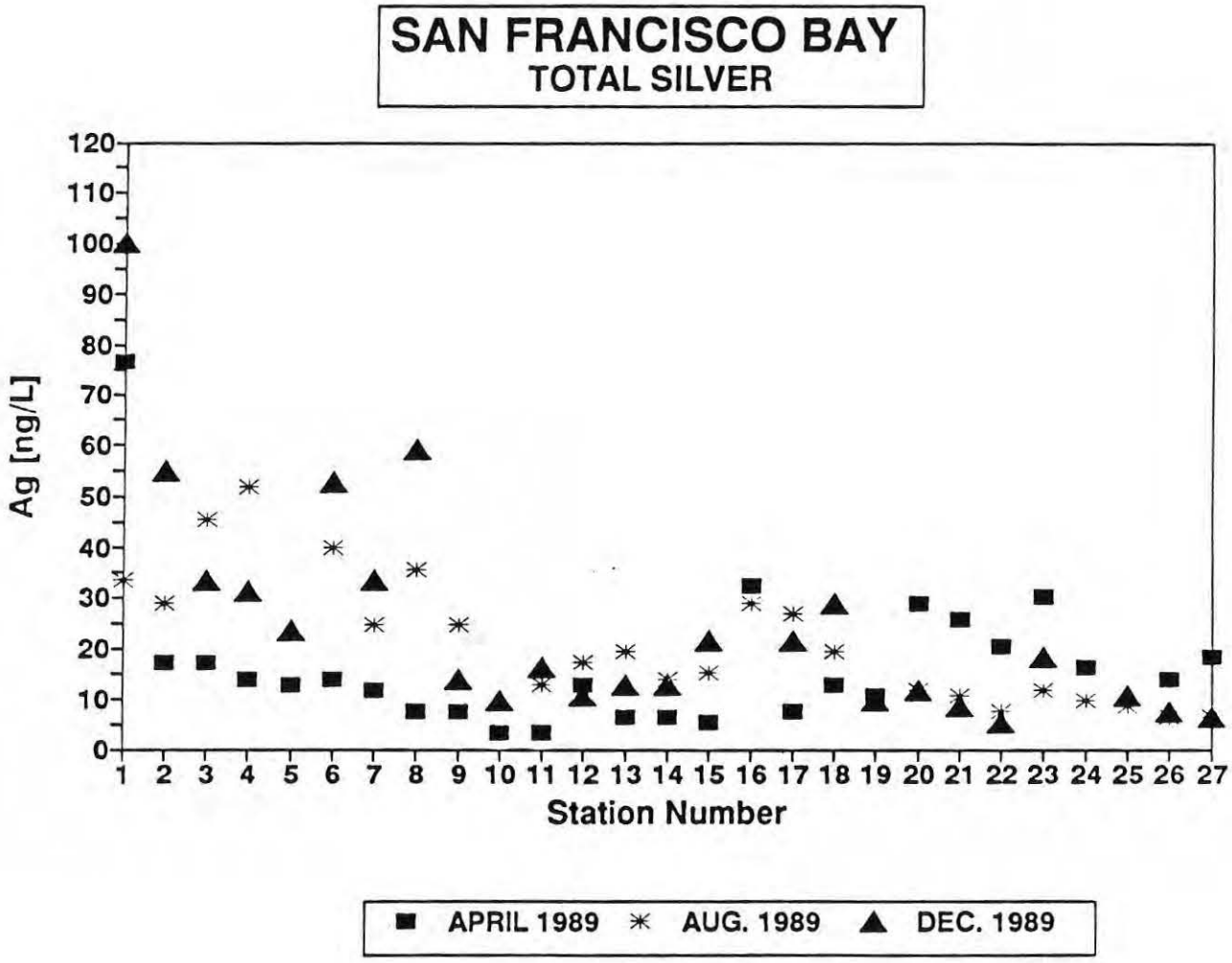

SAN FRANCISCO BAY
TOTAL COPPER
Cu [ug/L]
0
2
4
6
8
10
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989

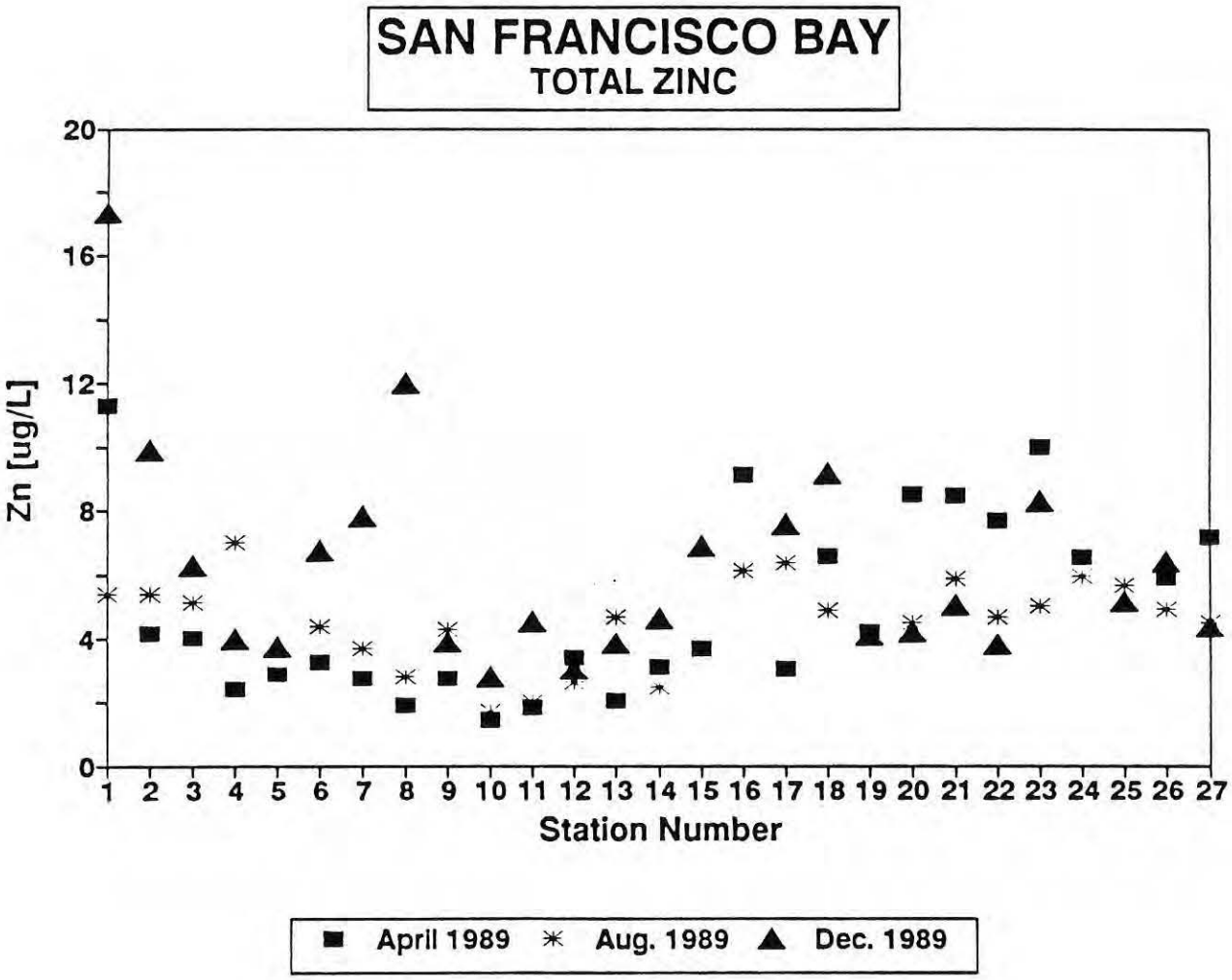

SAN FRANCISCO BAY
TOTAL IRON
Fe [mg/L]
0
1
2
3
4
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989


SAN FRANCISCO BAY
TOTAL LEAD
Pb [ug/L]
0
2
4
6
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989


SAN FRANCISCO BAY
TOTAL MERCURY
Hg [ng/L]
0
5
10
15
20
25
30
35
40
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989


SAN FRANCISCO BAY
TOTAL NICKEL
Ni [ug/L]
0
2
4
6
8
10
12
14
16
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989


SAN FRANCISCO BAY
TOTAL SILVER
Ag [ng/L]
120
110
100
90
80
70
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
APRIL 1989
AUG. 1989
DEC. 1989


SAN FRANCISCO BAY
TOTAL ZINC
Zn [ug/L]
0
4
8
12
16
20
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Station Number
April 1989
Aug. 1989
Dec. 1989

DISCUSSION

Estuarine Chemistry: A Brief Discussion of the Processes Influencing Trace Element Distributions in Estuaries

Distributions of dissolved nutrient and trace element concentrations along a salinity gradient in an estuary are influenced by several different processes (Figures 4a and 4b). Conservative distributions (i.e. simple linear correlations with salinity) are attributed to physical mixing processes and conservative biogeochemical properties. Nonconservative decreases are caused by geochemical and biological scavenging. Nonconservative increases may be due to either geochemical and biological remobilization processes within an estuary or to natural and anthropogenic inputs to that system. Apparent decreases and increases, which are indicated by nonconservative distributions within an estuary, may also be an artifact of nonsteady state conditions. For example, variations in riverine concentrations may be manifested as a pulse through the estuary. Additional details of the basic biogeochemical processes influencing trace element distributions in estuaries are provided in the review by Sharp et al. (1984) and Morris (1985). Numerous other articles on elemental cycles in other estuaries have been incorporated in this report for reference.

Complexities in the San Francisco Bay estuary

Estuarine chemical input and removal processes must be quantified through direct measurements and modelling in order to establish the relative significance of individual processes. This is difficult in a simple system, where physical mixing processes are straightforward and anthropogenic perturbations are not significant. It is extremely difficult in a complex system such as San Francisco Bay, where physical mixing processes are still enigmatic and anthropogenic perturbations may have been formidable. Therefore, the following discussion is qualified by critical limitations in our understanding of the system.

Multivariate statistical analyses reveal a clustering of stations within the system (Appendix 3). This statistically derived distribution is similar to the multicomponent estuary described by Conomos (1979), but it contains four rather than three discrete components. Those four major areas consist of: (1) the low salinity ($\approx$ 0 - 12 practical salinity units, psu) area in the northern reach (stations 20-27), which receives freshwater discharges from the Sacramento and San Joaquin rivers; (2) the intermediate salinity ($\approx$ 12 - 23 psu) transition area in the northern reach, which is centered in San Pablo Bay (stations 15 - 19); (3) the high salinity ($\approx$ 27 - 32 psu) region in the Central Bay (stations 9 - 14), which receives sea water inputs through the Golden Gate; and (4) the high salinity ($\approx$ 27 - 31 psu) area in the South Bay (stations 1-8). Although salinities varied between cruises and some stations located at the limit of a defined area on one cruise clustered with an adjacent area on another cruise, the separation of the estuary into four regions is clearly defined in the cluster analysis for all three cruises.

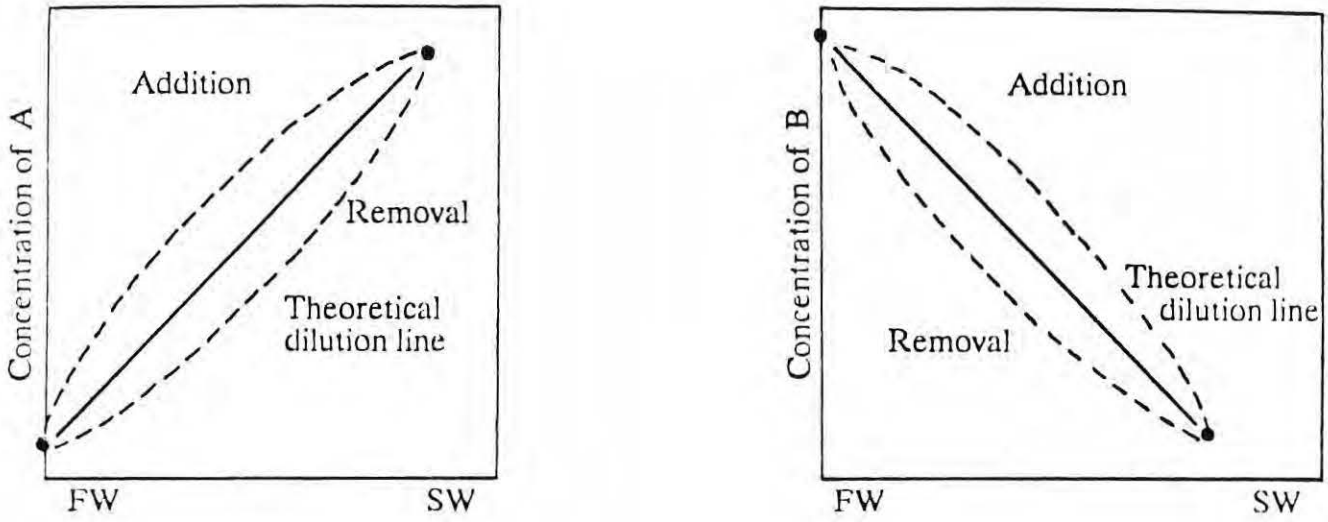


Figure 4a. Simple two component mixing model relationships of dissolved constituents in an estuary under steady state conditions. Concentration of A is lower in fresh water (FW) than sea water (SW), and concentration of B is higher in FW than SW. Dashed lines represent non-conservative mixing, due to additions and removals. Solid lines represent conservative mixing. (from Liss, 1976)

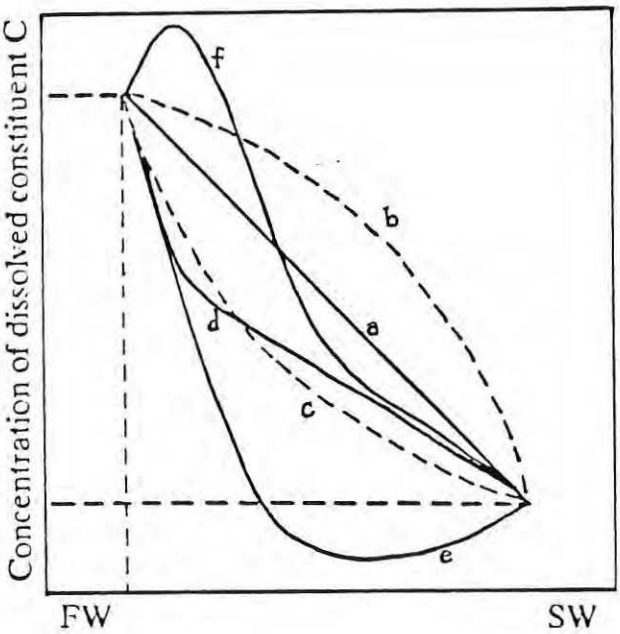


Figure 4b. Model relationships similar to those shown in Figure 3a, but illustrating more complex biogeochemical cycles. Lines a (conservative), b (addition) and c (removal) correspond to mixing models of B in figure 3a. Line d shows removal (biological and/or geological) in the upper estuary followed by conservative mixing in the lower estuary. Line e shows removal (e.g. biological and geological scavenging) within the estuary exceeding riverine input (i.e. an estuarine sink). Line f shows additions (i.e. an estuarine source) in the upper estuary (e.g. from sediments) followed by removal and then conservative mixing in the lower estuary. (from Morris, 1985)

The statistical clustering reflects spatial differences in the predominance of different factors influencing the biogeochemical cycles of nutrients and trace elements within the estuarine system. The first three areas in the northern reach are characteristic of the three biogeochemical zones in a typical estuary, which are described by Conomos (1979). The fourth area (stations 1 - 8), which includes the more lagoon type of water mass in the South Bay, is atypical. Consequently, the following descriptions of nutrient and trace element distributions within the San Francisco Bay estuarine system are separated into discussions of the northern reach, which extends from the Golden Gate to the confluence of the Sacramento and San Joaquin rivers (stations 9 - 27), and the South Bay (stations 1 - 8).

Nutrient distributions

Contrasting gradients in nutrient concentrations between the northern reach and the South Bay substantiate the subdivision of the discussion. This is illustrated by the nutrient-salinity distributions, which evidence two distinctly separate end-member mixing regimes within the San Francisco Bay estuary (Figure 5). Mixing of water masses occurs between the oceanic end-member and the South Bay and between the oceanic end-member and the Sacramento and San Joaquin rivers. These data indicate that there was relatively little mixing between the South Bay and riverine end-members.

a. "Conservative" nutrient distributions

Linear dissolved silicate distributions along the salinity gradient in the northern reach ($R > -.94$, simple linear correlations excluding one outlier at station 23 in April 1989 cruise) indicate conservative mixing between the riverine and oceanic end-members. These apparently conservative distributions were observed for all three sampling periods, in spite of substantial variations in end-member silicate concentrations (i.e. 96 - 262 μM in the Sacramento River and 27 - 48 μM at the Golden Gate). The distributions are indicative of the predominance of riverine mixing relative to biological removal during very dry years, as well as during high flow periods (Peterson, 1985).

