Moss
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Technical Publication 73-2

THE HYDROGRAPHY OF ELKHORN SLOUGH
A SHALLOW CALIFORNIA COASTAL EMBAYMENT

Annual Report, Part 2, 1973

by

Richard E. Smith

A NATIONAL SEA GRANT PROJECT
supported by the
OFFICE OF SEA GRANT PROGRAMS
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
DEPARTMENT OF COMMERCE
Grant No. SGP2-94

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Moss Landing Marine Laboratories
of the
California State University and Colleges
at
Fresno, Hayward, Sacramento, San Francisco, San Jose, and Stanislaus

Contributions from the Moss Landing Marine Laboratories No. 42
Technical Publication 73-2
CASUC-MLML-TP-73-02

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ABSTRACT

From October 1970 through February 1972, temperature, salinity, dissolved oxygen, secchi depth and five major nutrients were observed at approximately monthly intervals in Elkhorn Slough and Moss Landing Harbor. In addition, similar hourly observations were made during two tidal studies during the wet and dry seasons. From the salinity measurements during the summer, a salt balance for Elkhorn Slough is formulated and mean eddy diffusion coefficients are determined. The diffusion model applied to longitudinal phosphate distributions yielded a mean diffusive flux of 12 kg PO_4^{-3}/day (140 μg-at/m^2/day) for the area above the mean tidal prism. Consistent differences, apparently due to differing regeneration rates, were observed in the phosphate and nitrogen distributions. Bottom sediments are proposed as a possible source for phosphate and as a sink for fixed nitrogen.

Dairy farms located along central Elkhorn Slough are apparently a source for reduced nitrogen. During summer, nitrogen was found to be the limiting nutrient for primary production in the upper slough.

Tidal observations indicated fresh water of high nutrient concentration consistently entered the harbor from fresh water sources to the south. This source water had a probable phosphate concentration of 40 to 60 μg-at/l and seasonally varying P:N ratio of 1:16 and 1:5 during the winter and summer respectively.

Net production and respiration rates are calculated from diurnal variations in dissolved oxygen levels observed in upper Elkhorn Slough. Changes in phosphate associated with the variations in oxygen was close to the accepted ratio of 1:276 by atoms.

ACKNOWLEDGMENTS

I am deeply indebted to my research advisor, Dr. William W. Broenkow, for his continuing interest and assistance. I would also like to thank Dr. John P. Harville for his encouragement and support during the early stages of the project.

Without the assistance of many of the students at Moss Landing Marine Laboratories, the collection of much of the data would have been impossible. I also thank David Seielstad for his wit and tutoring during the many hours of analysis and Scott McKain and Sandra Benz for their assistance in collection and chemical analysis.

I also express my gratitude to my friends and committee members at the U.S. Geological Survey, Drs. T.J. Conomos and D.H. Peterson, for their patience, and to my wife, Joyce, to whom I owe the drafting and much of the typing.

This report constitutes an M.A. thesis in the Department of Natural Sciences at California State University, San Jose, and was supported by Grant 2-35137 from the office of Sea Grant Programs, National Oceanic and Atmospheric Administration, Department of Commerce.

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CHAPTER 1

INTRODUCTION

The oceanography of coastal waters, until recently, has been neglected by most oceanographers mainly because of the difficulty in dealing with the highly variable properties and distributions observed in this area. While large scale geochemical, biological and climatologic cycles require study of the open ocean, man has applied a great deal more stress to the interface between the land and the sea. In this area, the depths are often too shallow for the usual oceanographic sampling procedures and short term temporal variations due mainly to the tide make data interpretation difficult at best.

In spite of these problems, detailed knowledge of this area must be obtained. Understanding the mechanisms of transport and degradation of waste products as they move from the land to the sea is of utmost importance. Increasing commercial, industrial and recreational demands are competing for the use of the coastal zone. Unfortunately, these increased demands often create an imbalance in the natural environment. The importance of protected coastal lagoons and estuaries as spawning grounds for fish and nursery areas for many larval forms is well known. If this zone is to be protected, the sources and kinds of pollutant entering a system must be identified and managed.

Elkhorn Slough is a shallow, tidal embayment on Monterey Bay (Fig. 1) lying approximately halfway between Monterey and Santa Cruz, California. In October 1970, a survey of the seasonal variations in the water chemistry of the slough was begun and is still in progress. During the investigation, water samples were collected at approximately monthly intervals and two short term tidal surveys were conducted in March and August 1971 (Appendix 3). Data obtained between October 1970 and February 1972 (Broenkow and Smith 1972) is discussed here.

Purpose of Study

Elkhorn Slough is a unique feature along the predominantly rocky central California coast and because of this, its value as a natural resource is increased. According to Browning (1972), "...Elkhorn Slough remains one of the most ecologically important estuarine systems on the coast, encompassing the second largest salt marsh in California. Its importance takes on a greater significance because more than two-thirds of California's original coastal wetlands already have been filled in, reclaimed or otherwise destroyed."

While change is inevitable, either natural or man-induced, local and state agencies can direct these changes. Proposals such as increasing the size of the present Moss Landing Harbor to accommodate deep draft vessels and moving the Highway 1 Bridge further inland, or restricting discharge from small craft berthed in the harbor must be evaluated on the basis of environmental as well as economic impact. Effective management must be based on a clear understanding of the physical and biological processes taking place within the system.

Previous studies of the hydrography of Elkhorn Slough and Moss Landing Harbor were of short duration and limited scope. The California Department of Public Health (1966, 1967) investigated the coliform bacteria distribution in the water and shellfish of the area. As a result of the study, the area was classified as unfit for shellfish production. On the basis of the coliform distributions observed by the health department, Water Resources Engineers (1969) developed a mathematical hydrologic model of Elkhorn Slough and used the model for a cost benefit analysis of proposed sewage treatment plans. An earlier study by Stump (1967) dealt primarily with the influence of industrial pumping on the distribution of physical chemical properties of the water in the south harbor.

The primary objective of this study is to describe the major circulation patterns of Elkhorn Slough - Moss Landing Harbor system. No previous work has been published establishing mean distributions of hydrographic parameters on a seasonal basis. As the analysis of these data will demonstrate, there are major reversals of chemical distributions on a seasonal basis and there are identifiable source waters throughout the year. During the dry summer months, a quasi-steady state salinity distribution develops in the upper slough, permitting the formulation of a salt balance and tidal diffusion model. As a result of this model and observed gradients, estimates of nutrient fluxes are made.

In addition to the seasonal analysis, short term time series observations reveal relatively large variations in water properties

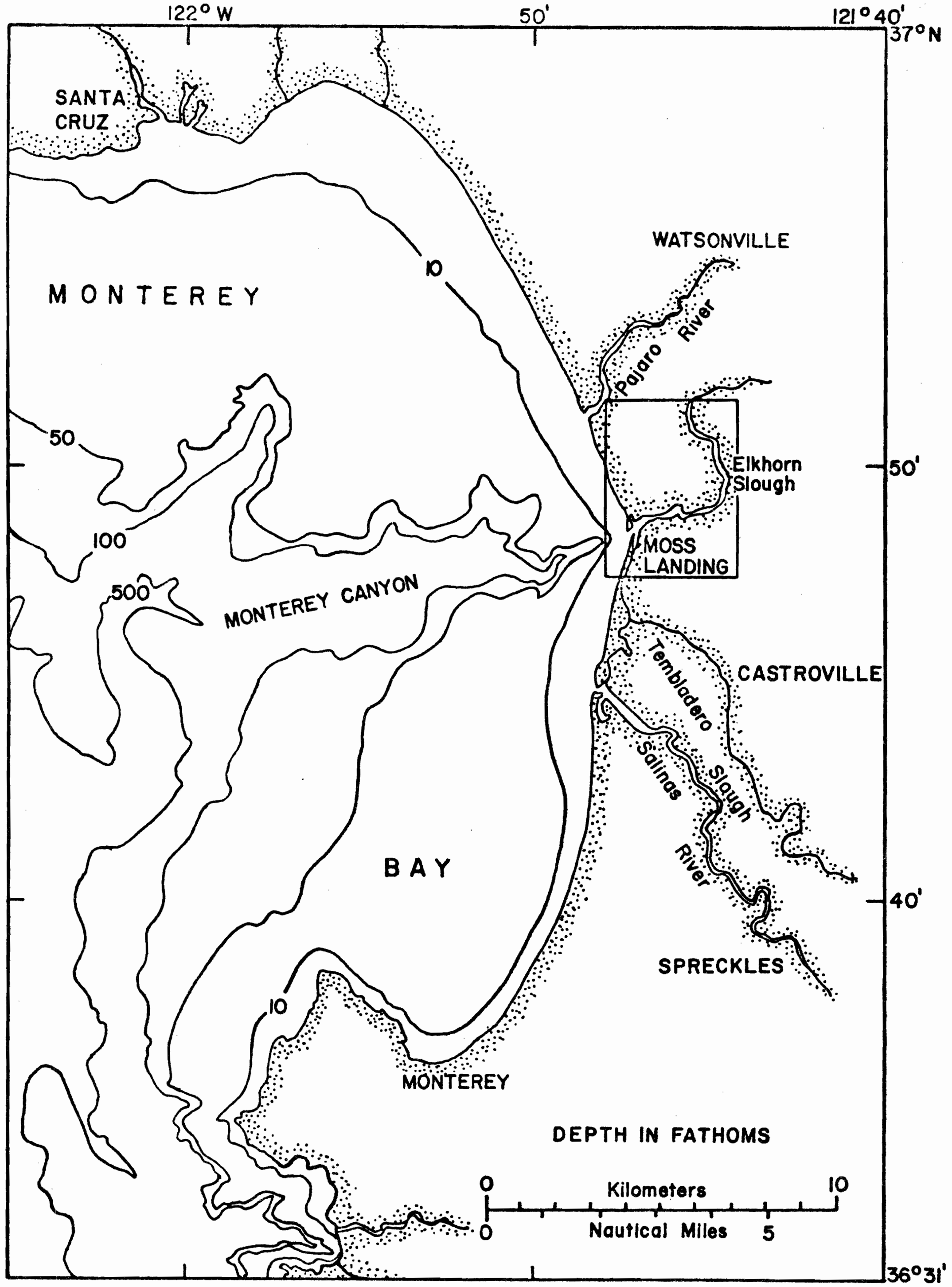

Figure 1. Chart of Monterey Bay indicating study area.

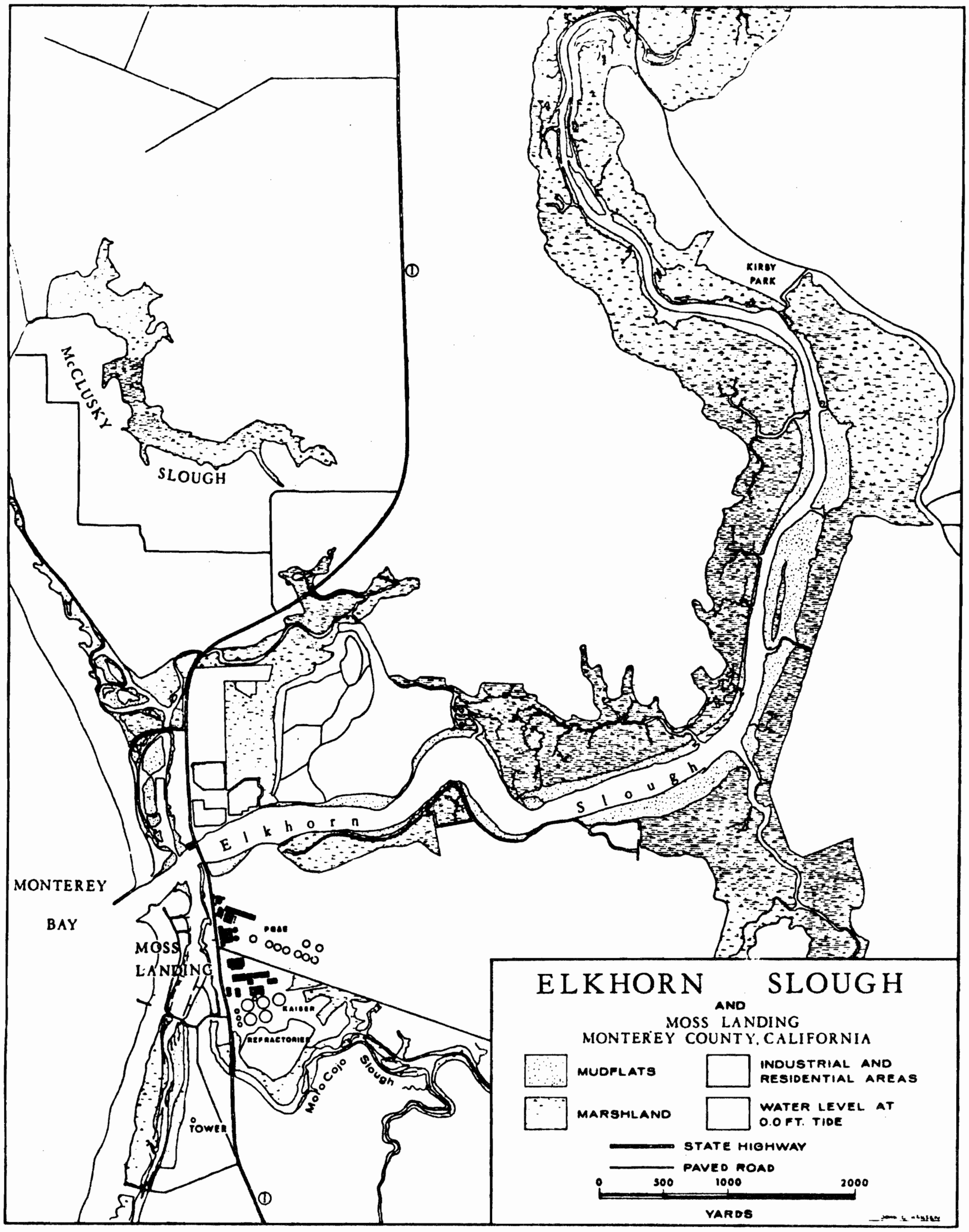

Figure 2. Elkhorn Slough and adjacent lands (Map drawn by John C. Hansen).

corresponding to the tidal period. In the upper slough, significant diurnal cycles are evident from which some conclusions are drawn regarding respiration and production rates.

Description of Elkhorn Slough and Moss Landing Harbor

The study area is comprised of two interconnecting water courses, Elkhorn Slough and Moss Landing Harbor in the Old Salinas River channel (Figs. 2 and 3). Elkhorn Slough extends inland approximately four km and has an axial length of about 10 km. The main channel is about 100 m wide and channel depth decreases monotonically from five m landward from the mouth (Fig. 5b). *Salicornia* marsh and tidal mud flats extend the length of the slough. The Old Salinas River channel runs in an approximately north-south direction parallel to the coast. The present harbor inlet (dredged in 1947) intersects the old river channel directly seaward of Elkhorn Slough and divides the navigable portion into two parts. The north area is occupied by a small private yacht club. The southern area, Moss Landing Harbor, is maintained by the U. S. Army Corps of Engineers as a small boat harbor and is used primarily by commercial fishing vessels. The inlet is dredged periodically to maintain a depth of five m (15 ft.) at mean lower low water and a width of 165 m. Overflow from the Salinas River and runoff from Tembladero and Moro Cojo Sloughs drain through the south harbor.

The drainage basin for Elkhorn Slough is small, only 585 km^2. The land in the vicinity of the slough is primarily used for agricultural purposes. To the south are large artichoke fields from which irrigation waters containing high concentrations of nutrients discharge into the Old Salinas River and combine with discharge from the Castroville sewage treatment plant which enters the system via Tembladero Slough. Dairies and cattle-grazing acreage occupy most of the rolling grass-covered hills east of Moss Landing. To the north a variety of crops, including strawberries, artichokes and Brussels sprouts are grown on the fertile remnant of uplifted alluvium. To the west is Monterey Bay, rimmed by sand dunes.

Historical Land Use The development of Moss Landing spans over a hundred years. In the past, local industry has varied from land speculation to whaling, and presently the major industries are the Pacific Gas and Electric power plant and Kaiser Refractories magnesium plant.

In the 1860's, Captain Charles Moss, the town's namesake, built a warehouse and later a pier which acted as a depot for transferring grain grown in the Salinas and Pajaro Valleys to ships anchored off-shore. For 15 years or more, the business thrived and grew. Elkhorn Slough, Moro Cojo Slough and the lower Salinas River provided excellent natural channels for transporting freight to the central warehouse at Moss's Landing. In 1874, the railroad was completed to Watsonville and from that time on the business dwindled.

A whaling station was established at Moss Landing in 1917 which met with some success for a few years. Later, during the thirties, the sardine fishery proved to be much more profitable and grew to dominate local industry. During this same period, commercial oyster growing was attempted and significant crops were realized during the years 1931-1938. At least two companies are currently investigating the possibility of re-establishing the oyster industry.

Moss Landing today, though still sparsely populated by urban standards, has changed considerably. The sardines are no longer found off the coast in abundance, a tide gate prevents tidal flow in Moro Cojo Slough and the Salinas River, which once emptied into Monterey Bay north of the present harbor entrance, now empties five km to the south. The trading and fishing port of old was dredged for a small craft harbor in 1947 and industry dominates the skyline. In 1942, Kaiser-Permanente established a plant to extract magnesium from seawater at Moss Landing. Pacific Gas and Electric built the first two of their present eight fossil fueled electric generators in 1949-50; this complex is now the second largest in the world, producing over 2×10^6 kilowatts and pumping 5×10^6 m^3/day of cooling water from the harbor.

<u>Climate</u> Felton (1965) describes the climate of the Monterey Bay region as follows: "The typical marine climate, beloved by many above all other types of climate to be found in California, prevails here in its nearly perfect form." Basically there are two seasons, a wet winter and a dry summer, with extremes in temperature limited by oceanic influences. The mean summer maximum observed at Watsonville is 22° C and the mean winter minimum is 3° C. More than 90 percent of the precipitation occurs during the months of November through April with an average seasonal total at Watsonville of 53 cm (Table 1). In the

summer, maximum temperatures and evaporation are limited by overcast and fog which commonly occur as a result of condensation in onshore flow moving over cool, recently upwelled waters along the continental shelf. Evaporation along the Monterey coast has been estimated to be 130 cm/year (Elford and Stilz 1968), about 68 percent of the mean evaporation observed inland. Using this factor and a similar correction for evaporation from lakes and reservoirs, monthly evaporation rates have been estimated for environments similar to that of Elkhorn Slough (Table 1).

