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**Chemical and Physical Limnology of the  
Salton Sea, California - 1999**

Prepared by

G. Chris Holdren and Andrew Montaña  
Ecological Research and Investigations Group  
P.O. Box 25007 (D-8220)  
Denver, CO 80225

U.S. Department of the Interior  
Bureau of Reclamation



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## Executive Summary

Keywords: Salton Sea, saline lakes, nutrients, nitrogen, phosphorus, ionic composition, dissolved solids, geochemical modeling

A one-year sampling program was conducted to assess the current chemical and physical conditions in the Salton Sea. Samples were collected from three locations in the main body of the Sea and from the three major tributaries over a one-year period. Samples were analyzed for general physical conditions and water quality variables, nutrients, major cations and anions, trace metals and organic compounds.

Temperatures followed normal seasonal patterns, with the maximum surface temperature of 36.5°C observed in the Sea on August 24, 1999, and the minimum surface temperature of 14.2°C observed on January 22, 1999. Temperature profiles indicated the Sea was well-mixed during the spring and fall months, with some thermal stratification occurring from June through September. The maximum observed temperatures of 30.5°C and 30.4°C for the Alamo and New Rivers, respectively, occurred on August 25, 1999. The maximum observed temperature of 29.6°C for the Whitewater River occurred on August 24, 1999. The minimum observed temperatures of 11.4, 12.7, and 14.7°C for the Alamo, New, and Whitewater Rivers, respectively, all occurred on December 14, 1999, when Sea surface temperatures were also at a minimum.

Dissolved oxygen levels in the Salton Sea are characteristic of a highly eutrophic system. Surface oxygen levels were often greater than 200 percent of saturation, while some oxygen depletion was observed in the bottom waters of the Salton Sea throughout the year. Hypolimnetic dissolved oxygen concentrations were often severely depleted, with observed concentrations at the lake bottom usually less than 2 mg/L from April through November. Dissolved oxygen levels in the rivers also exhibited oxygen depletion, with dissolved oxygen concentrations averaging 77.3, 66.2 and 73.2 percent of saturation in the Alamo, New, and Whitewater Rivers, respectively.

Conductivity levels were very consistent in the Salton Sea, with annual averages of 55.11, 55.19, and 55.23 mS/cm for Stations SS-1, SS-2, and SS-3, respectively; these minor differences are less than expected instrumental variation. Conductivities in the river samples were more variable than those in the Sea, with differences between maximum and minimum values ranging from 26 percent in the New River to 49 percent in the Alamo River. Average conductivities were 3.141, 4.089, and 2.145 mS/cm for the Alamo, New, and Whitewater Rivers, respectively.

The total dissolved solids (TDS) concentrations in both Sea and river samples were closely related to conductivity. Seasonal differences in TDS and conductivity for the summer (June through August), fall (September through November), winter (December through February) and spring (March through April) were minor, with changes of less than one percent for conductivity and about two percent for measured TDS concentrations. Slight, but inconsistent, seasonal changes were observed in the river stations and may be related to agricultural operations.

The Alamo and New Rivers were always very turbid, with total suspended solids (TSS) levels ranging from 237 to 480 mg/L in the Alamo River, and from 87 to 332 mg/L in the New River. Levels of TSS in the Whitewater River were lower, with a range of 40 to 188

mg/L. TSS levels in the Salton Sea were much lower than those in the rivers, with an annual average of 42 mg/L, indicating that the suspended sediment load rapidly settles within a short distance after reaching the Sea.

Secchi depth, a common measure of water clarity, ranged from 0.4 m to 1.4 m in the Salton Sea. Secchi depths often varied widely between stations on the same sampling date and there were no clear seasonal changes. The depth of 1% light penetration ranged from 1.8 to 4.8 m and was strongly correlated to Secchi depth. Average ratios of the depth of 1% light penetration to Secchi depth were 4.2:1 for all three sampling stations.

Phosphorus concentrations in the tributaries were all relatively high, and probably originate from intense agricultural activity in the Salton Sea watershed and from wastewater treatment plant discharges. Wastewater discharges are especially important for the New River, where some of the wastewater is untreated.

Phosphorus concentrations in the Salton Sea were approximately an order of magnitude lower than those in the river samples but varied throughout the year. Sedimentation, chemical precipitation, and burial following incorporation of phosphorus into aquatic organisms are all possible causes of the observed decrease in phosphorus in the Sea. Total phosphorus peaked at levels between 0.050 and 0.200 mg/L in March/April, May, July/August, and December. The March/April and July/August peaks were followed by steep reductions to below the detection limit of 0.005 mg/L. Concentrations of soluble orthophosphate were also frequently below detection limits in the Salton Sea. These low concentrations were observed in one or more of the Sea locations in January and in every month from April through September. Concentrations of both soluble orthophosphate and total phosphorus were highest during the winter months when biological activity would be at its lowest.

Total nitrogen concentrations in the river samples were 30 to 120 times greater than those in the Salton Sea. This difference can be attributed primarily to the high nitrate+nitrite-N concentrations in the rivers, which were more than one to two orders of magnitude greater than concentrations in the Sea. Nitrate+nitrite-N was the major form of nitrogen in the Alamo and Whitewater Rivers, comprising 70 and 88 percent of the total nitrogen, respectively for these rivers. In contrast to the other two rivers, oxidized nitrogen accounted for only 43 percent of the total nitrogen in the New River and ammonia concentrations were higher than nitrate+nitrite concentrations. The presence of untreated wastewater in the New River may explain this observation.

Oxidized nitrogen represented less than 5 percent of the total nitrogen present in the Salton Sea. In contrast, ammonia-N contributed 32 percent of the total nitrogen. Because nitrate and ammonium salts are generally soluble, uptake by aquatic organisms and denitrification are expected to be the major sinks for nitrogen in the Salton Sea. Volatilization of ammonia was recently suggested to be the major sink for inorganic nitrogen, but volatilization is a more complicated process than denitrification and additional research will be required before the relative importance of these two mechanisms can be verified.

Ammonia levels in the Salton Sea exceed water quality standards. The concentration of un-ionized ammonia at Station SS-1 during the August 10, 1999, fish kill was calculated as 0.062 mg/L, which exceeds the U.S. EPA criterion for un-ionized ammonia. While this concentration is below levels observed to cause acute toxic effects in freshwater systems,



it is possible that relatively high concentrations of un-ionized ammonia represent another stress to fish in the Salton Sea, in addition to the high temperature and low dissolved oxygen associated with algal blooms, and may be contributing to the observed fish kills.

Nitrogen to phosphorus (N:P) ratios in both the influent rivers and in the Salton Sea were high as a result of low phosphorus concentrations and relatively high nitrogen concentrations. The highest ratios were observed during the summer months when algal growth would be at a maximum. Annual N:P ratios were near 200:1 for both TN:TP and total inorganic nitrogen to soluble orthophosphate (TIN:SOP). The winter TN:TP ratio of 24.4 was the only ratio less than 100:1. These high ratios clearly indicate that phosphorus is the limiting nutrient in the Salton Sea.

Dissolved silicon (Si) concentrations were lower in the Salton Sea than in the river samples. Concentrations of dissolved Si averaged 5.89, 7.30, and 8.62 mg/L for the Alamo, New, and Whitewater Rivers, respectively, and 4.60 mg/L for the Salton Sea. Silicon concentrations in the Sea never appeared to reach concentrations low enough to be limiting to algal growth, with the settling of suspended particulate matter being the most probable explanation for the observed decrease in the Sea relative to the river samples.

Dissolved organic carbon (DOC) concentrations increased significantly in the Sea relative to the river concentrations, possibly indicating organic carbon loadings are too high to be assimilated through biological uptake. DOC concentrations averaged 4.2, 8.7, and 7.6 mg/L for the Alamo, New, and Whitewater Rivers, respectively, and 40.9 mg/L in the Salton Sea.

Trophic state indices were calculated from total phosphorus concentrations and Secchi depths in the Salton Sea. The average concentrations of 0.049 mg/L and 0.89 m for total phosphorus and Secchi depth, respectively, result in trophic state indices of 60 and 62, which place the Salton Sea in the eutrophic range.

Concentrations of nearly all major ions are higher in the Sea than in the rivers. The only exception is bicarbonate, which has a slightly lower concentration in the Sea than in a flow-weighted average of river concentrations. The most soluble ions, sodium, potassium and chloride, are enriched in the Sea by factors of 25 to 30 over river concentrations. Magnesium concentrations are about 17 times as high in the Sea compared to the rivers and sulfate concentrations are 14 times as high.

Trace metal concentrations were all low. This is not surprising because of the high concentrations of sulfide in the Salton Sea and the low solubility of most heavy metal sulfides.

No semi-volatile organics or chlorinated pesticides were found in the river inflows at concentrations above detection limits during the current study. Two phthalate esters, which are widely used as plasticizers, were the only organic compounds found in the Sea. Their presence at the low levels detected is not of concern from a water quality standpoint. The lack of organic compounds in the Salton Sea is consistent with previous studies and is not surprising given the low solubility of these compounds in water and the high salt levels in the Sea.

Data from the sampling program was used in conjunction with discharge data to calculate loadings from runoff for total P, total N, total suspended solids and total dissolved solids. Average annual discharges are 620,000 acre-ft from the Alamo River (46.1 percent of the total), 438,000 acre-ft from the New River (32.5 percent), 79,000 acre-ft from the Whitewater River (5.9 percent), and 106,000 acre-ft from agricultural drains (7.9 percent). Other sources are groundwater (3.7 percent), direct precipitation (3.5 percent), San Felipe Creek (0.4 percent), Salt Creek (0.1 percent) and other (1.3 percent). The first four sources listed account for 92.4 percent of the average annual inflow to the Salton Sea and may be expected to account for an even higher percentage of the total nutrient and solids loadings.

Nutrient and solids loadings calculated during this study were 1,385 tonnes/yr for total P, 14,300 tonnes/yr for total N, 468,100 tonnes/yr for TSS and 3,434,000 tonnes/yr for TDS. Comparison of these results with previous studies indicated that the total nitrogen load to the Salton Sea has increased between 0 and 25 over the past 30 years, accompanied by an increase of total nitrogen concentrations of between 70 and 140 percent. In contrast, it appears that total P loadings to the Sea have at least doubled over the past 30 years, but total P concentrations in the Sea are decreasing. The incorporation of phosphorus in fish tissue and bone and in the shells of aquatic invertebrates may represent pathways for the permanent removal of P from the Sea. Once incorporated into bone or shell material, the insolubility of inorganic phosphates would prevent dissolution of the precipitated phosphorus to provide a permanent removal mechanism.

The geochemical models PHREEQC and PHRQPITZ were used to evaluate potential mineral formation in the Salton Sea. Both models suggested that the Salton Sea is currently super-saturated with respect to several important minerals, including calcite, gypsum, celestite, hydroxyapatite and fluorapatite. Formation of the first three of these minerals may lead to precipitation of calcium, strontium and some of the sulfate entering the Sea, while formation of the apatites could provide a sink for phosphorus.

Other than high productivity leading to problems with low dissolved oxygen, water quality conditions in the Salton Sea are relatively good. Water from the Sea meets all U.S. EPA primary drinking water standards and most secondary standards, except those related to salinity.

## 1.0 Introduction

The Salton Sea is located in the Salton Sink, a depression with a minimum elevation of 278' (84.7 m) below sea level in the Colorado Desert in southern California. Geologic records indicate that the Salton Sink has periodically been filled with water and, as Lake Coahuilla, reached a maximum size of 2,100 mi<sup>2</sup> (5,440 km<sup>2</sup>), with a depth of 310' (95 m) (Buckles et al., 2002).

The current Salton Sea was created during floods of the Colorado River in 1904 and 1905 when dikes on diversion ditches created to bring agriculture to the region failed. During the 17-month period from October 1905 to February 1907, nearly the entire flow of the Colorado River was directed into the Salton Sink. The resulting water body covered an area of about 520 mi<sup>2</sup> (1,350 km<sup>2</sup>) and had a maximum depth of about 83' (25 m) at a surface elevation of 195' (59.4 m') below sea level.

The size of the Salton Sea has varied considerably since its formation as a result of changing water levels. The current Sea receded its minimum size, with a maximum depth of only 28' (8.5 m), in the early 1920's, primarily as a result of an average evaporation rate of over 100"/yr (2.5 m/yr) (Farnsworth et. al, 1982) in the area. Since that time, the surface level of the Sea has risen as a result of increased agricultural drainage and is currently stabilized at a maximum depth of about 51' (15 m) with a surface area of 366 mi<sup>2</sup> (948 km<sup>2</sup>) at a surface elevation of 227' (69.2 m) below sea level.

Water quality has been an issue in the Salton Sea since its formation. Although the Salton Sea initially contained fresh water, dissolution of salts from the underlying salt beds and continuing evaporation quickly caused salinity in the Sea to increase. With no surface outflows, salinity in the Sea continues to increase and is a major concern for planned restoration efforts.

High nutrient levels, which lead to frequent algal blooms that interfere with fishing and other recreational uses of the lake, are another major water quality concern. The high algal populations also contribute to oxygen depletion in the hypolimnion of the lake during the summer months. The tributaries, while having a much lower salt content than the Sea, primarily consist of agricultural irrigation return flows that contribute to the high nutrient levels.

Recreational use of the Salton Sea peaked in the 1950's and early 1960's, when it was one of the most popular recreation areas in California. Increased salinity has led to changes in the fish population of the Sea over the years and is of major concern for the sport fishery. Declining water quality has been cited as one of the factors leading to a decrease in use since that time. The low oxygen levels contribute to periodic fish kills, and odors caused by decaying fish and algal blooms have also been cited as a reason for the decrease in recreation. These odors may also have adverse impacts on economic development in the area.

The Sea is a major stopover for migrating waterfowl on the Pacific flyway, but has experienced repeated incidents of avian mortality beginning in 1987. A variety of causes, including algal toxins, have been implicated in avian mortality.

Elevated levels of selenium and organic pesticides have also been noted as potential water quality problems by previous reports. Although the Sea has been extensively studied over the years, the extent and quality of existing water quality data are not known (Thiery, 1999).

The last major study on water quality in the Sea (Setmire et al., 1993) reported field work that occurred in 1990. Salinity has continued to increase since that time, and proposed major reductions in water inflows could drastically affect future salinity levels. Because nutrients and salinity are of particular concern for planned management efforts at the Salton Sea, a new characterization of water quality was required to provide current information to fulfill the requirements of an Environmental Impact Statement and Environmental Impact Report recently prepared for the Salton Sea project (Salton Sea Authority/USBR, 2000).

This study was conducted as part of a year-long effort to produce current scientific data on the Sea. General physical conditions and a suite of water quality parameters, including nutrients, major ions, trace metals and organic compounds, were measured to provide information on key physical and chemical characteristics of the Salton Sea, including mixing processes, nutrient dynamics, trophic state variables and general water quality conditions.

## 2.0 Existing Data

In light of recent interest in the area, there is a surprising paucity of published historical water quality data on the Salton Sea. Although several agencies have performed chemical analyses on the Salton Sea, much of this information is unpublished (Thiery, 1999). The following sections summarize existing data on the Salton Sea.

### 2.1 Major Ions

The earliest water quality data on the Salton Sea were presented in reports by MacDougal (1907) and Ross (1915). MacDougal compared the major ion composition of the Salton Sea in 1907 to normal sea water. Ross presented data on cations and anions, as well as total and dissolved solids information, collected in May or June each year from 1907 to 1914. The composition of the Salton Sea underwent dramatic changes during the period when the Sea was forming in 1905 to 1907 as a result of dissolution of flooded salt deposits. Ross (1915) concluded that leaching of salts from the lake bottom had been completed by 1911. Since that time, fluctuations in water level and continued concentration of salts by evaporation have been the driving forces in changing the salinity of the Salton Sea.

Results collected along several transects in the Salton Sea from November 1953 to January 1955 were reported by Arnal (1961). Arnal compared data from 1907 (MacDougal, 1907), 1913 (Ross, 1915), 1929 (Coleman, 1929) and 1955 (Arnal, 1961) to examine changes in composition over time and to determine salt budgets for the Sea, but indicated that the data presented by Coleman were not very accurate. Arnal also presented data on turbidity and Secchi depth (0.10-3.05 m during the study), as well as data on currents, sediments and microorganisms.

Historical data on the major ions, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), carbonate ( $\text{CO}_3^{=}$ ), bicarbonate ( $\text{HCO}_3^-$ ), sulfate ( $\text{SO}_4^{=}$ ), and chloride ( $\text{Cl}^-$ ), in the Salton Sea was summarized by Carpelan (1958; 1961). These reports also provided detailed information on temperature, dissolved oxygen and nutrients (ammonia, nitrate and phosphate) for the period July 1954 to July 1956. Profiles for temperature, dissolved oxygen and pH were presented, as well as data on chlorinity and sulfide.

Historical chemical analyses of Salton Sea water were summarized by Hely et al. (1966). Data from a variety of sources provided information on major ion analyses (Ca, Mg, Na, K,  $\text{HCO}_3^-$ ,  $\text{SO}_4^{=}$ , and  $\text{Cl}^-$ ) for the years 1907-1916, 1923, 1929 and 1945-1964. In addition, Hely et al. calculated salinity for each year with available data, as well as water volume (millions of acre-ft) and mineral content (millions of tons) in the Sea.

Setmire et al. (1990) presented major ion concentrations from the Salton Sea area as part of a larger, comprehensive study. Specific conductance, pH, temperature, Ca, Mg, Na, K, alkalinity,  $\text{SO}_4^{=}$ ,  $\text{Cl}^-$ , fluoride ( $\text{F}^-$ ), silica ( $\text{SiO}_2$ ), and dissolved solids data were reported from nine tile drains, the Alamo and New River outlets and a composite sample from the Salton Sea. Single samples were collected at each location from August 12 to 14, 1986. Ogden (1996) also reported cation and anion concentrations collected from three stations near the center of the Salton Sea in April 1994.

Water and salt balances in the Salton Sea from its formation through 1989 were examined by Tostrud (1997) using published data, as well as unpublished data from the Imperial Irrigation District (IID) and the Coachella Valley Water District (CVWD). Tostrud estimated that 80 million tons of salt had dissolved from flooded salt deposits and were added to Sea water by 1914. He concluded that calcium, bicarbonates and sulfates have precipitated out of the Sea and indicated the Sea apparently reached saturation with respect to bicarbonate within the first year after its formation. Tostrud also reported that the Sea became saturated with respect to calcium in about 1950 and with respect to sulfate in about 1980. Some sodium has apparently been precipitated. Tostrud suggested that precipitation of calcite ( $\text{CaCO}_3$ ), calcium sulfate ( $\text{CaSO}_4$ ) and sodium sulfate ( $\text{Na}_2\text{SO}_4$ ) would account for the observed results. Similar results were presented by Ormat (1989, cited in Ogden, 1996). Ormat evaluated analyses of Salton Sea water collected by IID from 1981 to 1987. Ormat concluded that the Salton Sea was saturated with respect to  $\text{CaCO}_3$  and  $\text{CaSO}_4$  and predicted that  $\text{Na}_2\text{SO}_4$  would also precipitate as Salton Sea water is concentrated. Amrhein (2001) is currently using x-ray diffraction to assess mineral formation in Salton Sea sediments, but has not positively identified any minerals that could explain the observed loss of sodium noted by Ormat (1989) and Tostrud (1997).

## 2.2 Nutrients

Carpelan (1958; 1961) measured nitrate-N, ammonia-N and phosphate-P concentrations in surface and bottom samples at four locations in the Salton Sea in 1954 to 1955, although he indicated absolute values for both nitrate and phosphate were questionable because of the low concentrations present. Average reported concentrations for the four stations ranged from 0.075 to 0.172 mg/L for ammonia-N ( $\text{NH}_3\text{-N}$ ), 0.011-0.107 mg/L for nitrate-N ( $\text{NO}_3\text{-N}$ ), and 0.015-0.035 mg/L for phosphate-P ( $\text{PO}_4\text{-P}$ ). In all cases, the lowest concentrations were from mid-Sea stations and the highest concentrations were from a site off Mullet Island affected by the inflow from the Alamo River. Bottom water concentrations for both ammonia-N and phosphate-P were higher than surface concentrations.

The Federal Water Quality Administration (FWQA, 1970) presented information on nutrients in Sea inflows, water and sediment from both the FWQA and the California Department of Water Resources. Data from the period 1963 to 1969 was included in the report, which characterized the Sea as “objectionably eutrophic”. Information on internal loading and biological characteristics, including fish, invertebrates and phytoplankton was also presented. High algal growth led to dissolved oxygen super-saturation in surface waters and oxygen depletion at the bottom of the water column. Algal growth studies conducted as part of the study indicated nutrients were generally not limiting algal growth, with only one sample showing evidence of phosphorus limitation.

Research conducted by San Diego State University (Watts et al., 1999) compared nutrient loadings and concentrations in the Salton Sea from 1967-68 and 1996-97. Total P concentrations were similar for the two periods, averaging 0.095 mg/L in 1967-68 and 0.091 mg/L in 1996-97, although P loadings more than doubled. In contrast, nitrogen concentrations increased from 2.1 mg/L to 5 mg/L during the same period, while nitrogen loadings were unchanged. Reported concentration ranges for the 1996-97 period were 0.050 to 0.200/L for total P and 1.6 to 5.0 mg/L for total N.

## 2.3 Metals

There is detailed information on selenium, and to a lesser extent boron, in the Salton Sea area from the USGS (Setmire et al., 1990; Setmire et al., 1993; Setmire and Schroeder, 1998), but there is a lack of routine monitoring data. Setmire et al. (1990) analyzed trace elements, including arsenic (As), barium (Ba), boron (B), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), mercury (Hg), molybdenum (Mo), nickel (Ni), selenium (Se), silver (Ag), vanadium (V), and zinc (Zn) from 9 drains, the Alamo and New River outlets and a composite sample from the Salton Sea collected on August 12-14, 1986. Detailed analyses of Se and B in water, sediment and biota samples were presented by Setmire et al. (1990, 1993). The 1993 report included data collected from 1988 to 1990. A more detailed analysis of Se results, including data from 1994 to 1995, was presented by Setmire and Schroeder (1998).

## 2.4 Pesticides

Irwin (1971) also reported results of pesticide analyses for selected tributaries to the Salton Sea collected from August 1969 to June 1970. DDT and its metabolites and dieldrin were found in all samples at the stations from the New (Westmorland, CA) and Alamo (Niland, CA) Rivers closest to the Salton Sea. Concentrations up to 11 µg/L were observed for the DDT metabolites, while dieldrin was found at concentrations of 0.01 to 0.03 µg/L at both stations. Methyl parathion, 2,4-D and Silvex were also found in nearly all samples from the two stations. Maximum observed concentrations were 0.03, 0.65, 19 and 1.7 µg/L in the Alamo River and 0.19, 1.6, and 0.84 µg/L in the New River for methyl parathion, 2,4-D and Silvex, respectively. Endrin, lindane, parathion and 2,4,5-T were detected in some samples at both locations, while aldrin, heptachlor and heptachlor epoxide were not found in any of the samples.

Hogg (1973) examined chlorinated hydrocarbon pesticides in water sediment and tissue samples from the Salton Sea in 1970 to 1971. Hogg found DDT and its metabolites in 146 of the 159 samples examined, and dieldrin and its metabolites in 66 of the 159 samples. Total DDT in the water samples was found at a level of 0.006 mg/L while dieldrin was not detected. In general, pesticide residue concentrations were higher in samples collected from the southern part of the Sea.

Results of organochlorine pesticide analyses were presented by Setmire et al. (1990; 1993). Those studies included results from sediment and biota samples, but did not measure pesticides in Salton Sea water. Although the use of DDT was banned in the U.S. in 1972 and in Mexico in 1983, its metabolites were still detected in most samples analyzed by Setmire et al. (1993).

## 2.5 Other Results

Recent work at the University of California-Davis (Cook et al., 1998) collected detailed temperature and conductivity data for their hydrodynamic modeling efforts on the Salton Sea. These studies provided little information on additional water quality variables.

### 3.0 Methods

Water quality samples were collected from three lake stations (North Basin, SS-1; Mid-Lake, SS-2; and South Basin, SS-3), as well as from the three main rivers entering the lake (Whitewater River, Alamo River, and New River). Sampling locations are shown in Figure 1 and global positioning system (GPS) coordinates (NAD27) for those sites are listed in Table 1. Salton Sea sampling locations were located using a Rockwell HNV-560B PLGR global positioning system. The Alamo River (AR) site was located at the Garst Road bridge just downstream of USGS Station Number 10254730. The New River (NR) site was located west of Lack Road at USGS Station Number 10255550. The Whitewater River (WR) sampling site was located at the Lincoln Street crossing west of USGS Station 10259540.

**Table 1 - Coordinates of Sampling Stations**

Station	Latitude	Longitude
SS-1	33° 24' 00"	115° 55' 30"
SS-2	33° 20' 00"	115° 49' 00"
SS-3	33° 16' 00"	115° 45' 30"
Alamo River	33° 11' 57"	115° 35' 46.5"
New River	33° 06' 16.5"	115° 39' 50"
Whitewater River	33° 31' 29"	116° 04' 41"

Surface grab samples were collected from the river stations and the Sea. A Kemmerer sampler was used to collect samples at other depths in the Sea. Profiles were measured at 1-m intervals for general chemical and physical variables (temperature, dissolved oxygen concentration, pH, conductivity, turbidity, and oxidation-reduction potential). Samples for other variables were collected at the surface and bottom of the water column from January to March and October to December, and from the surface, bottom of epilimnion, top of hypolimnion, and bottom from April through September.

The sampling program included monthly measurements from January to March and October to December, and biweekly measurements from April through September 1999 for general chemical and physical variables, light penetration (Secchi depth and 1% light level), and nutrients (soluble orthophosphate, total phosphorus, nitrate+nitrite-N, ammonia-N, total Kjeldahl nitrogen, dissolved organic carbon, and dissolved silica). Major ions were measured in February, May, August, October, and December. All major ion samples included major cations (Ca, Mg, Na, K) and anions ( $\text{CO}_3^-$ ,  $\text{HCO}_3^-$ ,  $\text{SO}_4^-$ ,  $\text{Cl}^-$ ). In addition, analyses for  $\text{F}^-$ , Sr and B were added for the March, October and December samples. Trace elements (Al, As, Ba, B, Cd, Cr, Co, Cu, Fe, Pb, Mn, Hg, Mo, Ni, Se, Ag, Sr, V, and Zn) and organic compounds (semi-volatile organics and chlorinated pesticides) were measured once in March and once in October.