The latter characterization, which is applicable to this study, is enigmatic. Biological removal processes should be relatively significant compared to physical mixing processes during low flow periods, which would tend to make silicate distributions nonconservative. Moreover, primary productivity appeared to have varied over nearly two orders of magnitude from low to relatively high rates (based on Chlorophyll-a measurements that ranged from 0.4 to 31 μg/L), without any apparent effect on the conservative distribution of silicate in the northern reach of the estuary. This suggests a rapid cycling of biogenic silica, with benthic fluxes to the water column comparable to biological removal from the water column.

The influence of benthic fluxes is also suggested by dissolved silicate distributions in the South Bay. While the silicate concentrations were highly correlated ($R = -0.969$) with salinity in August 1989, the two were not strongly correlated on the April and December, 1989 ($R < -0.63$). The silicate:salinity gradients were also markedly dissimilar ($p < 0.05$, t-test) to gradients in the northern reach in August and December, 1989. During those two periods, silicate concentrations in the South Bay (89 - 180 μM) were elevated relative to silicate concentrations in the Central Bay (48 - 89 μM) at comparable salinities (28 - 32 psu).

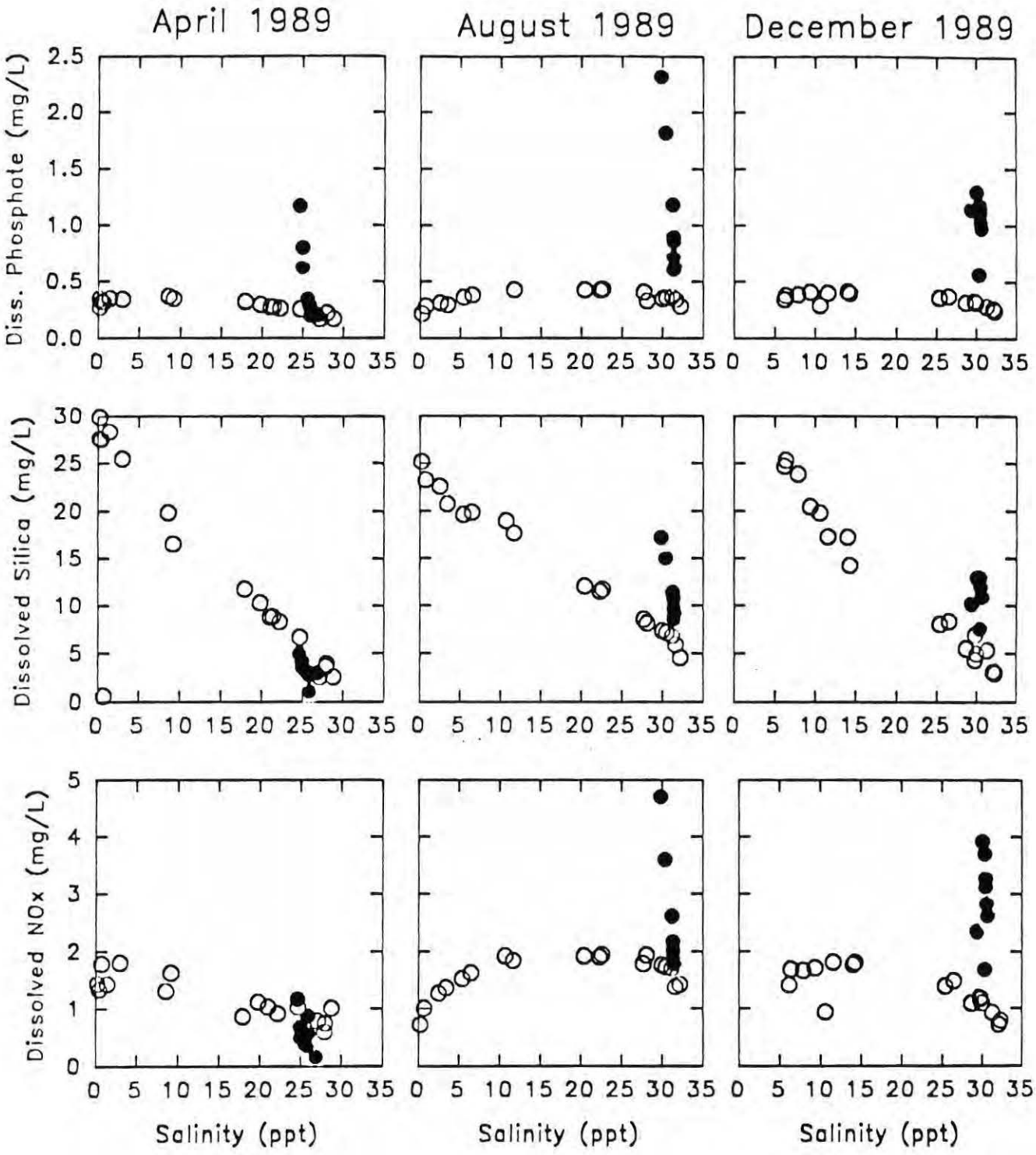


Figure 5. Dissolved nutrients versus salinity in San Francisco Bay Estuary for April, August, and December 1989. Open circles represent station 9-27 in the main estuary and filled circles represent stations 1-8 in the South Bay.

This is tentatively attributed to inputs from benthic sediment sources, as proposed by Hammond et al. (1985). Freshwater inflows to the South Bay were principally from municipal and industrial effluents during the study period. Those effluents are believed to contain relatively low concentrations of silicate and are relatively constant throughout the year. Therefore, elevated silica concentrations in surface waters appear to be derived from the diagenic remobilization of biogenic silica in South Bay sediments.

The preceding factors suggest that the linear distributions of silicate in the northern reach and South Bay, which are indicative of conservative mixing, may be artifacts. Silicate may be rapidly regenerated in the northern reach during very low flow periods in order to balance the relatively high rates of removal indicated by the chlorophyll data. Silicate may also be remobilized in South Bay sediments at rates that account for the disparity in silicate:salinity gradients between the northern and southern reaches of the estuary.

b. Nonconservative nutrient distributions

Other dissolved nutrient (phosphate and nitrate+nitrite) distributions, in contrast to silicate distributions, were nonconservative in the northern reach of the estuary on all three cruises. They increased at intermediate salinities, rather than decreased. This is inconsistent with previous studies that indicate nutrient distributions in the northern reach of the estuary are primarily influenced by the magnitude of riverine flow source and biological removal processes (Peterson, 1985). Nutrient concentrations show conservative mixing behavior during high flow periods and non-conservative mixing behavior during intermediate flow periods, when losses by biological removal processes exceed inputs from riverine sources (Peterson, 1985). It is also inconsistent with the distribution of nutrients in most estuaries, which characteristically exhibit non-conservative losses at low to intermediate salinities (Sharp et al., 1984).

Phosphate and nitrate concentrations were also elevated in the South Bay relative to locations with comparable salinities in the Central Bay on all three cruises. For example, phosphate concentrations in the extreme South Bay (25 μM) were nearly an order of magnitude greater than they were at the San Rafael bridge (3.7 μM) while the salinity at each location was essentially the same (30 psu) in April 1989. These nutrient data also contrast with the silicate data in the South Bay on the first cruise, when silicate concentrations were not elevated relative to concentrations in the Central Bay.

Differences between nutrient distributions within the estuary and between nutrient distributions in other estuaries evidence the complexity of biogeochemical cycles in the San Francisco Bay estuary. They appear to reflect differences in biological uptake and regeneration rates, diagenic remobilization, natural inputs and anthropogenic inputs. For example, elevated phosphate concentrations in the South Bay appear to reflect both benthic fluxes associated with the remobilization of biogenic silica and anthropogenic fluxes associated with municipal and industrial wastewater discharges.

Trace element distributions in the estuary: general comments

This brief discussion of trace element distributions has been simplified in the following manner. Distributions in the northern and southern reaches of the estuary are discussed separately, because of the pronounced differences between elemental concentration gradients in the two areas. The cycles of a few elements have been emphasized, because they are illustrative of the different processes influencing the system. The discussions focus on dissolved element concentrations, because they are the most diagnostic. Replicate measurements of suspended particulate loads are now being made in order to discuss the total distributions of trace elements appropriately.

Additional reports covering individual elements in detail will be provided subsequently. These will be submitted as reports to the California State Water Resources Control Board in the form of manuscripts for publication in peer reviewed scientific journals. They will follow the same sequence from relatively simplistic descriptions of the distribution of dissolved elements that are diagnostic of the system to more complicated descriptions of elemental speciation and dissolved:particulate interactions within the estuary. The first of these reports (Flegal et al., 1991) has already been submitted.

Trace element distributions in the northern reach

Dissolved metal: salinity distribution patterns for the northern portion of the estuary (stations 9-27) qualitatively suggest non-conservative behavior in all three sampling periods. This is illustrated by plots of dissolved copper, nickel and zinc versus salinity (Figure 6) and dissolved cadmium, cobalt and iron versus salinity (Figure 7). While all of the elemental distributions are non-conservative, the nature and degree of non-conservative distribution differs markedly for each element. The non-conservative distributions of zinc and cobalt also vary markedly between collection periods. There were relatively large internal inputs of dissolved copper, nickel and cadmium at low to intermediate salinities, similar to those of phosphate and nitrate during all three time periods. Dissolved zinc salinity distributions evidenced a non-conservative input during April and December, but a non-conservative loss during August. Dissolved cobalt exhibited fairly conservative estuarine mixing during April, a non-conservative decrease during August and a non-conservative increase during December.

Dissolved iron exhibited non-conservative losses during estuarine mixing during all three sampling periods. This non-conservative loss of dissolved iron during estuarine mixing is a common feature in the low salinity region of all estuaries and is associated with the flocculation of colloidal material, most notably humic-type materials (Boyle et al., 1977; Sholkovitz et al., 1978; Sharp et al., 1982). While that decrease is characteristic of all estuaries, dissolved iron concentrations in San Francisco Bay estuary are orders of

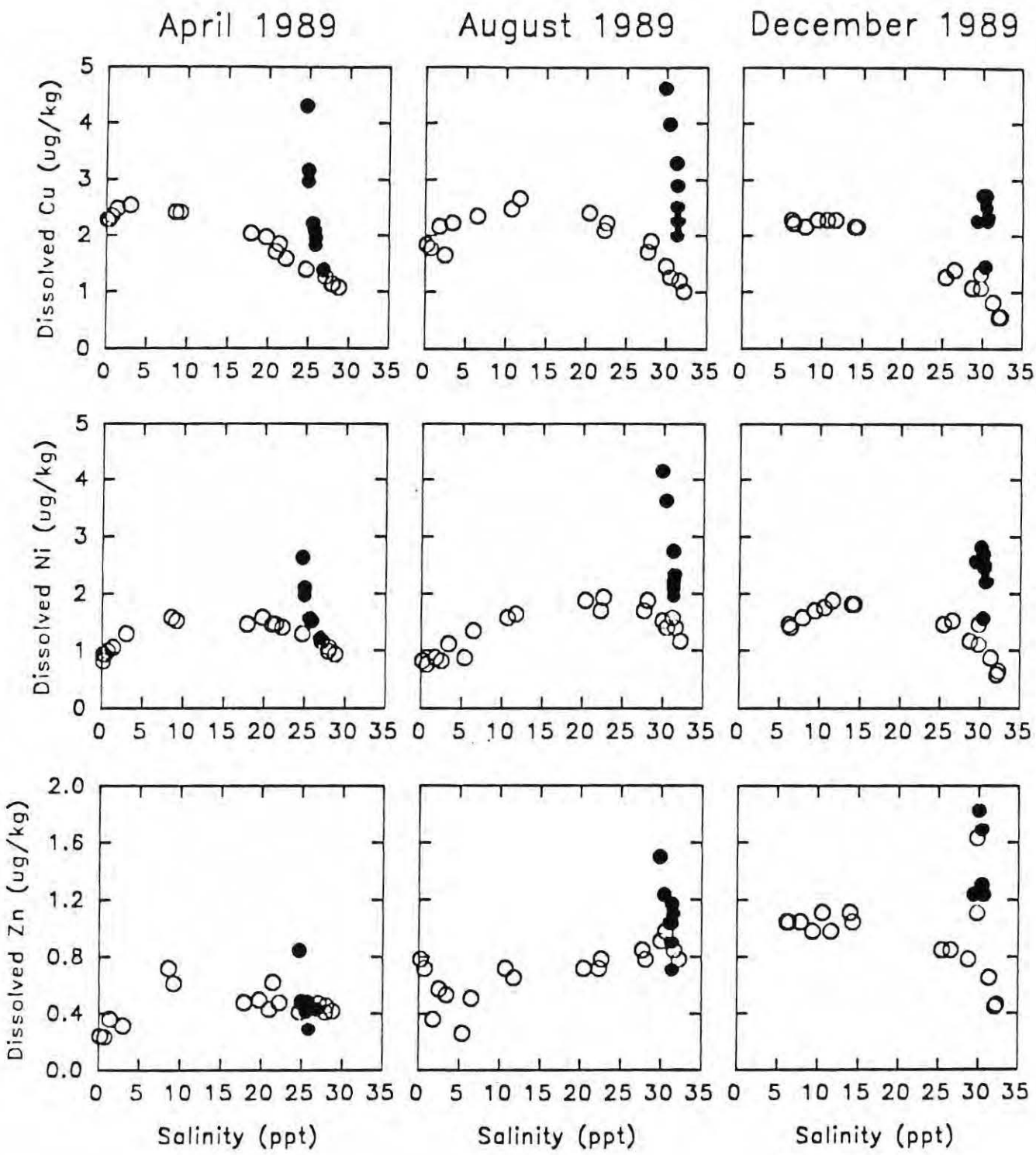


Figure 6. Dissolved copper, nickel and zinc concentrations versus salinity in surface waters of the San Francisco Bay estuary on cruises I (April), II (August) and III (December) in 1989. Open circles represent stations 9-27 in the northern reaches of the estuary and the Central Bay and filled circles represent stations 1-8 in the South Bay.