<u>Geological History</u> The geomorphology of Elkhorn Slough is interesting and rather complex. Though it is a relatively small geographic feature, its geologic history is tied into the formation of one of the world's largest submarine canyons.

Monterey Submarine Canyon is a submerged canyon comparable in dimension to the Grand Canyon (Fig. 1). The head of the canyon lies within one km of the entrance to Moss Landing Harbor. Deep well records and gravity anomaly data indicate a deep valley, filled with sediments to a depth of 2100 m, extends inland along the axis of the canyon beneath Elkhorn Slough. Stark and Howard (1968), Martin (1964) and Lawson (1924) have suggested various means for the formation of this feature. The most plausible of these explanations suggests an early peneplanation followed by uplift and subaerial erosion of a deep valley. During a subsequent period of slow subsidence, the valley was filled with sediments deposited in a marine-estuarine environment. The

TABLE 1

MONTHLY MEAN TEMPERATURE, PRECIPITATION AND EVAPORATION FOR AREAS NEAR ELKHORN SLOUGH (AFTER C. R. ELFORD AND J. E. STILZ, 1968)

	Watsonville Water Works		Nacimento Dam	
	Mean air Temperature (°C)	Precipitation (cm)	Evaporation (cm)	Evaporation corrected for coastal lakes or reservoirs (cm)
June	15.4	0.3	25.4	13.6
July	16.0	0.1	29.1	15.6
Aug.	16.0	0.1	27.4	14.7
Sept.	16.3	0.7	20.2	10.8
Oct.	14.9	2.1	13.9	7.4
Nov.	12.1	4.8	7.0	3.7
Dec.	10.2	11.1	4.5	2.4
Jan.	9.1	11.2	4.0	2.1
Feb.	10.7	10.1	5.6	3.0
Mar.	12.1	7.6	9.7	5.2
April	12.9	3.9	14.2	7.6
May	14.2	1.4	19.9	10.7
Year	13.3	53.3	181	97

present submarine canyon was finally formed by the submerged erosion of these unconsolidated sediments by turbidity currents.

Elkhorn Slough lies in the remnant bed of an ancient river which probably drained the central valley of California as the Sacramento River now does (Lawson 1924). This ancient river supplied the scouring force necessary to carve the original valley and later provided the sediment volume necessary to fill in the valley and form large fan-like deposits along the continental shelf.

More recently, the Salinas River and the post glacial rise in sea level have contributed to the slough and harbor's present appearance.

Hydrology The most flexible definition of an estuary is: a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage (Prichard 1967). Elkhorn Slough fits this description at least during the winter, and the harbor area exhibits the influence of fresh water throughout the year. During the summer months, the slough might be classified as a lagoon which is typified by shallow depths, vertical homogeneity and sluggish circulation. A qualified description would be that it is a tidally influenced lagoon or seasonal estuary.

Elkhorn Slough is an elongated, relatively shallow embayment having a single access to Monterey Bay and the open coast at the harbor entrance. The tides move freely through this inlet and are the major influence on its circulation. The tides in Monterey Bay are mixed, semi-diurnal with a mean tidal range of 1.1 m and a diurnal range of 1.6 m. Mean sea level is 0.8 m and mean higher high water is 1.7 m above the mean lower low water, the tidal datum (U. S. Coast and Geodetic Survey 1971).

Tides and currents associated with the tidal exchange have been measured at the Highway 1 Bridge (Fig. 3) (Clark 1972). During his study, Clark observed significant variations from the predicted tides at Monterey with differences of ± 30 min from predicted time of high or low water and up to 33 cm variation in predicted amplitude. Maximum tidal currents occur at the half-tide when total level is changing most rapidly. Maximum velocities occur between higher high water and lower low water with speeds of about 80 cm/sec for a tidal range of two m.

Nontidal currents in the harbor and Elkhorn Slough are a result of stream flow, local land runoff and industrial pumping and nontidal oscillations. Fresh water flow in Elkhorn Slough ranges from nil to an estimated mean maximum discharge of 1.5 m^3/sec (Water Resources Engineers 1969). Fresh water discharge into the south harbor area is a combination of commercial and residential wastes, irrigation runoff and an unknown quantity as overflow from the Salinas River (Table 2). Industrial pumping contributes significantly to nontidal circulation. Pacific Gas and Electric Company pumps approximately 5×10^6 m^3/day from the south harbor as coolant for their steam generators, increasing the temperature of the water 5 to 10° C. Two-thirds of this volume is discharged offshore and about one-third is discharged into Elkhorn

TABLE 2

MEAN MAXIMUM FRESH WATER DISCHARGE
(WATER RESOURCES ENGINEERS 1969)

	Volume (10^5 m^3/day)
Tembladero Slough at Castroville	1.5
Moro Cojo Slough at Kaiser Plant	0.4
Elkhorn Slough at State Highway No. 1	1.3
Salinas River at Spreckles	36.0
Castroville Sewage Treatment Plant	.11

TABLE 3

INDUSTRIAL PUMPING VOLUMES
IN ELKHORN SLOUGH AND MOSS LANDING HARBOR

	Average Volume (m^3/day)	Temperature Increase °C
Kaiser intake point D and outfall point E (Fig. 3)	8.5×10^4	nil
Kaiser addition of fresh water	1.5×10^2	nil
Pacific Gas & Electric old plant intake point B and outfall point A (Fig. 3)	average 8.7×10^5 maximum 1.9×10^6	5
Pacific Gas & Electric new plant intake point C and outfall point F (Fig. 3)	3.3×10^6	7-10

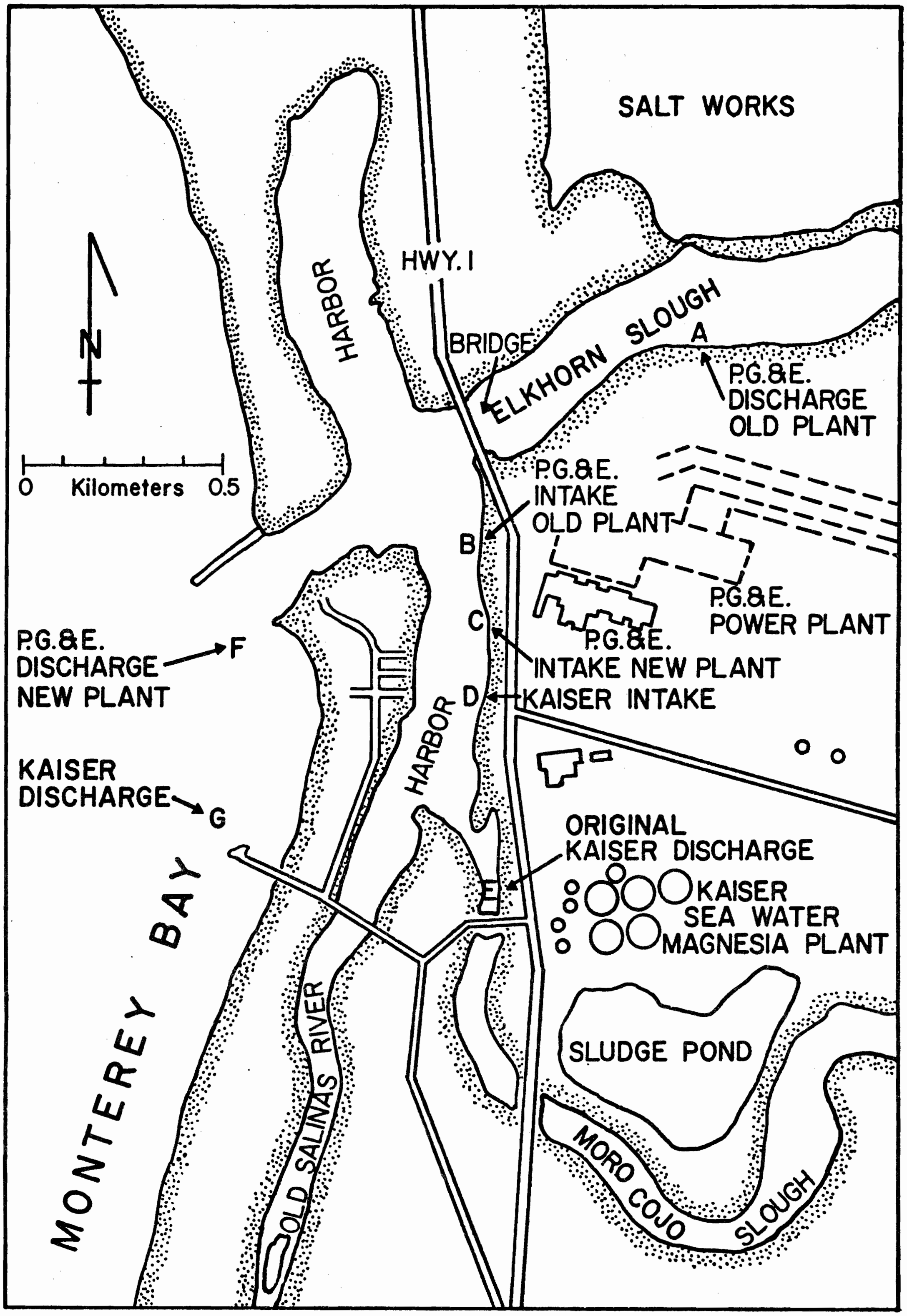

Figure 3. Moss Landing Harbor industrial pumping and discharge sites.

Slough (Fig. 3). Kaiser Refractories removed dissolved magnesium from sea water and returned the calcium-enriched, high pH effluent to the harbor, prior to the completion of an ocean outfall in April 1973. The mean discharge rate of the Kaiser plant is about 8.5×10^4 m^3/day. Stump (1967) calculated a mean tidal prism for the south harbor area of 2.5×10^5 m^3. During one tidal period, the Pacific Gas and Electric plant pumps about four times this volume through its harbor intakes (Fig. 3).

The interpretation of physical and chemical water property distributions in Elkhorn Slough requires a knowledge of its geometry and tidal prism. Figure 2, compiled from low level infrared photography (J. C. Hansen, unpublished map), provides the best available estimates of the surface areas for mud flats, *Salicornia* marsh and channel (Fig. 5a). The maximum channel depth at each of the hydrographic stations was determined by lead line (Fig. 5b). Volumes were calculated at various tidal heights from the following assumptions: 1) the mean elevation for the mud flats and *Salicornia* marsh surfaces are 0.88 and 1.45 m above mean lower low water; and 2) the cross-sectional area at each station is proportional to depth and width of the channel at the station (Figs. 4 and 5c). As an independent verification of these estimated volumes, tidal volumes were calculated from current observations (Clark 1972) taken at the Highway 1 Bridge. Figure 6 shows the agreement between the volumes calculated from the assumed geometry for a given change in tidal height and the volumes calculated from current meter observations for the same change in tidal height. The elevations of the mud flats and marsh were chosen to

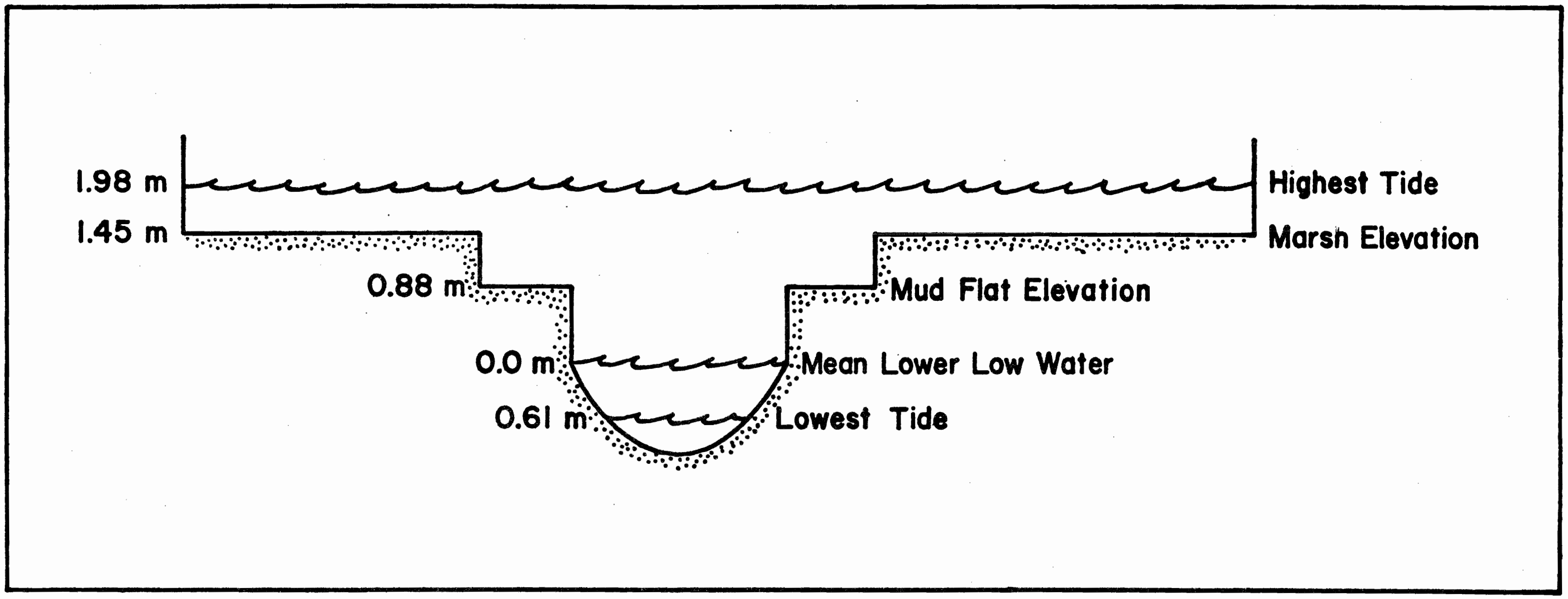

Figure 4. Elkhorn Slough idealized cross-section.

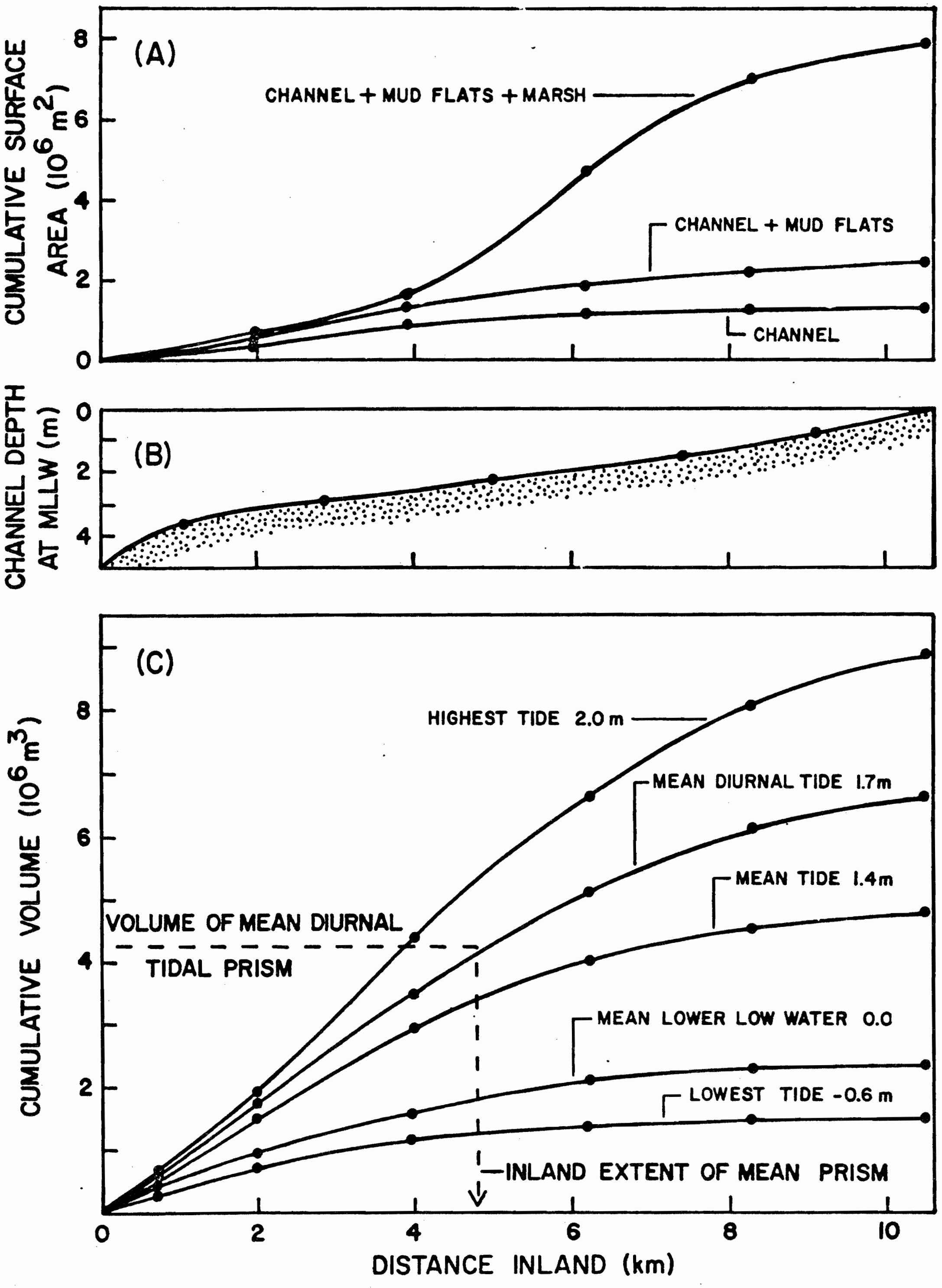

Figure 5. Elkhorn Slough surface areas and volumes. (A) Cumulative surface area versus distance. (B) Mid-channel depth at MLLW. (C) Cumulative volume versus distance.

