WATER QUALITY CHANGES

IN CONVEYANCE AND STORAGE

A Study of

Water Quality Changes in the State Water Project

A Report To

California Urban Water Agencies

By

Alex Horne Associates

Commins Consulting

March 1994

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FOREWORD

California Urban Water Agencies (CUWA) is an organization of the largest urban water providers in California, which serve water to metropolitan areas comprising about two-thirds of the state's 32 million population. CUWA was formed to work on statewide water supply issues. Among these concerns is the quality of waters which are the principal sources of California's drinking water.

This study of water quality changes in conveyance and storage within the California State Water Project was begun during the 1987-1992 drought. It was an effort to learn as much as possible about the changes in water quality characteristics of drinking water as water moves from the Sacramento-San Joaquin Delta southward to the areas of urban use. Most such water quality changes are subtle and current data collection programs are not adequate for the task undertaken. Both the regulatory importance and the scientific understanding of organic disinfection by-products precursors have escalated since this work began. Some of consultant Dr. Alex Horne's recommendations go to this important topic.

While this study did not answer all the questions presented to it, it produced as much information as possible under the circumstances. This work is a step along the way to a better understanding of water quality changes in conveyance and storage. Its recommendations should lead to better answers when more adequate data are available.

California Urban Water Agencies

Alameda County Water District
Contra Costa Water District
East Bay Municipal Utility District
Los Angeles Department of Water and Power
Metropolitan Water District of Southern California
Municipal Water District of Orange County
Orange County Water District
San Diego County Water Authority
San Diego Water Utilities Department
San Francisco Public Utilities Commission
Santa Clara Valley Water District

SUMMARY

Changes in important water quality indicators (suspended algae, total trihalomethane formation potential (TTHMFP), taste and odor) which could occur during conveyance and storage in the State Water Project (SWP) facilities upstream of San Luis Reservoir were examined for the period 1987-90. Suspended algae are a problem in drinking water supplies in that they clog sand filters, may produce taste and odor problems and THMFP precursors, increase pH and reduce nocturnal dissolved oxygen in storage systems, and some produce toxins. Attached algae are a problem for similar reasons but they also reduce the hydraulic capacity of aqueducts and must be controlled with copper sulfate or other algicides.

TTHMFP in the Sacramento-San Joaquin Delta (Delta) and the South Bay Aqueduct (SBA), shows a statistically significant change on both a large and small time scale (years and seasons), during the conveyance and storage of water in the SWP between the Sacramento River, the Delta, and the SBA terminal reservoir. There are large (about 1.5 fold) increases in annual average TTHMFPs between the Sacramento River and Delta stations. These differences in TTHMFP were statistically significant between the Sacramento River and the Delta ($p<0.05$) but not between the Delta and the SBA terminal reservoir. This indicates that the Delta is the main source of TTHMFP, as has been reported by others. Almost identical values for Rock Slough and Clifton Court suggest that TTHMFP contamination occurs primarily between Greene's Landing to Rock Slough, in agreement with the DWR's 1990 finding that much of the additional organic carbon loading in the Delta originates from the peaty islands of the central Delta. In contrast, statistically significant differences between the Delta and the SBA terminal reservoir were found only on a short-term basis (months). This is a new finding and indicates that, in spring, some TTHMFP is due to conveyance in the SBA. The presumed source is either algae on sunlit channel walls or any agricultural water that is allowed to flow into the SBA.

It is well known that suspended algae are more numerous in the Delta than in the Sacramento River source water but trends within the Delta conveyance routes and the aqueducts are less well known. Unfortunately, different types of measurement are used to determine suspended algae in the Delta (extracted chlorophyll *a*) and in the lower Delta and SBA (*in situ* fluorescence). Using an empirically derived conversion factor and deseasonalizing the data, general patterns become apparent. The trend for suspended algae in SWP is for it to increase greatly within a short distance after water enters the Delta, decrease slightly as water moves through the Delta, and then slightly increase again as it moves along the SBA. This is true in all seasons except in winter when a very large increase occurs within the SBA. This may be due to the cessation of copper treatments in winter in this aqueduct.

A severe blue-green algal-caused taste and odor problem occurred in San Luis Reservoir in 1988 and was conveyed at least to the Calero Reservoir in the Santa Clara Valley Water District Reservoir System. This was probably a drought-related event since the water level in San Luis at the time was so low that water was being withdrawn from its surface.

No serious diatom-caused taste and odor event in water from the Delta has occurred since the installation of continuous algae monitoring systems in the aqueducts. From an analysis viewpoint this was a drawback since such events have been important in the past and may occur in the future.

Despite good cooperation from most agencies, it was not easy and took a long time to obtain and process most of the data required for this type of report. Each agency collects data for its own purposes and these may not be in a form that is easily comparable with other data. Often the most reliable data source was the original written notebook files. These were then transferred to computer files. Many ongoing programs became known to us only by accident and baseline data were not available in the appropriate forms.

RECOMMENDATIONS

1. The seasonality and spatial patterns of suspended algae and TTHMFP in the Delta and SWP should be measured under normal water conditions. This is needed in light of possibly permanent changes in dominant algae and productivity that have occurred in other lakes and reservoirs following the 1977 and 1987-92 droughts. For example, there have been no nuisance taste and odor blooms of diatoms in the 1985-92 period but such blooms occurred irregularly prior to 1985. Is this a permanent and beneficial change or an effect of the long drought? In a similar vein, it is not clear if TTHMFP from the Delta will increase or decrease in normal water years when compared with the only good measurements made which were in low water years. The DWR is evaluating some data at the moment which will throw some light on this problem.

2. Standardization of the methods of analysis of TTHMFP and algal pigments is needed. The current in-line fluorescence data in the SBA are very valuable but cannot easily be compared with the spot samples of chlorophyll *a* pigment measured in the regular monitoring programs of the DWR and other agencies. Chlorophyll *a* is a much more reliable parameter than fluorescence so regular (biweekly) calibration of the on-line fluorescence with chlorophyll *a* in actual samples taken simultaneously are needed. Chlorophyll *a* data are valuable because it is a major variable measured by most other agencies and research workers. It would be useful to compare the Delta data with that from other locations. For such comparisons to be made an intercomparison of all the agencies and universities results using split samples is needed, especially since the methods are different. Recent experience with other agencies has shown that there can be very large differences (up to 2.4 times) due to different methods of measurement.

3. An ongoing data pool for the constituents of interest to the urban water agencies should be set up and annual trends should be reported in simple graphical form.

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CHAPTER 1: INTRODUCTION

OVERVIEW

From the viewpoint of drinking water users, all water is degraded as it passes from rain to streams, lakes, reservoirs, and rivers. Increases in both organic and inorganic compounds and both soluble and particulate matter are inevitable. In California, water quality degradation is particularly noticeable in water exported from the Delta because i) the quality of the water is highly variable over periods of weeks to years, ii) at worst the water is of marginal quality so further degradation poses serious problems, and iii) the detention time of SWP supplies from the Delta to consumers is highly variable (as low as 1 day in Alameda County to two years in the Los Angeles area). Of special interest are changes in water quality that occur as water carried by the SWP passes to consumers via rivers, reservoirs, pipes, and open channels as well as when passing through the Delta. A diagram of the SWP in the area of concern is shown in Figure 1-1 and a map of the most of the same facilities is shown in Figure 1-2.

The recent extensive Sanitary Survey of the State Water Project (Brown & Caldwell, 1990) suggests that, on a broad scale during 1975-1981, major degradation in the annual average values of many water quality parameters occurred as a result of Delta cross-transport, but not in reservoirs or aqueducts.

Increases in most contaminants are within the range of treatment capabilities of conventional water treatment facilities or are not objectionable or unhealthy for consumers. However, certain components such as the organic compounds that form TTHMFP are, or presage, problems for drinking water treatment facilities.

TTHMFP in the SWP is mostly due to organics in drainage and seepage water from within the Delta but extra-cellular products of photosynthesis and decay of attached and/or suspended algae in reservoirs and aqueducts contribute some TTHMFP. Chlorophyll and fluorescence both measure suspended algae, most of which actually grows within the SWP conveyance and storage facilities. Past experience indicated that algae were associated with taste and odor problems in the SWP facilities.

SCOPE OF WORK

This project considered two questions about water quality changes due to conveyance and storage. First, was there additional and useful water quality information on variables reported in the 1990 Sanitary Survey? Second, was there data on any changes not reported in the Sanitary Survey?

Some problems such as taste and odor were not considered in the 1990 Survey, due to lack of data. In addition, important effects at smaller space and time scales might have been obscured by annual averaging. Finally, the broad brush approach of the Sanitary Survey was not appropriate for rigorous statistical analysis of those variables where adequate data are available.

The initial finding was that there was some information that would add to the findings of the 1990 Sanitary Survey. These were in the areas of smaller spatial scale changes in suspended algae and TTHMFP for both the Delta and the 43 miles of the SBA. Recent collections of TTHMFP, chlorophyll, and continuous-flow fluorescence measurements were not of long enough duration to be included in the Sanitary Survey. Sufficient data were available for some statistical analysis of TTHMFP and algae (as chlorophyll or fluorescence). In addition, the lack of any recent algae-based taste and odor events was such a contrast with the past that some comment seemed appropriate. Other data were not available in a suitable form, were not available to us at the time, or were not being collected.

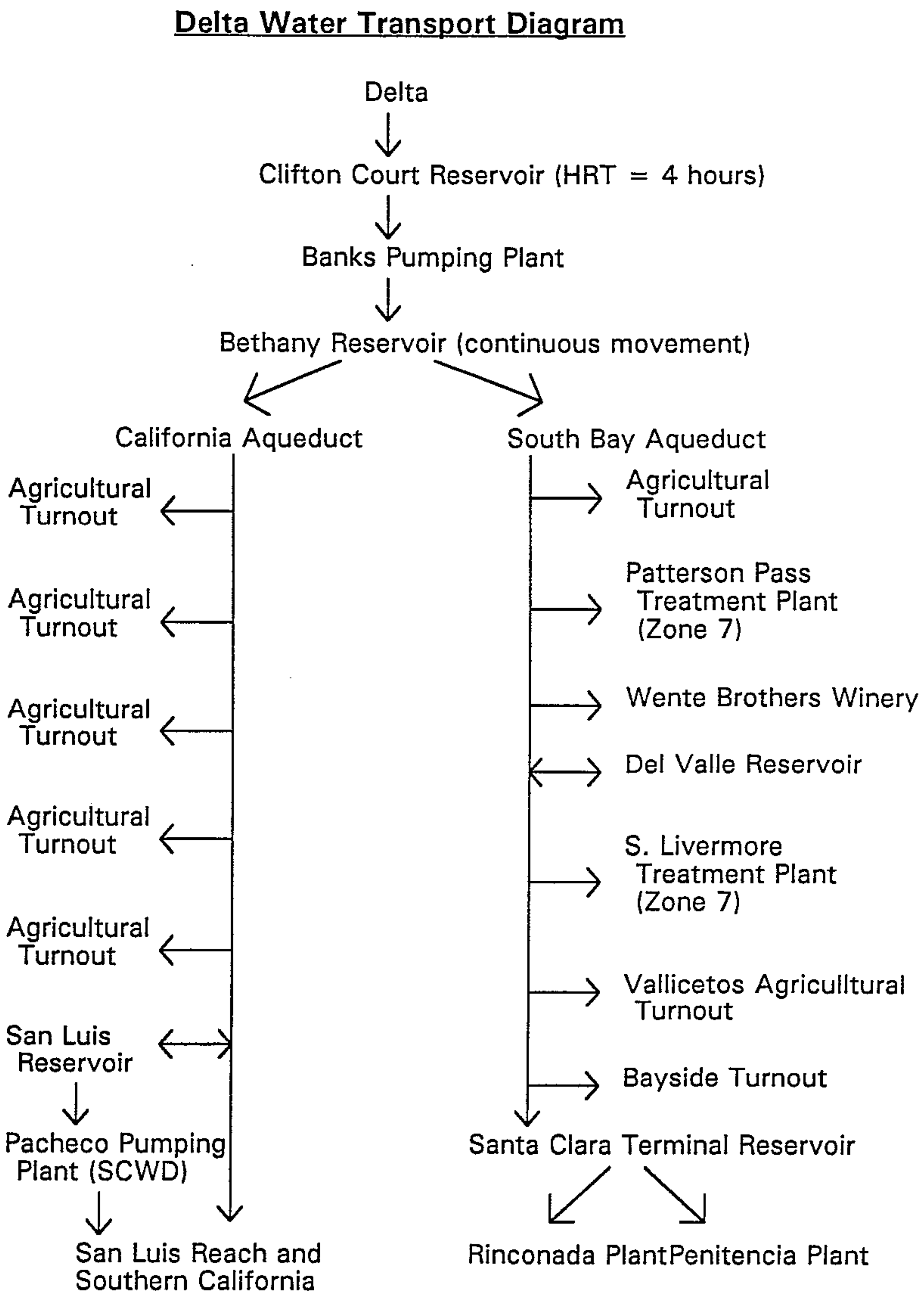

Figure 1-1. Diagram of the upper State Water Project distribution system.