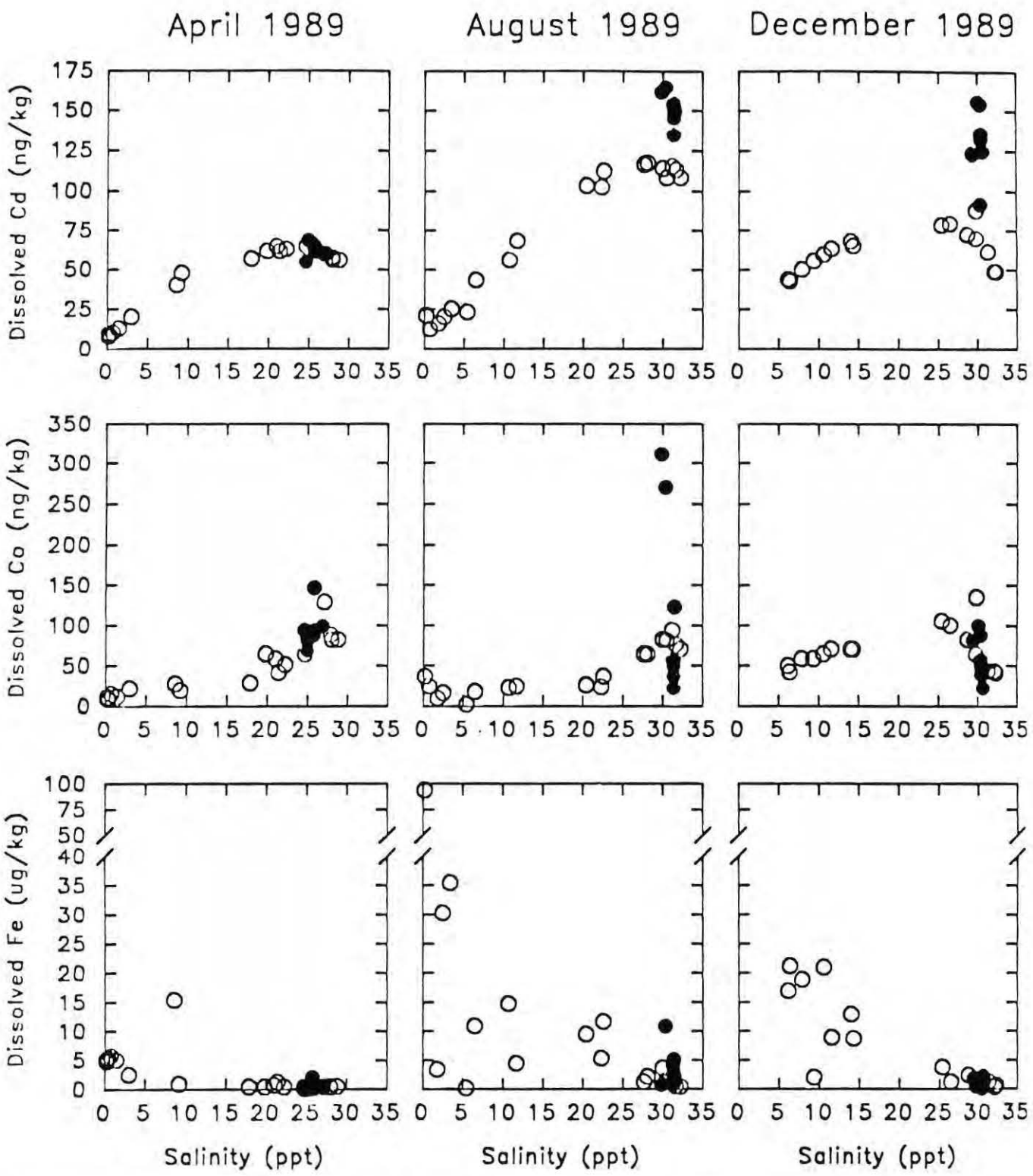


Figure 7. Dissolved cadmium, cobalt and iron concentrations versus salinity in surface waters of the San Francisco Bay estuary on cruises I (April), II (August) and III (December) in 1989. Open circles represent stations 9-27 in the northern reaches of the estuary and the Central Bay and filled circles represent stations 1-8 in the South Bay.

magnitude lower than reported for other estuaries (Holliday and Liss, 1976; Boyle et al., 1977). These differences are attributed, in part, to a lower dissolved organic loading and higher pH in the San Francisco Bay estuary compared to other estuaries. It has also recently been recognized that iron concentrations in sea water are lower than previously reported, which indicates that some earlier reports on iron concentrations in estuaries may have been erroneously high.

With the exception of iron, metal:salinity distributions in San Francisco Bay differ conspicuously from the distribution patterns of those metals in other estuaries. For example, Sharp et al. (1984) observed a strong non-conservative loss for cobalt and cadmium at low salinities and a more gradual loss for copper and nickel across the salinity gradient. However, little non-conservative behavior was observed for copper and nickel following the spring bloom during periods of high river flow.

Trace element distributions in the South Bay

Processes influencing the concentration and distribution of trace metals in the South Bay (Stations 1-8) are separated from processes influencing elemental and nutrient distributions in the rest of the estuary. This is evident in Figures 2,3,5-7, where the distribution of trace metals and nutrient concentrations show three end-members rather than two. The apparent decoupling of the South Bay from the rest of the estuary was consistent with the previously noted multivariate analyses, which grouped South Bay stations together and demonstrated that different factors were involved in their distribution patterns.

The complex distribution of dissolved trace elements established with these data is consistent with previous reports for some other dissolved transition metals (Gordon, 1980; Kuwabara et al., 1989), selenium (Cutter, 1989), dissolved inorganic nutrients (Cloern, and Nichols, 1985; Peterson et al., 1985) and humic substances (Kuwabara et al., 1989) in San Francisco Bay. In addition, other estuarine constituents including phytoplankton (Powell et al., 1986), zooplankton (Ambler et al., 1985); suspended sediments (Conomos et al., 1985), bottom sediments (Conomos et al., 1970; Sustar, 1982), benthic organisms (Nichols et al., 1986) and organic contaminants in surficial sediments (Rice et al., 1989; Spies et al., 1987) have distributional patterns in the South Bay which are distinct from those in the northern reach of the estuary.

Relatively large wastewater discharges in the South Bay are believed to be a major factor responsible for elevating some of the elements in that area. For example, copper inputs from waste water discharges are higher in the South Bay (28 to 46 kg d^{-1}) than in the Central Bay (7.8 to 13 kg d^{-1}) or the Sacramento - San Joaquin Delta (7.4 to 9.4 kg d^{-1}). This discharge pattern is similar for some other trace elements as well (Davis et al., 1990).

It is indicated by plots of dissolved copper and nickel versus salinity in the South Bay (Figure 8), which are extrapolated to fresh water (0 salinity). Ninety-five percent confidence limits on those regressions intercept the average concentrations of copper and nickel in waste water discharges (total concentrations) to the South Bay, which are indicated by the cross-hatched area at zero salinity.

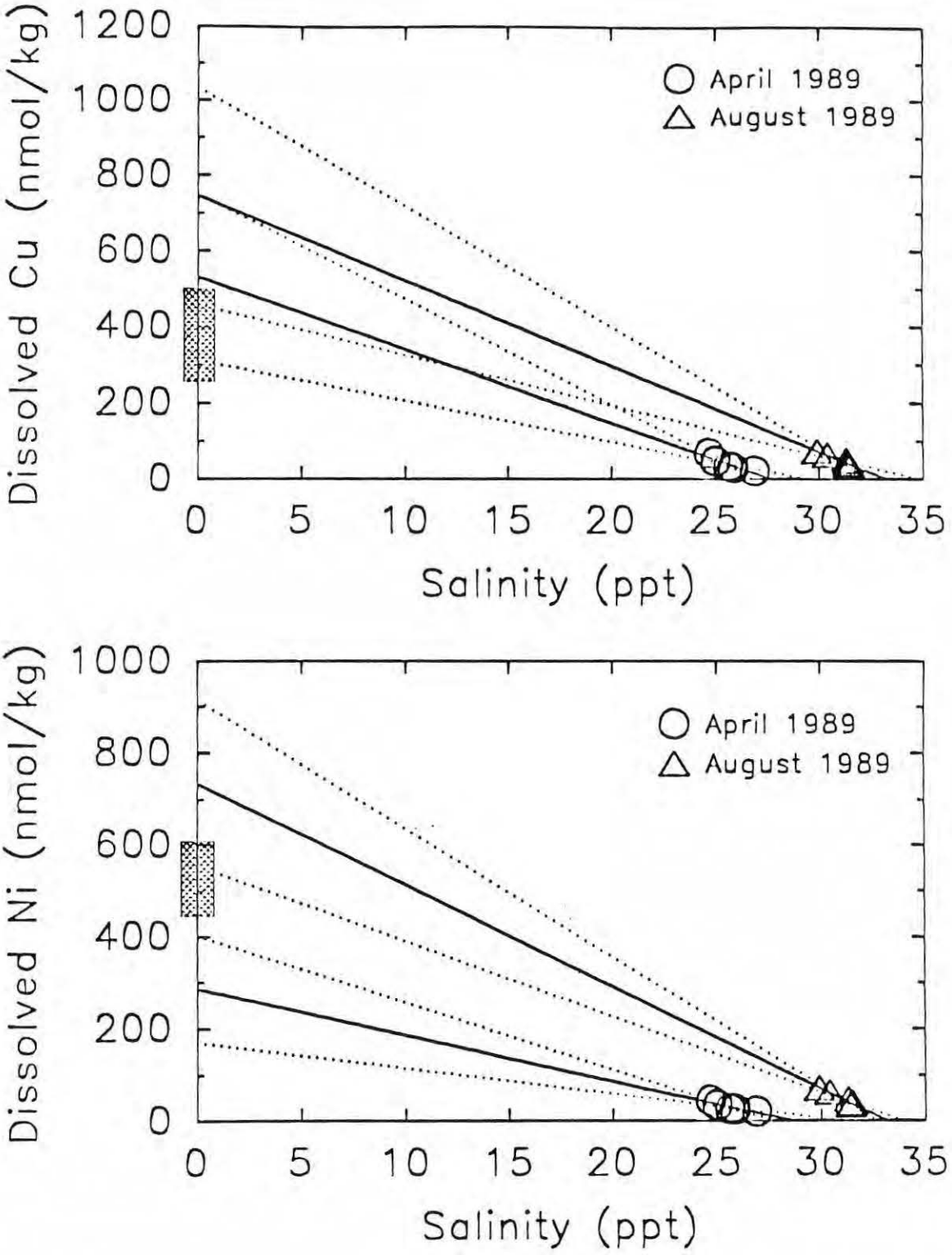


Figure 8. Extrapolations of dissolved copper and nickel concentrations (nanomoles per kilogram) in the South Bay to projected concentrations in waste water (0 salinity) discharges. Reported concentrations (total) of copper and nickel in waste water discharges to San Francisco Bay (Gunther et al., 1987) are indicated by cross-hatched areas at 0 salinity. Solid lines represent simple linear regressions derived from data collected in April and August, 1989. Dashed lined represent 95% confidence limits of those regressions.

As acknowledged in the preface to this report, these calculations have numerous simplistic assumptions and associated limitations. They do not conclusively demonstrate that waste water discharges entirely account for elevated concentrations of some elements in the South Bay. Nor do they preclude the potential influence of other inputs such as surface runoff. They simply provide a theoretical measure of the relative magnitude of a process which may be significant.

The long hydraulic residence time of water in the South Bay (120 to 160 days) is another major factor accounting for the relatively elevated trace element concentrations in that area. As previously noted, most (estimated to be > 95 % during the study period) fresh water inputs to the system are from waste water discharges and urban runoff. Moreover, flushing from fresh water discharges to the northern reaches is seasonal during normal precipitation periods and it is negligible during drought periods. The latter condition persisted throughout the three sampling periods and presumably contributed to the accumulation of dissolved trace element and nutrient concentrations in the South Bay.

Other processes that appear to be contribute to the elevation of some dissolved trace metal concentrations in the South Bay are remobilization by sediment diagenesis and resuspension. Perhaps the best benchmark indicator of benthic inputs to the South Bay is an elevation in dissolved silica above that found in other high salinity areas of the estuary. This has been discussed elsewhere in detail (Hammond et al., 1985).

The relative importance of sediment inputs versus waste water discharges can be qualitatively determined, by comparing the contrasting seasonal behavior of dissolved silica and phosphate in the South Bay with that for the dissolved trace metals. Note that during April dissolved phosphate was enriched and there was no enrichment of dissolved silica in the South Bay, as illustrated in Figure 5. However, dissolved silica and phosphate concentrations were elevated and were typical of the three end-member trace metal - salinity distributions in August and December.

Dissolved cadmium and, to a lesser extent, dissolved zinc, cobalt and iron show enrichments in August that were absent in April. This was similar to the enrichment in dissolved silica in the South Bay relative to the Central Bay during that period. The covariance of those dissolved constituents is indicative of substantial benthic sediment inputs, especially for cadmium, in the South Bay during that summer period.

In contrast, dissolved copper and nickel were elevated in the South Bay in both April and August. The relative elevation in concentrations of those two elements was similar to that of dissolved phosphate. This suggests that waste water discharges were the major source of increased concentrations of those trace elements in the South Bay during those periods. As previously noted, the extrapolation of dissolved copper and nickel concentrations in the South Bay to fresh water concentrations approximated the concentrations of those elements in waste water (Figure 8).

Freshwater End-member Variability

Variability in the concentration of a constituent over time in the riverine end-member can produce non-linear constituent-salinity plots and appear to suggest non-conservative behavior (Cutter, 1989; Loder and Reichard, 1981). At this time, we do not have sufficient information on the temporal variability in metal content of the Sacramento River to assess whether the non-conservative profiles observed could be explained by this process. Landing et al. (1990) obtained dissolved metal concentrations for copper (17-20 nM), zinc (3.4-3.8 nM), cadmium (61-74 pM) and iron (23-34 nM) in the Sacramento River

at Freeport in April 1985. Those values were slightly lower for all the metals than we observed at our freshwater end-member station during the April and August cruises.

Seawater end-member variability.

Concentrations of dissolved cadmium and cobalt in the saline waters of Central Bay also exhibited pronounced variabilities between sampling periods. Cadmium concentrations in the high salinity end-member increased from approximately 500 pmol/kg in April to approximately 950 pmol/kg in August and then decreased to 425 pmol/kg in December. A similar pattern was observed for dissolved nitrogen (nitrate + nitrite) concentrations at the Golden Gate, which has previously been attributed to seasonal variability in the magnitude of coastal upwelling (Peterson et al., 1985). The increase in cadmium from April to August of ~450 pmol/kg is consistent with the cadmium concentrations of shallow 50 - 100 m) coastal waters, which are upwelled during summer periods and increase surface cadmium concentrations off central California from 160 pmol/kg to 610 pmol/kg by 75 m depth (Bruland, 1980). However, a similar increase in zinc in August for the high salinity end-member cannot be accounted for by the same process, since upwelling waters do not contain sufficient zinc to account for the 6 nmol/kg enrichment observed within the bay. Trace element concentrations in the Central Bay may also be elevated by inputs from the South Bay.

Trace element complexation

There is evidence from a number of studies in different estuaries and open ocean areas that organic ligands play a dominant role in complexation of some dissolved trace elements, including copper and zinc (van den Berg and Dharmvanij, 1984; Apte et al., 1987; Sunda and Hanson, 1987; van den Berg et al., 1987; 1990; Bruland, 1990; Coale and Bruland, 1990;). The studies indicate that those trace elements would behave conservatively if sufficient ligand concentrations were present. Thermodynamic calculations and empirical measurements indicate lower ligand concentrations would result in a non-conservative removal of trace elements (Zn > Co > Cu > Ni), which is inversely correlated to the degree of complexation.

Reduced abundance of dissolved complexing organic ligands will increase competition between the metals, with nickel then copper dominating organic speciation. Removal mechanisms such as iron coagulation/ precipitation and biological removal may then control other trace metal distributions. Zinc and cobalt should be preferentially removed over copper, cadmium and nickel because they have a higher fraction of inorganic complexes as free aquated or hydrolysis ions making them available for oxyhydroxide sorption or biological uptake (Whitfield and Turner; Sigg, 1985). Cadmium exists predominantly as $Cd(Cl)_n$ with increasing salinity, making it less likely to interact with ironoxyhdroxides (Davis and Leckie, 1978).

While the amount of organic ligands within the San Francisco Bay is unknown, arguments can be made for their existence. Sewage waste water and agricultural drainage contain chelators such as NTA and EDTA; fresh water inflows provide increased dissolved organic carbon (DOC); and salt marsh interstitial waters are rich in organic compounds (Barcelona, 1980; Mopper and Taylor, 1986). Kuwabara et al (1988) found a strong correlation between surface water DOC and copper and zinc in the South Bay, and suggested that the trend was a result of organic complexation.

Trace element complexation in the North Bay.

The significance of organic complexation in the North Bay is suggested by the relatively conservative distributions of dissolved trace metals (cadmium, cobalt, copper, iron nickel and zinc) along salinity gradients in April, 1989. These contrast with predicted distributions of inorganic species of those elements, which do not follow the same biogeochemical cycles. As previously noted, metals which complex more strongly with organic ligands (e.g. copper and nickel) tend to remain in solution and behave conservatively, while other metals tend to be scavenged by precipitating oxides (e.g. cobalt) or phytoplankton (e.g. cadmium). These differences should be apparent as fresh water mixes with more saline water, which contains more cations and less organic ligands.

Different dissolved trace element distributions were observed in August, 1989, when there was a limited salinity gradient in the North Bay. Factor analyses indicated that zinc, cobalt and iron concentrations were highly correlated, but nickel concentrations were not (Appendix 3). This suggests there was a limited amount of ligands, which preferentially complexed with nickel and the other trace element distributions were governed by reactions with inorganic species. Under those conditions zinc and cobalt exist primarily as free or hydrolysis forms, which are scavenged by iron oxyhydroxides.

In contrast, those elements were all highly correlated with salinity in San Pablo Bay in August, 1989. The longer hydraulic residence time of water in that bay and its shallow bathymetry may have resulted in a relatively greater benthic flux of dissolved organics from interstitial pore waters into surface waters, which has been observed elsewhere (Barcelona, 1980; Mopper and Taylor, 1986; van den Berg, 1986). This would have increased the degree of complexation of metals, and contributed to their relatively conservative distribution within that bay.

Trace element complexation in the South Bay

The apparent influence of organic ligands on trace element distributions in the South Bay is most evident in the August data. Phosphate concentrations indicate substantial enrichment of the water column from sedimentary sources, as previously discussed. This is significantly correlated with other dissolved trace element concentrations, except for iron (Appendix 3). Organic ligands seem necessary for all the metals to remain in solution rather than be removed according to their preferential adsorption on iron oxyhydroxides. Notice that Cd does not correlate with Fe. This further suggests that rapid mineralization of biological material along with its complexation with chloride is controlling Cd solution chemistry rather than sorption on Fe oxyhydroxides.