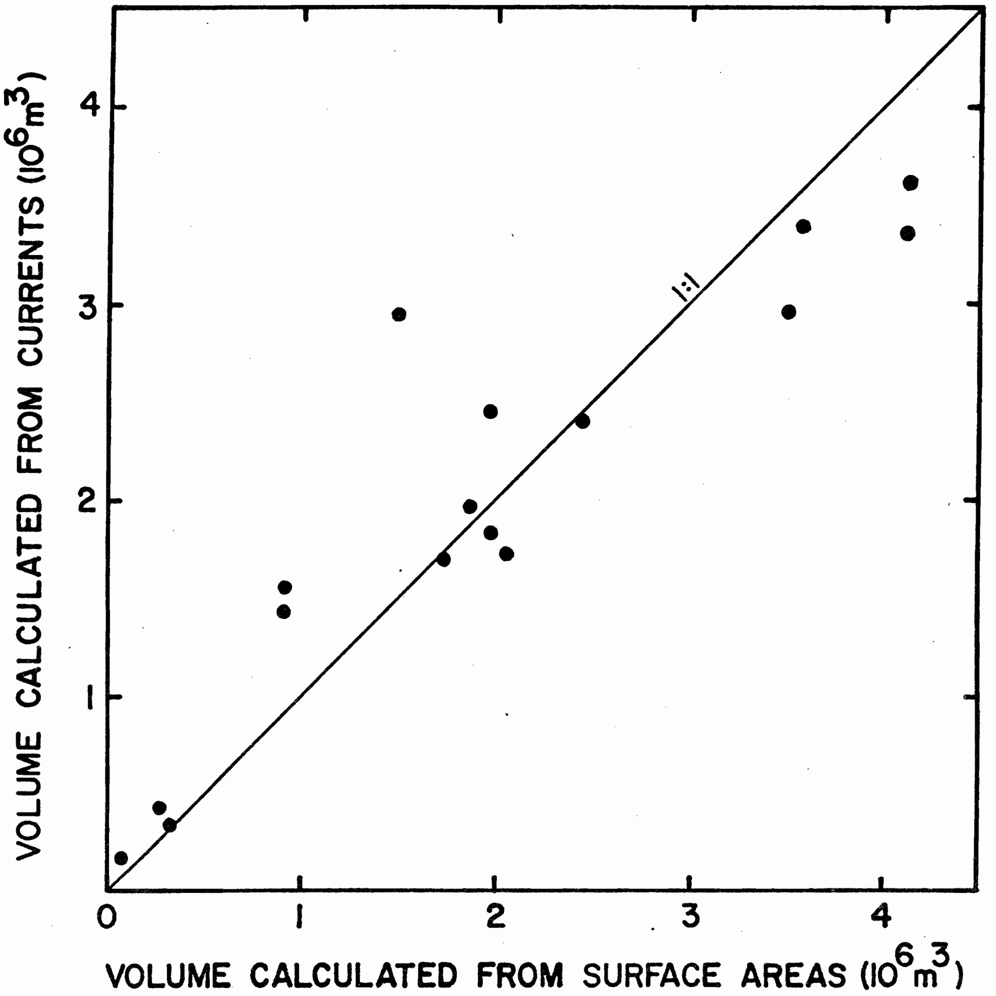

Figure 6. Correlation between volumes calculated from tidal height and volumes calculated from current observations.

minimize the difference between the two sets of data. While the elevations used are in fair agreement with cursory field observations, it should be noted that the elevations determined in this manner represent effective heights and should not be considered absolute.

Based on the geometry described in Figures 4 and 5, the longitudinal extent of the tidal prism can be estimated. If there is little mixing of the water remaining in the slough at low tide with the water intruding on a flood tide, the tidal prism for the mean diurnal tidal range would bring previously offshore waters 4.8 km up the slough as indicated in Figure 5a. This conclusion is substantiated by observation of a foam line, introduced at the Pacific Gas and Electric slough outfall (Fig. 3), which commonly extends four to five km inland at high tide.

CHAPTER 2

METHODS

To distinguish between physical and biological processes, temperature and salinity were measured as indicators of conservative processes and dissolved oxygen and the primary micronutrients (phosphate, silica, nitrate, nitrite and ammonia) were measured as indicators of nonconservative processes.

Determining seasonal variations in the water chemistry of an area such as Elkhorn Slough is difficult. At any location, water properties may double during the tidal cycle. This requires that relatively synoptic data be obtained for spatial comparisons and that the samples be collected at similar tidal stages so that seasonal comparisons can be made. Tidal and diurnal variations were determined by hourly sampling for 24 to 26 hour periods at three stations during the two major seasons.

Hydrographic Stations and Sampling

Nine hydrographic stations were located throughout the study area (Fig. 7). In general, they were located along the axis of the slough-harbor system near easily identifiable landmarks. The total number of stations was limited to nine because of sampling time considerations and these appear to reasonably resolve the longitudinal detail sought in this study. Three tidal survey stations were chosen to determine

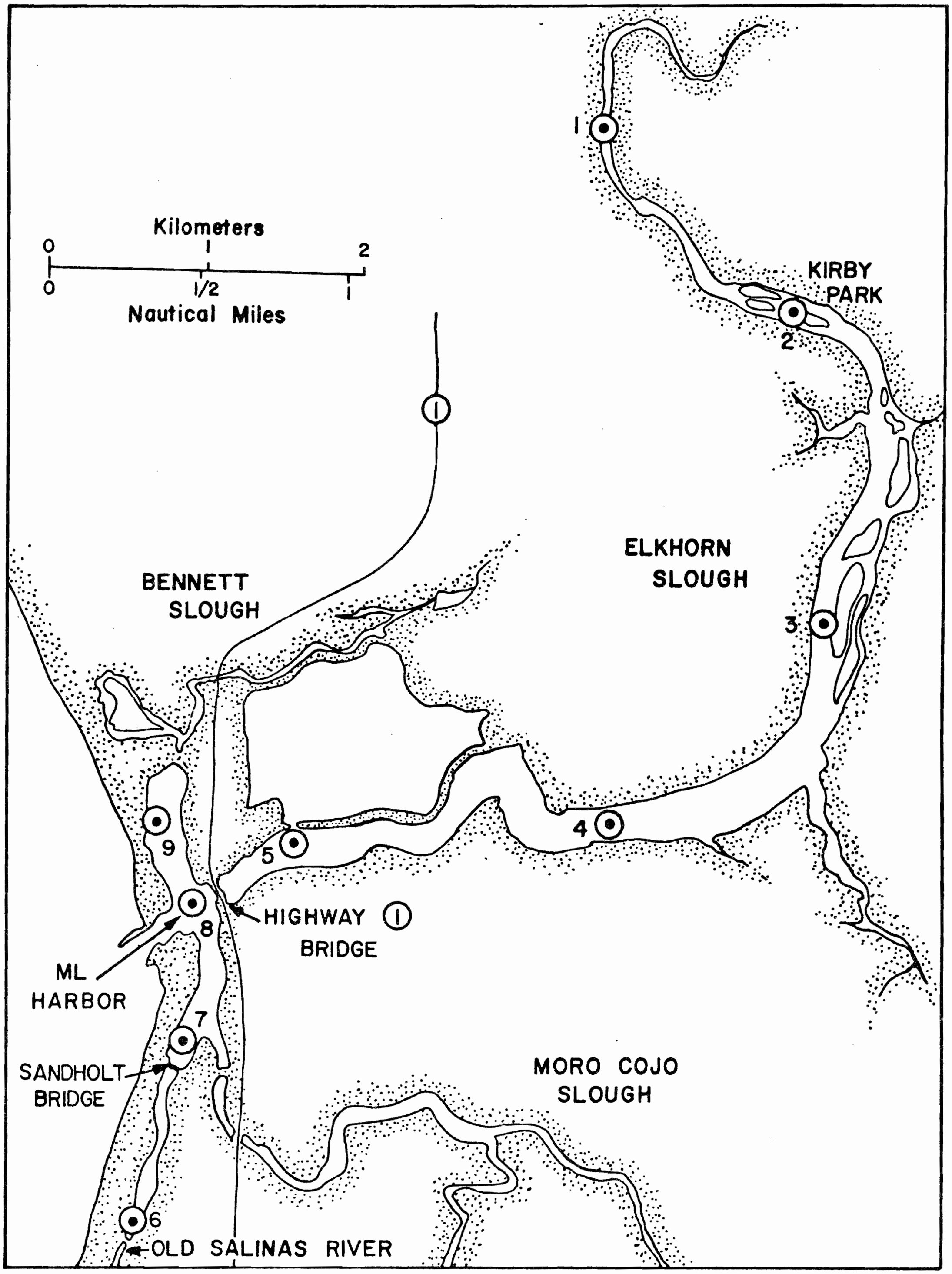

Figure 7. Hydrographic stations in Elkhorn Slough and Moss Landing Harbor.

variations close to the open ocean (Station 8), in the upper slough (Station 2) and in the south harbor area (Station 7). Station positions were determined by visual observation of prominent shore features and samples were taken while anchored in the deepest area of the channel. Considering wind and current conditions, samples were taken within 20 meters of the nominal station positions.

Samples were taken simultaneously from two outboard motor boats, one for Elkhorn Slough stations 1 to 5 and one for the harbor stations 6 to 9. Samples were collected with 5-liter Niskin bottles and hand lines at zero and one meter depth and 0.5 m above the bottom. Mid-depth samples were omitted at stations where the depth was less than two meters. Tidal influence on samples was minimized by sampling at approximately the same tidal stage on each cruise. With few exceptions, samples were collected within one hour of the predicted high tide at Monterey which approximates the time of high water in Moss Landing Harbor (Clark 1972). Samples were collected hourly at one meter depth during the tidal studies.

Analytical Methods

From October 1970 to January 1971, water temperature was determined using a -20 to 110° C laboratory thermometer placed in one end of the Niskin bottle immediately after an oxygen sample was drawn and read to the nearest 0.1° C. After January 1971, temperatures were determined using a bucket thermometer lowered to depth and allowed to soak for one minute, then rapidly pulled to the surface and read. This procedure was repeated until a constant reading was obtained to ± 0.1° C.

Salinity was determined using a Kahlisco precision induction salinometer. Analyses were made in the laboratory and salinity was computed from conductivity ratio using the equations of Cox, et al. (1967). Substandard seawater was used to calibrate the salinometer before and after each set of 27 or fewer samples. Copenhagen water was used each month to standardize the substandard water. The 2 SD precision of the analyses was ± 0.006 ^{o}/oo.

Dissolved oxygen samples were treated in the field to fix the oxygen in the basic form. The samples were acidified and titrated in the laboratory within eight hours of the sampling time using Carpenter's (1965) modification of the Winkler (1888) method. The total sample is titrated with approximately 0.02 N sodium thiosulfate to the starch endpoint. Precision of the analyses is about ± 0.06 ml/l (2 SD).

Nutrient samples were collected and stored in ice chests at 5° C for up to six hours until they could be filtered in the laboratory (0.3 μm pore size) and frozen. Within six weeks of freezing, the samples were quick thawed in groups of 18 or 36 and analyzed for phosphate, nitrate, nitrite, ammonia and silica. Standards and reagent blanks were prepared fresh daily and were determined with each set of samples. Some of the samples had concentrations beyond the normal range of the methods listed below. The absorbance of these samples was determined in one cm cells and their concentrations calculated from extended range curves which are linear to a sufficient degree for concentrations observed in this study.

Dissolved reactive phosphate was determined by the method of Murphy and Riley (1962) described in Strickland and Parsons (1968) using ascorbic acid to reduce the phosphomolybdate complex. The sample absorbance was determined in 10 cm cells on a Beckman DU II Spectrophotometer at 885 nm. Precision of the analyses is about ± 0.03 μg-at/l (2 SD) at the 2 μg-at/l level and ± 0.6 μg-at/l at the 10 μg-at/l level.

Nitrate was determined by the cadmium-reduction method of Wood, *et al.* (1967) followed by the nitrite color development. The sample absorbance was determined in one cm cells using a Spectronic 20 Colorimeter at 543 nm. Precision of the analyses is about ± 0.5 μg-at/l (2 SD) at the 20 μg-at/l level.

Nitrite was determined by the method of Bendschneider and Robinson (1952) described by Strickland and Parsons (1967). The absorbance of the diazo color was determined on the Beckman DU using 10 cm cells at 543 nm. Precision of the method is about ± 0.03 μg-at/l (2 SD) at the 1.5 μg-at/l level and ± 0.1 μg-at/l at the 10 μg-at/l level.

Ammonia was determined by the indophenol method of Solorzano (1969) with the color absorbance determined with the Beckman DU at 640 nm using 10 cm cells. Precision of the method is about

± 0.1 μg-at/l (2 SD) at the 3 μg-at/l level and ± 0.4 μg-at/l at the 20 μg-at/l level.

Reactive silica was determined by the method of Mullin and Riley (1955) as modified by Strickland and Parsons (1968). The silicomolybdate complex was reduced by a metol-sulfite, oxalic acid solution, and the color absorbance was determined in one cm cells on a Spectronic 20 at 810 nm. Precision of the method is about ± 1 μg-at/l (2 SD) at the 40 μg-at/l level.

CHAPTER 3

RESULTS AND DISCUSSION

General Nature of Chemical Distributions

Elkhorn Slough is well mixed and shows little vertical stratification (Figs. 8 and 9), except during periods of peak runoff. Significant vertical stratification was found throughout the year in south Moss Landing Harbor and the Old Salinas River channel. At Station 7 in Moss Landing Harbor, there was often a two fold variation between the sample collected at the surface and that at one meter. This stratification was maintained throughout the dry season by the addition of fresh water from the Castroville sewage treatment plant, local irrigation runoff and overflow from the Salinas River. All other parameters exhibit vertical distributions similar to those of salinity and phosphate.

During all seasons, three water types can be identified in the system. Each type varies independently and is easily distinguishable. The first and least variable water type is offshore water characterized by a small range in salinity (33 to 34 $^{o}/oo$) and temperature (9 to 15° C) (Fig. 11). The offshore waters vary to a relatively small degree throughout the season, with warm temperature and generally low nutrient concentrations in August through October and cooler, nutrient rich waters during the February to July upwelling season (Smethie 1973). The second major water type observed in the system is

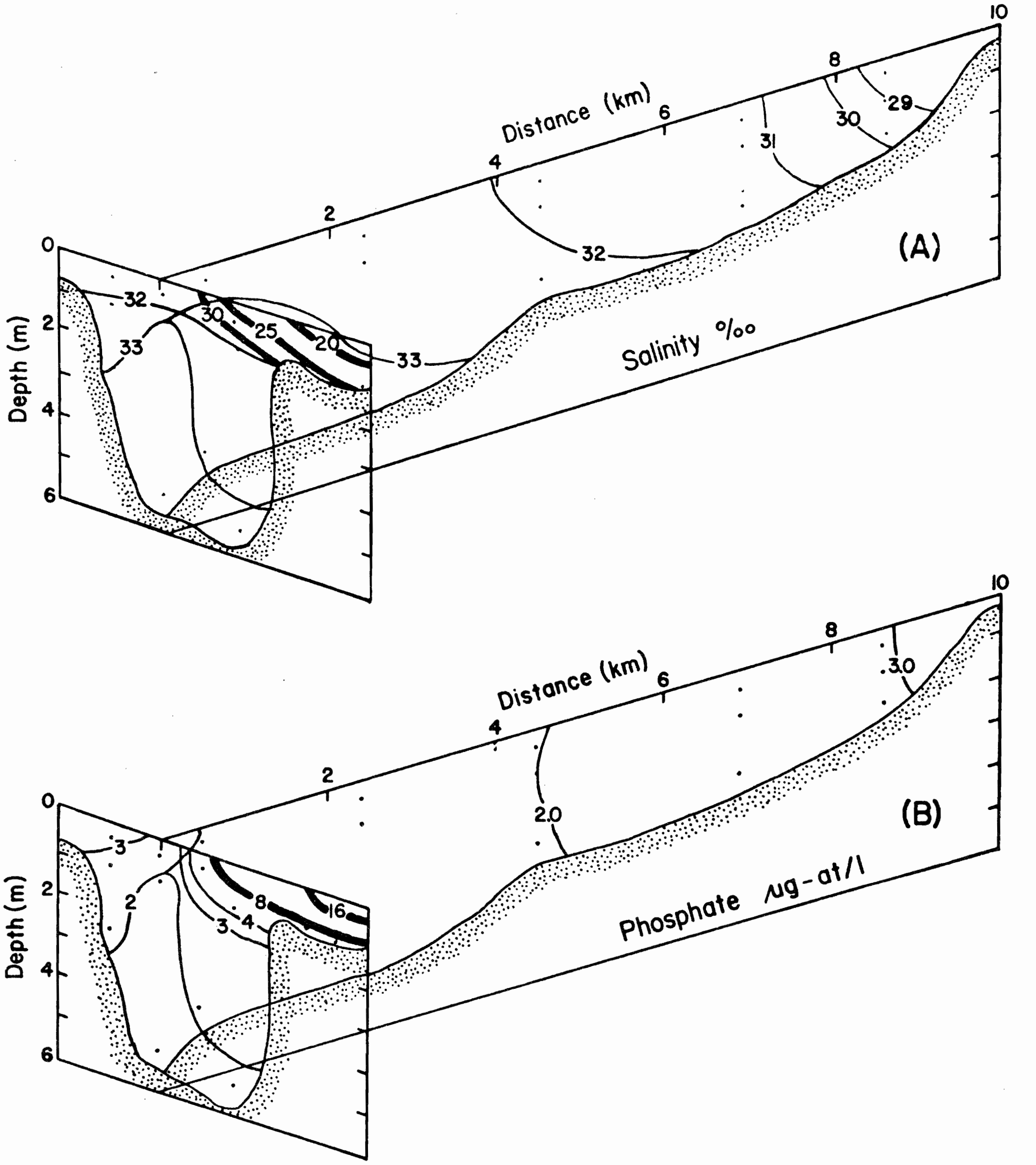

Figure 8. Mean vertical distributions of salinity (A) and phosphate (B) for the winter (January through March).