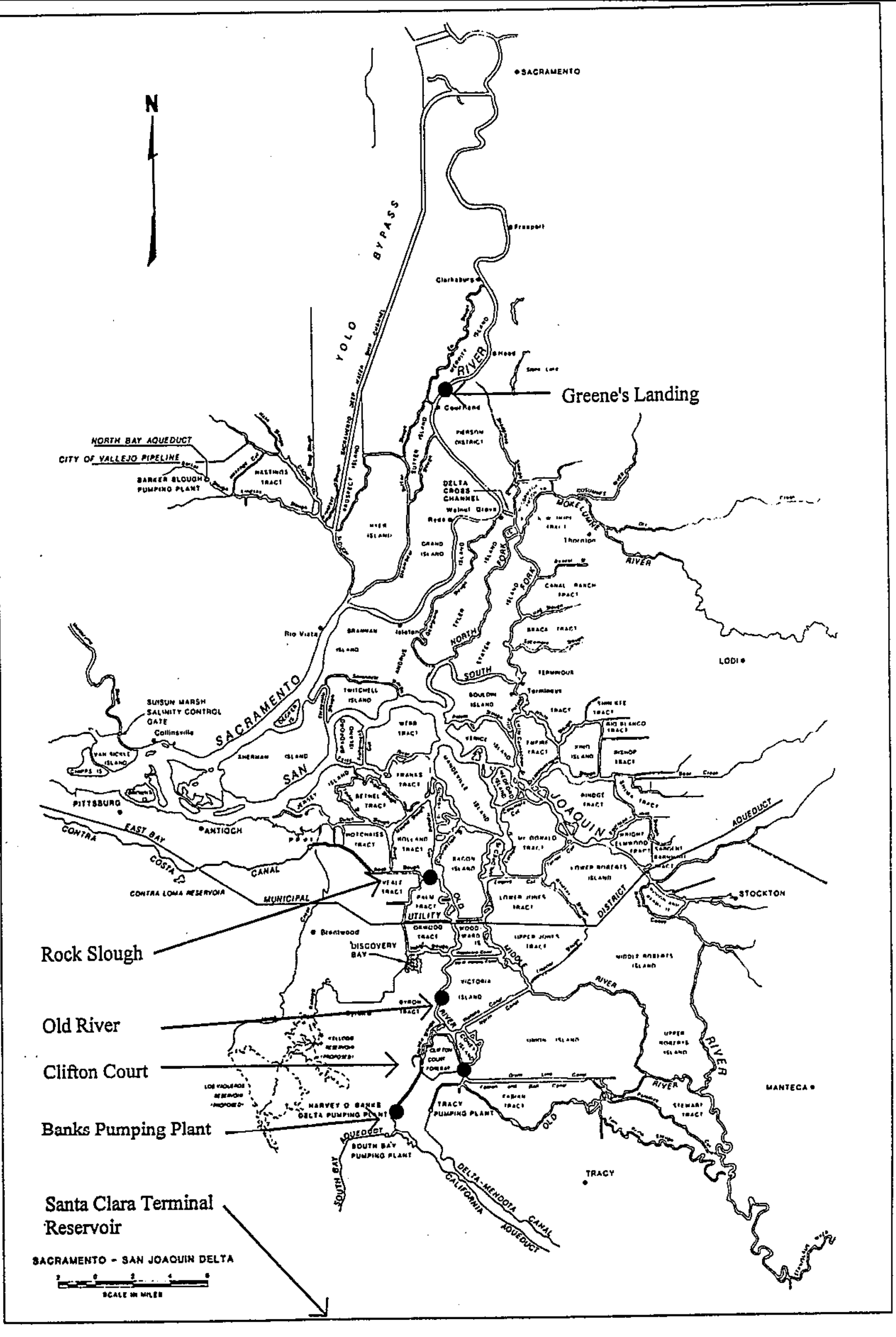

Figure 1-2. Map of State Water Project facilities in the vacinity of the Delta and monitoring stations used in this report.

CHAPTER 2: TOTAL TRIHALOMETHANE FORMATION POTENTIAL (TTHMFP)

CHAPTER SUMMARY

Statistical examination of total trihalomethane formation potential (TTHMFP) values from stations in the Sacramento River, the Sacramento-San Joaquin Delta (Delta), and the South Bay Aqueduct (SBA) terminal showed there are statistically significant changes in TTHMFP, on both a large and small time scale, during the conveyance and storage of water in the SWP. Over the long-term period, average annual TTHMFPs increased by about 1.5 times in the Delta over the levels found in the Sacramento River above the Delta. These increases were statistically significant ($p < 0.05$). There were no significant differences between the Delta stations and the terminal station. This indicates that the Delta is the main source of TTHMFP - as has been reported by others. The almost identical concentrations for annual TTHMFP values for the two lower Delta stations (Rock Slough and Clifton Court) suggests that contamination occurs in the upper or central Delta between Greene's Landing and Rock Slough. This is in agreement with Department of Water Resources data which indicate that agricultural drainage from the peat islands of the Central Delta are, in fact, the major source of organic loadings

In contrast, statistically significant differences between a Delta station and the terminal station were apparently short-term. This is a new finding and indicates that some TTHMFP is due to conveyance in the SBA. The presumed source is either the growth of algae in the channel walls where they are exposed to light or inflows of agricultural return waters.

There were indications of other short-term differences in the system. Further and more frequent data are needed to accurately quantify these differences.

INTRODUCTION

ORIGIN OF TRIHALOMETHANES

The production of possibly harmful contaminants during the chlorination of drinking water is one of the most troublesome problems for water supply agencies. It is particularly a problem for agencies which receive water transported over long distances in rivers or open canals. In these cases, especially in the Sacramento-San Joaquin Delta, algal growth and runoff from wetlands and terrestrial soils provide sources of organic molecules that are the precursors for trihalomethanes. The capacity to form trihalomethanes is measured as TTHMFP. In addition to algal growth in the large Delta canals, algal growth on the walls of smaller canals such as the SBA could also be a source of TTHMFP.

The time scales of TTHMFP are not well understood for Californian water supplies. Long-term trends in TTHMFP may be dissimilar from short-term fluctuations. Because large water treatment facilities must meet water quality standard on a running annual average, even small increases in TTHMFP are important if they begin to approach or exceed regulatory criteria. In addition, the USEPA is considering lowering the current THM standards and adding other specific compounds to the general group of disinfection by-products now regulated.

This section of the report examines the current differences in TTHMFP over both large and smaller time scales. Finally, the TTHMFP data available are given a rigorous statistical analysis since this was not the done in other studies.

DATA SOURCES AND DATA ANALYSIS

The analysis was divided into two sections. The first examines the long-term (years) patterns found for TTHMFP. This focuses on sites above, within and below the Delta and its conveyance facilities. The second section considers the short-term (months) patterns in TTHMFP between the Delta stations and the terminal water treatment plants in South San Francisco Bay (see Figures 1-1 and 1-2).

TTHMFP data were analyzed from Greene's Landing in the Sacramento River and two locations in the Delta: Rock Slough, and Clifton Court. These data were collected from February 1985 to November (Greene's Landing) and December 1987 (Rock Slough and Clifton Court). Data for TTHMFP from the raw water intake to the Mission San Jose Water Treatment Plant (MSJWTP) collected between January 1986 and December 1987 were also analyzed. The water supply to the MSJWTP comes entirely from State Water Project (SWP) via the SBA (Beard et al. 1984, J. Marchand pers. comm.).

Data on TTHMFP from Sacramento River and Delta water sources were obtained from Table G-3 in "The Delta as a Source of Drinking Water" (DWR 1989). They are also reported in "Delta Islands Drainage Investigation Report" (DWR 1990). Data on TTHMFP from raw water intake of the MSJWTP were provided by the Alameda County Water District. John Marchand, Chemist II in charge of analyzing TTHMFP for the Alameda County Water District, indicated that the methods they use are very comparable to those used by the laboratories for the DWR in producing data for the above report (J. Marchand, pers. comm.).

Data were first analyzed with WQStat II. This program allows detection of seasonality in data using the Kruskal-Wallis seasonality test and trends (an increase or decrease in a water quality variable over time) using the Kendall Tau test. Tests for significant differences were conducted using standard nonparametric tests (the Wilcoxon signed rank test and the Mann-Whitney test) available on statistical software (WQStat II and Statgraphics). Data from Clifton Court and the MSJWTP collected during 1987 were analyzed on a seasonal basis using the Mann-Whitney test. Spearman rank correlation coefficients were determined between all stations using average monthly data.

RESULTS

LONG-TERM PATTERNS FOR TTHMFP

Mean values for TTHMFP for the 3 years (2 in the case of MSJWTP) in this analysis ranged from 366 μg/L at Greene's Landing to 562 μg/L at the MSJWTP (Table 2-1).

Table 2-1. TTHMFP - descriptive statistics for Greene's Landing), Rock Slough, Clifton Court, and the MSJWTP.				
	Greene's Landing	Rock Slough	Clifton Court	MSJWTP
Dates	6 Feb. '85-3 Nov. '87	27 Feb. '85-8 Dec. '87	27 Feb. '85-8 Dec. '87	2 Jan. '86-3 Dec. '87
median (µg/L)	280	545	533	555
mean (µg/L)	366	521	544	562
s.d.	238	147	149	124
c.v. (%)	65%	28%	27%	22%
range (µg/L)	131-1110	225-775	174-910	386-968
seasonality	n.s.	n.s.	n.s.	n.a.
trend	n.s.	n.s.	n.s.	n.s.

n.s. = not statistically significant ($p < 0.10$)
n.a. = analysis not available

The TTHMFP from Greene's Landing was significantly lower ($p < 0.05$) than the TTHMFP found at all the other stations (Table 2-2). There were no significant differences between the TTHMFP values from any of the other stations ($p > 0.10$).

Table 2-2. Probability of differences between Greene's Landing, Delta stations, and the MSJWTP. (p < 0.05 indicates a 95% probability that the stations are different. n.s. indicates there is no significant difference between stations.)				
	Greene's Landing	Rock Slough	Clifton Court	MSJWTP
Greene's Landing	-	$p < 0.05$	$p < 0.05$	$p < 0.05$
Rock Slough	$p < 0.05$	-	n.s.	n.s.
Clifton Court	$p < 0.05$	n.s.	-	n.s.
MSJWTP	$p < 0.05$	n.s.	n.s.	-

With one exception, the Spearman rank correlation coefficients between the TTHMFP found at the four stations were low and not significant (Table 2-3). They ranged from

-0.191 (between Clifton Court and MSJWTP) and -0.456 (between Rock Slough and MSJWTP). The exception to this was the relatively high and statistically significant ($p < 0.001$) correlation of 0.704 between the TTHMFPs at Rock Slough and Clifton Court.

Table 2-3. Spearman rank correlation coefficients between TTHMFP values found at Greene's Landing, Rock Slough, Clifton Court, and the MSJWTP.

	Greene's Landing	Rock Slough	Clifton Court	MSJWTP
Greene's Landing	1.000	.2145	.1982	.3294
Rock Slough	.2145	1.000	.7043	-.4560
Clifton Court	.1982	.7043	1.000	-.1912
MSJWTP	.3294	-.4560	-.1912	1.000

This analysis, summarized in Tables 2-1 to 2-3, indicates that all the sites in the Delta or receiving water from the Delta received a dominant fraction of their TTHMFP compounds in the Delta.

Averaged over the year, the further a site is from Greene's Landing, the longer the water destined for the South Bay Aqueduct will have spent in the Delta. Since Rock Slough is situated in the mid south-eastern part of the Delta, water sampled there will have already spent a considerable fraction of its maximum time in the Delta. It is not surprising, therefore, that the median concentration of TTHMFP almost doubled between Greene's Landing and Rock Slough (Table 2-1). If general exposure to the Delta environment increases TTHMFP, one might expect a similar, but smaller increase between Rock Slough and Clifton Court. However, this is not the case. There is a slight increase (4%) in mean TTHMFP but a slight decrease (2%) in median TTHMFP levels between Rock Slough and Clifton Court. The mean and medians are so close that it appears that the are actually identical. This finding indicates that the main sources of TTHMFP are in the Upper or Central Delta or both (i.e. north or upstream of Rock Slough) or that the variability of the measured TTHMFP concentrations obscures any relationships.

Travel time for SPW water in the Delta is notoriously difficult to estimate and varies considerably over the year. The distance from Rock Slough to Clifton Court is about 30% of the total distance between Greene's Landing and Clifton Court. This last 30% of the travel distance through the Delta does not change the TTHMFP concentrations at all (-2% to +4%), but the first 70% of travel increases TTHMFP by 40% (mean) and 64% (median). One would thus expect the mean TTHMFP to increase from 521 µg/L to about 745 µg/L and the median TTHMFP to increase from 545 µg/L to about 890 µg/L between Rock Slough and Clifton Court.

The hydraulic residence between these two stations is likely to be shorter than between some similarly distant stations in other parts of the Delta due to the presence of the Federal and State pumping stations at Clifton Court and nearby Tracy. However, some measurable increase should have occurred in TTHMFP formation between Rock Slough and Clifton Court if the general Delta conditions were responsible for the input of organics that react with halogens to form trihalomethanes.

The provisional conclusion must then be that the upper and central Delta (above Rock Slough) is the main source of TTHMFP precursors. This could easily be directly investigated using more sites along the path of the SPW and measuring over shorter time intervals. Studies carried out under the dry hydraulic conditions of the late 1980s as part of the "Delta Islands Drainage Investigation Report" (DWR, June 1990), showed that organic carbon roughly doubled between Greene's Landing and the pumping plants in the south Delta. This is in agreement with the findings above that show about a 1.5 fold increases in TTHMFP (Table 2-1), because soluble organic carbon is a main source of precursors for TTHMFP. In addition, the "Delta Islands Drainage Investigation Report" reported that the peaty islands in the central Delta were the source of about half of the carbon loading to the entire Delta. Thus our findings corroborate those of the DWR (1990) and indicate that the sources of TTHMFP are not in the south but in the Delta upstream of Rock Slough.

DATA VARIABILITY

The TTHMFP at any one station was quite variable through time (Figure 2-1). This variability is indicated by the range and standard deviations. The coefficients of variation (c.v.) for Rock Slough, Clifton Court, and the San Jose treatment plant were 22-28% (Table 2-1). In contrast the c.v. at Greene's Landing was 65%. In natural systems such as lakes and rivers a c.v. of 20-35% is not unusual and reflects the inherent variability of natural processes. However, even moderate and "natural" variability through a relatively long time period would mask any differences between sites over a shorter time period.

SHORT-TERM PATTERNS FOR TTHMFP

To overcome masking due to data variability, shorter-term patterns were examined. When analyzed by season, it was found that, although the annual TTHMFPs were not significantly different, the TTHMFP values found in Clifton Court during spring 1987 were significantly lower ($p < 0.05$) than those found in the MSJWTP during the same time period (Figure 2-2). There were no significant differences between the TTHMFPs at these two sites during winter or fall 1987 (there were insufficient data to conduct the analysis for summer). Since the water is conveyed from Clifton Court to San Jose via the SBA, the differences found between the two sites must be due to some effect of the aqueduct. As mentioned earlier, differences in methods are not a likely cause of the observed differences.