Salinities within the South Bay were high during April and August (Tables 6 and 7). Factor analysis of April data shows a high positive correlation of dissolved copper, nickel and zinc concentrations, which were inversely correlated with iron and cadmium concentrations (Appendix 3). These relationships are consistent with the relative degree of organic complexation derived from a model system with EDTA as the organic ligand. The correlation of cadmium and iron may not result from cadmium sorption onto iron oxyhydroxides, because thermodynamic calculations indicate inorganic cadmium species are predominantly chloro-complexes, Cd(Cl)n, which may be rapidly scavenged on biological surfaces. This is consistent with the reported removal of dissolved cadmium associated with a phytoplankton bloom in the Scheldt Estuary (Valenta et al., 1986).

Models of trace element and nutrient fluxes

a. Non-conservative mixing models

The metal : salinity plots (Figures 6 and 7) qualitatively suggest that there is an internal source for dissolved copper, nickel and cadmium and an internal sink for dissolved iron and cobalt in the northern reaches of the estuary. Dissolved zinc gradients show an internal source in April and an internal sink in August. Estimates of the flux associated with those internal sources and sinks can be derived from the non-conservative estuarine mixing model described by Officer (1979). This method was used by Cutter (1989) to model the estuarine behavior of selenium in San Francisco Bay estuary and by Froelich et al (1985) to model dissolved metals and metalloids in Charlotte Harbor, Florida.

Using that model, the flux of a dissolved constituent entering the estuary from the river (F_{riv}) is given by $F_{riv} = RC_o$ and the flux leaving the estuary at the seawater end-member (F_{est}) is $F_{est} = RC^*$, where R is the river discharge (in liters day^{-1}), C_o is the concentration of the constituent in the riverine end-member (in molar units), and C^* is the hypothetical concentration of the riverine end-member (in molar units) that would explain the concentration of the constituent at the sea water end-member if conservative estuarine mixing occurred. An internal input or removal flux (F_{int}) within the estuary is estimated from $F_{int} = R(C^* - C_o)$. A best-fit straight line is drawn through a linear portion of a constituent-salinity plot at the seawater end-member to calculate C^*. The regression is extrapolated to zero salinity to determine C^*. It is important to note that the internal flux (F_{int}) represents the net result of all internal sources and sinks for the constituent within the estuary, rather than an individual source or sink.

A summary of the modeling results for the trace metals and phosphate for the April and August cruises is shown in Table 3. A negative value for F_{int} indicates that a net removal of material from the dissolved phase occurs within the estuary and a positive value suggests that there is a source for the dissolved constituent. No attempt was made to model the December data, because insufficient information was obtained for the low (≈ 0) salinity region.

b) Wastewater input and biological scavenging models

Estimates of two other fluxes are also listed in Table 3: (1) the amount of material introduced to the northern reach of the estuary from municipal and industrial discharges (F_{dis}) and (2) the amount of sequestering of dissolved metals and nutrients by phytoplankton during photosynthesis (F_{bio}). The municipal and industrial discharges in that table were derived from Davis et al. (1990), and represent the sum of the discharges which enter the western portion of the Delta, Suisun Bay, San Pablo Bay, and the Central Bay. A representative range in mass loadings was determined for the major dischargers by multiplying flow rates by trace element concentrations (total) in treated effluents (Davis et al., 1990).

The biological removal flux (F_{bio}) was based on surface areas and estimated primary production measurements for various portions of San Francisco Bay and carbon to metal ratios for phytoplankton. Estimates of the primary productivity (PP) were obtained by applying the empirical expression obtained by Cole and Cloern (1984) relating chlorophyll-a, light intensity (I_o) and water column light extinction coefficient for San Francisco Bay:

$$PP\ (mg\ m^{-2}\ day^{-1}) = 3.8(\text{chlorophyll a})(I_o/\ ) + 58.$$

Table 3

Estimates of Metal Fluxes in the Northern Reach

Metal	C_o (ug/kg)	$C*$ (ug/kg)	F_{riv} (kg/day)	F_{est} (kg/day)	F_{int} (kg/day)	F_{dis} (kg/day)	F_{bio} (kg/day)
April 1989							
Cu	2.3	3.4	71	104	33	18-28	11
Ni	0.82	2.9	25	89	64	22-29	10
Cd	0.0098	0.088	0.30	2.7	2.4	1.5-3.8	19
Zn	0.24	0.58	7.5	18	10	71-75	33
Co	0.010	-0.054	0.31	-1.6	-1.9	--	10
Fe	5.1	0.034	160	11	-149	--	95
PO_4	275	513	8,500	16,100	7,600	--	16,000
August 1989							
Cu	1.8	4.6	36	91	55	18-28	1.9
Ni	0.82	4.9	16	99	82	22-29	1.8
Cd	0.021	0.16	0.43	3.1	2.7	1.5-3.8	3.4
Zn	0.78	0.57	16	11	-4.6	71-75	5.9
Co	0.037	-0.082	0.77	-1.6	-2.4	--	1.8
Fe	94	26	1,880	510	-1,340	--	17
PO_4	218	646	4,370	13,300	8,900	--	2,700

The river discharge (R) used for the April 1989 and the August 1989 sampling periods was R = 3.1×10^{10} L/day and 2.0×10^{10} L/day, respectively, and is the average discharge for a 14 day period prior to sampling. C_o and $C*$ are the concentration of the constituent in the river water endmember for the actual and hypothetical cases, respectively. F_{riv} and F_{est} represent the flux into and out of the estuary, respectively. F_{int} is the net result of all source and sinks fluxes occuring internally within the estuary. F_{dis} represents fluxes associated with inputs to the northern reach of the estuary from industrial and municipal discharges. F_{bio} represents an estimate of the removal flux into organic material during phytoplankton growth. A discussion of how these fluxes are derived is given in the text.

Chlorophyll-a measurements were taken from Appendix 2. Values for I_o/ were estimated from Figures 3 and 4 of Cole and Cloern (1984) for mid April and early August time periods. Metal incorporation into organic tissues was estimated using Redfield-type ratios hypothesized by Morel and Hudson (1985) for Fe (C:Me; 106:0.01) and Cd,Co,Ni,Cu (C:Me; 106:0.001) and as measured by Sherrell and Boyle (1988) for Zn (C:Me; 106:0.003). Again, these theoretical calculations are based on numerous simplistic assumptions and have recognized limitations.

Model estimates of non-conservative fluxes

The non-conservative estuarine mixing model predicts significant internal inputs of dissolved copper, nickel, cadmium and phosphate during April and August (Table 3). The internal flux of copper, nickel, cadmium and phosphate in April was estimated to have increased the total dissolved metal exported out of the Bay (relative to freshwater input) by 46%, 250%, 780% and 89%, respectively. Similarly, the estimated increase in August was 150%, 500%, 630% and 200%, respectively.

Calculations of dissolved iron and cobalt fluxes showed significant internal losses in both sampling periods. It was estimated that 73% to 93% of the river borne dissolved iron was removed within the estuary and none of the river borne dissolved cobalt left the estuary during those periods. In fact, negative C* values calculated for cobalt indicated that there was a flux of dissolved cobalt into the estuary (i.e. F_{est} is negative) from the ocean to account for the non-conservative loss of cobalt within the estuary (F_{int}). The estimated flux of dissolved cobalt into the estuary from the oceanic end-member exceeded the riverine flux of dissolved cobalt by 530% and 215% for the April and August sampling periods, respectively.

Calculated internal fluxes of dissolved zinc indicated contrasting net flows during the two sampling periods. Internal sources increased dissolved zinc 135% above riverine inputs during April, while internal sinks removed 29% of the riverine input in August.

A substantial portion of the internal inputs of dissolved cadmium, copper, nickel and zinc can be accounted for by wastewater discharges (F_{dis}) in the northern reaches of the estuary. Those discharges are equivalent to large percentages of excess dissolved cadmium (62 - 100%), copper (54 - 85%), nickel (34 - 45%) and zinc (100%) in the estuary in April. Wastewater discharges also appear to account for comparable or relatively greater inputs in the South Bay, as previously discussed.

The flux estimates in Table 3 suggest biological scavenging in Suisun and San Pablo Bays could remove all of the riverine flux of dissolved cadmium, cobalt and zinc, but only negligible amounts of copper, nickel and iron. However, the presence of non-conservative excesses of all those elements within that region indicates additions from internal sources exceed uptakes by phytoplankton. This may be partially attributed to rapid rates of biological remineralization relative to hydraulic residence times in the northern reaches of the estuary during low flow conditions (60 days). This is consistent with the proposed benthic flux in the South Bay.

While we only have estimates for two time periods, the magnitude of the internal flux for a given trace element was reasonably similar (i.e. same order of magnitude) in April and August. This is noteworthy since riverine end-member concentrations were considerably different in some cases and the river discharge in August was about one-third lower than in April (Table 3). It indicates that internal sources for many of the trace elements are relatively constant, in spite of seasonal differences during drought conditions.

The internal flux of many trace elements may also be smaller relative to riverine inputs under more typical hydraulic regimes.

SUMMARY AND CONCLUSIONS

Preliminary analyses of trace element concentrations in the San Francisco Bay estuarine system reveal two distinct distribution patterns. Trace element and nutrient concentration gradients extending from the confluence of the Sacramento and San Joaquin rivers to the Golden Gate are comparable to gradients in other estuaries. Many reflect the dilution of trace element concentrations in fresh water by physical mixing with sea water with relatively lower concentrations. Some characteristic geochemical and biological scavenging within the estuary is also evident, although many dissolved trace element concentrations evince atypical non-conservative excesses. In contrast, nutrient and trace element concentration gradients in the South Bay reflect the predominance of waste water discharges with elevated trace element concentrations and the long hydraulic residence times of that lagoon area.

The influence of numerous other factors on the distribution of nutrients and trace elements in the estuarine system are also evident. These include the flocculation of iron oxyhydroxides in the low salinity region, the co-precipitation of inorganic species on those inorganic surfaces, the intrusion of upwelled water, the systematic organic complexation of trace elements, the biological scavenging of nutrient and nutrient-like trace elements, and the remineralization of inorganic and organic complexes in surficial sediments.

There is insufficient information to quantify each of the preceding factors or to distinguish natural processes from anthropogenic perturbations. However, preliminary calculations suggest that the latter are significant for many trace elements. This is most evident in the South Bay, where many trace element concentrations appear to reflect waste water diluted with sea water. Anthropogenic perturbations also appear to, at least partially, account for non-conservative excesses in the northern reaches of the San Francisco Bay system, which are atypical of other estuaries. Again, these preliminary calculations are highly speculative.

Whether these preliminary data are representative of the system is also speculative, because the samples were all collected during atypical conditions. Low flow conditions, which substantially increased hydraulic residence times and minimized seasonal flushing, developed more than a year before the onset of the study and persisted throughout the three sampling periods. Therefore, it is not known whether these data are characteristic of the system during normal periods, the system during seasonal low flow conditions or the system during drought conditions.

These qualifications must be resolved to understand the significance of both natural and anthropogenic processes on the biogeochemical cycles of trace elements in the San Francisco Bay estuarine system. Trace element distributions during high flow conditions and normal precipptation periods need to be determined. Other studies are needed to determine trace element speciation, organic complexation, geochemical scavenging, biological scavenging, sediment diagenesis and colloidal processes. These may be incorporated in more rigorous models of trace element cycling within the estuary, which will also require more detailed information on natural and anthropogenic inputs, sediment processes, primary productivity, benthic productivity and physical circulation patterns.

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REFERENCES

Ackroyd, D.R., G.E. Millward and A.W. Morris (1987). Periodicity in the trace metal content of estuarine sediments. Oceanol. Acta, 10: 161-168.

Aller, R.C. (1978). Experimental studies of changes produced by deposit feeders on pore water, sediment, and overlying water chemistry. Am. J. Sci., 278: 1185-1190.

Ambler, J.W., J.E. Cloern and A. Hutchinson (1985). Seasonal cycles of zooplankton from San Francisco Bay. Hydrobiologia, 129: 177-197.

Anderson, L.C.D. and K.W. Bruland (1991). Biogeochemistry of arsenic in natural waters: The importance of methylated species. Environ. Sci. Technol., 25: 420-427.

Anderson, S.L., E. Hofmann, D. Steward and J. Harte (1990). Ambient toxicity characterization of San Francisco Bay abd adjacent wetland ecosystems. Report to the San Francisco Regional Water Quality Control Board.

Barcelona, M.J. (1980). Dissolved organic carbon and volatile fatty acides in marine sediment pore waters. Geochim. Cosmochim. Acta. 44: 1977-1983.

Berman, S.S., R.E. Sturgeon, J.A.H. Desaulniers, and A.P. Mykytink (1983). Preparation of the sea water reference material for trace metals, NASS-1. J. Mar. Pollut. Bull., 14: 69-73.

Boyle, E.A., J. M. Edmond, and E.R. Sholkovitz (1977). The mechanism of iron removal in estuaries. Geochim. Cosmochim. Acta, 41: 1313-1324.

Bruland, K.W. (1980). Oceanographic distributions of cadmium, zinc, nickel, and copper in the North Pacific. Earth Planet. Sci. Lett., 47: 176-198.

Bruland, K.W. (1988). Trace element speciation: organometallic compounds and metal-organic ligand complexes. Appl. Geochem. 3: 75.

Bruland, K.W., K.H. Coale, and L. Mart (1985). Analysis of seawater for dissolved cadmium, copper, and lead: An intercomparison of voltametric and atomic absorption methods. Marn. Chem., 17: 285-300.

Burton, J.D. (1978). Behavior of some trace chemical constituents in estuarine waters. Pure & Appl. Chem. 50: 385-393.

Byrne, R.H., L.R. Kump and K.J. Cantrell (1988). The influence of temperature and pH on trace metal speciation in seawater. Mar. Chem., 25: 163-181.

Cabaniss, S.E. (1987). Titrator: An interactive program for aquatic equilibrium calculations. Environ. Sci. Technol., 21: 209-210.

Capodaglio, G., K.H. Coale and K.W. Bruland (1989). Lead speciation in surface waters of the eastern North Pacific. Mar. Chem. 29: 221-233.

Carlton, J.T. (1979). Introduced invertebrates of San Francisco Bay. In San Francisco Bay: The Urbanized Estuary, (T.J. Conomos, Ed.), pp. 427-444. American Association for the Advancement of Science. San Francisco, California.

Cloern, J.E., B.E. Cole, R.L.J. Wong and A.E. Alpine (1985). Temporal dynamics of estuarine phytoplankton: A case study of San Francisco Bay. Hydrobiologia, 129: 153-176.

Cloern, J.E. and F.H. Nichols (1985). Time scales and mechanisms of estuarine variability, a synthesis from studies of San Francisco Bay. Hydrobiologia, 129: 229-237.

Coale, K.H. and A.R. Flegal (1989). Copper, cadmium, zinc and lead concentrations of surface waters in Lake Erie and Lake Ontario. Sci. Total Environ. 87/88: 297-304.

Cole, R.L.J. and J.E. Cloern (1984). The significance of biomass and light availability to phytoplankton productivity in San Francisoc Bay (USA). Mar. Ecol. Progr. Ser., 17: 15-25.

Conomos, T.J. (1979). Properties and circulation of San Francisco Bay waters. In: San Francisco Bay: The Urbanized Estuary (T.J. Conomos, Ed.), American Association for the Advancement of Science, San Francisco, California pp. 47-84.

Cutter, G.A. (1989). The estuarine behavior of selenium in San Francisco Bay. Estuar.Coast. Shelf Sci., 28: 13-34.

Davis, J.A. and J.O. Leckie (1978). Effect of adsorbed complexing ligands on trace metal uptake by hydrous oxides. Environ. Sci. Technol., 12(12): 1309-1315.

Davis, J.A., A.J. Gunther, J.M. O'Conner, B.J. Richardson, R.B. Spies, E. Wyatt, E. Larson and E.M. Meiorin (1989). Status and Trends Report on Contaminants in the San Francisco Estuary. Aquatic Habitat Institute, Richmond, CA 271 pp.

Dyer, R.R. (1989). Sediment processes in estuaries: future research requirements. J. Geophys. Res., 94: 14,327-14,340.

Eaton, A. (1979a). Observations on the geochemistry of soluble copper, iron, nickel, and zinc in the San Francisco Bay estuary. Environ. Sci. Technol., 13: 425-431.