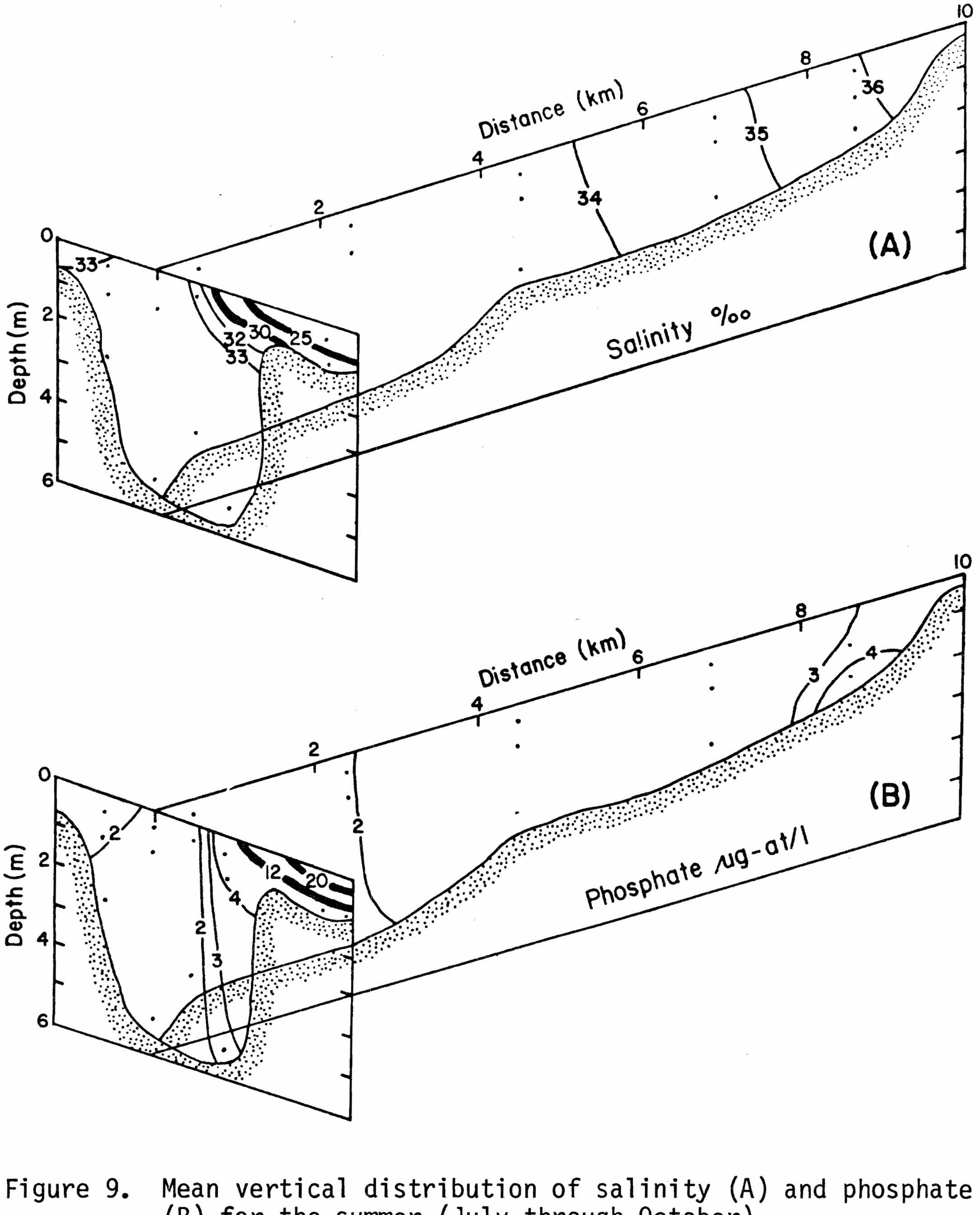

Figure 9. Mean vertical distribution of salinity (A) and phosphate (B) for the summer (July through October).

the low salinity, high nutrient water found in the surface waters of Moss Landing Harbor. This water type, derived from fresh water discharged into the Old Salinas River channel, is less dense than the offshore water and flows into the harbor on the surface above the offshore water. At high tide, this low salinity surface layer seldom extends to Station 8 at the harbor entrance. The inability of this fresh water to extend its influence beyond the south harbor basin, except under unusual conditions, is a result of the Pacific Gas and Electric Company pumping which is sufficient to maintain a net flow of offshore water into the harbor. The third identifiable water type is found in upper Elkhorn Slough. The waters inshore of the tidal wedge at MHHW have a relatively much longer residence time than the waters in the remainder of the slough. Consequently, boundary and nonconservative processes such as evaporation and algal growth play an important role in modifying the upper slough water chemistry. In the summer, the upper slough water is more saline and warmer than open ocean water, in winter it is less saline than open ocean water.

Interpretation of the data collected in this study must take into consideration the sample collection procedure and the time scale of the various cycles involved. In a tidally modulated embayment, such as Elkhorn Slough, where waters of varying chemical identities mix, natural gradients will develop and observations will depend not only on geographical position but on tidal stage as well. In addition to tidal variations, nonconservative solutes such as inorganic nutrient ions will vary in relation to photosynthesis and respiration. While tidal and diurnal cycles are most important in explaining hourly or daily variations, there are longer term variations that involve annual cycles of precipitation, evaporation, incident radiation and primary production. In reviewing the data, it must be remembered that at the high slack water sampling time, offshore influence is at its maximum and longitudinal gradients are compressed.

The waters of Elkhorn Slough are essentially isolated from the influence of the Old Salinas River, except under unusually high discharge periods, and tidally induced turbulence keeps the water of the slough well mixed. The net result is a longitudinal gradient with small vertical stratification. Due to the vertical homogeneity of the slough waters, the following analysis has been based on mean water column values for the various chemical parameters.

Seasonal Cycles

Annual variations in the water chemistry of the harbor area were dominated by fresh water runoff from the Old Salinas River channel. The effects of seasonal differences in algal production or benthic respiration could not be resolved by the sampling procedures utilized. Some significant variations in nutrient ratios were observed in the harbor area and will be discussed in the section on tidal studies. Further discussions of seasonal distributions will be restricted to Elkhorn Slough.

Conservative Parameters

In shallow waters where surface area to volume ratios are high, radiational, evaporative and sensible heat exchanges with the atmosphere become significant and temperature can no longer be described in terms of mixing processes alone. Even though temperature may not be used to indicate mixing in a quantitative sense, it is still useful in interpreting physical processes on a qualitative level. For instance, the cool ($<$10° C) water found at Stations 8 and 5 in February and April indicated the presence of cold, recently upwelled water in the slough (Fig. 10b).

The temperature of Elkhorn Slough waters, except during periods of high runoff, increased in a landward direction reaching a maximum difference of about 6° C between Station 1 and 8 in June. There was a general correlation between air temperature and water temperature at the head of the slough; however, the warmest air temperatures occurred in September while warmest water temperatures were observed in July. In addition to the air temperature lag, it is interesting to note that due to insolation the maximum water temperatures exceed maximum mean air temperatures. Temperatures at the head of the slough were 19° to 20° C in July while the mean air temperature at Watsonville was 16° C.

Another important factor influencing the distribution of temperature in Elkhorn Slough is the addition of heat as coolant discharge from the Pacific Gas and Electric Company (Fig. 3). A comparison of the quantity of heat discharged by Pacific Gas and Electric into the slough with the net heat flux through solar radiation yields some interesting results. The average annual net heat flux for coastal waters near Monterey Bay is about 170 cal/cm^2/day (Wyrtki 1966). The

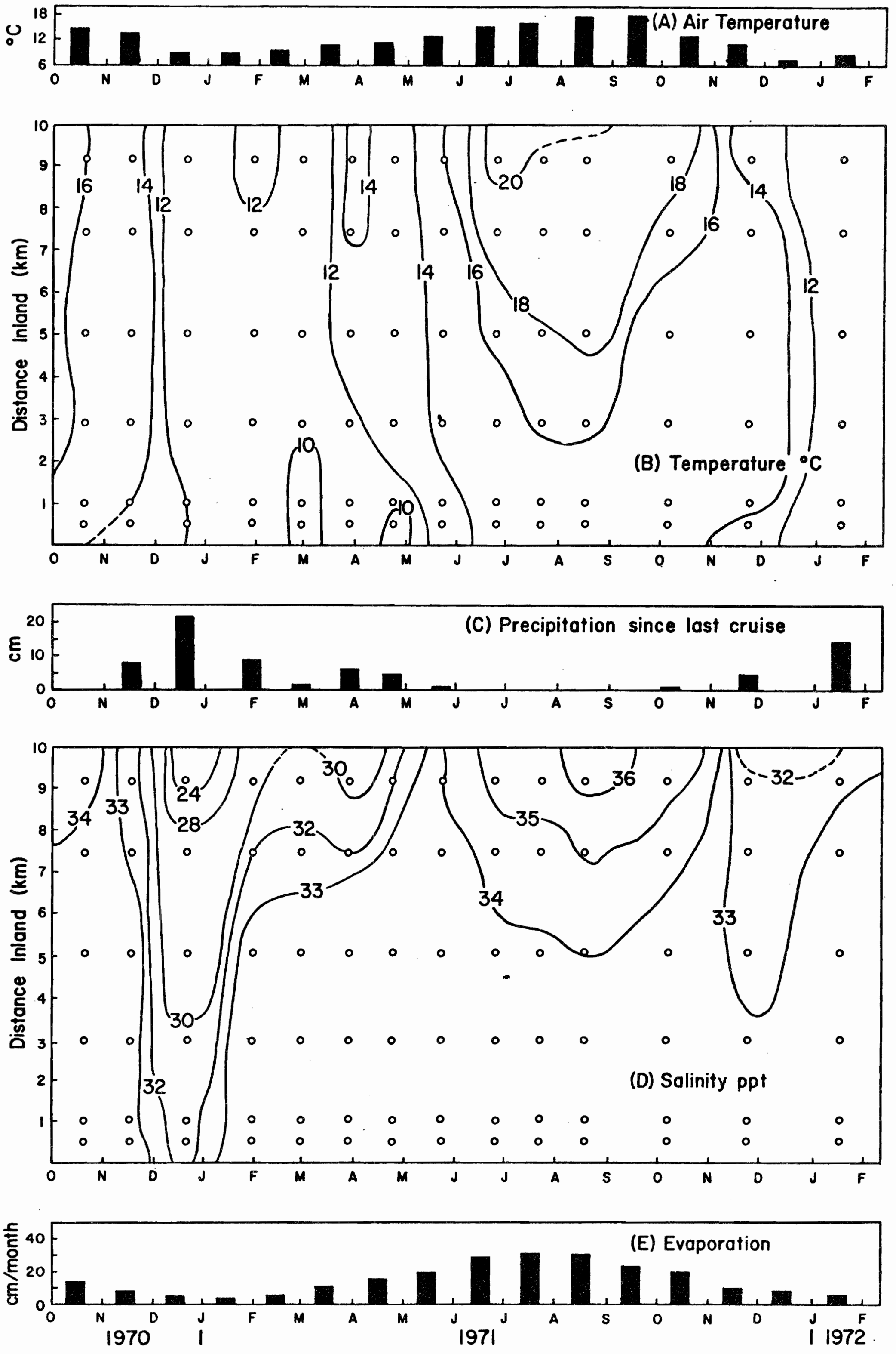

Figure 10. (A) Monthly mean air temperature at Watsonville. (B) Mean water column temperature in Elkhorn Slough. (C) Total precipitation since previous sampling. (D) Mean water column salinity. (E) Estimated evaporation rate.

average water surface area in Elkhorn Slough is approximately that of the channel plus mud flats (2.4 x 10^6 m^2) (Fig. 5a). The direct radiational solar heat flux through this area would be about 4.1 x 10^{12} cal/day, and the maximum input from Pacific Gas and Electric would be about 9.5 x 10^{12} cal/day (1.9 x 10^6 m^3/day at 5° C above ambient) (Table 3). This makes a startling comparison, however, relatively little of the Pacific Gas and Electric cooling water is retained by the slough. Nearly all of the coolant water moves out of the slough on the ebbing tides and very little of it returns to the system on flooding tides.

It is difficult to draw any conclusions about the effect of Pacific Gas and Electric on the temperature structure of the slough from monthly observations of temperature distribution. However, one observation may be pertinent. During the summer, evaporation from waters above the tidal wedge was sufficient to create waters which had slightly greater density than the offshore values (from July to August, Station 1 mean sigma-t = 25.7; for Station 8 during the same period, the mean sigma-t = 25.0). Since both salinity and temperature increased monotonically landward during this period, it would be expected that density should follow the same pattern. This was not the case; instead of exhibiting a distribution indicative of a two point mixing process, a density minimum occurred in the mid-slough region. The observed density minimum can be attributed either to the addition of fresh water (this is not substantiated by the salinity distribution) or to warming, possibly as a result of Pacific Gas and Electric thermal effluent.

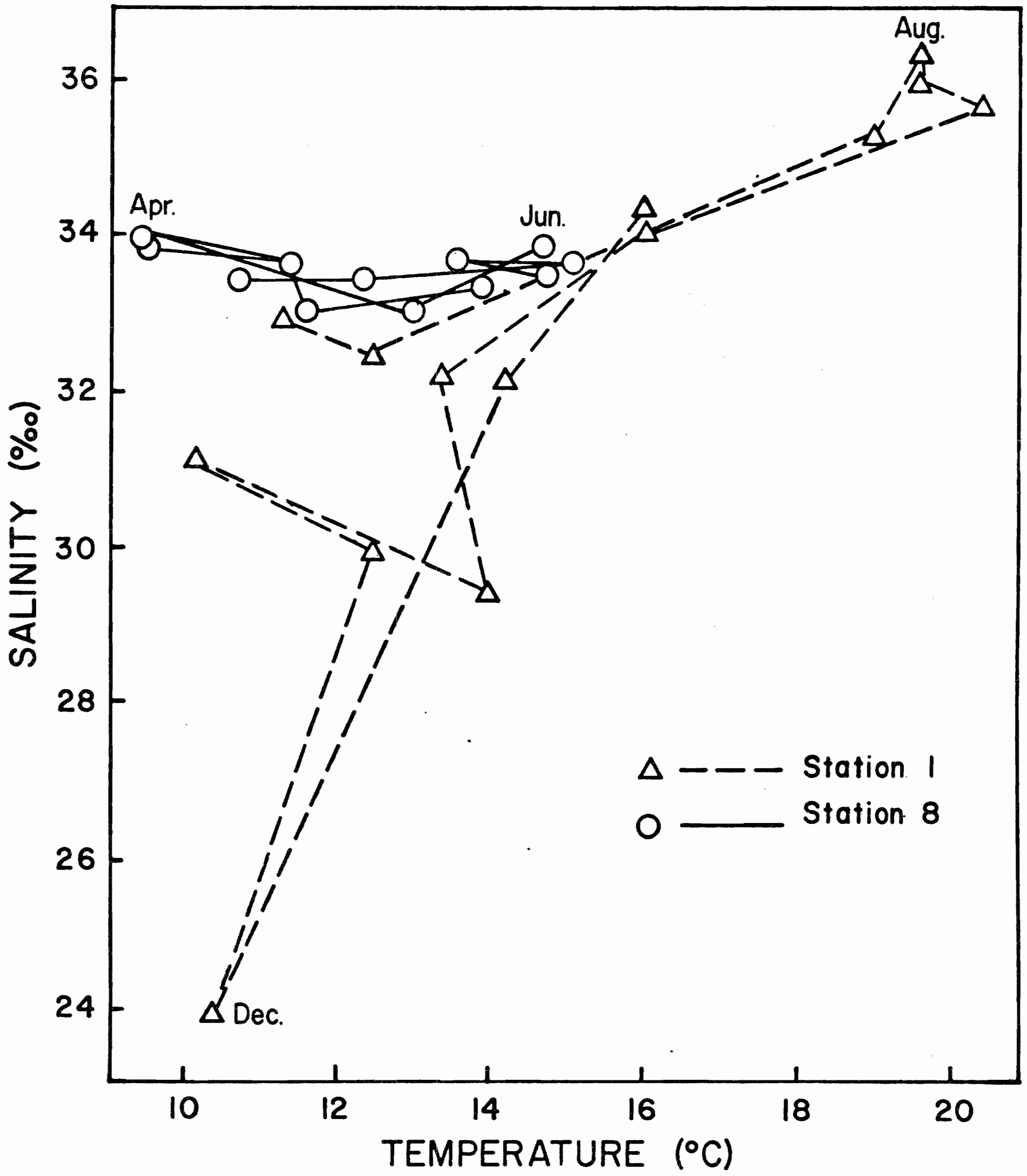

Figure 11. Seasonal temperature - salinity relations for offshore (Station 8) and upper Elkhorn Slough waters (Station 1).

Salinity may be considered to be truly conservative, though there may be a small addition of salts derived from land runoff. The effect of these additions is negligible considering that the observed salinities were greater than 20 $^{o}/oo$. Consequently, the distribution of salinity is determined by the relative rates of evaporation, precipitation, runoff and mixing.

The seasonal range in salinity observed at the head of Elkhorn Slough was 23 to 37 $^{o}/oo$ (Fig. 11). At the slough entrance, offshore conditions dominate giving rise to relatively constant salinities with a 6° C seasonal range in temperature. Apparently only during a single period of heavy rains in December 1971 did estuarine conditions develop in Elkhorn Slough (Fig. 10d). There was a recovery to near oceanic salinities within 30 days after this single washout. As the annual cycle progressed through spring and into summer, evaporation became increasingly important in establishing salinity distributions. Evaporation was sufficient to reverse the salinity gradient and maintain a landward increase in salinity from May through October. During this period, offshore waters served as a dilutant for the hypersaline waters of the upper slough.

The longitudinal salinity distribution throughout the year was dominated by the inland extension of the tidal prism as is indicated by the relatively homogenous salinities observed from Station 3 seaward (Fig. 10d). Considering the variations in tidal height at the time of sampling, the apparent excursion of the tidal prism is in fair agreement with the mean diurnal excursion predicted from the geometry of the slough, assuming the limiting case where incoming waters simply displace their volume without mixing with waters which remained in the slough at low tide. Under these conditions, the tidal prism would extend to a point between Station 3 and 2, depending on the tidal range (Fig. 5a).

Tidal Diffusion Model When the salinity gradient is reversed during the summer months, the slough is essentially a closed system. There is no rainfall and local creeks dry up so that evaporation and tidal dispersion are the competing processes that establish the observed salinity distributions. The relation between these two processes can be expressed mathematically in a salt balance equation. The observed change in salinity must be due to a difference in these two processes or any change in the total salt content above a cross-section of the slough must equal the increase due to advective replacement of evaporated waters less dispersive loss of salt due to eddy diffusion.