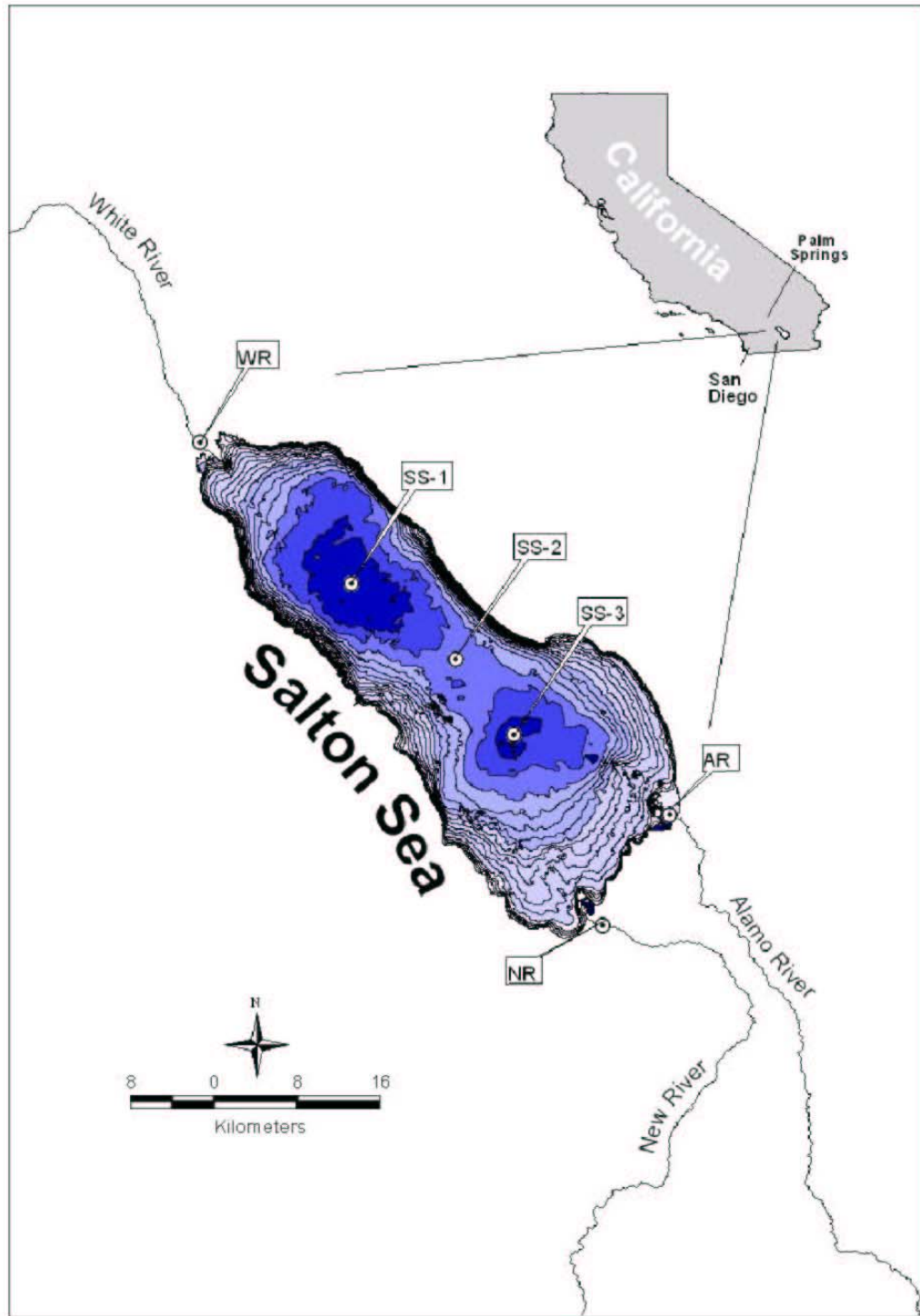


Figure 1. Locations of Sampling Stations

Profiles were measured with a Hydrolab Surveyor 4 calibrated following manufacturer's instructions. The probe corrects dissolved oxygen readings for salinity with the equation:

$$(1) \quad F = 1 - C \times (3.439 \times 10^{-3} + 0.361/(22.1 + T)^2),$$

where F = the factor correcting dissolved oxygen readings for salinity, C = specific conductance and T is the temperature in degrees Celsius. The factor F calculated from equation 1 was approximately 0.8 for conditions at the Salton Sea and agrees to within about 1 percent with salinity correction factors published by Weiss (1970).

Most analyses for the project were performed by the Bureau of Reclamation's Denver Environmental Research Chemistry Laboratory. Nutrients were analyzed with a Perstorp segmented flow analyzer. Cations/metals were analyzed with a Thermo-Ash Model ICP-61E, Varian Techtron Model SpectrAA-220Z atomic absorption spectrophotometer using serial dilution techniques to minimize salt interference. A Dionex Model DX-500 ion chromatograph was used for the analysis of  $\text{SO}_4^-$  and  $\text{Cl}^-$  and an ion selective electrode was used for  $\text{F}^-$  analyses. Alkalinity was measured in the field by titration with 0.02 N  $\text{H}_2\text{SO}_4$  and in the laboratory with a Metrohm Brinkmann Model 716 Auto-Titrator for the determination of carbonate and bicarbonate. Total dissolved solids (TDS) and total suspended solids (TSS) were determined gravimetrically after drying at 180°C and 103 to 105°C, respectively.

Arsenic, selenium and mercury were analyzed by Frontier Geosciences, Inc., Seattle, WA. Arsenic and selenium were analyzed by hydride generation, atomic fluorescence spectrometry, and mercury was analyzed by oxidation, purge and trap, cold vapor atomic fluorescence spectrometry.

Semivolatile organics and chlorinated pesticide and PCBs were analyzed by gas chromatography using a mass spectrophotometric detector. Analyses were performed by Barringer Laboratoires, Inc., Golden, CO, and Evergreen Analytical, Inc., Wheat Ridge, CO, for the March 15-16, 1999, and October 20-21, 1999, sampling dates, respectively.

A 20-cm, black and white Secchi Disk was used to determine water clarity. Light penetration was determined using a Li-Cor LI-1000 data logger equipped with LI-190SA and LI-192SA quantum sensors. Profiles were collected from the surface to below the depth of 1% light penetration.

Information on analytical methodology and measurement performance criteria for the measured water quality variables is presented in Tables 2 and 3, respectively. Detailed information on the project analytical program was provided in the Quality Assurance Project Plan (Holdren, 1999). Some information from that document was corrected and updated for this report.

All field data are included in Appendix A. Data from the Denver Environmental Research Chemistry Laboratory are summarized and found in Appendix B, and contract laboratory data are included in Appendix C.

**Table 2 - Project Analytical Methods**

<b>Sample Parameter</b>	<b>Matrix</b>	<b>Analytical Method Reference</b>
Soluble Orthophosphate	Water	365.1*
Total Phosphorus	Water	365.4*
Nitrate+Nitrite-N	Water	353.2*
Ammonia Nitrogen	Water	350.1*
Total Kjeldahl Nitrogen	Water	351.2*
Dissolved Silica	Water	200.7*
Dissolved Organic Carbon	Water	5310 B**
Total Suspended Solids	Water	160.2*
Alkalinity	Water	310.1*
Dissolved Oxygen Profile	Water	4500-O G**
Temperature Profile	Water	2550 B**
Conductivity Profile	Water	2551 A**
pH Profile	Water	4500-H**
Turbidity Profile	Water	2130 B**
ORP Profile	Water	2580 B**
Secchi depth	Water	N/A
Light penetration	Water	N/A
Calcium	Water	200.7*
Magnesium	Water	200.7*
Sodium	Water	200.7*
Potassium	Water	200.7*
Carbonate	Water	310.1*
Bicarbonate	Water	310.1*
Sulfate	Water	300.0*
Chloride	Water	300.0*
Trace elements (dissolved and total Al, B, Ba, Cd, Cr, Co, Cu, Fe, Pb, Mn, Mo, Ni, Si, Ag, Sr, V, Zn)	Water	200.7*
As	Water	206.3*
Se	Water	270.3*
Hg	Water	1631***
Semivolatile Organics	Water	8270/3540****
Pesticide/PCB Organics	Water	8080/3540****

\*U.S. EPA, 1983

\*\*Standard Methods, 1995

\*\*\*U.S. EPA, 1996

\*\*\*\*U.S. EPA, 1986

**Table 3 - Measurement Performance Criteria**

Parameter	Detection Limit (mg/L)	Reporting Limit (mg/L)	Estimated Accuracy (%)	Accuracy Protocol*	Estimated Precision (%)	Precision Protocol**
Soluble Orthophosphate	0.001	0.005	75-125	% recovery	<20	RPD
Total Phosphorus	0.005	0.005	75-125	% recovery	<20	RPD
Nitrate+Nitrite-N	0.016	0.030	75-125	% recovery	<20	RPD
Ammonia Nitrogen	0.009	0.01	75-125	% recovery	<20	RPD
Total Kjeldahl Nitrogen	0.05	0.1	75-125	% recovery	<20	RPD
Dissolved Silica (As silicon)	0.02	0.02	75-125	% recovery	<20	RPD
Dissolved Organic Carbon	0.5	1.5	85-115	% recovery	<20	RPD
Total Suspended Solids	4	4	N/A	N/A	N/A	N/A
Alkalinity	1.0 mg/L as CaCO <sub>3</sub>	1.0 mg/L as CaCO <sub>3</sub>	85-115	% recovery	<20	RPD
Dissolved Oxygen Profile	0.01	0 - 20	± 0.2 mg/L	Instrument response	N/A	Instrument response
Temperature Profile	-5°C	-5 - 50°C	± 0.15°C	Instrument response	N/A	Instrument response
Conductivity Profile	1 µS/cm	0 - 100 mS/cm	± 1%	Instrument response	N/A	Instrument response
pH Profile	N/A	0 - 14 units	± 0.2 units	Instrument response	N/A	Instrument response
Turbidity Profile	1 NTU	0 - 1000 NTU	± 5%	Instrument response	N/A	Instrument response
ORP Profile	N/A	-999 - 999 mV	± 20 mV	Instrument response	N/A	Instrument response
Secchi depth	0.01 m	0.1 m	N/A	N/A	N/A	N/A
Light penetration	0.1 m	0.1 m	N/A	N/A	N/A	RPD
Carbonate	1.0 mg/L as CaCO <sub>3</sub>	1.0 mg/L as CaCO <sub>3</sub>	85-115	% recovery	<20	RPD
Bicarbonate	1.0 mg/L as CaCO <sub>3</sub>	1.0 mg/L as CaCO <sub>3</sub>	85-115	% recovery	<20	RPD
Sulfate	0.2	1.0	75-125	% recovery	<20	RPD
Chloride	0.2	1.0	75-125	% recovery	<20	RPD

**Table 3 - Measurement Performance Criteria - Continued**

Parameter	Detection Limit (mg/L)	Reporting Limit (mg/L)	Estimated Accuracy (%)	Accuracy Protocol*	Estimated Precision (%)	Precision Protocol**
Al	0.012	0.03	75-125	% recovery	<20	RPD
As	0.03	0.07	75-125	% recovery	<20	RPD
B	0.004	0.01	75-125	% recovery	<20	RPD
Ba	0.0006	0.004	75-125	% recovery	<20	RPD
Cd	0.001	0.004	75-125	% recovery	<20	RPD
Ca	0.002	0.03	75-125	% recovery	<20	RPD
Cr	0.004	0.01	75-125	% recovery	<20	RPD
Co	0.003	0.003	75-125	% recovery	<20	RPD
Cu	0.002	0.004	75-125	% recovery	<20	RPD
Fe	0.001	0.004	75-125	% recovery	<20	RPD
Pb	0.026	0.03	75-125	% recovery	<20	RPD
Mg	0.002	0.03	75-125	% recovery	<20	RPD
Mn	0.0003	0.004	75-125	% recovery	<20	RPD
Hg	0.005	0.01	75-125	% recovery	<20	RPD
Mo	0.005	0.01	75-125	% recovery	<20	RPD
Ni	0.003	0.01	75-125	% recovery	<20	RPD
K	0.601	1.00	75-125	% recovery	<20	RPD
Se	0.021	0.03	75-125	% recovery	<20	RPD
Si	0.003	0.02	75-125	% recovery	<20	RPD
Ag	0.003	0.004	75-125	% recovery	<20	RPD
Na	0.010	0.03	75-125	% recovery	<20	RPD
Sr	0.0003	0.01	75-125	%recovery	<20	RPD
V	0.001	0.004	75-125	%recovery	<20	RPD
Zn	0.001	0.004	75-125	%recovery	<20	RPD
Semivolatile Organics	varies	varies	varies	varies	varies	varies
Pesticide/PCB Organics	varies	varies	varies	varies	varies	varies

\*Accuracy is estimated by % recovery, calculated from the formula:  $\%R = (S - u)/C_{sa}$ , where S is the measured concentration in the spiked aliquot, u is the measured concentration in the unspiked aliquot, and  $C_{sa}$  is the actual concentration of the spike added.

\*\*The precision of duplicate samples collected for QC purposes is determined as Relative Percent Difference, calculated from the formula:  $RPD = (C_1 - C_2) \times 100 / (C_1 + C_2) / 2$ , where  $C_1$  is the larger of the two observed values and  $C_2$  is the smaller of the two values.

\*\*\*Precision and accuracy for temperature, dissolved oxygen, pH, conductivity, turbidity, and ORP profiles are based on performance limits reported by instrument manufacturer.

## 4.0 Results and Discussion

Summary results for nutrients, major ions, and solids are presented in Table 4 for the Salton Sea and river stations. Salton Sea results are presented as whole lake average concentrations, calculated by multiplying measured concentrations of samples collected at all depths and stations on each sampling date by corresponding volume increments obtained from current hypsometric factors for the Salton Sea (Bureau of Reclamation, 2000, modified from Ferrari and Weghorst, 1997). Values for months with more than one sampling date were averaged to produce a single observation from each month for both lake and river nutrient samples.

### 4.1 Temperature

Temperature affects a number of physical, chemical, and biological processes in natural waters. One of the most biologically-important temperature effects is the decrease in oxygen solubility with increasing temperature. Increases in temperature typically increase the rates of both chemical and biological reactions. Temperature is controlled primarily by climatic conditions, but human activity can also have an influence.

The Salton Sea temperature distribution for 1999 is shown in Figure 2. Temperatures followed normal seasonal patterns, with the maximum surface temperature of 36.5°C observed at Station SS-3 on August 24, 1999. The maximum observed temperatures for all lake stations were reached on that date. Minimum surface temperatures were observed in the Salton Sea on January 22, 1999, with SS-3 having the lowest temperature of 14.2°C. Temperature profiles indicated the Sea was well-mixed during the spring and fall months, with some thermal stratification occurring from June through September. Temperature differences between the top and the bottom of the water column ranged from 1 to 3°C during the cooler months and from 3 to 9°C during the summer.

Figure 3 shows the temperature distribution for river stations. Temperatures in the rivers were generally slightly lower than Salton Sea surface samples. The maximum observed temperatures of 30.5°C and 30.4°C for the Alamo and New Rivers, respectively, occurred on August 25, 1999. The maximum observed temperature of 29.6°C for the Whitewater River occurred on August 24, 1999. The minimum observed temperatures of 11.4, 12.7, and 14.7°C for the Alamo, New, and Whitewater Rivers, respectively, all occurred on December 14, 1999, when Sea surface temperatures were also at a minimum.

### 4.2 Dissolved Oxygen and Oxidation-Reduction Potential

Dissolved oxygen concentrations are of concern in lakes because oxygen is essential for the long-term survival of fish and many other aquatic organisms. Most desirable aquatic organisms require a dissolved oxygen concentration of 4.0 mg/L or greater for long-term survival. Dissolved oxygen gradients provide an indication of mixing patterns and the effectiveness of mixing processes in a lake. Dissolved oxygen concentrations also have an important bearing on a lake's physical-chemical properties and the composition of the biota.

**Table 4 - Summary Data for 1999**

Variable	Location (concentrations in mg/L)			
	Salton Sea	Alamo River	New River	Whitewater River
Ortho-P	0.021	0.408	0.697	0.710
Total P	0.069	0.719	1.11	0.865
Ammonia-N	1.16	1.26	3.14	0.729
Nitrate+Nitrite-N	0.12	6.42	3.55	14.3
Total Kjeldahl N	3.5	2.8	4.7	2.0
Dissolved Organic Carbon	40.9	4.2	8.8	7.6
Dissolved Si	4.60	5.89	7.30	8.62
Calcium	944	166	177	122
Magnesium	1400	83.0	82.8	32.2
Sodium	12368	389	566	303
Potassium	258	8.17	12.6	9.0
Strontium	22.0	2.88	3.200	1.94
Boron	11.1	0.560	0.879	0.632
Chloride	17240	443	724	235
Total Alkalinity (mg/L as CaCO <sub>3</sub> )				
Sulfate	10500	762	716	527
Bicarbonate	245	259	300	245
Carbonate	2	<1	<1	<1
Fluoride	2.1	1.2	1.8	2.6
Total Dissolved Solids	44,087	2,049	2,470	1,425
Total Suspended Solids	36.6	355	210	87.1

# Temperature (°C)

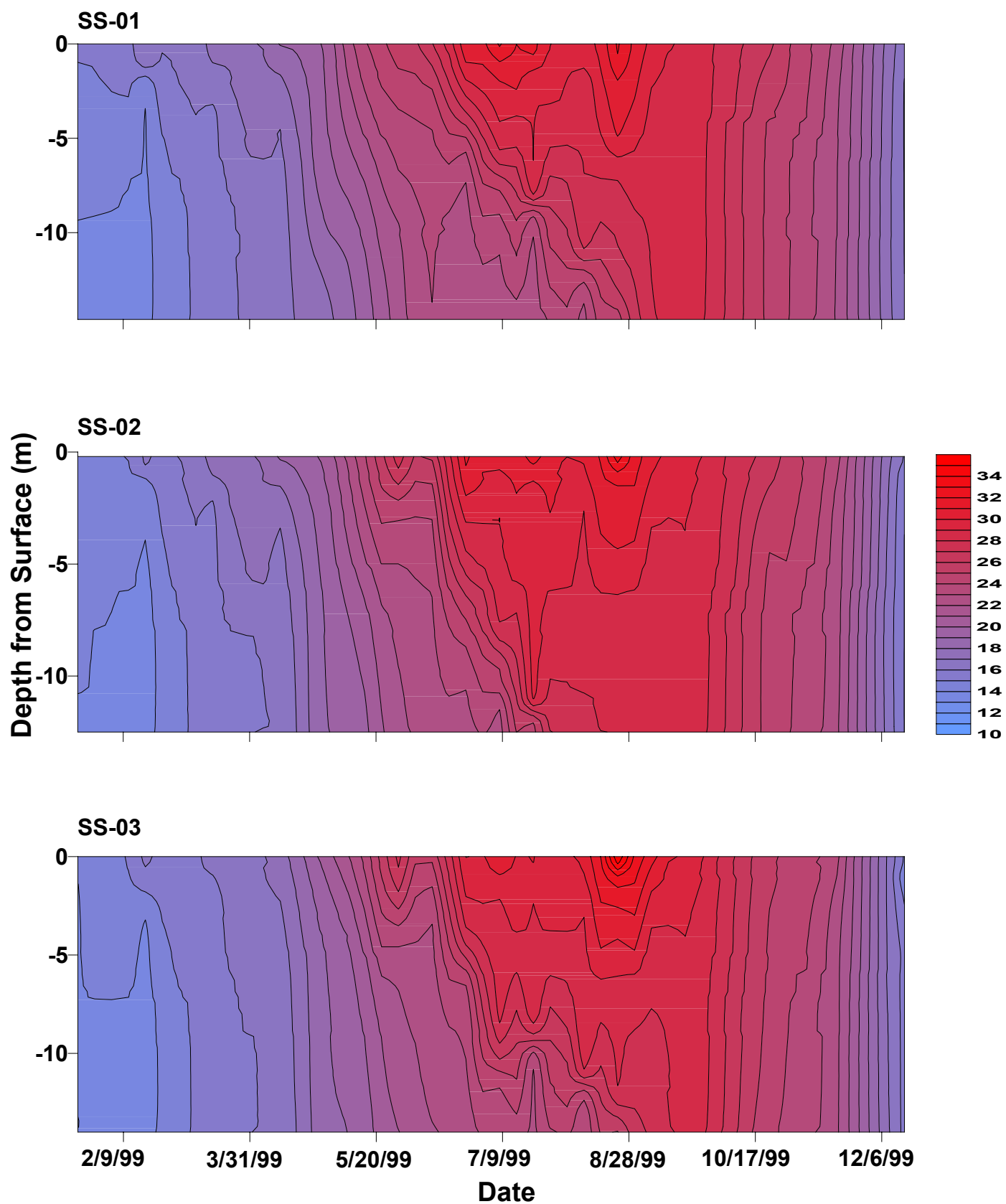


Figure 2. Salton Sea Temperature Variation



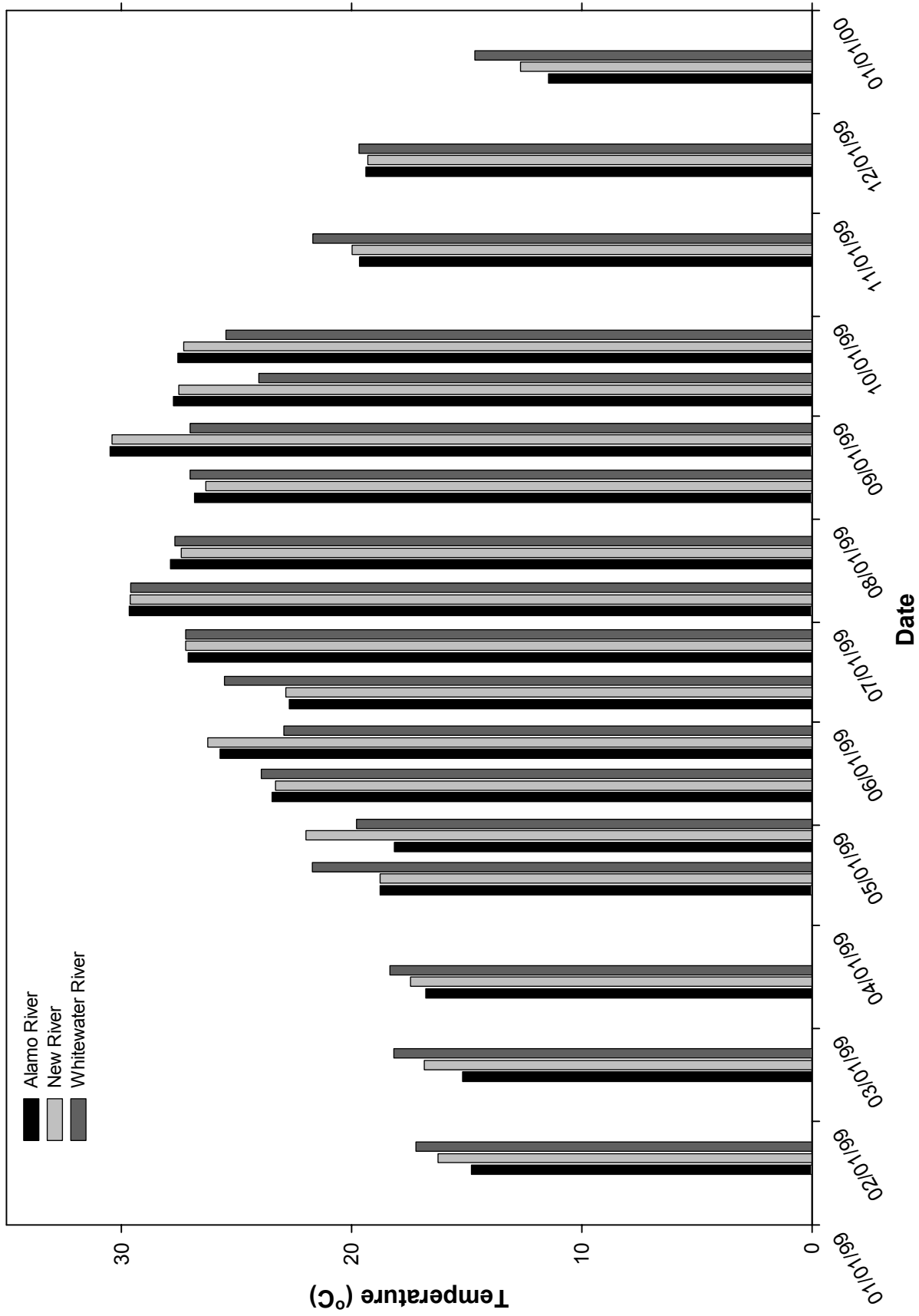


Figure 3. Temperature Distribution at River Stations

The amount of oxygen which can dissolve in water is subject to fluctuations caused in part by variations in temperature, photosynthetic activity, and stream flow. Respiratory processes, oxidation of inorganic wastes, and the decomposition of organic matter deplete oxygen, while photosynthesis and re-aeration by contact with the atmosphere increase oxygen concentrations in water.

In addition to concentration, dissolved oxygen levels in water can be expressed in terms of percent saturation. Since the amount of oxygen that can dissolve in water decreases with increasing temperature and dissolved solids concentration, with temperature being of particular importance, dissolved oxygen saturation often provides a better means of comparing oxygen concentrations from different sampling dates and depths in the water column than concentration.

Dissolved oxygen levels in the Salton Sea are characteristic of a highly eutrophic system. Surface oxygen levels during several months were often greater than 200 percent of saturation, while some oxygen depletion was observed in the bottom waters of the Salton Sea throughout the year. Hypolimnetic dissolved oxygen concentrations were often severely depleted, with observed concentrations at the lake bottom usually less than 2 mg/L from April through November. The zone of severe oxygen depletion ranged up to the surface in both August and September (Figure 4); with a minimum observed surface dissolved oxygen concentration of only 0.21 mg/L at Station SS-1 on September 8, 1999. The August and September surface oxygen minima coincided with extensive fish kills.

Dissolved oxygen levels in the rivers flowing into the Salton Sea also exhibited oxygen depletion, with nearly all measured concentrations below the 90 percent saturation level (Figure 5). Dissolved oxygen concentrations averaged 77.3, 66.2 and 73.2 percent of saturation in the Alamo, New, and Whitewater Rivers, respectively.

Oxidation-reduction reactions play an important role in driving the geochemical cycles of many elements. The measured oxidation-reduction potential (usually referred to as the redox potential) of a water provides an indication of the relative potential for oxidation or reduction reactions taking place. Most redox reactions are biologically mediated as various micro-organisms use the energy gained by the transfer of electrons for their growth.

As expected, oxidation-reduction potential (ORP) closely followed dissolved oxygen concentrations in both river and Sea samples (Figures 5 and 6, respectively). The ORP in the Sea was usually in the range of 200 to 300 mV at the surface, but dropped to a minimum of -12 mV at the surface at Station SS-1 during the extreme low oxygen event that occurred on September 8, 1999 (Figure 6). River samples were always above the 200 mV level (Figure 5) indicative of oxidizing conditions.

### **4.3 pH**

The pH of water is an important general water quality indicator because it is a major factor affecting most chemical and biological interactions. The pH scale ranges from 1 to 14 standard units. A pH of 7 indicates neutral conditions, while waters with a pH less than 7 are acidic and those with pH values greater than 7 are basic.