Eaton, A. (1979b). Leachable trace elements in San Francisco Bay sediments: indicators of sources and estuarine processes. Environ. Geol., 2: 333-339.

Elbaz-Poulichet, F., J.M. Martin, W.W. Huang and J.X. Zhu (1987). Dissolved Cd behavior in some selected French and Chinese estuaries. Consequences on Cd supply to the ocean. Marn. Chem., 22: 125-136.

Ferrari, G.M. and P. Ferrario (1989). Behavior of cadmium, lead, and copper in the marine deltaic area of the Po River (North Adriatic Sea). Water, Air, Soil Pollut., 43: 323-343.

Flegal, A.R., T.F. Duda and S. Niemeyer (1989). High gradients of lead isotopic compositions in northeast Pacific coastal waters. Nature, 339: 458-460.

Flegal, A.R., J.O. Nriagu, K.S. Coale and S. Niemeyer (1989). Isotopic tracers of lead contamination in the Great Lakes. Nature, 339: 455-458.

Flegal, A.R. and C.C. Patterson (1983). Vertical concentration profiles of lead in the central Pacific at 15°N and 20°S. Earth Planet. Sci. Lett., 64: 19-32.

Flegal, A.R., K.J. Rosman and M.R. Stephenson (1987). Isotope systematics of contaminant leads in Monterey Bay. Environ. Sci. Technol., 21: 1075-1079.

Flegal, A.R. and D.S. Smith (1988). Lead dispersion gradients in San Francisco Bay. Proceedings of the Seventh International Ocean Disposal Symposium. Environment Canada 40-11/12-1987, pp. 468-483.

Flegal, A.R., G.J. Smith, G.A. Gill, S. Sanud0-Wilhelmy and L.C.D. Anderson (1991). Dissolved trace element cysles in the San Francisco Bay estuary. Mar. Chem. (in press).

Flegal, A.R. and V.J. Stukas (1987). Accuracy and precision of lead isotopic composition measurements in sea water. Mar. Chem. 22: 163-177.

Gill, G.A. and K.W. Bruland (1990). Mercury speciation in surface freshwater systems in California and other areas. Environ. Sci. Technol., 24: 1392-1400.

Gordon, R.M. (1980). Trace element concentrations in seawater and suspended particulate matter from San Francisco Bay and adjacent coastal waters. Masters Thesis, Department of Biological Sciences, San Jose State University, 85 p.

Hammond, D. E., C. Fuller, D. Harmon, B. Hartman, M. Korosec, L. G. Miller, R. Rea, S. Warren, W. Berelson, and S. W. Hager (1985). Benthic Fluxes in San Francisco Bay. Hydrobiologia, 129: 69-90.

Harper, D.J. (1988). Dissolved cadmium and lead in the Thames estuary. Mar. Pollut. Bull. , 19: 535-538.

Helz, G.R., G.H. Setlock, A.Y. Cantillo and W.S. Moore (1985). Processes controlling the regional distribution of lead-210, radium-226 and anthropogenic zinc in estuarine sediments. Earth Planet. Sci. Lett., 76: 23-34.

Holliday, L.M. and P.S. Liss (1976). The behaviour of dissolved iron, manganese, and zinc in the Beaulieu estuary, S. England. Estuar. Coastal Mar. Sci., 4: 349-353.

Honeyman, B.D. and P. Santchi (1988). Critical review: Metals in aquatic systems. Environ. Sci. Technol., 22: 862-871.

Kuwabara, J.S., C.C.Y. Chang, J.E. Cloern, T.L. Fries, J.A. Davis and S.N. Luoma (1989). Trace metal distribution along a dissolved organic carbon gradient in sourth San Francsico Bay. Estuar. Coastal Shelf Sci., 28: 307-325.

Landing, W.M., G.A. Gill, and K.W. Bruland (1990). An ion-exchange column technique for the separation and concentration of free and organically-complexed trace metals from natural waters. Environ. Sci. Technol., (submitted).

Loder, T.C. and R.P. Reichard (1981). The dynamics of conservative mixing in estuaries. Estuaries, 4: 64-69.

Luoma, S.N. and J.A. Davis (1983). Requirements for modeling trace metal partitioning in oxidixed estuarine sediments. Mar. Chem., 12: 159-181.

Luoma, S.N. and D.J.H. Phillips (1988). Distribution, variability and impacts of trace elements in San Francisco Bay. Marine Pollution Bulletin, 19: 413-425.

Morel, F.M.M. (1983). Complexation. In: Principles of Aquatic Chemistry. John Wiley & Sons, NY, NY.

Morel, F.M.M. and R.J.M. Hudson (1985). The geobiological cycle of trace elements in aquatic systems: Redfield revisited. In: Chemical Processes in Lakes (ed. W Stumm) John Wiley and Sons, Inc. NY, NY.

Morris, A.W. (1986). Removal of trace metals in the very low salinity region of the Tamar estuary, England. The Science of the Total Environment: 49: 297-304.

National Research Council (1983). Fundamental Research on Estuaries: The Importance of an Interdisciplinary Approach. National Academy Press, Washington, D.C.

Nichols, F.H., J.E. Cloern, S.N. Luoma and D.H. Peterson (1986). The modification of an estuary. Science, 231: 567-573.

Nichols, F.H. and J.K. Thompson (1985). Time scales of change in the San Francisco Bay benthos. Hydrobiologia, 129: 121-127.

Nriagu, J.O. and J.M. Pacyna (1988). Quantitative assessment of worldwide contamination of air, water and soils by trace metals. Nature, 333: 134-139.

Olsen, C.R., M.Thein, I.L.Larson, D. Philip, P.J. Mulholland, N.H. Cutshall, J.T. Byrd and H.L. Windom (1989). Plutonium, lead-210 and carbon isotopes in the Savannah estuary: riverborne versus marine sources. Environ. Sci. Technol., 23: 1475-1481.

Parsons, T.R., Y. Maita, and C. M. Lalli (1984). A manual of chemical and biological methods for seawater analysis. Pergamon Press, New York, 173 p.

Patterson, C.C. and D.M. Settle (1976). The reduction of orders of magnitude errors in lead analyses of biological materials and natural waters by evaluating and controlling the extent and sources of industrial lead contamination introduced during sampling collecting and analysis. In: Accuracy in Trace Analysis (P. LaFleur, ed.) Natural Bureau of Standards (U.S.) Special Publication 422: 321-351.

Paulson, A.J., R.A. Feeley, H.C. Curl, Jr. and D.A. Tenant (1989). Estuarine transport of trace metals in a buoyant riverine plume. Estuar. Coastal Shelf Sci., 28: 231-248.

Paulson, A.J., R.A. Feeley, H.C. Curl, Jr., E.A. Crecelius and G.P. Romberg (1989). Separate dissolved and particulate trace metal budgets for an estuarine system: an aid for management decisions. Environ. Pollut., 57: 317-339.

Peterson, D.H., R.E. Smith, S.W. Hager, D.D. Harmon, R.E. Herndon, and L.E. Schemel (1985). Interannual variability in dissolved inorganic nutrients in Northern San Francisco Bay Estuary. Hydrobiologia, 129: 37-85.

Phillips, D.J.H. (1988). Monitoring of Toxic Contaminants in the San Francisco Bay - Delta: A Critical Review Emphasizing Spatial and Temporal Trend Monitoring. Aquatic Habitat Institute, Richmond, CA.

Powell, T.M., J.E. Cloern and R.A. Walters 1986. Phytoplankton spatial distribution in South San Francisco Bay: mesoscale and small-scale variability. In: Estuarine Variability (D.A. Wolfe, ed.), Academic Press, New York, pp. 369-383.

Rice, D.W., R.B. Spies, C. Zoffman, M. Prieto and R. Severeid (1989). Organic contaminants in surficial sediments of the San Francisco Bay-Delta. Environ. Sci. Technol., (in press).

Sanudo-Wilhelmy, S. and A.R. Flegal (1991). Trace metal concentrations and stable lead isotopic compositions in northeast Pacific coastal waters along the United States-Mexico boundary. Mar. Chem. (in press).

Sharp, J.H., C.H. Culberson and T. M. Church (1982). The chemistry of the Deleware Estuary. General Considerations. Limnol. Ocean. 27: 1015-1028.

Sharp, J.H., J.R. Pennock, T.M. Church, J.M. Tramontano, and L.A. Cifuentes (1984). The estuarine interaction of nutrients, organics, and metals: A case study in the Deleware estuary. In: The estuary as a filter. V.S. Kennedy (Ed.), Academic Press, pp. 241-257.

Sherrell, R.M. and E.A. Boyle (1988). Zinc, chromium, vanadium and iron in the Mediterranean Sea. Deep-Sea Res., 35(8): 1319-1322.

Sholkovitz, E.R., E.A. Boyle, and N.B. Price (1978). The removal of dissolved humic acids and iron during estuarine mixing. Earth Planet. Sci. Lett., 40: 130-136.

Sigg, L. (1985). Metal transfer mechanisms in lakes; the role of settling particles. In: Chemical Processes in Lakes (ed. W Stumm) John Wiley and Sons, Inc., NY.

Smith, L.H. (1987). A Review of Circulation and Mixing Studies of San Francisco Bay, California. U.S. Geological Survey Circular 1015. U.S. Geological Survey, Denver, CO.

Spies, R.B., J.S. Felton and D.W. Rice (1987). Benzthiazoles in estuarine sediments as indicators of street runoff. Nature, 327: 697-699.

Stumm, W. and J. Morgan (1981). Aquatic Chemistry. John Wiley & Sons, Inc. NY.

Sunda, W.G. (1990). Trace metal interactions with marine phytoplankton. Limnol. Oceanogr. (in press).

Sunda, W.G. and Hanson, A.K. (1987). Measurement of free ion concentration in seawater by a ligand competition technique involving copper sorption onto C-18 SEP-PAK cartridges. Limnol. Oceanogr., 32(3): 537-542.

Sustar, J.F. (1982). Sediment circulation in San Francisco Bay. In: San Francisco Bay, Use and Protection (W.J. Kockelman, T.J. Conomos and A.E. Leviton, eds.) American Association for the Advancement of Science, San Francisco, CA pp 271-279.

Turekian, K.K. (1977). The fate of metals in the oceans. Geochim. Cosmochim. Acta, 41: 1139-1144.

Turner, D.R. (1987). Speciation and cycling of arsenic, cadmium, lead and mercury in natural waters. SCOPE 31 (Lead, Mercury, Cadmium and Arsenic in the Environment), pp. 175-186.

Valenta, P., R. Breder, L. Mart, H. Rutzel and A.G.A. Merks (1987). Distribution of cadmium and lead between dissolved and particulate phases in estuaries. Toxicol. Environ. Chem., 14: 129-141.

Valenta, P., E.K. Duursma, A.G.A. Merks, H. Ruetzel and H.W. Nuernberg (1986). Distribution of cadmium, lead and copper between the dissolved and particulate phase in the Eastern Scheldt and Western Scheldt estuary. Sci. Total Environ., 53: 41-76.

van den Berg, C.M.G., A.G.A. Merks and E.K. Duursma (1987). Organic complexation and its control of dissolved concentrations of cupper and zinc in the Scheldt Estuary. Estuar. Coast. Shelf Sci., 24: 785-797.

van den Berg, C.M.G. and S. Dharmvanij (1984). Organic complexation of zinc in estuarine interstitial and surface water samples. Limnol. Oceanogr., 29(5): 1025-1029.

Vuceta, J. and J.J. Morgan (1978). Chemical modeling of trace metals in fresh waters: role of complexation and adsorption. Environ. Sci. Technol., 12(12): 1302-1307.

Walters, R.A., R.T. Cheng and T.J. Conomos (1985). Time scales of circulation and mixing processes of San Francisco Bay waters. Hydrobiologia, 129: 13-36.

Westall, J.C., J.L. Zachary, F.M.M. Morel (1976). Mineql, a computer program for the calculation of chemical equilibrium composition of aqueous systems. Cambridge, MA; Dept. of Eng., MIT, 91p.

Whitfield, M. and D.R. Turner (1987). The role of particles in regulating the composition of sea water. In: Aquatic Surface Chemistry. Wiley-Interscience, New York.

Whitelaw, K., J.A. Cole, P.C. Head and P.D. Jones (1985). Transport of mercury, lead, chromium, copper, nickel, zinc between the Mersey estuary and Liverpool Bay during selected tidal cycles. Fifth International Conference on Trace Metals in the Environment, Volume 1: 377-379.

Windom, H.L., R.G. Smith, Jr., C. Rawlinson, M. Hungspreugs, M. Dharmvanij and G. Wattayakorn (1988). Trace metal transport in a tropical estuary. Mar. Chem., 24: 293-305.

Zhang, J., W.W. Jing and J.M. Martin (1988). Trace metals distribution in the Huanghe (Yellow River) estuarine sediments. Estuar. Coastal Shelf Sci., 26: 499-516.

APPENDIX 1

Dissolved and Total Arsenic in San Francisco Bay

Station number	Station Name	Dissolved As (ug/kg) April	August	Dec.	Total As (ug/kg) April	August	Dec.
1	Extreme South Bay	2.0	4.5	1.9			
2	Dumbarton Br.	2.0	3.1	2.4			
3	Redwood Cr.	1.9	3.3				
4	San Bruno Shoals	0.9	1.7	2.9			
5	Hayward Flats	1.5	3.3	1.3			
6	S.F. Airport	1.2	2.8	2.0			
7	San Leandro Chan.		2.8	1.5			
8	Hunter's Pt. Chan.	1.1	2.5	1.2			
9	Berkeley Flats	1.1	0.9	1.7			
10	Golden Gate	1.4	1.8	1.0			
11	Alcatraz Is.	1.0	2.0	1.0			
12	Angel/Treasure Is.	1.1	2.1	0.9			
13	San Rafael Br. shore	1.1	2.1	1.3			
14	San Rafael Br. Chan.	1.1		1.2			
15	San Pedro Pt.	1.1	2.4	1.4			
16	Petaluma R.	1.1	2.2				
17	Pinole Shoal Chan.	1.3	2.5	1.4			
18	Pinole Shoal shore	0.9	2.3	1.0			
19	Benicia Br.	1.3	2.4	1.1			
20	Pacheco Cr.	0.7	2.1	1.0			
21	Grizzly Bay	1.3	1.9	0.5			
22	Port Chicago	1.5	2.6	0.9			
23	Honkers Bay	1.5	1.7	1.0			
24	Stake pt.	1.5	1.7				
25	Chips Is.		1.6	1.5			
26	New York Slough	1.5	1.8	0.7			
27	Sacramento R.	1.6	1.3	1.0			

Dissolved and Total Cadmium in San Francisco Bay

Station number	Station Name	Dissolved Cd (ng/kg) April	August	Dec.	Total Cd (ng/kg) April	August	Dec.
1	Extreme South Bay	56	162	156	81.2	158.6	124.5
2	Dumbarton Br.	69	165	155	86.7	144.6	93.0
3	Redwood Cr.	69	155	125	85.1	131.5	110.8
4	San Bruno Shoals	67	149	133	78.2	133.3	115.5
5	Hayward Flats	64	153	136	78.3		117.2
6	S.F. Airport	62	146	125	73.4	126.4	103.2
7	San Leandro Chan.	65	150	124	74.4	145.8	129.8
8	Hunter's Pt. Chan.	60	136	92	69.2	145.8	104.7
9	Berkeley Flats	60	109	88	67.0	115.3	94.6
10	Golden Gate	56	109	49	64.6	88.1	48.2
11	Alcatraz Is.	56	114	49	61.7	109.7	54.9
12	Angel/Treasure Is.	58	116	65	62.9	116.5	66.3
13	San Rafael Br. shore	65	114	70	58.8	101.2	55.7
14	San Rafael Br. Chan.	63	117	61	60.3	112.8	64.6
15	San Pedro Pt.	65	118	73	58.5	134.9	66.3
16	Petaluma R.	62	112		57.4	102.6	
17	Pinole Shoal Chan.	57	104	79	56.7	94.1	66.6
18	Pinole Shoal shore	62	103	80	73.6	74.2	73.8
19	Benicia Br.	48	68	65	44.5	70.4	70.3
20	Pacheco Cr.	40	56	68	37.7	56.2	73.6
21	Grizzly Bay	21	43	64	34.3	35.5	77.5
22	Port Chicago	13	23	60	26.3	38.8	49.9
23	Honkers Bay	11	25	56	39.2	31.1	62.5
24	Stake pt.		20		21.6	23.3	
25	Chips Is.	9	17	50		18.5	55.1
26	New York Slough	8	13	43	27.1	5.4	48.3
27	Sacramento R.	10	21	44	34.1	20.0	51.1