If it is assumed that the salinity distribution is one dimensional (that is, cross-channel and vertically homogeneous), then the distribution of variables equation becomes

$$\frac{\partial s}{\partial t} = \frac{\partial}{\partial x} K_x \frac{\partial s}{\partial x} - U \frac{\partial s}{\partial x} ; \qquad (1)$$

where the local salinity time rate of change is $\frac{\partial s}{\partial t}$, K_x is the longitudinal coefficient of eddy diffusivity, U, the time and cross-sectional mean velocity in the direction of x, the distance along the channel (Sverdup, Johnson and Fleming 1942). Integration of (1) between a given location and the head of the slough (x = 1), where

U = 0 and simultaneous integration in the y-z plane from surface to bottom (z = 0 to h) and across channel (y = 0 to d)

$$\int_0^h \int_0^d \int_x^l \frac{\partial s}{\partial t}\, dxdydz = \int_0^h \int_0^d \int_x^l \frac{\partial}{\partial x} K_x \frac{\partial s}{\partial x}\, dxdydz - \int_0^h \int_0^d \int_x^l U \frac{\partial s}{\partial x}\, dxdydz$$

yields

$$\frac{\partial s}{\partial t} V\ (x) = -K_x \frac{\partial s}{\partial x} A_{yz}\ (x) + \overline{U}\, A_{yz}\ s(x), \tag{2}$$

where V (x) is the MHHW volume between x and l and A_{yz} (x) is the cross sectional area at x. If it is furthermore assumed that the mean cross sectional velocity, U, is determined by evaporative water lost between x and l, that is

$$\overline{U}\ (x) = \int_0^d \int_x^l (E-P)\ dxdy/A_{yz}\ (x) = (E-P)\ A_{xy}\ (x)\ /A_{yz}\ (x),$$

then the salt balance equation (2) becomes

$$\frac{\partial s}{\partial t} V\ (x) = -K_x A_{yz}\ (x) \frac{\partial s}{\partial x} + (E-P)\ A_{xy}\ (x)\ s - Q\ (x)\ s, \tag{3}$$

where E-P is the evaporation minus precipitation rate, A_{xy} (x) is the surface area between x and l, and Q (x) is the net stream discharge.

The hydrographic observations made in June, July, August and October 1971 (Broenkow and Smith 1972) were smoothed in time and distance to form a matrix for salt budget analysis. Since it was assumed that vertical and cross channel variations were negligible, water column mean values were plotted against time, and concentrations were interpolated at 1 km intervals. The distance-smoothed values were then plotted against time and interpolated values were again determined at 30 day intervals starting May 31. The final time distance smoothed matrix (Appendix 2) was then used in the finite difference form of the salt flux equation (3) to determine the eddy diffusion coefficients at one km intervals throughout the slough (Fig. 12). These coefficients represent monthly mean values and are valid only under zero runoff conditions. The coefficients calculated for the first time interval, May 31 to June 30, were disregarded because zero runoff conditions had not been met by May 31. The coefficients calculated for the following three time intervals show good agreement (Fig. 12) indicating evaporation and tidal diffusion controlled steady state conditions until the first rainfall in October. In terms of equation (3) an input of fresh water greater than 100 m^3/day at the head of Elkhorn Slough would significantly alter the salinity gradient, advective velocity and corresponding eddy diffusion constants. An important assumption made in this analysis was that the waters seaward of the Pacific Gas and Electric Elkhorn Slough outfall have a residence time of less than one day and therefore an effectively infinite eddy diffusion coefficient.

These eddy coefficients can be used to estimate the residence time, τ , of water parcels in the slough during the summer months

$$\tau = \frac{\Delta s}{K_x A_{yz} \frac{\partial s}{\partial x}} ,$$

where Δs is the total salt in excess of 33.5 ^{o}/oo inland of x where the longitudinal diffusive salt flux is $K_x A_{yz} \frac{\partial s}{\partial x}$. The residence time for waters above the tidal wedge (4.8 km inland) is about 300 days. Thus during the summer, the upper slough waters are essentially

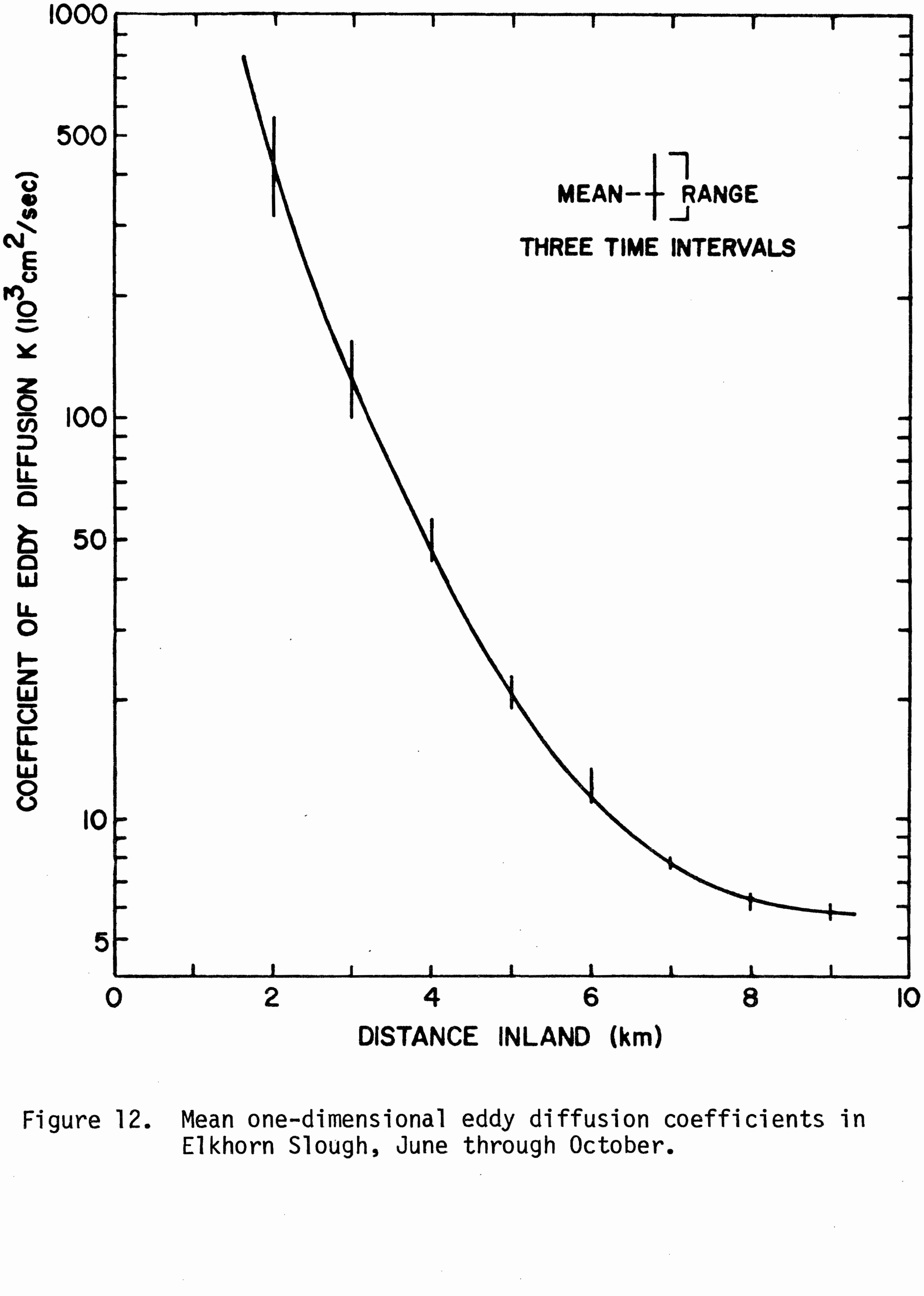

Figure 12. Mean one-dimensional eddy diffusion coefficients in Elkhorn Slough, June through October.

isolated from the open ocean, and a monthly sampling frequency is sufficient to resolve seasonal variability. This is in contrast with the rapid return to near oceanic salinities following the heavy rains of December 1970. From December 1970 to January 1971, the salinities in the upper slough increased by 8 $^{o}/oo$ (Fig. 10d) indicating a residence time on the order of a month.

The only other estimates of dispersion coefficients available for Elkhorn Slough are those given by Water Resources Engineers (1969) which were not determined from observational data. Their assumed coefficients were used with some success in a steady state model predicting coliform bacteria distributions in Elkhorn Slough and Moss Landing Harbor. The Water Resources Engineers (WRE) coefficients ranges from 3.7×10^5 cm^2/sec at the mouth of Elkhorn Slough to 1.4×10^5 cm^2/sec for all segments greater than three km inland. While these values are comparable with the values developed here ($4.3 - .016 \times 10^5$ cm^2/sec) the departures between these estimates are significant. The steady state coliform distribution predicted by the WRE model diverged from the observed distributions near the mouth of the slough, where the values predicted were higher than observed concentrations, and at the head of Elkhorn Slough, where values predicted were lower than observed concentrations. From the observed coliform distributions and the coefficients developed here, it appears the dispersion coefficients estimated by WRE were too low at the mouth of Elkhorn Slough and too high in the upper slough.

Nonconservative Solutes Dissolved nutrient distributions, as with salinity, are related to physical mixing processes with two important differences. First, in the nearshore environment, land drainage is commonly the source of dissolved nutrients. Each source can have widely varying concentrations of nutrients as well as varying ratios of the individual nutrients depending on the history of the incoming waters. In addition to the variable inputs, once in the system, biological processes may alter concentrations and/or ratios of the various nutrients. These changes depend on algal species, solar radiation, nutrient availability, residence time of the water, among other things. Further alteration of nutrient distributions occur in the regeneration of detrital matter related to inorganic equilibria with the sediments and the regeneration rates of the individual nutrients.

The most conspicuous factors affecting annual and spatial distributions of plant nutrients in Elkhorn Slough (Figs. 13 and 14) are increased residence time in upper Elkhorn Slough and seasonal influences related to precipitation. Each of these nonconservative solutes is affected by the same processes (i.e. dissolution, diffusion, photosynthesis and respiration). However, the rates and biochemical pathways for each solute gives rise to widely varying distributions. In the upper slough, the water transparency (Fig. 15b) is low due to salt marsh detritus and a large phytoplankton standing stock which is in part attributable to a lengthy residence time. Benthic respiration associated with this increased organic content causes generally depressed oxygen levels in this area throughout the year (Fig. 13c).

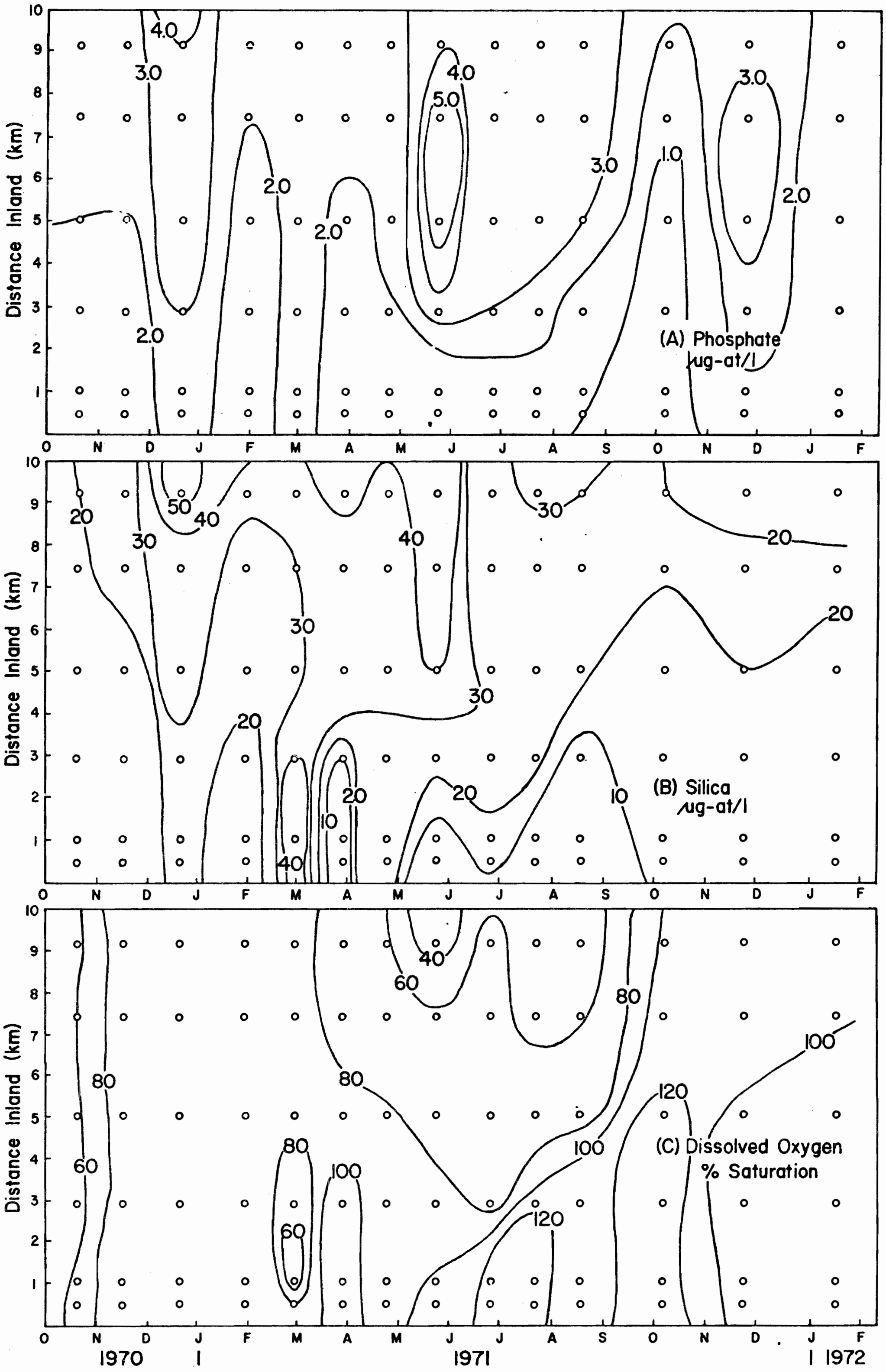

Figure 13. Mean water column distributions in Elkhorn Slough for (A) phosphate, (B) silica, (C) dissolved oxygen.

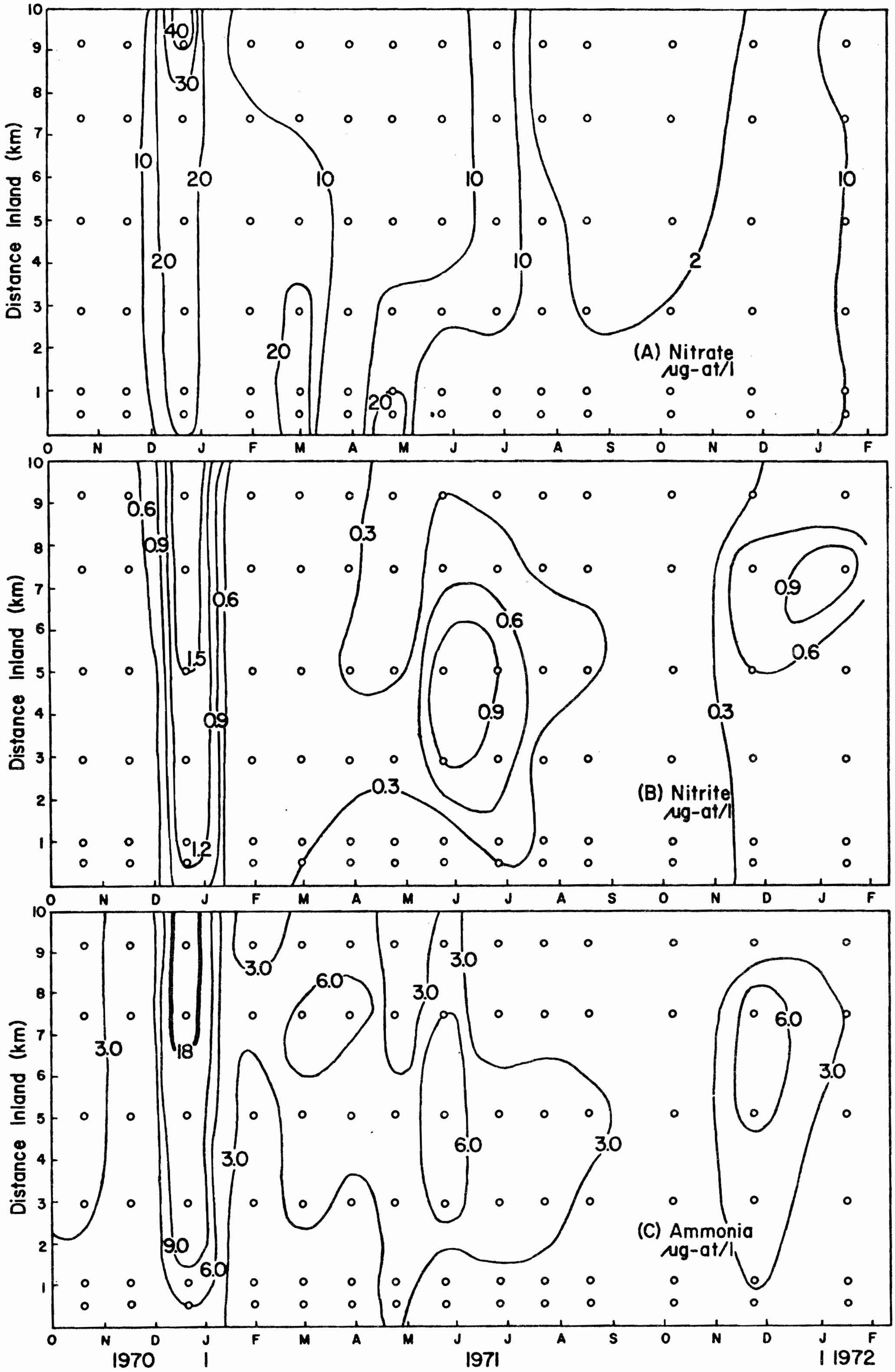

Figure 14. Mean water column distributions in Elkhorn Slough for (A) Nitrate, (B) Nitrite, (C) Ammonia.

The influence of runoff following the heavy rains of December 1970 was apparent in all nutrient distributions (Figs. 13 and 14). During periods of peak runoff, concentrations of all nutrients are higher, residence time and insolation are decreased and, in general, nutrients behave more conservatively than during summer. Throughout the year, in the Old Salinas River channel, the combined effects of short residence time and high concentrations resulted in quasi conservative nutrient distributions.

As runoff decreased and radiation increased, effects of primary production and nutrient regeneration became important in upper Elkhorn Slough. Although the distribution of phosphate and nitrate during runoff periods indicated similar source waters, by June their longitudinal gradients (Figs. 15 and 16) were in opposing directions. Apparently during the summer period, the upper slough acts as a sink for dissolved nitrogen and a source for dissolved phosphate. For example, during July and August the concentration of nitrate, nitrite plus ammonia was about 1 μg at/l while the phosphate concentration was about 3 μg at/l. The explanation for this probably lies in the differing regeneration and assimilation rates for phosphate and nitrate.

