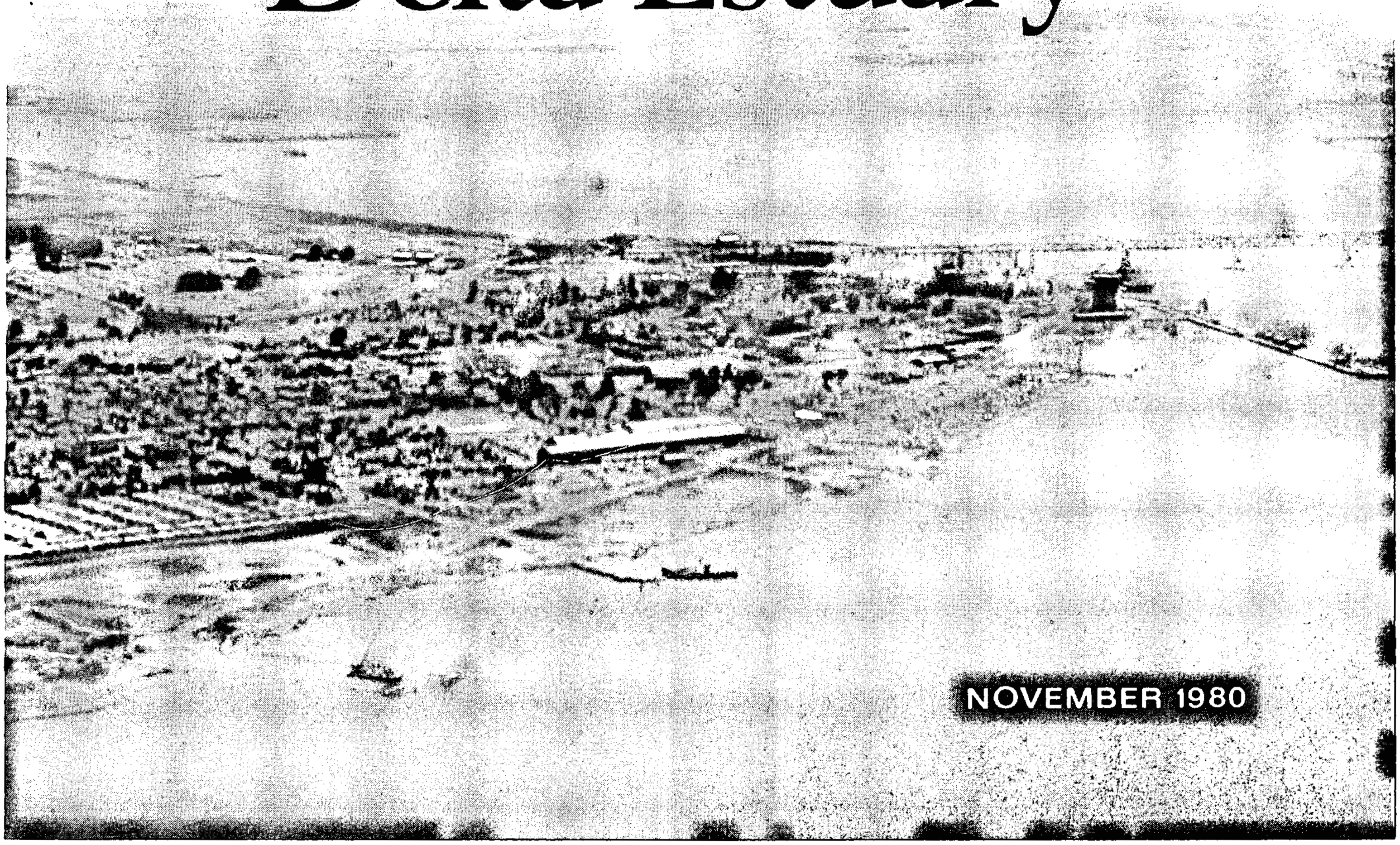
The Significance of the Entrapment Zone Location to the Phytoplankton Standing Crop in the San Francisco Bay - Delta Estuary



United States Department of the Interior
WATER AND POWER RESOURCES SERVICE

MID-PACIFIC REGIONAL OFFICE
2800 COTTAGE WAY
SACRAMENTO, CALIFORNIA 95825

IN REPLY
REFER TO: MP-780
123.4

NOV 20 1980

We are pleased to send you a copy of our latest report on ecological studies being conducted in the San Francisco Bay-Delta Estuary of California. The report documents a 1978 study conducted by the Water and Power Resources Service on the effects of regulating the entrapment zone to its hypothetical optimal location for maximizing the phytoplankton standing crop in Suisun Bay.

Sincerely yours,

Jack E Simons

Acting Regional Planning Officer

Enclosure

THE SIGNIFICANCE OF THE ENTRAPMENT ZONE LOCATION TO THE PHYTOPLANKTON STANDING CROP IN THE SAN FRANCISCO BAY-DELTA ESTUARY

by

James F. Arthur

Melvin Douglas Ball

November 1980

UNITED STATES
DEPARTMENT OF THE INTERIOR
WATER AND POWER RESOURCES SERVICE
2800 Cottage Way
Sacramento, California 95825

COVER CAPTION

Aerial photograph of Suisun Bay, San Francisco Bay-Delta Estuary, looking upstream (east) of Martinez, California. The photograph was taken on the morning of July 14, 1978, approximately during high slack tide in Suisun Bay and illustrates turbidity patchiness characteristically observed in Suisun Bay resulting from wind and tidal resuspension of particulate material being transported by tidal and estuarine circulation.

FOREWORD

This report presents the findings of a study conducted by the Water and Power Resources Service (formerly the Bureau of Reclamation) during the summer of 1978 in Suisun Bay, San Francisco Bay-Delta Estuary, California. The Water and Power Resources Service (Service) is a member of the Interagency Ecological Study Program (4-Agency). This program consists of the Service, the California Departments of Water Resources (DWR) and Fish and Game (DFG), and the U.S. Fish and Wildlife Service (FWS). Information obtained in this and other 4-Agency studies is being used to evaluate the effects of present and proposed Central Valley Projects (CVP) and State Water Projects (SWP) operations on the Delta environment.

ABSTRACT

A study conducted during the summer of 1978 in the upper San Francisco Bay-Delta Estuary of California further supported the theory that phytoplankton standing crops are highest when the entrapment zone (an area where peak suspended materials concentrate as a result of two-layered flow circulation) is adjacent to the expansive shallows of Suisun Bay. The photic zone in the shallows of Suisun Bay constitutes a greater percentage of the total depth than in the channels. Also, wind and tidal mixing distribute the phytoplankton more uniformly throughout the water column in the shallows than in the deeper channel areas. Consequently, phytoplankton spend more time in the photic zone, and growth rates are higher in the shallows. Because of the longer residence time in the entrapment zone, large phytoplankton standing crops have the potential to concentrate. The entrapment zone was maintained in Suisun Bay from approximately mid-July through October 1978 by regulating Delta outflow through operational control of the Federal and State Water Projects. The phytoplankton standing crop in the entrapment zone and adjacent shallows increased substantially, to peak values of about 60 ug/L, a few weeks following movement of the zone into upper Suisun Bay. Peak chlorophyll levels in the entrapment zone and adjacent shallows remained about 60 ug/L or greater during the study and were approximately ten times higher than upstream or downstream concentrations. Also, inorganic nitrogen became limiting in areas of peak concentration from the time of the initial peak, until the end of the study in the fall. Maximum phytoplankton concentrations occurred when the tidally averaged position of the entrapment zone was in the vicinity of Honker Bay (upper part of Suisun Bay). Delta outflows of approximately 140 to 230 m^3/s (5,000-8,000 ft^3/s) were required to maintain the entrapment zone in this location. Forty-one species of phytoplankton (at the 20 cell/ml detection level) were identified in the study, with the diatom <u>Thalassiosira excentricus</u> being the most numerous and frequently occurring phytoplankter in the study area. At the Delta outflow range studied, preliminary evidence indicates the settling rate of <u>T. excentricus</u> is nearly equal to the theoretical average net upward vertical water velocity occurring in the channel occupied by the entrapment zone. Downstream of the zone where the net upward vertical water velocity has been calculated to be greatly reduced, <u>T. excentricus</u> apparently settle into the upstream-flowing bottom layer and are returned to the entrapment area. This settling-vertical velocity relationship is hypothesized to be the mechanism by which these organisms are concentrated in the entrapment zone. The decrease in inorganic nitrogen (nitrite, nitrate, and ammonia) to phytoplankton-limiting levels (<0.02 mg/L) was inversely related to increased chlorophyll levels and limited the maximum standing crop. Silica depletion by diatoms was estimated to be about 12 mg/L. Although dissolved silica in the water column was depleted to as low as 1.2 mg/L, it is uncertain at what levels silica limits the diatom growth rate. The entrapment zone was observed to move upstream and downstream throughout the study in response to tides and changes in outflow. Peak concentrations of chlorophyll, along with minimal concentrations of inorganic nitrogen, and orthophosphate occurred in waters with specific conductances ranging from approximately 5 to 14 millimho/cm (3-8 $^{o}/oo$ salinity). Chlorophyll concentrations tended to build up near the bottom, upstream of the surface chlorophyll peaks. Comparative measurements of chlorophyll throughout the study area indicated concentrations vary considerably throughout Suisun Bay. The results of this study suggest that the phytoplankton standing crop in Suisun Bay can be regulated, within water availability limits, by manipulating Delta outflow to optimize the entrapment zone location.

a4

TABLE OF CONTENTS

TABLE OF CONTENTS

FIGURES

TABLE OF CONTENTS

FIGURES

TABLE OF CONTENTS

TABLES

SIGNIFICANT FINDINGS

An evaluation of the data obtained in this study resulted in the following findings:

1. Evidence evaluated in the present study and earlier studies indicates the following. The photic zone in the shallows of Grizzly and Honker Bays constitutes a greater percentage of the total depth than in the channel areas. Wind and tidal mixing in the shallows distribute the phytoplankton more uniformly through the water column than in the deeper channel areas. Because phytoplankton in the shallows spend more time in the photic zone, available light (combined solar radiation and water transparency) is less limiting for phytoplankton growth rates in the shallows than in the channels. Also, there is a longer residence time of particulate materials in the entrapment zone, and large phytoplankton standing crops have the potential to concentrate. Consequently, the location of the entrapment zone (area of peak suspended materials concentration) in and adjacent to large, shallow, well-mixed embayments is a major factor concentrating specific diatoms where high growth rates occur and stimulates the production of a large phytoplankton standing crop.

2. The phytoplankton standing crop in the entrapment zone increased substantially during the study, apparently in response to movement of the zone into Suisun Bay. Peak chlorophyll levels were approximately 60 ug/L or greater in the entrapment zone during the 3-months duration of the study, as compared to "pre-study" and to adjacent upstream and downstream chlorophyll concentrations during the study of 1-6 ug/L. The maximum chlorophyll level observed during the study was 85 ug/L.

3. Inorganic nitrogen was reduced to less than 0.02 mg/L (N) (phytoplankton growth rate limiting concentrations) in the area of peak chlorophyll concentration as the result of phytoplankton growth.

4. The entrapment zone moved throughout the study area in response to changes in tide and Delta outflow.

5. Forty-one phytoplankton species were identified as occurring in the study area. Thalassiosira excentricus (synonymous with Coscinodiscus decipiens), a centric diatom, was the predominant phytoplankter observed in the entrapment zone. T. excentricus was the most numerous phytoplankter observed (approximately 90 percent of the cells counted) and was present in over 97 percent of the samples enumerated. Its distribution generally corresponded to measurements of chlorophyll distribution in the area. Settling rate data collected in this and earlier studies, although preliminary, indicate that the settling rate of T. excentricus is nearly equal to the maximum net upward vertical velocity in the water column (as determined by mathematical modeling). The settling of T. excentricus from the downstream-flowing surface layer into the upstream-flowing bottom layer is the theorized mechanism by which these organisms are concentrated in the entrapment zone.

RECOMMENDATIONS

Based upon the results of this study, the following recommendations should be considered:

1. The entrapment zone is an extremely important feature in estuaries. In the Suisun Bay, maximum concentrations of inorganic suspended materials, phytoplankton, Neomysis, certain other zooplankton, and juvenile striped bass (as well as other organisms) occur in the entrapment zone. If additional definitive information is required, water quality and biological monitoring programs in the upper San Francisco Bay-Delta Estuary should be of an intensive nature in the general area of the entrapment zone. Monitoring stations established throughout this area to study the entrapment zone should be flexible to reflect spatial changes of the zone with outflow.

2. River and tidal flow influence estuarine circulation in Suisun Bay and can greatly influence the distribution of suspended materials. Therefore, it is important to determine the representativeness of sample sites, especially the biota, while conducting studies in this area.

3. Chlorophyll levels increased in Grizzly Bay prior to developing in the channel areas of Suisun Bay. If more definitive biological models are to be constructed, further studies should be conducted to determine how tidal exchange between the shallow areas of the Suisun Bay and the river channel influence the accumulation of suspended materials, including biota, in the entrapment zone in different areas at varying Delta outflows.

4. The location of the entrapment zone appears to be a significant factor influencing the phytoplankton standing crop in this portion of the estuary. Several hypotheses have been presented as to the mechanisms regulating the phytoplankton standing crop in Suisun Bay. Preliminary data suggest that the settling rate of Thalassiosira excentricus, relative to the upward net vertical velocity, may be an important mechanism by which these organisms predominate throughout the study area. Specifically, if more definitive biological models are to be constructed, phytoplankton settling rate and calculations of water velocity measurement studies should be conducted to further evaluate this hypothesis.

5. The entrapment zone and its influence on other ecologically important organisms not measured in the present study, sediment shoaling, and the accumulation of heavy metals and pesticides should also be considered.

6. Thus far, chlorophyll levels up to 100 ug/L in Suisun Bay have not had any measurable deleterious effect on the Suisun Bay environment. Conversely, the low Delta outflows during the 1976-77 drought resulted in a significant reduction in phytoplankton (as well as other biota) levels in Suisun Bay when the entrapment zone was upstream of Honker Bay. Consideration should be given to determining what level of phytoplankton standing crop will enhance overall estuarine productivity without causing deleterious effects.

GLOSSARY

Aggregate. Materials aggregate when they collect in clumps.

Entrapment zone. An entrapment zone is an area (or areas) in an estuary where suspended materials (including certain biota) accumulate. Net upstream transport of the particulate materials that settle into the bottom density current is nullified by the net downstream transport of materials in the river inflow. As a result, certain suspended materials concentrate in the area where the bottom current is nullified. The entrapment zone location varies with river inflow and tide and has its upstream boundary theoretically in the area of the null zone. (See section on theoretical concepts.)

Estuarine circulation (also termed two-layered flow and gravitational circulation). Estuarine circulation generally refers to the net nontidal flow patterns resulting from less dense fresh water interacting with the more dense ocean water.

Flocculate. Materials flocculate when they collect in small clumps to form larger particles. In water, flocculation is induced by increased salinity, causing neutralization of partical charges which allows particles to come in contact with each other.

Growth rate. The growth rate is the rate of increase or decrease in a particular population of organisms.

Inhibiting growth. A substance or physical factor is inhibiting growth when an excessive level interferes with and slows or stops the rate of growth.

In Vivo fluorescence. The fluorescence of a compound, such as chlorophyll, which occurs in live organisms.

Limiting growth. A substance or physical factor is limiting growth when its absence, or presence at a lower than required level, slows the growth rate.

Mixing zone. The mixing zone is that area of an estuary extending from the fresh to salt water boundary where mixing of fresh and salt waters occurs.

Null zone. The null zone is an area in a two-layer flow estuary in the lower half of the water column where river inflow nullifies the landward flowing density current. This zone refers to net flow patterns and extends across the width of the channel from the plane-of-no-net-motion to the bottom.

Photic zone. The photic (euphotic) zone is that portion of the water column where algal photosynthesis exceeds algal respiration. Averaged out over the full period of a day, this zone generally extends to a depth where the amount of light entering the water's surface has been reduced to about one percent.

Plane-of-no-net-motion. The plane-of-no-net-motion is a theoretical undulating plane in a two-layered flow estuary separating the net seaward and net landward flowing layers and intercepts the bottom in the null zone.

INTRODUCTION

The present study evolved from work conducted since 1973 by the Water and Power Resources Service (Service) on the entrapment zone (see section on theoretical concepts) and its effect on the estuarine environment. The purpose of the study was to determine if the phytoplankton standing crop in Suisun Bay could be enhanced by outflow manipulation of the entrapment zone location as hypothesized by Arthur and Ball in earlier studies (1978; 1979a and b).

Background

The Service began its environmental studies of the San Francisco Bay-Delta Estuary in 1968. The emphasis for such a program resulted from a State Water Quality hearing held in 1967 which recognized that more information was needed on the impacts of the Federal and State Water Projects on the estuarine environment. The 4-Agency group (Service, USFWS, DWR, and DFG) was formed in the early seventies to better plan, coordinate, and execute environmental studies within the estuary. An evaluation of data collected early in the program (Arthur, 1975) led to the conclusion that phytoplankton and other suspended constitutents were being concentrated in the Suisun Bay area, where the least water transparency occurred, and that unknown factors were somehow influencing the phytoplankton dynamics.

Further field studies, data evaluation, and review of the literature resulted in the entrapment zone scenario described by Arthur and Ball (1978; 1979a and b).

Ball (1975 and 1977) and Ball and Arthur (1979) have evaluated phytoplankton growth throughout the Suisun Bay-Western Delta since 1968. The timing of peak chlorophyll levels between years has been highly variable, occurring in all months between February and October and ranging from as high as 100 ug/L in 1970 to below 10 ug/L in 1977, depending on various environmental factors. There is no typical year. Chlorophyll peaks from 1968 to 1977 were measured at under 50 ug/L five times and over 50 ug/L five times.

From the evaluation of chlorophyll *a* data for the period 1969-1974, it was observed that the Suisun Bay phytoplankton standing crop tended to either increase or remain high whenever the entrapment zone was adjacent to the shallows of Grizzly and Honker Bays, (Ball, 1977). Chlorophyll data collected from 1968-1977 supports this conclusion, figure 1. A phytoplankton bloom occurred in Suisun Bay in February of 1976 as the entrapment zone moved landward into the Honker Bay area with decreasing Delta outflow. This bloom was the earliest observed in any year since monitoring was initiated in 1968. It also occurred as the entrapment zone was centered near Honker Bay and when the water transparency was unusually clear for that time of the year.

As Delta outflow declined in 1976 and remained low throughout 1977, the entrapment zone was centered upstream of Honker Bay in the deeper ship channel. The Suisun Bay summer phytoplankton standing crop was at the lowest summer levels ever recorded (generally <10 ug/L). As a result of the low sediment discharge to the estuary, water transparencies were at record highs which should have been conducive to phytoplankton growth. During this same period, chlorophyll levels were at record highs in the Northern and Southern Delta.

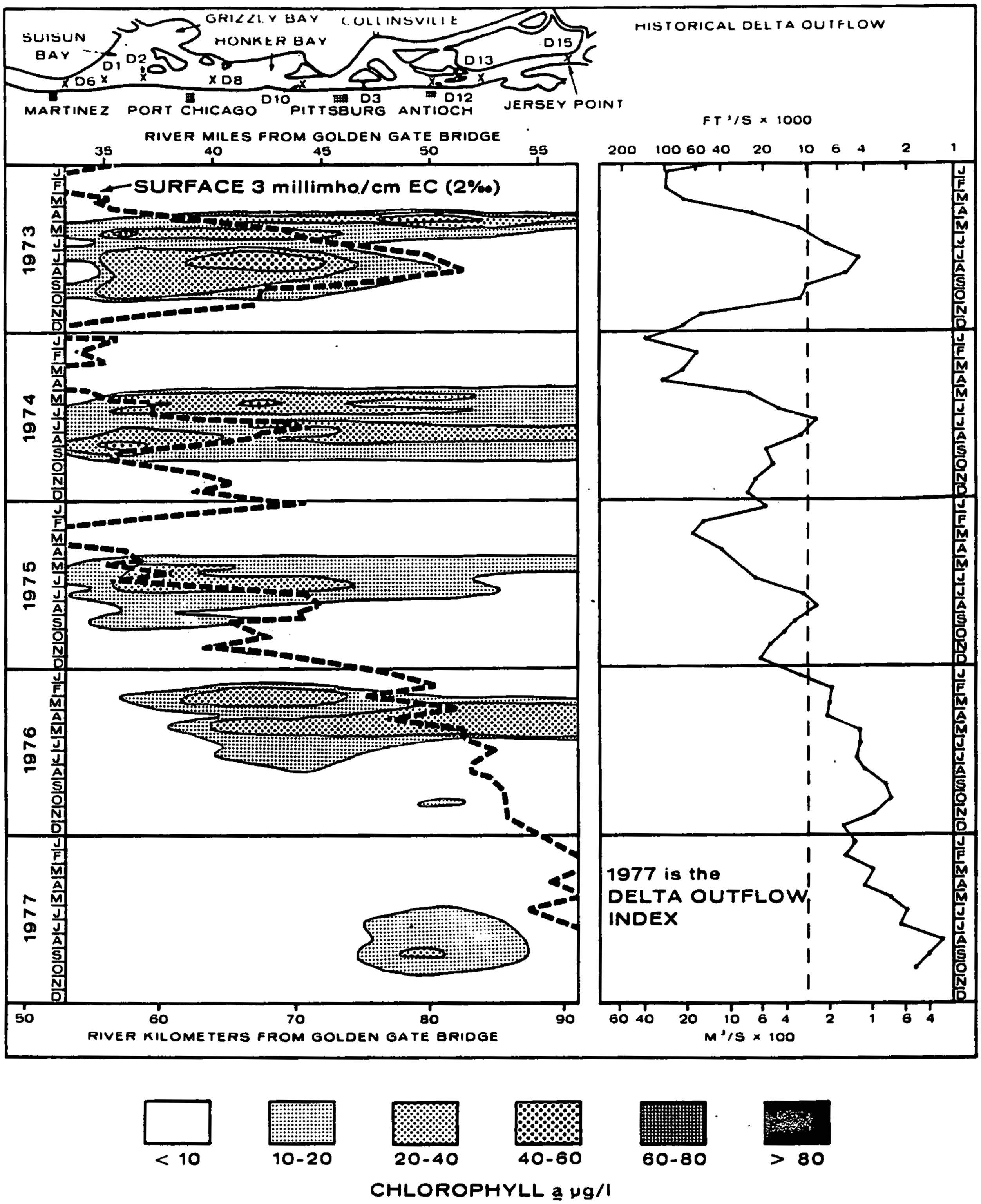


Figure 1 b. Chlorophyll a distribution on high slack tides from 1973–1977, between Jersey Point and Martinez, as related to salinity intrusion and Delta outflow. (The 3 millimho/cm EC line is an approximate location of the upstream edge of the entrapment zone at high slack tides.)

et al., 1978). Conomos (1979b) in "San Francisco Bay - the Urbanized Estuary" summarizes the current knowledge of estuarine processes in the Bay-Delta, including previous work by the Service to describe and define the significance of the entrapment zone to estuarine productivity.