Dissolved and Total Cobalt in San Francisco Bay

Station number	Station Name	Dissolved Co (ng/kg) April	August	Dec.	Total Co (ug/kg) April	August	Dec.
1	Extreme South Bay	97	312	102	1.9	1.1	1.8
2	Dumbarton Br.	80	272	89	0.6	1.1	1.1
3	Redwood Cr.	71	59	47	0.4	0.6	0.6
4	San Bruno Shoals	88	39	40	0.3	0.9	0.4
5	Hayward Flats	90	24	52	0.3		0.4
6	S.F. Airport	92	52	24	0.3	0.5	0.7
7	San Leandro Chan.	50	125	81	0.4	0.5	1.0
8	Hunter's Pt. Chan.	99	56	57	0.2	0.2	1.4
9	Berkeley Flats	31	81	138	0.5	0.5	0.4
10	Golden Gate	83	68	43	0.2	0.2	0.3
11	Alcatraz Is.	84	75	41	0.2	0.2	0.5
12	Angel/Treasure Is.	87	94	74	0.4	0.3	0.4
13	San Rafael Br. shore	65	82	66	0.2	0.6	0.4
14	San Rafael Br. Chan.	52	65	44	0.4	0.3	0.5
15	San Pedro Pt.	57	66	84	0.5	0.5	1.0
16	Petaluma R.	62	37		1.5	0.8	
17	Pinole Shoal Chan.	29	27	105	0.3	0.8	0.9
18	Pinole Shoal shore	42	24	103	0.7	0.7	1.4
19	Benicia Br.	20	25	73	0.4	0.5	0.5
20	Pacheco Cr.	28	23	73	1.1	0.5	0.5
21	Grizzly Bay	22	18	71	1.2	0.8	0.6
22	Port Chicago	12		67	1.0	0.5	0.4
23	Honkers Bay	15	24	56	1.5	0.6	1.2
24	Stake pt.		17		0.8	0.7	
25	Chips Is.	11	10	57		0.6	0.7
26	New York Slough	12	26	42	0.7	0.6	0.9
27	Sacramento R.	10	37	50	0.9	0.5	0.5

Dissolved and Total Copper in San Francisco Bay

Station number	Station Name	Dissolved Cu (ug/kg) April	August	Dec.	Total Cu (ug/kg) April	August	Dec.
1	Extreme South Bay	4.4	4.7	2.7	6.0	5.8	1.7
2	Dumbarton Br.	3.2	4.0	2.7	2.4	5.7	5.4
3	Redwood Cr.	3.0	3.3	2.3	3.8	5.5	4.2
4	San Bruno Shoals	2.2	2.5	2.7	2.6	5.0	3.4
5	Hayward Flats	2.1	2.9	2.6	1.7		3.5
6	S.F. Airport	2.0	2.3	2.3	2.5	3.7	4.4
7	San Leandro Chan.	1.9	2.3	2.3	1.8	3.4	4.7
8	Hunter's Pt. Chan.	1.4	2.0	1.4	1.1	2.7	5.4
9	Berkeley Flats	1.3	1.3	1.3	1.6	2.6	2.4
10	Golden Gate	1.1	1.0	0.5	1.1	1.2	1.5
11	Alcatraz Is.	1.2	1.2	0.6	0.9	1.6	2.2
12	Angel/Treasure Is.	1.1	1.4	0.9	1.9	1.9	4.6
13	San Rafael Br. shore	1.4	1.4	1.1	1.5	2.7	2.2
14	San Rafael Br. Chan.	1.6	1.7	0.8	2.1	2.5	2.4
15	San Pedro Pt.	1.7	1.9	1.1	2.1	2.8	3.5
16	Petaluma R.	2.0	2.2		2.6	4.6	
17	Pinole Shoal Chan.	2.0	2.4	1.3	1.8	4.9	4.1
18	Pinole Shoal shore	1.8	2.1	1.4	3.8	3.9	5.1
19	Benicia Br.	2.4	2.7	2.2	3.4	4.0	3.3
20	Pacheco Cr.	2.4	2.5	2.1	5.5	4.2	3.5
21	Grizzly Bay	2.5	2.4	2.3	6.1	4.7	4.1
22	Port Chicago	2.5	1.4	2.3	5.5	4.2	3.5
23	Honkers Bay	2.4	2.2	2.3	7.2	4.4	5.4
24	Stake pt.		1.7		5.2	4.6	
25	Chips Is.	2.3	2.1	2.1		4.6	4.1
26	New York Slough	2.3	1.8	2.2	4.6	3.9	4.9
27	Sacramento R.	2.3	1.8	2.3	5.5	3.6	4.0

Dissolved and Total Iron in San Francisco Bay

Station number	Station Name	Dissolved Fe (ug/kg) April	August	Dec.	Total Fe (mg/kg) April	August	Dec.
1	Extreme South Bay	0.1	0.9	0.7	2.21	0.98	3.36
2	Dumbarton Br.	0.2	10.9	2.1	0.68	0.98	2.11
3	Redwood Cr.	0.2	4.2	2.2	0.57	2.11	1.13
4	San Bruno Shoals	0.3	5.2	1.4	0.32	1.67	0.53
5	Hayward Flats	2.1	3.1	0.2	0.36		0.49
6	S.F. Airport	0.3	4.9	1.3	0.39	0.79	1.29
7	San Leandro Chan.	0.7	2.3	1.9	0.40	0.61	1.45
8	Hunter's Pt. Chan.	0.5	1.1	0.5	0.19	0.34	2.61
9	Berkeley Flats	0.5	1.6	0.7	0.36	0.85	0.42
10	Golden Gate	0.5	0.4	0.4	0.15	0.17	0.54
11	Alcatraz Is.	0.5	0.6	0.7	0.19	0.26	0.95
12	Angel/Treasure Is.	0.6	1.1	1.1	0.57	0.36	0.46
13	San Rafael Br. shore	0.4	3.6	1.7	0.24	0.88	0.64
14	San Rafael Br. Chan.	0.4	1.3	1.3	0.43	0.34	0.90
15	San Pedro Pt.	0.8	2.2	2.4	0.55	0.70	1.42
16	Petaluma R.	0.5	11.7		1.78	1.45	
17	Pinole Shoal Chan.	0.5	9.5	3.8	0.39	1.45	1.63
18	Pinole Shoal shore	1.3	5.3	1.3	0.85	1.08	2.07
19	Benicia Br.	1.0	4.5	8.8	0.61	0.92	0.72
20	Pacheco Cr.	5.4	14.8	12.9	1.44	0.99	0.75
21	Grizzly Bay	2.5	10.9	8.9	1.50	1.34	0.91
22	Port Chicago	5.1	0.2	21.0	1.30	0.98	0.55
23	Honkers Bay	5.8	35.4	2.0	1.60	0.37	1.74
24	Stake pt.		30.3		0.97	1.30	
25	Chips Is.	5.4	3.4	18.9		1.25	0.99
26	New York Slough	4.8	50.6	21.2	0.77	0.97	1.17
27	Sacramento R.	5.1	93.9	17.0	0.94	0.81	0.76

Dissolved and Total Lead in San Francisco Bay

Station number	Station Name	Dissolved Pb (ng/kg) April	August	Dec.	Total Pb (ug/kg) April	August	Dec.
1	Extreme South Bay	59.7	63.4	37.2	3.54	0.73	3.28
2	Dumbarton Br.	33.7	63.8	36.9	0.84	0.78	2.41
3	Redwood Cr.	27.1	28.6	25.9	0.64	0.80	1.07
4	San Bruno Shoals	19.7	10.8	26.5	0.36	1.34	0.56
5	Hayward Flats	20.4	17.6	24.7	0.43		0.49
6	S.F. Airport	20.3	17.4	15.5	0.52	0.66	1.42
7	San Leandro Chan.	25.8	17.0	39.6	0.55	0.55	1.50
8	Hunter's Pt. Chan.	17.8	15.5	19.5	0.27	0.29	2.51
9	Berkeley Flats	18.0	21.3	17.4	0.47	0.78	0.44
10	Golden Gate	12.2	16.4	9.7	0.22	0.15	0.50
11	Alcatraz Is.	12.5	15.3	11.1	0.25	0.21	0.85
12	Angel/Treasure Is.	11.9	13.1	12.7	0.61	0.31	0.37
13	San Rafael Br. shore	7.8	23.2	15.8	0.27	0.68	0.55
14	San Rafael Br. Chan.	7.8	13.5	12.9	0.43	0.24	0.77
15	San Pedro Pt.	7.4	9.1	18.9	0.50	0.48	1.34
16	Petaluma R.	8.2	13.1		2.43	1.05	
17	Pinole Shoal Chan.	4.7	9.1	16.9	0.37	1.05	1.49
18	Pinole Shoal shore	7.0	9.5	14.3	0.88	0.71	2.01
19	Benicia Br.	3.8	9.9	21.2	0.67	0.61	0.56
20	Pacheco Cr.	15.6	17.4	24.4	1.97	0.71	0.58
21	Grizzly Bay	5.7	14.9	21.5	2.00	1.03	0.71
22	Port Chicago	14.7	4.4	34.3	1.75	0.69	0.47
23	Honkers Bay	10.0	32.7	15.6	2.67	0.85	1.69
24	Stake pt.		42.3		1.44	1.05	
25	Chips Is.	13.0	8.6	32.0		1.00	0.85
26	New York Slough	17.2	100.7	44.3	1.61	1.04	1.16
27	Sacramento R.	18.2	94.3	36.2	1.77	0.61	0.73

Dissolved and Total Mercury in San Francisco Bay

Station number	Station Name	Dissolved Hg (ng/kg) April	August	Dec.	Total Hg (ng/kg) April	August	Dec.
1	Extreme South Bay		1.5	0.9		7.4	28.9
2	Dumbarton Br.		1.5	1.7		6.9	15.4
3	Redwood Cr.		1.6	1.0		6.8	10.4
4	San Bruno Shoals		1.3	1.3		11.8	5.2
5	Hayward Flats		1.6	1.7		31.7	5.4
6	S.F. Airport		1.2	1.5		4.8	12.8
7	San Leandro Chan.		1.2	1.4		4.1	10.4
8	Hunter's Pt. Chan.		1.0	0.7		3.3	23.3
9	Berkeley Flats		0.5	1.3		3.0	3.4
10	Golden Gate	0.9	0.5	0.3	1.7	2.2	10.2
11	Alcatraz Is.	0.9	0.4	0.4	2.2	2.1	3.6
12	Angel/Treasure Is.		0.8	0.8	3.1	2.4	5.6
13	San Rafael Br. shore	1.1	0.5	0.4	2.4	3.6	11.0
14	San Rafael Br. Chan.	1.0	0.9	0.4	2.4	6.2	4.0
15	San Pedro Pt.	1.0	0.6	0.7		7.4	4.4
16	Petaluma R.	1.1	1.2		9.7		
17	Pinole Shoal Chan.	1.1	0.7	0.7	3.2	10.2	13.2
18	Pinole Shoal shore	1.1	0.9	0.6	6.4	6.7	22.9
19	Benicia Br.	2.1	0.8	1.4	5.6	5.0	5.8
20	Pacheco Cr.	1.1	0.7	0.7	0.5	6.8	5.8
21	Grizzly Bay	8.1	0.8	1.0	5.2	7.7	4.8
22	Port Chicago	4.0	0.6	0.6	8.2	6.8	12.8
23	Honkers Bay	1.4	0.9	0.6	3.4	4.9	4.8
24	Stake pt.		0.9		8.7	5.5	
25	Chips Is.	1.9	0.8	0.6		6.0	7.4
26	New York Slough	1.7	0.9	0.7	0.0	3.6	4.4
27	Sacramento R.	1.6	1.0	0.7	1.5	5.4	6.4

Dissolved and Total Nickel in San Francisco Bay

Station number	Station Name	Dissolved Ni (ug/kg) April	August	Dec.	Total Ni (ug/kg) April	August	Dec.
1	Extreme South Bay	2.6	4.1	2.8	10.73	6.81	11.28
2	Dumbarton Br.	2.1	3.6	2.7	5.06	7.01	8.39
3	Redwood Cr.	2.0	2.7	2.3	4.53	6.19	5.18
4	San Bruno Shoals	1.6	2.2	2.5	2.81	6.67	3.46
5	Hayward Flats	1.5	2.2	2.5	2.97		3.92
6	S.F. Airport	1.5	2.0	2.2	3.10	4.96	5.36
7	San Leandro Chan.	1.5	2.3	2.6	2.97	4.49	6.49
8	Hunter's Pt. Chan.	1.3	2.1	1.6	2.27	2.97	8.24
9	Berkeley Flats	1.2	1.4	1.5	2.50	3.69	2.51
10	Golden Gate	0.9	1.2	0.6	1.59	1.22	1.96
11	Alcatraz Is.	1.0	1.4	0.6	1.98	2.06	3.03
12	Angel/Treasure Is.	1.0	1.6	1.1	3.17	2.29	2.42
13	San Rafael Br. shore	1.3	1.5	1.1	2.28	4.07	2.77
14	San Rafael Br. Chan.	1.4	1.7	0.9	2.86	2.70	3.09
15	San Pedro Pt.	1.4	1.9	1.2	3.24	3.71	5.20
16	Petaluma R.	1.6	1.9		7.43	5.64	
17	Pinole Shoal Chan.	1.5	1.9	1.5	3.03	5.50	5.77
18	Pinole Shoal shore	1.4	1.7	1.5	4.59	4.52	6.88
19	Benicia Br.	1.5	1.7	1.8	4.15	3.81	3.70
20	Pacheco Cr.	1.6	1.6	1.8	6.33	3.97	3.71
21	Grizzly Bay	1.3	1.3	1.9	6.16	4.49	4.62
22	Port Chicago	1.0	0.9	1.7	5.34	3.57	3.28
23	Honkers Bay	1.0	1.1	1.7	6.90	3.82	6.46
24	Stake pt.		0.8		4.59	4.25	
25	Chips Is.	0.9	0.9	1.6		4.05	4.05
26	New York Slough	0.9	0.8	1.4	3.90	2.96	4.75
27	Sacramento R.	0.8	0.8	1.5	4.94	2.68	3.49

Dissolved and Total Silver in San Francisco Bay

Station number	Station Name	Dissolved Ag (ng/kg) April	August	Dec.	Total Ag (ng/kg) April	August	Dec.
1	Extreme South Bay	3.7	7.5	8.6	76.6	33.4	100.3
2	Dumbarton Br.	2.6	9.2	9.6	17.3	29.1	55.0
3	Redwood Cr.	4.2	18.6	9.6	17.3	45.3	33.4
4	San Bruno Shoals	3.3	24.2	12.5	14.0	51.8	31.3
5	Hayward Flats	2.8	26.3	13.6	12.9		23.7
6	S.F. Airport	5.3	21.4	14.3	14.0	39.9	52.9
7	San Leandro Chan.	3.7	15.4	2.7	11.9	24.8	33.4
8	Hunter's Pt. Chan.	3.3	12.7	7.7	7.6	35.6	59.3
9	Berkeley Flats	2.8	4.2	3.3	7.6	24.8	14.0
10	Golden Gate	3.0	3.9	1.9	3.2	4.3	9.7
11	Alcatraz Is.	2.3	6.1	2.5	3.2	12.9	16.2
12	Angel/Treasure Is.	3.5	6.0	3.1	12.9	17.3	10.8
13	San Rafael Br. shore	2.9	3.9	3.6	6.5	19.4	12.9
14	San Rafael Br. Chan.	2.7	6.6	3.0	6.5	14.0	12.9
15	San Pedro Pt.	3.1	6.7	4.0	5.4	15.1	21.6
16	Petaluma R.	2.7	7.5		32.4	29.1	
17	Pinole Shoal Chan.	3.0	6.2	2.7	7.6	27.0	21.6
18	Pinole Shoal shore	3.1	5.7	3.2	12.9	19.4	29.1
19	Benicia Br.	2.7	2.4	2.0	10.8	10.8	9.7
20	Pacheco Cr.	3.0	1.4	2.4	29.1	11.9	11.9
21	Grizzly Bay	2.5	1.2	1.9	25.9	10.8	8.6
22	Port Chicago	2.5		2.4	20.5	7.6	5.4
23	Honkers Bay	2.4	0.6	1.7	30.2	11.9	18.3
24	Stake pt.				16.2	9.7	
25	Chips Is.	2.5		1.6		8.6	10.8
26	New York Slough	2.3	0.6	1.6	14.0	6.5	7.6
27	Sacramento R.	2.4	0.6	1.6	18.3	6.5	6.5