# Dissolved Oxygen (%Sat)

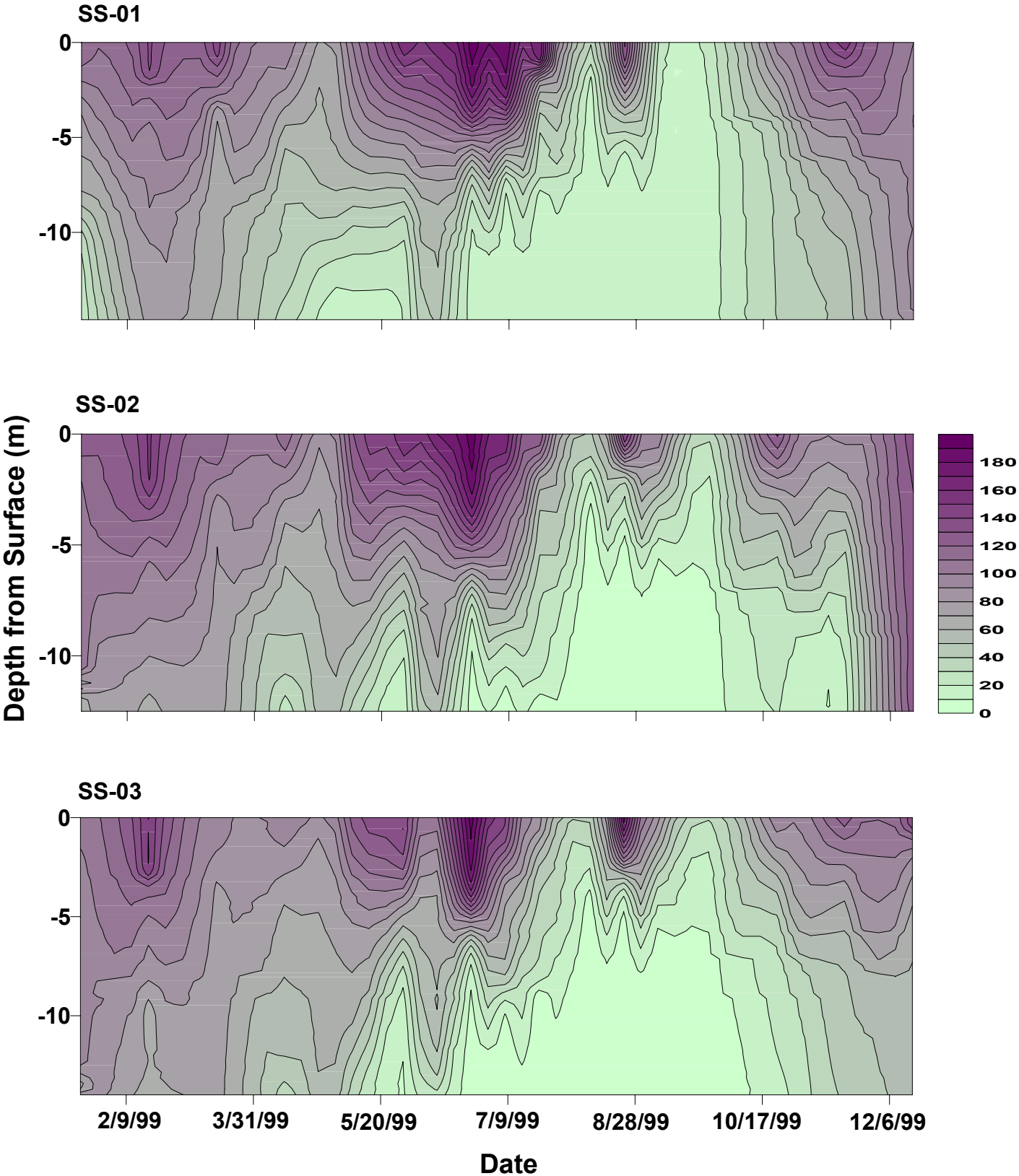


Figure 4. Dissolved Oxygen Saturation Levels in the Salton Sea

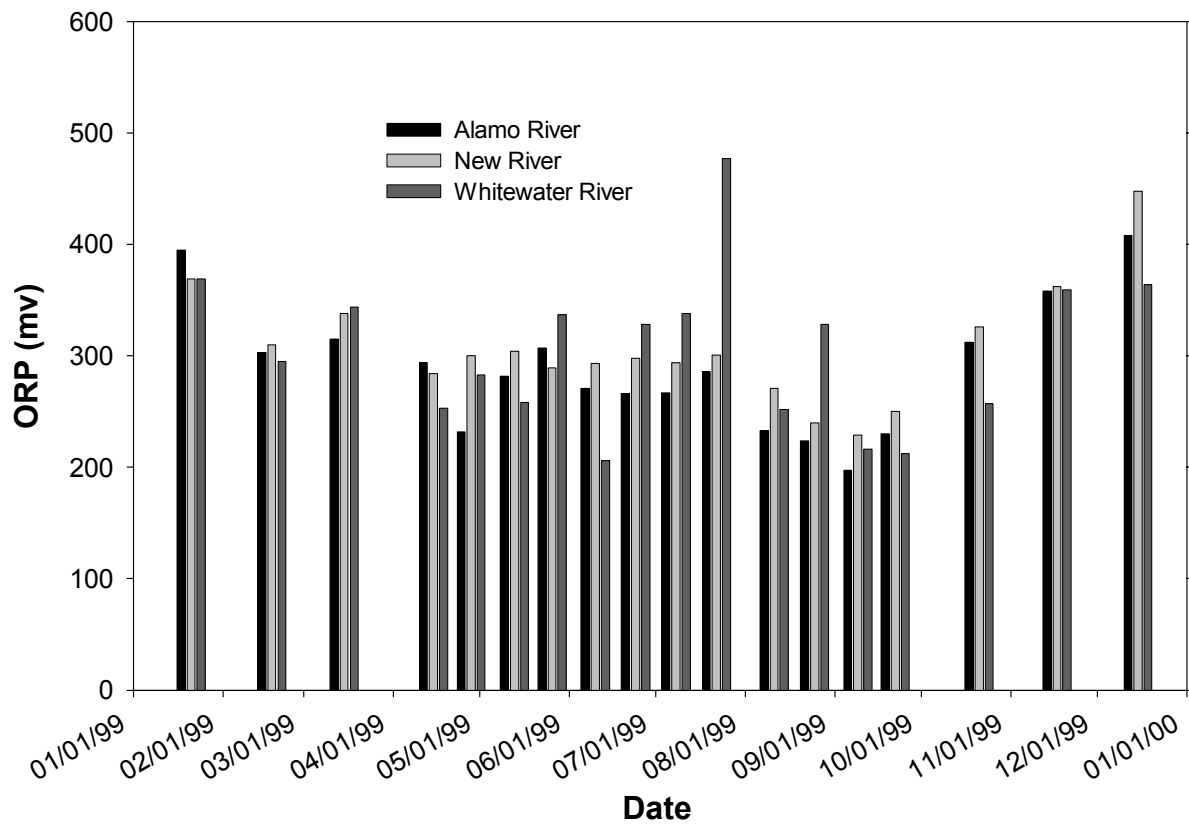
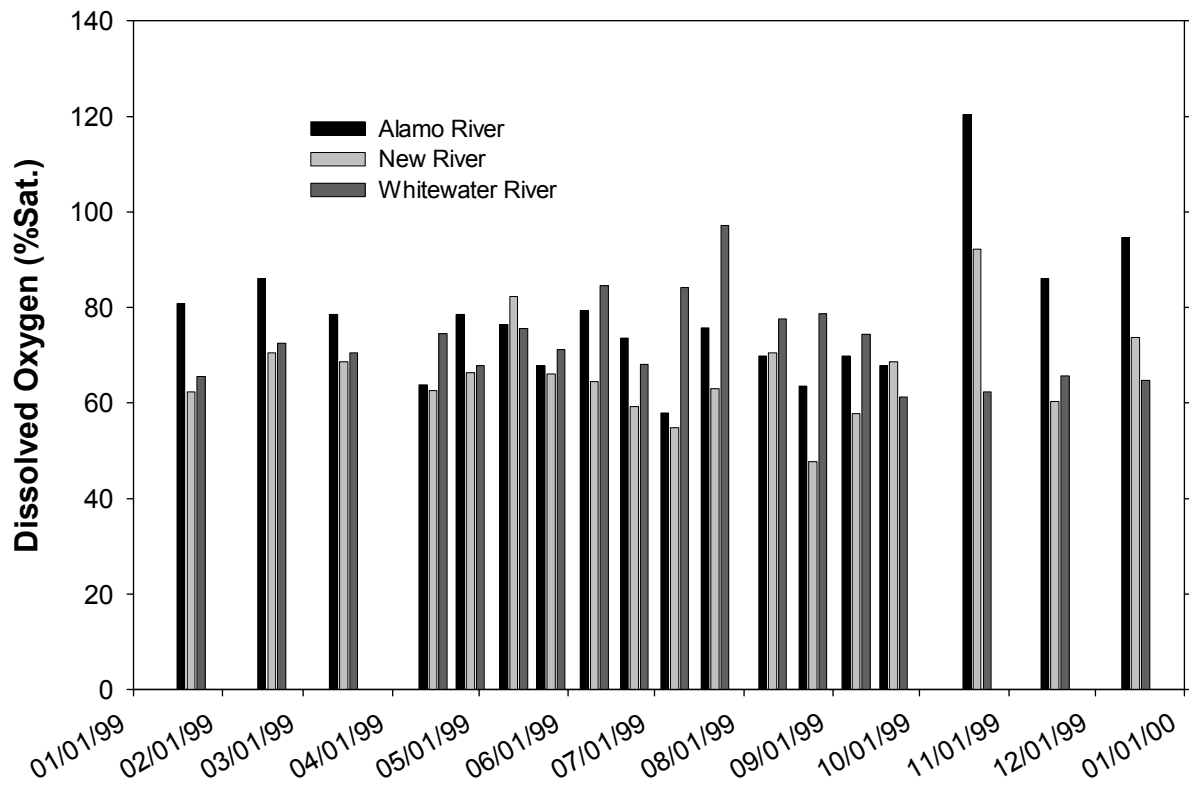


Figure 5. Dissolved Oxygen Saturation Levels and Oxidation-Reduction Potentials at River Stations

# Oxidation-Reduction Potential (mV)

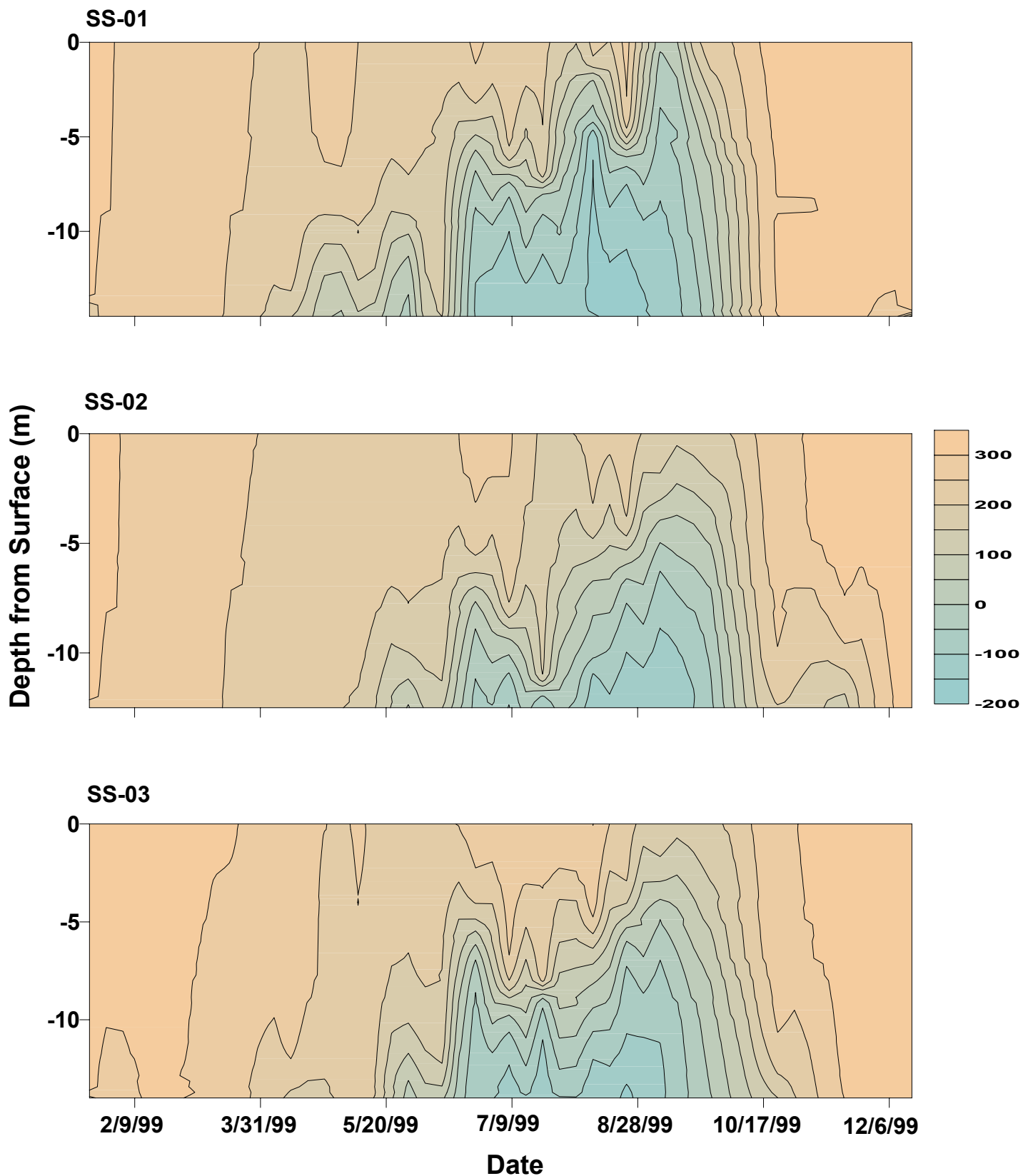


Figure 6. Oxidation-Reduction Potential in the Salton Sea

Since pH is expressed on a logarithmic scale, each 1 unit change in pH represents ten-fold increase or decrease in hydrogen ion concentration. Therefore, a pH of 6 would be 10 times more acidic than a pH of 7 and 100 times more acidic than a pH of 8. The pH of normal rainwater (containing no pollutants) is about 5.6. As the rainwater travels over and through rocks and soil, chemical reactions with minerals affect the pH and buffering capacity of the water.

There was little variation in pH levels in river samples and only small temporal and spatial variations samples from the Salton Sea. The pH levels for the river samples was usually between 7.5 and 7.65, with differences of only 0.4 units between the high and low values at each station. The surface pH at all three lake stations averaged about 8.2. As is typical of eutrophic conditions, the pH at the surface was frequently more than 1 pH unit higher than the pH at the bottom of the water column as a result of the removal of carbon dioxide in surface water during photosynthesis and the formation of carbon dioxide and organic acids in bottom waters during decomposition.

#### 4.4 Alkalinity

Alkalinity is a measure of the capacity of water to neutralize acids. Alkalinity is a capacity factor and is directly related to pH, which is a measure of the overall intensity of acid and base reactions in water. Carbonate minerals are the major source of alkalinity in most waters, with bicarbonate ion representing the major form of alkalinity in natural waters at neutral pH levels. As a result, alkalinity is usually expressed as mg CaCO<sub>3</sub>/L. The salts of other weak acids, such as borates, silicates and phosphates can be significant in some cases, particularly in more arid regions.

Alkalinity was measured both in the field on each sampling date. Ratios of total alkalinity and phenolphthalein alkalinity were used to provide estimates of bicarbonate and carbonate concentrations. Results are shown in Figures 24 and 25 for Sea and river samples, respectively

Alkalinity changes in the Sea (Figure 7) were marked by relatively stable values interspersed with high peaks. The peaks occurred at approximately the same times as the periods of low oxygen concentrations and oxidation-reduction potential in bottom waters (Figures 3 and 6). These results could be explained by episodes of sulfate reduction, which occur at low dissolved oxygen concentrations and generate alkalinity (HCO<sub>3</sub><sup>-</sup>) according to the following formula:



As Equation 2 indicates, two equivalents of alkalinity are produced for each mole of sulfate reduced. Alkalinity is also generated by other reactions, such as the microbial decomposition of organic carbon and the reduction of nitrate to ammonia. The potential importance of these reactions is discussed in more detail in Section 5.0.

Total alkalinity in the river samples was highly variable (Figure 8). Alkalinity levels in the river samples could be affected by both dissolved and suspended solids.

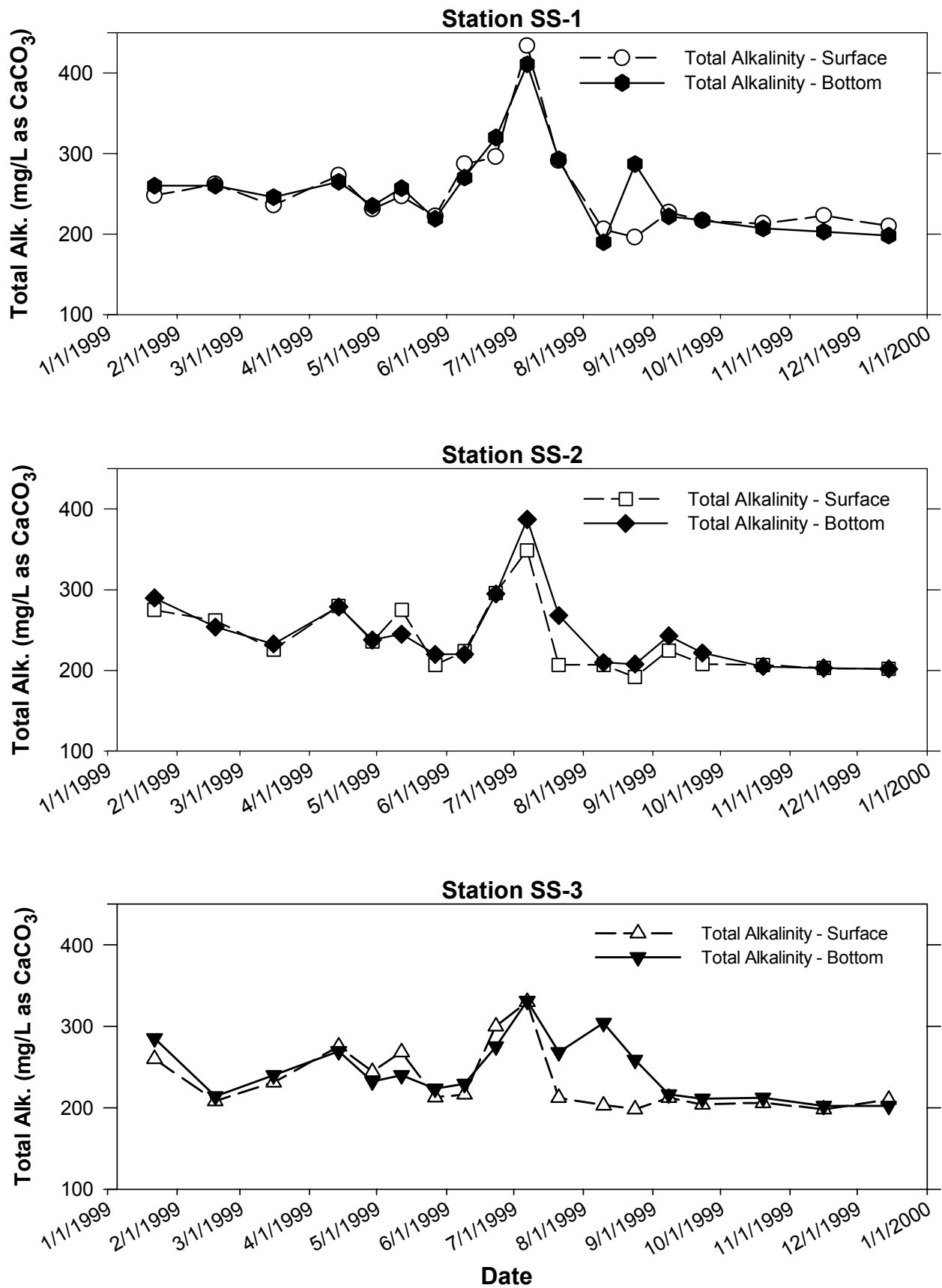


Figure 7. Total Alkalinity Concentrations in Salton Sea Samples

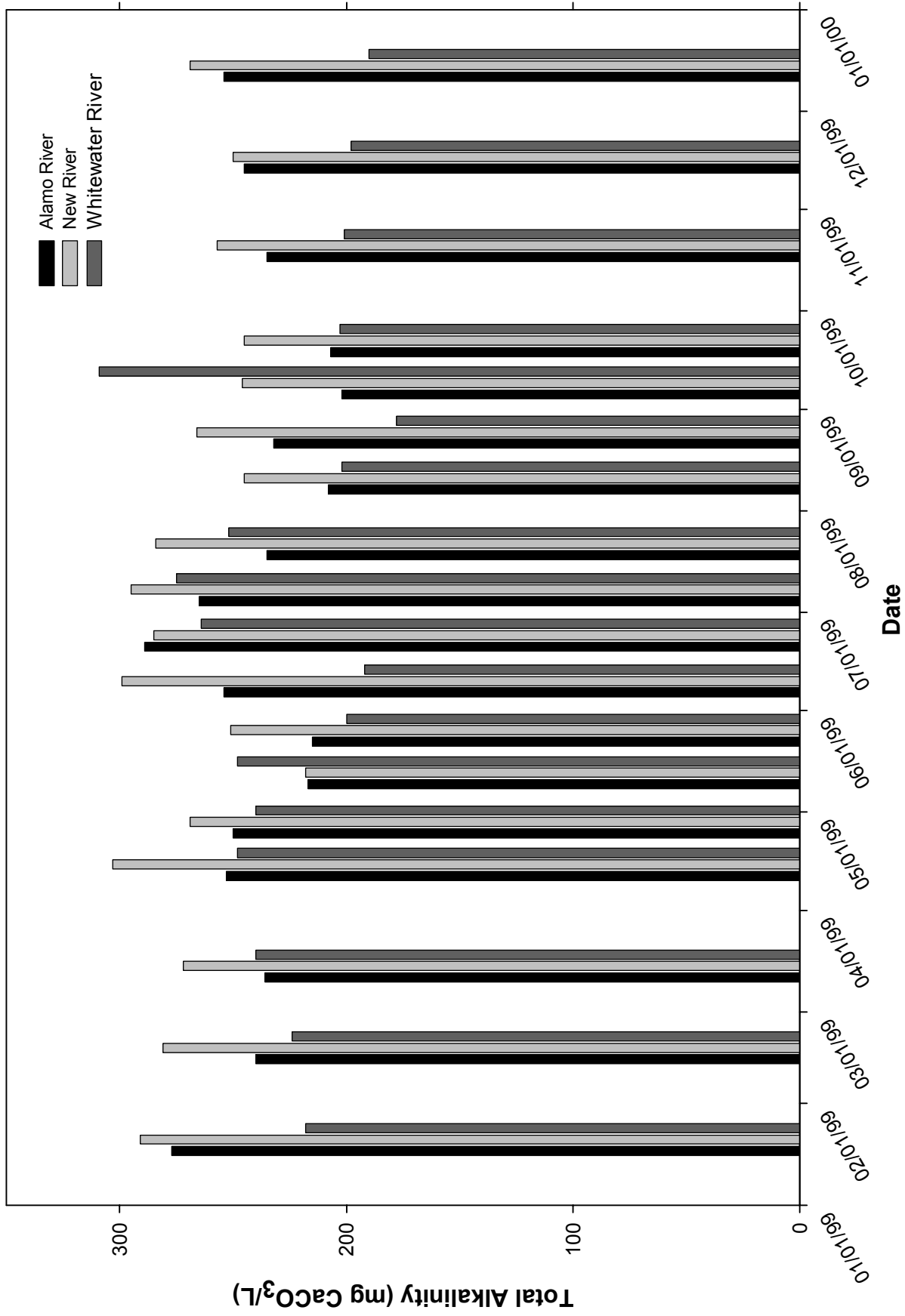


Figure 8. Total Alkalinity Concentrations in River Samples



## 4.5 Conductivity and Total Dissolved Solids

Conductivity is a measure of the ability of water to conduct an electric current and is dependent on the number of dissolved ions in solution. The total dissolved solids (TDS) concentration is closely related to conductivity, but includes both dissolved ions and all other dissolved material.

Observed conductivities in lake waters vary widely and are largely a function of geology and soils in the watershed. Conductivity varies significantly with temperature and, to a lesser extent, with the individual ions present. Conductivity is typically corrected to 25 °C to allow direct comparison of samples collected at different temperatures.

Conductivity in the Salton Sea was very consistent (Figure 9). Changes with depth were small and inconsistent. Average conductivity levels over the entire year were 55.11, 55.19, and 55.23 mS/cm for Stations SS-1, SS-2, and SS-3, respectively. These minor differences between the stations are less than expected instrumental variation.

Conductivities in the river samples were more variable than those in the Sea (Figure 10), with differences between maximum and minimum values ranging from 26 percent in the New River to 49 percent in the Alamo River. Average conductivities were 3.141, 4.089, and 2.145 mS/cm for the Alamo, New, and Whitewater Rivers, respectively.

Total dissolved solids concentrations were measured directly by evaporation at 180 °C and were also calculated as the sum of the major cations and anions (Ca, Mg, Na, K,  $\text{CO}_3^-$ ,  $\text{HCO}_3^-$ ,  $\text{SO}_4^-$ ,  $\text{Cl}^-$ ). The mean measured TDS concentrations for the Alamo River, New River, and Whitewater Rivers are presented in Table 1; calculated TDS concentrations were 2,060, 2,520, and 1,430 mg/L, respectively. Directly measured and TDS calculated concentrations calculated from the sum of major ion concentrations for the Salton Sea were 43,940 and 42,160 mg/L, respectively. Note that this measured value of 43,940 mg/L was based on all measurements made during the sampling program and therefore differs slightly from the weighted mean of 44,090 mg/L calculated in Table 4.

The TDS concentrations in both Sea and river samples closely tracked conductivities (Figures 9 and 10). Possible seasonal differences were examined by calculating averages for measured concentrations of TDS and conductivity, as well as TSS, for the summer (June through August), fall (September through November), winter (December through February) and spring (March through April). Concentrations were averaged for months with more than one sampling date so as not to skew seasonal averages (Table 5).

Seasonal differences observed in the Salton Sea were minor, with changes of less than one percent for conductivity and about two percent for measured TDS concentrations. Seasonal mean conductivities varied by less than 10 percent from mean annual values for all three rivers and showed no consistent patterns. Summer TDS levels were less than the annual means and winter levels were higher for all three rivers, but seasonal TDS concentrations still varied by less than 10 percent from annual means for the Alamo and New Rivers. Winter TDS levels were 16 percent higher and summer levels were 11 percent lower than the annual mean in the Whitewater River, but absolute concentration differences were lower than those in the other rivers. Seasonal changes in agricultural operations are the most likely cause for the slight differences that were noted.