Briefly, the current understanding of the entrapment process is that suspended materials (including inorganic suspended materials and certain biota) tend to concentrate in the entrapment zone due to the three interrelated factors. These include the effects of (1) net two-layered flow circulation, (2) the net upward vertical velocities in the water column throughout the mixing zone, and (3) the settling rate of particles.

Net upward two-layered flow circulation results from the density differences between fresh and salt water. As fresh water river flow enters the estuary, the fresher water tends to flow over the surface of the more dense, saltier water. Negating tidal effects, this creates a net downstream surface flow. Conversely, the denser, saltier water tends to flow in a net upstream direction under the fresher water, creating a theoretical plane-of-no-net-motion between the two layers, figure 2a. One result is a net vertical flow from the lower landward flowing layer, through the plane-of-no-net-horizontal motion into the upper seaward flowing fresher water, figures 2a and b.

The term "null zone", figure 2a, is conceptualized as that area in the lower layer where net non-tidal velocities in the seaward-flowing fresher river water and landward-flowing saltier water approaches zero. The null zone is also the theoretical area where the plane-of-no-net-motion intersects the bottom. The null zone location oscillates daily with tidal excursion and seasonally with changes in river discharge to the estuary.

Phytoplankton (as well as other suspended materials) are greatly influenced by the net flow patterns in and about the null zone. Conceptually, if phytoplankton cells are small, possess radiating extensions of their cell walls, and/or have a density close to that of the water, they tend to have relatively low settling rates. If their settling rate is less than the net upward vertical water velocity, the tendency is for the algal cells to be carried upward and concentrate in the surface water. The net flow in the surface water is downstream, and likewise the algal cells as well as other particulate material with similar settling rates will be transported downstream.

In contrast, if phytoplankton cells (such as Thalassiosira excentricus, the dominant phytoplankton observed in this study) are relatively large, compact in shape, tend to accumulate inorganic materials on their exteriors, aggregate together or with particulate materials as a result of flocculation, and/or have densities greater than water, they tend to have relatively high settling rates. Consequently, they tend to settle into the lower layer and are carried upstream. When they encounter the greatest upward vertical velocities while moving upstream they tend to move up in the water column and concentrate in the surface waters. This circular path increases the residence time of the phytoplankton over that of the water. Also, the phytoplankters that tend to be carried in the lower layer upstream beyond the maximum upward vertical velocities (be it by chance or that their settling rates are greater than the maximum upward vertical velocities) experience reduced vertical velocities and tend to remain in the lower layer. The interaction of the above phenonmenon creates the entrapment of phytoplankton as well as other suspended materials. Correspondingly, the area where greatest accumulations occur is the entrapment zone.

The level of the phytoplankton standing crop in the entrapment zone at a given time is thought to result from transport of phytoplankton to the zone from upstream and downstream as well as from growth in the intermediate vicinity.

In summary, it is theorized that the dominant phytoplankton species most commonly found to accumulate in the entrapment zone have settling rates nearly equal to the maximum vertical velocities occurring downstream of the null zone, figure 2b. If the phytoplankton become entrapped in and adjacent to shallow wind and tidally mixed bays where there is a large surface area and where the photic zone constitutes a greater percentage of the water column than in the deep channels, available light (water transparency and sunlight) is less limiting and the maximum algal standing crop can develop.

Thus far only preliminary phytoplankton settling rate studies have been conducted in the estuary. The accuracy of these measurements has not been determined, nor is it possible to directly measure vertical velocities throughout the mixing zone (see section on settling rates and vertical velocities for more discussion).

Study Rationale

The study proposal was to regulate the Delta outflow in such a manner that the tidally averaged location of the entrapment zone would be adjacent to Honker Bay for a minimum of two months during the summer of 1978. The analysis of chlorophyll data and electrical conductivity (EC) measurements from the Service's telemetering station at Pittsburg indicated the zone would be in the approximate area of Honker Bay at specific conductances (EC's) of 5-8 millimho/cm, which corresponds to a Delta outflow index of about 140-230 m^3/s (5,000-8,000 ft^3/s).

The ideal scenario was for the entrapment zone to be upstream or downstream from Suisun Bay prior to the test. Based on past observations, the predicted phytoplankton standing crop would be low under these conditions. As the entrapment zone moved adjacent to the shallows of Honker Bay, predictions were that the phytoplankton standing crop would increase and remain high as long as the zone remained in that area. Finally, the phytoplankton standing crop would decline as the entrapment zone was moved out of the "optimal" area.

It was realized from the onset that the study could not conclusively support the earlier observations nor define the mechanisms responsible for the phenomenon, since it is difficult to replicate or adequately control all factors in a field study. However, a positive phytoplankton response to flow regulation of the entrapment zone location would provide strong support for the theory.

The general approach taken in evaluating the results of optimizing the entrapment zone location for a maximum phytoplankton standing crop was to document changes in the level of the phytoplankton standing crop throughout

METHODS

The specific methods used in the collection, preservation, and analysis of water quality and biological constituents have been described in detail in earlier reports (USBR, 1975 and 1977; Arthur and Ball, 1978 and 1979a). A general summary of the procedures utilized in this study is provided in the following paragraphs.

Delta Outflow Regulation

Based on water storage in the reservoirs, the Federal (Service) and State (DWR) Water Project Operations offices were able to begin Delta outflow regulation in mid-June of 1978. The Service's Pittsburg telemetering station, figure 3a, at the confluence of the Sacramento and San Joaquin Rivers was monitored daily to determine if the specific conductances were in the 5-8 millimho/cm range requested for the study. Reservoir releases and Delta pumping were adjusted, within the variance allowed under normal operations, to try to meet the test criteria.

Study Area

Sites in the entrapment zone study area are illustrated in figure 3a. Sampling in this program was largely restricted to the channel and embayments of Suisun, Grizzly, and Honker Bays between Benicia (site 5) and Collinsville (site 14). Early in the study, several runs were also made in the main sloughs of Suisun Marsh (Montezuma and Suisun Sloughs) to determine if the Marsh contributed to or was the source of phytoplankton to the embayments. The major bays and channels in upper San Francisco Bay are illustrated in figure 3b. Areas with depths of 2 meters or less at mean low, low tides have been indicated.

Sampling

Water quality and phytoplankton samples were collected by the Service. The study plan called for sampling both the embayments and the Sacramento Ship Channel on the selected tides.

A 6 meter (19.5-foot) inboard-outboard boat was utilized in the study. The boat was equipped with a dual sample-water intake system. Water could be pumped on board while underway from an intake pipe mounted approximately 0.3 meter (1 foot) under the surface near the stern. At each site, the sample intake was switched through a three-way valve to a hose system that could be lowered vertically to the desired depth. The intake on this hose system was 1 meter (3 feet) from the end of a 2 meter (6 feet) weighted rigid section. When touching the bottom substrate, the sample was collected approximately 1 meter (3 feet) from the bottom. Samples were collected at varying depth intervals, depending on the site depth.

Water from either intake system was split, flowing both to a sample collection area and to flow-through chambers for measurements of dissolved oxygen and temperature (with a Yellow Springs instrument meter), and through a Turner Designs fluorometer, modified for measurements of *in vivo* chlorophyll fluorescense. Fluoresence was recorded on a Rustract analog strip-chart recorder.

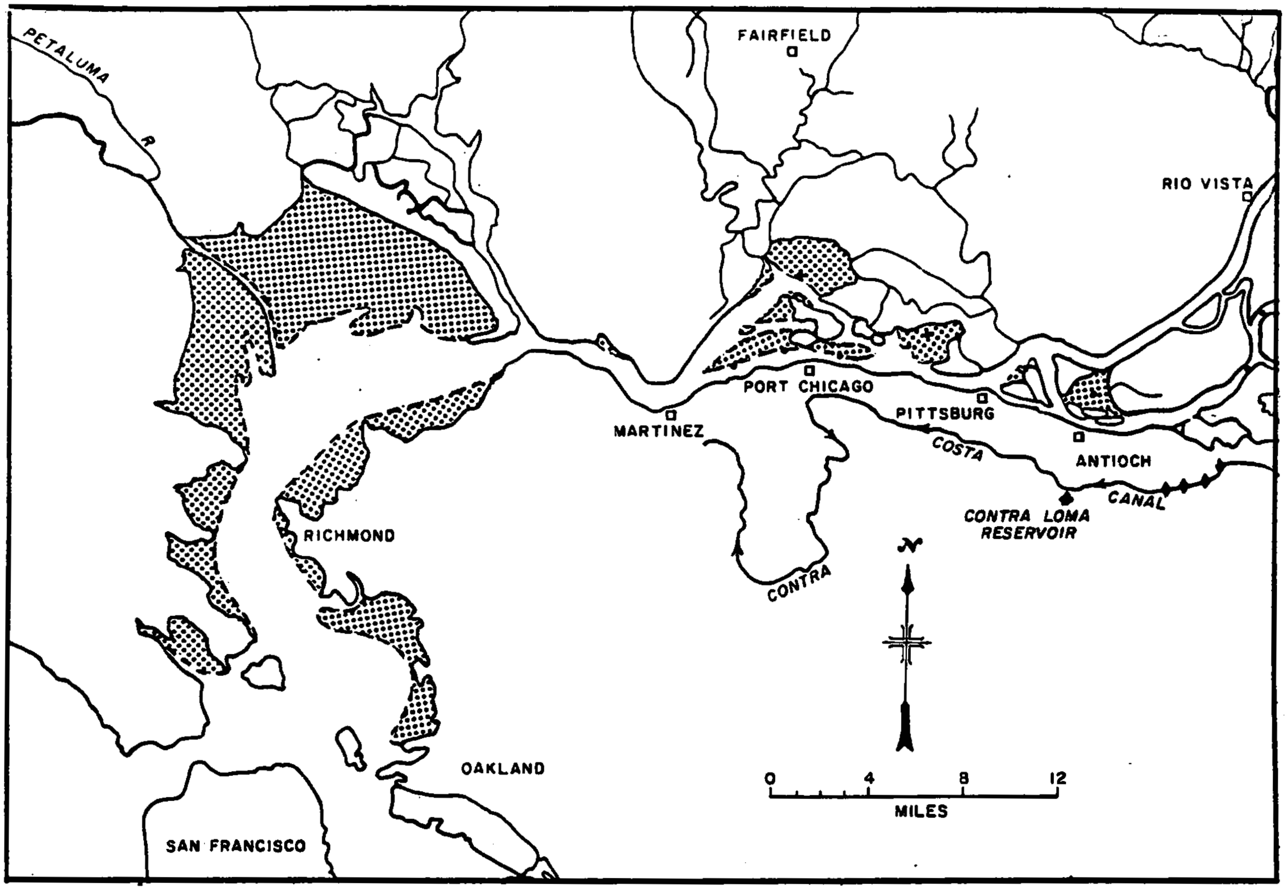


Figure 3b Upper San Francisco Bay Estuary illustrating the major bays and channels (shaded area with a mean low, low water depth of 2 meters or less).

Table 1. Schedule of Runs, 1978

Run	Date	Tide*	Station sequence
33	July 12	L.Ebb-L.L.Sl.	40-31
34	July 12	L.L. Sl.	5-14
35	July 13	L.H. Sl.	4-18
36	July 25	L.H. Sl.	4-16
37	July 27	L.H. Sl.	39-31
38	Aug. 2	L. Fl.	40-31
39	Aug. 2	L.H. Sl.	5-18
40	Aug. 9	L.L. Sl.	35-37, 34-31, 38-40
41	Aug. 10	L.H. Sl.	38-36, 8-12
42	Aug. 17	L.H. Sl.	35-31
43	Aug. 17	L.H. Sl.	5-8, 37, 38, 9-11, 39, 40, 12-16
44	Aug. 23	L.H. Sl.	4-18
45	Aug. 23	G. Fl.	25, 23, 21, 11, 9, 7, 5
46	Aug. 23	H.L. Sl.	40-31
47	Aug. 24	G. Fl. - L.H. Sl.	40-31, 5-12
48	Aug. 24	L. Ebb	40-31
49	Aug. 24	H.L.Sl.	5-12
50	Aug. 30	G. Fl. - L.H. Sl.	40-31, 5-16
51	Aug. 30	L.L. Sl.	40-31, 5-12
52	Sept. 7	G. Fl. - L.H. Sl.	12, 10, 8, 6, 5-16
53	Sept. 7	H.L. Sl.	31-40
54	Sept. 7	L.L. Sl.	6, 8, 10, 12
55	Sept. 13	L.H. Sl.	40-31, 5-18
56	Sept. 20	L.H. Sl.	4-15
57	Sept. 20	H.L. Sl.	3-12
58	Sept. 20	L. Ebb-H.L. Sl.	40-31, 5, 4
59	Oct. 10	L.H. Sl.	3-13
60	Oct. 10	L. Ebb	40-31
61	Oct. 11	L.L.Sl.	4, 5, 31-37

*Tide Abbreviations	Tide stage
H.H. Sl.	higher high water slack
G. Ebb	greater ebb
L.L. Sl.	lower low water slack
G. Fl.	greater flood
L.H. Sl.	lower high slack
L. Ebb	lower ebb
H.L. Sl.	higher low water slack
L. Fl.	lesser flood

Data Processing and Evaluation

Data collected in the study were stored in the Environmental Protection Agency (EPA) water quality storage and retrieval system, STORET. In this system, parameters are stored by station, depth, and time. In order to facilitate the evaluation, the Statistical Analysis System (SAS), a software package available through EPA, was used to reformat the STORET data by river miles and run number. These data were transferred to the Michigan Terminal System (MTS) where they were utilized in the Adroit statistical and plotting program developed by Unidata (Ann Arbor, Michigan).

Many of the illustrations and analyses presented in this report were prepared utilizing a Tektronix terminal, model 4051, connected to MTS and Adroit.

Since September 1973 there have been a total of 64 entrapment zone runs. The data collected in the present study were stored as runs 33-61. Run numbers are occasionally referred to throughout this report.

In the current study, surface specific conductance and chlorophyll data collected by the DFG during 1978 were also evaluated. The data provided had not been completely processed by DFG nor stored in STORET; consequently, this necessitated transferring the data base directly to MTS and plotting the data via the Adroit display system.

RESULTS AND DISCUSSION

The present study - regulating the entrapment zone to its hypothetical optimal location for maximizing the phytoplankton standing crop - is unique. Few, if any, large-scale studies have ever been conducted in an estuary for the express purpose of manipulating biological production through outflow regulation. This chapter discusses the findings of the controlled flow study.

Delta Outflow

The two water years, 1975-76 and 1976-77, preceding the current study, were classified as the driest two consecutive years on record. The drought of 1976-77 was the most severe since the 1930's; storage in many of the Project reservoirs dropped to record-low levels, and the Delta outflow index was extremely low.

The Delta outflow index is a daily calculation consisting of the Sacramento River discharge at Sacramento plus the San Joaquin River discharge at Vernalis, less the pumped Delta export and the estimated Delta consumptive use. The consumptive use coefficient estimate varies seasonally but is constant between years. The coefficient varies from 130 m^3/s (4,600 ft^3/s) in August to minus 30 m^3/s (1,000 ft^3/s) in January. The same table is used from year to year: however, crop usage patterns and weather patterns do change. As a result, the calculated outflow could be off an estimated plus or minus 0-60 m^3/s (0-2,000 ft^3/s). The index does not account for discharges from the Delta peripheral streams or the Yolo Bypass. Flows from these sources can be appreciable following major storms. Subsequently, caution should be used in data interpretation.

Another outflow measurement, the monthly historical Delta outflow, includes the measurements of all significant discharges (calculated only once per month) but still uses the estimated consumptive value. The historical Delta outflow was calculated to evaluate discharges from the Delta and was used in some of the evaluations. Since the Delta outflow index is the number most readily available, it has been used in this report to indicate Delta outflow unless otherwise stated. Although the Delta outflow index is the best daily number readily available, it is only an approximation of the actual Delta outflow at any given time.

The Delta outflow index for the period April 1976 through early January 1978 was usually less than 280 m^3/s (10,000 ft^3/s). During most of 1977, the period preceding the study, the outflow index was below 140 m^3/s (5,000 ft^3/s). Fortunately, the winter and spring of 1978 turned out to be extremely wet. The Project reservoirs filled in three months and the winter and spring Delta outflows were high.

The Delta outflow index, figure 4, ranged from 230-2,500 m^3/s (8,000 to 90,000 ft^3/s) from early January to mid-June 1978. By mid-June, the outflow was reduced to the requested range for the study. By July, the Delta Outflow Index was about 140 m^3/s (5,000 ft^3/s), the minimum flow required to meet the 5-8 millimho/cm specific conductance (also referred to as EC or salinity in this report) criterion requested for the study. Based upon past evaluations of the entrapment zone location as related to specific conductance measurements at

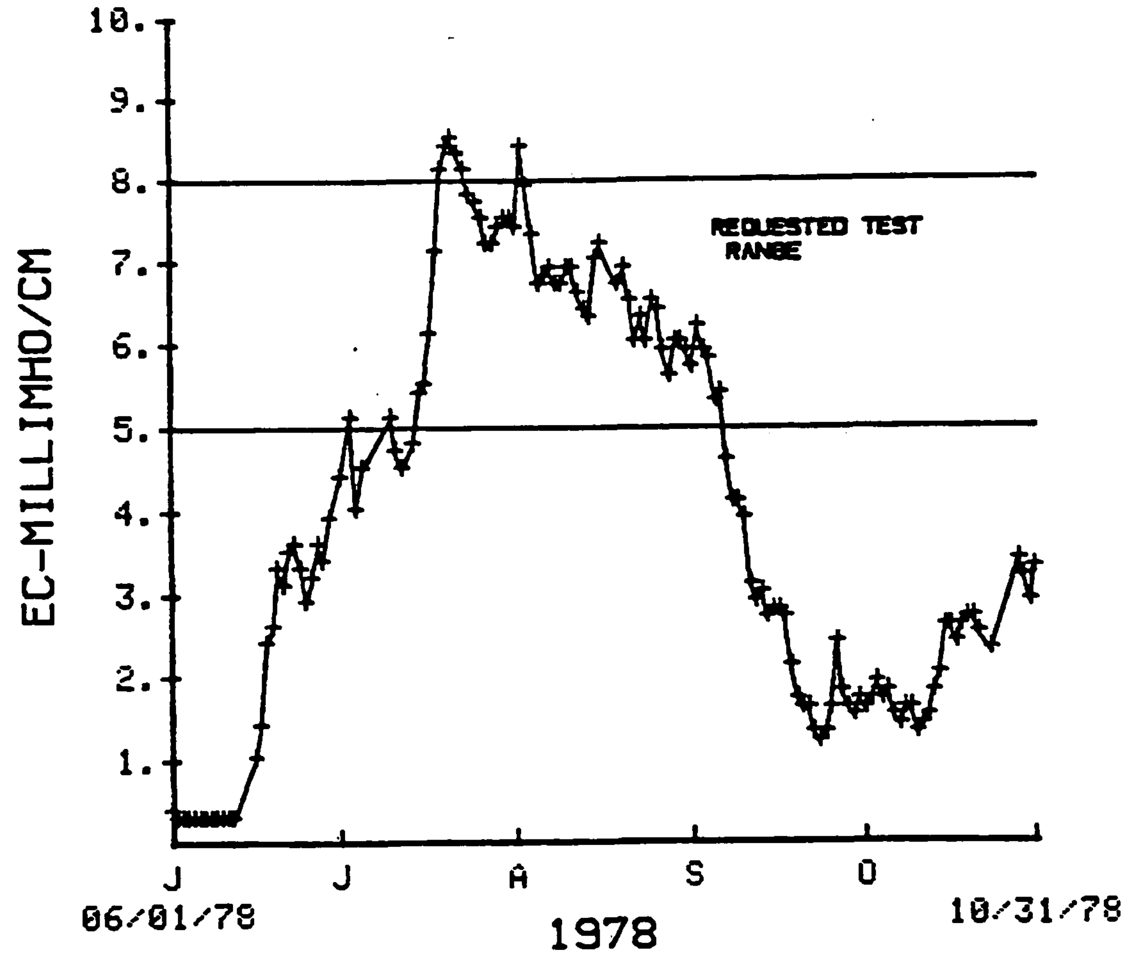


Figure 5. Mean daily specific conductances measured at the Service's telemetering station at Pittsburg, June–November, 1978. (Measurements taken 1 meter from the bottom.)