Dissolved and Total Zinc in San Francisco Bay

Station number	Station Name	Dissolved Zn (ng/kg) April	August	Dec.	Total Zn (ug/kg) April	August	Dec.
1	Extreme South Bay	875	1471	1824	11.3	5.4	17.4
2	Dumbarton Br.	479	1223	1720	4.2	5.4	9.9
3	Redwood Cr.	492	896	1216	4.0	5.1	6.3
4	San Bruno Shoals	415	915	1334	2.4	7.0	4.0
5	Hayward Flats	483	706	1255	2.9		3.7
6	S.F. Airport	441	1033	1236	3.3	4.4	6.8
7	San Leandro Chan.	298	1112	1210	2.8	3.7	7.8
8	Hunter's Pt. Chan.	435	1184	1275	1.9	2.8	12.0
9	Berkeley Flats	471	961	1641	2.8	4.3	3.9
10	Golden Gate	418	772	451	1.4	1.7	2.8
11	Alcatraz Is.	459	870	464	1.8	2.0	4.6
12	Angel/Treasure Is.	409	1020	785	3.4	2.6	3.0
13	San Rafael Br. shore	409	909	1105	2.0	4.7	3.9
14	San Rafael Br. Chan.	475	837	660	3.1	2.5	4.6
15	San Pedro Pt.	433	811	785	3.7	3.7	6.9
16	Petaluma R.	496	778		9.1	6.1	
17	Pinole Shoal Chan.	477	745	830	3.0	6.4	7.6
18	Pinole Shoal shore	622	719	837	6.6	4.9	9.2
19	Benicia Br.	614	621	1053	4.2	4.1	4.1
20	Pacheco Cr.	701	700	1099	8.5	4.5	4.2
21	Grizzly Bay	313	510	1007	8.5	5.9	5.1
22	Port Chicago	362	262	1112	7.7	4.7	3.8
23	Honkers Bay	234	536	981	10.0	5.0	8.3
24	Stake pt.		575		6.6	5.9	
25	Chips Is.	288	360	1027		5.7	5.2
26	New York Slough	333	700	1020	5.9	4.9	6.4
27	Sacramento R.	245	791	1072	7.2	4.5	4.4

APPENDIX 2

Dissolved Nutrients and Salinity in San Francisco Bay: April 1989

Station number	Station Name	Salinity ($^{o}/_{oo}$)	Phosphate (uM)	Silicate (uM)	Nitrate + Nitrite (uM)
1	Extreme South Bay	24.7	12.4	52.8	19.0
2	Dumbarton Br.	25.0	8.5	44.6	8.3
3	Redwood Cr.	25.0	6.7	38.6	11.1
4	San Bruno Shoals	25.6	3.7	33.3	6.4
5	Hayward Flats	25.8	3.2	31.5	6.1
6	S.F. Airport	25.9	2.9	29.9	9.3
7	San Leandro Chan.	25.9	2.2	12.8	14.2
8	Hunter's Pt. Chan.	26.9	2.2	31.8	2.8
9	Berkely Flats	27.1	1.8	27.0	12.6
10	Golden Gate	28.8	1.8	27.2	16.3
11	Alcatraz Is.	28.0	2.4	41.2	12.0
12	Angel/Treasure Is.	27.9	2.3	38.2	9.6
13	San Rafael Br. shore	24.7	2.7	69.4	16.7
14	San Rafael Br. Chan.	22.2	2.8	86.2	14.8
15	San Pedro Pt.	21.0	2.9	91.7	16.7
16	Petaluma R.	19.8	3.1	107	18.0
17	Pinole Shoal Chan.	17.9	3.4	122	13.9
18	Pinole Shoal shore	21.4	2.9	92.4	-
19	Benicia Br.	9.2	3.7	172	26.3
20	Pacheco Cr.	8.6	3.9	207	21.1
21	Grizzly Bay	3.0	3.6	265	29.1
22	Port Chicago	1.4	3.7	294	23.1
23	Honkers Bay	0.7	3.4	6.6	28.9
24	Stake pt.	-	-	-	-
25	Chips Is.	0.4	3.4	287	21.6
26	New York Slough	0.2	3.7	300	-
27	Sacramento R.	0.2	2.9	311	23.2

Dissolved Nutrients and Salinity in San Francisco Bay: August 1989

Station number	Station Name	Salinity (°/oo)	Phosphate (uM)	Silicate (uM)	Nitrate + Nitrite (uM)
1	Extreme South Bay	29.9	24.5	180	76.2
2	Dumbarton Br.	30.4	19.2	157	58.2
3	Redwood Cr.	31.3	12.5	119	42.2
4	San Bruno Shoals	31.4	9.1	103	30.6
5	Hayward Flats	31.4	9.5	112	35.2
6	S.F. Airport	31.4	7.7	94.7	33.0
7	San Leandro Chan.	31.5	6.8	96.9	29.0
8	Hunter's Pt. Chan.	31.4	6.5	89.5	32.4
9	Berkely Flats	30.5	3.8	74.4	28.0
10	Golden Gate	32.2	3.0	47.8	23.0
11	Alcatraz Is.	31.6	3.6	61.7	22.4
12	Angel/Treasure Is.	31.2	3.9	71.3	27.7
13	San Rafael Br. shore	30.0	3.7	76.6	28.5
14	San Rafael Br. Chan.	27.7	4.3	89.1	28.9
15	San Pedro Pt.	28.1	3.5	84.9	31.2
16	Petaluma R.	22.6	4.6	122	31.3
17	Pinole Shoal Chan.	20.4	4.5	125	31.0
18	Pinole Shoal shore	22.3	4.5	119	30.8
19	Benicia Br.	11.7	4.5	184	29.7
20	Pacheco Cr.	10.7	-	189	31.0
21	Grizzly Bay	6.5	4.0	207	26.2
22	Port Chicago	5.4	3.8	204	24.6
23	Honkers Bay	3.4	3.1	187	22.0
24	Stake pt.	2.5	3.3	235	20.5
25	Chips Is.	1.8	-	-	-
26	New York Slough	0.7	3.0	242	16.3
27	Sacramento R.	0.2	2.3	262	11.7

Dissolved Nutrients and Salinity in San Francisco Bay: December 1989

Station number	Station Name	Salinity (°/oo)	Phosphate (uM)	Silicate (uM)	Nitrate + Nitrite (uM)
1	Extreme South Bay	30.1	13.7	135	63.3
2	Dumbarton Br.	30.4	12.5	135	60.0
3	Redwood Cr.	30.6	11.0	116	45.8
4	San Bruno Shoals	30.5	11.7	115	52.9
5	Hayward Flats	30.5	12.2	125	50.6
6	S.F. Airport	30.7	10.4	114	42.4
7	San Leandro Chan.	29.4	12.1	106	38.0
8	Hunter's Pt. Chan.	30.4	6.06	79.3	27.4
9	Berkely Flats	29.8	3.41	72.1	19.5
10	Golden Gate	32.1	2.79	32.4	11.7
11	Alcatraz Is.	32.3	2.60	31.4	12.8
12	Angel/Treasure Is.	30.0	3.36	52.1	17.8
13	San Rafael Br. shore	29.8	3.51	55.5	18.9
14	San Rafael Br. Chan.	31.3	2.98	45.4	15.0
15	San Pedro Pt.	28.7	3.36	57.0	17.6
16	Petaluma R.	-	-	-	-
17	Pinole Shoal Chan.	25.4	3.80	83.8	22.5
18	Pinole Shoal shore	26.5	3.94	86.5	22.5
19	Benicia Br.	14.3	4.23	149	24.0
20	Pacheco Cr.	14.0	4.37	180	29.3
21	Grizzly Bay	11.6	4.23	180	28.6
22	Port Chicago	10.6	4.28	206	29.3
23	Honkers Bay	9.4	3.08	213	15.1
24	Stake pt.	-	-	-	-
25	Chips Is.	7.9	4.04	249	26.9
26	New York Slough	6.4	3.60	263	27.2
27	Sacramento R.	6.2	3.99	257	22.9

APPENDIX 3

South Bay Cruise 1

LATENT ROOTS (EIGENVALUES)

1	2	3	4	5
6.200	2.330	1.668	0.742	0.060
6	7	8	9	10
0.000	0.000	0.000	-0.000	-0.000
11				
-0.000				

COMPONENT LOADINGS

	1	2	3	4
NI	0.946	-0.266	0.146	0.048
ZN	0.942	0.283	0.102	0.146
NOX	0.937	-0.002	-0.296	0.179
CU	0.936	-0.283	0.192	0.079
DISPO4	0.905	-0.352	0.212	0.037
SAL	0.902	0.411	0.011	-0.060
FE	-0.742	0.508	0.375	0.219
CD	-0.621	-0.760	0.193	0.013
CO	0.210	0.891	-0.036	-0.383
SIO2	-0.103	0.354	0.835	0.409
CHLA	-0.199	0.227	-0.769	0.560

VARIANCE EXPLAINED BY COMPONENTS

1	2	3	4
6.200	2.330	1.668	0.742

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
56.366	21.180	15.164	6.744

ROTATED LOADINGS QUARTIMAX

	1	2	3	4
CU	0.986	-0.078	0.033	0.142
NI	0.985	-0.044	-0.014	0.132
DISPO4	0.965	-0.136	0.003	0.198
NOX	0.912	0.201	-0.183	-0.301
ZN	0.883	0.423	0.190	-0.073
SAL	0.783	0.608	0.048	-0.006
FE	-0.763	0.161	0.623	-0.033
CO	-0.030	0.988	0.033	0.094
CD	-0.435	-0.864	-0.056	0.246
SIO2	-0.057	0.058	0.982	0.170
CHLA	-0.210	0.064	-0.168	-0.959

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3	4
5.919	2.372	1.458	1.191

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
53.808	21.562	13.253	10.831

COMPONENT LOADINGS

	1	2	3	4
NI	0.946	-0.266	0.146	0.048
ZN	0.942	0.283	0.102	0.146
NOX	0.937	-0.002	-0.296	0.179
CU	0.936	-0.283	0.192	0.079
DISPO4	0.905	-0.352	0.212	0.037
SAL	0.902	0.411	0.011	-0.060
FE	-0.742	0.508	0.375	0.219
CD	-0.621	-0.760	0.193	0.013
CO	0.210	0.891	-0.036	-0.383
SIO2	-0.103	0.354	0.835	0.409
CHLA	-0.199	0.227	-0.769	0.560

VARIANCE EXPLAINED BY COMPONENTS

1	2	3	4
6.200	2.330	1.668	0.742

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
56.366	21.180	15.164	6.744

ROTATED LOADINGS

	1	2	3	4
CU	0.983	0.045	0.031	0.173
NI	0.975	0.079	0.077	0.163
DISPO4	0.966	-0.016	0.060	0.228
NOX	0.875	0.317	0.239	-0.272
ZN	0.835	0.531	-0.136	-0.043
FE	-0.735	0.065	-0.671	-0.053
SAL	0.702	0.702	-0.003	0.022
CO	-0.155	0.975	-0.042	0.098
CD	-0.333	-0.914	0.035	0.227
SIO2	-0.006	0.050	-0.984	0.172
CHLA	-0.197	0.045	0.152	-0.965

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3	4
5.520	2.680	1.530	1.210

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
50.180	24.364	13.907	11.002

Golden Gate Cruise 1

LATENT ROOTS (EICENVALUES)

1	2	3	4	5
7.319	1.823	1.058	0.495	0.304
6	7	8	9	10
0.000	0.000	-0.000	-0.000	-0.000
11				
-0.000				

COMPONENT LOADINGS

	1	2	3	4
CD	0.984	0.118	0.112	-0.004
CU	0.946	0.254	-0.073	0.130
NI	0.929	0.311	0.116	0.141
CO	0.921	-0.086	0.266	0.222
SAL	-0.918	-0.349	-0.130	-0.098
SIO2	-0.910	0.298	0.078	-0.081
CHLA	0.875	-0.304	0.252	-0.209
ZN	-0.808	0.094	0.521	0.167
FE	0.808	-0.335	-0.232	-0.399
NOX	0.052	-0.798	-0.420	0.399
DISSPO4	0.052	0.761	-0.606	0.051

VARIANCE EXPLAINED BY COMPONENTS

1	2	3	4
7.319	1.823	1.058	0.495

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
66.540	16.577	9.615	4.503

ROTATED LOADINGS

	1	2	3	4
CD	0.992	0.106	-0.003	0.014
CU	0.956	0.037	-0.248	-0.065
NI	0.954	0.173	-0.150	-0.170
SAL	-0.944	-0.229	0.159	0.151
CO	0.942	-0.059	0.214	-0.195
SIO2	-0.891	0.321	-0.125	-0.127
CHLA	0.860	-0.006	0.411	0.237
ZN	-0.757	0.294	0.299	-0.462
FE	0.750	-0.192	0.107	0.606
NOX	0.012	-0.971	0.170	0.056
DISSPO4	0.052	0.173	-0.959	0.007

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3	4
7.258	1.298	1.389	0.750

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
65.984	11.804	12.626	6.821

COMPONENT LOADINGS

	1	2	3	4
CD	0.984	0.118	0.112	-0.004
CU	0.946	0.254	-0.073	0.130
NI	0.929	0.311	0.116	0.141
CO	0.921	-0.086	0.266	0.222
SAL	-0.918	-0.349	-0.130	-0.098
SIO2	-0.910	0.298	0.078	-0.081
CHLA	0.875	-0.304	0.252	-0.209
ZN	-0.808	0.094	0.521	0.167
FE	0.808	-0.335	-0.232	-0.399
NOX	0.052	-0.798	-0.420	0.399
DISSPO4	0.052	0.761	-0.606	0.051

VARIANCE EXPLAINED BY COMPONENTS

1	2	3	4
7.319	1.823	1.058	0.495

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
66.540	16.577	9.615	4.503

ROTATED LOADINGS

	1	2	3	4
NI	0.946	-0.137	0.119	0.256
SAL	-0.932	0.146	-0.177	-0.261
CO	0.918	0.226	-0.114	0.259
CU	0.889	-0.237	0.000	0.366
CD	0.889	0.007	0.080	0.445
SIO2	-0.708	-0.132	0.323	-0.553
CHLA	0.657	0.417	0.006	0.600
DISSPO4	0.074	-0.958	0.171	0.001
NOX	-0.107	0.166	-0.952	0.175
FE	0.383	0.107	-0.119	0.897
ZN	-0.450	0.297	0.241	-0.783

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3	4
5.487	1.384	1.177	2.647

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
49.885	12.583	10.699	24.068

San Pablo Bay Cruise 1

LATENT ROOTS (EIGENVALUES)

1	2	3	4	5
6.291	2.352	1.527	0.732	0.213
6	7	8	9	10
0.014	0.000	0.000	-0.000	-0.000
11				
-0.130				

COMPONENT LOADINGS

	1	2	3	4
SIO2	0.972	-0.035	0.222	0.005
CU	0.959	0.199	0.199	-0.028
DISPO4	0.936	-0.212	0.243	0.029
CD	-0.911	0.250	0.117	0.229
SAL	-0.884	-0.460	-0.042	0.042
CO	-0.795	0.323	0.504	-0.031
NI	0.779	0.339	0.493	-0.015
FE	0.168	0.697	-0.439	0.553
ZN	0.500	0.668	-0.538	-0.159
CHLA	-0.480	0.657	-0.125	-0.572
NOX	-0.438	0.640	0.607	0.134

VARIANCE EXPLAINED BY COMPONENTS

1	2	3	4
6.291	2.352	1.527	0.732

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
57.194	21.381	13.885	6.659

COMPONENT LOADINGS

	1	2	3	4
SIO2	0.972	-0.035	0.222	0.005
CU	0.959	0.199	0.199	-0.028
DISPO4	0.936	-0.212	0.243	0.029
CD	-0.911	0.250	0.117	0.229
SAL	-0.884	-0.460	-0.042	0.042
CO	-0.795	0.323	0.504	-0.031
NI	0.779	0.339	0.493	-0.015
FE	0.168	0.697	-0.439	0.553
ZN	0.500	0.668	-0.538	-0.159
CHLA	-0.480	0.657	-0.125	-0.572
NOX	-0.438	0.640	0.607	0.134

VARIANCE EXPLAINED BY COMPONENTS

1	2	3	4
6.291	2.352	1.527	0.732

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
57.194	21.381	13.885	6.659

ROTATED LOADINGS VARIMAX

	1	2	3	4
NI	0.967	0.149	0.084	-0.027
CU	0.961	-0.212	0.171	-0.042
SIO2	0.924	-0.316	0.031	-0.199
SAL	-0.888	0.155	-0.399	-0.154
DISPO4	0.859	-0.371	-0.086	-0.313
CD	-0.700	0.681	0.066	0.035
NOX	0.025	0.980	0.089	0.140
CO	-0.382	0.878	-0.210	0.176
FE	0.046	0.091	1.001	0.005
ZN	0.364	-0.293	0.704	0.544
CHLA	-0.249	0.358	0.091	0.898