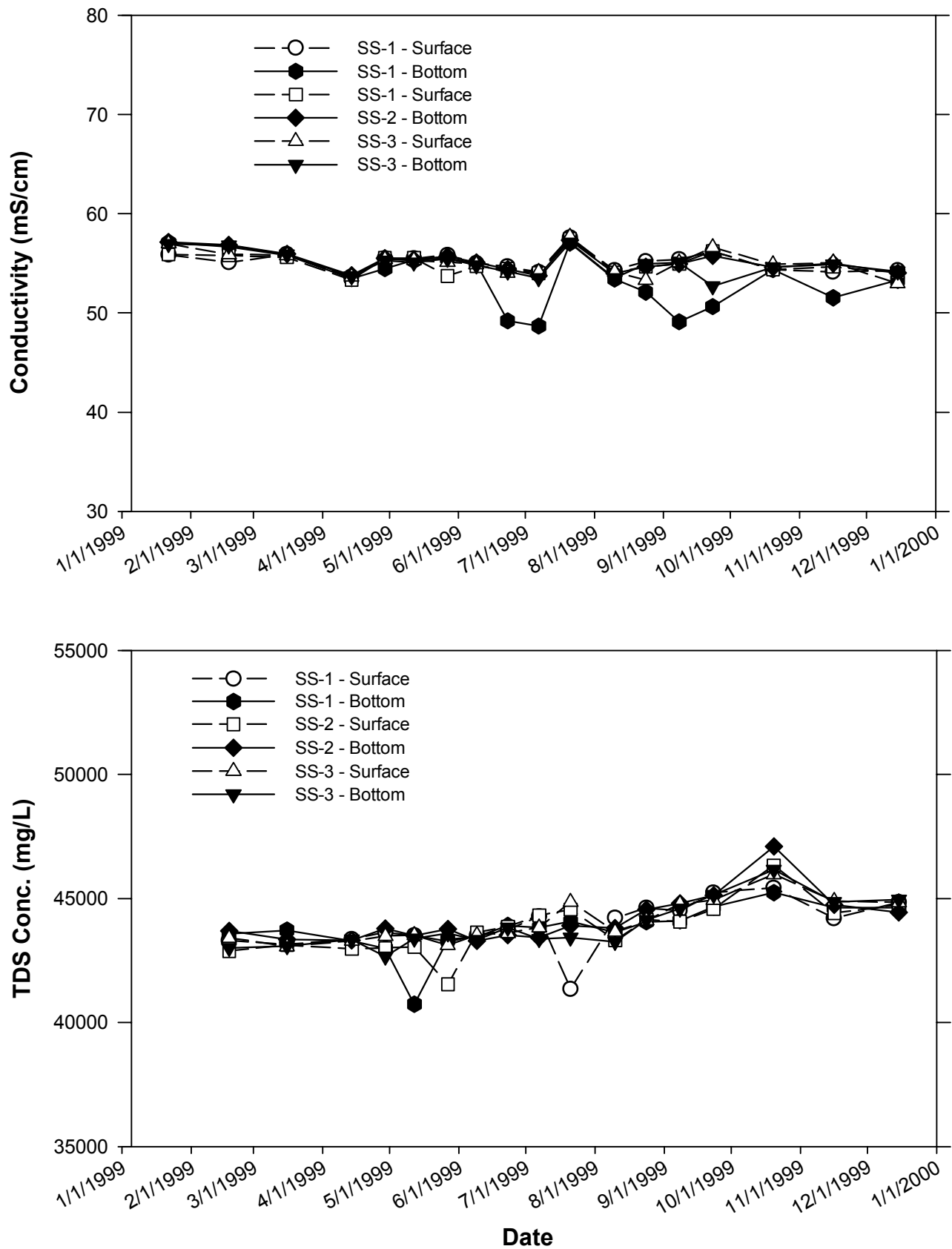


Figure 9. Salton Sea Conductivity and Total Dissolved Solids Concentrations

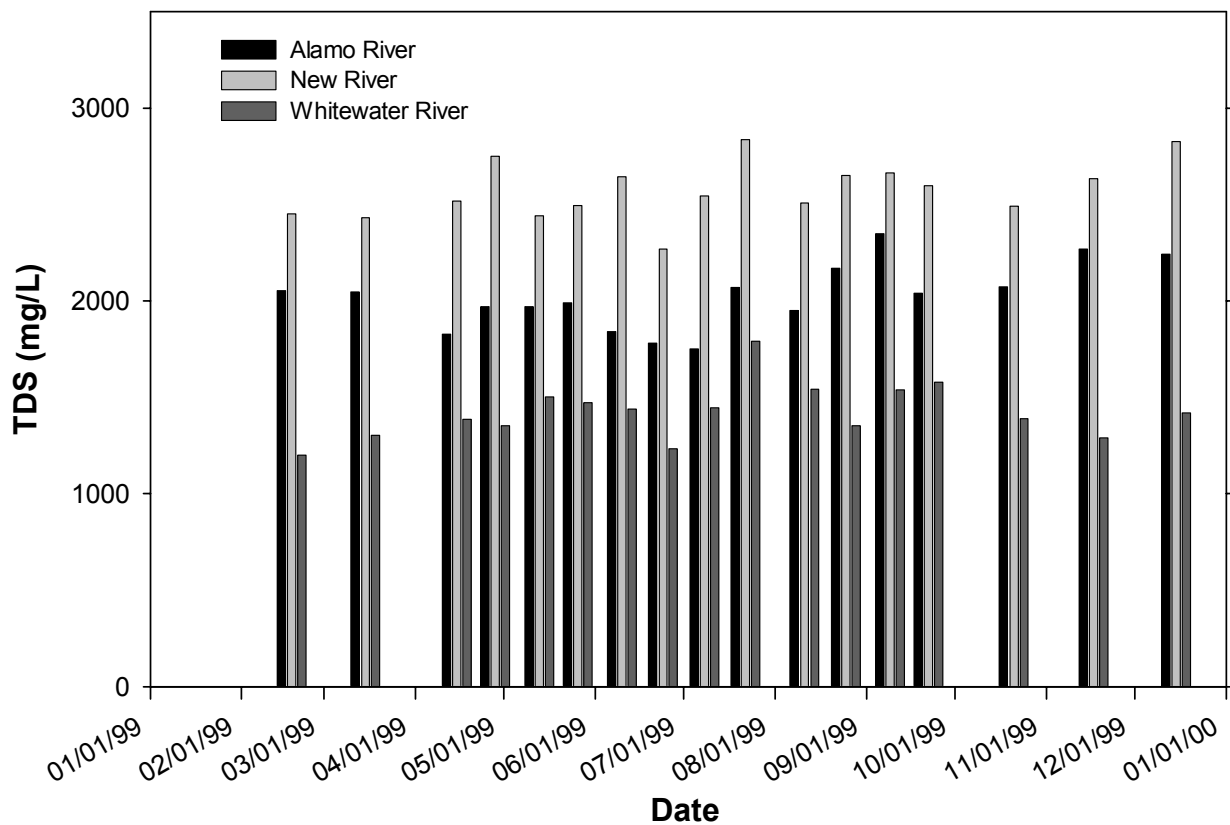
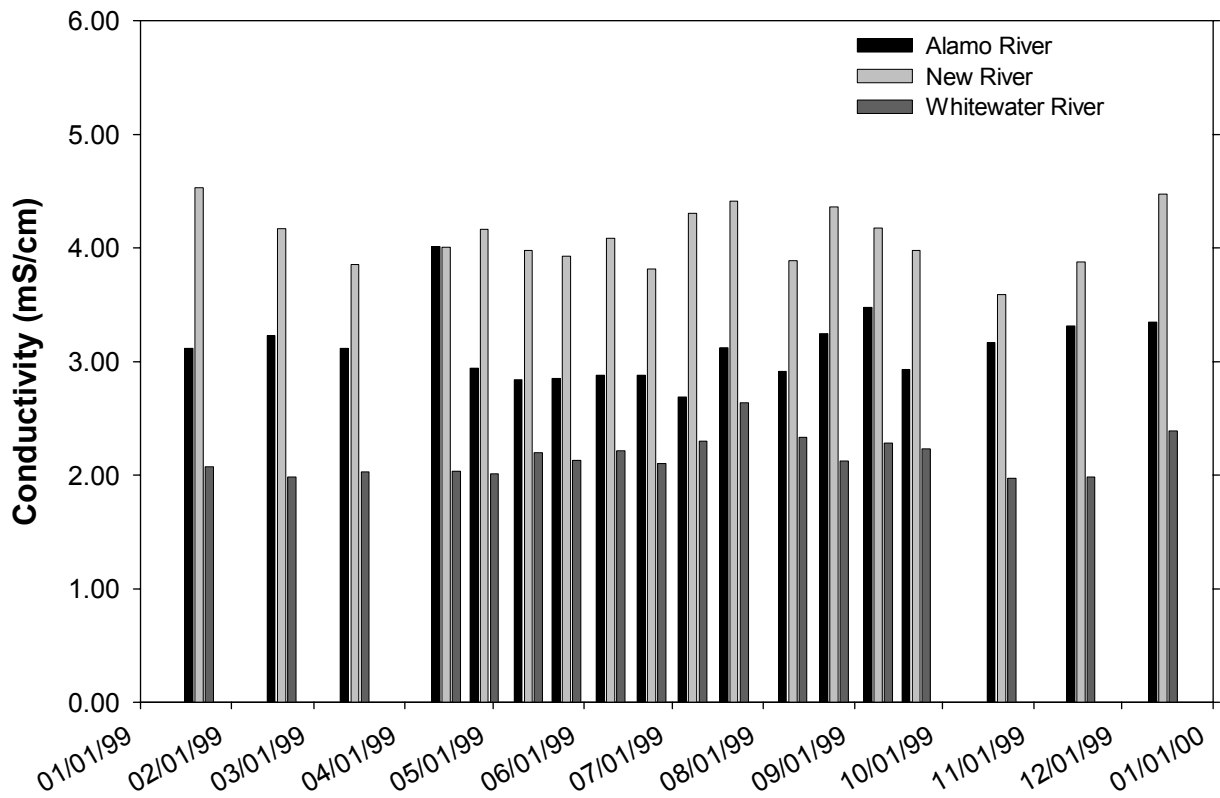


Figure 10. Conductivity and Total Dissolved Solids Concentrations at River Stations

**Table 5 - Seasonal Changes in Salton Sea and River Conductivity and Solids Concentrations**

Variable	Summer	Fall	Winter	Spring	Annual Mean
Alamo River					
TDS (mg/L)	1928	2180	2147	1975	2049
Conductivity (mS/cm)	2.956	3.229	3.232	3.147	3.141
TSS (mg/L)	357	298	361	403	355
New River					
TDS (mg/L)	2392	2397	2639	2511	2470
Conductivity (mS/cm)	4.144	3.849	4.391	3.966	4.089
TSS (mg/L)	205	158	214	264	210
Whitewater River					
TDS (mg/L)	0.632	0.709	0.823	0.675	0.710
Conductivity (mS/cm)	2.285	2.072	2.150	2.074	2.145
TSS (mg/L)	0.753	0.920	0.899	0.889	0.865
Salton Sea					
TDS (mg/L)	43,933	45,097	44,021	43,227	44,087
Conductivity (mS/cm)	54.97	55.00	55.52	55.29	55.20
TSS (mg/L)	24.7	30.9	46.0	44.8	36.6

The difference between calculated and measured TDS concentrations were generally within expected analytical error. The differences between measured and calculated TDS concentrations for the river samples were all less than two percent. The measured concentrations of TDS for the Salton Sea were higher than calculated concentrations, even if minor ions are included. The difference of about four percent could be analytical error or result from the presence of hydrated salts that are stable at 180 °C.

Standard Methods (1998) indicates that drying at 180 °C removes most physically occluded water, but water of crystallization may not be completely removed, especially in waters, like the Salton Sea, that are high in sulfate. Many historic analyses at the Salton Sea relied on drying at 103-105 °C. Under those conditions, the occlusion of water during the drying process would lead to even higher reported values for TDS and may represent a significant source of error in older work.

Regression analyses were performed to determine whether or not TDS concentrations could be estimated from conductivity values. There were a total of 15 river samples and 35 Sea samples that had both measured and calculated TDS in addition to conductivity. Regressions of both measured ( $r^2 = 0.9961$ ) and calculated ( $r^2 = 0.9863$ ) TDS concentrations against conductivity produced relationships that were statistically significant at the 99 percent confidence level.

Closer examination of the data indicated the calculated relationships could not be used for predictive purposes. The apparent relationships based on both river and Sea data resulted from the combination of two non-significant relationships (Figure 9). There was a weak, but not statistically significant, relationship between TDS and conductivity for river samples. In contrast, both measured and calculated TDS levels in the Sea were much more variable than conductivity (Figure 11) and no significant relationship existed.

#### 4.6 Total Suspended Solids

The total suspended solids (TSS) concentration provides a measure of water clarity and the amount of particulate matter in the water column. Suspended solids include both organic matter, such as algae and other plant material, and inorganic material, including sand, silt, and clay particles.

Total suspended solids levels were very high in the river samples (Table 4 and Figure 12). The Alamo and New Rivers were always very turbid, with TSS levels ranging from 237 to 480 mg/L in the Alamo River, and from 87 to 332 mg/L in the New River. Levels of TSS in the Whitewater River were much lower, with a range of 40 to 188 mg/L.

The TSS concentrations varied only slightly during the summer, winter, and spring for the Alamo and New Rivers (Table 5), with averages of about 360 mg/L for the Alamo River and 210 mg/L for the New River during those months. TSS concentrations were approximately 50 mg/L lower during the fall months for both rivers. Seasonal variations in the Whitewater River were more apparent. The summer TSS concentration of 121 mg/L was over twice as high as the winter concentration of 58 mg/L, but the magnitude of this seasonal variation is similar to that of the other two rivers. Seasonal changes in TSS may be related to agricultural operations, with less irrigation during the fall and winter.

As expected, TSS levels in the Salton Sea were much lower than those in the rivers, indicating that the suspended sediment load rapidly settles within a short distance after reaching the Sea. The suspended solids levels were also quite variable (Figure 13), with observed TSS concentrations ranging from 9 to 179 mg/L during the sampling program and *in situ* turbidity measurements ranging from 0 to 479 NTU. In contrast to the river samples, algal cells may be an important component of the TSS levels in the Salton Sea.

Some variations with both season and depth in the water column were noted. In contrast to the river samples, TSS levels in the Salton Sea were highest during the winter months, with a whole-lake average TSS concentration of 46 mg/L. The spring concentration of 43 mg/L was next highest, with lower levels of 31 mg/L for the fall months and 25 mg/L during the summer. Surface TSS levels, which averaged 42 mg/L, were higher than TSS levels at the bottom of the water column, where the average was 26 mg/L.

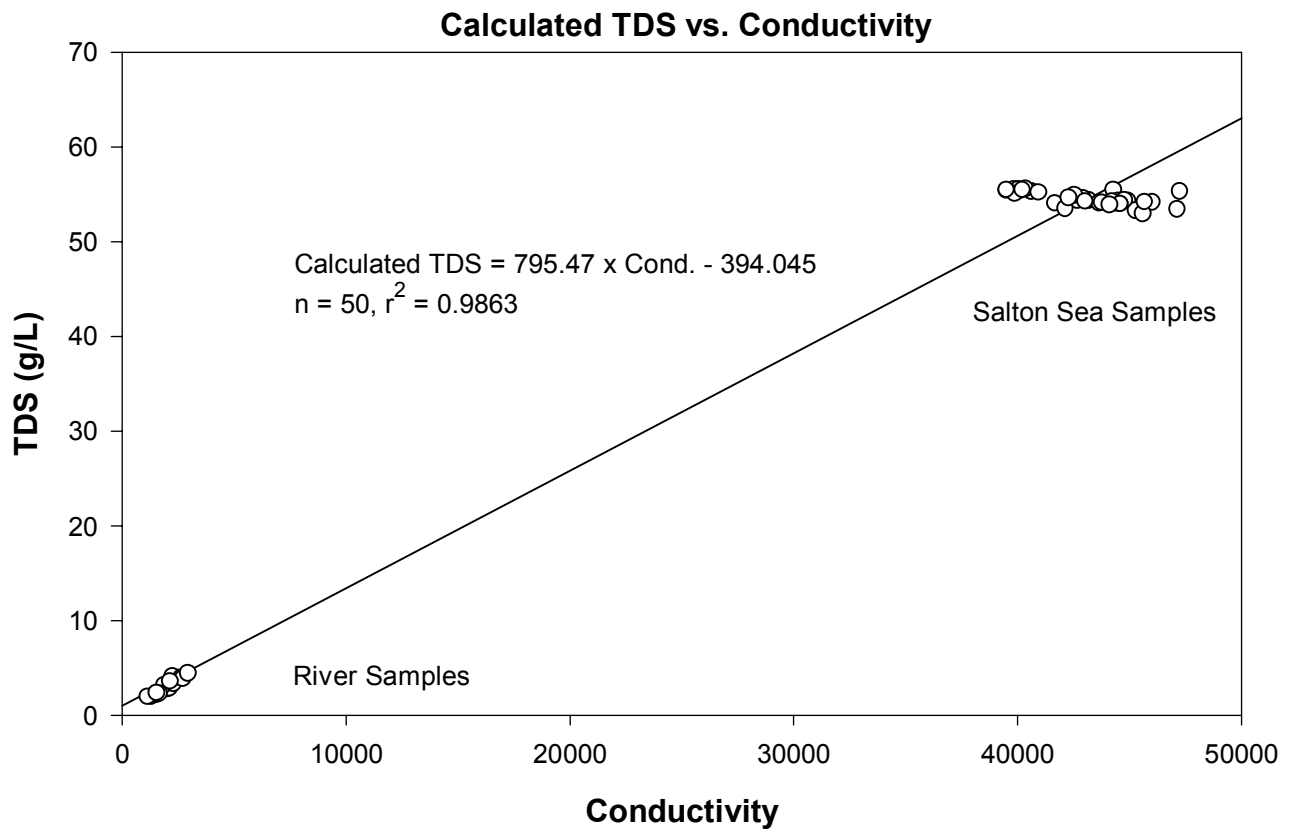
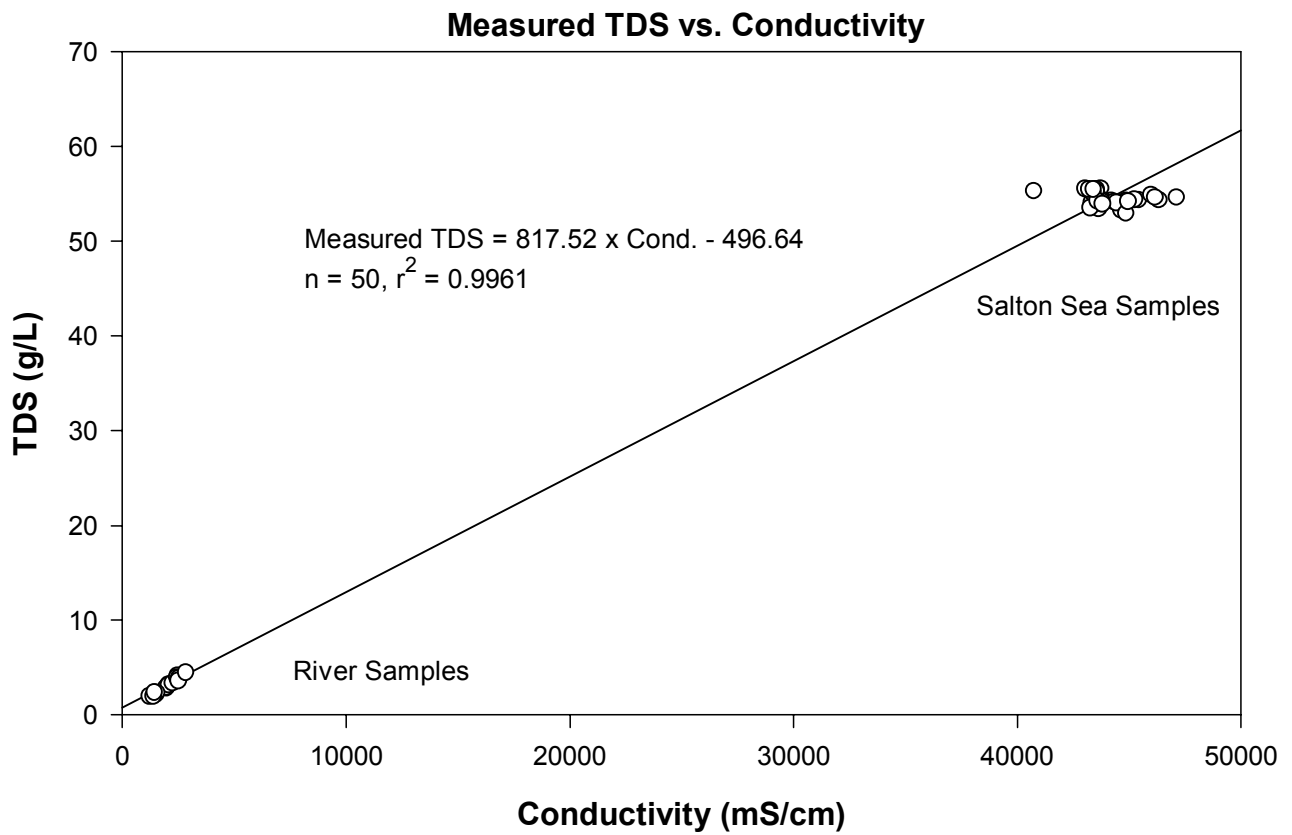


Figure 11. Regressions of Total Dissolved Solids and Conductivity

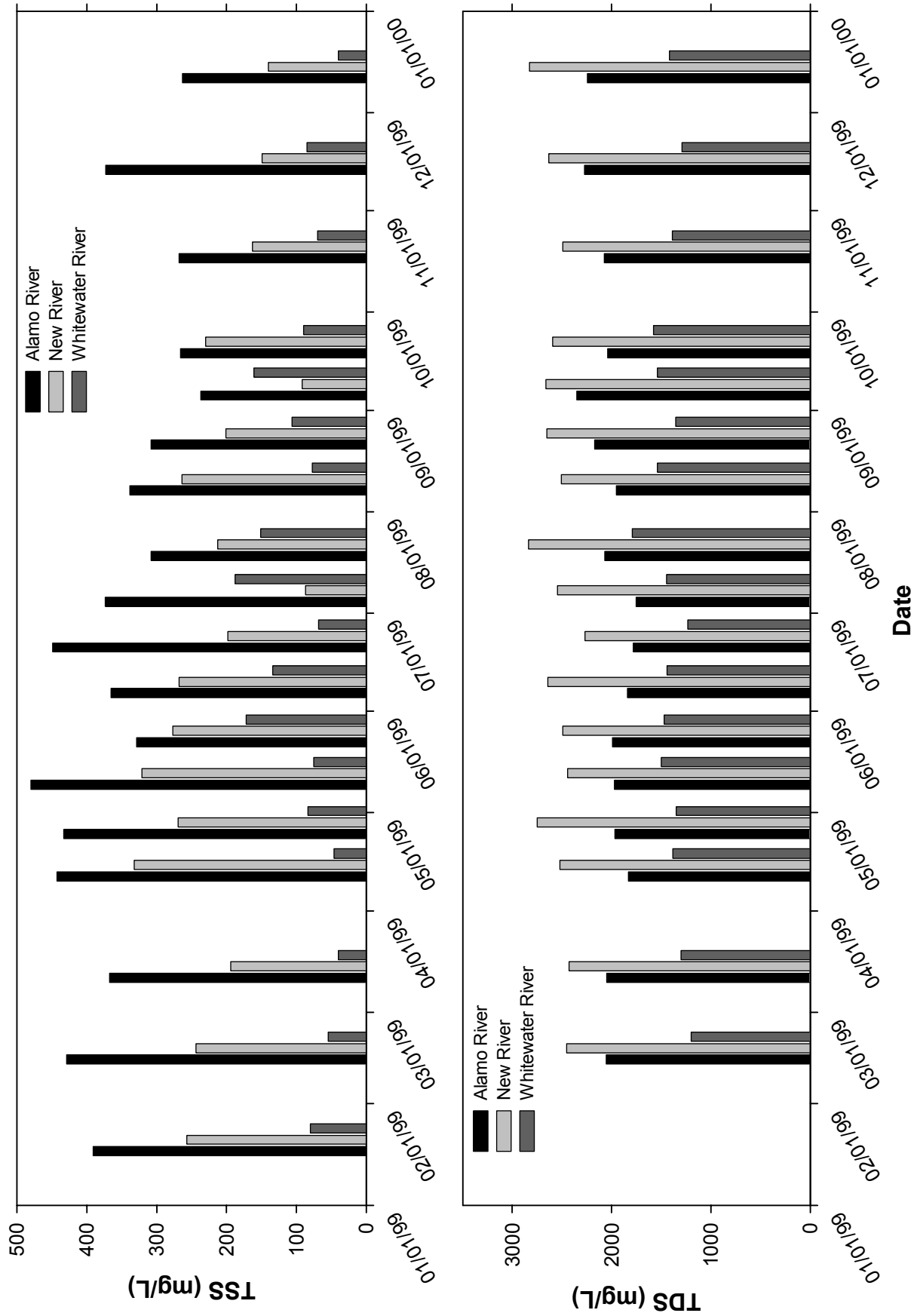


Figure 12. River Solids Concentrations

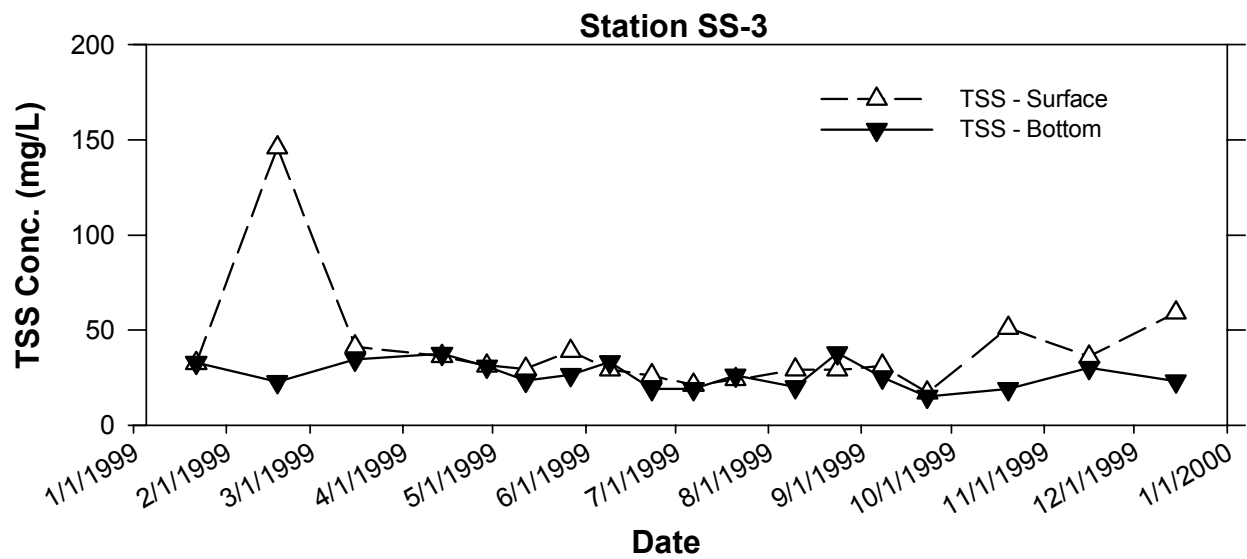
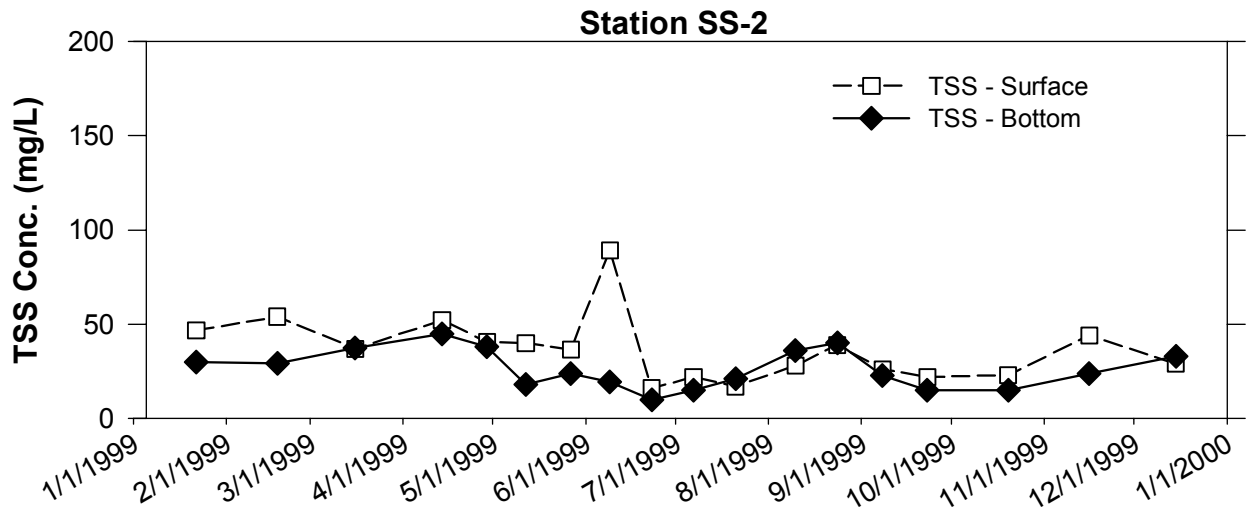
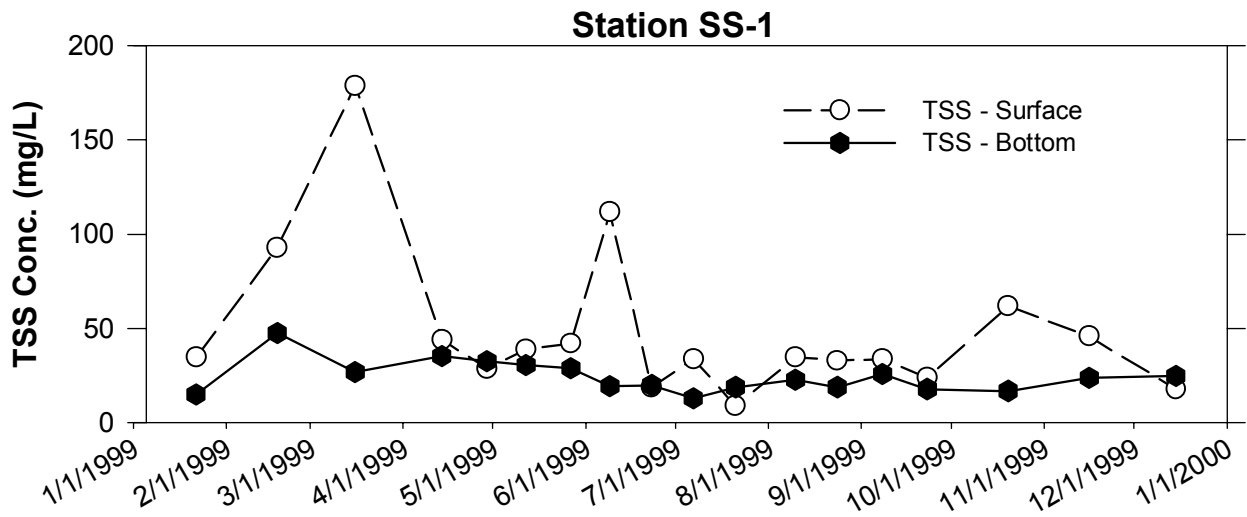


Figure 13. Total Suspended Solids Concentrations in the Salton Sea



## 4.7 Transparency

The transparency, or clarity, of water is most often reported as the Secchi depth. Observed Secchi depths range from a few centimeters in very turbid lakes to over 40 meters in the clearest known lakes (Wetzel, 1983). Although somewhat subjective, this method probably best represents the conditions which are most readily visible to most lake users.

Secchi depth is related to the transmission of light in water, and depends on both the absorption and scattering of light. The absorption of light in dark-colored waters reduces light transmission. Light scattering is usually a more important factor than absorption in determining Secchi depths. Scattering can be caused by color, by particulate organic matter (e.g., algal cells) and by inorganic materials such as suspended clay particles.

The depth at which light levels in the water column are reduced to 1 percent of surface levels is frequently used as the maximum depth for algal growth, also called the euphotic depth. Scheffer (1998) reported that the euphotic depth in many shallow lakes can be estimated as 1.7 times the Secchi depth.

Secchi depths in the Salton Sea were low (Figure 14), ranging only from 0.4 m to 1.4 m. Secchi depths often varied widely between stations on the same sampling date and there were no clear seasonal changes. Light penetration in the Salton Sea (Figure 14) was greater than expected based on the low Secchi depths. The depth of 1% light penetration ranged from 1.8 to 4.8 m and was strongly correlated ( $\alpha < 0.01$ ,  $n = 54$ ) to Secchi depth. Average ratios of the depth of 1% light penetration to Secchi depth were 4.2:1 for all three sampling stations. These ratios are high compared to freshwater lakes and may result from flocculation and settling of fine inorganic particles in the highly saline waters of the Sea.

## 4.8 Nutrients

Phosphorus and nitrogen are major nutrients required for the growth of aquatic organisms in lakes. The dissolved inorganic nutrients, soluble orthophosphate, nitrate, nitrite and ammonia nitrogen, are regarded as the forms readily available to support aquatic growth, while total phosphorus and total Kjeldahl nitrogen concentrations provide an indication of the maximum growth which could be achieved.