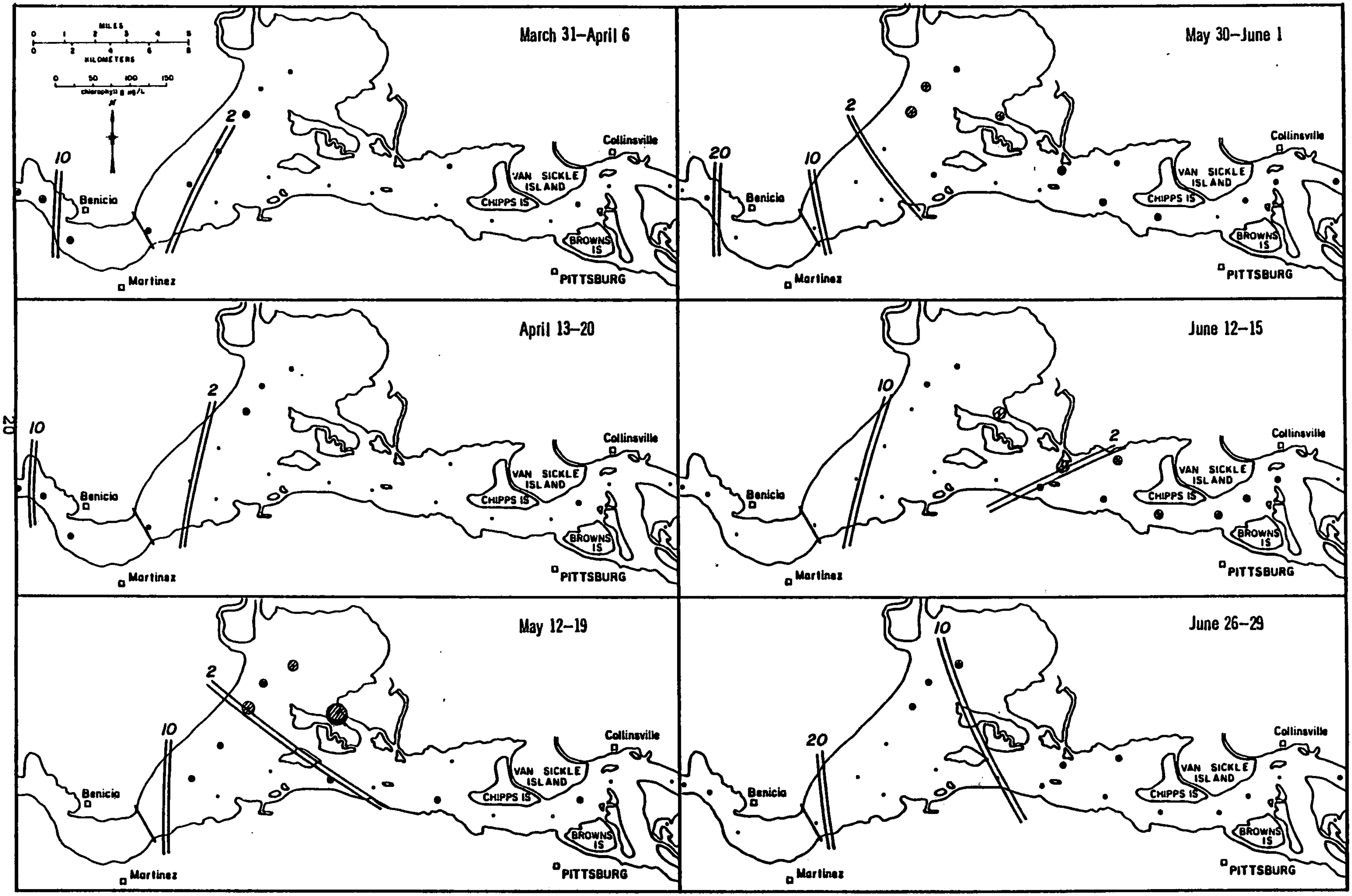


Figure 6 a. Surface chlorophyll a measurements on high slack tide, April through June, 1978 (DFG data). Approximate location of the 2, 10, and 20 millimho/cm surface iso-conductivity contours are indicated.

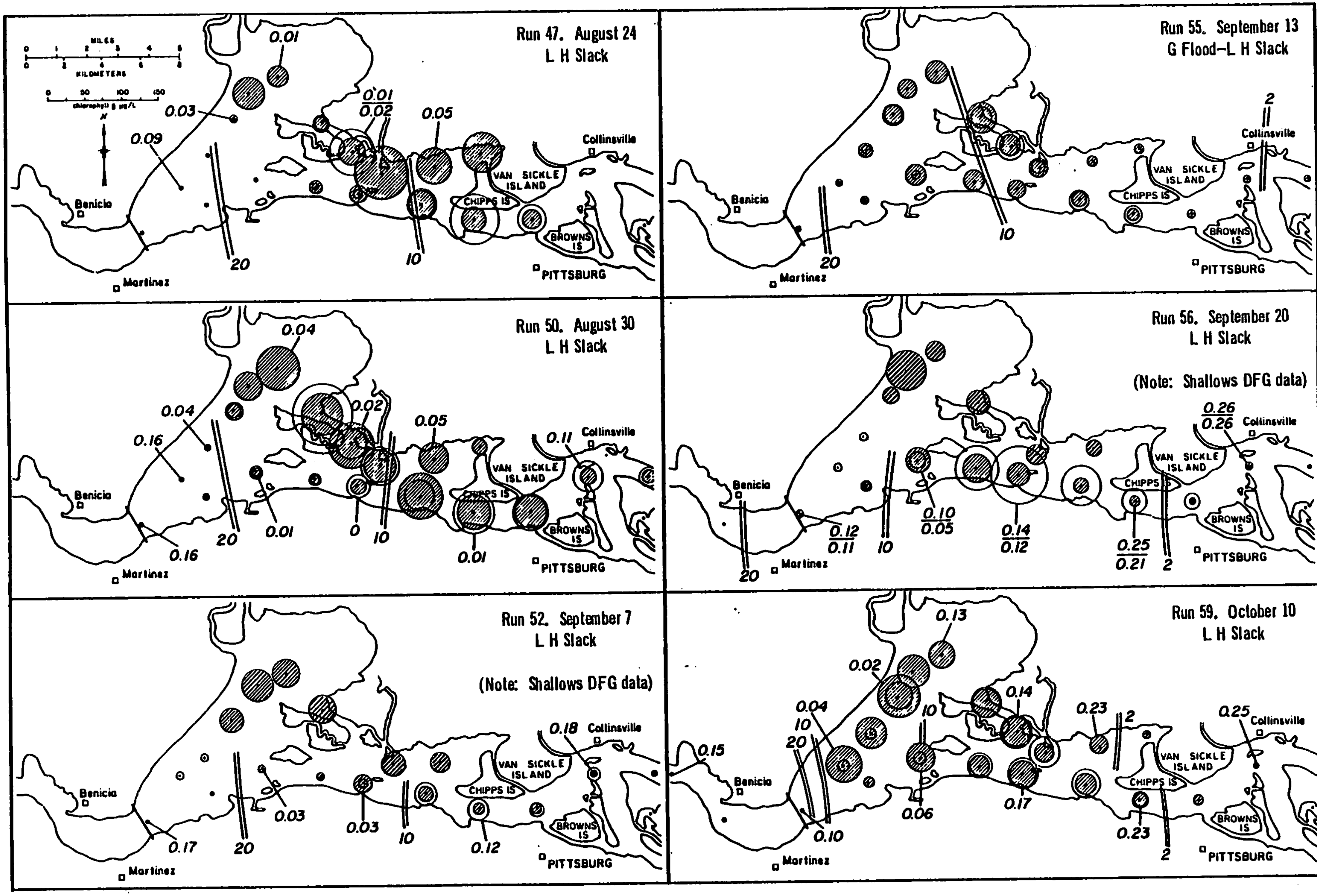


Figure 6c. Surface (hashed) and bottom (open) chlorophyll a levels measured on high slack tide. Approximate location of the 2, 10, and 20 millimho/cm surface iso-conductivity contours are indicated. Values represent inorganic nitrogen levels $\frac{\text{(SURFACE)}}{\text{BOTTOM}}$ (mg/L).

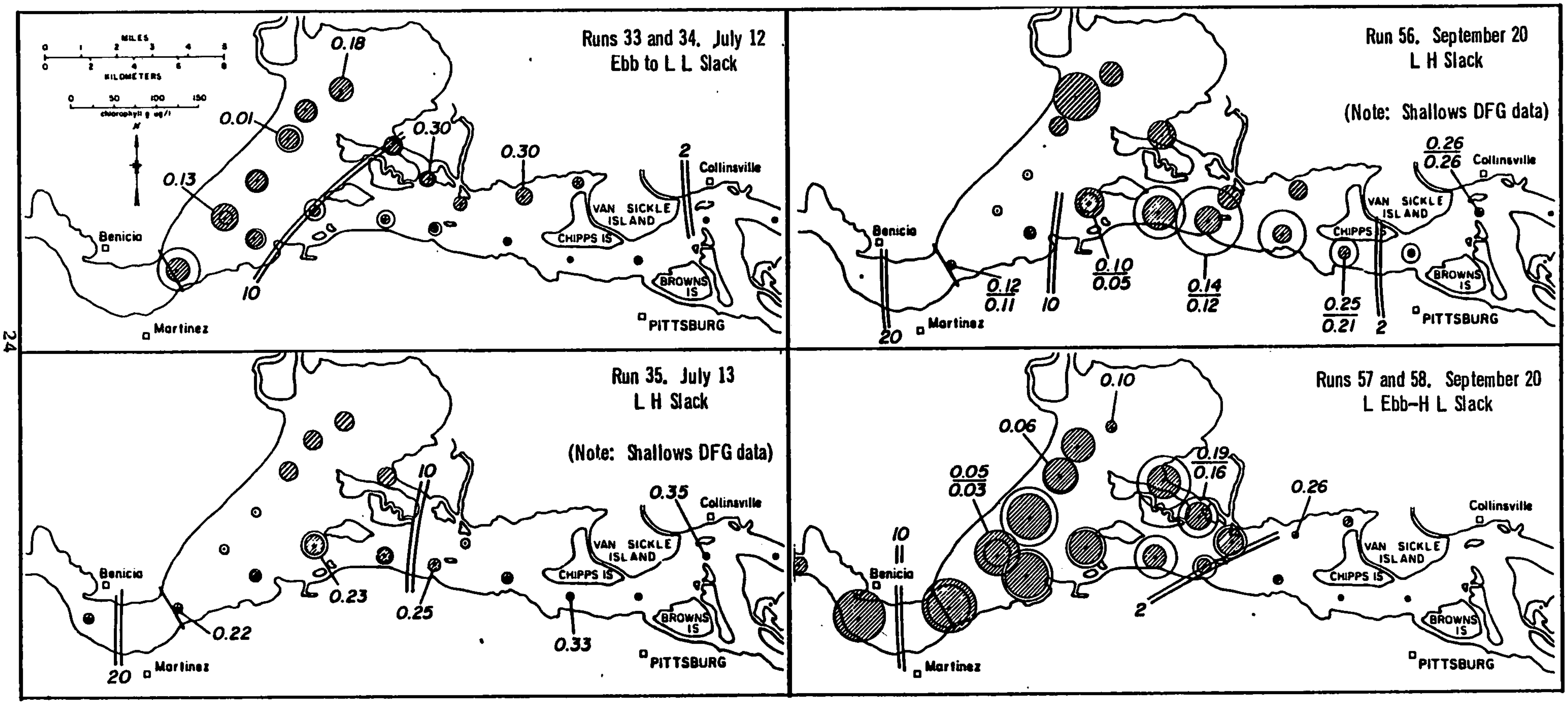


Figure 6 e. Surface (hashed) and bottom (open) chlorophyll levels illustrating the effects of tidal excursion on chlorophyll distribution (Service and DFG where indicated). Approximate location of the 2, 10, and 20 millimho/cm surface iso-conductivity contours is indicated. Values represent inorganic nitrogen levels $\frac{(\text{SURFACE})}{\text{BOTTOM}}$ (mg/L).

Measurements during the first three weeks of September, figure 6c, indicated a decrease in concentration throughout the study area, although chlorophyll levels by September 20 were again peaking in the high 60 ug/L range.

In October-December, figure 6d, chlorophyll levels generally decreased. The peak surface value, 58 ug/L, occurred at site 33 on October 10. Surface chlorophyll measurments by DFG in November and December indicated chlorophyll a levels were very low during this period.

It was concluded in previous evaluations (Arthur and Ball, 1978; 1979a; and 1979b) that the location of the entrapment zone was centered approximately where surface specific conductances were from 2-10 millimho/cm. Also the zone's location was thought to shift, relative to surface salinity, in response to the quantity and pattern of Delta outflow.

In early April the 2 millimho/cm contour was near the upstream end of Carquinez Strait, figure 6a. As Delta outflows declined in May and June, figure 4, the 2 to 20 millimho/cm contours shifted upstream into Suisun Bay. Chlorophyll levels started to increase, figure 6b, a few weeks after the Delta outflows were reduced to the 140-230 m^3/s (5,000-8,000 ft^3/s) range requested for the study and the highest chlorophyll levels were observed in the shallows of Grizzly Bay, downstream from the surface 10 millimho/cm iso-contour.

Flows were held near 140 m^3/s (5,000 ft^3/s) for most of July and August. The salinity continued to intrude until near the end of July, figure 5, and the 10 millimho/cm iso-contour shifted upstream to near Chipps Island. There was a corresponding upstream shift in the peak chlorophyll areas, as well as a substantial increase in chlorophyll levels. By August 10, peak chlorophylls occurred in waters with surface specific conductances of approximately 10 millimho/cm. In mid-August the surface peak chlorophyll area was either upstream or near the 10 millimho/cm iso-contour on high slack tides. The peak chlorophyll a levels on the bottom, on high slack tide, were generally upstream in waters with bottom specific conductances of about 10 millimho/cm. By late August, figure 6c, the surface chlorophyll peaks were generally downstream of the 10 millimho/cm iso-contour as Delta outflows started to increase.

Delta outflows increased to above 230 m^3/s (8,000 ft^3/s) during September, figure 4. There was a corresponding downstream shift in both the 10 millimho/cm iso-contour and in the areas of peak chlorophyll, figures 6c and d. Generally, the peak chlorophyll area was near or downstream of the 10 millimho/cm iso-contour.

There was a decrease in Delta outflow in October to the 140-230 m^3/s (5,000-8,000 ft^3/s) range. The 10 millimho/cm iso-contour again shifted upstream, figure 6d.

Typical responses of the entrapment zone location to tidal excursions are illustrated in figure 6e. Changes in chlorophyll distributions are illustrated for low and high slack tides near the start, July 12 and 13, and near the end, The peak concentration observed, 440 cells/mL, although relatively low, was five and one-half times greater than the next most abundant organism, Melosira nummuloides, at 80 cells/mL. By July 27, run 37 - the T. excentricus concentration had increased to 3,600 cells/mL. The next most abundant organism at that time, Coscinodiscus lacustris, concentration was 300 cells/mL.

T. excentricus concentrations greatly increased during August. The peak concentration, 9,000 cells/mL, was measured on August 17, 1978. Generally, the concentrations of all other organisms measured during the entire study were under 300 cells/mL.

A typical example of the relationship between chlorophyll a distribution and the dominant phytoplankters is illustrated in figure 7. These measurements are from samples collected in the main ship channel, sites 4-18, on high slack tide on August 23, 1978. Chlorophyll a levels were near the high for the study period, about 80 ug/L. Bottom chlorophyll a concentrations were higher and occurred upstream of the surface chlorophyll peak. The three dominant organisms enumerated during this run were T. excentricus, M. nummuloides, and Skeletonema costatum. Although the next most dominant organisms varied throughout the study, T. excentricus always dominated. In this typical example, the chlorophyll a and T. excentricus peak occurred adjacent to Honker Bay. T. excentricus levels were at 8,500 cells/mL, while the next most abundant organisms were both under 1,000 cells/mL. The surface peaks of these two organisms were downstream of the T. excentricus surface peak, whereas the bottom peaks were nearer the bottom peaks of T. excentricus.

In September and October there was a decline in both the chlorophyll a (to about 60 ug/L) and T. excentricus (to about 5,000 cells/mL) levels.

Since T. excentricus was the most frequently occurring organism and by far the most numerous throughout the study area, its concentration was plotted against the chlorophyll a concentration measured in the study, figure 8. As illustrated there was substantial scatter. However, the correlation coefficient indicated the relationship was significant. At the 99 percent level an r value of at least .25 (statistical table) is needed to be significant. The correlation coefficients for the data were r=.72 (surface) and r=.76 (bottom).

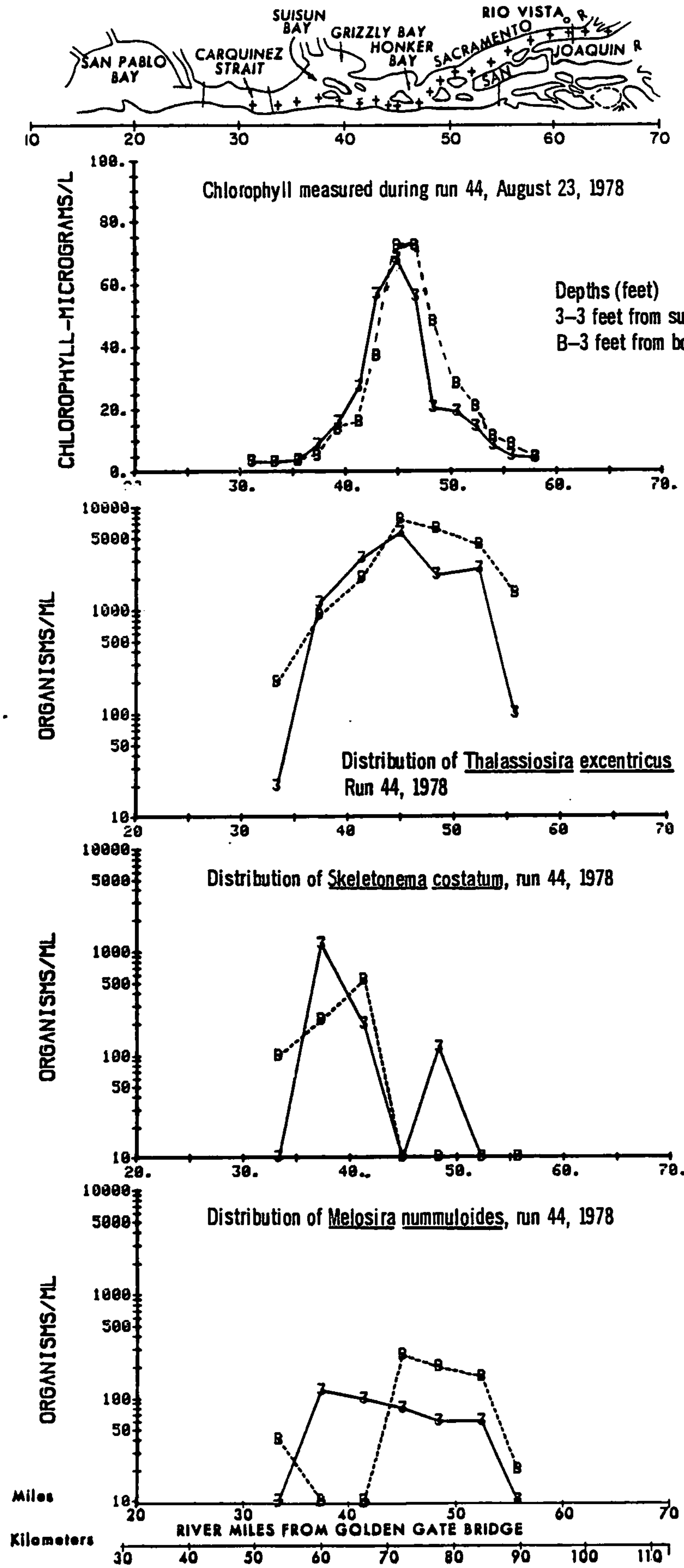


Figure 7. Surface and bottom chlorophyll $\underline{a}$ and dominant phytoplankter distributions on August 23, 1978, in ship channel of Suisun Bay.