Nitrate regeneration involves bacterial oxidation of ammonia. Under anoxic conditions, typical of interstitial waters in the slough mud flats, this process is halted and ammonia derived from decaying organic matter remains in the reduced form. In this anoxic environment, the ammonium ion may be readily sorbed by clay minerals and retained by the sediments. For example, in anoxic lake sediments, it

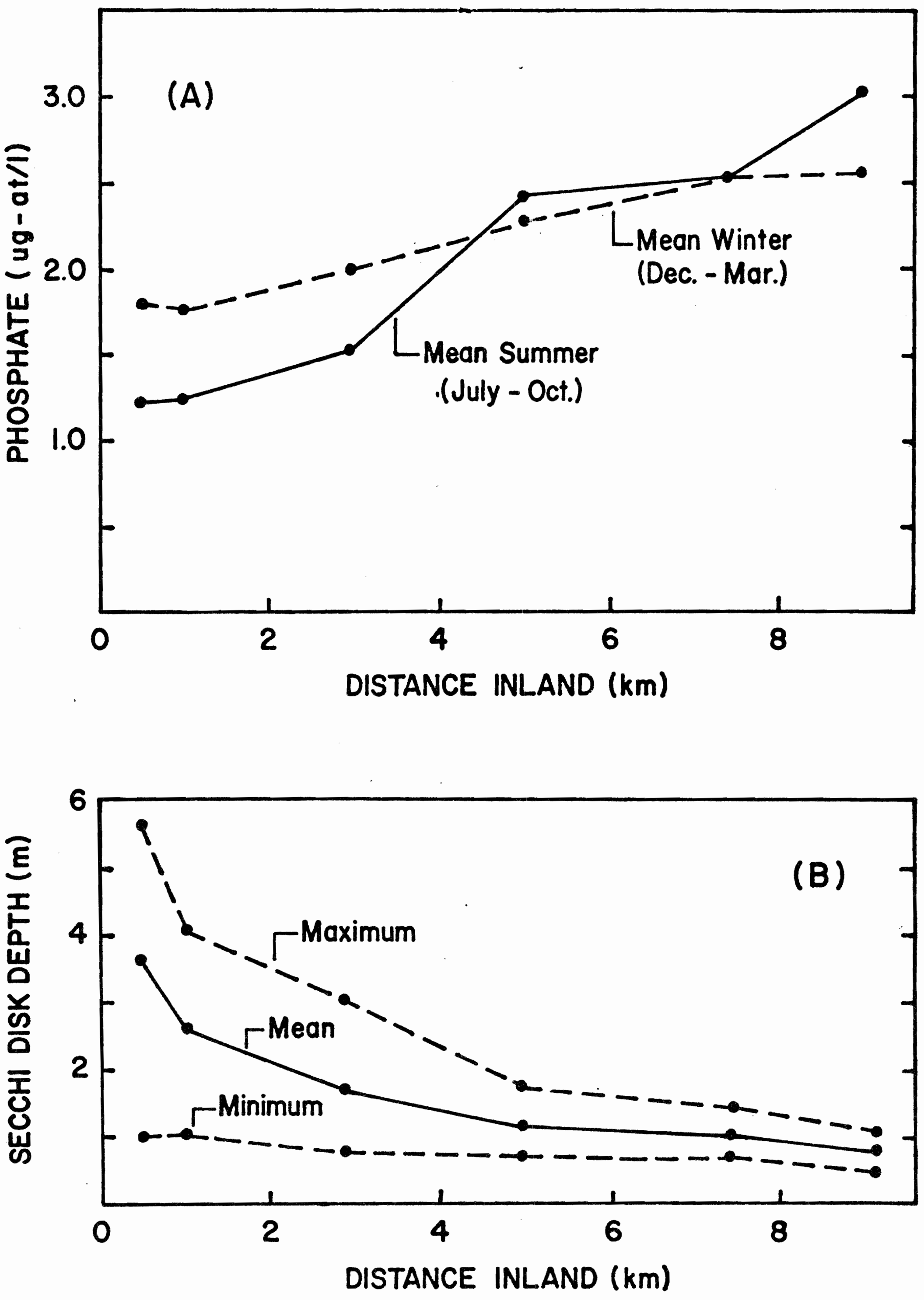

Figure 15. Mean longitudinal distribution of (A) phosphate and (B) secchi depth.

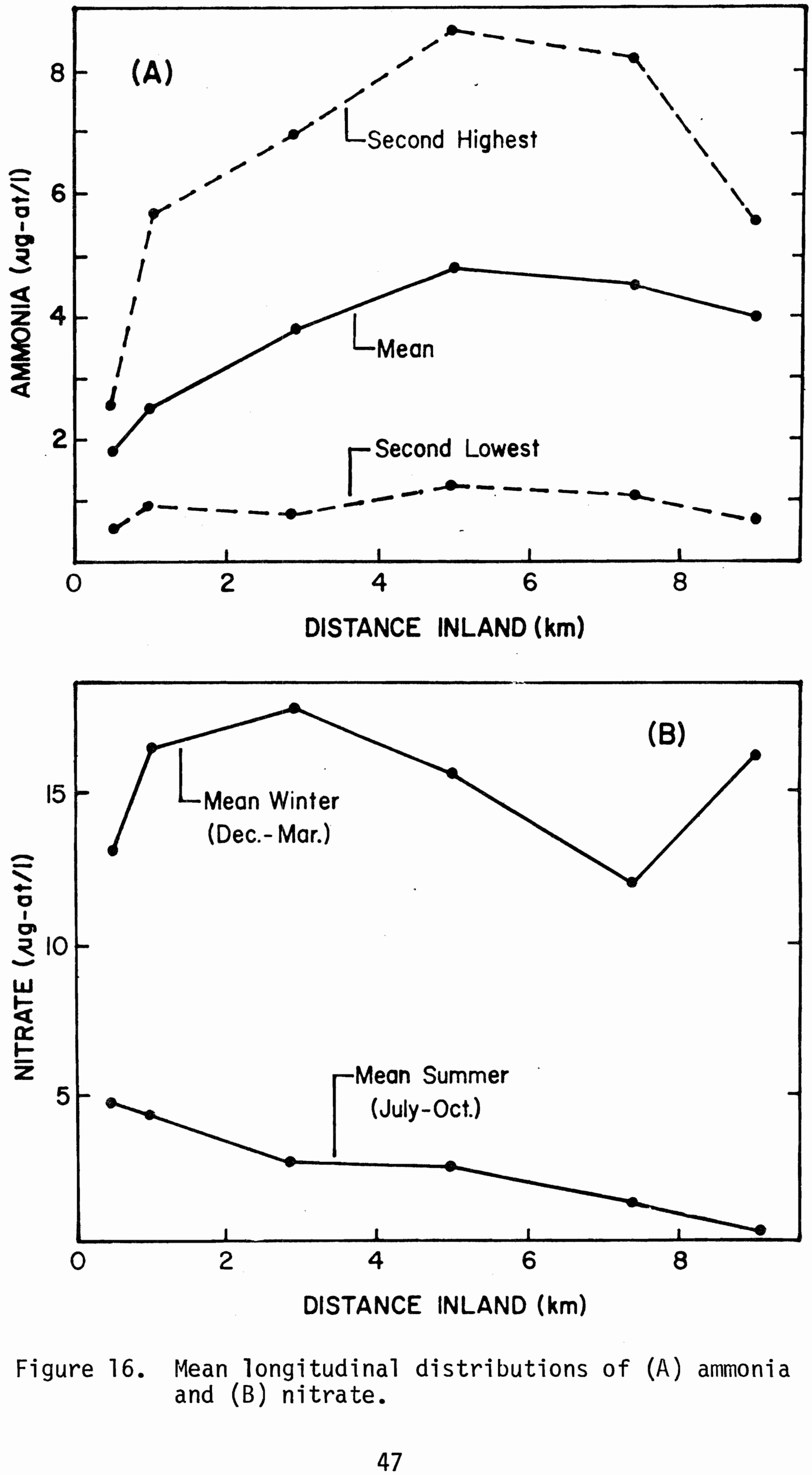

Figure 16. Mean longitudinal distributions of (A) ammonia and (B) nitrate.

has been observed that less than one-third of the available nitrogen is released to the water in 100 days (Austin 1973), while greater than one-third of the available phosphate in anoxic lake sediments are exchangeable within three days (Wan 1973).

Reduced forms of nitrogen, nitrite and ammonia (Figs. 14b and 14c), show consistent maximum concentrations in the mid-slough region (Fig. 16a). The location of these maxima are in agreement with the observations of the Bureau of Sanitary Engineers (1967) who identified the dairies located along the mid-section of the slough as contributors of bacterially polluted waters. Because the primary inorganic decomposition product of amide-nitrogen is ammonia, the observed ammonia maximum was probably caused by the release of septic wastes from the dairy farms.

Salt marsh phosphate equilibrium has been studied by several investigators (Pomeroy 1972, Riemold 1970, Rochford 1951). It has been postulated that the sediments act as a buffer for phosphate, releasing phosphate when the concentration of the overlying waters falls below some threshold, storing organic detrital phosphate and absorbing excess inorganic phosphate when concentration in overlying water is high. Pomeroy (1959) and Riemold (1972) have studied the marsh grass <u>Spartina</u> and found it to be a phosphate pump, removing phosphate from sediments, releasing it to the water at high tide. In Elkhorn Slough, the transfer of phosphate between the water, sediment and biota is an important process in maintaining the phosphate concentration of the slough waters. Although existing data support this hypothesis, the pathways remain to be defined.

Seasonal variations similar to those observed in other localities are found in Elkhorn Slough (Waldichuck 1969). During the period of study, spring and fall minima in phosphate were observed corresponding somewhat to Monterey Bay productivity peaks (David Garrison, personal communication 1972) with maxima occurring during the winter rainy season and a slow buildup during the summer to concentrations greater than that which can be explained by evaporation (Fig. 13a).

Throughout the year, a seaward phosphate gradient was maintained. Based on the mean gradient observed during the summer when runoff is negligible and there are no external sources of phosphate, a diffusive loss of phosphate from the upper slough can be estimated assuming that the same eddy diffusivity calculated from the salinity distribution applies as well to phosphate. The diffusive loss of phosphate from the area above the mean diurnal extent of the tidal prism is proportional to the diffusion coefficient, the longitudinal gradient and the cross sectional area.

The diffusive flux of phosphate, F_p, seaward past Station 3 (5 km from the mouth of the slough) was estimated from

$$F_p = K_x\left(\frac{\Delta PO_4}{\Delta x}\right)A_{xy}$$

and was about

$$F_p = (2.1 \times 10^6\ m^2/day)\ (0.23\ \mu g\text{-}at/m^4)\ (270\ m^2)$$

$$F_p = 1.3 \times 10^8\ \mu g\text{-}at/day$$

$$F_p = 12\ kg\ PO_4^{-3}/day.$$

This is hardly a significant source of phosphate for Monterey Bay when compared with upwelling (2 x 10^4 kg PO_4^{-3}/day; Smethie 1973) or the Castroville sewage treatment plant, 50 to 100 kg PO_4^{-3}/day. Although release of phosphate from Elkhorn Slough appears small relative to these contributors, it does raise some interesting questions about nutrient regeneration rates and pathways in a semi-closed system such as upper Elkhorn Slough. A probable source of phosphate in a system such as this is benthic respiration. To maintain the gradient observed, the rate of phosphate release from the upper slough mud flats and channel would be 0.14 mg-at/m^2/day, a figure comparable with rates given by Pomeroy (1972) of 0.03 to 0.33 mg-at/m^2/day for similar areas in Georgia.

Concomitant with the apparent release of dissolved inorganic phosphate from the sediments to the water and the sorption of ammonia by the sediments, dissolved inorganic nitrogen and phosphorus are assimilated by algae. Nitrogen and phosphorus are incorporated by plants at a relatively constant ratio (Redfield, Ketchum and Richards 1965), therefore the observed low nitrogen and high phosphorus concentration in the dissolved inorganic forms must be a function of their differing regeneration rates. In order for there to be a continual flux of phosphate from the sediments to the overlying water and seaward, there must be a net flux of particulate phosphorus from the water to the sediments. Furthermore, it should be pointed out that while the phosphate gradient was such that a continued seaward diffusive phosphate flux was evident during this entire study period, further study may indicate a seasonal reversal of this gradient.

The effects of runoff and residence time were also apparent in the silica distribution (Fig. 13b). Upper slough concentrations varied between 20 and 40 μg-at/l except during the December washout when silica concentrations doubled. Linear silica salinity correlations, which are consistent with the conservative mixing of silica-rich fresh water with silica-poor seawater, indicated a silica concentration of 200 μg-at/l at zero salinity. This figure is comparable to average river concentrations, i.e. 170 to 330 μg-at/l for Sacramento River (Livingstone 1963). Even though there was negligible fresh water runoff during the summer, the increased water temperature, residence time and high surface area to volume ratio in the upper slough may have maintained the minimum silica level of about 20 μg-at/l, over twice the concentration in surface waters just offshore.

The observed distributions of nonconservative parameters represent a sum of multiple influences. All of the nutrients are affected by essentially the same processes, physical mixing, biological metabolism and inorganic equilibria. However, the kinetic factors for individual processes or reactions are quite variable. Consequently, when conservative factors dominate, strong correlations between all parameters are observed. When chemical equilibria or biological influences dominate, divergences result.

Tidal and Diurnal Cycles

As mentioned earlier, there are three major water sources for the slough-harbor system and two major climatic seasons. While large seasonal variations have been identified, tidal variations are much more important in determining a single sample value or the instantaneous spatial distributions. In addition to tidal influences, in areas where physical mixing rates are small and biological activity is high, diurnal influences are significant. To evaluate these short term cycles in the major source waters, during the wet and dry seasons, hourly samples were collected at Sandholt Bridge, Highway 1 Bridge and Kirby Park in March and August (see Chapter 2). The results of those two studies are graphically presented in Figs. 17 through 22 (tabular values in Appendix 3).

In reviewing these data, one should note that the position of the Sandholt Bridge station was slightly different during the two sampling periods. The March samples were collected from a floating dock inside the harbor about 30 m to the side of the channel. The August samples were taken from a small boat moored to Sandholt Bridge in mid-channel. Even though fresh water discharge was greater in March than in August, lower salinities were observed in August (Figs. 17 and 18). This

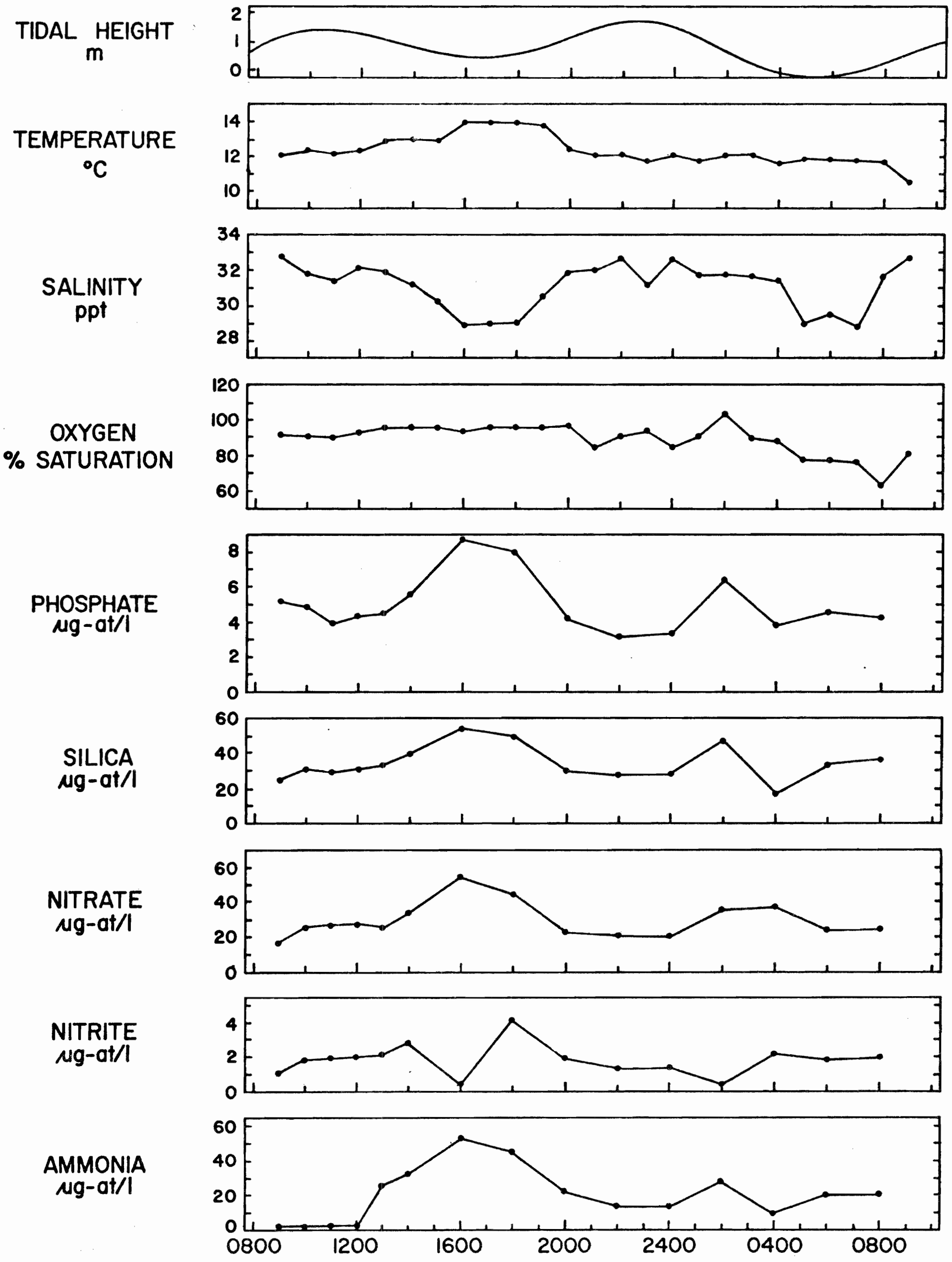

Figure 17. Water chemistry observations at Sandholt Bridge, 27-28 March 1971; sample depth 1 m.