Some important external sources of phosphorus and nitrogen are fertilizers, septic leachate, sewage effluent, detergents and soaps, particulate material transported by stormwater, and precipitation. Lake sediments, particularly those which are highly organic or mucky, can serve as an internal source of nutrients, especially if the overlying waters become devoid of oxygen. The decomposition of dead algal cells or aquatic weed tissue is another internal source of nutrients.

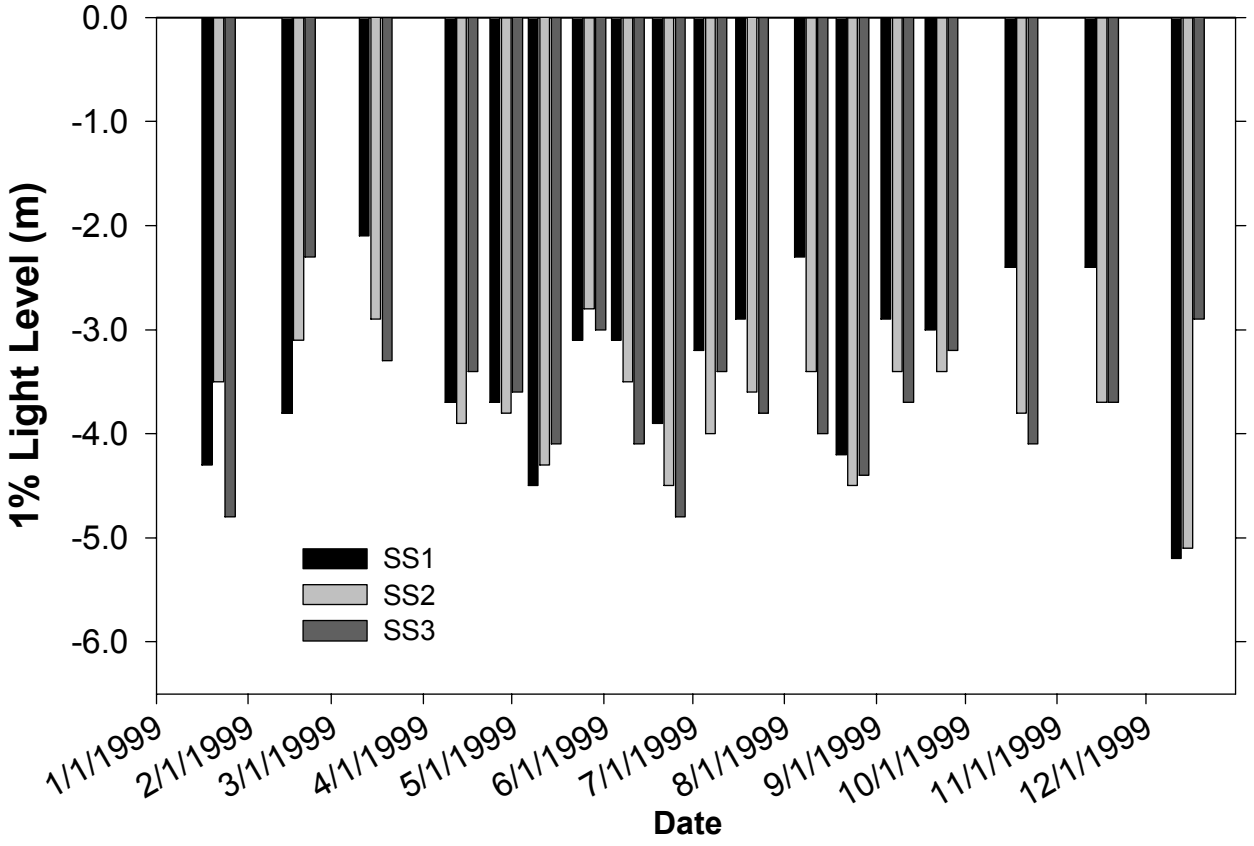
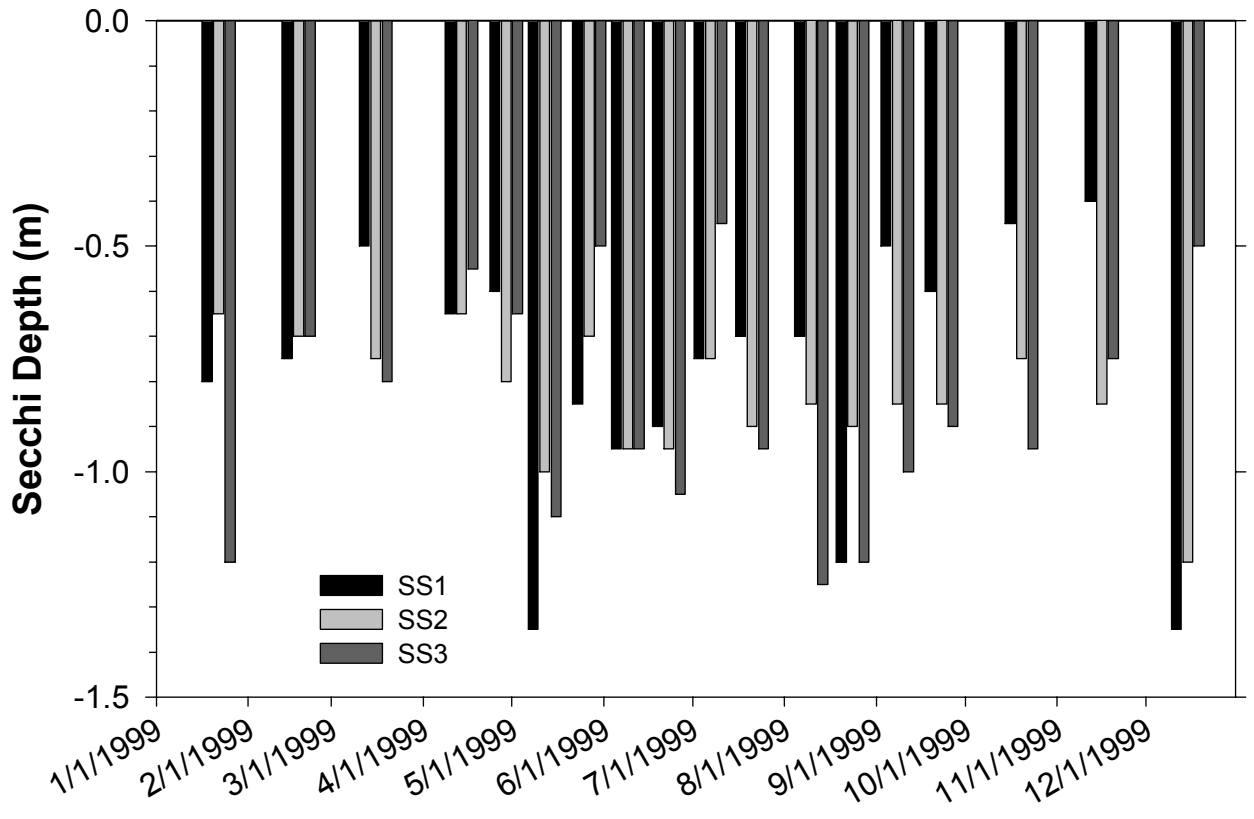


Figure 14. Salton Sea Secchi Depth and Depth of 1% Light Penetration

### 4.8.1 Phosphorus

Phosphorus is an essential nutrient and is often the factor limiting additional growth of aquatic organisms in lakes. Total phosphorus (Total P) represents the sum of all phosphorus forms, including dissolved and particulate organic phosphates from algae and other organisms, inorganic particulate phosphorus from soil particles and other solids, polyphosphates from detergents, and dissolved orthophosphates. Soluble orthophosphate ( $\text{PO}_4\text{-P}$ ) is the phosphorus form that is most readily available for algal uptake. Total phosphorus levels are strongly affected by the daily phosphorus loads that enter the lake, while soluble orthophosphate levels are more likely to be affected by algal consumption during the growing season.

The EPA eutrophic criterion is a mean concentration of 0.02 to 0.03 mg/L for total phosphorus (U.S. EPA, 1980). Lakes with phosphorus concentrations below 0.01 mg/L are relatively unproductive, while lakes with total phosphorus concentrations above 0.03 mg/L can be expected to experience problems with nuisance algal blooms and/or aquatic weed growth.

Phosphorus concentrations in the Salton Sea showed wide variations throughout the year (Figure 15). Total phosphorus peaked at levels between 0.050 and 0.200 mg/L in March/April, May, July/August, and December. The March/April and July/August peaks were followed by steep reductions to below the detection limit of 0.005 mg/L.

Concentrations of soluble orthophosphate were frequently below detection limits in the Salton Sea. These low concentrations were observed in one or more of the Sea locations in January and in every month from April through September (Figure 15). This is reflected in the low whole lake averages observed during the spring and summer months (Table 6). Orthophosphate concentrations were highest during the winter months when biological activity would be at its lowest. Total P concentrations were also highest during the winter months, with the lowest concentrations observed in the fall.

Because removal of phosphorus by chemical precipitation mechanisms would be mostly irreversible due to the high salinities in the Salton Sea, biological mechanisms are the most probable cause of the relatively rapid fluctuations observed. Microorganisms would be included in the analyses of total P, therefore, the observed changes would need to be explained by changes in populations of fish, macrobenthos and benthic algae.

An estimated population of 90,000,000 tilapia (*Oreochromis sp.*) with an average weight of 0.5 kg/tilapia was provided by Costa Pierce (cited in Setmire et al., 2001). Tan (1971) reported that tilapia contain approximately 76 percent water and about 2.9 percent phosphorus on a dry weight basis. Therefore, about 260,000 kg of phosphorus are tied up in the tilapia population alone.

As a rule of thumb, nutrient conversion efficiency is about 10 percent when moving from one level of the food chain to the next. Therefore, over 2,600,000 kg phosphorus would be present in zooplankton and benthic invertebrates, such as pile worms (*Neanthes succinea*) and barnacles (*Balanus amphitrite*). An additional 26,000,000 kg of phosphorus would be present in algal cells. These are conservative estimates because tilapia comprise only a fraction of the total fish population in the Sea.

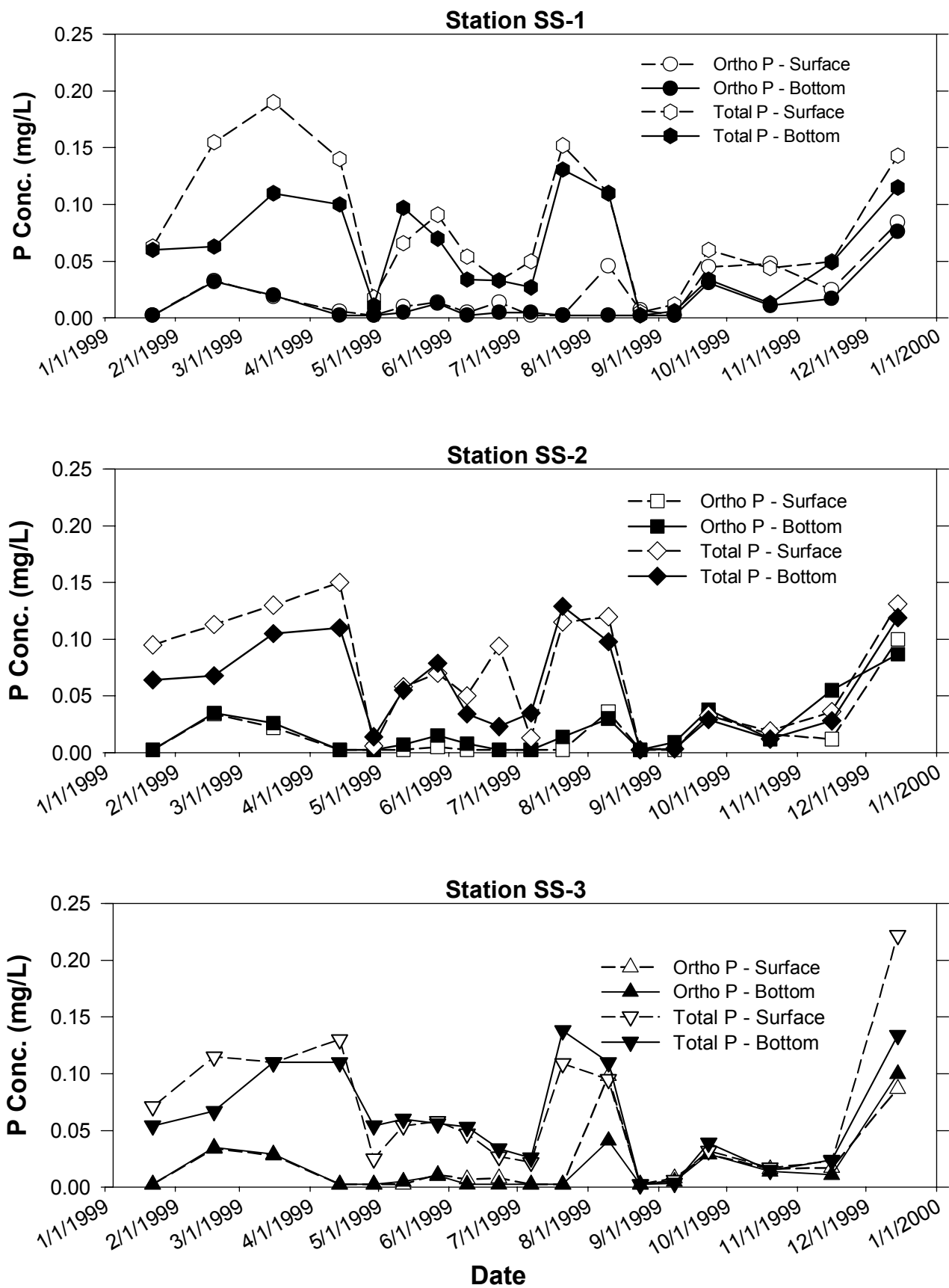


Figure 15. Salton Sea Phosphorus Concentrations

A change in storage of 940,000 kg of phosphorus is required to change concentrations in the Sea by an average of 0.10 mg/L. In light of the above estimates, fluctuations in the amount of phosphorus stored in biomass do appear to be a reasonable explanation for the observed changes in phosphorus concentrations in the Salton Sea.

Phosphorus concentrations in the tributaries were all relatively high (Table 4). High phosphorus concentrations in the river samples originate from intense agricultural activity in the Salton Sea watershed and from wastewater treatment plant discharges, which are especially important for the New River where some of the wastewater is untreated.

Total phosphorus concentrations in the Salton Sea were approximately an order of magnitude lower than those in the river samples (Table 4). Sedimentation, chemical precipitation and burial following incorporation of phosphorus into aquatic organisms are all possible causes of the observed decrease in phosphorus in the Sea.

Relatively high percentages of the phosphorus in the river samples was in the form of soluble orthophosphate (Figure 16), which accounted for 54, 61, and 82 percent of the total phosphorus in the Alamo, New, and Whitewater Rivers, respectively. As expected, the fraction of soluble orthophosphate was inversely related to the total suspended solids concentrations in the rivers.

#### **4.8.2 Nitrogen**

The nitrogen cycle in lakes is considerably more complicated than the phosphorus cycle. Nitrogen can exist in either oxidized forms, usually nitrate ( $\text{NO}_3^-$ ) or nitrite ( $\text{NO}_2^-$ ), or reduced forms, including ammonia ( $\text{NH}_3$ ) and organic nitrogen. Atmospheric nitrogen ( $\text{N}_2$ ) can also be used as a nutrient source by some species of algae, and various other reduced forms of nitrogen can be produced by decomposition processes.

The form of nitrogen present depends primarily on dissolved oxygen concentrations and plant growth. Nitrate is the most common form of nitrogen in surface waters. Nitrate and nitrite are often analyzed together and reported as  $\text{NO}_3+\text{NO}_2\text{-N}$  because nitrite concentrations are usually insignificant. Ammonia, the nitrogen form that is most easily assimilated and utilized by phytoplankton, can be present as either un-ionized ammonia ( $\text{NH}_3$ ) or as ammonium ion ( $\text{NH}_4^+$ ); ammonium ion predominates below pH 9.3. Ammonia is usually the predominant form of nitrogen in low oxygen environments, but low concentrations of ammonia are common in the aerobic surface waters of most lakes. Extensive algal blooms can deplete concentrations of the inorganic nutrients, nitrate and ammonia, as nitrogen is converted into organic nitrogen in the form of algal cells. Total Kjeldahl nitrogen (TKN) provides a measure of ammonia plus organic nitrogen.

Total nitrogen concentrations in the river samples were 30 to 120 times greater than those in the Salton Sea (Table 4). This difference can be attributed primarily to the high nitrate+nitrite-N concentrations in the rivers (Figure 17), which were more than one to two orders of magnitude greater than concentrations in the Sea (Figure 18). Nitrate+nitrite-N was the major form of nitrogen in the Alamo and Whitewater Rivers, comprising 70 and 88 percent of the total nitrogen, respectively for these rivers.

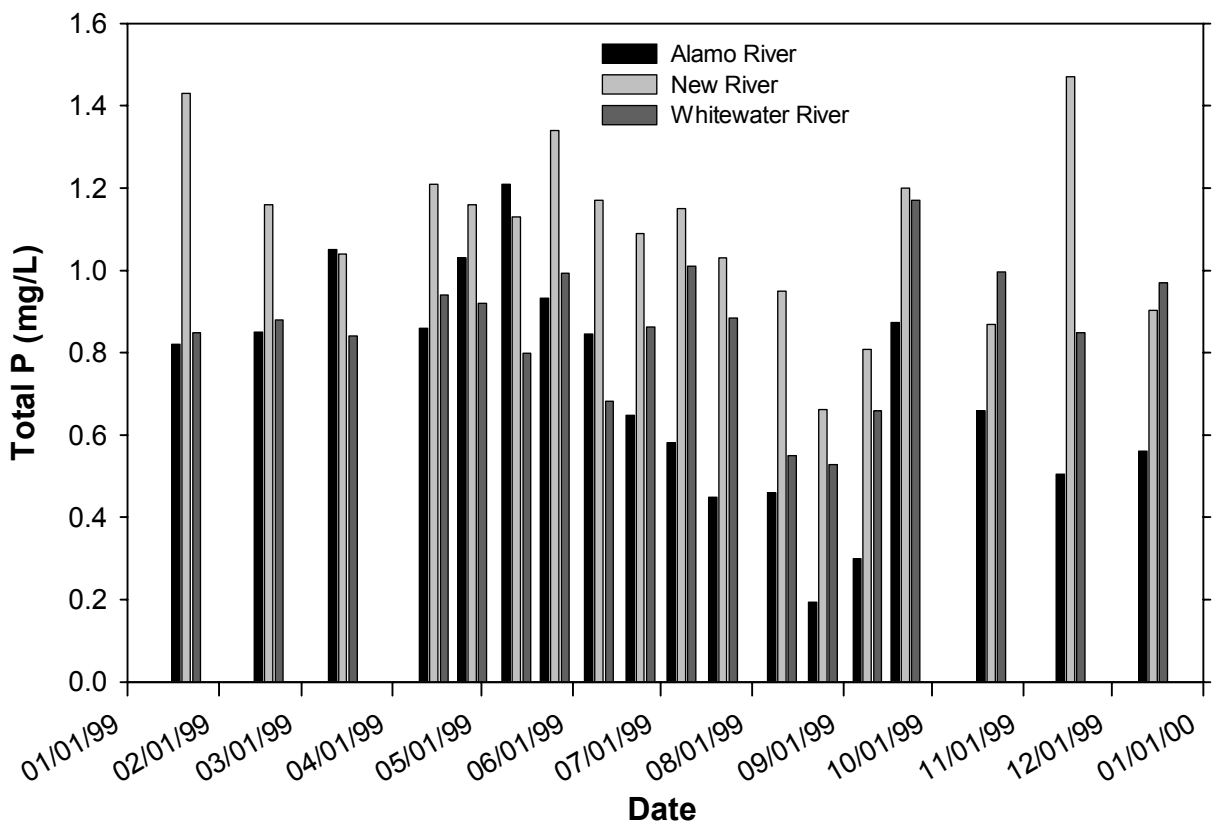
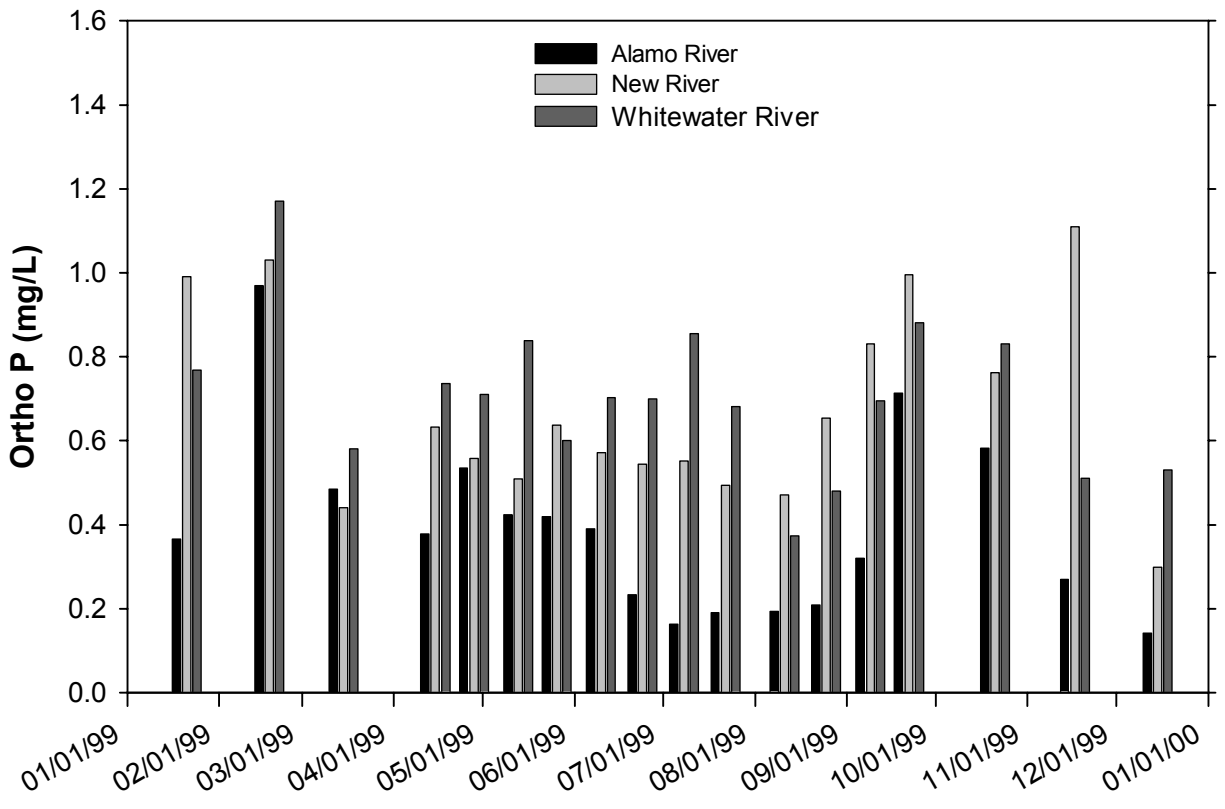


Figure 16. Phosphorus Concentrations in River Samples

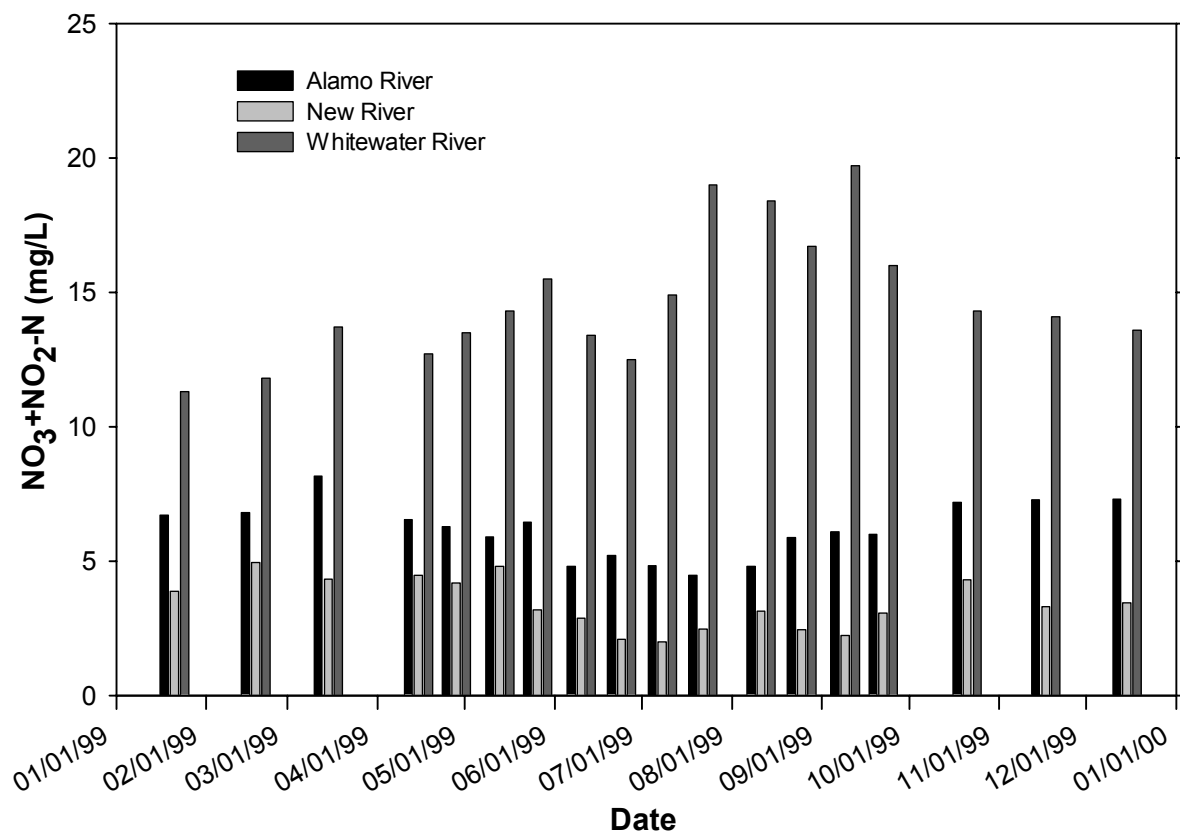
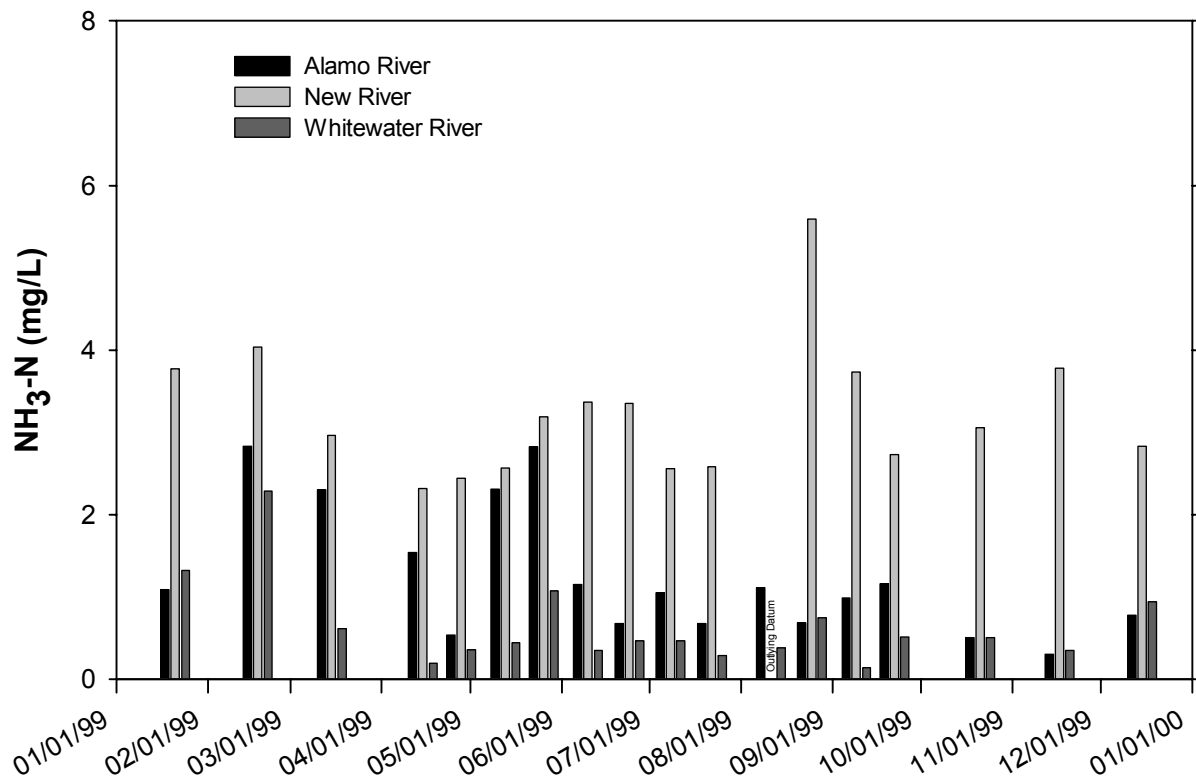