Chlorophyll a measurements are used to indicate the total concentration of the phytoplankton community, while counts and identifications are used to indicate dominant organisms and species composition in the community. The scatter illustrated in figure 8 probably is the result of several factors. First of all, the samples were collected over a large area, in and outside the entrapment zone. Although the numbers of other organisms were generally small, they do contribute to total chlorophyll concentrations. It is also difficult to distinguish between living and dead diatom frustules, although our consultant attempted to do this. The quality of chlorophyll present in a cell also varies, depending upon the physiological condition of the phytoplankter. According to Jim Cloern of the USGS (personal communications) there is some evidence that the concentration of chlorophyll per algal cell varies with location, particularly between phytoplankton in the channels and shallows (suggesting physiological changes due to differences in available light). Finally, cell count precision is not thought to be as good as the precision of the chlorophyll measurements.

CHLOROPHYLL-PHEO-PIGMENT RELATIONSHIPS

Pheophytin a, a breakdown product of chlorophyll a, is generally thought to be caused by stress to the organisms (such as by light inhibition or nutrient depletion). Pheophytin a can also be formed by acid decomposition of chlorophyll in the digestive tract of zooplankton or higher animal forms. The term "percent chlorophyll a" (of the total chlorophyll a plus pheophytin a) is commonly used in defining the general health of the algal community since it indicates the percentage of degradation products present, detrital material and/or zooplankton grazing (Yentsch, 1965a and b).

There is always some quantity of pheophytin present in phytoplankton samples. Based on our data and studies from the literature, with a healthy and growing phytoplankton population in the estuary, the samples generally have 70-90 percent chlorophyll a (10-30 percent pheophytin) levels. Levels lower than 70 percent chlorophyll a probably indicate increasing degrees of stress on the phytoplankton community (such as light limitation or zooplankton grazing).

Previous trends indicate that the percent chlorophyll a decreases (1) downstream of the entrapment zone, (2) with depth (to a greater extent downstream of the zone), (3) during maximum tidal velocity (greater resuspension of settled materials), and (4) with lower phytoplankton populations (Arthur and Ball, 1978).

The typical distribution of percent chlorophyll a measured in this study is illustrated in figures 9(a, b). The 70 percent chlorophyll a level has been indicated as a reference point. The plots represent data measured in the channel at the start, midway through, and near the end of the study. Near the start of the study, figure 9a, run 35, the peak percent chlorophyll a in the entrapment zone was in approximately the same location as the peak chlorophyll, figure 6b. As the entrapment zone moved upstream into Honker Bay, the peak percent chlorophyll also was measured in Honker Bay, figure 9b. Later in the study, as the entrapment zone moved downstream, the peak percent chlorophyll also moved downstream. In most cases, the percent chlorophyll decreased upstream and downstream of the entrapment zone and with depth.

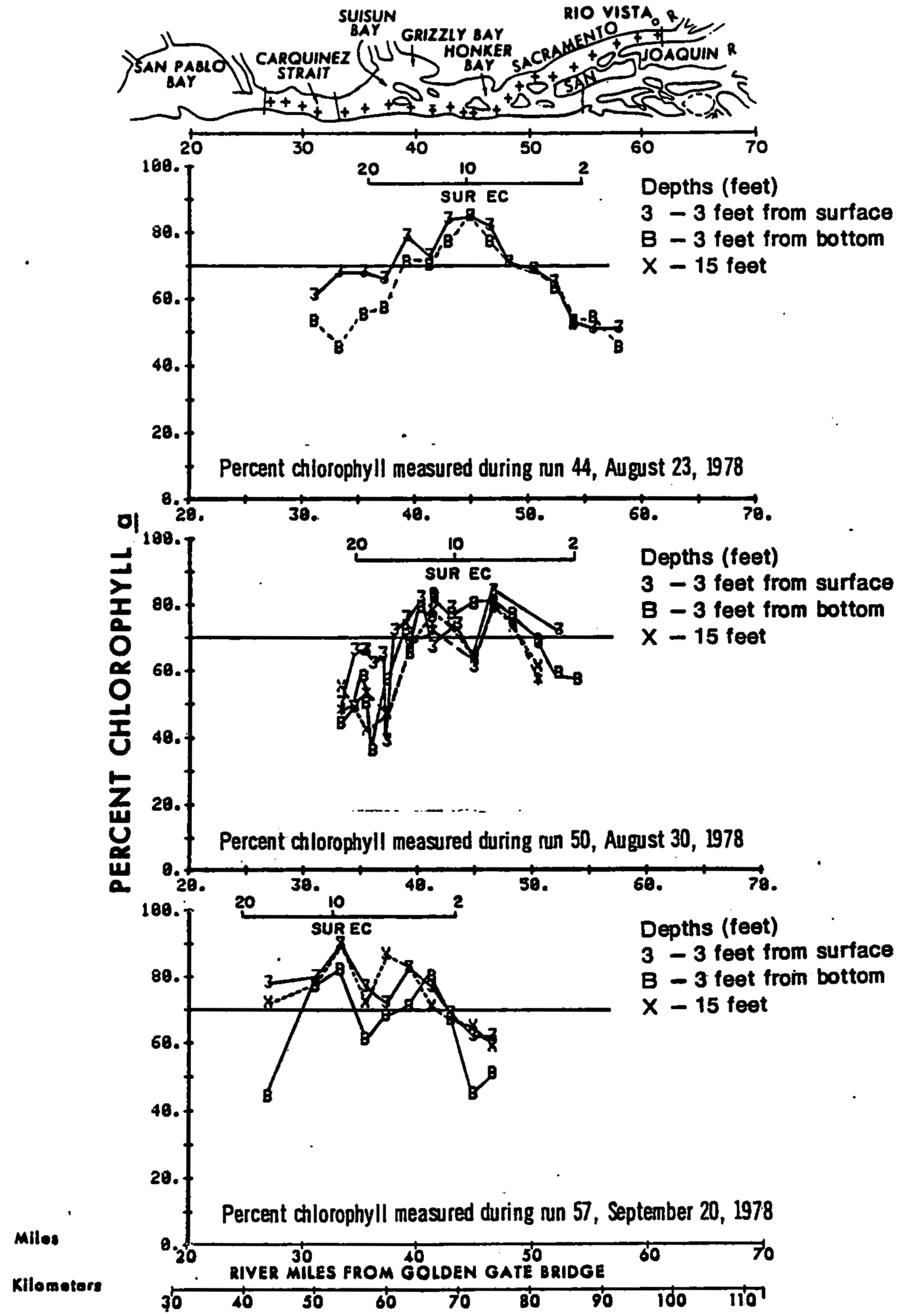


Figure 9 b. Typical distribution of percent chlorophyll a at the channel sites near the middle of the study, August 23 (run 44), August 30 (run 50), and near the end of the study, September 20, 1978 (run 57), illustrating the relative physiological condition of the phytoplankton community. The 70 percent chlorophyll a line is a point of reference. Surface EC's of 2, 10, and 20 millimho/cm are also indicated as reference points for salinity intrusion.

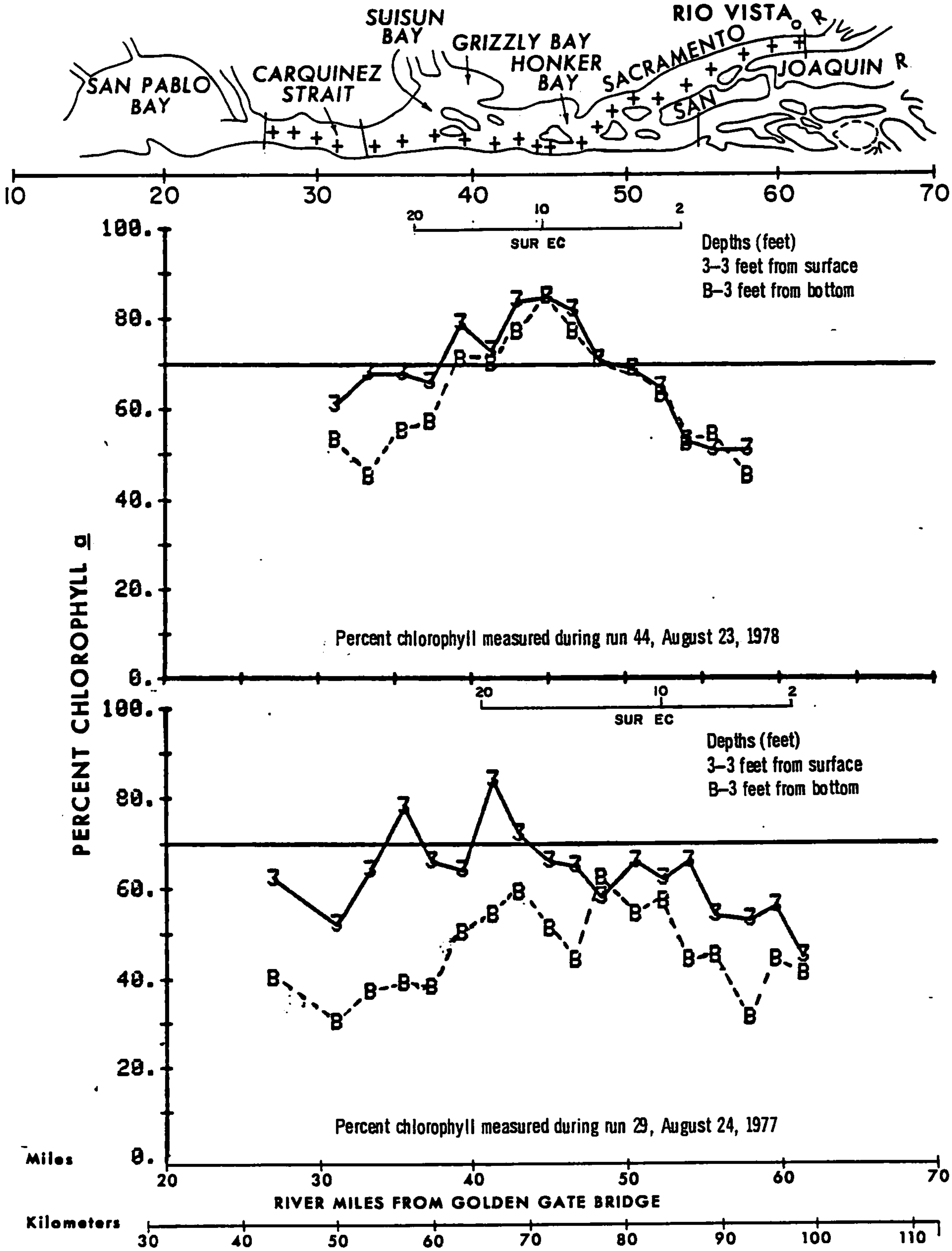


Figure 10. Comparison of the percent chlorophyll a distribution in years of low (1977) and relatively high (1978) phytoplankton standing crops. The 70 percent line is a point of reference. Surface EC's of 2, 10, and 20 millimho/cm are also indicated as reference points of salinity intrusion.

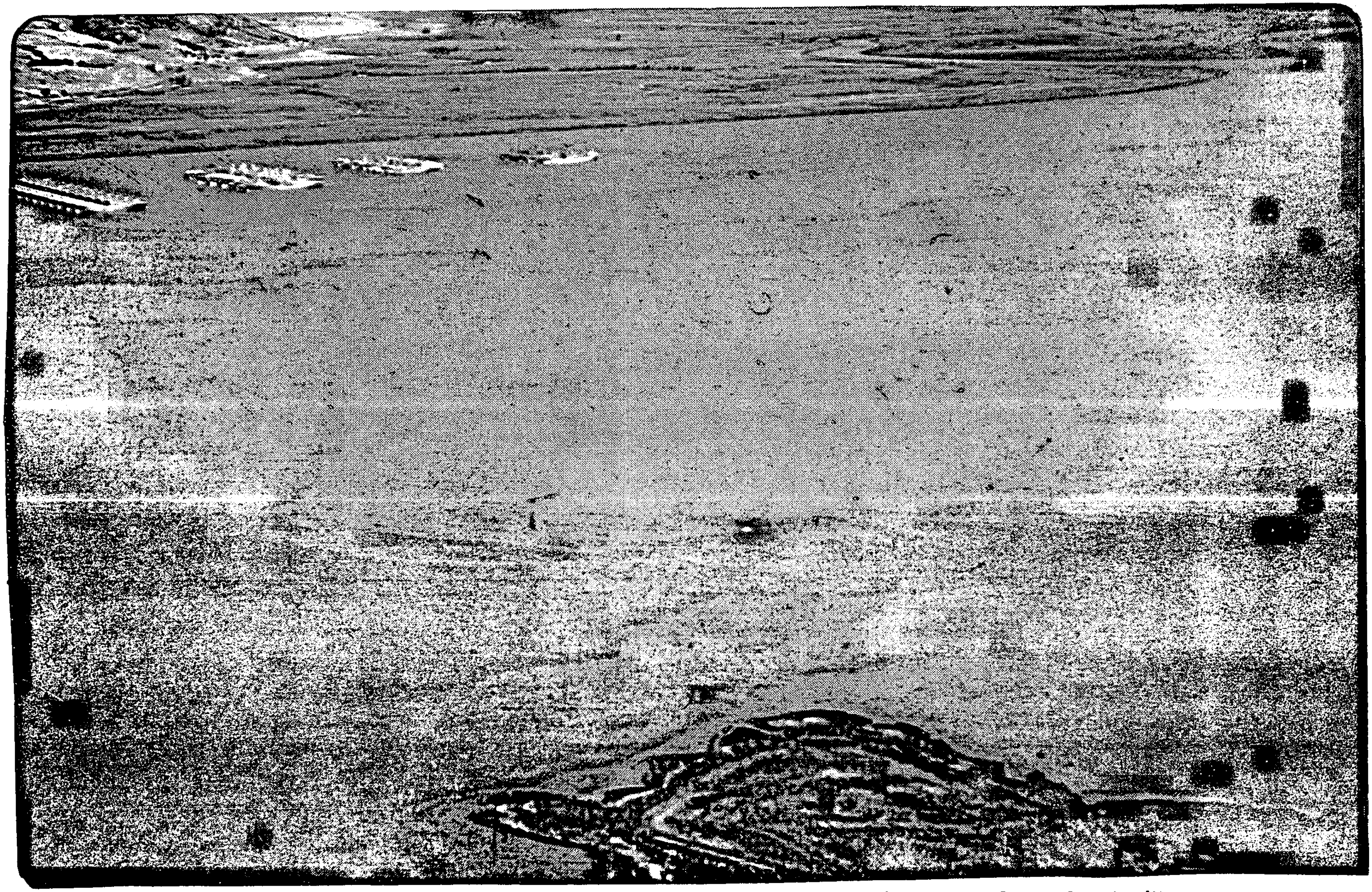


Figure 11a. Aerial photograph, July 14, 1978, of Suisun Bay east of Benicia, looking north at Suisun Slough. Illustrates typical patchiness observed throughout the study area.

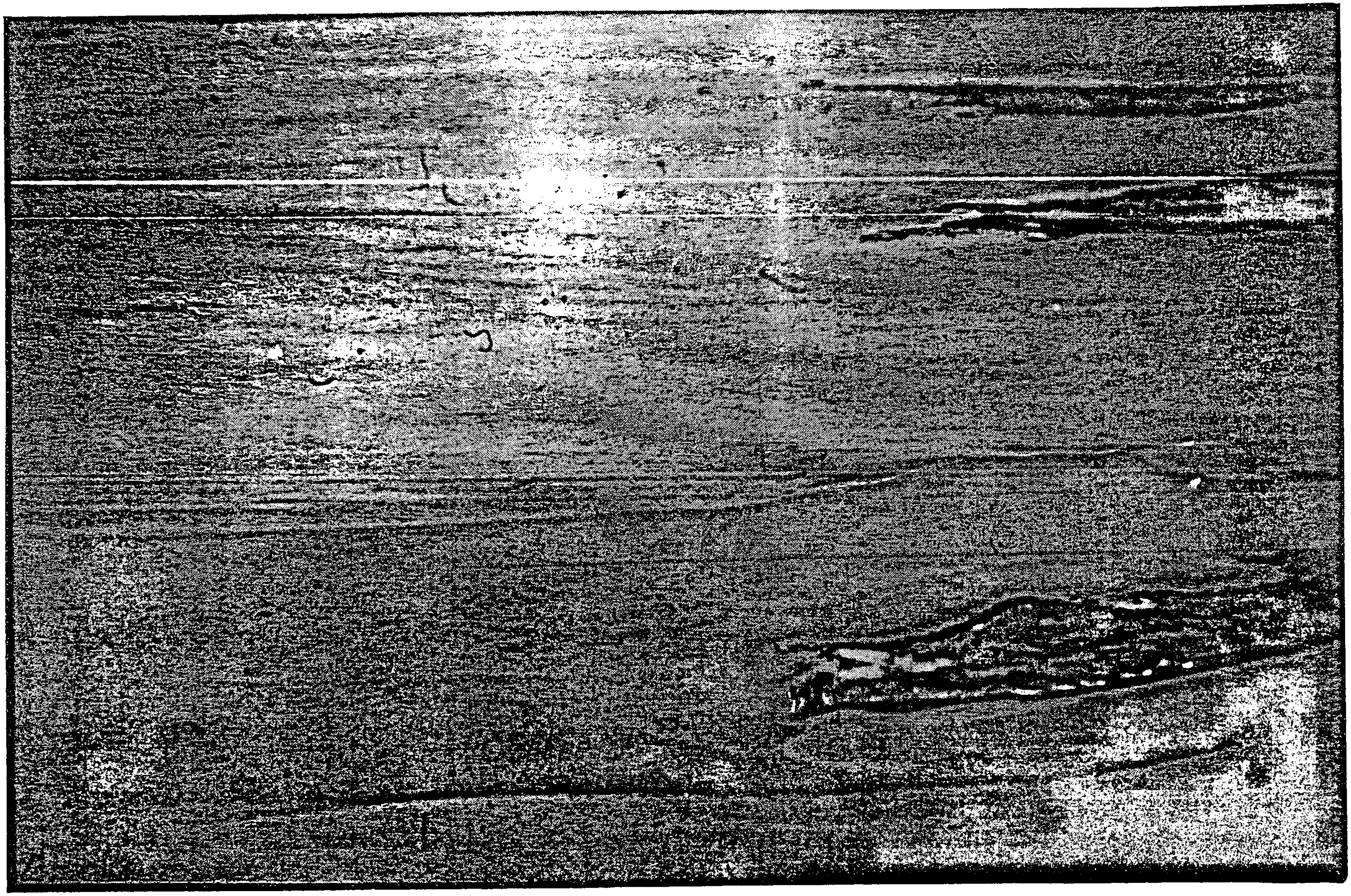
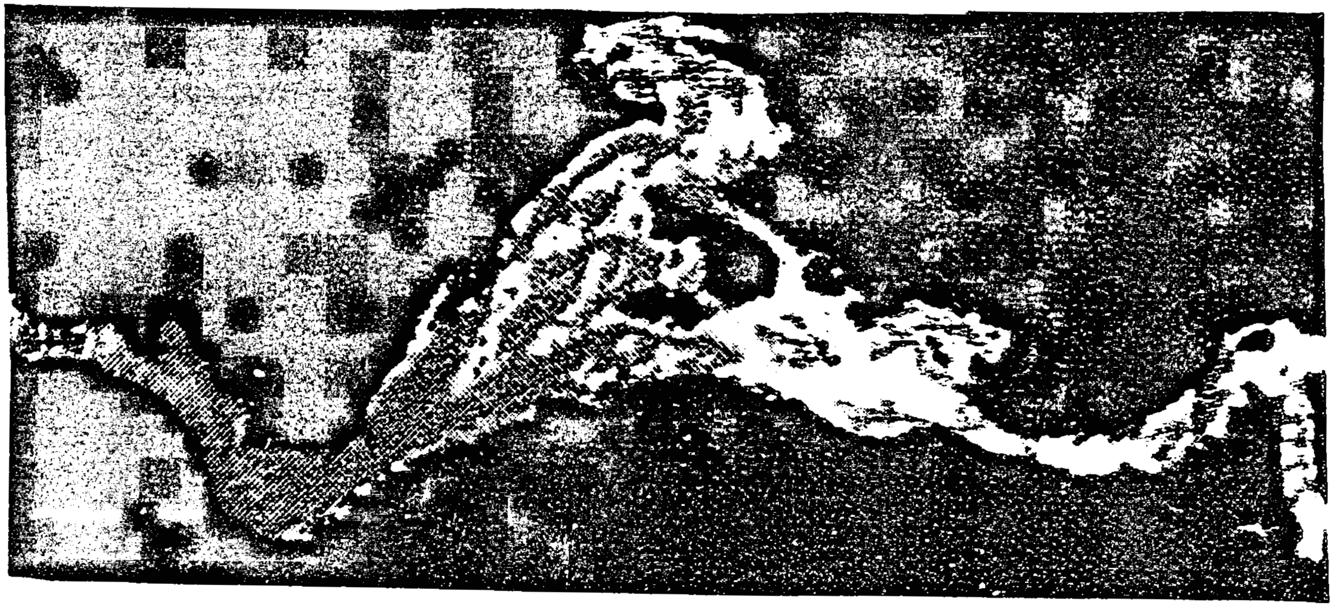
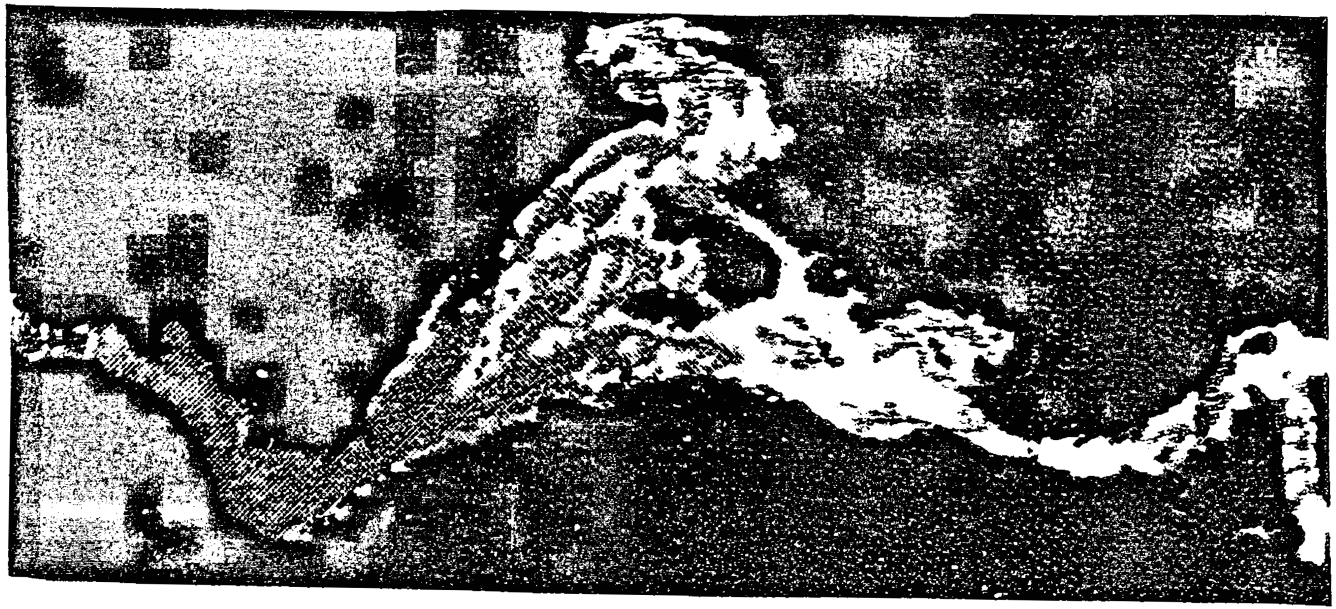


Figure 11 b. Aerial photograph, July 14, 1978, of Suisun Bay near Port Chicago, looking north at Seal, Roe, and Ryer Islands. Illustrates typical patchiness observed throughout the study area.