SEASONAL TRENDS AT ANY STATION

There were no significant seasonality or trends in TTHMFP values from any of the stations examined.

DISCUSSION

LONG-TERM PATTERNS IN TTHMFP

Our finding that over the moderately large temporal scale of several years TTHMFPs were significantly lower in the Sacramento River than in the Delta and MSJWTP confirms, in part, the conclusions by the Sanitary Survey of the State Water Project (Brown and Caldwell 1990). Although no rigorous statistical analyses were applied, the Sanitary Survey used annual means over several years and concluded that, with respect to

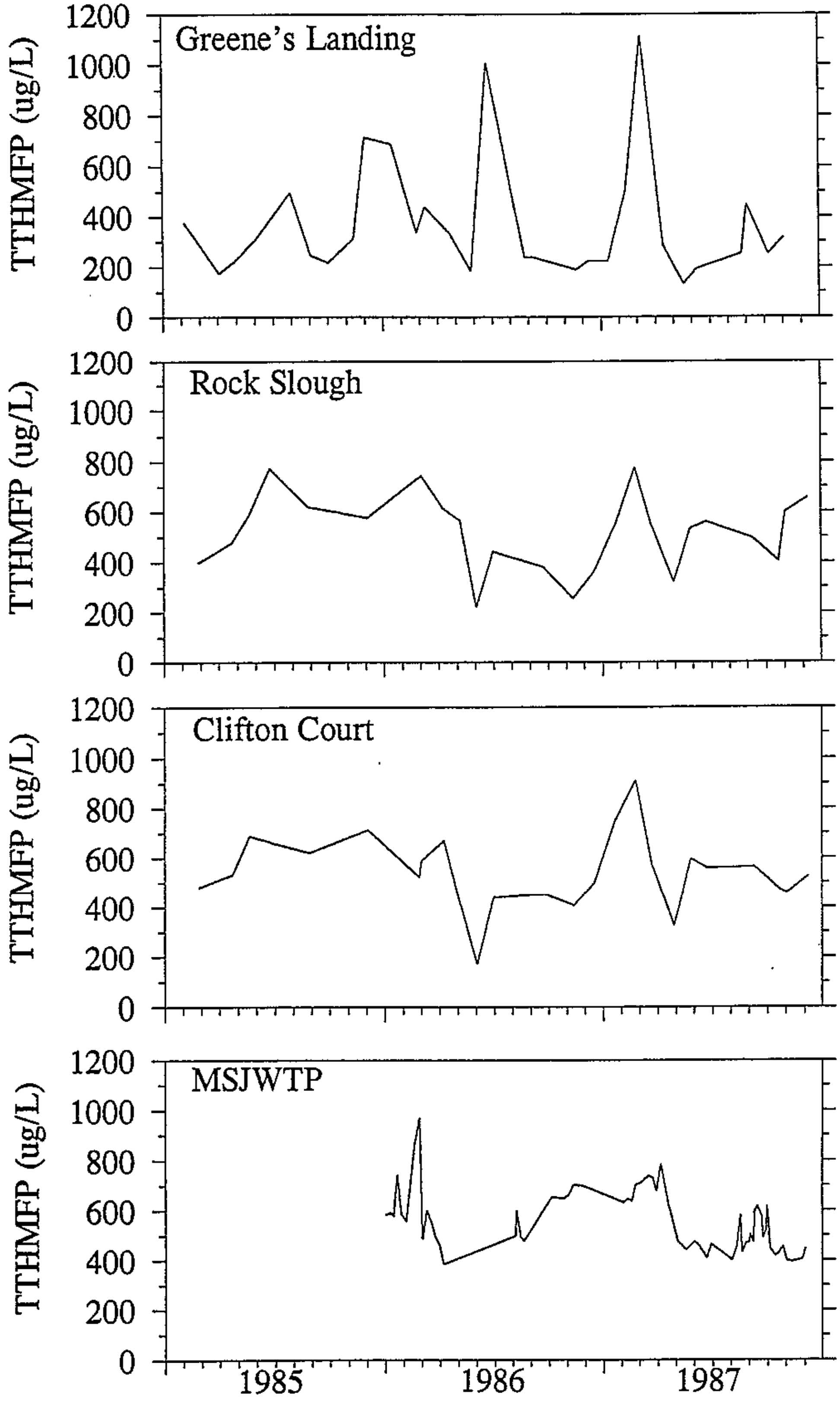

Figure 2-1. TTHMFP for three stations in the Delta and at the terminus of the South Bay Aqueduct (Mission San Jose Water Treatment Plant).

TTHMFP, water diverted from the Delta is significantly degraded below the Sacramento River quality (Brown and Caldwell 1990).

The 1990 Sanitary Survey also concluded that, on a yearly mean basis, there did not appear to be any significant further degradation between the Delta and the SWP terminal reservoirs (Brown and Caldwell 1990). This was also confirmed by our analyses which showed that over a time period of 2-3 years there were no significant differences between the levels of TTHMFP in the 2 Delta stations and the level of TTHMFP at the MSJWTP.

SHORT-TERM PATTERNS FOR TTHMFP

Although on the scale of years there is no difference in levels of TTHMFP between the Delta stations and the terminal station (MSJWTP), there are effects over months between single stations. This is exemplified by the significant difference in values of TTHMFP between Clifton Court and the MSJWTP during spring of 1987. There may have been a significant difference in TTHMFP between these two sites in summer 1987 (Figure 2-2), but there were insufficient data to test for statistical significance.

At times (spring 1987 in this case), transport through the SBA appears to increase TTHMFP rather than reduce it as would be expected if Delta compounds were the sole source of contamination. The main producers of TTHMFP in the SBA are attached algae, such an *Cladophora* and diatoms. During the summer, these are controlled by weekly additions of acid and copper sulfate. However, at other times of year, including the early spring bloom of algae, no copper is added.

Despite the weak overall correlations, there is a fairly good correspondence in the timing of peak TTHMFP values (Figure 2-1). Lack of strong correlation coefficients may result from samples being collected on different days of the month. The two stations that did show a strong correlation (Clifton Court and Rock Slough) were generally sampled on the same day indicating that there may be important small time scale variability in TTHMFP.

These analyses indicate that there are significant changes in TTHMFP, on both a large and small time scale, during the conveyance and storage of water in the SWP.

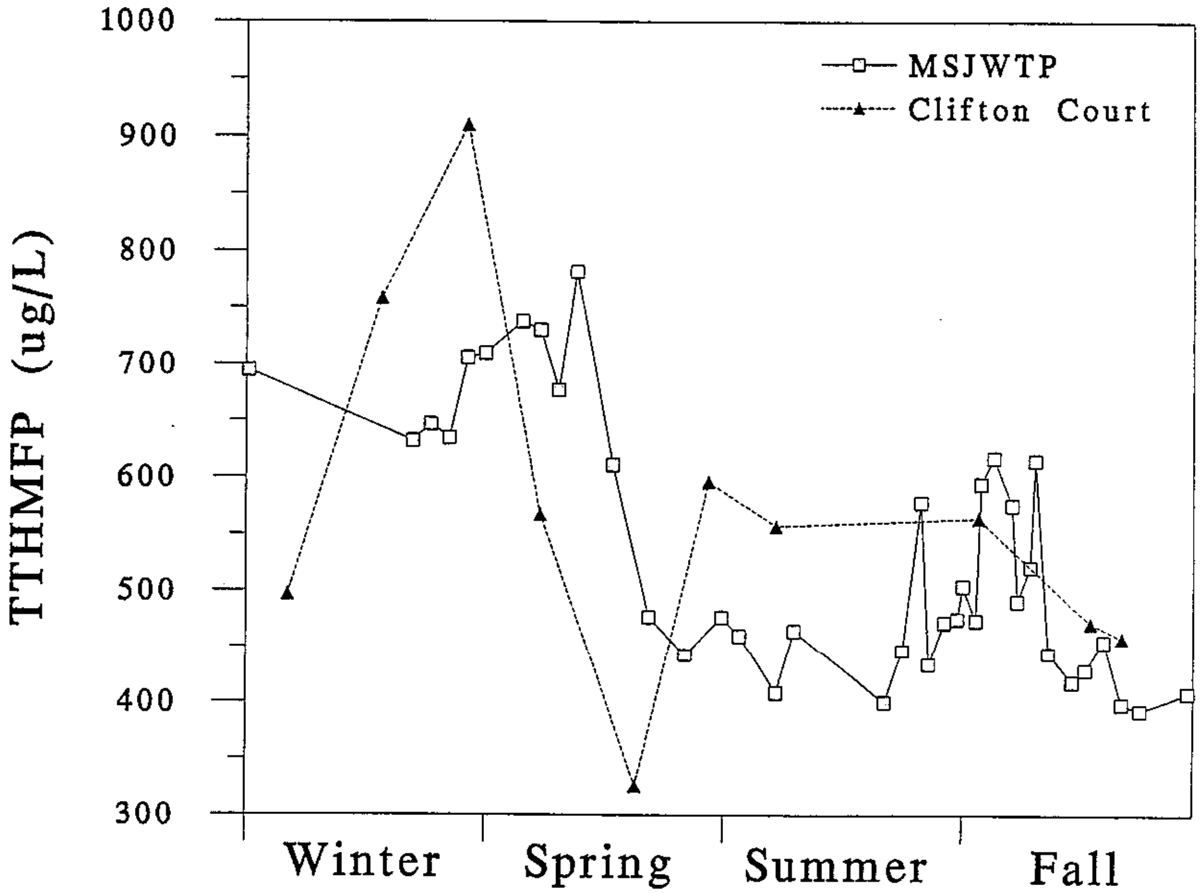

Figure 2-2. TTHMFP for the stations at the beginning (Clifton Court) and end (Mission San Jose Water Treatment Plant) of the South Bay Aqueduct.

CHAPTER 3: SUSPENDED ALGAE (CHLOROPHYLL *A* & FLUORESCENCE)

CHAPTER SUMMARY

Algae in the Delta (as measured with chlorophyll *a*) showed a significant seasonality for the two stations examined (Old River and Clifton Court). Highest mean values occurred in summer with progressively lower values in spring, fall, and winter. In contrast, there was no significant seasonality at the Sacramento River station, Greene's Landing. Significant seasonality in algae (as measured with fluorescence) also occurred at the Santa Clara Terminal but not at Clifton Court and Banks Pumping Plant. Winter values were over twice as high as those found in other seasons, presumably due to growth suppression by copper for most of the year.

Suspended algae in the Delta increased significantly as water passed from the Sacramento River through the Delta to the SWP pumps (deseasonalized values of chlorophyll *a*). In contrast, deseasonalized algae concentrations did not change significantly within the Delta. This new finding indicates an unknown algal growth-regulating mechanism in the Delta. Spatial patterns of suspended algae along the SBA (deseasonalized chlorophyll *a* fluorescence over three years, 1988-1990) showed the Santa Clara Terminal to be significantly higher than other stations, presumably due to growth in the aqueduct. No significant difference was found in the shorter distance between Clifton Court and Banks Pumping Plant.

When examined by season, summer chlorophyll *a* showed a large and significant elevation soon after entering the Delta but little change thereafter. In spring, there was a significant difference between Greene's Landing and Old River but not between other stations. There were no significant differences in chlorophyll *a* levels between any of the stations in winter. In the SBA, there were small but significant differences between Clifton Court and Santa Clara Terminal in all four seasons as shown by chlorophyll *a* fluorescence levels. Although Clifton Court and Banks Pumping Plant are spatially close, significant differences in fluorescence levels were found between them for winter, spring, and fall.

Using an empirically derived conversion factor to compare fluorescence and extracted chlorophyll and deseasonalizing the data, some general patterns become apparent. Suspended algae increase greatly soon after Sacramento River water enters the Delta, decrease slightly as water moves through the Delta, and then slightly increase again as water flows along the Santa Clara Terminal. This is true in all seasons except in winter when a very large increase occurs within the SBA. This is probably due to cessation of copper treatments in winter in this aqueduct.

DATA SOURCES AND DATA ANALYSIS

Suspended algae includes phytoplankton that live and reproduce entirely in open water. Because the water in the Delta is shallow, attached species (periphyton) can temporarily become suspended. In the aqueducts, attached forms of algae routinely become detached and form part of the pseudo-phytoplankton. The entire assemblage of true plankton and temporarily detached periphyton is referred to here as suspended algae. Two types of data used to measure suspended algae were analyzed. The first type of data, chlorophyll *a*, are measured by a filtration, solvent extraction, and photometric method. This is the most reliable measurement of chlorophyll and also the most reliable way to estimate suspended algae abundance. Extracted chlorophyll data were analyzed from Greene's Landing in the Sacramento River and two stations in the Delta: Old River and Clifton Court. These data were collected between 1986 to 1988 and were obtained from the Department of Water Resources.

The second type of data is *in situ* fluorescence of the chlorophyll *a* found in suspended algae. Fluorescence can be measured after filtration and solvent extraction but also can be measured directly in the field. Field or *in situ* measurements are less easy to calibrate and are subject to interference by some other dissolved compounds. The advantage of *in situ* measurements is that much more data can be collected and this may compensate for the lower reliability of the information. Although the two types of data measure the same parameter, uncalibrated fluorescence cannot be directly translated into chlorophyll *a*.

Fluorescence data were available from Clifton Court, Banks Pumping Plant and Santa Clara Terminal at the terminus of the SBA. These data were collected between 1988 to 1990. Some 1986 - 1987 fluorescence data from Clifton Court were also available. Data were obtained from the Department of Water Resources. Both chlorophyll *a* and fluorescence data were only available from Clifton Court.

Data were first analyzed with WQStat II. This program allows detection of seasonality in data using the Kruskal-Wallis seasonality test and trends (an increase or decrease in a water quality variable over time) using the Kendall Tau test. In some cases data were deseasonalized prior to further analyses. This was done by removing seasonal means from each of the data points. Tests for significant differences were conducted using standard nonparametric tests (the Wilcoxon signed rank test and the Mann-Whitney test) available on statistical software (WQStat II and Statgraphics). Data were also analyzed on a seasonal basis using the Mann-Whitney test.