Figure 17. Inorganic Nitrogen Concentrations in River Samples

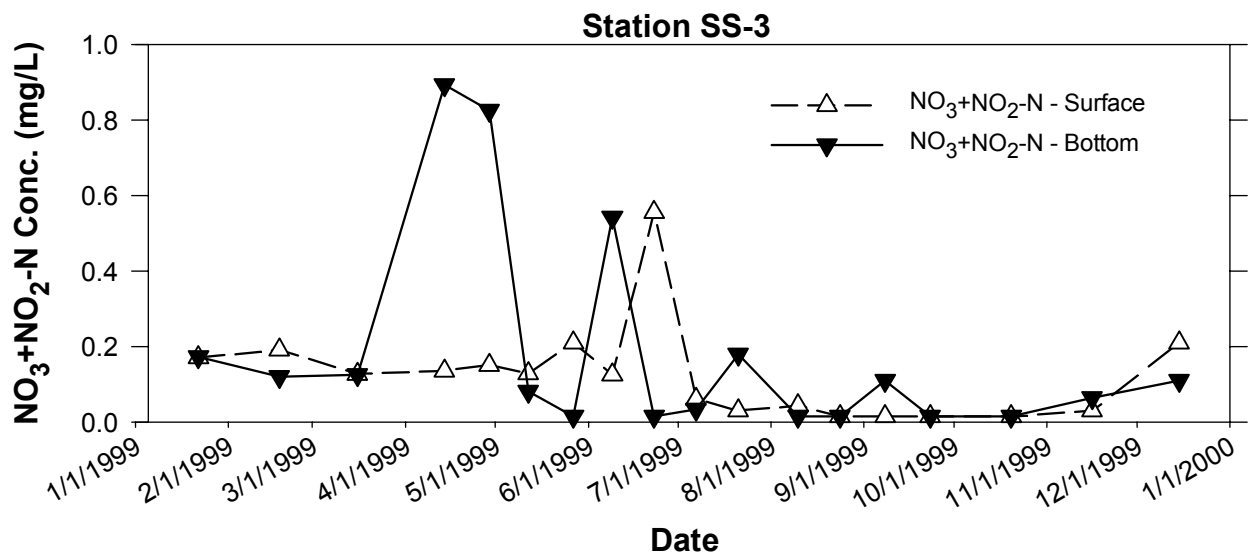
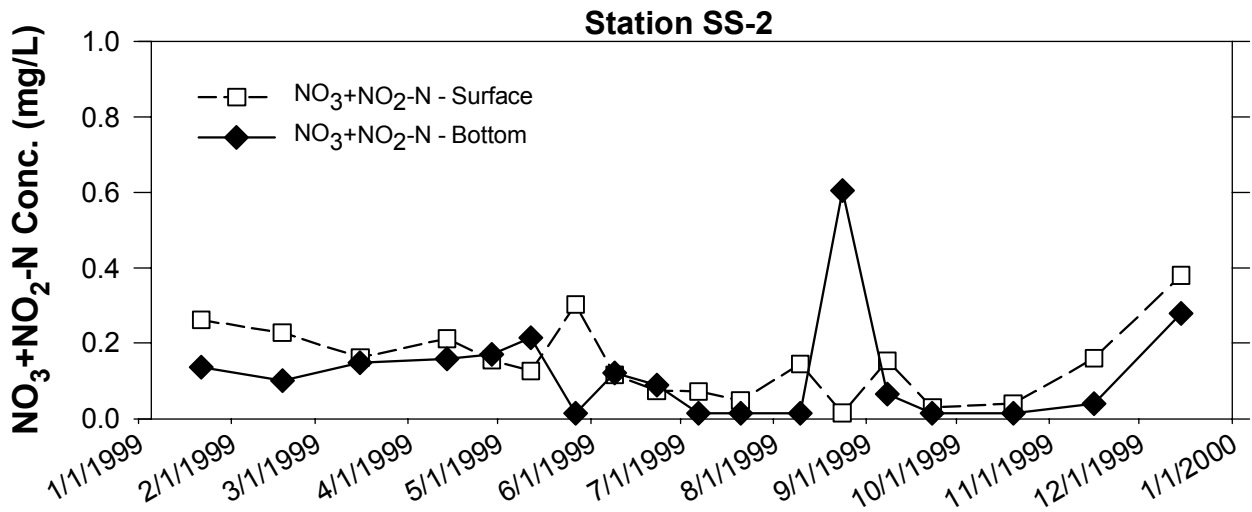
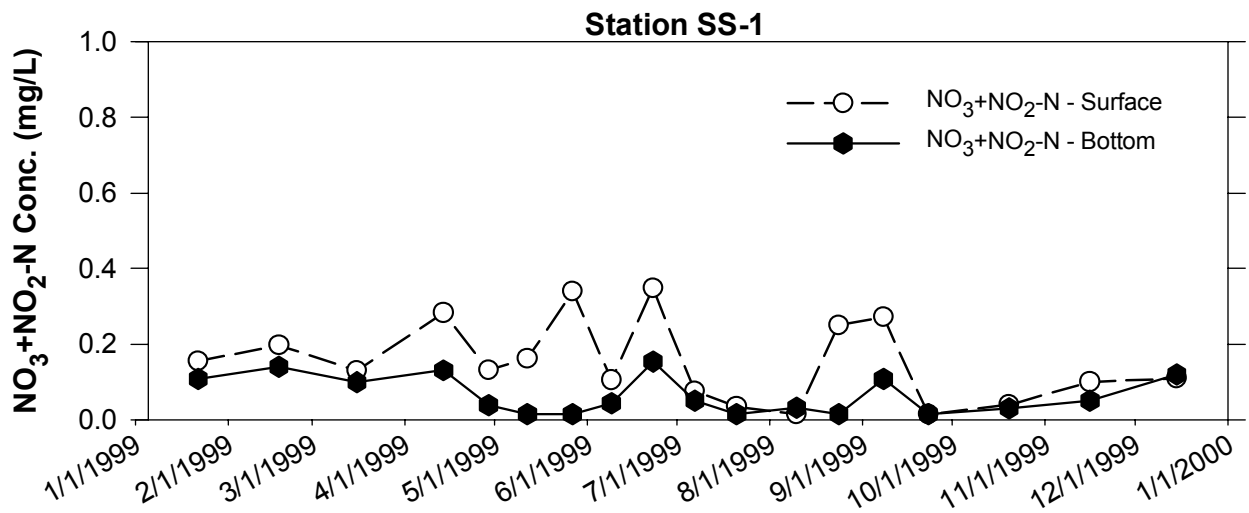


Figure 18. Salton Sea Nitrate+Nitrite-Nitrogen Concentrations

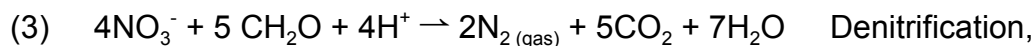


In contrast to the other two rivers, oxidized nitrogen accounted for only 43 percent of the total nitrogen in the New River and ammonia concentrations were higher than nitrate+nitrite concentrations. The presence of untreated wastewater in the New River may explain this observation.

Oxidized nitrogen represented less than 5 percent of the total nitrogen present in the Salton Sea. In contrast, ammonia-N contributed 32 percent of the total nitrogen. Ammonia concentrations also varied with depth, with bottom concentrations averaging about 50 percent higher (1.47 vs. 1.05 mg/L) than surface concentrations (Figure 19). The higher concentration near the bottom may be indicative of internal nitrogen loading or decomposition of organic matter falling through the water column.

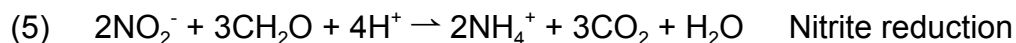
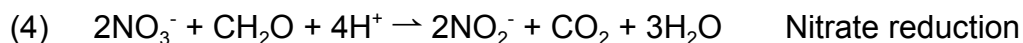
Total Kjeldahl nitrogen concentrations in the Sea (Figure 20) were of the same magnitude as those in the rivers (Figure 21), indicating that removal of organic nitrogen entering the Sea is limited. Ammonia-N comprised about 33 percent of the TKN in the Sea and the Whitewater River, 43 percent of the TKN in the Alamo River, and 67 percent of the TKN in the New River. The relatively high NH<sub>3</sub>-N levels in the New River are another indication of the presence of wastewater in that water body.

Because nitrate and ammonium salts are generally soluble, uptake by aquatic organisms and denitrification are expected to be the major sinks for nitrogen in the Salton Sea. Denitrification converts nitrate directly to nitrogen gas through microbial activity under anaerobic conditions according to the following reaction:



where CH<sub>2</sub>O represents organic matter.

Anderson et al. (2002) recently suggested volatilization of ammonia as a major sink for inorganic nitrogen. This process requires two separate biological reduction steps, followed by a gas transfer step, according to the following reactions:



Volatilization is a more complicated process than denitrification and additional research will be required before the relative importance of these two mechanisms can be verified.

Biological uptake is less likely to be the major sink for nitrate because nitrogen levels far exceed those of phosphorus, so biological uptake will be limited by the supply of phosphorus (see below) and cannot explain the large losses of oxidized nitrogen that were observed.

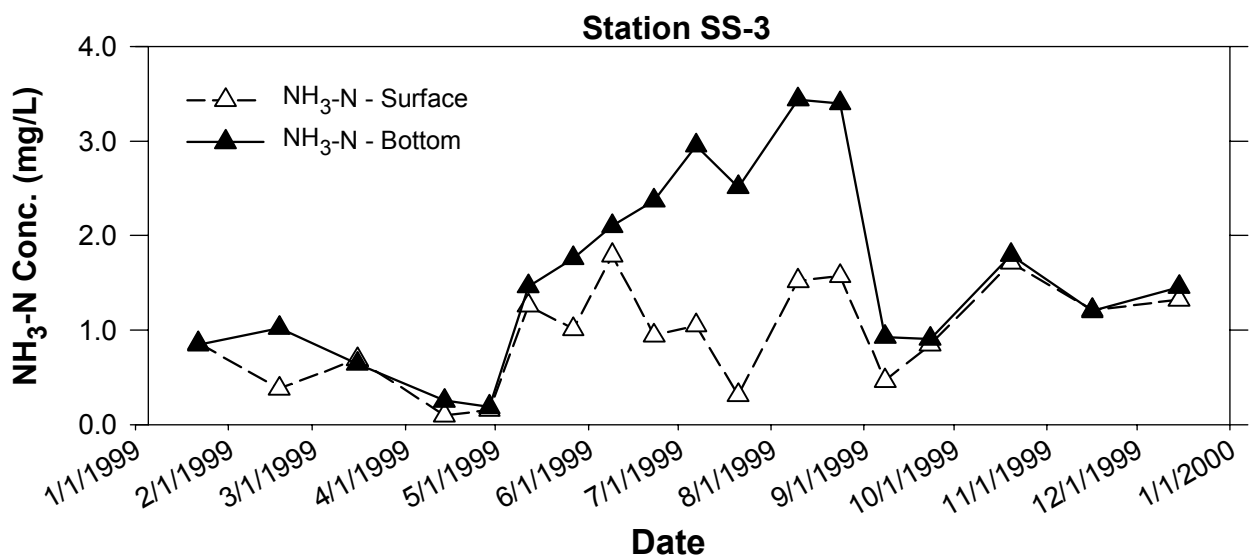
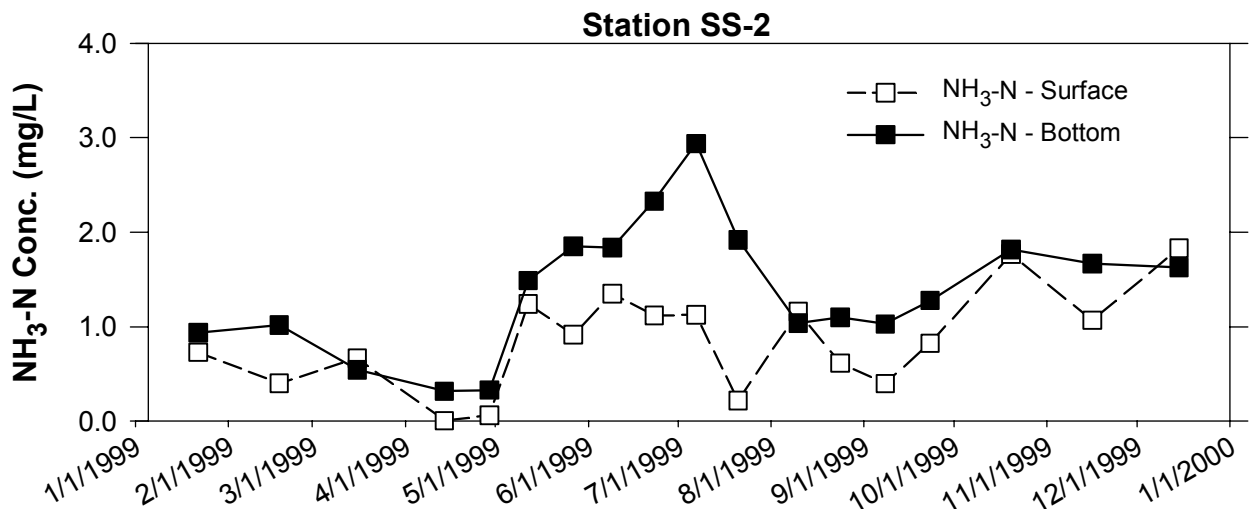
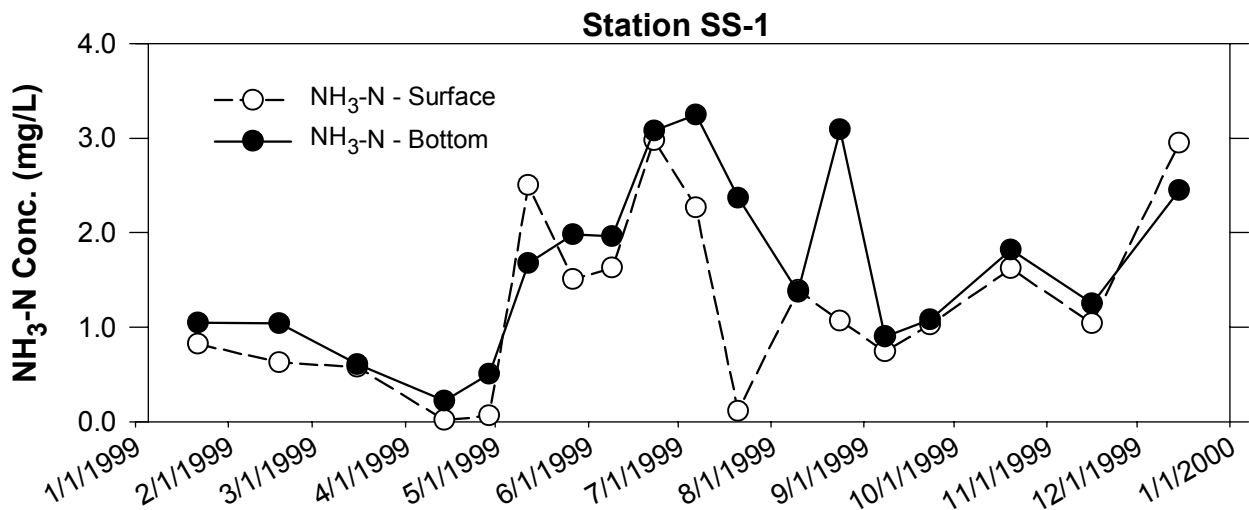


Figure 19. Salton Sea Ammonia-Nitrogen Concentrations

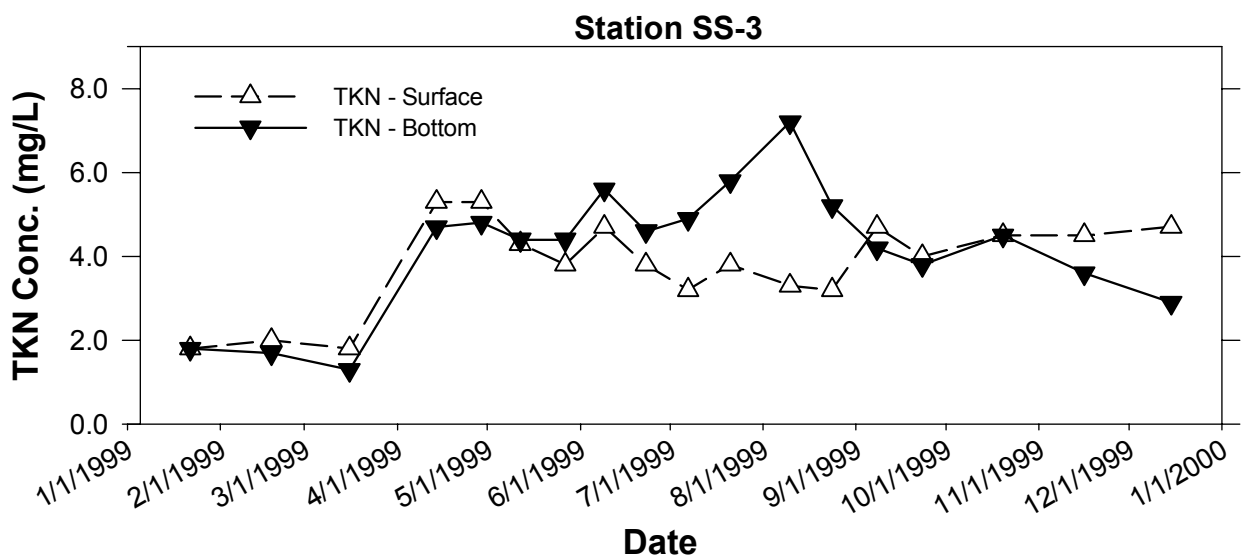
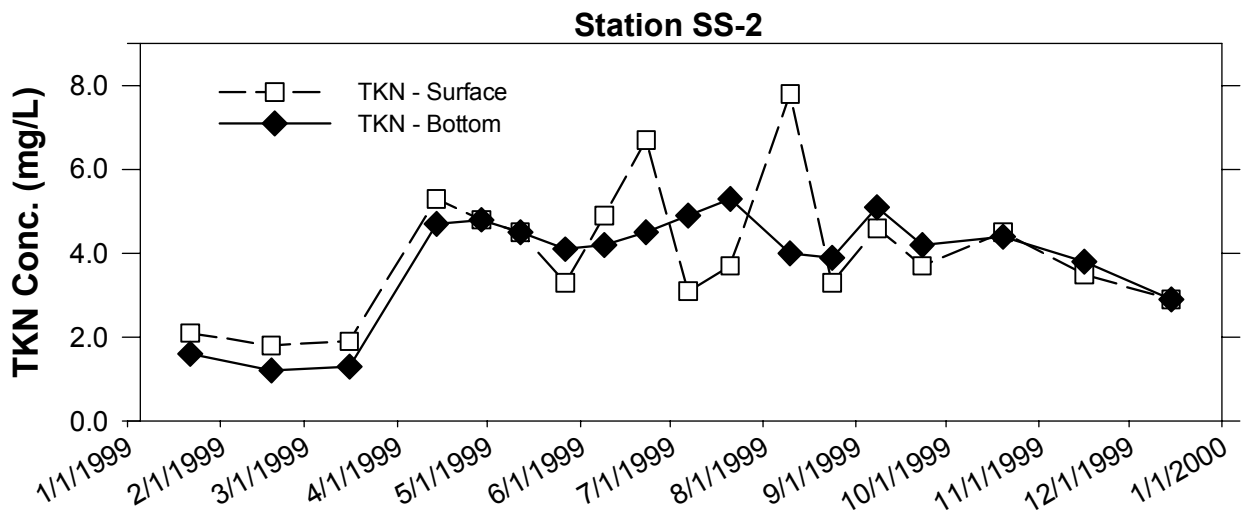
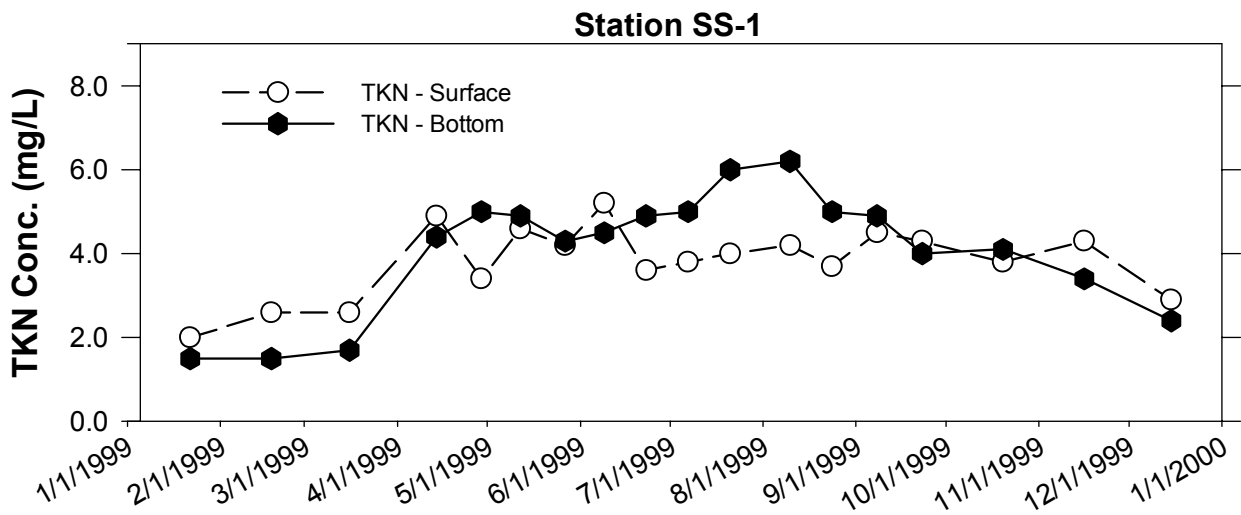


Figure 20. Salton Sea Total Kjeldahl Nitrogen Concentrations

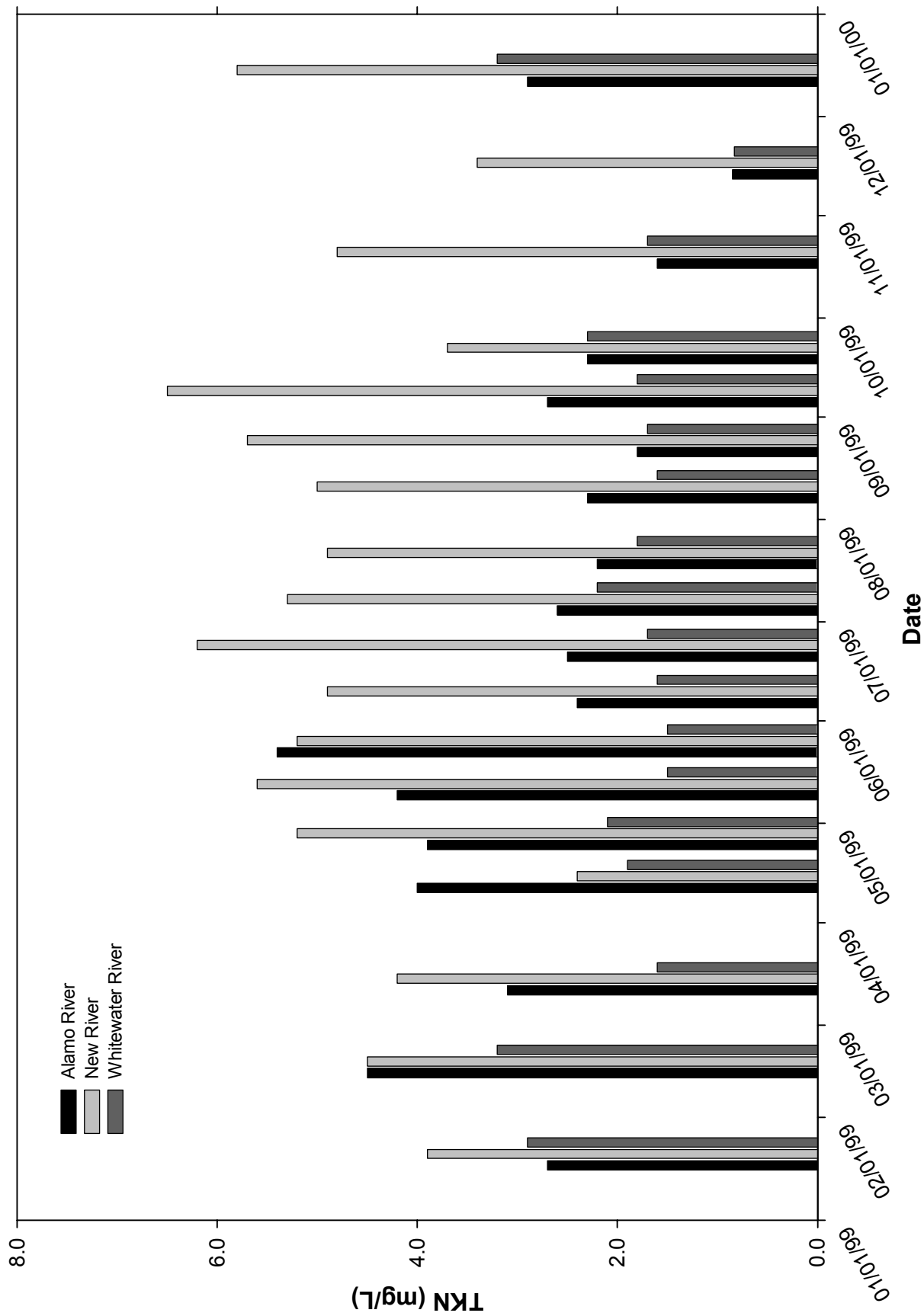


Figure 21. Total Kjeldahl Nitrogen Concentrations in River Samples

Ammonia levels in the Salton Sea exceed water quality standards. The California Ocean Plan (SWRCB, 1997) lists a 6-month median of 600 µg/L and a daily maximum of 2400 µg/L as objectives for ammonia (as N) to protect marine aquatic life. The whole-lake median ammonia-N concentration for 1999 of 1.18 mg/L was nearly twice the allowable 6-month median. In addition, the daily maximum was exceeded for bottom samples at Stations SS-1 and SS-3. The U.S. EPA (1976) listed an un-ionized ammonia concentration of 0.02 mg/L (as NH<sub>3</sub> = 0.016 mg/L as N) as the criterion for freshwater aquatic life. This value was based on observed toxic effects on some species in the range of 0.20 - 2.0 mg/L.

There is little information available on the toxicological effects of ammonia on marine species, but ammonia levels in the Salton Sea are higher than the applicable standards and may be contributing to fish toxicity. The sampling event on August 10, 1999 coincided with a major fish kill at Station SS-1. Un-ionized ammonia concentrations were for this station and date were calculated following procedures outlined by Messer et al. (1984) and adapted for the high salinity of the Salton Sea by use of the Lewis equations to calculate activity coefficients. The fraction of un-ionized ammonia was estimated from the formula:

$$(7) \quad (M_{\text{NH}_3}) / [(M_{\text{NH}_3}) + (M_{\text{NH}_4^+})] = 1 / [1 + 10^{(pK_{a,T} - \text{pH} - s)}],$$

where (M<sub>NH<sub>3</sub></sub>) is the concentration of un-ionized ammonia; (M<sub>NH<sub>3</sub></sub>) + (M<sub>NH<sub>4</sub><sup>+</sup></sub>) is the analytical concentration of ammonia; pK<sub>a,T</sub> is the ionization constant of ammonia adjusted for ionic strength, calculated as 9.40; pH is 8.23; and s is a salinity correction term, which was calculated from the Lewis equation:

$$(8) \quad s = -A \times [I^{1/2} / (1 + I^{1/2})] - 0.2 I,$$

where A is a coefficient that is a function of the dielectric constant and temperature of water and I is the ionic strength of the solution, calculated for the Salton Sea as 0.76 from the PHREEQC model (Parkhurst and Appelo, 1999; see Section 5.0). Although the Lewis equation is generally considered applicable to an ionic strength range of 0.3 - 0.7, it should be able to provide a reasonable estimate for the slightly higher ionic strength observed in the Salton Sea.