Color	Chlorophyll, mg/L
Black	.000
Dark Blue	.001 – .004
Blue	.005 – .009
Light Blue	.010 – .014
Green	.015 – .019
Yellow	.020 – .024
Yellow-Orange	.025 – .029
Orange	.030 – .034
Light Red	.035 – .039
Red	.040 – .044
Brown-Red	.045 – .084

Figure 11c. Chlorophyll a distribution in the study area on September 14, 1978 at 10:48 am (daylight savings time) as derived from a U-2 color infrared photograph. From: Khorram, Siamak, 1979. *Remote sensing analysis of water quality in the San Francisco Bay–Delta.* Proceedings of the Thirteenth International Symposium on Remote Sensing of the Environment, April 23–27, 1979, Ann Arbor, Michigan, pp. 1591–1601.



Color	Chlorophyll, mg/L
Black	.000
Dark Blue	.001 – .004
Blue	.005 – .009
Light Blue	.010 – .014
Green	.015 – .019
Yellow	.020 – .024
Yellow-Orange	.025 – .029
Orange	.030 – .034
Light Red	.035 – .039
Red	.040 – .044
Brown-Red	.045 – .084

Figure 11c. Chlorophyll a distribution in the study area on September 14, 1978 at 10:48 am (daylight savings time) as derived from a U-2 color infrared photograph. From: Khorram, Siamak, 1979. *Remote sensing analysis of water quality in the San Francisco Bay–Delta.* Proceedings of the Thirteenth International Symposium on Remote Sensing of the Environment, April 23–27, 1979, Ann Arbor, Michigan, pp. 1591–1601.

Color	Chlorophyll, mg/L
Black	.000
Dark Blue	.001 – .004
Blue	.005 – .009
Light Blue	.010 – .014
Green	.015 – .019
Yellow	.020 – .024
Yellow-Orange	.025 – .029
Orange	.030 – .034
Light Red	.035 – .039
Red	.040 – .044
Brown-Red	.045 – .084

Figure 11c. Chlorophyll a distribution in the study area on September 14, 1978 at 10:48 am (daylight savings time) as derived from a U-2 color infrared photograph. From: Khorram, Siamak, 1979. *Remote sensing analysis of water quality in the San Francisco Bay–Delta.* Proceedings of the Thirteenth International Symposium on Remote Sensing of the Environment, April 23–27, 1979, Ann Arbor, Michigan, pp. 1591–1601.

vs. in vivo fluorescence measurements of surface (r=.92) and bottom (r=.91) water samples collected in the study, are illustrated in figure 12. The correlations indicate the relationship between chlorophyll and in vivo fluoresence is highly significant. At the 99 percent level the relationship would be significant at r=.19 (statistical table). The standard deviation for surface samples was 6.7 and for the bottom samples was 7.2.

The continuous in vivo fluorometry measurements proved to be a valuable tool during the study and provided insight into the degree of variability throughout the area. It was found that (1) a grab sample does not always adequately represent the chlorophyll concentration in an area; (2) areas of high chlorophyll were fairly well defined, although there were variations within the high chlorophyll mass; (3) there are often plumes of high chlorophyll water extending like fingers from the area of high chlorophyll concentration as the tide changes; (4) during windy periods and/or at higher tidal velocities, the chlorophyll concentrations at a site in the shallows were usually fairly uniform top and bottom; however, on calm days, by the end of the slack periods, settling had been so great that at times the 0-.7m (0-2 foot) depth fluorescence readings were only 20 percent of the reading at the 1.0m (3 foot) depth; (5) the surface in vivo measurement for each run was generally higher between stations than at a station. This infers that the grab-sampling data presented in this report does not necessarily reflect the maximum concentrations for the area, but still provide a reasonable estimate of general trends, and that peak Suisun Bay chlorophyll concentrations most likely were missed in past monitoring programs.

A second approach to evaluating variability throughout the study area was to compare independent chlorophyll data collected by the Service, DWR, and DFG for the summer of 1978. Typical examples of surface and bottom chlorophyll grab sample data collected during the study period on high slack tide are illustrated in figures 13(a-c). In comparing the Service's chlorophyll data to DWR and DFG, runs were selected as close to their sampling dates as possible. DWR collects approximately five sites in the study area, compared to about 14 sites by the DFG and 18 sites by the Service. Chlorophyll analyses by all three agencies are conducted in the Service's laboratory utilizing the same procedures, with the exception that the Service collected 0.06X the sample volume and used a fluorometer to measure extracted chlorophyll a rather than a spectrophotometer.

Average surface chlorophyll levels for the Suisun Bay area (including Grizzly and Honker Bays), collected on high slack tide during similar time periods, are illustrated in table 4 and figure 14. The Service collected multi-depth samples. Samples collected 1 meter from the surface and 1 meter off the bottom were also included for comparison with surface samples.

The average measured chlorophyll levels for Suisun Bay between the three sampling programs were similar despite the differences in the number of observations. All three sampling programs indicated that chlorophyll levels increased in Suisun Bay towards the latter part of July, and that high levels were sustained through the early part of October. Increases and decreases in average surface chlorophyll levels are thought to be in part the result of patchiness throughout the area.

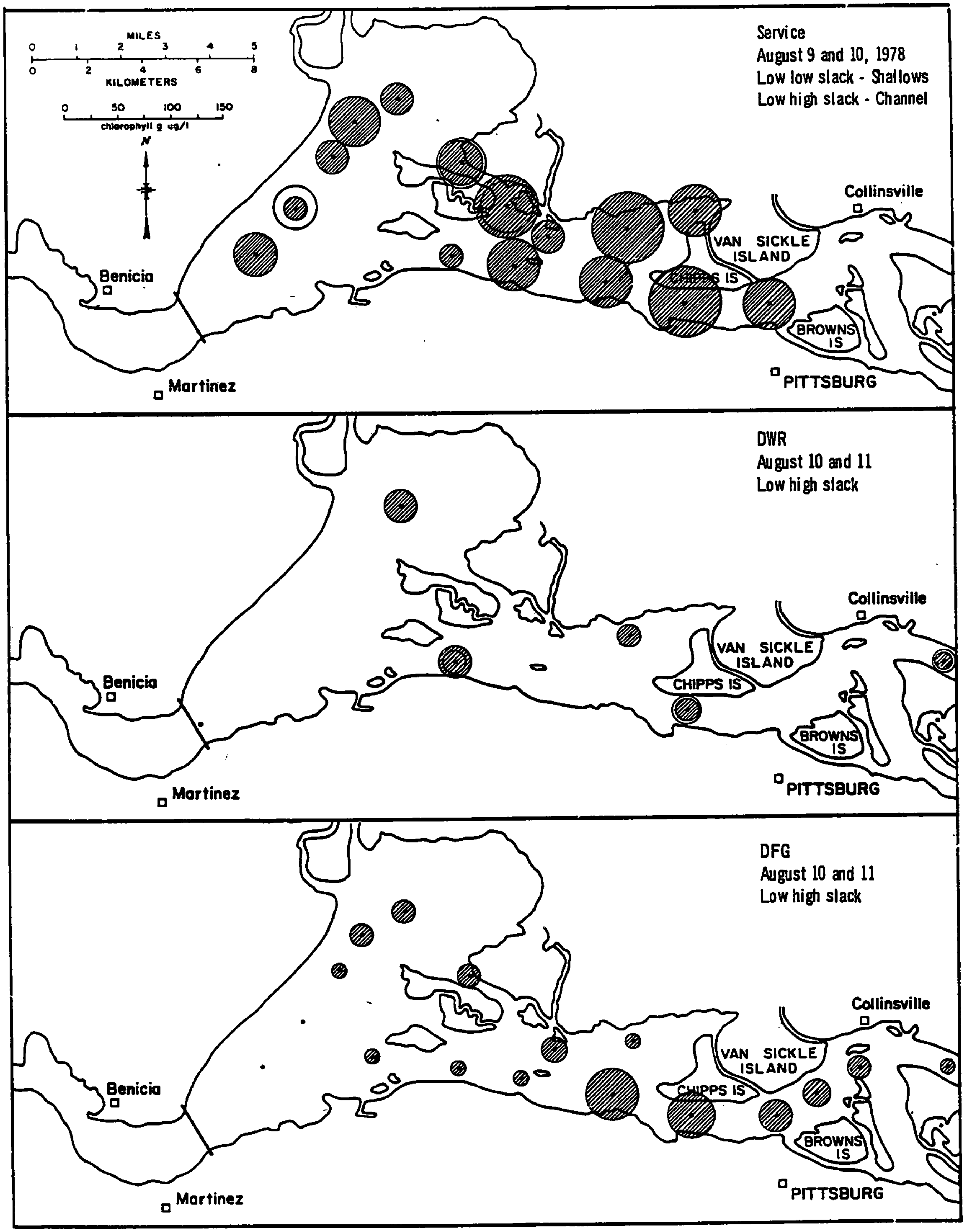


Figure 13a. Surface (hashed) and bottom (clear) chlorophyll *a* distribution in Suisun Bay on August 9–11, 1978, as determined by the Service, DWR, and DFG. Samples collected on high slack tides unless otherwise indicated.

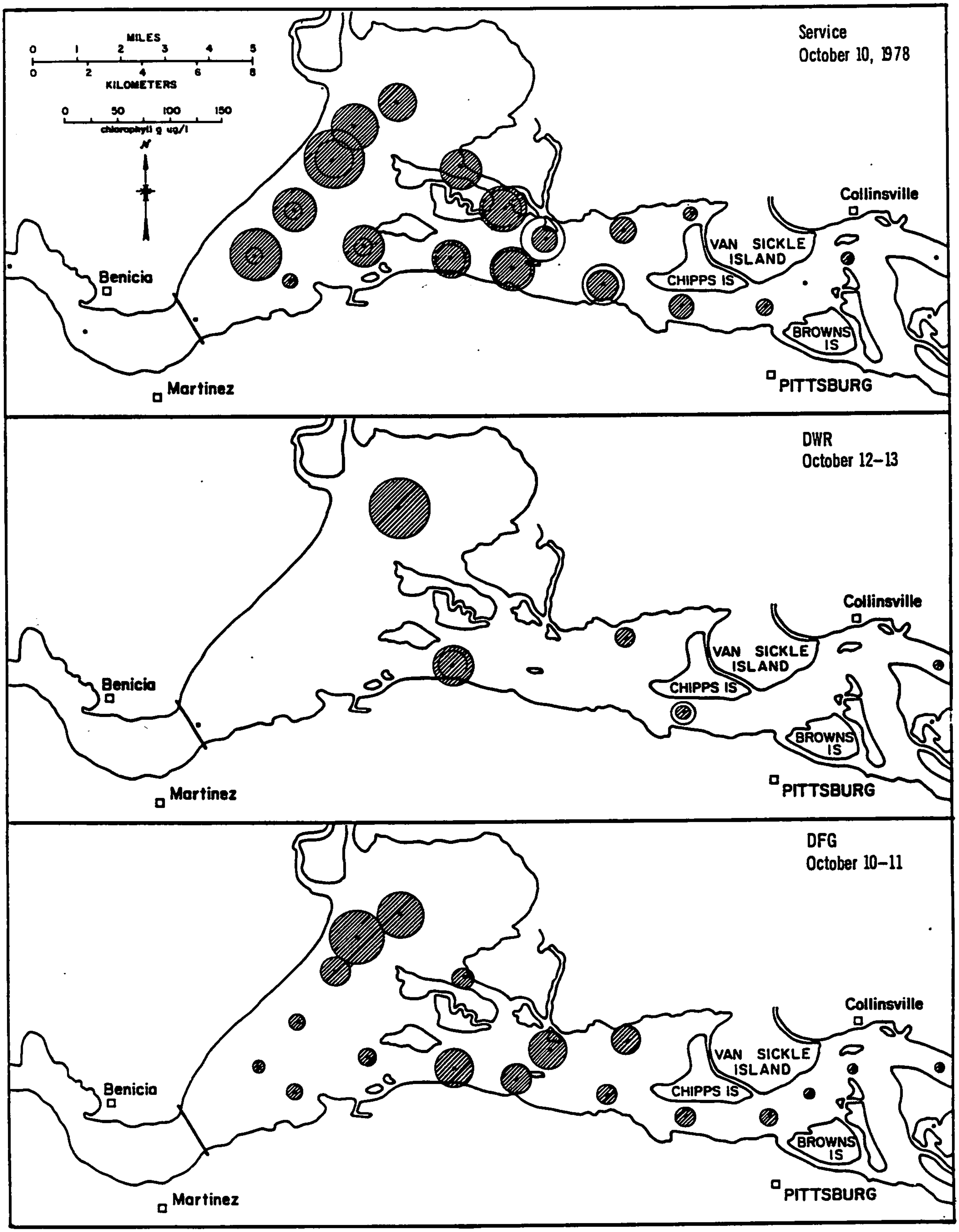


Figure 13c. Surface (hashed) and bottom (clear) chlorophyll a distribution in Suisun Bay on October 10–13, 1978, as determined by the Service, DWR, and DFG. Samples collected on high slack tide unless otherwise indicated.

Table 4. Comparison of average surface chlorophyll (ug/L) levels in the Suisun Bay area including Grizzly and Honker Bays collected by the Service, DWR, and DFG on high slack tides during the summer of 1978

SAMPLING PERIOD	Service (1 m)				Service (1 m,b)3/				DWR (1 m)				DFG (1 m)			
	OBS	MIN	AVG	MAX	OBS	MIN	AVG	MAX	OBS	MIN	AVG	MAX	OBS	MIN	AVG	MAX
July 12-14 1/	18	8	18	31	32	8	17	32	5	8	11	17	14	6	13	23
July 25-28	17	8	26	47	31	5	25	47	5	7	20	35	14	4	17	20
August 10-11		2/				2/			5	5	25	36	10	15	29	53
August 23-25	17	3	28	74	27	3	28	74	5	3	31	53	14	1	19	59
September 9-14	18	7	22	41	31	6	20	41	5	5	22	43	14	7	24	38
September 20-28 4/	18	5	26	51	32	5	33	68	5	8	31	61	14	5	19	53
October 10-13 1/	18	4	32	58	32	3	29	58	5	4	26	59	14	6	25	54

NOTES:

1/ Sampling in the shallow bays by the Service was partially on an ebbing tide.
2/ Weather conditions prevented full coverage of the area by the Service.
3/ Includes samples collected 1 m from the surface and 1 m off the bottom.
4/ Sampling in shallow bays by the Service was partially on a flooding tide.

Although any of these factors, as well as others not measured, can potentially limit phytoplankton growth, previous work has indicated that available light (combined effects of solar radiation, water transparency, and average water depth) is the factor most likely to be limiting phytoplankton growth. In addition, when there were large phytoplankton standing crops in Suisun Bay, inorganic nitrogen often became depleted.

Light Availability

The quantity and quality of light available for phytoplankton growth is determined by the solar insolation (light reaching the water surface), the transparency of the water, and average water depth. Also there are signficant differences resulting from seasonal changes and localized conditions; e.g., overcast and fog. Since light is necessary for photosynthesis, variations in intensity and wavelengths can dramatically affect phytoplankton growth (Fogg, 1965).

Past evaluations of solar insolation (Ball, 1977; Arthur and Ball, 1979a and b; and Ball and Arthur, 1979) collected at the University of California at Davis have demonstrated that although the daily intensity and quality of light reaching the water surface varies greatly, monthly averages between years are relatively constant. Consequently, variations in phytoplankton levels for the same months between years are thought to result from other factors.

Routine measurements of water transparency throughout the estuary in past years have included turbidity, secchi disc, and photometer measurements. Of these methods, secchi disc measurements appear to be the most reliable over an extended period of time, primarily because of spectral sensitivity variations between the photodetector cells in the different instruments used. In this study, secchi disc and turbidity measurements were taken at every site on each run.

The study of the entrapment zone was initially prompted by the inability to account for the high chlorophyll levels in Suisun Bay associated with low water transparencies; i.e., phytoplankton require light for photosynthesis, yet were at their highest levels in an area with the lowest water transparencies (Arthur, 1975).

In examining figure 15, it is apparent that during the spring through fall months the water transparency is lowest in the Suisun Bay area. However, the photic zone occupies a larger percent of the average depth in the shallows of Grizzly and Honker Bays than in the channel of Suisun Bay, or up and downstream of Suisun Bay.

Phytoplankton, which are uniformly distributed in the water column as a result of tidal and/or wind mixing, spend a greater percent of the time in the photic zone in the shallow bays than in the deeper channel areas. Consequently, phytoplankton production rates are higher in the shallows than in the channels.

Figure 16 compares phytoplankton dissolved oxygen production (which is proportional to carbon assimilation) in Grizzly Bay with production at a site in the ship channel adjacent to Grizzly Bay. The maximum production rate at

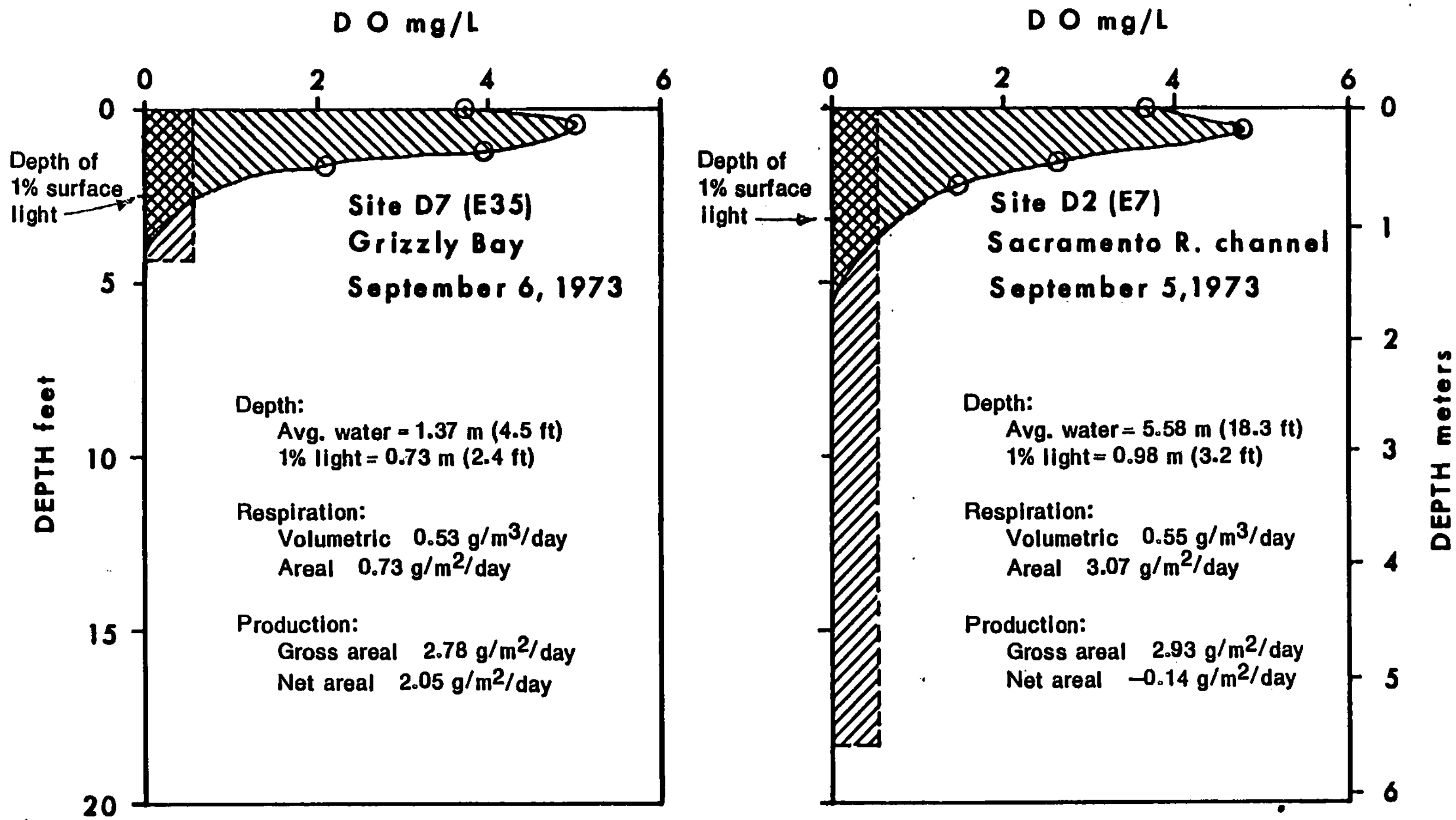


Figure 16. Typical example of phytoplankton dissolved oxygen production and respiration for a deep and shallow site in Suisun Bay. *NOTE:* Zooplankton were not filtered from the samples. This would make the respiration rates higher than for phytoplankton alone.