RESULTS

CLIFTON COURT (DELTA) TO SANTA CLARA (SBA)

Changes in suspended algal fluorescence between Clifton Court Forebay in the Delta and the Santa Clara Terminal of the SBA have been monitored automatically by DWR since 1988 (a map of the sites of concern is shown in Figure 1-2). Algal growth in the open channel of the SBA is important for two reasons: attached forms can reduce flow and suspended forms may be harbingers of taste and odor or filter-clogging problems. Suspended algal fluorescence at three sites: Clifton Court and Banks Pumping Plant prior to the aqueduct, and the Santa Clara Terminal at the end of the aqueduct between 1988 and 1990 is shown in Figure 3-1. Considerable year-to-year, season-to-season, and site-to-site variation is evident. Nevertheless, the amounts of algae present at the three sites are quite similar for much of the spring-autumn period. In the winter there was a definite increase between the Banks Pumping Plant and the Santa Clara Terminal. A very large peak of up to 500 TFUs) was reported at the Santa Clara Terminal in February 1989 and can be compared to values of about 50-200 TFUs for the rest of the year. A similar occurrence was found in early winter 1990 (Figure 3-1). For the rest of the year there is little obvious difference between the sites, although the seasonal breakdown shown later does indicate a significant overall increase through the system.

Deseasonalized trends. Mean fluorescence values for the three years (1988-1990) in this analysis ranged from 66 at Clifton Court to 108 at Santa Clara Terminal. There was a significant difference ($p < 0.05$) between the fluorescence values found at Santa Clara Terminal and those found at the other stations. There was no significant difference between the fluorescence values at Clifton Court and Banks Pumping Plant. Data were deseasonalized prior to analysis.

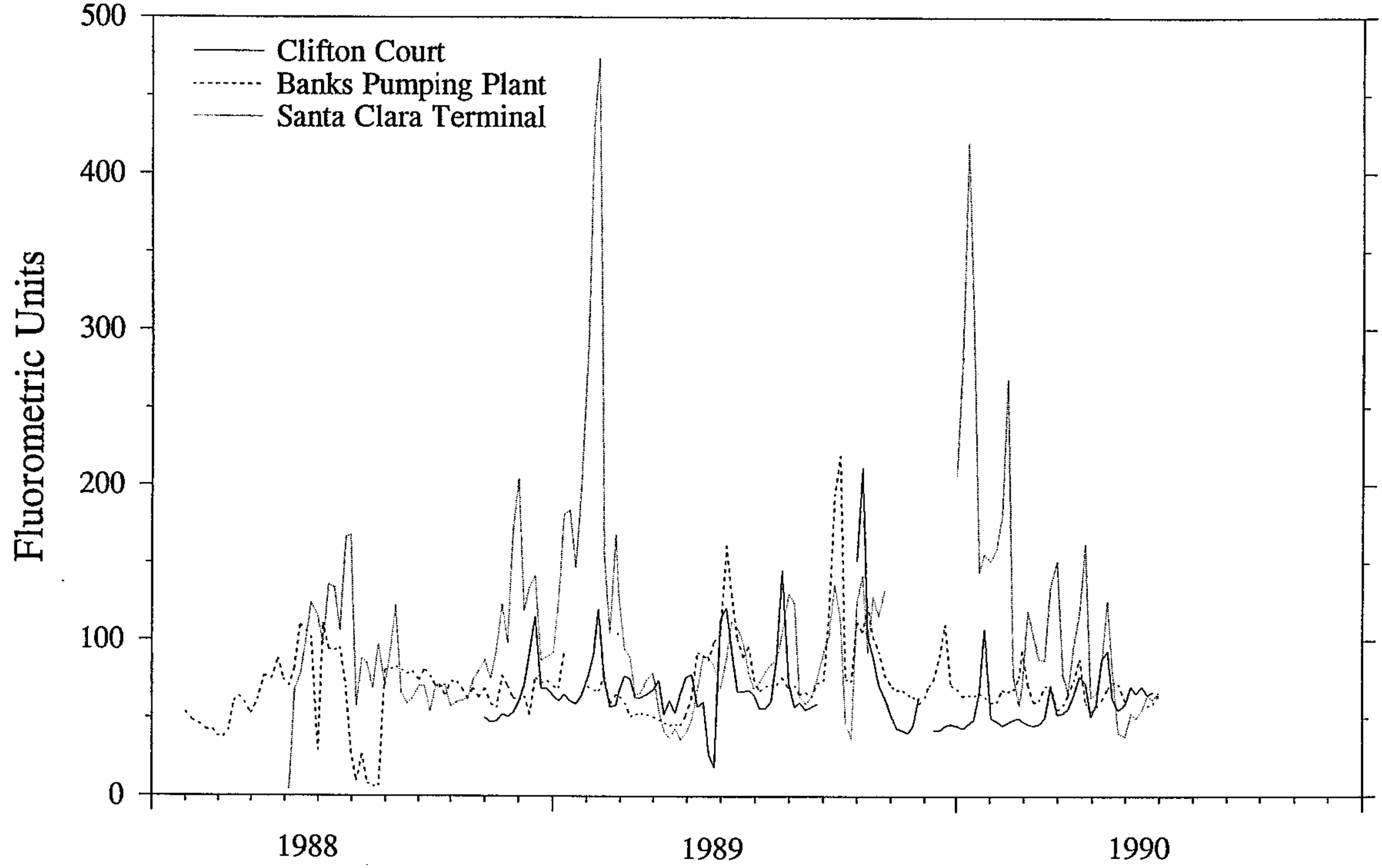

Figure 3-1. Algal biomass (as fluorescence) at 3 sites in the South Bay Aqueduct, 1988-1990.

Seasonality. Fluorescence levels showed significant seasonality at the Santa Clara Terminal. At this station, winter values were over twice as high as those found in other seasons (Table 3-1). There was no significant seasonality in the fluorescence levels at Clifton Court and Banks Pumping Plant.

Table 3-1. Fluorescence descriptive statistics for Clifton Court, Banks Pumping Plant, and Santa Clara Terminal.

	Overall	Summer	Fall	Winter	Spring
Clifton Court					
mean TFU	66	73	71	63	61
median TFU	61	66	51	59	61
s.d.	25	23	45	21	15
c.v.	38%	32%	63%	33%	25%
Banks Pumping Plant					
mean TFU	71	70	83	67	66
median TFU	69	71	72	67	62
s.d.	26	32	34	13	18
c.v.	37%	46%	41%	19%	27%
Santa Clara Terminal					
mean TFU	108	87	90	191	81
median TFU	89	87	83	157	79
s.d.	70	30	32	105	33
c.v.	65%	34%	36%	55%	41%

The presence of significant seasonality at most of the stations indicates that temporal differences in chlorophyll *a* and fluorescence may be present. Therefore the stations were analyzed by season using the Mann Whitney test.

There were significant differences in fluorescence levels between Clifton Court and Santa Clara Terminal in all four seasons (Figure 3-2). There were significant differences in fluorescence between Banks Pumping Plant and Santa Clara Terminal in three seasons (winter, spring, and fall). Although Clifton Court and Banks Pumping Plant are spatially close, significant differences in fluorescence levels were found for three seasons (winter, spring, and fall).

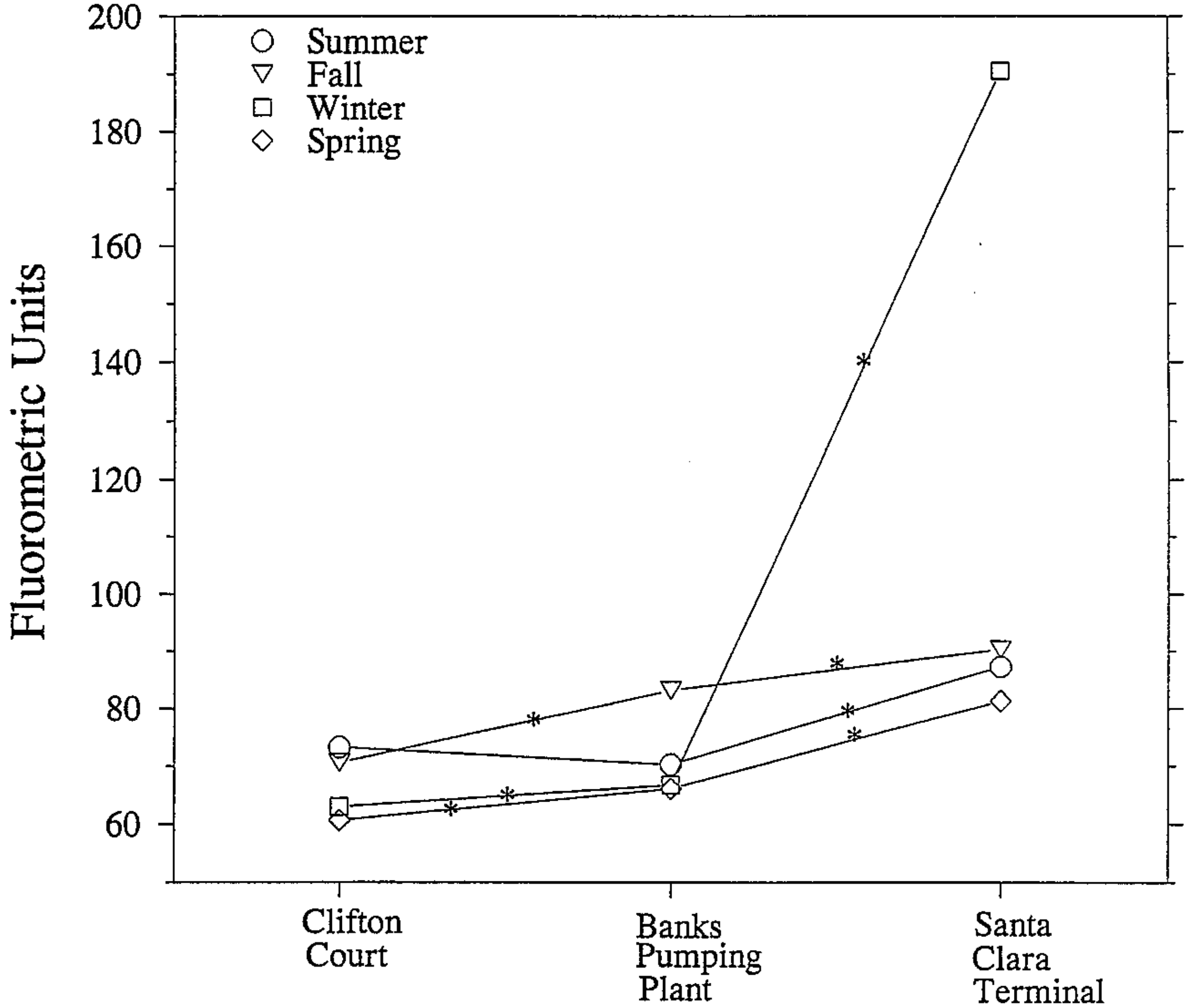

Figure 3-2. Algal seasonality in the South Bay Aqueduct, 1988-89 (as mean fluorometric units.) * indicates a significant difference between adjacent stations.

ABOVE AND WITHIN THE DELTA

The seasonal and spatial patterns of suspended algae as measured by extracted chlorophyll *a*, are shown in Figure 3-3 for Greene's Landing, Old River, Clifton Court (see Figure 1-2 for locations). As is well known from past Delta studies and from other rivers, algae do not grow well in rivers - even in the slow-moving waters of the lower Sacramento River. Thus the low chlorophyll levels at Greene's Landing are expected. The high values (up to 65 µg/l at Old River in summer, and to 30 µg/l for Clifton Court) represent a eutrophic system. For most of the time patterns of chlorophyll at the two Delta stations are very similar as shown in Figure 3-4.

Deseasonalized trends. Mean values for chlorophyll *a* for the three years (1986-1988) in this analysis ranged from 1.3 µg/l at Greene's Landing to 7.8 µg/l at Old River. The chlorophyll *a* level at Greene's Landing was significantly different ($p < 0.05$) from the chlorophyll *a* found at the two Delta stations. The Delta stations (Old River and Clifton Court) were not significantly different from each other. Data were deseasonalized prior to analysis.

Seasonality. Chlorophyll *a* levels showed significant ($p < 0.05$) seasonality at the two Delta stations. The highest mean chlorophyll *a* values occurred in summer with progressively lower values in spring, fall, and winter (Table 3-2). There was no significant seasonality at the Sacramento River station, Greene's Landing.