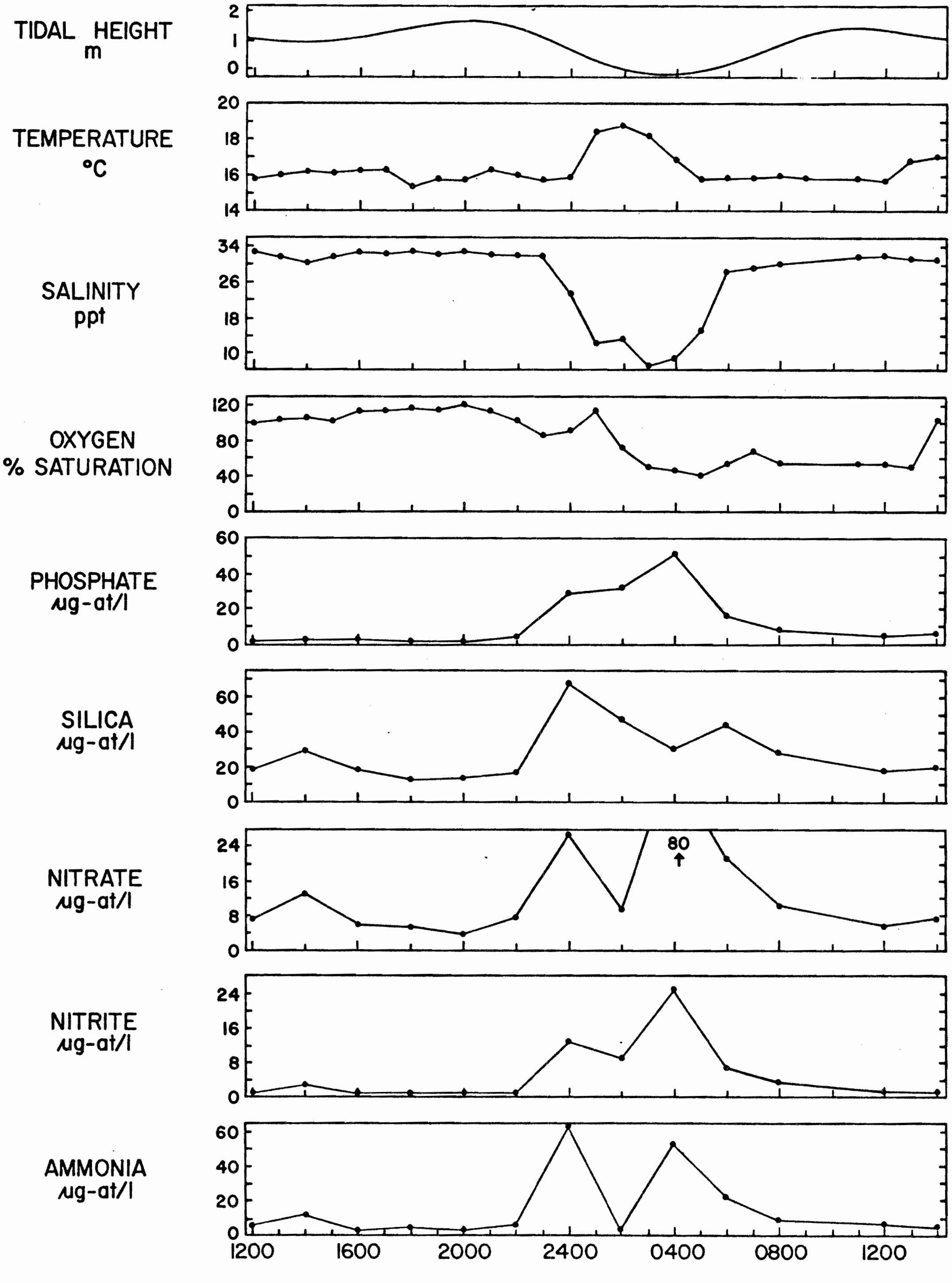

Figure 18. Water chemistry observation at Sandholt Bridge, 16-17 August 1971; sample depth 1 m.

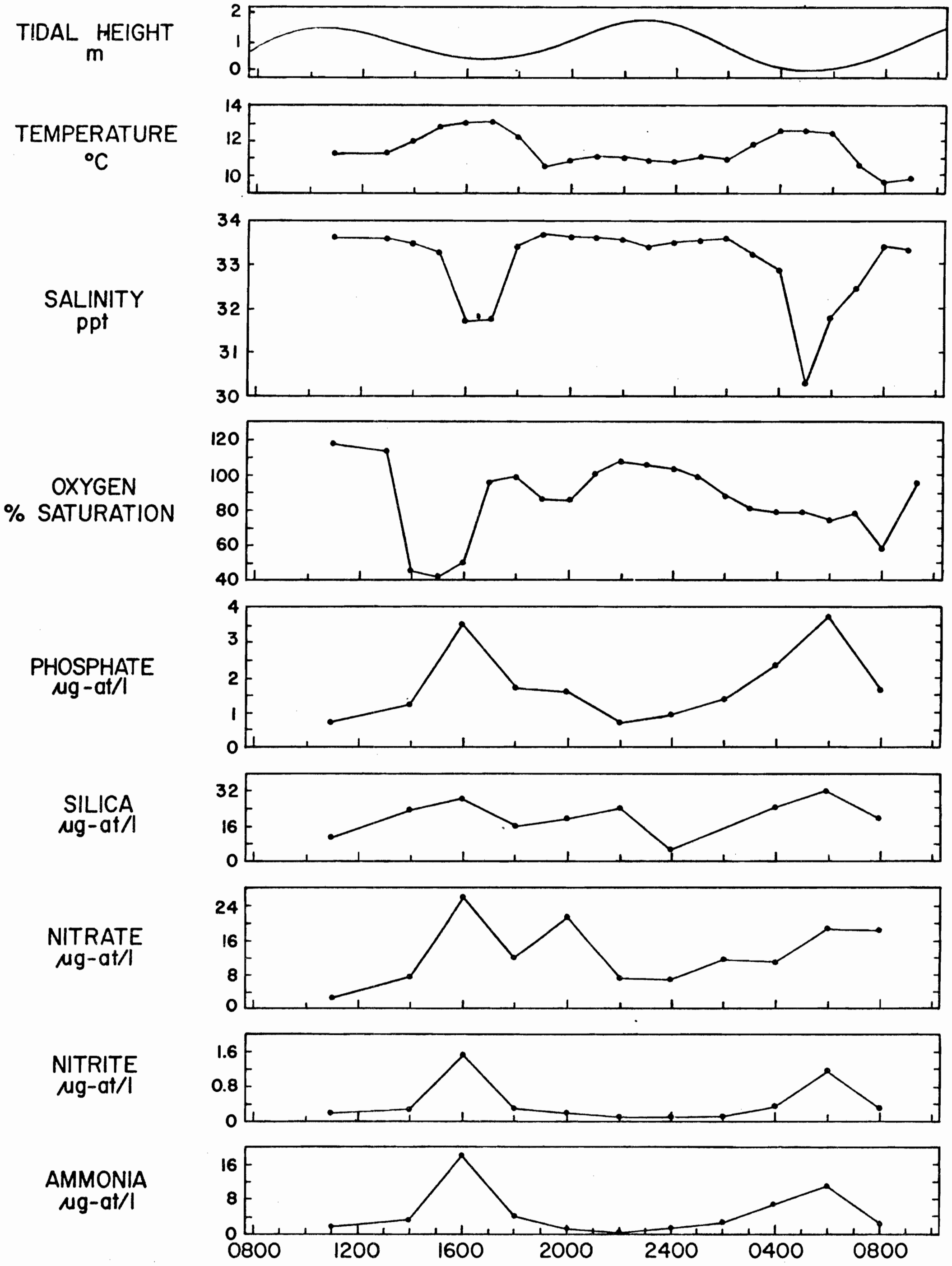

Figure 19. Water chemistry observations at Highway 1 Bridge, 27-28 March 1971; sample depth 1 m.

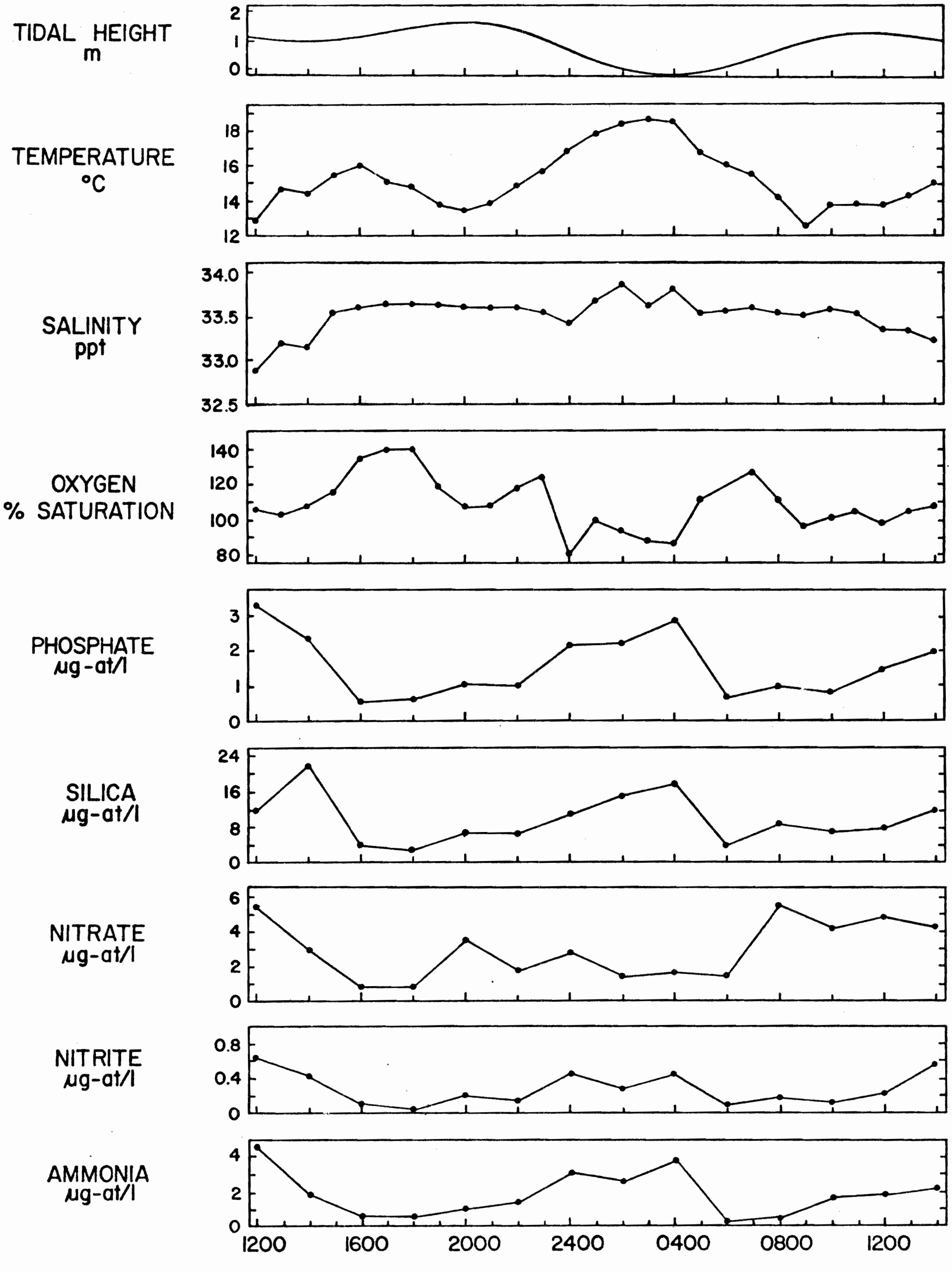

Figure 20. Water chemistry observations at Highway 1 Bridge, 16-17 August 1971. Sample depth 1 m.

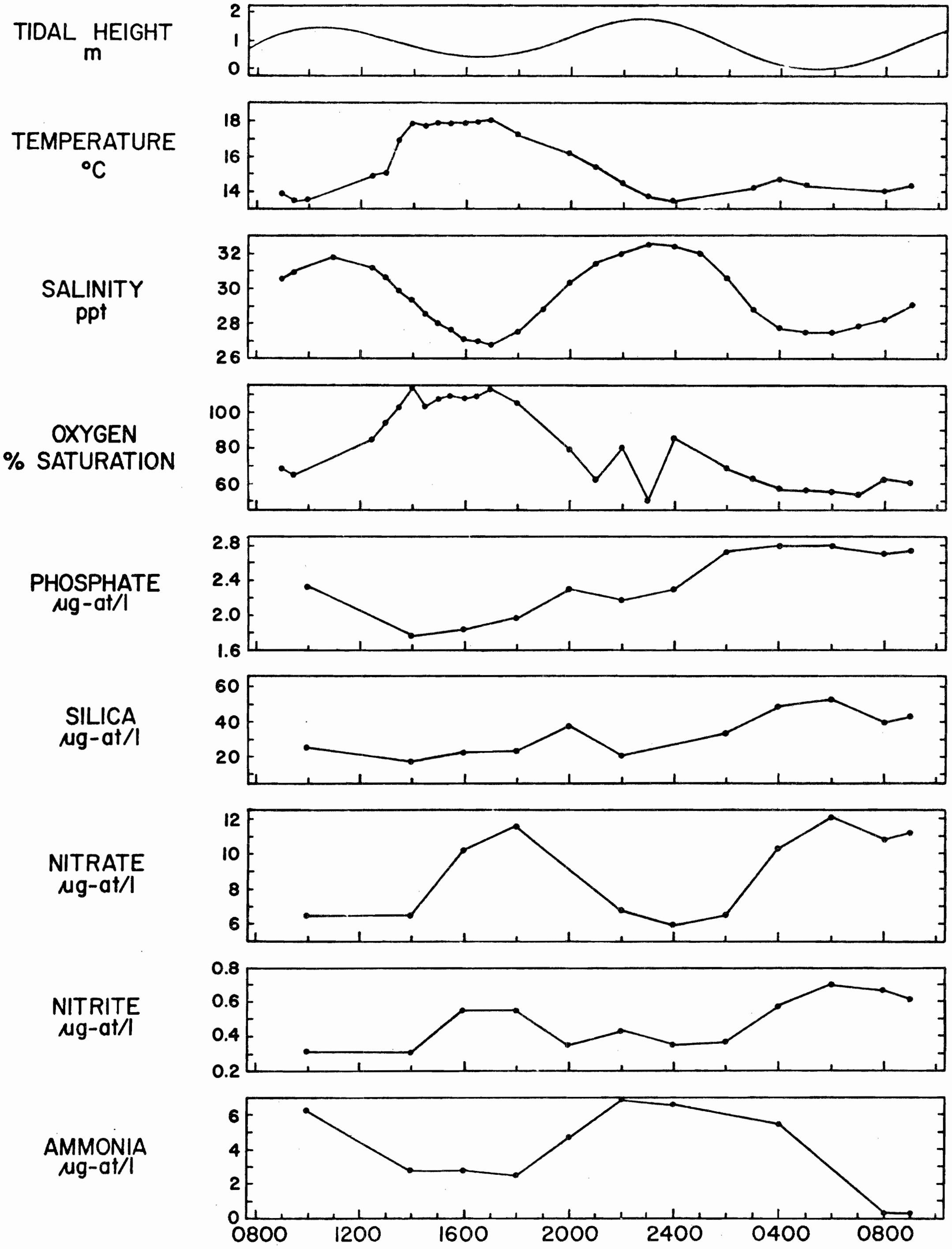

Figure 21. Water chemistry observations at Kirby Park, 27-28 March 1971; sample depth 1 m.

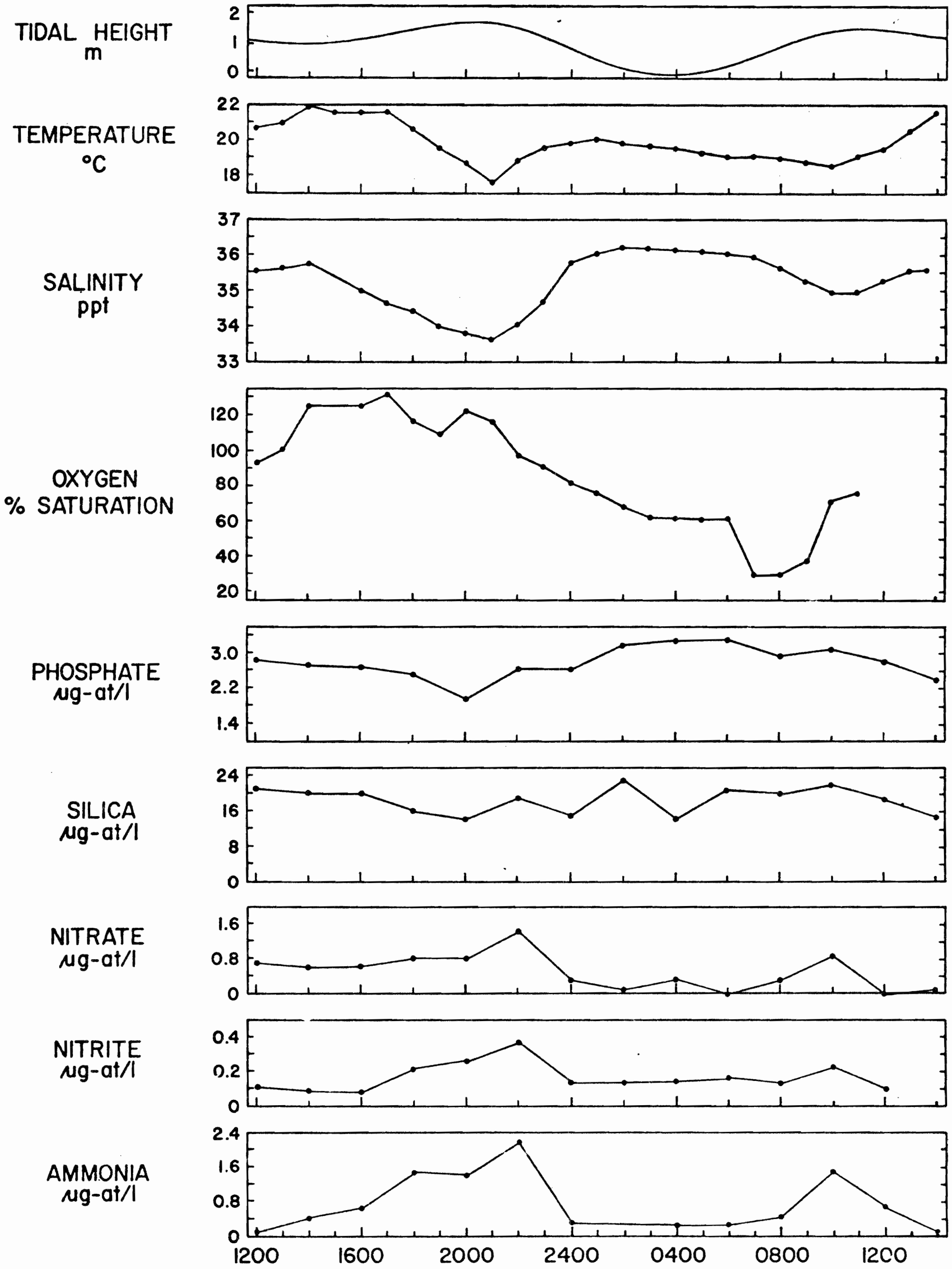

Figure 22. Water chemistry observations at Kirby Park, 16-17 August 1971; sample depth 1 m.

apparent inconsistency is due to the difference in collection sites or greater density stratification during the August sampling or both.