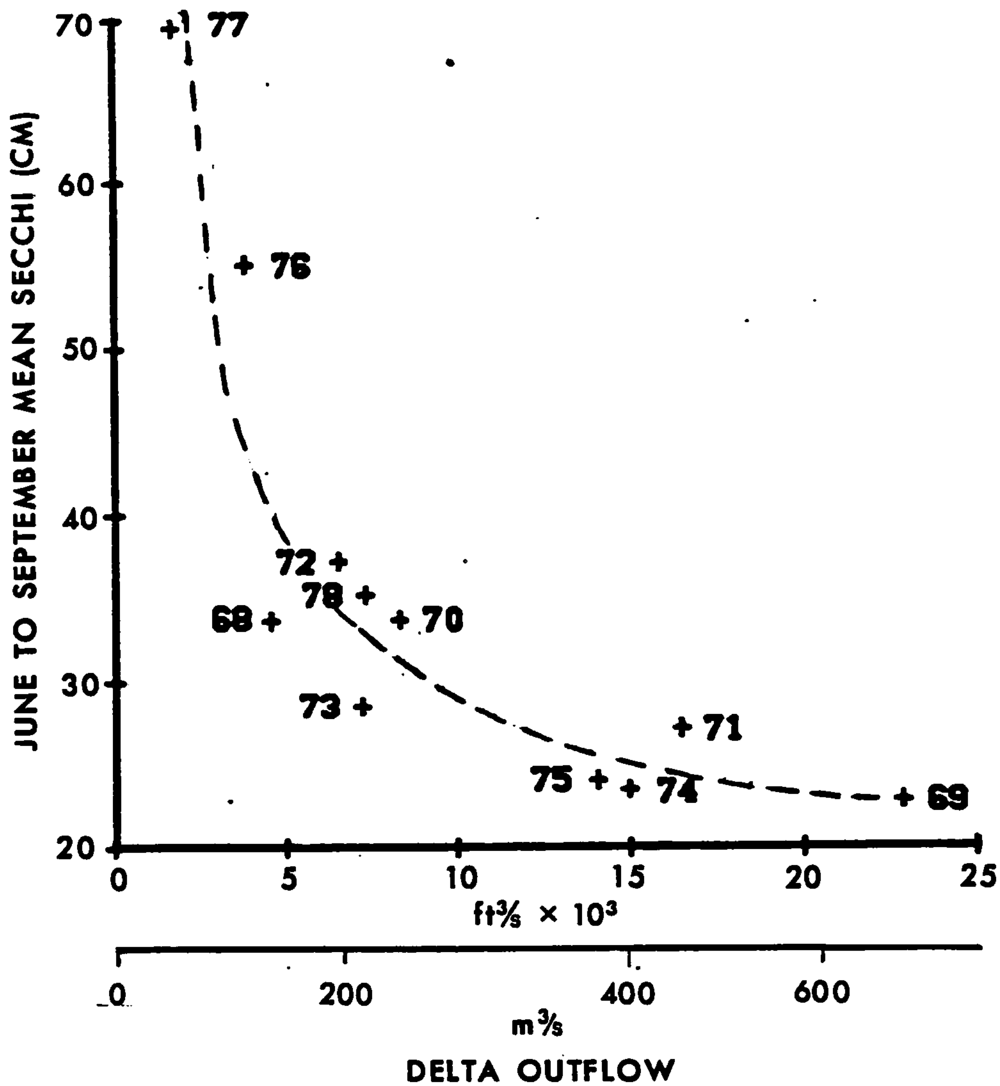


Figure 17. Mean DFG secchi disk vs. mean Delta outflow indices, June to September, 1968–1978, for Suisun Bay. (Secchi measurements were made by the Service in 1978)

February to October and at water temperatures ranging from 12-26°C. Apparently water temperatures within that range are sufficient to allow moderate to high phytoplankton standing crops to develop if other conditions are favorable.

Nutrients

Major nutrients required for phytoplankton growth are carbon, nitrogen, and phosphorus. Diatoms (which predominate in this part of the estuary) also require dissolved silica as a major nutrient. Depending on the unique chemical requirement of the species, a wide variety of micronutrients including such elements as potassium, sulfur, magnesium, sodium, calcium, iron, manganese, zinc, copper, boron, molybdenum, cobalt, and vanadium may also be required (Hutchinson, 1967).

Nutrient levels can affect algal growth rates in several ways (Fogg, 1965). As one or more nutrients approach a high toxic concentration, growth can be inhibited. Conversely, when the reverse occurs, and one or more nutrients are depleted to a relatively low level, then the growth rate is limited. Nutrient levels at a relatively low concentration reduce their rate of assimilation by algae, and this limiting effect then interacts with such factors as temperature, light, residence time, predation, and parasitism to determine the quantity of algae produced. The concentration, by weight, of inorganic nitrogen required to produce various concentrations of chlorophyll *a* for endemic Delta diatom populations was determined in algal growth potential studies to be about 7:1 (USBR, 1972).

The assimilatory mechanisms of algae function at saturation (maximum) rates when all nutrients are present in optimum concentrations. However, as low concentrations for any one nutrient are reached, the growth rate is reduced and that nutrient is then said to be limiting the growth rate.

An expression used to define nutrient-limiting concentrations for any nutrient is the half-saturation constant. The half-saturation constant for inorganic nitrogen (K_N) is equivalent to that concentration of nitrogen at which the assimilation rate has been reduced to one-half the rate at nutrient saturation (nonlimiting concentrations). The relative growth constant, K_1, decreases as the limiting nutrient level, N, decreases to levels approaching or below the half-saturation constant, K_N, for that nutrient as expressed below:

$$K_1 = \frac{N}{N+K_N}$$

A nutrient is limiting only when N is small compared to K_N (Fogg, 1965).

Half-saturation constants for inorganic nitrogen (ammonium and nitrate) were reported for several species of marine algae by Eppley, et al. (1969). Species of two diatom genera, *Coscinodiscus* and *Skeletonema*, which they studied also, were at times the dominant species that occurred during algal blooms in the western Delta to San Pablo Bay. The half-saturation constants they measured

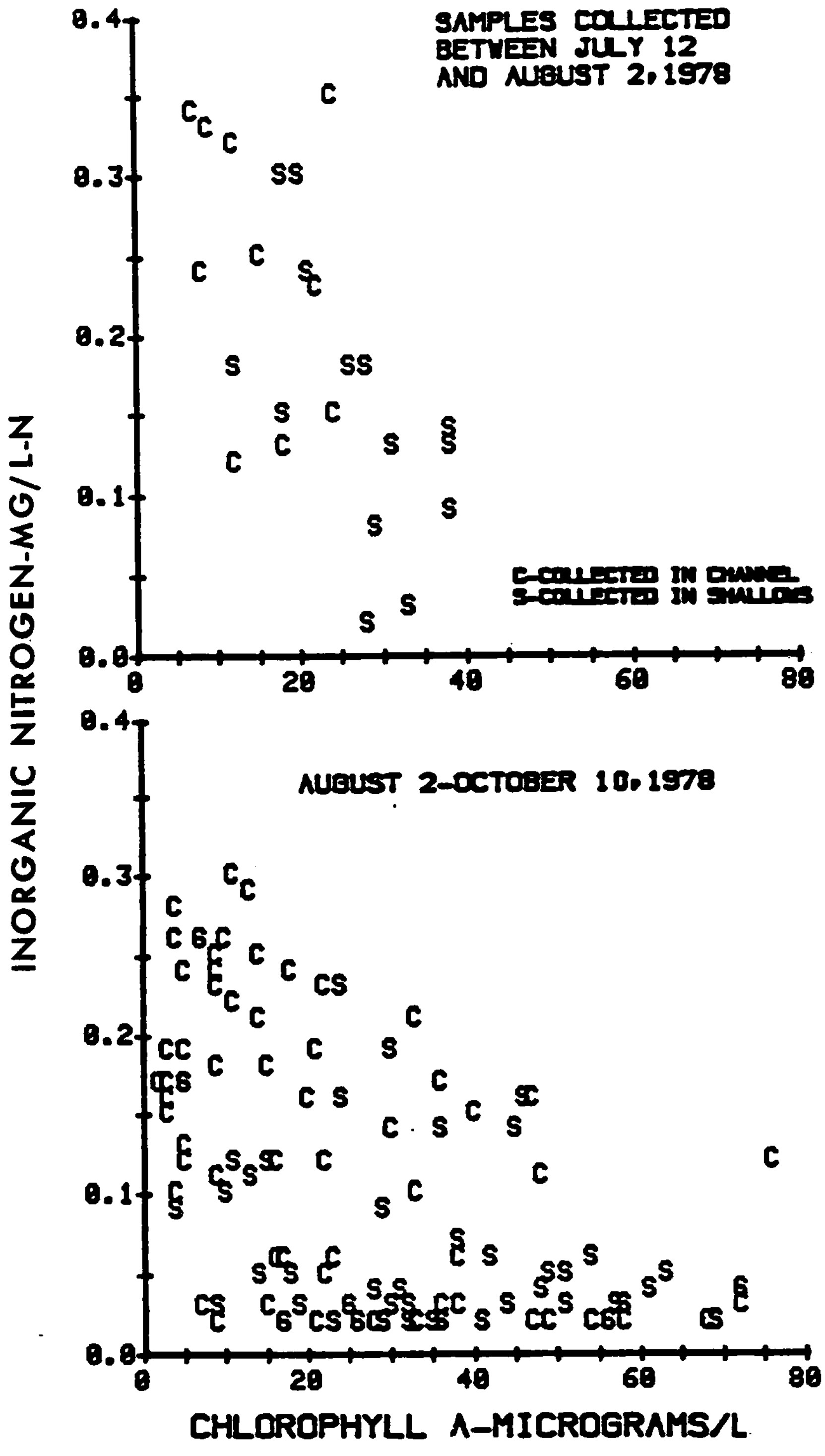


Figure 18. Chlorophyll a vs. inorganic nitrogen (NO_2, NO_3, and NH_4) prior to (top) and after (bottom) chlorophyll measurements reached 40 µg/L in either the ship channel (C) or Grizzly and Honker Bays (S).

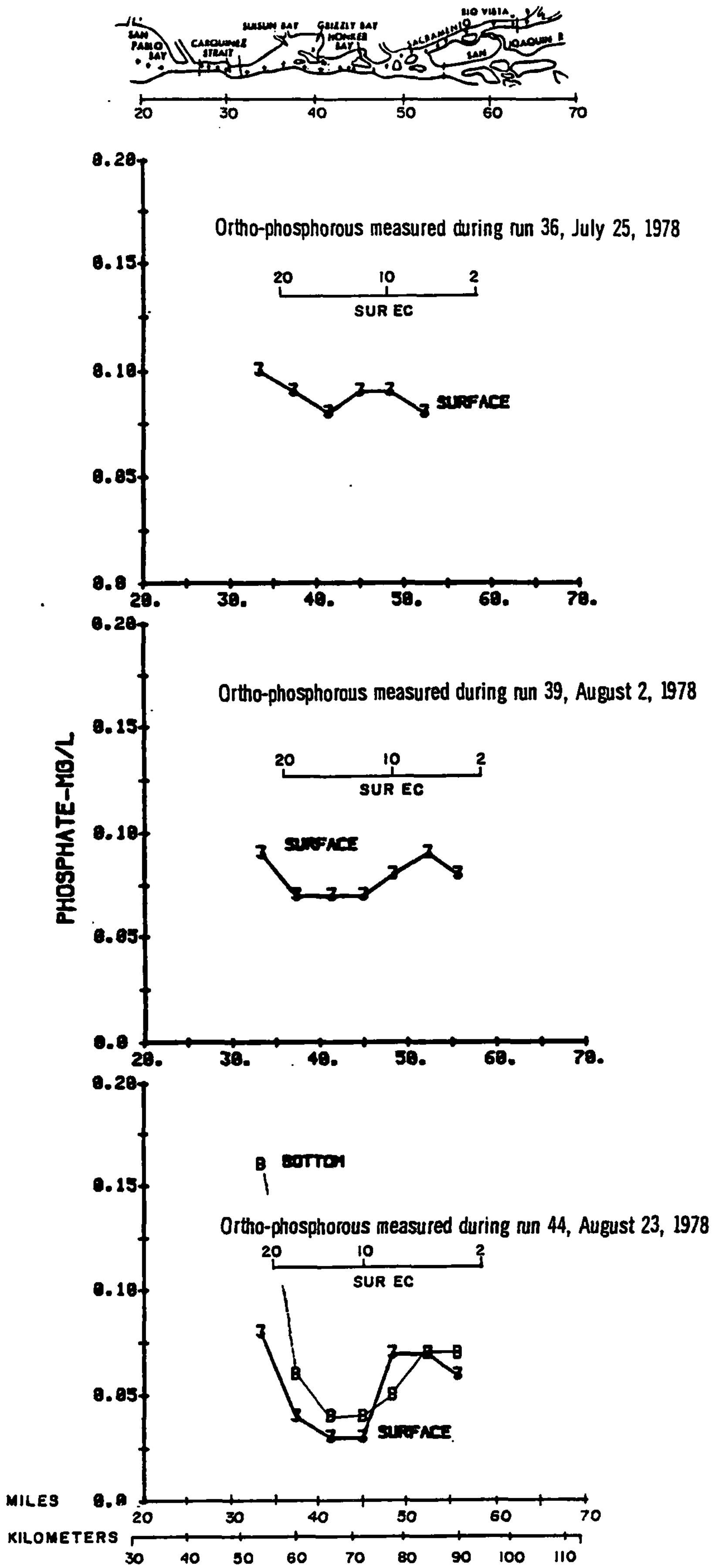
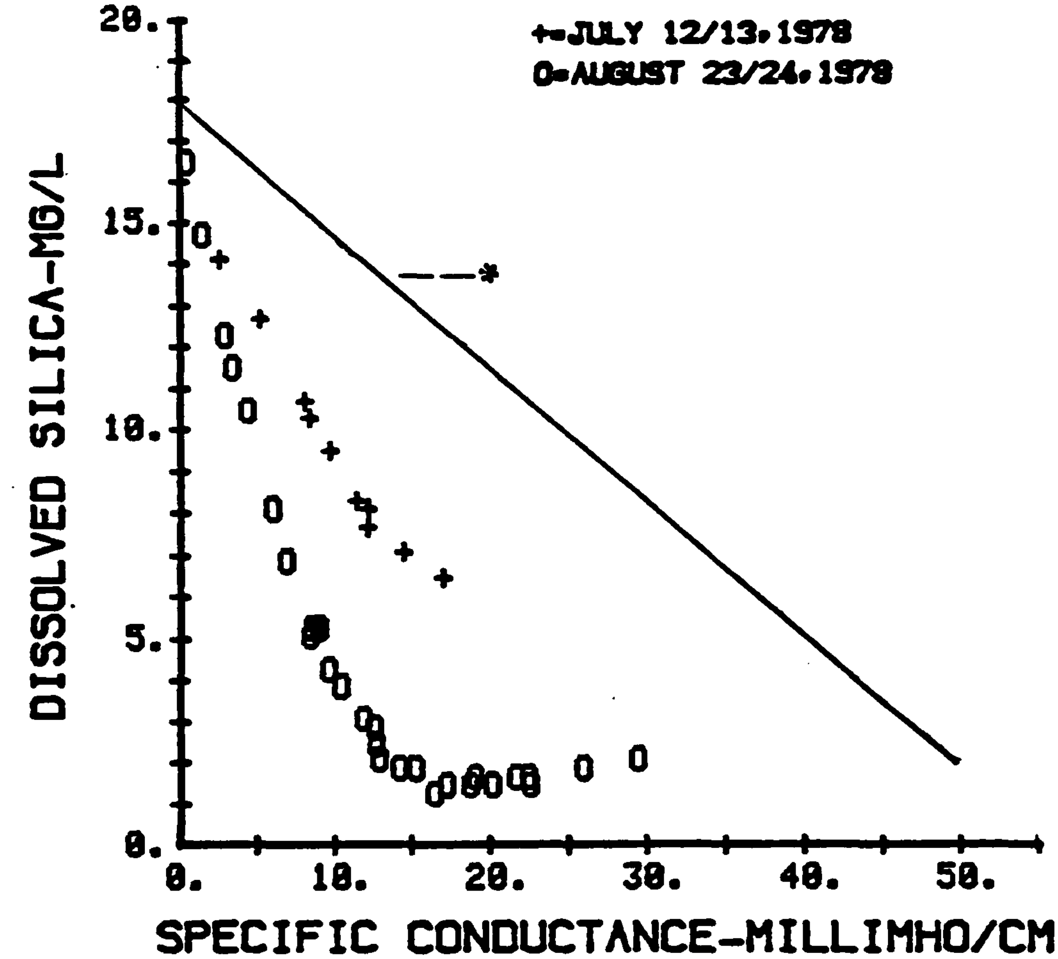


Figure 19. Typical ortho-phosphate distribution in Suisun Bay during the present study. Surface EC's of 2, 10, and 20 millimho/cm are also indicated as reference points for salinity intrusion.



* Diagonal line indicated a theoretical concentration of dissolved silica due to seawater dilution.

Figure 20. Dissolved silica vs. specific conductance measurement at approximately 1 meter depth throughout the study area on July 12–13 and August 23–24, 1978. Illustration is theoretical assimilation of silica by phytoplankters.