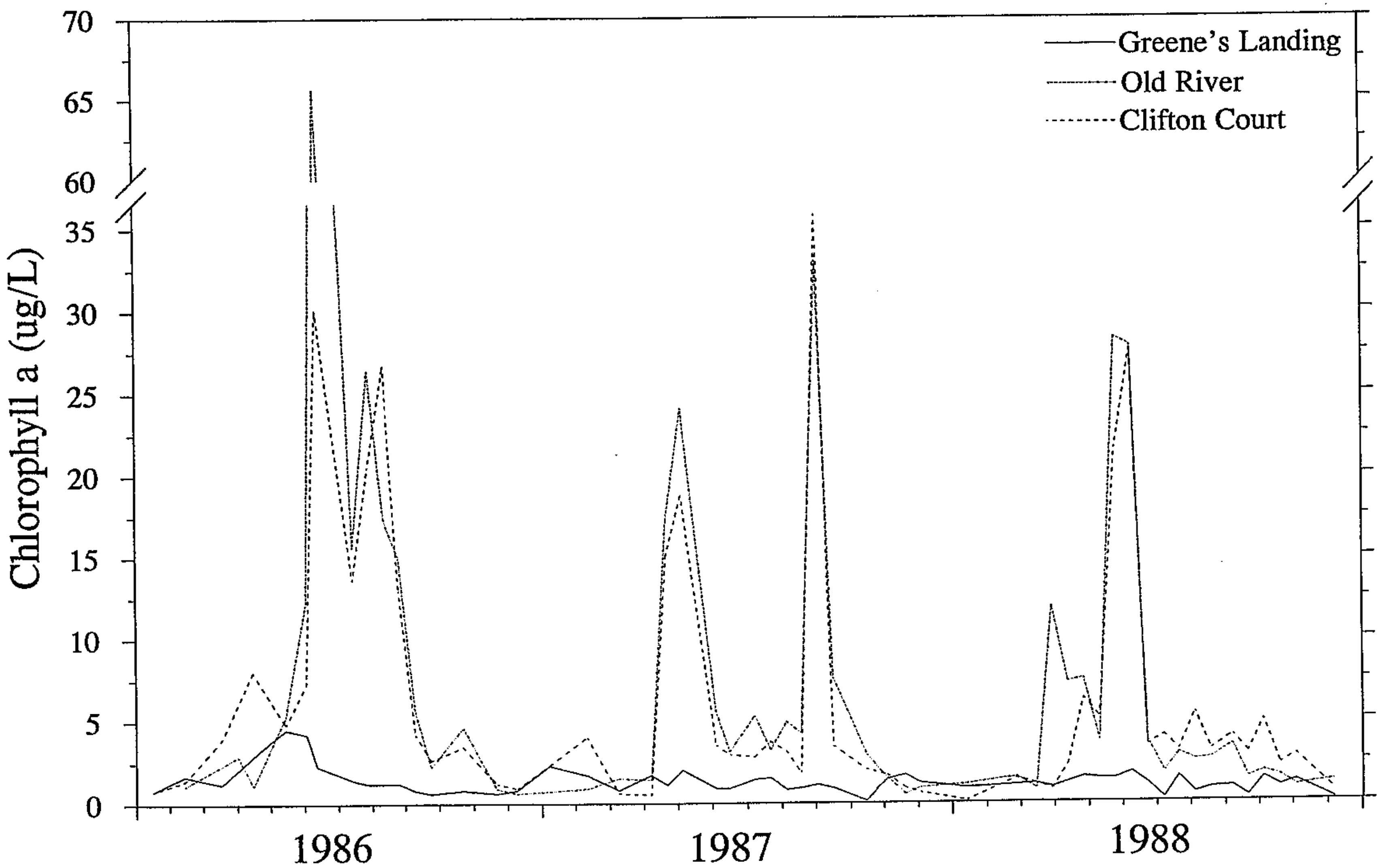

Figure 3-3. Algal biomass (as chlorophyll a) in the SWP. Figure shows values above the Delta (Greene's Landing), in the Delta center (Old River), and at the Delta outlet of the SWP (Clifton Court).

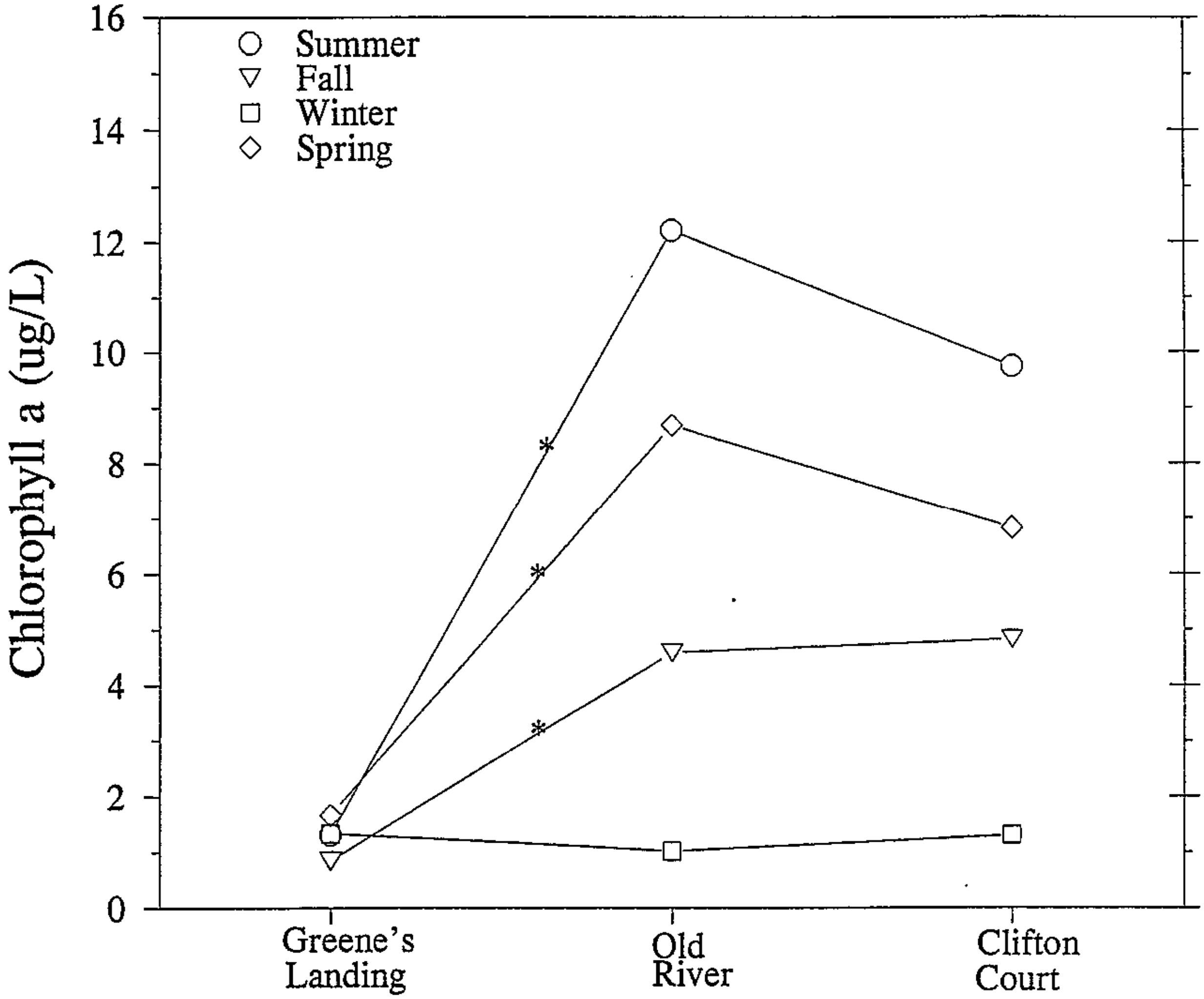

Figure 3-4. Algal seasonality in Delta sites of the SWP and Santa Clara Terminal, 1986-1988 (as mean chlorophyll a values). * indicates a significant difference between adjacent stations.

Table 3-2. Chlorophyll *a* descriptive statistics for Greene's Landing, Old River, and Clifton Court.					
	Overall	Summer	Fall	Winter	Spring
Greene's Landing					
mean µg/L	1.3	1.3	0.85	1.3	1.7
median µg/L	1.2	1.2	0.9	1.2	1.4
s.d.	0.82	0.86	0.47	0.57	1.0
c.v.	64%	66%	55%	44%	59%
Old River					
mean µg/L	7.8	12.2	4.6	1.0	8.7
median µg/L	3.1	5.1	1.8	1.0	5.3
s.d.	11.6	15.7	8.1	0.30	9.1
c.v.	148%	129%	176%	30%	105%
Clifton Court					
mean µg/L	6.5	9.7	4.8	1.3	6.8
median µg/L	3.4	3.8	2.8	0.9	4.8
s.d.	8.4	9.8	8.7	1.3	7.1
c.v.	129%	101%	181%	100%	104%

In summer and fall there was a significant difference in chlorophyll *a* levels between Greene's Landing and both Old River and Clifton Court ($p < 0.01$) (Figure 3-4). There were no significant differences in the chlorophyll *a* levels between Old River and Clifton Court. In spring, there was a significant difference in chlorophyll *a* levels between Greene's Landing and Old River ($p = 0.01$) but no significant difference between Greene's Landing and Clifton Court or Clifton Court and Old River. There were no significant differences in chlorophyll *a* levels between any of the stations in winter.

INTEGRATED OVERALL SEASONAL TRENDS IN SUSPENDED ALGAE (CHLOROPHYLL *A*)

The fluorometric units are not calibrated with respect to chlorophyll *a* and, therefore, cannot be directly converted to chlorophyll *a*. To estimate chlorophyll *a* from the fluorometric reading, we calculated the linear regression between chlorophyll *a* and fluorometric units on the days when both chlorophyll *a* and fluorescence were available from Clifton Court ($r^2 = 0.86$) (Figure 3-5). From the equation of this line, we estimated chlorophyll *a* from fluorescence standardized to the Clifton Court chlorophyll *a* measurements. Chlorophyll *a* and fluorescence converted in this manner to chlorophyll *a* for all stations are shown in Figure 3-6. Examination of the detailed changes in suspended algae (chlorophyll) between the three sites (Clifton Court, Banks Plant, and the Santa Clara Terminal) indicates that some activity is occurring within the channel system. The trend in chlorophyll *a* is to increase greatly by the time water has reached the central Delta stations Jersey Point and Old River, decrease slightly as water moves through the southern Delta (Middle River), and then slightly increase again as it moves along the Santa Clara Terminal (Figure 3-6).

DISCUSSION

Definite and statistically significant increases in suspended algal biomass occur within the SWP system between Greene's Landing and the terminus of the SBA. During the main growth seasons (spring, summer, and fall) there is an increase in chlorophyll *a* as the water moves from the Sacramento River (Greene's Landing) into the Delta (Old River and Clifton Court). This increase is particularly large during summer. Changes in algal biomass also occur as the water moves from the Delta (Clifton Court) through the SBA to the Santa Clara Terminal. Unlike the changes occurring in the Delta, in the SBA there are no significant changes in the summer, but large increases in chlorophyll *a* in the winter.

In the Delta three factors are most likely to account for the increase in algae. These are high nutrient loadings, a longer hydraulic residence time, and shallower water depths. Nutrient loading is high due to the discharge of treated sewage rich in nitrogen and phosphorus from the cities of Sacramento and Stockton, combined with multiple sources of agricultural drainage, also rich in all algal nutrients. Although the Sacramento wastewater treatment plant outfall is above Greene's Landing, the hydraulic residence time in the Sacramento River is too short (few hours at normal flows) to allow the growth of phytoplankton which would require several days to produce even a doubling in growth. Because of the more favorable conditions for algae growth in the Delta, a six-fold increase in chlorophyll *a* between Greene's Landing and Old River was shown in summer (Fig. 3-4). The current velocity and turbulence in the artificially-confined channel of the Sacramento River downstream of Greene's Landing are also not conducive to phytoplanktonic growth since the photic zone is thin and the depth of mixing large. Similar arguments have been used to account for the low phytoplankton growth in the channels upstream of Susuin Bay relative to growth in the Bay itself (Arthur and Ball, 1979). In contrast, the slower flows and consequently longer hydraulic residence time of the Delta water permits algal growth unhindered by washout of cells or deep mixing into dark bottom waters. However, since the Delta and the SBA are very different limnological systems, the increase in hydraulic residence time in the Delta cannot be the only reason for the continued increase through the system.

In the SBA, the large winter increase in chlorophyll *a* as the water moves from Banks Pumping Plant to the Santa Clara Terminal is probably due to a combination of good growth conditions within the channel and the cessation of copper treatment. The attached

forms frequently slough off from the concrete walls of the channel and block outlet pipes and gratings. The most common attached algae in the SBA is the large filamentous green algae, *Cladophora*, and its common name of blanket weed signifies its nuisance potential. The high algae biomass at the end of the channel in winter (January-April) is clearly due to growth and sloughing off since copper is not used at this time. *Cladophora* is now

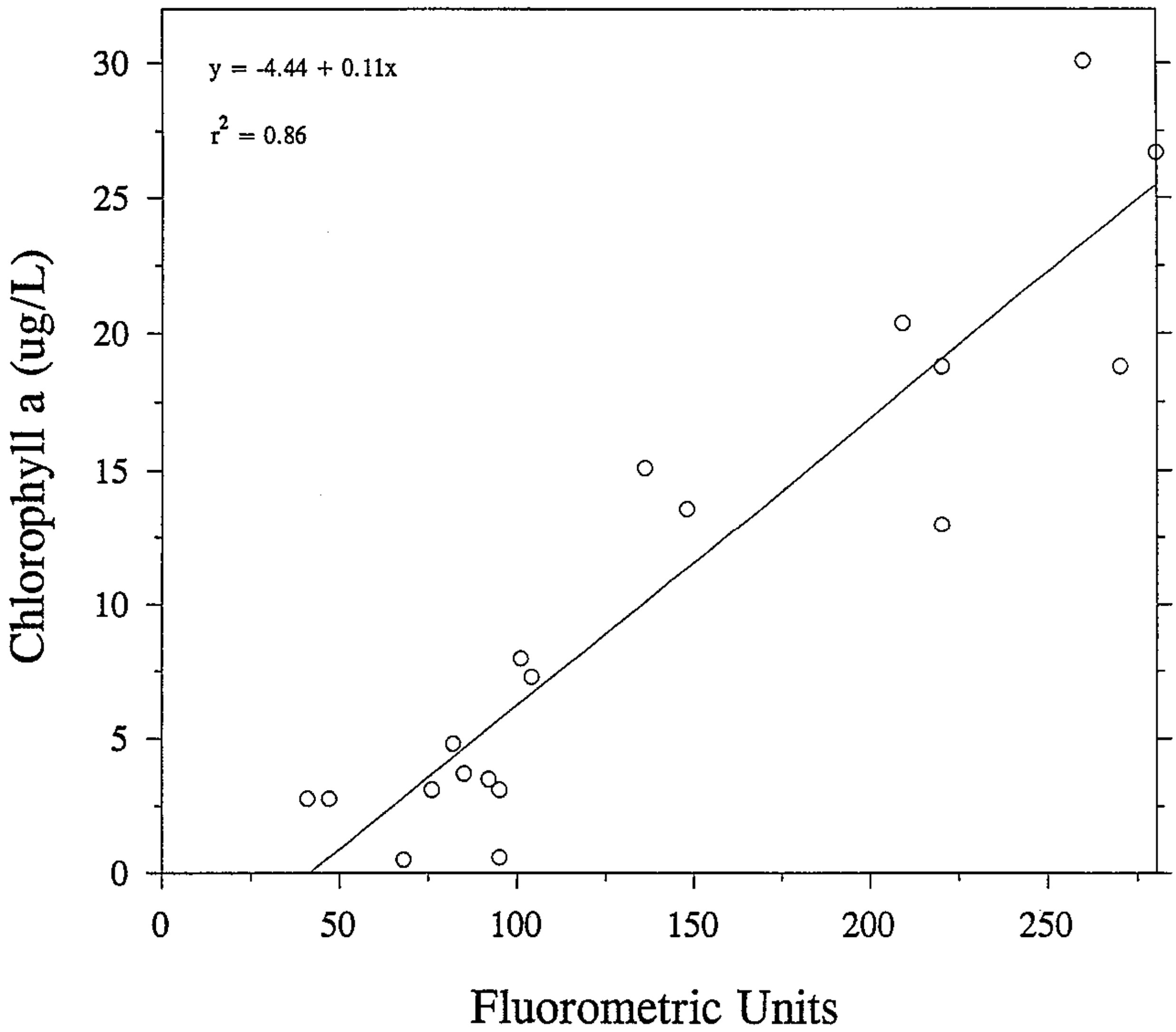

Figure 3-5. Regression of chlorophyll a and fluorometric units for the Clifton Court site.