The coefficient A was calculated from the formula:

$$(9) \quad A = 1.82483 \times 10^6 \times [E \times (T + 273.16)]^{-1.5}$$

where T is the temperature in degrees Celsius (29.35) and E was calculated from the following formula presented by Truesdell and Jones (1974):

$$(10) \quad E = 87.74 - 0.4008 \times T + 9.398 \times 10^{-4} \times T^2 - 1.41 \times 10^{-6} \times T^3$$

From the above considerations and the analytical ammonia concentration of 1.39 mg/L, the concentration of un-ionized ammonia at Station SS-1 during the August 10, 1999, fish kill was calculated as 0.062 mg/L. This value exceeds the U.S. EPA (1976) criterion for un-ionized ammonia. While this concentration is below levels observed to cause toxic effects in freshwater systems, U.S. EPA (1976) indicated that the toxicity of un-ionized

ammonia does increase with salinity. As a result, it is possible that relatively high concentrations of un-ionized ammonia, which represent another stress to fish in the Salton Sea in addition to the high temperature and low dissolved oxygen associated with algal blooms, may be contributing to the observed fish kills.

#### **4.8.3 Seasonal Phosphorus and Nitrogen Concentrations**

Possible seasonal changes in phosphorus and nitrogen concentrations were evaluated using the same approach as that used for solids (Sections 4.5 and 4.6). Some seasonal differences were apparent, with nitrogen concentrations showing more variability in the river samples and phosphorus being more variable in the Salton Sea (Table 6). Both soluble ortho phosphate and total phosphorus were highest in the winter in the Salton Sea, when biological activity is lowest. Soluble orthophosphate was lowest in the spring and summer, when concentrations were frequently below detection limits. Total phosphorus concentrations were lowest in the fall as a result of concentrations below detection limits throughout September (Figure 5).

Seasonal phosphorus concentrations varied among the three river inflows. The Alamo River had the lowest nutrient concentrations and the greatest seasonal nutrient variation, while the New and Whitewater Rivers had higher nutrient concentrations and lower seasonal variability. This likely occurs because the Alamo River contains primarily agricultural return flows, while the New and Whitewater Rivers also contain wastewater treatment plant effluents. Soluble orthophosphate concentrations were generally lowest during the summer months, with the biggest drop occurring in the Alamo River. Total phosphorus concentrations were highest in the winter and spring in the Alamo and New Rivers and in the fall in the Whitewater River.

Seasonal trends in nitrogen concentrations were not as pronounced as seasonal phosphorus concentrations (Table 6). Total nitrogen concentrations were highest in the Winter and Spring in the Alamo and New Rivers and in the Summer and Fall in the Whitewater River.

#### **4.8.4 Limiting Nutrient**

Nitrogen and phosphorus are the nutrients that usually limit algal growth in natural waters. Both the relative concentrations of nitrogen and phosphorus and the absolute concentrations of these nutrients play important roles in structuring phytoplankton communities (Schindler, 1977; Reynolds, 1986). The average N:P ratio of healthy, growing algal cells is 7 to 1 by weight (or between 15 and 16 by molar ratio). This value, known as the Redfield ratio, is generally assumed to be the ratio in which these nutrients are ultimately required by algal cells (Reynolds, 1986). Generally, large N:P ratios (>7) indicate that the growth of the phytoplankton community will be limited by the concentration of phosphorus present, while small N:P ratios (<7) indicate that growth will be limited by nitrogen concentrations (Schindler, 1977). The ratios of total inorganic nitrogen (TIN = nitrate-N, nitrite-N and ammonia-N) to soluble orthophosphate (SOP) may be more meaningful than the ratio of total nitrogen to total phosphorus because the inorganic nutrient forms are more directly available to support the growth of aquatic organisms.

**Table 6 - Seasonal Nutrient Concentrations in Salton Sea  
and Tributary Samples**

Variable	Summer	Fall	Winter	Spring	Annual Mean
Alamo River					
Soluble ortho-P	0.230	0.456	0.492	0.454	0.408
Total P	0.530	0.583	0.744	1.02	0.719
NO <sub>3</sub> +NO <sub>2</sub> -N	5.00	6.84	6.94	6.91	6.42
NH <sub>3</sub> -N	0.890	0.629	1.57	1.97	1.26
TKN	2.3	1.6	3.4	4.0	2.8
New River					
Soluble ortho-P	0.548	0.928	0.773	0.537	0.697
Total P	1.01	1.11	1.16	1.15	1.11
NO <sub>3</sub> +NO <sub>2</sub> -N	2.50	3.41	4.08	4.21	3.55
NH <sub>3</sub> -N	3.84	3.36	3.55	2.74	3.14
TKN	5.3	4.4	4.7	4.5	4.7
Whitewater River					
Soluble ortho-P	0.632	0.709	0.823	0.675	0.710
Total P	0.753	0.920	0.899	0.889	0.865
NO <sub>3</sub> +NO <sub>2</sub> -N	15.8	15.4	12.2	13.9	14.3
NH <sub>3</sub> -N	0.450	0.396	1.52	0.551	0.729
TKN	1.8	1.5	3.1	1.7	2.0
Salton Sea					
Soluble ortho-P	0.010	0.020	0.042	0.011	0.021
Total P	0.053	0.026	0.107	0.088	0.069
NO <sub>3</sub> +NO <sub>2</sub> -N	0.10	0.05	0.19	0.16	0.12
NH <sub>3</sub> -N	1.45	1.27	1.17	0.76	1.16
TKN	4.1	4.1	2.3	3.6	3.5

Nitrogen to phosphorus ratios in both the influent rivers and in the Salton Sea were high as a result of low phosphorus concentrations and relatively high nitrogen concentrations. These ratios were calculated on a seasonal basis and are summarized in Table 7.

**Table 7. Nitrogen to Phosphorus Ratios in Salton Sea and Tributary Samples**

Variable	Summer	Fall	Winter	Spring	Annual Mean
Alamo River					
TN:TP	17.2	16.3	14.3	10.8	14.6
TIN:SOP	27.6	19.2	29.4	19.8	24.0
New River					
TN:TP	8.1	7.7	7.9	7.6	7.8
TIN:SOP	10.7	7.5	12.5	13.3	12.0
Whitewater River					
TN:TP	25.0	19.3	17.0	17.6	19.7
TIN:SOP	28.5	23.3	18.6	21.9	23.1
Salton Sea					
TN:TP	334	316	24.4	100	194
TIN:SOP	479	112	154	165	228

Calculated N:P ratios were similar for the Alamo and Whitewater Rivers, with the highest ratios of both TN:TP and TIN:SOP observed during the summer months and all ratios indicating phosphorus limitation. The N:P ratios for the New River were much lower than for the other two rivers, probably reflecting the importance of wastewater treatment plant discharges. The highest N:P ratios in the New River were observed during the spring, but the lower values observed did not clearly indicate the limiting nutrient.

The N:P ratios in the Salton Sea were extremely high. The highest ratios (Table 7) were observed during the summer months when algal growth would be at a maximum. Annual N:P ratios were near 200:1 for both TN:TP and TIN:SOP, and the winter TN:TP ratio of 24.4 was the only ratio less than 100:1. These high ratios clearly indicate that phosphorus is the limiting nutrient in the Salton Sea.



#### 4.8.5 Silicon

Silicon is one of the most abundant elements in the earth's crust. It is present as an oxide (silica, SiO<sub>2</sub>) in quartz and sand and combines with aluminum and other metals to form clays and other minerals. Silicon is also required for the growth of some aquatic organisms, particularly diatoms, a group of algae that incorporate silicon into their cells.

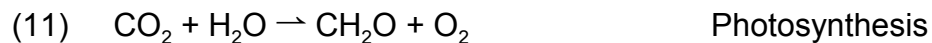
Dissolved silicon (Si) concentrations were lower in the Salton Sea than in the river samples (Figures 22 and 23). Concentrations of dissolved Si averaged 5.89, 7.30, and 8.62 mg/L for the Alamo, New, and Whitewater Rivers, respectively. In contrast, the average concentration in the Salton Sea was 4.60 mg/L. Silicon concentrations in the Sea never appeared to reach concentrations low enough to be limiting to algal growth. As a result, the settling of suspended particulate matter is the most probable explanation for the observed decrease in the Sea relative to the river samples.

Silicon in the rivers is probably associated with soil particles, although the highest Si concentrations were found in the Whitewater River, which has the lowest suspended solids load. Differences in soil chemistry between the northern and southern parts of the watershed are the likely reason for this observation.

#### 4.8.6 Carbon

Carbon is present in aquatic systems in both organic and inorganic forms. It is both a major nutrient and an important energy source in aquatic systems. Inorganic carbon is present primarily as bicarbonate and carbonate ions and dissolved carbon dioxide. The carbonate system is extremely important in affecting the composition of natural waters through the formation of carbonate minerals.

Measured organic carbon concentrations include numerous organic compounds with a wide range of oxidation states. The energy derived from the conversion of inorganic carbon into cellular material (CH<sub>2</sub>O) through photosynthesis (Equation 11) and cellular material back to carbon dioxide and water during decomposition (Equation 12) affect the chemical composition of all aquatic systems:



Inorganic carbon levels were discussed previously (Section 4.4). In contrast to nitrogen and phosphorus concentrations, dissolved organic carbon concentrations increased significantly in the Sea relative to the river concentrations, possibly indicating organic carbon loadings are too high to be assimilated through biological uptake. DOC concentrations averaged 4.2, 8.7, and 7.6 mg/L for the Alamo, New, and Whitewater Rivers, respectively, and 40.9 mg/L in the Salton Sea. DOC concentrations in the Sea peaked in early September (Figure 24), which may be related to the extensive fish kills occurring in August. The low average for the Alamo River occurred in spite of a very high reading of 32 mg/L (Figure 25) on September 9, 1999, which may be an outlier.

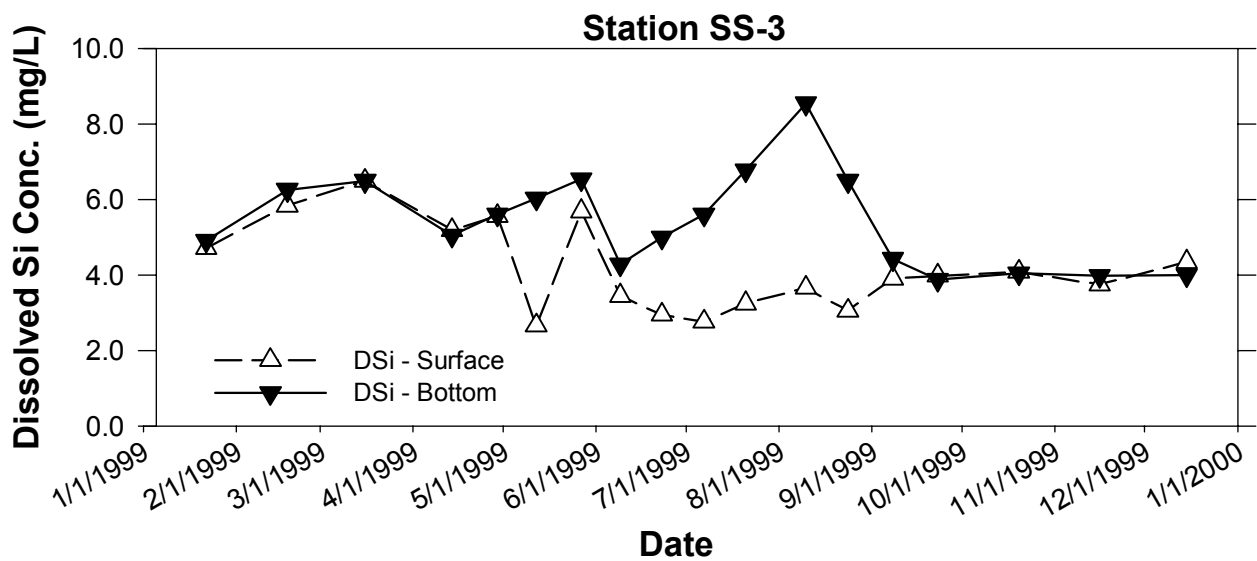
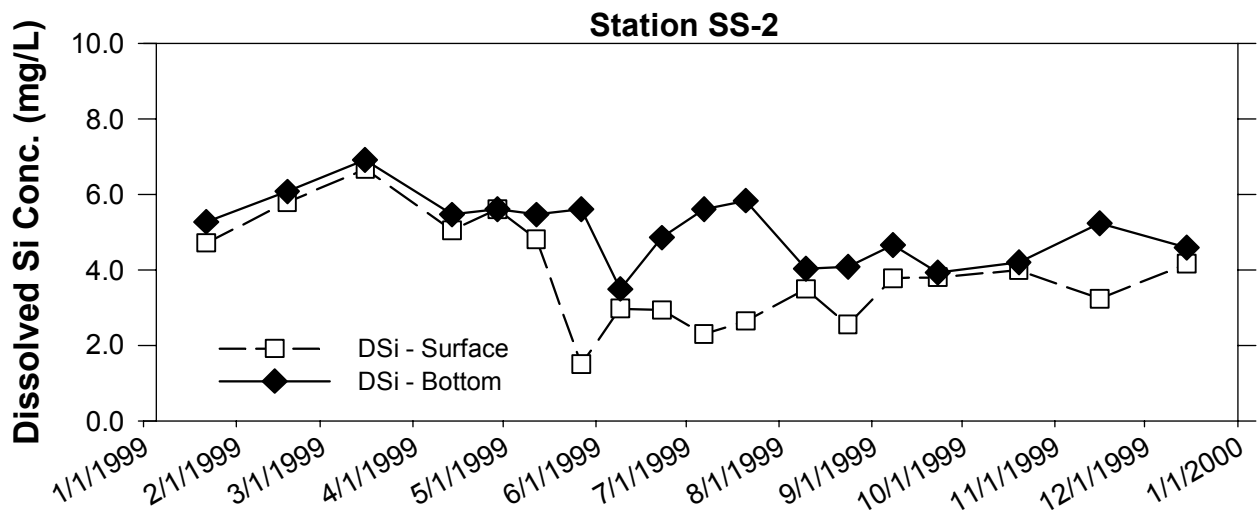
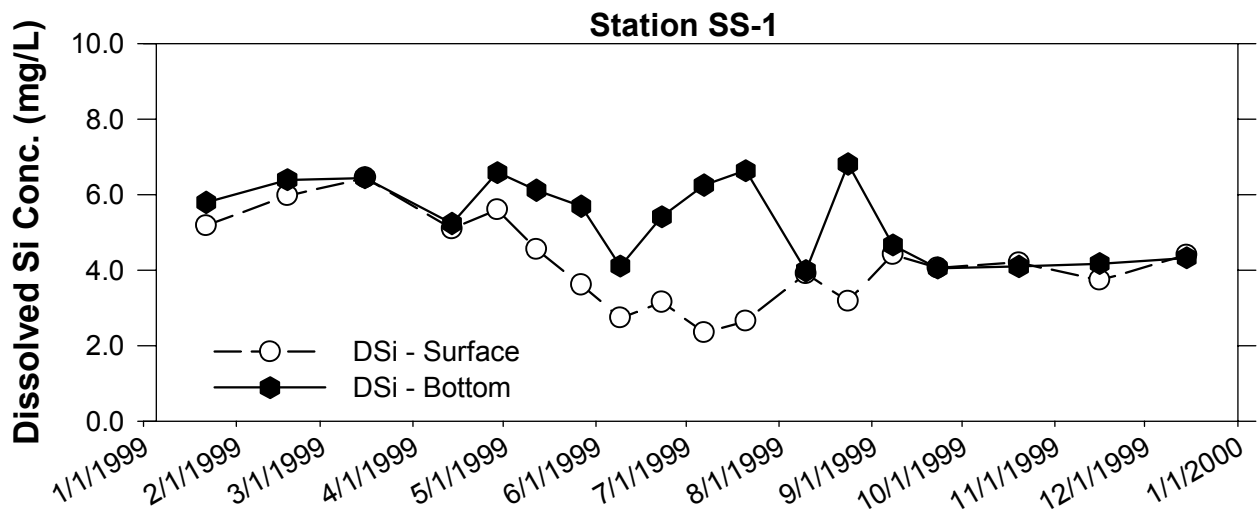


Figure 22. Dissolved Silicon Concentrations in Salton Sea Samples

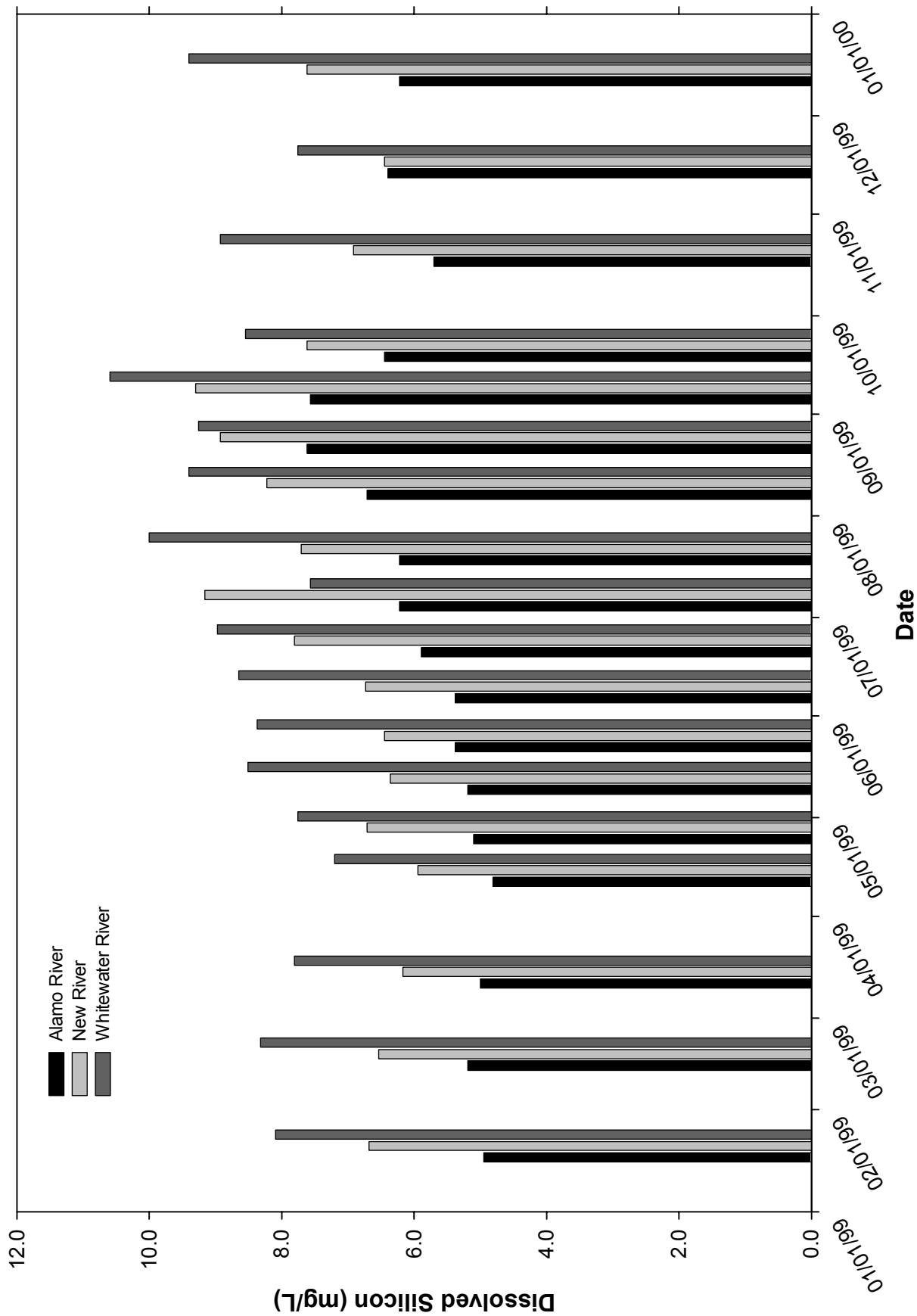


Figure 23. Dissolved Silicon Concentrations in River Samples

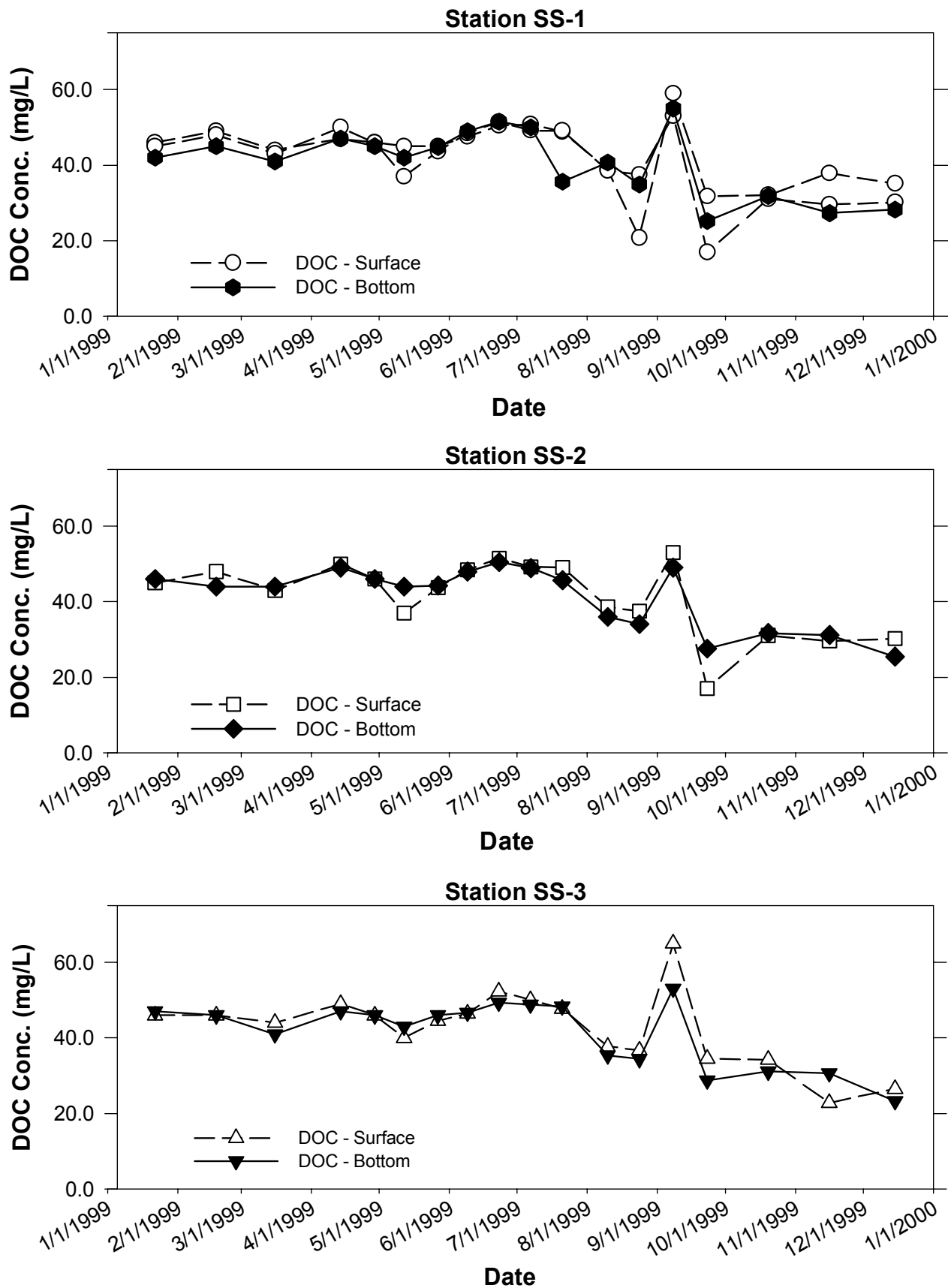


Figure 24. Dissolved Organic Carbon Concentrations in Salton Sea Samples

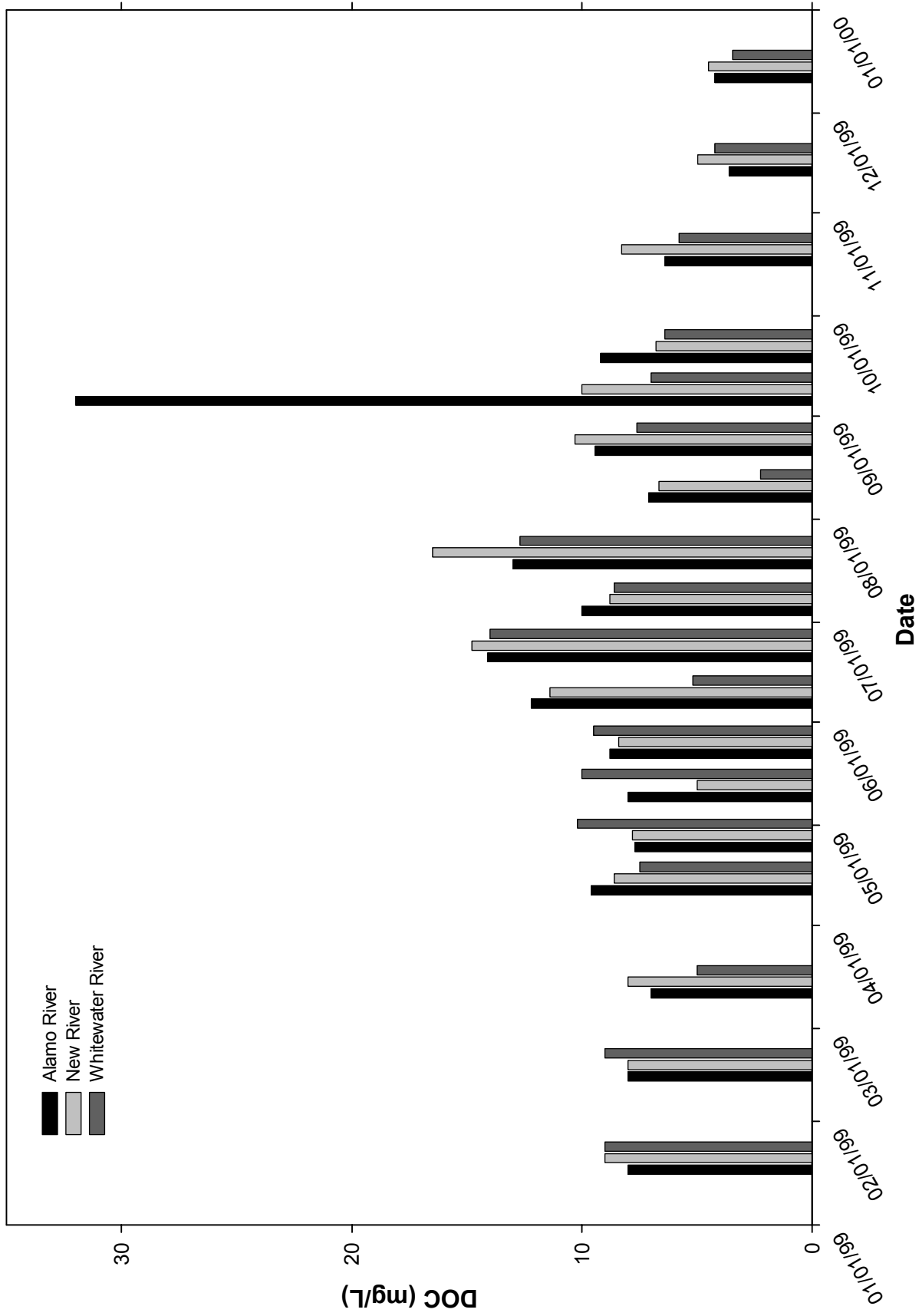


Figure 25. Dissolved Organic Carbon Concentrations in River Samples

## 4.9 Trophic State Indices

A trophic state index provides a relative expression of the biological productivity of a lake. The Trophic State Index (TSI) developed by Carlson (1977) is a commonly used indicator of lake trophic state. A TSI of less than 35 indicates oligotrophic conditions, a TSI between 35 and 50 indicates mesotrophic conditions, and a TSI greater than 50 indicates eutrophic conditions. Hypereutrophic, or excessively productive lakes, have TSI values greater than 70. Higher numbers are associated with increased probabilities of encountering nuisance conditions, such as excessive algal growth.

The Carlson TSI was developed from a data set on lakes primarily from the Great Lakes region of the United States and from Northern Europe. As a result, application of these indices to the Salton Sea is questionable; however, these indices have been widely applied (and misapplied) to many other lake systems and can at least provide some indication of the trophic state of the Salton Sea.