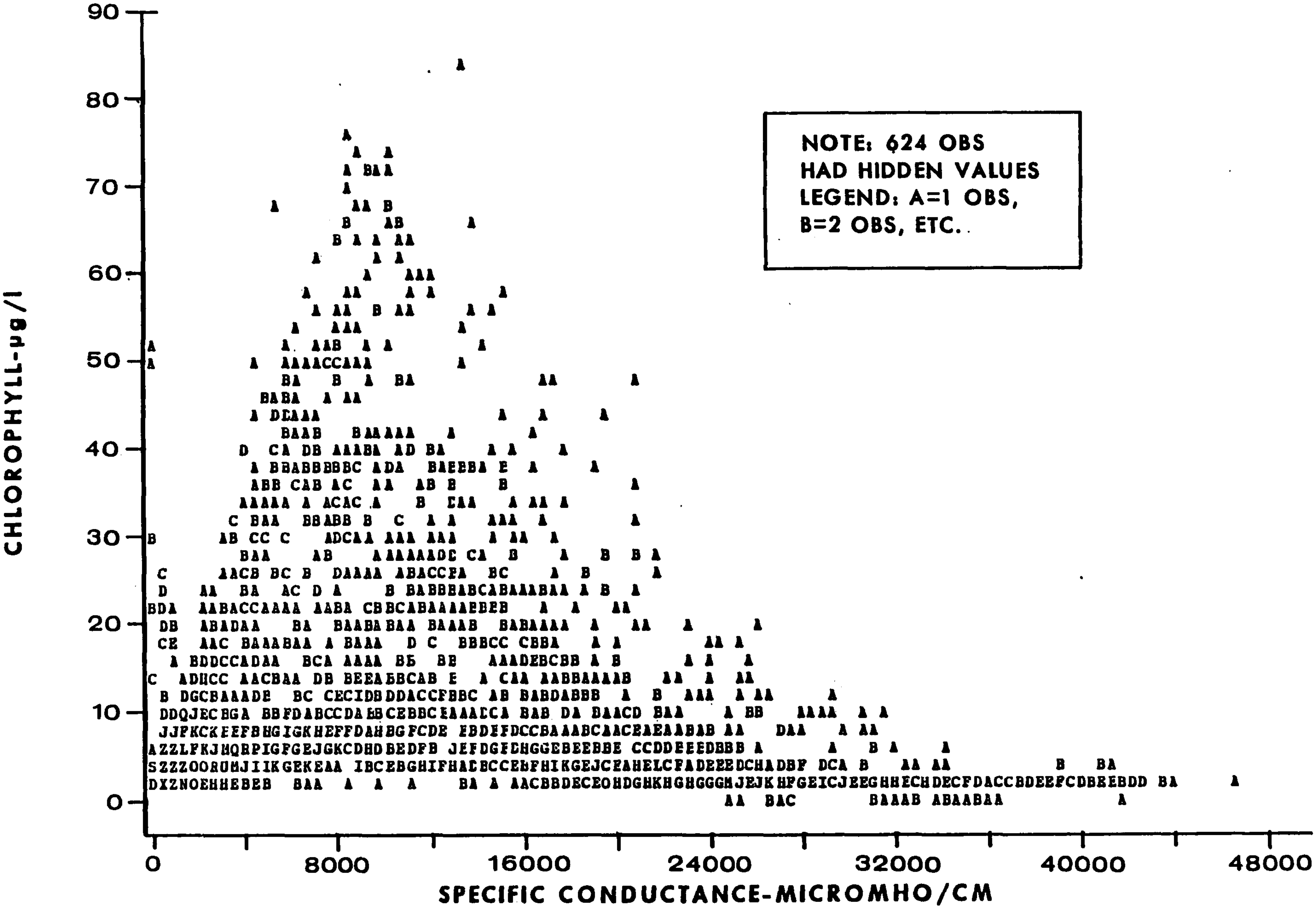


Figure 21. Chlorophyll *a* vs. specific conductance distribution from all depths measured in the entrapment zone studies, 1973–1978. (See figure 3 for location of sampling sites)

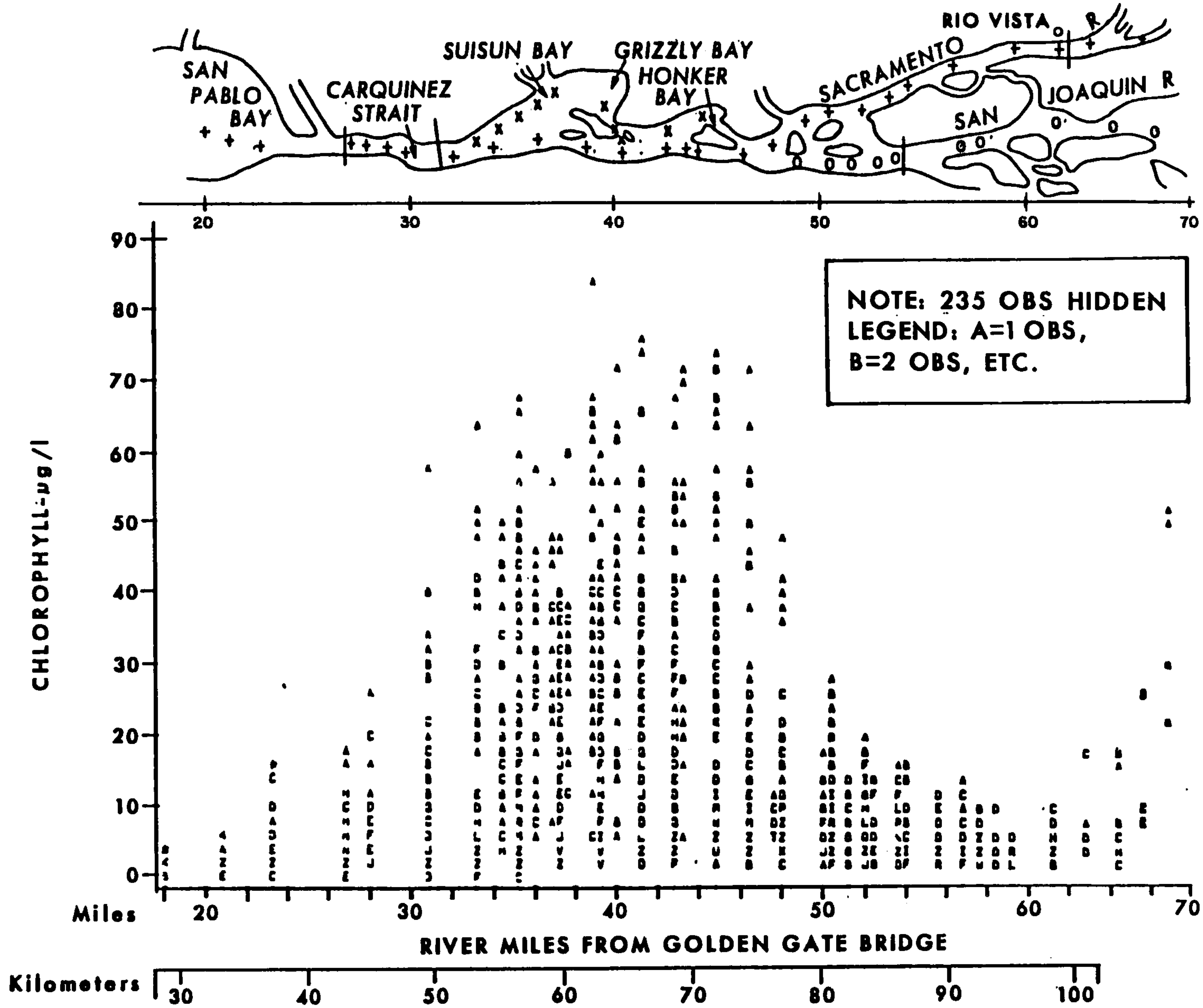


Figure 22. Chlorophyll measurements for all entrapment zone studies, 1973–1978. (See figure 3 for location of sampling sites.)

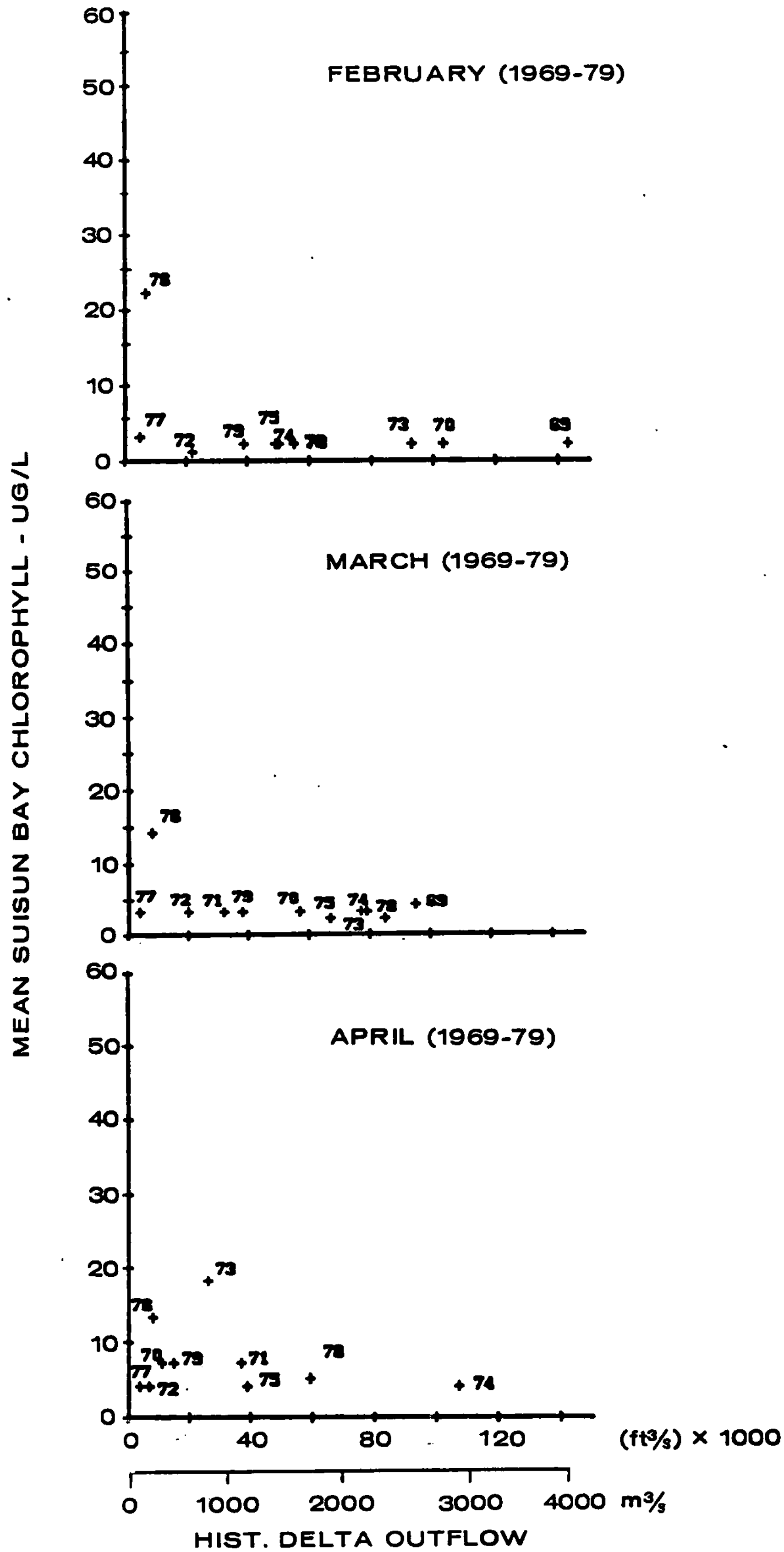


Figure 24a. Mean monthly Suisun Bay chlorophyll a measurements (Service, DWR, and DFG data) vs. Historical Delta outflows, 1969–1979.

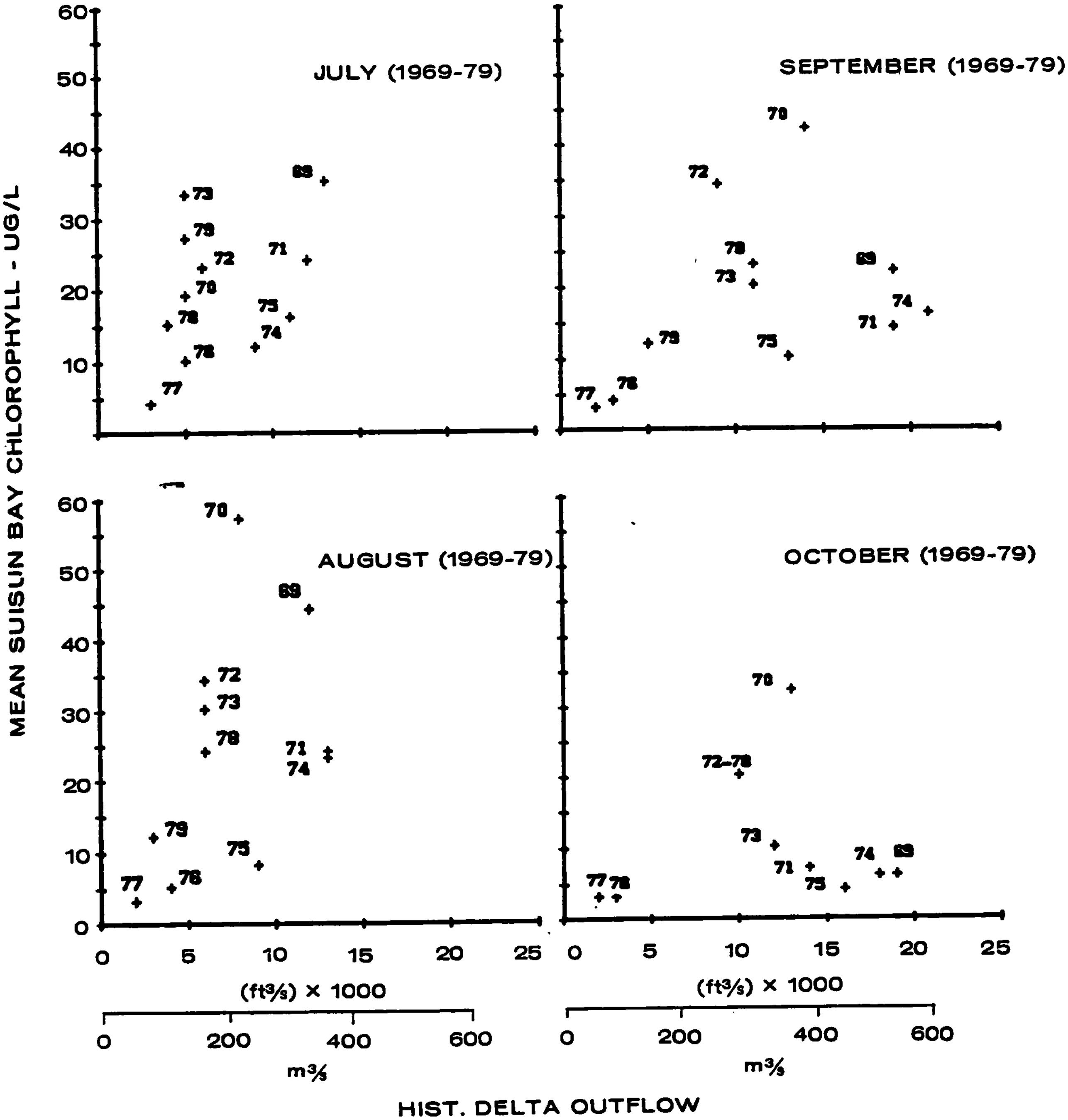


Figure 24 c. Mean monthly Suisun Bay chlorophyll *a* measurements (Service, DWR, and DFG data) vs. Historical Delta outflows, 1969–1979.

The factors evaluated have been summarized in table 6. They include (1) the February through November 1969-79 average chlorophyll a levels, (2) the range of chlorophyll levels, (3) years that had above average chlorophyll values in a given month, and (4) the average outflow and range of outflows for above-average chlorophyll years.

Certain trends are apparent from data illustrated in figures 24(a-c) and summarized in table 6. First of all, chlorophyll levels, coincide with annual changes in solar insolation. Chlorophyll levels were lower in the early spring and late fall than in the summer. Maximum day length and solar insolation occurs in July and August, the months of highest chlorophylls.

Although some years may have been nitrogen-limiting, the minimal chlorophyll a level years should not have been affected. Also, since nutrient limiting conditions occur only in the entrapment zone (see discussion on nutrients), limited data collection in past years makes it difficult to actually determine when nutrients were limiting.

Superficially, water transparencies do not seem to be the main factor influencing chlorophyll levels (see discussion of figure 17). As illusrated by these data, water transparencies were generally low during years with highest chlorophyll levels. Perhaps when the entrapment zone is in Suisun Bay, a combination of water transparencies, day length, solar insolation, and Delta outflows (residence times) are partially responsible for annual and between-year (on a monthly basis) differences in chlorophyll levels.

The primary factor evaluated was the effect of outflow (the entrapment zone location), on years with above average monthly chlorophylls, table 6. As indicated, the highest chlorophyll years generally occurred when Delta outflows were in the 140-425 m^3/s (5,000 to 15,000 ft^3/s) range, the same outflow range thought to be required to place the entrapment zone in and adjacent to the shallows of Suisun Bay. Months that could not be explained by outflow included April 1973, May 1971, June 1971, June 1975, and July 1969. Based on phytoplankton identification, it is thought that all of these periods had high chlorophylls transported into Suisun Bay from the western Delta, with the exception of June 1975. It is uncertain what happened in that year.

In conclusion, the most significant factor evaluated which was common to years of high chlorophyll levels appears to be the entrapment zone location. However, it is uncertain why many periods that happened to fall within this 140-425 m^3/s (5,000-15,000 ft^3/s) range had relatively low chlorophylls. Possible explanations include the data limitations previously mentioned. In particular, past chlorophyll trends (including data presented in this report for 1978) indicate that the levels of chlorophyll in Suisun Bay increase the longer the entrapment zone remains near Honker Bay (until some other factor becomes phytoplankton-limiting). Further evaluations in the future may provide some insight into how the length of time the entrapment zone is in and adjacent to the shallow embayments influences chlorophyll levels.

PHYTOPLANKTON SETTLING RATES

The results of the present study, strongly support the earlier observations that the entrapment zone location is a significant factor regulating chlorophyll

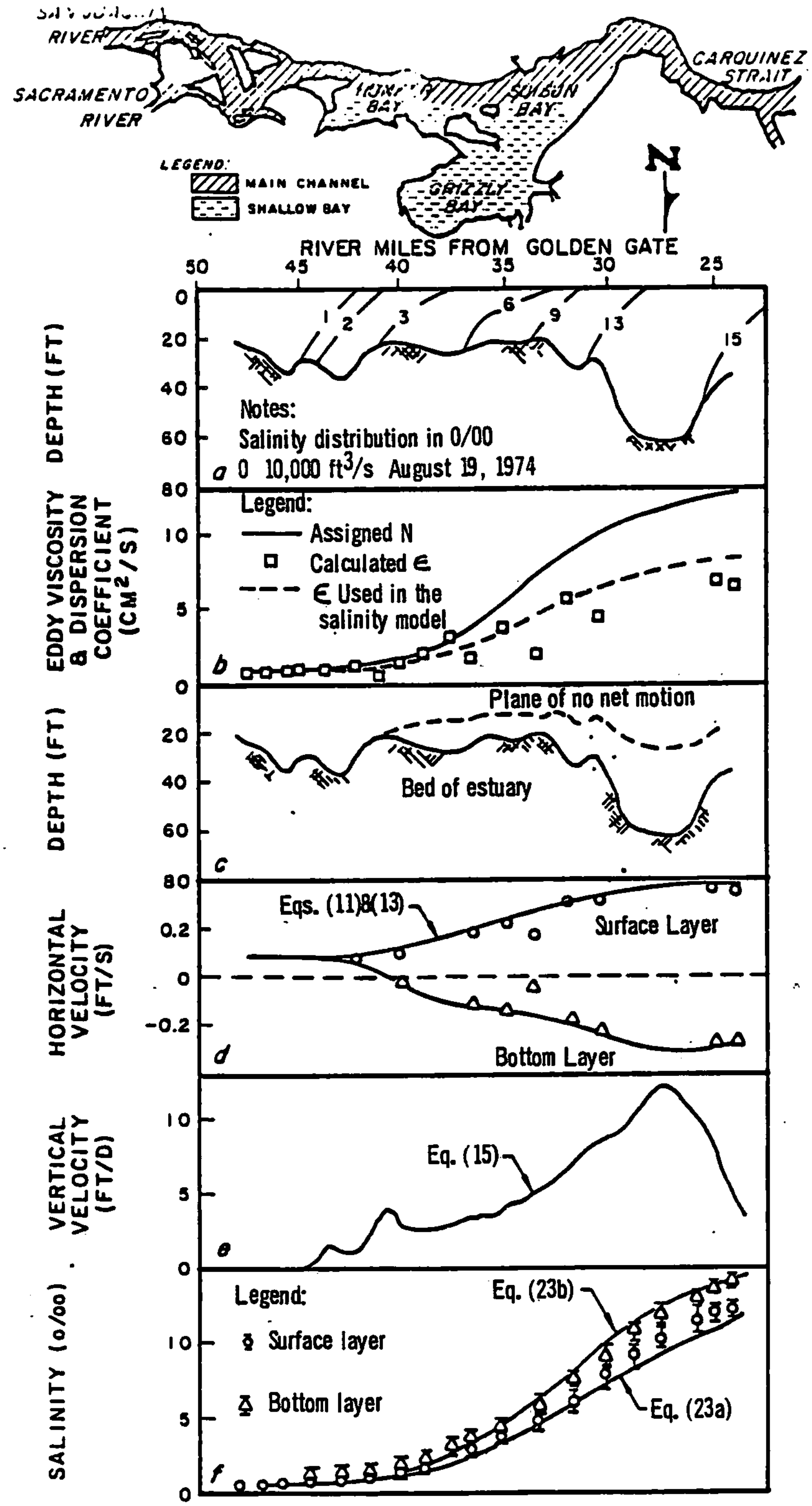


FIGURE IV-3

SALINITY CALCULATION FOR SACRAMENTO-SAN JOAQUIN ESTUARY (AUGUST, 1974)

Figure 25. Figure IV–3, from Hydroscience, Inc. (O'Connor and Lung, 1977), illustrating the physical dimensions, salinity, net velocities, and eddy viscosity coefficients used to simulate suspended solids distribution in the upper estuary. Points represent field data. Lines represent simulations except salinity which were determined from field data. (See O'Connor and Lung, 1977, for equations)

summer months. In fact, the highest chlorophyll measurements so far recorded in the western and central Delta for the months of July and August were measured in 1969. Algal identification data were very limited both temporally and spatially but extended from the western Delta to Martinez. Organisms of the genus Cyclotella dominated from the western and central Delta areas to Chipps Island, figure 26. Organisms of the genus Thalassiosira (presumably the same species that dominated throughout 1978) increased greatly in the area of Grizzly Bay, suggesting the same developmental pattern as occurred in 1978. In 1969, the area of high chlorophyll concentration was spread over a larger area than the bloom of 1978. As a result of downstream transport, the area of high phytoplankton standing crop throughout the Suisun Bay area in 1969 appears to have had an extended spatial range over what is believed normally would have occurred if the total phytoplankton standing crop had developed in the Suisun Bay area as it did in 1978.