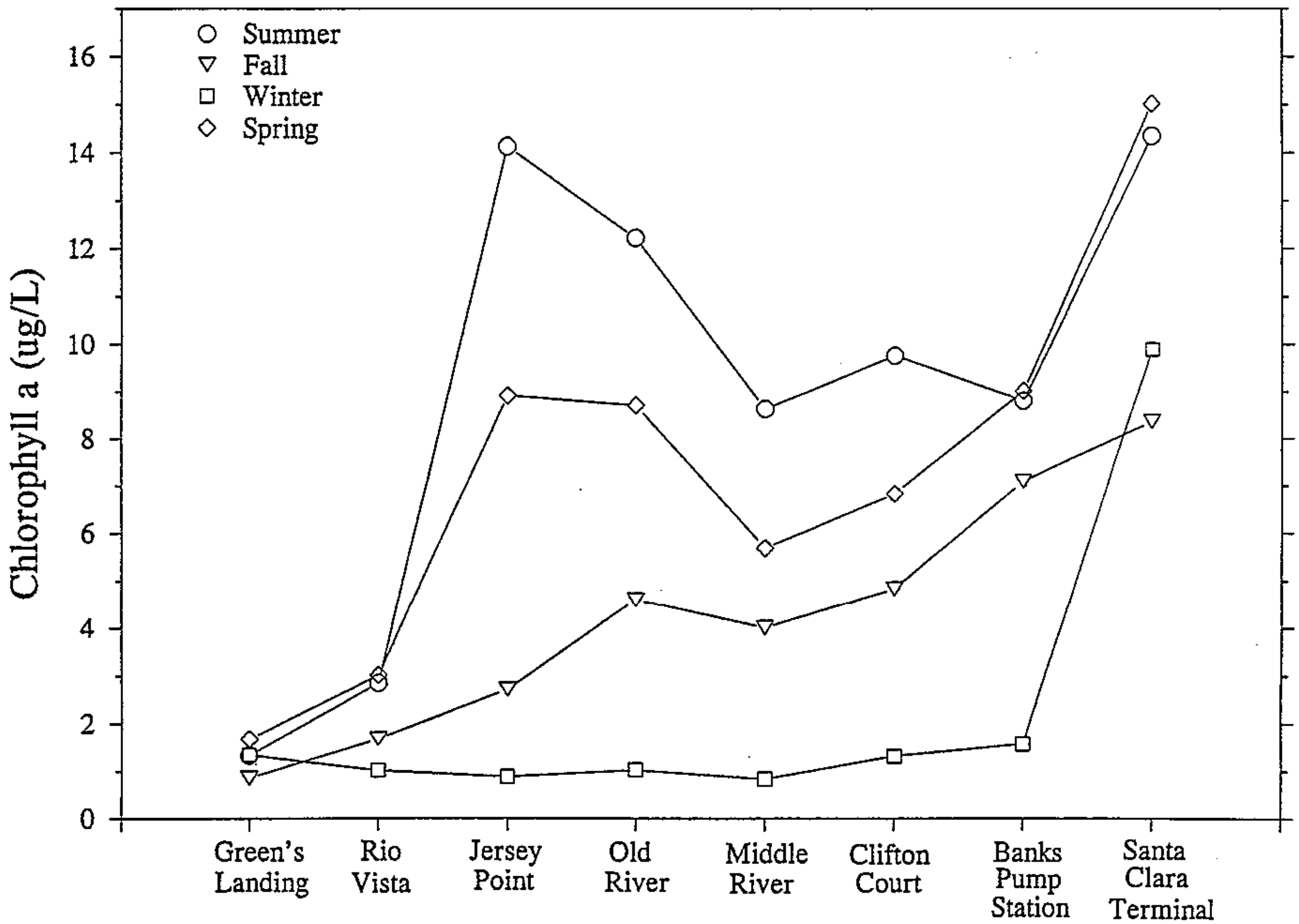

Figure 3-6. Seasonal means for suspended algae (as chlorophyll a) from above the Delta (Greene's Landing) to the terminus of the South Bay Aqueduct.

controlled by addition of copper sulfate (or a more effective copper-based substitute). However, copper may soon become a more problematic algaecide since it contributes to the copper load of the most sensitive region of the Bay-Delta, the southern part of South San Francisco Bay.

The effectiveness of the copper treatment can be seen by comparing the spring-autumn period with the winter season. Copper is not applied in winter. Even though the winter season has a lesser growth potential than in other seasons the large peaks in late winter (January-March) at the Santa Clara Terminal are about four times the peaks at any other time of year. The peaks are due to growth in the aqueduct and are not due to growth in the Delta being passed through the system since at this time the Delta phytoplankton is quite low. Although the difference is small, there is a also a noticeable increase in algae over the short distance between Clifton Court and the Banks Pumping Plant. This may be due to growth in the channel. Some of the increase could be due to the influence of the Clifton Court reservoir although its hydraulic residence time of 4 hours indicates that no algae would be able to reproduce and sustain a population since washout would occur.

CHAPTER 4. TURBIDITY, TASTE AND ODOR, AND EFFECT OF SAN LUIS RESERVOIR

CHAPTER SUMMARY

Turbidity in water is a combination of suspended algae and suspended inorganic detritus such as fragments of leaves and fine silts. In midsummer 1989, there was a considerable increase in turbidity at the Banks Pumping Plant which apparently did not come from Clifton Court. For the months of May-July, turbidity averaged approx. 30 NTU (Banks Pumping Plant) but only about 20 NTU (Clifton Court). The increase was not due to algae which showed no change at this time and may be due to the increased velocity of the water scouring the channel. One effect of siting a large reservoir on the SWP aqueduct is shown by the large, long-term decrease in turbidity at the outlet of the San Luis reservoir, relative to its supply water (Banks Pumping Plant). In autumn 1988 the effect was reversed with a high (non-algal) turbidity peak which was out of phase with the Delta sources.

For much of the 1970-mid 1980s agencies receiving water from the Delta via the SBA experienced taste and odor problems in late spring. These did not occur every year but were usually coincident with blooms of diatom phytoplankton in the Delta. Taste and odor is retained in healthy algae until they decompose and so, in theory, they can be traced as chlorophyll or fluorescence. However, no taste and odor outbreaks have occurred since the installation of the continuous algal monitoring stations in summer 1988. The current 1986-92 drought or changes in biota in the Delta may have eliminated conditions conducive to taste and odor blooms in the Delta. It is not clear if this change will be permanent but such long-term changes are known to occur.

A serious taste and odor event did occur in Calero Reservoir (Santa Clara Valley Water District) in 1988. It was traced to a bloom of floating blue-green algae in San Luis Reservoir. The event may be quite common but the very low water level of San Luis in the drought year(1988) allowed near-surface water to be transported to the next reservoir.

TURBIDITY

Turbidity in drinking water supplies is undesirable in that it presents a treatment problem (clogged filters), indicates potential pathogens (viruses, bacteria, and parasites), and is aesthetically unpleasant.

Any detention structure will allow settling of particulate turbidity. In addition, in permanent lakes or detention ponds, smaller particles are filtered out by the activity of zooplankton. The latter are particularly effective at removing small, bacteria-sized pathogens such as parasite spores or resting stages. Water is supplied to San Luis Reservoir from the California Aqueduct. The San Luis Reservoir has an outlet to the Santa Clara Valley Water District via the Pacheco Pumping Plant. Water flows from the Pacheco Pumping Plant to Calero Reservoir.

CLIFTON COURT (DELTA) TO SANTA CLARA (SBA)

Between Clifton Court Forebay and the Santa Clara Terminal the changes in turbidity have been monitored automatically since 1988. In the case of nephelometrically-measured turbidity, both algae and suspended sediment are recorded. Thus the summer patterns are usually dominated by planktonic or detached algae, while the winter turbidity is dominated by suspended inorganic sediments. Although suspended algae can contribute to turbidity, sizable increases in nephelometric turbidity require larger amounts of algae than are usually present in the Delta or aqueducts. Thus this section considers primarily non-algal turbidity. The results are shown in Figure 4-1.

For most of the period of record, the turbidity levels at Clifton Court and the Banks Pumping Plant were similar (Figure 4-1), although the patterns of small increases and decreases were not similar. In midsummer 1989, there was a large increase in turbidity at the Banks Pumping Plant that was not present at Clifton Court. For the months of May-July, turbidity ranged between 22 and 39 NTU (Banks Pumping Plant) but only between 11 and 23 NTU (Clifton Court). The increase was not due to algae which showed no change at this time and may be due to the increased velocity of the water scouring the channel. This would increase benthic sediment erosion and transport as well as increasing algal sloughing from the sides of the channel. A similar event did not occur in 1990, although data are only available to the end of July 1990.

THE EFFECT OF SAN LUIS RESERVOIR

The large contrast in the turbidity of the water in San Luis Reservoir, compared to that in Clifton Court or at the Banks Pumping Plant, is shown in Figure 4-1. The 1989-90 data show very low turbidity (approx. 1-5 NTU) in the reservoir, which was about 25% of that in Clifton Court and Banks Pumping Plant. As might be expected the large turbidity events in the Delta (up to 40 NTU, July 1990) were not reflected in the turbidity in San Luis which remained at 2-3 NTU at this time.

In autumn, 1988, but not 1989, turbidity in San Luis Reservoir rose to 10-15 NTU, compared with values of 7-9 NTU at Clifton Court and the Banks Pumping Plant. At this time there was a large blue-green algae bloom in the reservoir in 1988 but not in the Delta. This algae bloom also was associated with a taste and odor event. At this time the reservoir elevation was about 400 ft amsl, a relatively low water level. Nevertheless, the volume of water in the reservoir at this time would still be much too large to treat with conventional methods such as copper sulfate.

TASTE AND ODOR

During the 1980's taste and odor were occasionally serious problems in water coming from the Delta via the SBA. There are also recent records of taste and odor problems in the East Branch of the California Aqueduct. The taste and odor was attributed to large blooms of a common diatom species in late spring in the Delta. One effect of the large San Luis Reservoir and the future Los Banos Grandes Reservoir is to prevent transmission of Delta taste and odors to more southern agencies. However, no problem (no bloom) has occurred recently in the Delta. The reasons for the absence of the problem may be natural fluctuations, the 6-year drought, or long-term changes due to the introduction of new species into the Bay-Delta ecosystem.

In the autumn of 1988 a serious taste and odor problem occurred in that section of the Santa Clara Valley Water District's facilities that received water from Calero Reservoir. This reservoir is a small system that is fed directly from San Luis Reservoir via the Pacheco-Santa Clara Valley Conduit rather than the SBA (Figure 4-2). Calero Reservoir contained an extensive bloom of blue-green algae at this time including *Anacystis* and *Aphanizomenon* - known taste and odor producers. Under non-drought conditions, Calero Reservoir in mostly filled with local runoff. Because taste and odor apparently only occurred in this reservoir when it was filled with San Luis Reservoir water, a check was made of the San Luis system. Algal counts indicated a large bloom of *Anacystis* in

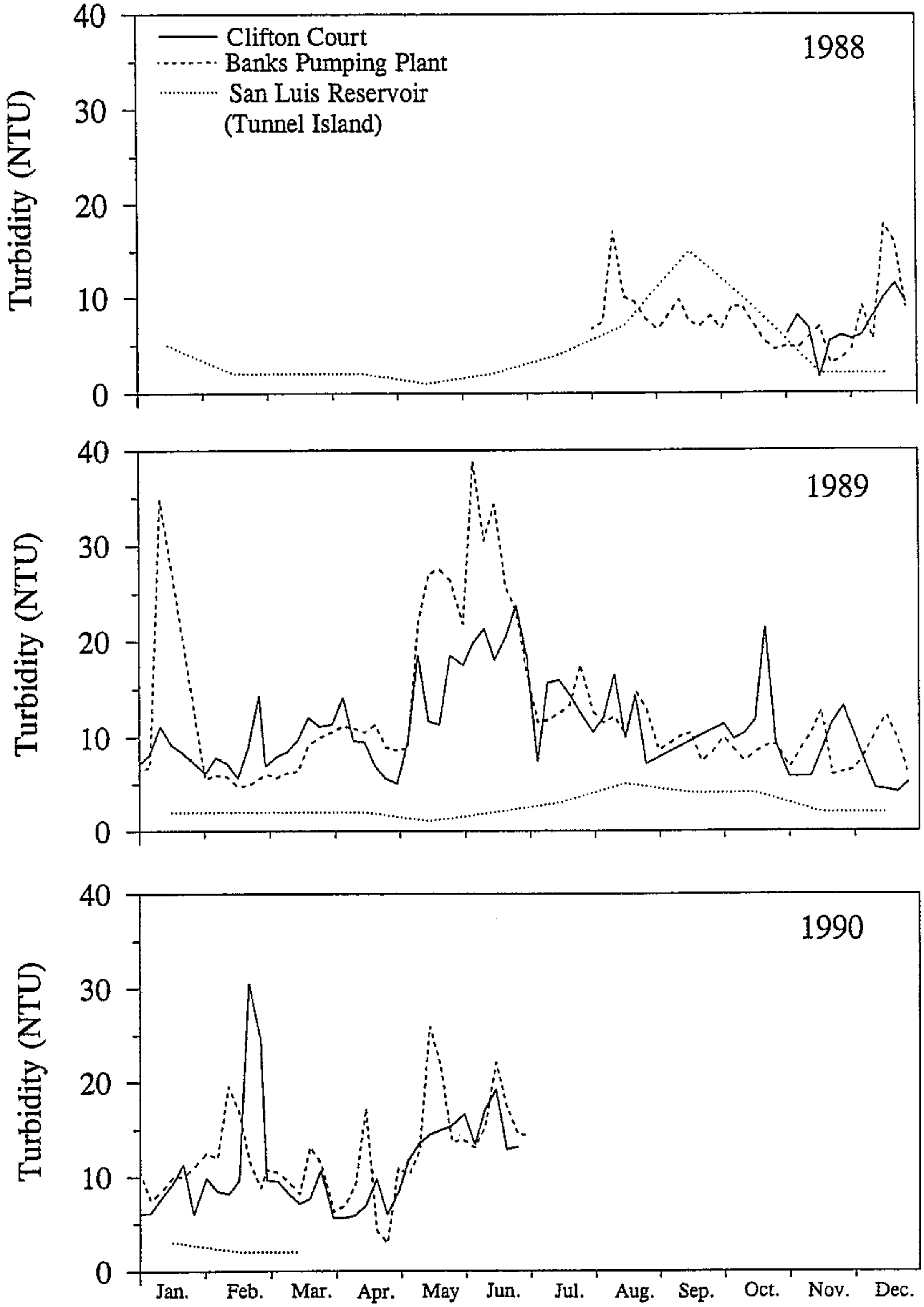

Figure 4-1. Changes in turbidity at two sites in the South Bay Aqueduct (Clifton Court and Banks Pumping Plant) and in the outlet of San Luis Reservoir in 1988, 1989, and 1990.