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3	4
5.074	2.745	1.766	1.317

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
46.131	24.953	16.058	11.976

ROTATED LOADINGS Quartimax

	1	2	3	4
CU	0.993	0.106	-0.045	0.013
SIO2	0.974	-0.031	-0.158	-0.143
NI	0.931	0.024	0.313	0.013
DISPO4	0.918	-0.142	-0.226	-0.260
SAL	-0.917	-0.335	-0.005	-0.208
CD	-0.801	0.123	0.549	-0.023
CO	-0.548	-0.173	0.805	0.118
FE	0.095	0.997	0.092	0.024
ZN	0.425	0.664	-0.211	0.586
NOX	-0.145	0.102	0.973	0.103
CHLA	-0.347	0.097	0.338	0.872

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3	4
5.758	1.645	2.238	1.261

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
52.347	14.958	20.348	11.465

North Bay Cruise 1

LATENT ROOTS (EIGENVALUES)

1	2	3	4	5
6.110	1.736	1.187	1.109	0.581
6	7	8	9	10
0.442	0.063	0.005	-0.000	-0.000
11				
-0.232				

COMPONENT LOADINGS

	1	2	3	4
NI	0.988	0.019	-0.045	-0.006
SAL	0.976	0.147	-0.000	0.027
CD	0.931	0.255	0.036	0.072
ZN	0.919	0.089	0.425	-0.130
CO	0.908	-0.008	-0.198	-0.164
DISPO4	0.751	-0.614	0.061	-0.124
CU	0.656	0.151	-0.566	0.084
CHLA	0.623	-0.719	-0.106	0.024
NOX	-0.316	-0.831	0.134	0.246
SIO2	0.360	0.166	0.755	0.312
FE	-0.181	-0.075	0.203	-0.937

VARIANCE EXPLAINED BY COMPONENTS

1	2	3	4
6.110	1.736	1.187	1.109

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
55.544	15.779	10.787	10.080

ROTATED LOADINGS Quathuax

	1	2	3	4
NI	0.985	0.066	0.056	0.050
SAL	0.975	-0.053	0.122	0.080
CD	0.931	-0.156	0.177	0.122
CO	0.930	0.053	-0.141	-0.066
ZN	0.807	0.016	0.474	-0.195
CU	0.706	-0.128	-0.433	0.277
DISPO4	0.702	0.663	0.025	-0.164
CHLA	0.572	0.758	-0.121	0.008
NOX	-0.405	0.831	0.057	0.105
SIO2	0.275	-0.029	0.856	0.121
FE	-0.132	-0.038	-0.075	-0.966

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3	4
6.015	1.758	1.239	1.129

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
54.680	15.984	11.262	10.264

ROTATED LOADINGS VARIMAX

	1	2	3	4
SAL	0.919	0.181	0.299	0.086
NI	0.910	0.303	0.236	0.062
CO	0.896	0.291	0.032	-0.056
CD	0.894	0.067	0.346	0.123
CU	0.783	0.056	-0.297	0.275
ZN	0.754	0.225	0.630	-0.185
NOX	-0.604	0.695	-0.023	0.143
CHLA	0.375	0.879	-0.018	0.051
DISPO4	0.496	0.822	0.151	-0.124
SIO2	0.116	-0.002	0.892	0.124
FE	-0.107	-0.018	-0.093	-0.968

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3	4
5.233	2.200	1.577	1.131

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
47.569	20.004	14.338	10.279

South Bay Cruise 2
Stations 1-6

LATENT ROOTS (EIGENVALUES)

1	2	3	4	5
8.644	1.410	0.809	0.107	0.030
6	7	8	9	10
0.000	0.000	0.000	-0.000	-0.000
11				
-0.000				

COMPONENT LOADINGS

	1	2
DISPO4	0.995	-0.003
SIO2	0.992	0.028
NI	0.992	-0.008
NOX	0.991	-0.073
SAL	-0.975	0.155
CU	0.970	0.077
CO	0.938	-0.063
CD	0.935	0.336
ZN	0.806	-0.370
CHLA	0.537	0.781
FE	-0.343	0.714

VARIANCE EXPLAINED BY COMPONENTS

1	2
8.644	1.410

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2
78.578	12.819

ROTATED LOADINGS Quartimax

	1	2
DISPO4	0.995	0.017
NOX	0.992	-0.053
NI	0.992	0.012
SIO2	0.992	0.048
SAL	-0.978	0.136
CU	0.968	0.097
CO	0.939	-0.044
CD	0.928	0.355
ZN	0.814	-0.354
CHLA	0.521	0.792
FE	-0.358	0.707

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2
8.641	1.413

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2
78.551	12.845

Golden Gate Cruise 2
Stations 7-15

LATENT ROOTS (EIGENVALUES)

1	2	3	4	5
6.461	2.120	1.085	0.629	0.460
6	7	8	9	10
0.132	0.088	0.025	0.000	-0.000
11				
-0.000				

COMPONENT LOADINGS

	1	2	3
NI	0.963	0.030	0.103
CU	0.962	-0.115	0.091
SIO2	0.943	-0.272	-0.053
DISSPO4	0.885	0.387	0.186
CD	0.863	0.394	0.075
NOX	0.830	-0.404	0.103
ZN	0.735	0.528	0.079
CHLA	-0.676	0.120	-0.129
FE	0.621	-0.392	-0.593
SAL	-0.212	0.945	0.054
CO	0.271	0.473	-0.797

VARIANCE EXPLAINED BY COMPONENTS

1	2	3
6.461	2.120	1.085

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3
58.735	19.275	9.866

ROTATED LOADINGS Quartimax

	1	2	3
NI	0.968	-0.033	0.025
CU	0.957	-0.175	-0.005
DISSPO4	0.923	0.339	0.041
SIO2	0.910	-0.364	0.084
CD	0.886	0.316	0.145
NOX	0.813	-0.436	-0.116
ZN	0.767	0.457	0.165
CHLA	-0.679	0.142	0.076
FE	0.508	-0.599	0.523
SAL	-0.149	0.938	0.197
CO	0.183	0.204	0.926

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3
6.341	2.078	1.248

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3
57.641	18.890	11.345

San Pablo Bay Cruise 2
Stations 16-21

LATENT ROOTS (EIGENVALUES)

1	2	3	4	5
7.419	1.656	1.100	0.705	0.168
6	7	8	9	10
0.020	0.000	0.000	-0.000	-0.000
11				
-0.068				

COMPONENT LOADINGS

	1	2	3
SAL	0.980	0.043	-0.172
CD	0.976	0.038	-0.185
NI	0.970	0.116	0.091
DISSPO4	0.955	0.295	0.175
ZN	0.947	0.043	0.231
SIO2	-0.924	0.093	0.308
CO	0.889	-0.215	0.232
NOX	0.878	0.263	0.311
CHLA	-0.316	0.830	-0.013
FE	-0.104	-0.645	0.640
CU	-0.482	0.567	0.537

VARIANCE EXPLAINED BY COMPONENTS

1	2	3
7.419	1.656	1.100

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3
67.444	15.053	10.001

ROTATED LOADINGS Quartimax

	1	2	3
DISSPO4	0.996	0.181	-0.074
NI	0.981	-0.007	-0.014
ZN	0.965	0.037	0.139
SAL	0.954	-0.239	-0.157
CD	0.948	-0.250	-0.163
NOX	0.931	0.262	0.048
CO	0.879	-0.140	0.315
SIO2	-0.868	0.419	0.164
CU	-0.353	0.847	0.010
CHLA	-0.219	0.642	-0.573
FE	-0.107	-0.022	0.908

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3
7.270	1.548	1.357

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3
66.090	14.074	12.335

North Bay Cruise 2
Stations 22-27

LATENT ROOTS (EIGENVALUES)

1	2	3	4	5
6.805	2.522	1.043	0.518	0.138
6	7	8	9	10
0.039	0.020	0.000	-0.001	-0.037
11				
-0.047				

COMPONENT LOADINGS

	1	2	3
SAL	0.947	0.214	0.001
NOX	0.928	0.179	-0.132
DISSPO4	0.923	-0.178	-0.208
ZN	-0.922	0.061	0.273
CO	-0.901	0.343	0.100
FE	-0.883	0.265	0.186
CHLA	0.779	-0.426	0.418
SIO2	-0.764	-0.627	0.044
NI	0.430	0.883	0.089
CU	-0.405	0.822	-0.375
CD	0.461	0.438	0.734

VARIANCE EXPLAINED BY COMPONENTS

1	2	3
6.805	2.522	1.043

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3
61.861	22.929	9.483

ROTATED LOADINGS Quartimax

	1	2	3
ZN	-0.960	-0.040	0.080
DISSPO4	0.955	-0.093	-0.074
CO	-0.924	0.288	0.055
NOX	0.922	0.194	0.150
FE	-0.918	0.180	0.100
SAL	0.913	0.166	0.285
SIO2	-0.715	-0.562	-0.389
CHLA	0.710	-0.586	0.339
CU	-0.378	0.913	-0.055
NI	0.346	0.743	0.548
CD	0.281	0.060	0.927

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3
6.572	2.241	1.557

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3
59.742	20.372	14.158

South Bay Cruise 3
Stations 1-6

LATENT ROOTS (EIGENVALUES)

1	2	3	4	5
8.278	2.146	0.245	0.196	0.135
6	7	8	9	10
0.000	0.000	-0.000	-0.000	-0.000
11				
-0.000				

COMPONENT LOADINGS

	1	2	3	4
NI	0.992	0.083	-0.042	0.077
CD	0.982	-0.093	0.141	0.027
DISNOX	0.980	-0.098	-0.104	0.114
DISPO4	0.974	0.159	-0.147	-0.025
SALINITY	-0.949	0.035	0.287	0.094
CO	0.942	-0.102	0.022	-0.238
DISSI	0.941	0.045	0.300	-0.145
ZN	0.931	-0.293	0.039	-0.009
CU	0.889	0.321	0.111	0.285
CHLA	-0.197	0.976	0.035	-0.090
FE	-0.223	-0.970	0.051	0.017

VARIANCE EXPLAINED BY COMPONENTS

1	2	3	4
8.278	2.146	0.245	0.196

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
75.255	19.510	2.224	1.785

ROTATED LOADINGS Quartimax

	1	2	3	4
NI	0.991	0.091	-0.061	-0.075
CD	0.982	-0.085	0.130	-0.070
DISNOX	0.981	-0.092	-0.130	-0.081
DISPO4	0.973	0.173	-0.133	0.049
SALINITY	-0.952	0.016	0.246	-0.166
CO	0.945	-0.078	0.092	0.219
DISSI	0.941	0.060	0.330	0.041
ZN	0.934	-0.282	0.043	0.006
CU	0.882	0.314	0.024	-0.330
CHLA	-0.208	0.976	0.053	0.023
FE	-0.212	-0.972	0.049	0.025

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3	4
8.277	2.141	0.241	0.207

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
75.242	19.461	2.188	1.882

Golden Gate Cruise 3
Stations 7-14

LATENT ROOTS (EIGENVALUES)

1	2	3	4	5
8.486	1.043	0.920	0.448	0.060
6	7	8	9	10
0.033	0.010	0.000	0.000	-0.000
11				
-0.000				

COMPONENT LOADINGS

	1	2	3	4
NI	0.995	0.044	0.028	0.056
CU	0.995	0.055	-0.003	0.071
CD	0.992	0.050	0.070	0.065
DISSI	0.988	-0.013	0.038	0.132
DISNOX	0.958	0.217	0.011	0.166
SALINITY	-0.925	0.282	0.209	-0.028
ZN	0.880	-0.427	0.069	0.130
DISPO4	0.862	0.490	0.068	0.052
CHLA	0.734	0.334	0.321	-0.488
CO	0.718	-0.600	0.112	-0.304
FE	0.447	0.126	-0.862	-0.199

VARIANCE EXPLAINED BY COMPONENTS

1	2	3	4
8.486	1.043	0.920	0.448

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
77.148	9.486	8.362	4.074

ROTATED LOADINGS *Quartimax*

	1	2	3	4
DISSI	0.997	-0.021	0.001	-0.044
NI	0.997	-0.006	0.040	0.043
CD	0.997	0.002	-0.001	0.052
CU	0.996	0.011	0.067	0.026
DISNOX	0.974	0.200	0.042	0.024
SALINITY	-0.903	0.292	-0.229	0.164
ZN	0.881	-0.379	-0.084	-0.230
DISPO4	0.877	0.391	0.046	0.257
CHLA	0.701	-0.002	-0.064	0.704
CO	0.671	-0.726	-0.031	0.053
FE	0.380	0.022	0.924	-0.025

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3	4
8.369	0.949	0.928	0.652

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
76.081	8.628	8.434	5.927

San Pablo Bay Cruise 3
Stations 15-20

LATENT ROOTS (EIGENVALUES)

1	2	3	4	5
7.070	2.662	0.922	0.241	0.105
6	7	8	9	10
0.000	0.000	0.000	-0.000	-0.000
11				
-0.000				

COMPONENT LOADINGS

	1	2	3	4
DISSI	0.991	0.092	0.079	-0.053
SALINITY	-0.989	0.108	0.059	0.076
CU	0.975	0.134	-0.101	-0.115
FE	0.932	-0.200	-0.072	0.084
NI	0.874	0.444	0.070	-0.185
CD	-0.853	0.441	0.266	0.075
ZN	0.844	-0.123	0.378	0.351
CO	-0.825	0.363	0.402	-0.133
CHLA	-0.629	-0.510	-0.584	0.055
DISNOX	0.076	0.945	-0.314	0.050
DISPO4	0.074	0.944	-0.279	0.159

VARIANCE EXPLAINED BY COMPONENTS

1	2	3	4
7.070	2.662	0.922	0.241

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
64.276	24.196	8.386	2.187

ROTATED LOADINGS Quartimax

	1	2	3	4
SALINITY	-0.997	0.025	-0.038	-0.059
DISSI	0.965	0.114	0.233	0.021
CU	0.962	0.209	0.092	0.118
FE	0.949	-0.090	-0.039	-0.098
CD	-0.915	0.267	0.288	-0.083
CO	-0.889	0.124	0.420	0.090
NI	0.815	0.420	0.359	0.173
ZN	0.811	-0.153	0.344	-0.440
CHLA	-0.518	-0.297	-0.801	0.044
DISNOX	0.006	0.997	0.058	0.058
DISPO4	0.000	0.996	0.073	-0.055

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3	4
6.972	2.425	1.223	0.275

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
63.385	22.042	11.120	2.497

North Bay Cruise 3
Stations 21-25

LATENT ROOTS (EIGENVALUES)

1	2	3	4	5
7.932	1.537	1.128	0.403	0.000
6	7	8	9	10
0.000	0.000	0.000	-0.000	-0.000
11				
-0.000				

COMPONENT LOADINGS

	1	2	3	4
SALINITY	0.991	0.068	0.097	0.056
CD	0.978	0.136	0.115	0.111
DISSI	-0.960	-0.246	-0.068	0.115
NI	0.958	0.215	0.106	0.159
CHLA	-0.892	0.046	-0.335	0.300
DISPO4	0.862	-0.494	-0.116	0.023
CO	0.830	0.355	0.333	0.273
DISNOX	0.809	-0.542	0.142	-0.177
ZN	-0.773	0.520	0.364	0.004
FE	-0.664	-0.059	0.721	-0.190
CU	0.484	0.684	-0.426	-0.342

VARIANCE EXPLAINED BY COMPONENTS

1	2	3	4
7.932	1.537	1.128	0.403

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
72.109	13.973	10.254	3.663

ROTATED LOADINGS Quartimax

	1	2	3	4
SALINITY	0.992	-0.099	0.063	0.036
CD	0.992	-0.036	0.075	0.098
NI	0.980	0.018	0.113	0.166
DISSI	-0.962	-0.002	-0.266	0.065
CO	0.922	0.303	0.012	0.238
CHLA	-0.919	0.002	0.029	0.392
DISPO4	0.771	-0.603	-0.188	-0.078
DISNOX	0.762	-0.452	-0.303	-0.351
ZN	-0.627	0.777	0.052	0.033
FE	-0.503	0.600	-0.471	-0.406
CU	0.417	0.051	0.908	-0.006

VARIANCE EXPLAINED BY ROTATED COMPONENTS

1	2	3	4
7.544	1.638	1.269	0.549

PERCENT OF TOTAL VARIANCE EXPLAINED

1	2	3	4
68.583	14.894	11.537	4.986