Example of phytoplankton being transported upstream from where they developed to the entrapment zone is suggested in the 1979 data (as the zone moved upstream of Honker Bay during August). Another example occurred in March 1974 as the zone moved upstream from San Pablo Bay. However, in both cases insufficient species data were collected to fully illustrate the transport and concentration of phytoplankton in the zone.

In conclusion, if more definitive data is required on the entrapment zone, then more emphasis must be placed on collecting adequate phytoplankton species data to account for origins of growth, development, changes, and transport of the dominant species. This must be done to fully understand the mechanisms controlling the phytoplankton standing crop and to be able to produce an adequate phytoplankton model to make predictions of the standing crop levels under varying conditions of Delta outflow, etc.

SUMMARY AND ENVIRONMENTAL IMPLICATIONS

The cause-effect mechanisms regulating the level of the phytoplankton standing crop in Suisun Bay are not fully understood; however, evaluations thus far indicate that the location of the entrapment zone near the upstream edge of large, shallow bays stimulates the accumulation of a large phytoplankton standing crop for the entire area. Apparently, the longer phytoplankton residence time created by the entrapment zone, combined with the large surface area, and the phytoplankton occupying the photic zone for a greater percentage of time in shallow water than in deep channels, provides a sufficiently high phytoplankton growth rate and retention in the area for a large standing crop to develop. The concentration of phytoplankton that develops in the shallow areas is in turn regulated by other phytoplankton growth controlling factors, such as water temperature, nutrient levels, water transparencies, zooplankton grazing, sufficient time for growth, etc.

When the entrapment zone is confined only to river channels (i.e., upstream of the bays), the surface area is relatively small and the average depth for the area is greater. Top to bottom mixing is also less. As a result, the photic zone constitutes a smaller percentage of the water column. Under such conditions, the phytoplankton spend less average time in the photic zone. The respiration rate may exceed the production rate, and the net production rate in the area of entrapment could be reduced to zero or less even though a sizeable standing crop is transported there and accumulates from growth in distant shallows.

Although there is no such thing as a "typical" year in the San Francisco Bay-Delta estuary, there appears to be some general trends from year to year. In summary, it is thought that during periods of high winter outflow the entrapment zone is pushed downstream of Suisun Bay. Data from San Pablo Bay in the last 3 years (Four-Agency and USGS) indicate that there have been late winter to spring phytoplankton blooms when the entrapment zone was in the upstream end of the bay, and that the intensity of the blooms was nearly equal to those observed in Suisun Bay (DWR, personal communications).

As Delta outflows decrease later in the year, the entrapment zone moves upstream into the deeper, narrow confines of Carquinez Strait. Although measurements in Carquinez Strait during the period of decreasing Delta outflow are sparse, the measurements have indicated that surface chlorophylls are generally low. Perhaps the high downstream surface velocities, combined with the deep channel area (over 30 meters) with a limited photic zone, prevent high surface chlorophyll concentrations. However, very little is known about the upstream phytoplankton transport in the bottom layer from San Pablo Bay.

Chlorophyll data evaluated so far suggest that chlorophyll levels first start to increase in the shallows of Grizzly Bay as the entrapment zone moves into Suisun Bay. As Delta outflows further decrease (140-230 m^3/s), the highest chlorophyll levels generally occur when the entrapment zone is tidally centered in the upstream end of Suisun Bay adjacent to Honker Bay. It is thought that the highest chlorophyll levels occur when the entrapment zone is in this area because entrapment occurs in and downstream of the null zone, i.e., phytoplankton are entrapped in both Grizzly and Honker Bays. When the

In the present study, surface and bottom measurements of DO were taken in special early morning runs and at each site on every regular run. DO percent saturation levels were corrected for salinity and temperature.

In summary, DO levels during the study were always above 7.0 mg/L and near or above saturation levels. Figures 27(a-c) illustrate the typical dissolved oxygen saturation levels observed in 1978 during a period of high phytoplankton standing crop, as compared to similar periods in 1976 and 1977 when there was little phytoplankton growth. The data from August 1976 and all of 1977 typify base dissolved oxygen levels with minimal DO phytoplankton production throughout Suisun Bay.

Chlorophyll a levels during August of 1976 and 1977 in the ship channel (and shallows) were below 10 ug/L, figure 27a. Chlorophyll a levels during these periods were slightly higher on the surface than near the bottom and showed a slight peak near river mile 40, Honker Bay, and upstream.

Percent DO saturation levels, figure 27a, in August of 1976 and 1977 were higher on the surface than near the bottom. Peak levels also occurred about river mile 40. Saturation levels of 80 to 95 percent DO saturation during these periods probably represent near-baseline conditions for Suisun Bay, since there were minimal phytoplankton standing crops. Peak levels observed may have resulted from either phytoplankton DO production and/or the effects of wind mixing of the shallow bays and exchange with the channel.

The August 1976 and 1977 data presented in figure 27a were collected on high slack tide runs in the early afternoon, when phytoplankton DO production would be at a maximum. These data were compared to August 1978, a period when chlorophyll a levels were high, figure 27b. The August 1978 data were further compared for an early morning run (6:50 a.m. to 9:50 a.m.) after a long period of no phytoplankton production, to a late afternoon run (2:00 p.m. to 3:30 p.m.) when oxygen production would be maximum.

In 1978 measured chlorophyll a levels varied from a morning peak of about 70 ug/L to an afternoon peak of about 55 ug/L in the ship channel. The morning run was conducted on a high slack tide while the afternoon run was on a low slack tide. Chlorophyll a peaks on both runs occurred at about river mile 40, Honker Bay. The surface to bottom chlorophyll a levels in the morning were slight, while the surface levels in the afternoon were considerably higher than the levels near the bottom. Generally, the percent DO saturation levels, figure 27b, followed the chlorophyll a trends, being higher on the surface than near the bottom. However, the peak levels for both runs occurred approximately 5 miles downstream from the chlorophyll a peaks.

In 1978 the percent DO saturation levels in the early morning run ranged from about 90 to slightly over 100 percent saturation, which was higher than observed in the 1976 and 1977 afternoon runs, figure 27a.

The percent DO saturation levels in the August 1978 afternoon run, at the surface were as high as 127 percent. The bottom levels remained at about the same level as the morning run.

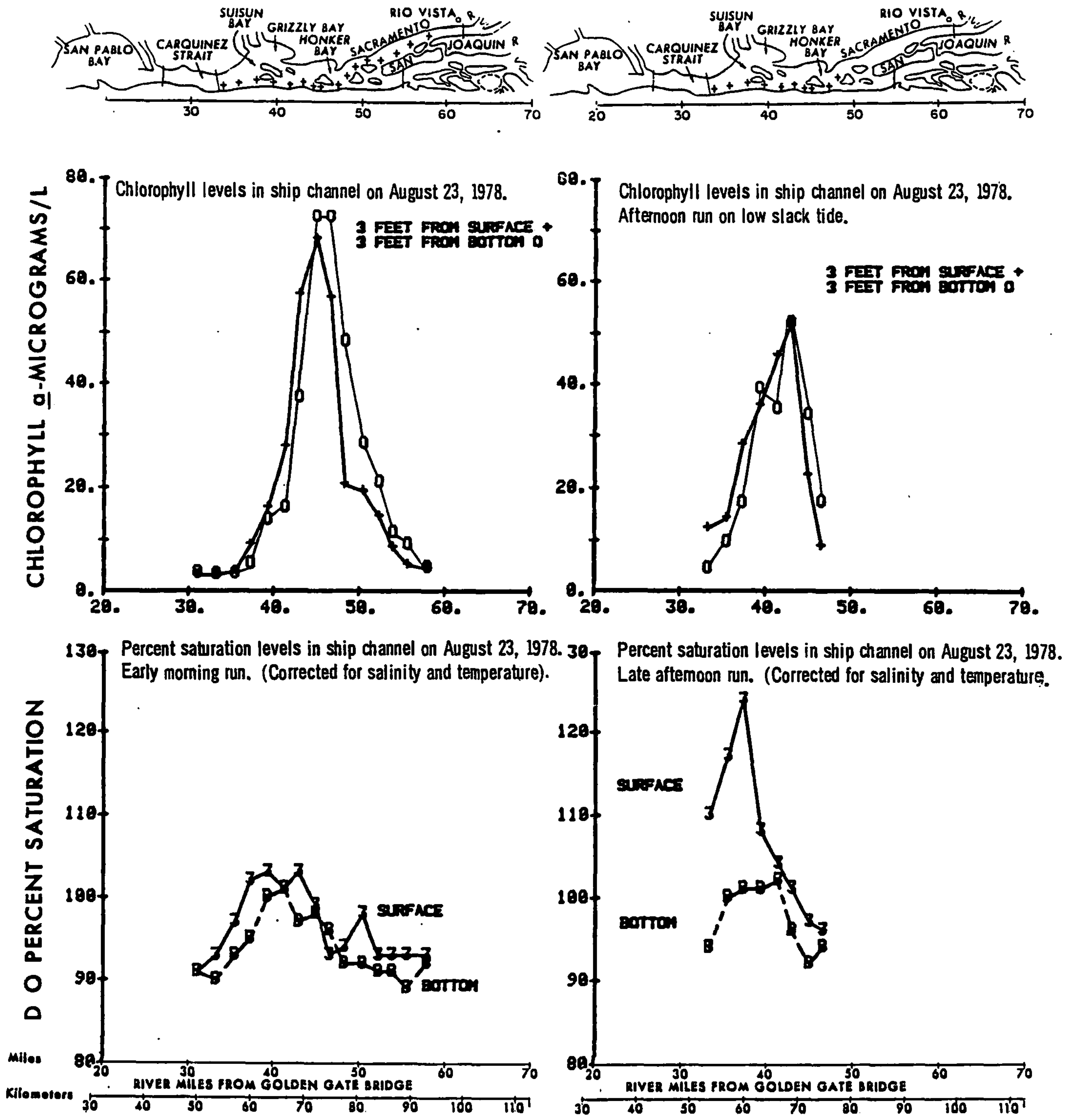


Figure 27 b. Surface and bottom chlorophylls and DO percent saturation levels in the ship channel of Suisun Bay on August 23, 1978, illustrating differences between morning and afternoon percent saturation levels.

In an attempt to explain why the percent DO saturation levels in August 1978 occurred downstream of the chlorophyll a peaks, an early morning run, 6:30 a.m. to 8:15 a.m., and an afternoon run, 1:00 p.m. to 1:45 p.m., were plotted for the shallows of Grizzly and Honker Bays. The morning run was conducted on a greater flood tide (August 24), and the afternoon run was conducted on a high-low slack tide (August 23), figure 27c.

The chlorophyll a peak in the morning run was 74 ug/L, and in the afternoon run, 67 ug/L. The percent DO saturation levels in the morning ranged from 90 to 103 percent. Surface levels were slightly higher than bottom levels at deeper sites. In the afternoon run, the percent DO saturation levels were generally above 100 percent on the surface and near the bottom.

The high DO saturation levels downstream of the peak chlorophyll a levels in the ship channel may have resulted partially from circulation of high DO waters from the shallows into the channel. These high levels also may have resulted from the effects of two-layered flow increasing the net vertical water velocities and thereby retaining the algae near the surface. Examination of figure 27b indicates DO saturation levels are generally low upstream of the surface chlorophyll a peaks, peaked downstream in the surface waters, then rapidly declined. A fuller understanding of circulation appears essential to evaluating these relationships.

In conclusion, the DO measurements during the study agree with previous observations (DFG and DWR, 1972) that the current level of eutrophication does not appear to result in dissolved oxygen depletion. However, it should be noted that the study was terminated when the phytoplankton standing crop on the surface was still relatively high. Low DO levels, if they occur, would follow the phytoplankton decline on the surface and be lowest near the bottom in the entrapment zone. Theoretically, the timing of the bloom decline would also be important. A decline early in the fall when temperatures are still high might result in lower DO's than a decline later in the fall when temperatures are lower.

Aesthetics

Diatoms are the predominant phytoplankters in the Suisun Bay-Western Delta area. There are apparently few aesthetic problems associated with diatoms. Diatoms are also known to be a food source for zooplankton.

Future Conditions

Although it is impossible to predict estuarine conditions in the future, the State Water Resources Control Board (SWRCB) has set some interim minimal Delta outflow standards for the year 2000 (Decision 1485) for critical, wet, and average precipitation years. The SWRCB outflow criteria require certain monthly total dissolved solids (TDS) levels at Chipps Island be maintained. These standards can be renegotiated as more information becomes available in the future.

Figure 28 was constructed based on these criteria and on the assumption that a large phytoplankton standing crop in Suisun Bay is dependent upon the entrapment zone being located approximately adjacent to Honker Bay. These figures do not project the levels of the phytoplankton standing crop which is dependent upon other growth variables. The 6 ppt total dissolved solid (TDS) line (specific conductance of 10 millimho/cm) at Chipps Island is indicated on these figures to illustrate the theoretical optimal location of the entrapment zone as related to salinity intrusion, necessary for a maximum phytoplankton standing crop to develop. As illustrated, low flows (<140 m^3/s) would result in a low phytoplankton standing crop in Suisun Bay.

Federal and State Water Projects

Planned development of the Federal and State water projects could substantially alter the phytoplankton standing crop in Suisun Bay (as well as downstream) in two ways. First of all, if increased export results in a corresponding decrease in Delta outflows below 113 m^3/s (4,000 ft^3/s), the phytoplankton standing crop in Suisun Bay will most likely decrease as the entrapment zone becomes located upstream. Secondly, the discharge of subsurface agricultural drainage water into Suisun Bay with an average discharge of 9 m^3/s (300 ft^3/s), nitrate-nitrogen of 30 mg/L, and a dissolved silica level of 30 mg/L should increase the phytoplankton standing crop if Delta outflows are sufficient to maintain the entrapment zone in its optimal location for phytoplankton production.

The current level of eutrophication (10 year chlorophyll maximum for Suisun Bay is 100 ug/L) does not appear to be detrimental to the estuary. Significantly, the major concern is not that there will be too high a phytoplankton standing crop with reduced Delta outflows, but that the phytoplankton standing crop along with total estuarine productivity might be reduced in the future. The key factor is to determine what levels of phytoplankton are desirable in the food web, i.e., would 150, 200, or 300 ug/L chlorophyll *a*, for example, enhance or be detrimental to the estuarine environment? Although the interagency studies over the past 10 years have dealt primarily with gathering and evaluating data for individual organisms in the food web, i.e., phytoplankton, zooplankton, and fish, much more needs to be understood of the dependency of one organism on another. This should be a major objective of future studies.

Ship Channel Deepening

Current plans by the Army Corps of Engineers call for channel deepening in the Sacramento and San Joaquin ship channel. Based on the present understanding of phytoplankton dynamics, the deepening would result in the upstream movement of the entrapment zone (if other conditions were maintained), and a possible reduction in the phytoplankton standing crop if the zone were moved upstream into deeper channels. Also, greater Delta outflows might be required to maintain the zone in Suisun Bay.

Other

There are numerous other unanswered questions. Some of these are:

1. Is maximization of the phytoplankton standing crops a beneficial use of water? If so, what is it's worth compared to other beneficial uses?

2. How much do diversions and discharges in the area of the entrapment zone affect the biota?

ACKNOWLEDGEMENTS

The Service and authors wish to express their appreciation for review of the draft report by the staff members of the Interagency Ecological Study Program (Dr. Martin Kjelson, FWS; Pete Chadwick, Don Stevens, and Jim Orsi, DFG; Randy Brown, DWR; Matt Rumboltz, Service); Ross Swenerton, California State Water Resources Control Board; Dr. James Cloern, USGS; Dr. Ray Krone and Dr. Allen Knight, UCD; and Anne Sands, private consultant. Thanks, also, to other staff members, particularly Sheryl Baughman and Hazel Coulson, for their participation and assistance in the preparation of this report.

REFERENCES

Arthur, J. F., 1975. Preliminary studies on the entrapment of suspended materials in Suisun Bay, San Francisco Bay-Delta Estuary, pp. 17 to 36. In R.L. Brown (ed.) Proceeding of a workshop on algal nutrient relationships in the San Francisco Bay and Delta, November 1973. California Department of Water Resources, State of California.

Arthur, J. F., and M. D. Ball, 1978. Entrapment of suspended materials in the San Francisco Bay-Delta estuary. U.S. Bureau of Reclamation, Sacramento, California. 106 pp.

Arthur, J. F., and M. D. Ball, 1979a. Factors influencing the low phytoplankton standing crop in Susuin Bay during the 1976-77 drought. U.S. Bureau of Reclamation, Mid-Pacific Region Report, 84 pp.

Arthur, J. F., and M. D. Ball, 1979b. Factors influencing the entrapment of suspended material in the San Francisco Bay-Delta estuary. In T. J. Conomos (ed.) San Francisco Bay: The urbanized estuary. Amer. Assoc. Advancement Science, San Francisco, California.

Ball, M. D., 1975. Chlorophyll levels in the Sacramento-San Joaquin Delta to San Pablo Bay. In R. L. Brown (ed.) Proceedings of a workshop on algal nutrient relationships in the San Francisco Bay and Delta, November 1973. California Department of Water Resources, Sacramento, California.

Ball, M. D., 1977. Phytoplankton growth and chlorophyll levels in the Sacramento-San Joaquin Delta through San Pablo Bay. U.S. Bureau of Reclamation, Sacramento, California. 96 pp.

Ball, M. D., and J. F. Arthur, 1979. Planktonic chlorophyll dynamics in the northern San Francisco Bay and Delta. In T.J. Conomos (ed.) San Francisco Bay: The Urbanized Estuary. Pacific Division, American Association Advance: Science, San Francisco, California.

Bowden, K. F., 1967. Circulation and Diffusion, pp. 15-36. In G.H. Lauff (ed.) Estuaries, Am. Assoc. for Adv. Sci. Publ. No. 83, Washington, D.C.

Cloern, J. E., 1978. Empirical model of Skeletonema costatum Photosynthetic rate, with applications in the San Francisco Bay Estuary, Advances in Water Resources, Vol. 1, No. 5, 1978, pp. 267-284.

Cloern, J. E., 1979. Phytoplankton ecology of the San Francisco Bay system, the status of our current understanding. Pages 247-264. In. Pacific Division, American Association Advancement Science, San Francisco, California.

Conomos, T. J., 1979a. Properties and circulation of San Francisco Bay waters, pp. 47-84. In T.J. Conomos, (ed.) San Francisco Bay: The Urbanized Estuary Pacific Div., Amer. Assoc. Advance. Science, San Francisco, California.

Conomos, T. J. (ed.), 1979b. San Francisco Bay: The Urbanized Estuary. Pacific Division, American Association Advancement of Science, San Francisco, California. 493 pp.

O'Conner, D. J., and W. Lung, 1977. Preliminary report on two dimensional hydrodynamic, salinity transport and suspended solids distribution in western Delta. Hydroscience, Inc., Westwood, New Jersey. 66 pp.

Officer, C. B., 1976. Physical oceanography of estuaries. John Wiley and Sons, Publishers, New York, New York. 465 pp.

Peterson, D. H.; T. J. Conomos; W. W. Broenkow; and P. C. Dohery, 1975a. Location of the non-tidal current null zone in Northern San Francisco Bay, Estuarine and Coastal Mar. Sci. 3:1-11.

Peterson, D. H.; T. J. Conomos; W. W. Broenkow; and E. P. Scrivani, 1975b. Process controlling the dissolved silica distribution in San Francisco Bay. Pages 153-187. In L. E. Cronin, (ed.) Estuarine Research, Vol. 1. Chemistry and Biology. Academic Press. New York.

Round, F. E., 1965. The biology of the algae. Edward Arnold, Publishers, London, England. 269 pp.

Siegfried, C. A.; A. W. Knight; and M. E. Kopache, 1978. Ecological studies in the western Sacramento-San Joaquin Delta during a dry year. Water Science Engin. Paper No. 4506. University of California, Davis. 121 pp.

U.S. Army Corps of Engineers, 1967. Report on survey on San Francisco Bay and tributaries, California. App. V, Sedimentation and Sholing and Model Test. Army Eng. Dist., San Francisco, California. 176 pp.

U.S. Bureau of Reclamation, 1972. Delta-Suisun Bay surveillance program. A progress report on the Delta San Luis Drain surveillance portion of the program. Sacramento, California.

U.S. Bureau of Reclamation, 1975. Delta-Suisun Bay ecological studies. A water quality data report of the coordinated monitoring program. Methods and data for 1973. U.S. Bureau of Reclamation, Sacramento, California. 408 pp.

U.S. Bureau of Reclamation, 1977. Delta-Suisun Bay ecological studies. A water quality data report of the coordinated monitoring program. Biological methods and data for 1968-1974. U.S. Bureau of Reclamation, Sacramento, California. 592 pp.

Wiley, M., 1977. Estuarine Processes. Vol. 2. Circulation, Sediments, and Transfer of Material in the Estuary. Academic Press, New York. 428 pp.

Yentsch, C. S., 1965a. The relationship between chlorophyll and photosynthetic carbon production with reference to the measurement of decomposition products of chloroplastic pigments. Primary productivity in aquatic environments. Mem. Inst. Ital. Idrobiol. 18 (suppl.), also University of California, 1966.

Yentsch, C. S., 1965b. Distribution of chlorophyll and pheophytin in the open ocean. Deep-Sea Res. 12:653-666.