Trophic state indices for the Salton Sea were calculated using data collected during the months of May through September because Carlson (1977) suggested that summer average values may produce the most meaningful results. The average concentrations of 0.049 mg/L and 0.89 m for total phosphorus and Secchi depth, respectively, result in trophic state indices of 60 and 62, which place the Salton Sea in the eutrophic range.

## 4.10 Major Ions

Concentrations of major ions in the Salton Sea have undergone many changes since the Sea was formed (Figure 26). Figure 26 includes additional data for selected dates from previous studies, including Ross, 1915 (1907 and 1913); Hely et al., 1966 (1916, 1923, 1945, 1949, 1954, 1959, 1964); Setmire et al., 1990 (1986), Tostrud, 1997 (1989), Ogden, 1996 (1994) and this study (1999). Hely et al. (1966) and Tostrud (1997) presented only a sum for sodium and potassium, which was plotted as sodium in Figure 26. Setmire et al. (1990) did not include bicarbonate concentrations for the 1986 data set; and Ross (1915) did not report bicarbonate for the 1907 data set, but this ion is present only in small amounts in the Salton Sea.

Major ion concentrations increased dramatically from the time the Sea was formed to the mid 1920's as a result of dissolution of salts from underlying soils and concentration resulting from volume loss by evaporation. Slight decreases were observed in the 1940's and 1950's as the volume of the Sea expanded with increasing agricultural runoff. Concentrations have increased from the 1960's to present as a result of evaporative concentration and relatively stable water levels.

Concentrations of nearly all major ions are higher in the Sea than in the rivers. The only exception is bicarbonate, which has a slightly lower concentration in the Sea than in a flow-weighted average of river concentrations. The most soluble ions, sodium, potassium and chloride, are enriched in the Sea by factors of 25 to 30 over river concentrations. Magnesium concentrations are about 17 times as high in the Sea compared to the rivers and sulfate concentrations are 14 times as high.

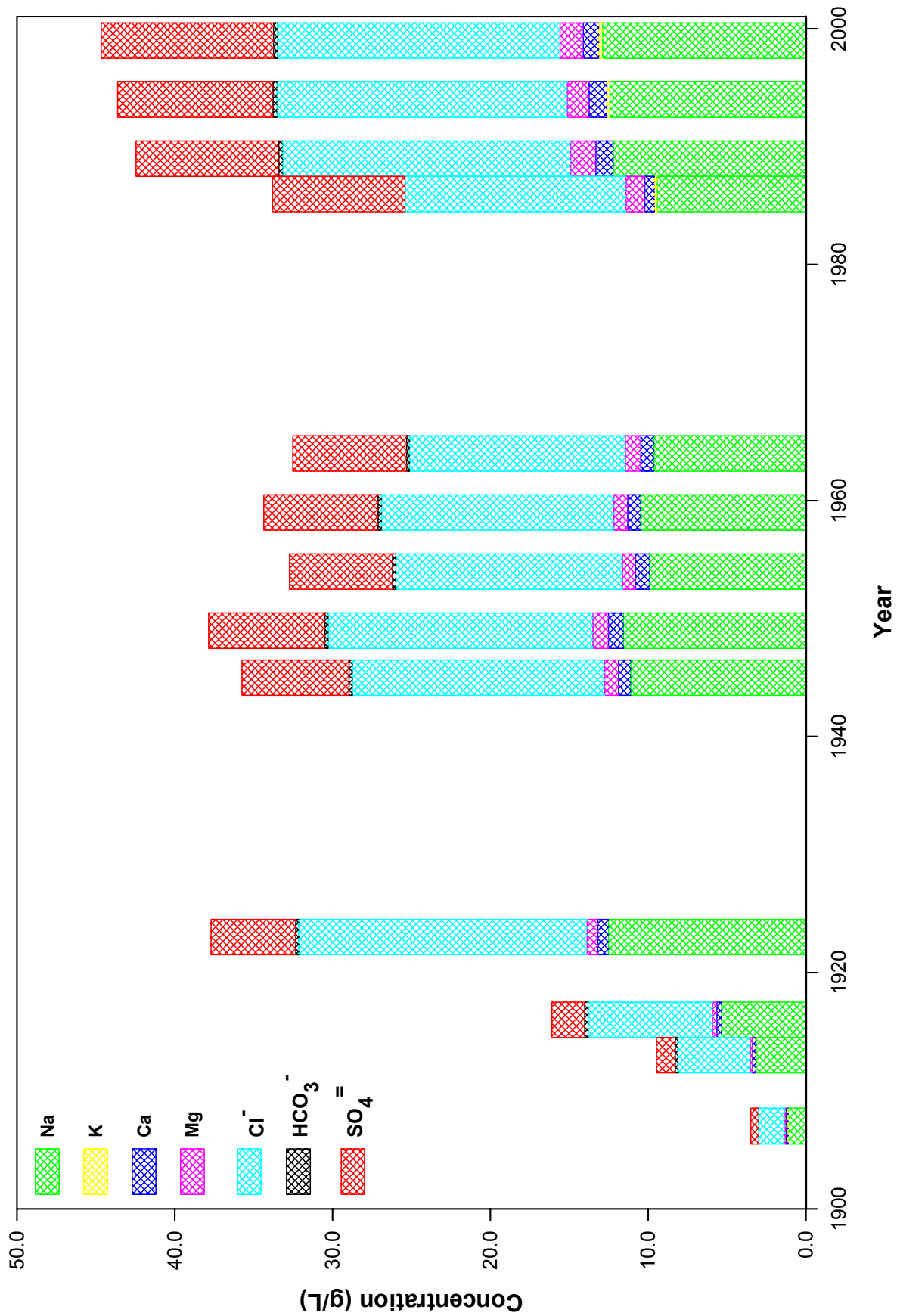


Figure 26. Major Ion Concentrations in the Salton Sea

Cation concentrations show less relative variation over time than anion concentrations. Relative potassium concentrations have remained fairly constant, comprising 0.7 and 0.6 percent of the total ions in 1907 and 1999, respectively. Relative sodium concentrations decreased from 32.0 to 28.8 percent and relative calcium concentrations decreased from 2.9 to 2.2 percent of the total ion concentration between 1907 and 1999. In contrast, magnesium concentrations have increased from 1.9 to 3.3 percent of the total. The observed changes in relative cation concentrations are a function of both individual ion solubilities and loadings from the Colorado River.

Bicarbonate has undergone the greatest relative change of the major ions, decreasing from 1.6 percent of the total major ion concentration in 1916 to 0.6 percent in 1999. A decrease in bicarbonate would be expected if the Sea became saturated with respect to bicarbonate salts within a year after its formation as suggested by Tostrud (1997), because concentrations of other, more soluble ions would continue to increase at a faster rate than bicarbonate.

Sulfate has increased from 13.7 percent of the total ions in 1907 to 24.4 percent in 1999. The increase in sulfate is partially balanced by a decrease in chloride from 48.9 percent of the total in 1907 to 40.1 percent in 1999. This change can be attributed to the composition of Colorado River water, which contributed over 2.5 times more sulfate than chloride to the Salton Sea basin between 1905 and 1989 (Tostrud, 1997).

At present, the major ion composition of the Salton Sea is different from most other saline lakes because of the relatively large concentration of sulfate. If the Sea has indeed reached saturation with respect to sulfate, as suggested by Ormat (1989), Tostrud (1997), and geochemical modeling conducted during this study (see below), two significant changes will occur. First, the increase in salinity will be less than predicted by current models because sulfate minerals should begin to precipitate, and second, the long-term trends of relative concentrations of increasing sulfate and decreasing chloride should eventually reverse.

#### 4.11 Trace Metals and Organic Compounds

Ranges for heavy metals from the two sampling dates are presented in Table 4. Trace metal concentrations were all low (Table 8). This is not surprising because of the high concentrations of sulfide in the Salton Sea and the low solubility of most heavy metal sulfides. Heavy metals are readily precipitated as sulfides according to the following reaction:



The only metals with high concentrations were total iron and aluminum, which are both present at high levels in many soils. The concentrations of dissolved iron was nearly two orders of magnitude lower than the total iron concentration and the concentration of dissolved aluminum was below or at the detection limit of 30 µg/L. This indicates that both of these metals were associated with soil particles in the river samples.



**Table 8 - Trace metal concentrations in Salton Sea and river samples collected on 15-16 March and 19-20 October 1999**

Variable	Location (concentration ranges for total metals in µg/L)			
	Salton Sea	Alamo River	New River	Whitewater River
Aluminum	<30	14,900 - 18,800	4,340 - 7,530	2,070 - 3,590
Arsenic	1.55 - 9.95	5.33 - 6.98	4.23 - 6.74	6.05 - 7.35
Barium	65 - 80	162 - 176	104 - 146	58 - 75
Cadmium	<4	<4	<4	<4
Chromium	<4	10 - 14	4.5 - 6.1	<4
Cobalt	<3 - 3.4	3.8 - 7.9	<3	<3
Copper	<4	7.4 - 10.9	4.3 - 4.7	<4 - 4.1
Iron	8.3 - 65	8,070 - 9,320	2,160 - 4,220	1,910 - 3,230
Lead	<30	<30	<30	<30
Manganese	17 - 59	186 - 253	190 - 205	87 - 91
Mercury	0.001 - 0.030	0.009 - 0.011	0.017 - 0.017	0.006 - 0.006
Molybdenum	<10 - 12	<10 - 13	12 - 17	33 - 39
Nickel	<10	<10 - 15.1	10 - 12.5	<10
Selenium	1.1 - 2.1	5.9 - 6.6	3.4 - 3.5	2.4 - 2.5
Silver	<4	<4	<4	<4
Vanadium	<4 - 7.5	30 - 31	12 - 16	16 - 18
Zinc	<4 - 4.1	28 - 40	14 - 18	16 - 31

Selenium is of concern for many water bodies in the southwest, but was not present at elevated concentrations in the Salton Sea. Like all of the other trace metals, selenium concentrations were lower in the Salton Sea than in the rivers (Table 4), and the Salton Sea concentration of 1.1 to 2.1 µg/L is well below levels of concern for aquatic life.

No semi-volatile organics or chlorinated pesticides were found in the river inflows at concentrations above detection limits during the current study. Two phthalate esters, di-n-octylphthalate and bis(2-Ethylhexyl)phthalate were present at concentrations of 5.4 and 46 µg/L, respectively, at Station SS-1 on the October 20, 1999, sampling date. The former compound was present just above the detection limit of 5 µg/L and the latter result

is in question because the analyte was also detected in the method blank. These compounds are widely used as plasticizers and their presence at these low levels is not of concern from a water quality standpoint. The lack of organic compounds in the Salton Sea is consistent with previous studies and is not surprising given the low solubility of these compounds in water and the high salt levels in the Sea.

#### **4.12 Nutrient and Solids Loadings**

Data from the sampling program was used in conjunction with discharge data to calculate loadings from runoff for total P, total N, total suspended solids and total dissolved solids. The average annual inflow to the Salton Sea was reported as 1,346,000 acre-ft in the Salton Sea Restoration Draft EIS/EIR (Salton Sea Authority/USBR, 2000). This total is composed of 620,000 acre-ft from the Alamo River (46.1 percent of the total), 438,000 acre-ft from the New River (32.5 percent), 79,000 acre-ft from the Whitewater River (5.9 percent), 106,000 acre-ft from agricultural drains (7.9 percent), groundwater (3.7 percent), direct precipitation (3.5 percent), San Felipe Creek (0.4 percent), Salt Creek (0.1 percent) and other (1.3 percent). The first four sources listed account for 92.4 percent of the average annual inflow to the Salton Sea and may be expected to account for an even higher percentage of the total nutrient and solids loadings.

Actual discharge data for 1999 for the three influent rivers (Rockwell et al., 2000 and provisional data) and the average data from the agricultural drains was used in the calculation of pollutant loads for 1999. The measured discharges were 617,130 acre-ft measured at USGS Station Number 10254730, Alamo River near Niland, CA, 488,080 acre-ft measured at USGS Station Number 10255550, New River near Westmoreland, CA, and 52,984 acre-ft measured at USGS Station Number 10259540, Whitewater River near Mecca, CA. Discharges for the Alamo and Whitewater Rivers were below the long-term averages and the New River discharge was higher; however, the total discharge from the three rivers of 1,158,200 acre-ft was less than two percent above the long-term average.

Although there was a general tendency for nutrient and solids concentrations to increase with increasing flow, none of the pollutants of concern had consistently strong correlations with flow for all three of the major inflows, and differences in flow varied by less than a factor of three between maximum and minimum flows for all of the three major rivers. As a result, data from the 18 sampling dates were multiplied by river flows on those days to determine daily pollutant loadings. The calculated daily loadings were averaged and multiplied by 365 to determine the annual load. These loads were compared to loads calculated by multiplying the average annual pollutant concentrations by the total river flows and with loads calculated using regression relationships to calculate daily pollutant concentrations. Differences between these three methods were usually less than five percent, and none of the methods was consistently higher or lower than the others for all pollutants and rivers. Therefore, the reported pollutant loadings are those calculated from average daily loadings. Loadings from the agricultural drains were calculated by assuming those loads were in proportion of the flows from the agricultural drains and the Alamo River because both discharges are draining land with similar uses (Setmire, 2000).

The total dissolved solids loading of 3,434,000 tonnes/yr (Table 9) is only 73 percent of the loading projected from the average TDS inflow concentration of 2,800 mg/L

reported in the Salton Sea EIS/EIR (Salton Sea Authority/USBR, 2000); however, a recent examination of salt loads by Weghorst (2001) found an average salt loading of 3,290,000 tonnes/yr for 1985 to 2000.

**Table 9 - 1999 Nutrient and Solids Loadings for the Salton Sea**

Source	Parameter (annual load, tonnes/yr)			
	Total P	Total N	TSS	TDS
Alamo River	574	7,080	281,100	1,584,000
New River	660	4,960	132,700	1,480,000
Whitewater River	52	1,030	6,020	96,600
Agricultural Drains	99	1,220	48,300	272,000
<b>Total</b>	<b>1,385</b>	<b>14,300</b>	<b>468,100</b>	<b>3,434,000</b>

Watts et al. (1999) presented nitrogen and phosphorus loadings for the periods 1967-68 and 1997-98 and Cagle (1998) calculated nutrient loadings using data collected by the California Regional Water Quality Control Board from 1980-92. The results from Watts et al. (1999) were converted from g/m<sup>2</sup>/yr to tonnes/yr and the Cagle (1998) results were converted from tons/yr to tonnes/yr for comparison with results from the current study (Table 10). Total P and total N concentrations reported by Cagle (1998) and Watts et al. (1999) are also included in Table 10.

**Table 10 - Current and Previous Nutrient Loadings and Concentrations for the Salton Sea**

Dates	Total P		Total N	
	Concentration (mg l <sup>-1</sup> )	Annual Load (tonnes yr <sup>-1</sup> )	Concentration (mg l <sup>-1</sup> )	Annual load (tonnes yr <sup>-1</sup> )
1967-68*	0.095	663	2.1	11,400
1980-92**	--	1,135	--	12,500
1996-97*	0.091	1,515	5	11,400
1999***	0.069	1,385	3.6	14,300

\*Watts et al. (1999)  
 \*\*Cagle (1998)  
 \*\*\*This study

Some variations in both concentration and loading are expected because the different studies have used different sampling sites and frequencies, and different methods for evaluating results. It is clear, however, that nutrient loadings to the Salton Sea have been increasing, but their impacts on nutrient concentrations in the Sea are variable.

Watts et al. (1999) found no difference in nitrogen loading to the Salton Sea between the 1967-68 and 1996-97 time periods, but reported that total nitrogen concentrations more than doubled. In contrast, both Cagle (1998) and this study found higher nitrogen loadings than those reported by Watts et al. This study found lower total nitrogen concentrations than those reported by Watts et al., but still showed a significant increase over the 1967-68 levels. It appears the total nitrogen load to the Salton Sea has increased between 0 and 25 over the past 30 years, accompanied by an increase of total nitrogen concentrations of between 70 and 140 percent.

In contrast to the nitrogen results, it appears that total P loadings to the Sea have at least doubled over the past 30 years, but total P concentrations in the Sea are apparently decreasing. Geochemical modeling (see next section) indicates the Sea is often supersaturated with respect to hydroxyapatite [ $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ ], as well as other apatite minerals. While direct precipitation of hydroxyapatite is known to be kinetically hindered, it often forms initially on the surface of calcite crystals (Stumm and Morgan, 1981) and could be forming in the Salton Sea. The incorporation of phosphorus in fish tissue and bone and in the shells of aquatic invertebrates would be another means of phosphorus removal. Once incorporated into bone or shell material, the insolubility of hydroxyapatite would prevent dissolution of the precipitated phosphorus to provide a permanent removal mechanism.

## 5.0 Geochemical Modeling

The geochemical programs PHRQPITZ (Plummer et al, 1988) and PHREEQC (Parkhurst and Appelo, 1999) were used to evaluate the equilibrium conditions that may affect the concentrations of various ions in the Salton Sea.

PHRQPITZ is a computer program that uses the Pitzer virial coefficient approach for activity coefficient corrections. It was designed for geochemical calculations in brines and other electrolyte solutions with high concentrations. The database used for the program has been partially validated for the system Na-K-Mg-Ca-H-Cl-SO<sub>4</sub>-OH-HCO<sub>3</sub>-CO<sub>3</sub>-CO<sub>2</sub>-H<sub>2</sub>O, and extended with largely untested data for Fe<sup>2+</sup>, Mn<sup>2+</sup>, Sr, Ba, Li and Br and provisions for temperatures other than 25°C. Because the temperature dependence on the solubility of many minerals in the PHRQPITZ database is not known, large errors could result for calculations at temperatures other than 25°C.

PHREEQC is a more versatile program; however, it uses ion-association and Debye-Huckel expressions to account for the non-ideality of aqueous solutions. These corrections may break down for ionic strengths in the range of seawater and above, particularly in systems, like the Salton Sea, which are not dominated by sodium chloride.

Both models were used to evaluate the equilibrium status of minerals within the Salton Sea and the precipitation of minerals resulting from salt loading from the rivers. Weighted mean concentrations of major ions profiles for the Salton Sea and a composite river concentration, calculated by flow-weighting mean concentrations for the Alamo, New and Whitewater Rivers, with flows from the agricultural drains added to the Alamo River flow, were used as model inputs (Table 11). Profiles for the dates with the maximum (August 24, 1999) and minimum (January 22, 1999) observed temperatures were also used to evaluate the impacts of temperature on chemical equilibria.

Results from the two programs were similar, although greater solubilities were predicted by PHRQPITZ, primarily as a result of lower calculated activities for Ca<sup>++</sup> and SO<sub>4</sub><sup>=</sup>. More mineral phases were available for evaluation through PHREEQC, particularly when the data base from the program Wateq4f was used. These programs were used to determine which minerals should be precipitating under current conditions in the Salton Sea.

Both programs suggested that the Salton Sea is currently super-saturated with respect to calcite (CaCO<sub>3</sub>), gypsum (CaSO<sub>4</sub>·2H<sub>2</sub>O), magnesite (MgCO<sub>3</sub>) and dolomite [CaMg(CO<sub>3</sub>)<sub>2</sub>]. The larger database for PHREEQC also indicated super-saturation with respect to celestite (SrSO<sub>4</sub>), huntite [CaMg<sub>3</sub>(CO<sub>3</sub>)<sub>4</sub>], and several silicate minerals. Saturation levels were exceeded for the phosphate minerals, hydroxyapatite [Ca<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>OH] and fluorapatite [Ca<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>F], for phosphate concentrations greater than 0.005 mg/L. Both programs also predicted that the composite river sample was super-saturated with respect to calcite, dolomite, and magnesite, and PHREEQC included super-saturation with respect to hydroxyapatite and fluorapatite in the rivers.

While the geochemical programs predict that the Salton Sea is super-saturated with respect to the minerals listed above, this do not provide proof of their existence. Kinetics and other unknown factors can also influence precipitation. The problem of super-

**Table 11 - Input Data for Geochemical Models**

Variable	Location (concentrations in mg/L)					
	Salton Sea			River Composite		
	Average	1/22/99	8/24/99	Average	1/21/99	8/25/99
Ortho-P	0.021	.003	.003	0.510	0.624	0.392
NH3-N	1.16	0.858	1.13	1.99	2.13	2.58
NO3+NO2-N	0.12	0.174	0.076	5.45	5.80	5.00
Si (as SiO2)	9.84	10.8	8.13	14.0	12.3	17.5
Ca	944			168		
Mg	1,400			80.8		
Na	12,400			454		
K	258			9.9		
Sr	22.0			2.97		
B	11.1			0.686		
Cl <sup>-</sup>	17,200			543		
SO4 <sup>=</sup>	10,500			734		
HCO <sub>3</sub> <sup>-</sup>	245			274		
CO <sub>3</sub> <sup>=</sup>	2			0		
F <sup>-</sup>	2.1			1.5		
Temp. (°C)	23.0	14.3	29.9	22.6	15.4	30.3
pH	8.12	8.24	7.97	7.58	7.56	7.71
pe	3.09	5.06	0.085	5.02	4.99	5.51
DO	5.48	7.41	2.71	6.41	7.30	4.34
Density (kg/L)	1.04			1.0		

saturation with respect to hydroxyapatite was mentioned earlier, however, it is likely that both hydroxyapatite and fluorapatite are forming in the Salton Sea, and their formation would provide a sink for phosphorus.

Celestite is found mostly as a minor constituent of limestones but may form in the sulfate-rich environment of the Salton Sea. The prevalence of dolomite super-saturation has been widely discussed in the geochemical literature. Seawater and many saline lakes are super-saturated with respect to dolomite, and this mineral is not known to form except under extreme saline conditions and is not expected to be forming in the Salton Sea. Likewise, it is unlikely that either magnesite or huntite are forming in significant amounts.

Calcite readily forms in lake systems and is expected to be forming in the Salton Sea. Several independent observations also support gypsum formation. These include direct observations of gypsum crystals in Salton Sea sediments by principal investigators of other reconnaissance studies on the Salton Sea (LFR Levine Fricke, 1999; Dexter and Hurlbert, 2000; Amrhein, 2001) and precipitation of gypsum in unpreserved samples stored in this laboratory after analysis as part of this study.

Although both Ormat (1989) and Tostrud (1997) postulated precipitation of a sodium sulfate mineral to account for the ion balance in the Sea, the PHREEQC program indicated this was not likely. Saturation indices were -1.75 for mirabilite ( $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ ) and -2.69 for thenardite ( $\text{Na}_2\text{SO}_4$ ), indicating that neither of these minerals is close to saturation. In addition, sodium sulfates do not form in seawater (Krauskopf, 1979), except as evaporites, leaving substitution in other minerals or the adsorption of  $\text{Na}^+$  on clay minerals, or formation of some other unidentified mineral, as possible explanations for the observed sodium loss.

Additional evaluations of chemical equilibria in the Salton Sea were made by using the geochemical programs to equilibrate Sea water with calcite and gypsum, the two minerals that currently exceed saturation levels that are the most likely to be forming at the present time, as well as with atmospheric carbon dioxide. The amount of these minerals that would need to precipitate to establish equilibrium was calculated for a mixture of Salton Sea water and composite river water (Table 7), followed by evaporation to the original volume to mimic current conditions of salt loading to the Sea, as well as for average Sea water alone.

Each program produced similar results for the two scenarios, although in both cases greater amounts of salt were calculated to precipitate under the PHREEQC program because of the higher ion activities for calcium and sulfate with PHRQPITZ. The total dissolved solids concentration of Salton Sea water in equilibrium with calcite, gypsum, and atmospheric carbon dioxide was calculated as 42.1 g/L by PHREEQC and 42.3 g/L by PHRQPITZ. The amount of  $\text{CaCO}_3$  and  $\text{CaSO}_4$  precipitation required to reach these levels from the current concentration of 43.1 g/L calculated from the average concentrations of the major ions was also calculated from both programs. In order to reach equilibrium with calcite and gypsum, PHREEQC required precipitation of about 1.1 g/L of calcite and gypsum (water of hydration was not included for gypsum) and PHRQPITZ required precipitation of 0.7 g/L. When applied to the entire volume for the Salton Sea of  $9.41 \times 10^9 \text{ m}^3$ , these values correspond to  $1.1 \times 10^{10}$  and  $6.6 \times 10^9$  kg, respectively, for the two programs, or 1.5 to 2.5 percent of the total salt in solution and 2 to 3 times the calculated annual salt load from the rivers.

The above considerations indicate that the Salton Sea is not at equilibrium with respect to the formation of gypsum, but may be in equilibrium with respect to calcite. Evidence from sediment cores (LFR Levine Fricke, 1999) and on-going studies (Amrhein,

2000) indicates both of these minerals are forming in the Sea. Once formed, the high salinity in the Sea would probably prevent re-dissolution. Recent results from evaporation pond studies conducted by the Bureau of Reclamation (Weghorst, 2002) indicated that gypsum readily precipitates after salinity increases by about 20 percent over current levels. In addition, sulfate reduction (Section 4.4, Equation 2) under the anaerobic conditions frequently present in the bottom waters of the Salton Sea produces bicarbonate ions, which could result in additional salt removal through the precipitation of calcite which is almost equivalent to salt removal through gypsum formation.

Precipitation of calcite and gypsum, would slow the rate of salt accumulation in the water column, which is of major concern for proposed restoration alternatives. Additional evidence for precipitation was provided by Tostrud (1997), who evaluated salt inputs from Colorado River water and the amounts of salt in the Sea water in 1989, to predict a drop in salt gain of about 1/3 of the inflow beginning in 1980. This drop resulted from salt precipitation, which was calculated to be about 1.469 million tons/yr from 1980 through 1996.



## 6.0 Conclusions

The Salton Sea is a eutrophic system characterized by very low oxygen concentrations which lead to frequent fish kills during the summer months. Nutrient ratios indicate that algal growth in the Sea should be phosphorus limited and management efforts should focus on phosphorus removal. Although phosphorus loadings to the Salton Sea have doubled over the past 30 years, phosphorus concentrations appear to have decreased. Both biotic mechanisms, such as incorporation of phosphorus in fish tissue and bone and in the shells of aquatic invertebrates, and abiotic mechanisms, such as precipitation of hydroxyapatite or phosphorus adsorption on clay particles, may account for this observation.

Nitrate concentrations are high in the influent rivers, but denitrification is apparently responsible for keeping nitrate levels low in the Sea. In contrast, ammonia concentrations show little reduction and remain high in the Salton Sea. Ammonia levels are high enough to lead to un-ionized ammonia concentrations above regulatory limits. Ammonia toxicity represents an additional stress that may have synergistic effects with low oxygen levels and high temperatures to lead to fish kills.

Other than high productivity leading to problems with low dissolved oxygen, water quality conditions in the Salton Sea are relatively good. Water from the Sea meets all U.S. EPA primary drinking water standards and most secondary standards, except those related to salinity (Table 12).

The Salton Sea is currently super-saturated with respect to several minerals, including calcite, gypsum, celestite, hydroxyapatite and fluorapatite. Formation of the first three of these minerals may lead to precipitation of calcium, strontium and some of the sulfate entering the Sea, while formation of the apatites could provide a sink for phosphorus.

The geochemical models PHREEQC and PHRQPITZ indicated that precipitation of 1.5 to 2.5 percent of the total amount of salt currently in the Sea, or 2 to 3 times the average annual salt inflow, would be required for the Salton Sea to reach equilibrium with respect to calcite and gypsum. Depending on the rate and extent of the precipitation actually occurring, salt levels are expected to rise at a slower rate in the future than in the period prior to about 1989 when the gypsum saturation level was reached.

**Table 12 - Comparison of Results to EPA Drinking Water Standards**

<b>Variable</b>	<b>EPA Standard (mg/L)</b>	<b>Salton Sea Concentration (mg/L)</b>
<b>Primary Standards</b>		
Arsenic	0.05	0.002 - 0.010
Barium	2	0.064 - 0.080
Cadmium	0.005	<0.004
Chromium	0.1	<0.004
Copper	1.3	<0.004 - 0.005
Fluoride	4.0	1.98 - 2.15
Lead	0.015	<0.03
Mercury	0.002	0.000001 - 0.000030
Nitrate-N	10	<0.03 - 0.89
Selenium	0.05	0.00004 - 0.0021
<b>Secondary Standards</b>		
Aluminum	0.05-0.2	<0.03
Chloride	250	14,800 - 22,600
Copper	1.0	<0.004 - 0.005
Fluoride	2.0	1.98 - 2.15
Iron	0.3	0.0083 - 0.065
Manganese	0.05	0.017 - 0.059
pH	6.5-8.5	6.81 - 8.69
Silver	0.10	<0.004 - 0.0048
Sulfate	250	9,370 - 11,500
TDS	500	40,740 - 48,130
Zinc	5	<0.004 - 0.041

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