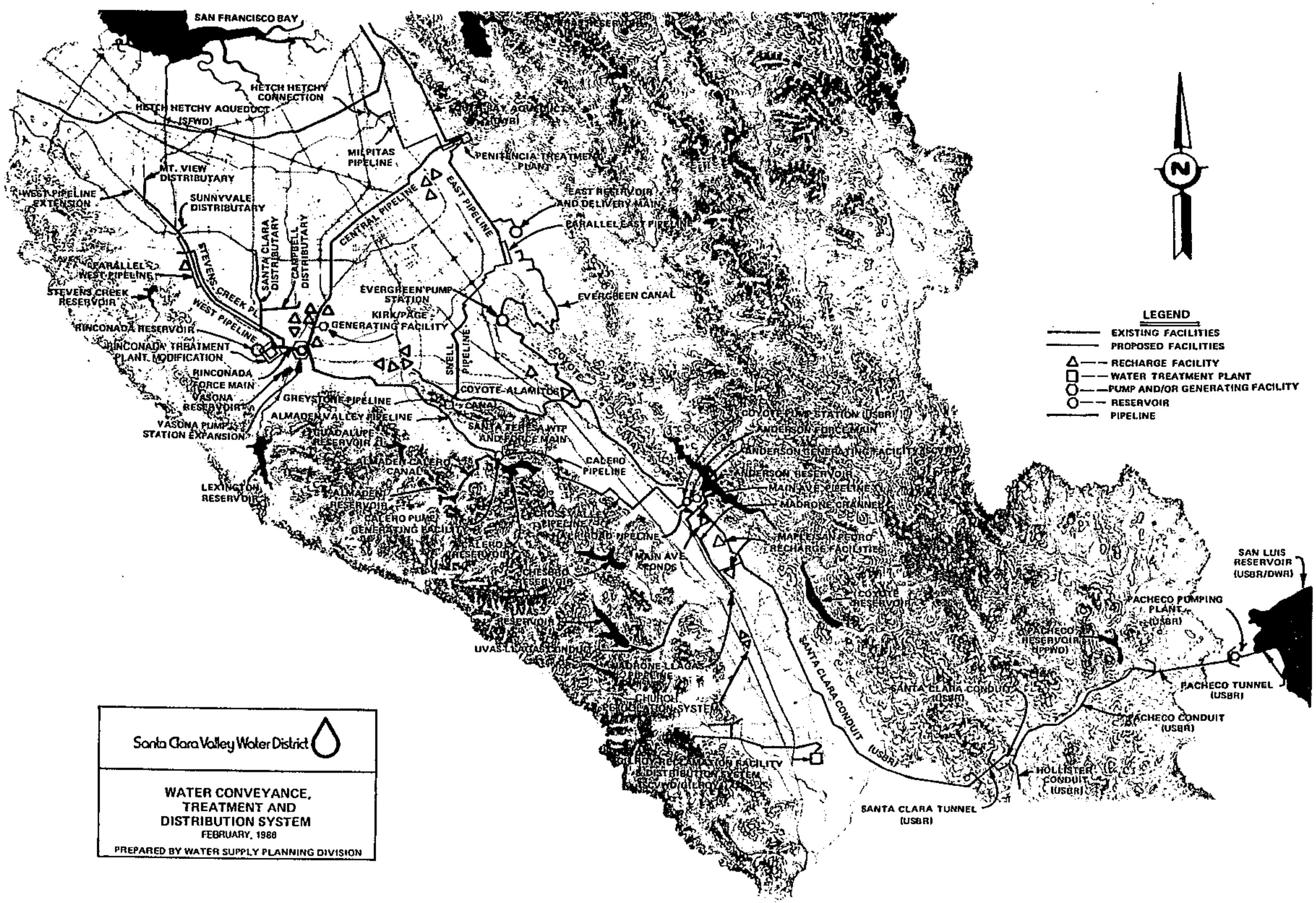

Figure 4-2. Map of the integration of the SBA and the Pacheco Conduit supply to Santa Clara Valley.

San Luis and observations showed that they were present on the surface during at least part of the day. A whirlpool on the surface was observed sucking the extensive surface film of the algae down into the outlet gates. Due to the drought and full supply of irrigation water in 1988, the reservoir level was lower than normal and the lowest outlet gate was already in use. The conventional solution to this water quality problem, use of a lower gate, that would have prevented sucking in of the surface bloom was thus not available.

Changes in 1988 and 1989 in the dominant algae, including the nuisance taste and odor causing species *Anacystis* are shown in Figure 4-3. The huge increase in *Anacystis* in 1988 rather than 1989 and its absence in the South Bay Aqueduct or the California Aqueduct is one of the clearest examples of the changes in water quality in the SWP due to conveyance and storage. This nuisance should be compared with the nuisance algae that occurred in the SBA at other times. Other potentially nuisance blue-green algae were did not bloom at this time. The increase in this species may be due to the changes in whole lake mixing in San Luis as discussed below.

Physical Limnology of San Luis Reservoir. The seasonal changes in physical limnology of the reservoir are indicated in the temperature-depth isopleths (Figure 4-4) and the equivalent isopleths for oxygen (Figure 4-5). As stated above the changes may be important in stimulating water quality degradation due to blue-green algae blooms.

The physical stability of a reservoir can be ascertained by an examination of the seasonal sets of temperature-depth curves. Examination of the 1987-1990 data set indicates that the reservoir stratifies thermally relatively late in the year (June-July) and destratifies (turns over) relatively early (mid October). Large water bodies usually stratify later and destratify later than small ones so the early destratification is probably due to reservoir management. It is of interest to note that there was little difference between the thermal stability in 1988 (nuisance bloom of *Anacystis* and taste and odor problems) and that in other years. Thus warmer water (or concomitant increased thermal stratification) known to favor blue-green algae do not seem to have occurred.

The oxygen isopleths for 1987-90 reveal some differences between the 1988 (bloom) and 1989 years. *Anacystis* growth is stimulated by several factors (increased water column stability, increased ammonia, zooplankton predation on competing algae, anoxia in the winter sediments) and low dissolved oxygen in deep water is related to several of them. Although the differences are not large and anoxia in the water column was not present (no sediment data), the 1988 season was definitely lower in dissolved oxygen than 1989. Further data and knowledge of the true bottom water chemistry is needed before more conclusions can be drawn.

ACKNOWLEDGMENTS

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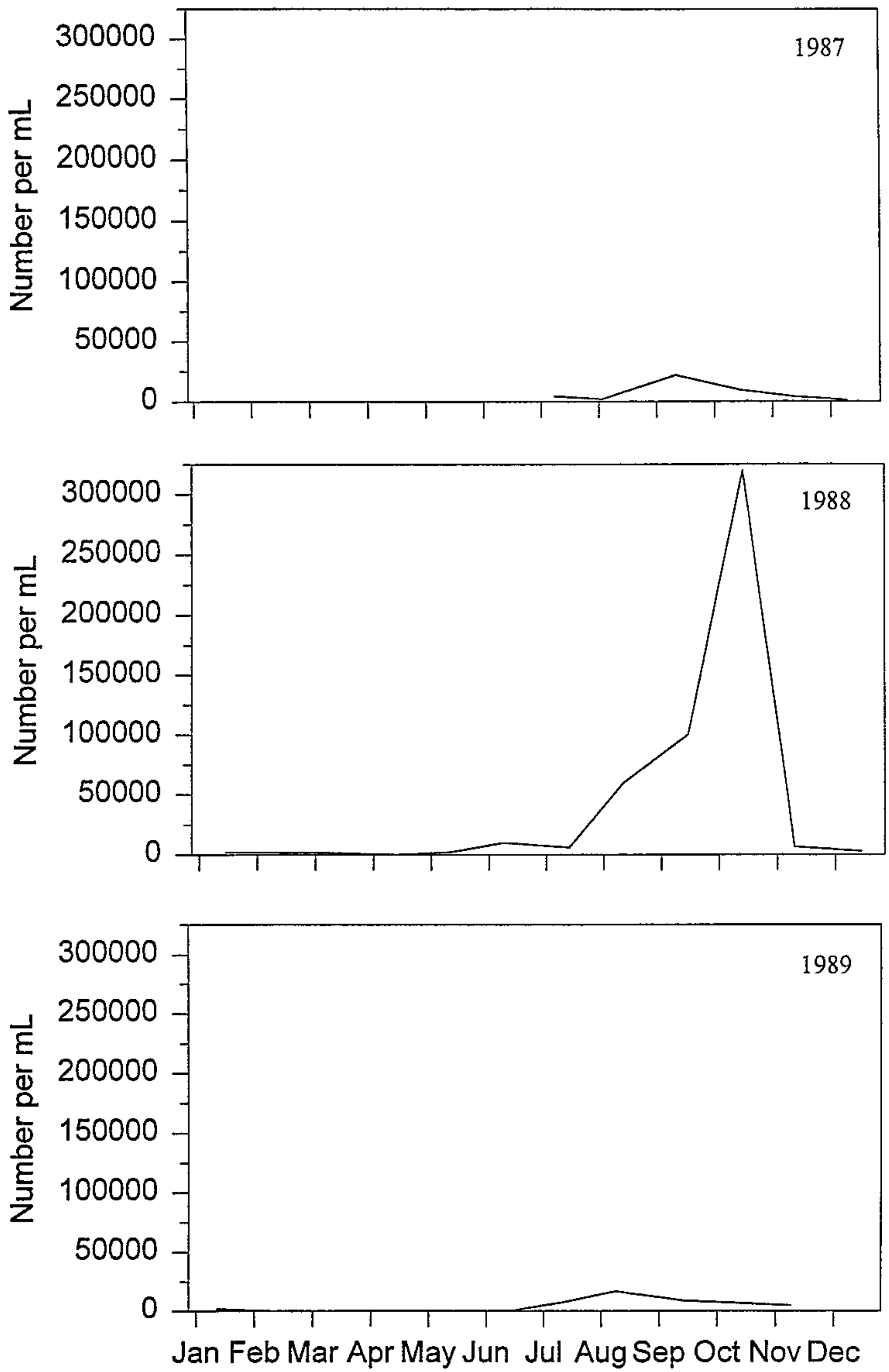

Figure 4-3. Changes in the nuisance taste and odor causing algae, *Anacystis*, in 1987 through 1989.

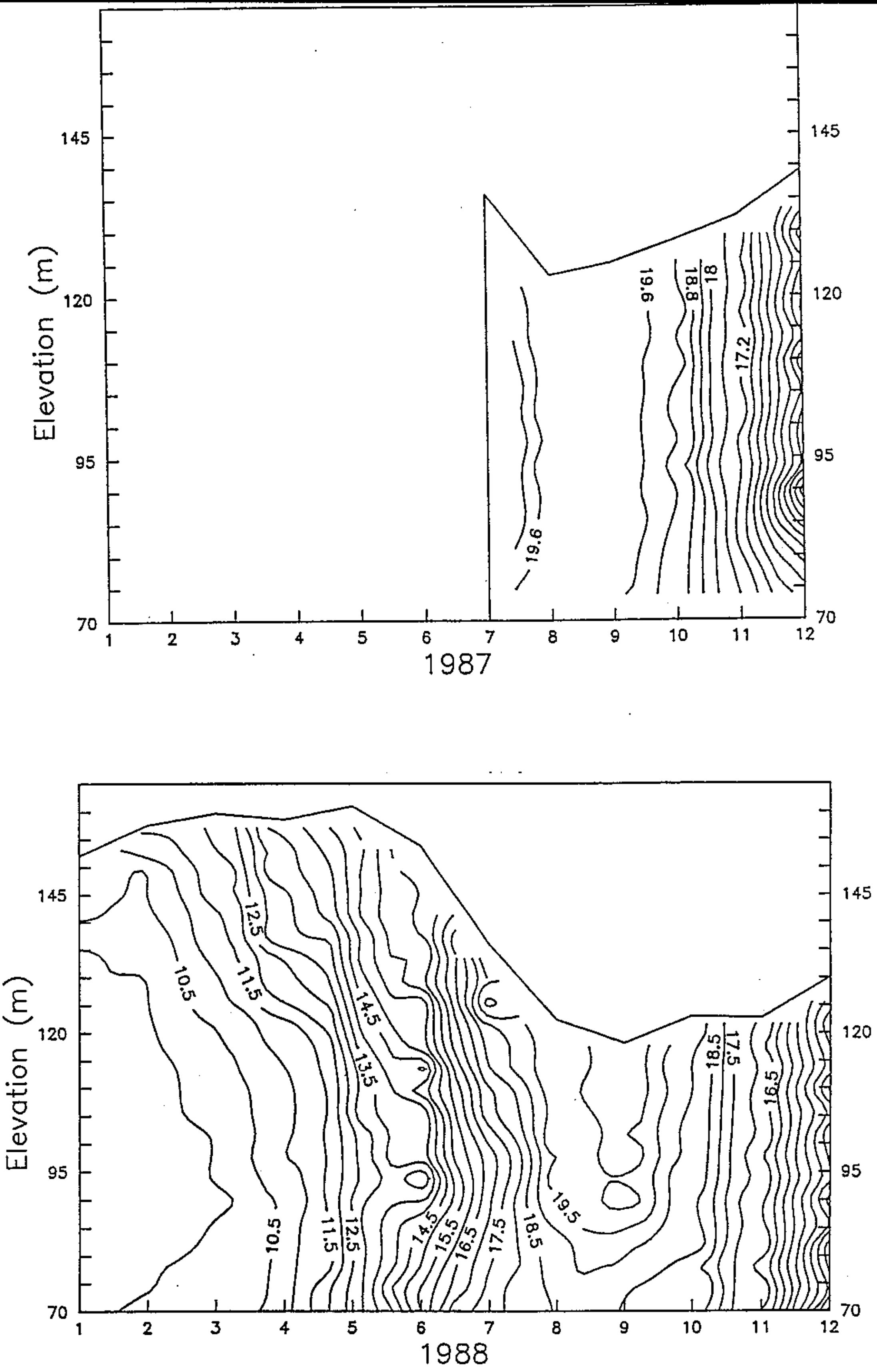

Figure 4-4 a. Seasonal changes in physical limnology of San Luis Reservoir (1987 and 1988) as indicated in the temperature-depth isopleths (isotherms are at intervals of approximately 0.5°C).

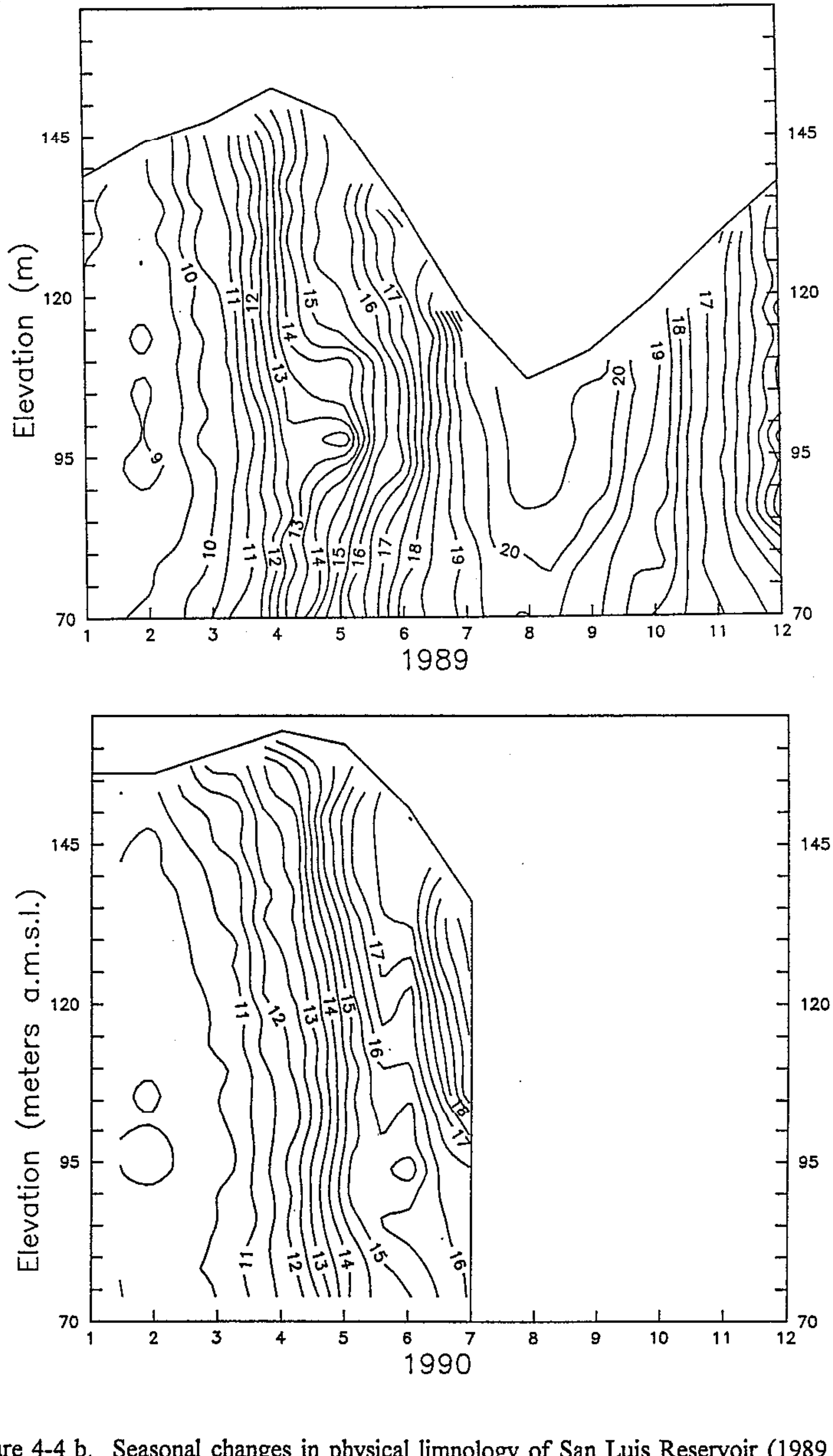

Figure 4-4 b. Seasonal changes in physical limnology of San Luis Reservoir (1989 and 1990) as indicated in the temperature-depth isopleths (isotherms are at intervals of approximately 0.5°C).

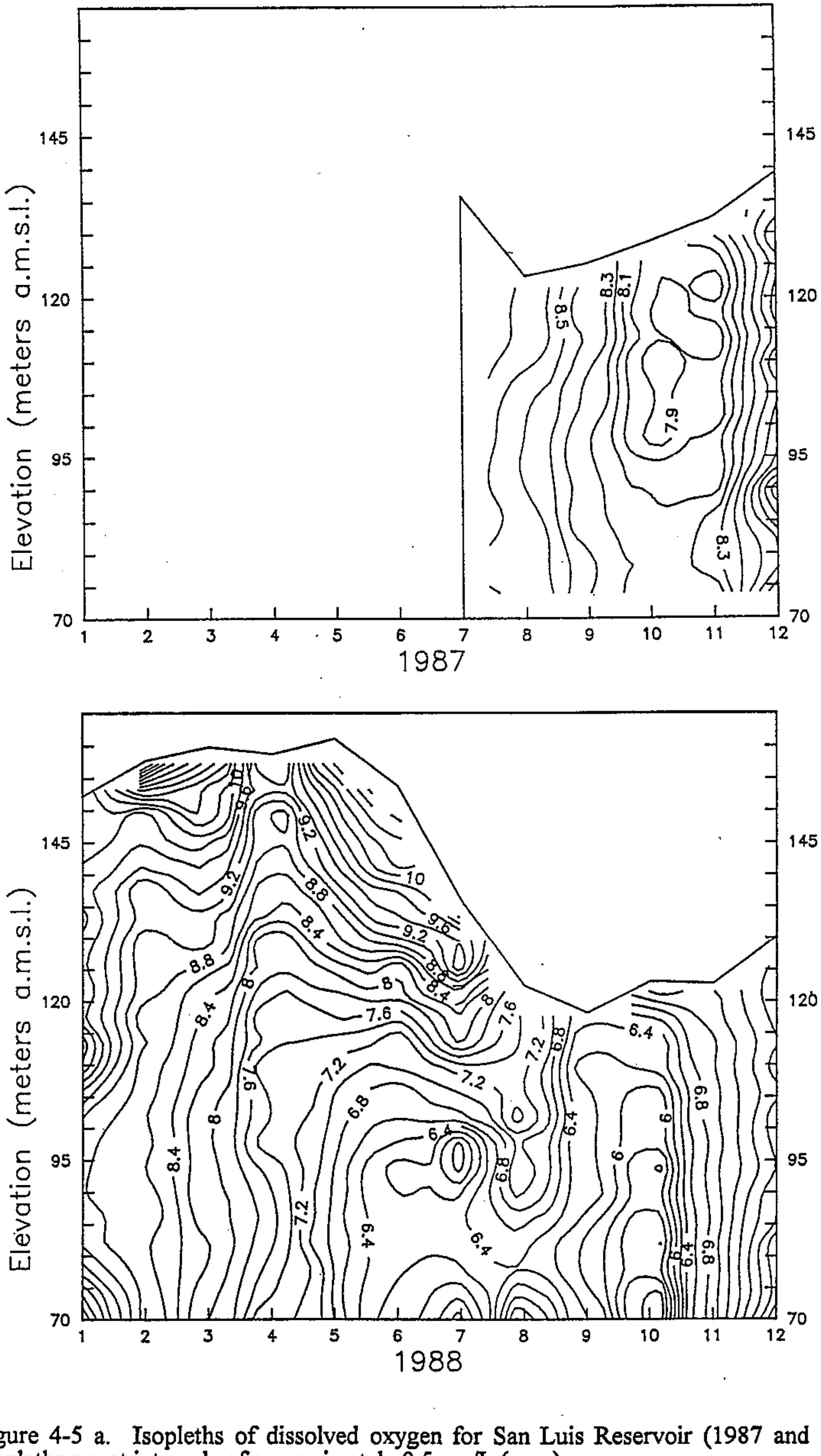

Figure 4-5 a. Isopleths of dissolved oxygen for San Luis Reservoir (1987 and 1988). Isopleths are at intervals of approximately 0.5 mg/L (ppm).

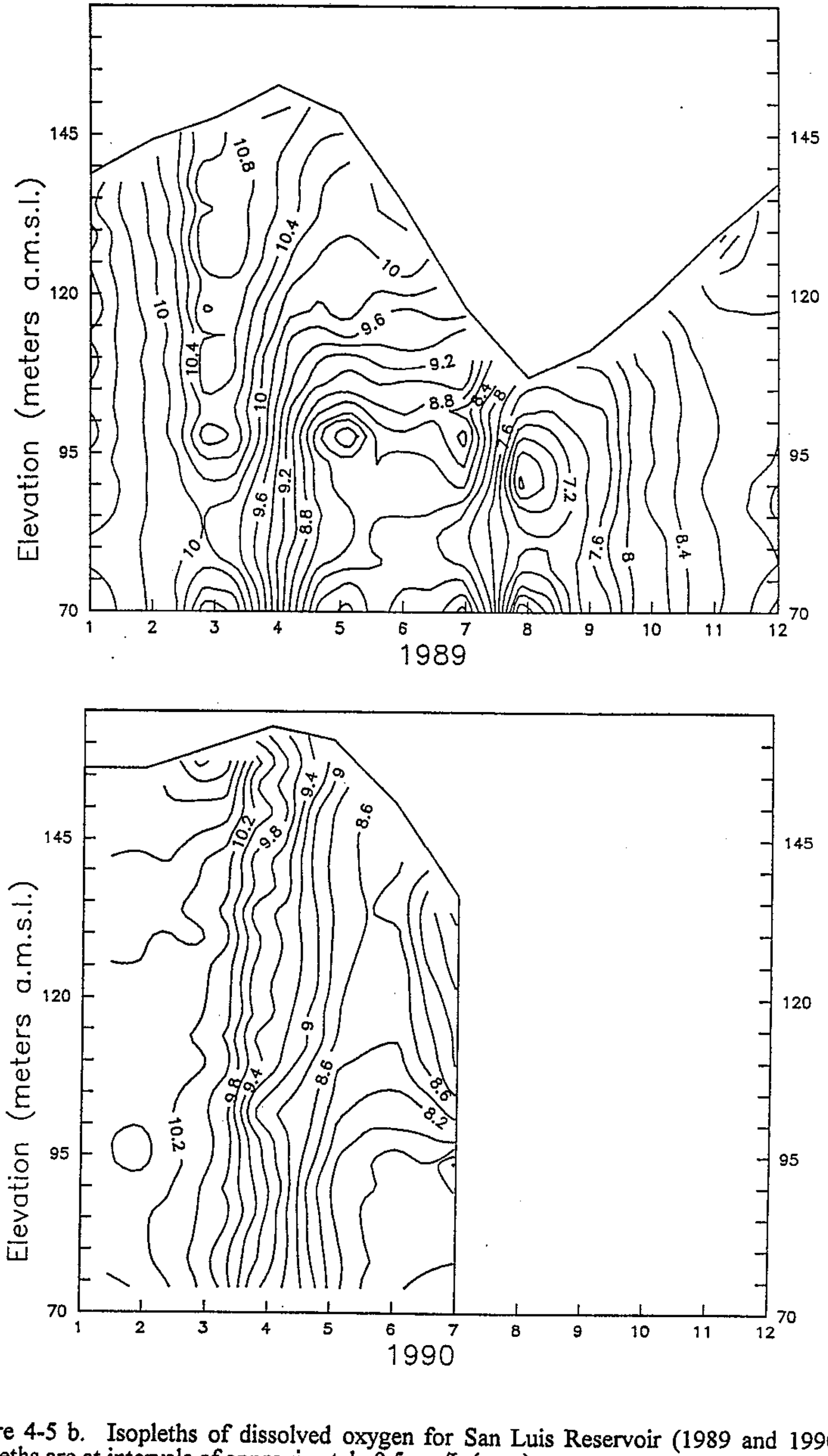

Figure 4-5 b. Isopleths of dissolved oxygen for San Luis Reservoir (1989 and 1990). Isopleths are at intervals of approximately 0.5 mg/L (ppm).

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