The movement of water in an embayment exposed to the tidal fluctuations of the open coast can result in large variations in chemical properties observed at a given point which are proportional to the spatial gradients and the tidal height. In Elkhorn Slough and Moss Landing Harbor, salinity serves as an excellent indicator of tidal displacement and emphasizes the importance of longitudinal gradients. Near the harbor entrance, at the Highway 1 Bridge, currents are strongest and greater volumes of water pass by this station than any other. The salinity at this station during a 24 hour period was relatively constant and exhibited variations only at low tide (Figs. 19 and 20). In contrast to observations at the bridge, however, salinities at Kirby Park during the same periods nearly paralleled the predicted tidal curves for Monterey Bay. These differences are essentially due to longitudinal gradient. The upper slough waters are vertically well mixed and reflect a continuous longitudinal mixing of offshore waters with fresh water during the winter and with evaporatively concentrated seawater during the summer.

Very large horizontal gradients exist in south Moss Landing Harbor due to the influx of nutrient-rich fresh water from Tembladero Slough and the Old Salinas River channel. Consequently, large temporal variations were observed with largest variations occurring at low tide when the gradients moved seaward and smallest variations occurring at high tide when relatively homogeneous Monterey Bay waters moved inland (Figs. 17 and 18).

It is interesting to note that the outflow of lower salinity water at low tide observed at the Highway 1 Bridge in March (Fig. 19) can be identified as Old Salinas River channel water rather than upper Elkhorn Slough water. The distinction is made on the basis of temperature. Although similar salinities (31 to 32 $^{0}/oo$) were observed in both areas, the temperature of the upper slough water of this salinity was about 15° C, 2° C warmer than the water of the same salinity observed at the Sandholt and Highway 1 Bridges. During the August survey, the discharge from the Old Salinas River was small, and at lower low tide relatively warm upper Elkhorn Slough water of high salinity (19° C, 33.8 $^{0}/oo$) was observed at the Highway 1 Bridge (Fig. 20). At higher high tide, water with this temperature and salinity was found at Station 3, five km inland. This agrees well with the model developed earlier which predicted that the mean diurnal tidal wedge would extend inland 4.8 km (Fig. 5c).

Temperature observations, as with salinity, are tidally influenced. Near the head of the slough, above the penetration of the tidal prism, the residence time is long and the surface area to volume ratio is sufficiently large to effect diurnal heating and cooling. In both March and August (Figs. 21 and 22), late afternoon temperatures were observed to be about 3° C greater than those in the early morning. A comparison between the apparent heat loss due to back radiation is within an order of magnitude of the mean solar input for the appropriate latitude and time of year. For a daily mean incoming radiation of 350 cal/cm^2 day (Wyrtki 1965) to the area inland of offshore tidal influence (the upper 5.7 km) the mean solar input is about 3 x 10^{12} cal/day. The observed 3° C temperature change between morning and afternoon at Kirby Park (Figs. 21 and 22) requires a heat exchange of 6 x 10^{12} cal/day for the mean higher high tide volume in the upper slough.

Samples collected at Sandholt Bridge reveal an inverse correlation between nutrients and salinity during both seasons. Even though the biologically reactive compounds appear to behave conservatively, there is some evidence of seasonality in absolue and relative composition concentrations of nutrients in the incoming waters (Table 4). The salinity-phosphate regression in March yields a phosphate concentration of 46 μg-at/l at zero salinity while in August it was 64 μg-at/l. The increased concentration of phosphate in the incoming fresh water in the summer was probably due to a decrease in natural runoff relative to domestic sewage effluent from Castroville and Salinas.

Seasonal changes in the dissolved reactive nitrogen (nitrate + nitrite + ammonia) are also evident although they do not follow the same pattern as phosphate. The apparent concentration of reactive nitrogen in the incoming waters range from 750 μg-at/l in March to 340 μg-at/l in August (Table 4). Another way of viewing the data is in terms of the N:P ratio. Natural runoff is highly variable in its N:P ratio, but usually this ratio is 5:1 to 30:1 by atoms (for example, Park, Osterberg and Forester, 1972). In contrast to natural runoff, however, municipal sewage may exhibit a N:P ratio as low as 1:1 (Natural Resources Council 1970) due to the addition of inorganic phosphate as detergents. For the Old Salinas River channel, the N:P ratio varied from 16:1 during the winter, when natural runoff was maximum, to 5:1 during the summer when sewage effuent from the Castroville treatment plant contributed a significant fraction of the total fresh water discharge.

At the Highway 1 Bridge, the nutrient, as well as oxygen distributions, primarily reflect the mixing or movement of various water types. Consistent maxima in nutrient concentrations or minima in oxygen saturation occur at low tide during both sampling periods. These low tide extrema are indicative of the high nutrient concentrations of the upper slough. A comparison of ammonia changes observed at the Highway 1 Bridge with those at Kirby Park (Figs. 19 to 22) provides the only clear evidence of a mid-slough source of reduced nitrogen, as was suggested by the mean longitudinal distribution (Fig. 16a). Maximum ammonia and nitrite concentrations at low tide were observed at the Highway 1 Bridge and at high tide, maximum ammonia and nitrite concentrations were observed at Kirby Park.

<u>Primary Production and Respiration in Upper Elkhorn Slough</u> As suggested from temperature observations at Kirby Park, the only area in which significant diurnal variations were observed was in upper Elkhorn Slough. Variations in community metabolism from day to night clearly dominated the dissolved oxygen levels during the March and August tidal

TABLE 4

LINEAR REGRESSION ANALYSIS OF TOTAL REACTIVE NITROGEN, N_t = (NITRATE + NITRITE + AMMONIA) AND PHOSPHATE WITH SALINITY FOR SAMPLES COLLECTED IN MOSS LANDING HARBOR IN MARCH AND AUGUST, 1971

	Slope b µg-at/l $^o/oo$	Intercept at 0 $^o/oo$ salinity a µg-at/l	Correlation coefficient r
March			
N_t	-22	750	-.89
PO_4^{-3}	- 1.3	46	-.88
August			
N_t	-10	340	-.99
PO_4^{-3}	- 1.8	64	-.97

studies. Estimation of production and respiration rates can be made from these diurnal oxygen curves. Odum (1956) and others have pointed out that in shallow waters, benthic algae may be the major contributor to the primary production of an area and benthic respiration will usually far exceed the water column respiration. Therefore, diurnal oxygen variations for a homogeneous water mass are a more accurate indicator of the community activity than are traditional productivity experiments involving incubation of discrete water samples.

Even though diurnal oxygen variations provide data on community metabolism quantifying the data in terms of net production or respiration requires detailed knowledge of atmospheric exchange and water mass homogenity. Several observers (Odum 1956, Ryther 1958, Emery 1969) have used diurnal oxygen curves to estimate primary production. In all cases, the exchange of oxygen with the atmosphere was either assumed to be negligible or impirical diffusion rates were determined for the conditions during the period of observation. At Kirby Park, tidal currents are as large as 60 cm/sec and the surface area of the volume of water above the tidal prism varies from 1.4 to 4.5 x 10^6 m^2 between low and high tide, making compensation for atmospheric diffusion difficult. These problems have been reduced by determining the rates of respiration and net production from the slope of the diurnal oxygen curve when concentrations were near 100 percent saturation, thereby minimizing the effects of atmospheric exchange. Ideally, the respiration rate was determined from the slope of the curve just after sunset and the net production rate was determined shortly after sunrise. The results, assuming an average depth of one m through the tidal cycle, are given in Table 5. Net daily production rates cannot be determined accurately because of the cumulative errors involved in calculating small differences between large numbers, but the values computed here agree well with similar estimates in other areas (Table 5).

A comparison of dissolved oxygen and phosphate concentrations during the March and August tidal studies at Kirby Park (Figs. 21 and 22) shows a close correlation suggesting their temporal variations are determined largely by photosynthesis and respiration. A least squares regression of phosphate vs. apparent oxygen utilization (AOU) yielded a $\Delta PO_4^{-3}:\Delta AOU$ ratio of change close to the theoretical value observed for phytoplankton of 1:276 by atoms (Redfield, et al. 1965). In March, the $\Delta PO_4^{-3}:\Delta AOU$ ratio of change was 1:280 (Fig. 23a) and in August it was 1:290. Throughout the year, oxygen values in the upper slough appeared to be consistently undersaturated (Fig. 13c). The seasonal oxygen distribution is somewhat biased because samples were generally taken around noon whereas oxygen values reach their daily maximum about four hours later (Figs. 21 and 22). The previous observation that there is a net phosphate flux from the upper slough during the summer is consistent with a net oxygen consumption. As stated earlier, if benthic respiration occurring in the tidal flats and channel above the tidal prism is considered to be the major source of phosphate, then the rate of release would be 140 µg-at PO_4-P/m^2 day or in terms of oxygen consumption, 39 mg -at O_2-O/m^2 day. Although the diurnal oxygen curve observed at Kirby Park in August does not confirm this figure, it does

TABLE 5

NET PRODUCTION AND RESPIRATION RATES BASED ON DIURNAL DISSOLVED OXYGEN CURVES

	Net Production	Respiration
	μg-at O_2 -O/m^2/hr	
Elkhorn Slough		
March	45	27
August	55	47
Senix Creek, N. Y. (Ryther *et al*. 1958)	67	45
Oyster Pond, Mass. (Emery 1968)	58	42
Texas Lagoons (Odum 1958)	6 to 120	9 to 92

not prohibit it. If extremes in net production rates are considered for a 12-hour day, the range in net daily production is from -84 to 250 mg-at O_2-O/m^2 day.

The silica variations observed at Kirby Park during the March study correlated with the variations in phosphate (Fig. 23b). During August, the correlation was not sustained. Apparently during the summer months, warm temperatures, extended residence time and the large surface area to volume ratio combined to maintain a minimum silica level of 15 to 20 µg-at/l. It may be a fortuitous observation, but the ratio of change $\Delta PO_4/\Delta SiO_2$ in March is about 1:20 by atoms, well within the range observed for diatoms (Redfield, _et_ _al_. 1965). From field observations, there is a noticeable shift in the algal community from diatoms in the spring to filamentous mats of green algae during the summer.

Although there were significant diurnal variations in oxygen and phosphate, the nitrogen compounds did not reflect this pattern. Instead, they followed the tidal curve rather closely. During the August study (Fig. 22), this could be attributed to tidal advection and the longitudinal gradient. Nitrogen appeared to be limiting at that time in the upper slough, therefore, nitrogen maxima would be expected at high tide. During March, though, this explanation will not suffice because nitrate and nitrite concentrations were highest in the upper slough and were probably not growth limiting. As has been pointed out by Riley (1967) in his discussion of nutrient distributions in coastal

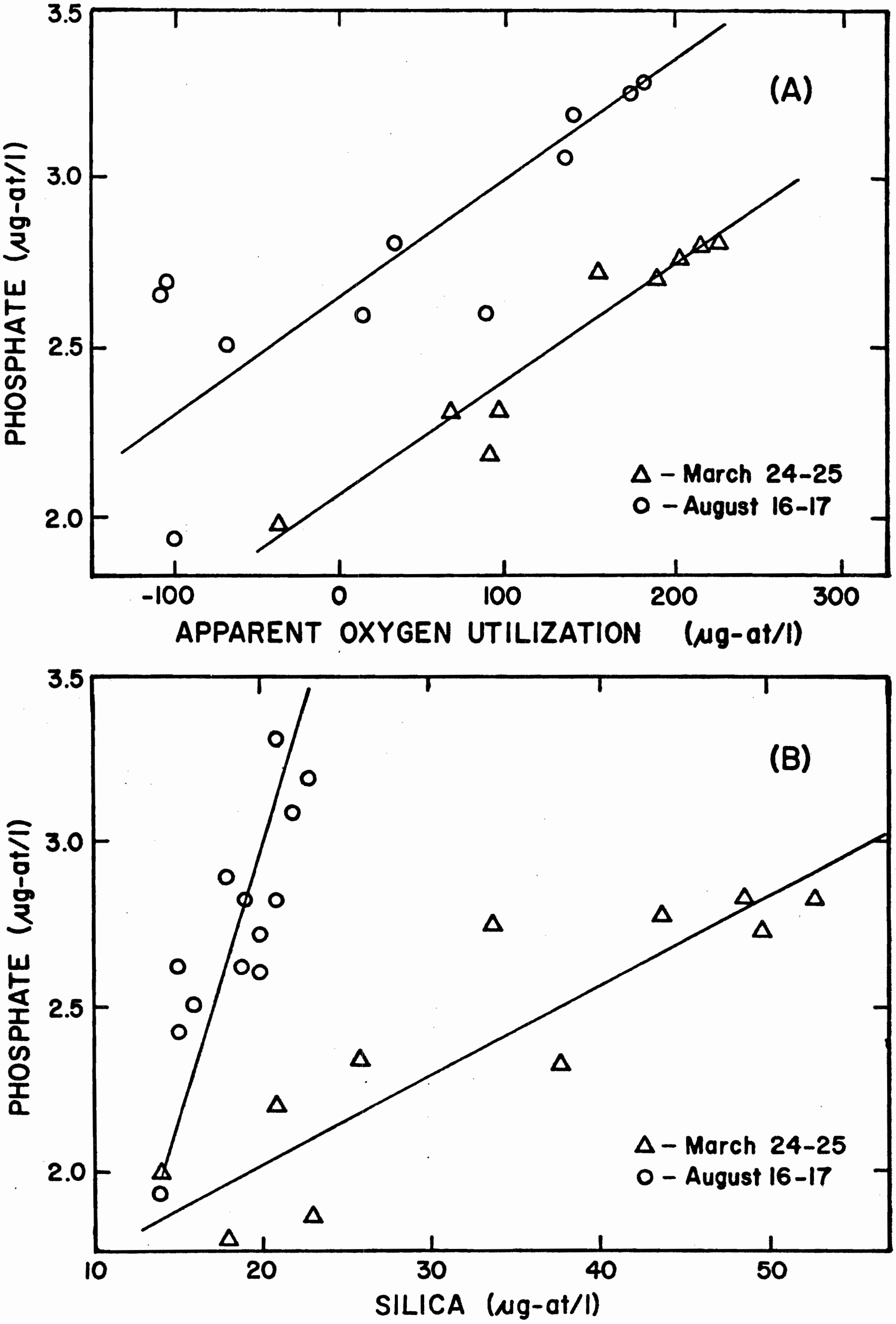

Figure 23. Correlation of (A) apparent oxygen utilization and (B) silica with phosphate during the March and August tidal sampling at Kirby Park.

waters, the differences in the regeneration rates of these nutrients is sufficient to cause apparently inconsistent distributions when waters of varying chemical histories are mixed.

CHAPTER 4

SUMMARY AND CONCLUSIONS

Elkhorn Slough and Moss Landing Harbor are essentially two separate systems. The Old Salinas River channel and Tembladero Slough supply to the harbor fresh water having a high nutrient content throughout the year. This water is of low density and flows into the harbor forming a surface layer. Often at low tide a plume of the low density waters can be seen extending out the harbor entrance into Monterey Bay where it is mixed and carried southward. In the harbor itself, industrial pumping plays an important role in flushing the harbor and maintaining a net flow of Monterey Bay waters into the harbor. Pacific Gas and Electric alone removes 10 times the low water volume of the south harbor daily. Elkhorn Slough, except under unusual conditions is isolated from the harbor system. The slough is shallow, five m at the mouth to less than one m at the head, and tidal currents keep its waters vertically well mixed. The tides are the dominant mixing mechanism for the slough, removing over 3/4 of the mean high water volume daily. While this is a large fraction of the total volume of the slough, only a small portion of the waters inland of the shoreward extent of the tidal prism are flushed from the slough daily.

The observed distribution of properties indicate that three major water types are present in the harbor-slough system, offshore waters, Old Salinas River channel waters and upper Elkhorn Slough waters. In Elkhorn Slough the waters above the tidal prism have a long residence time, and its chemistry develops somewhat independently of offshore conditions. Longitudinal gradients of most parameters are indicative of mixing between the upper slough and offshore waters.

In addition to tidal influences, large seasonal variations were observed. The apparent nitrogen to phosphate ratio for the harbor source waters varied from 1:16 in the winter to 1:5 in the summer, indicating increased relative influence of sewage on the composition of fresh waters entering the harbor. Most of the longitudinal gradients in Elkhorn Slough reversed from winter to summer. During the winter, conditions responded rapidly to variations in precipitation and local runoff. The first (and only) heavy rains of the season brought about decreases in salinity accompanied by large increases in nutrient concentrations. This single washout was followed by a recovery to near oceanic conditions in less than a month. During the summer, evaporation controlled salinity distributions and the upper slough became a semi-closed system. Under these conditions, a tidal diffusion model was formulated based on a salt budget involving estimated evaporation rates and observed salinity distributions. Tidal diffusion coefficients were calculated at various distances inland. The mean diffusion coefficient of three 30 day time intervals ranged from 430×10^4 cm^2/sec two km inland to 5.9×10^4 cm^2/sec nine km inland. These diffusivities lead to a residence time in excess of 300 days for the waters inland of the mean diurnal tidal prism.

The seasonal variations in the nutrient distributions in Elkhorn Slough are more complex, involving biochemical and inorganic processes as well as tidal diffusion. Phosphate concentrations increased landward throughout the study periods. During the summer months, a mean rate of phosphate diffusion from the upper slough was calculated to be 12 kg PO_4^{-3}/day. Unlike phosphate, nitrogen gradients were not consistent through the year. During the winter, land drainage maintained minimum levels of nitrate at about 8 μg-at/l. Throughout the study period, maximum concentrations of reduced nitrogen (ammonia and nitrite) were observed in the mid-slough region, correlating with the presence of dairy farms in this area.

During the summer, in the upper slough, nitrogen probably limited primary production. Under these summer conditions, the upper slough was eutrophic in terms of phosphate. Thus, if the observed phosphate concentrations of 2 to 3 μg-at/l were synthesized into organic matter which then decomposed, the dissolved oxygen in the water column would be depleted, creating anoxic conditions (Ketchum 1969). However, the limited availability of nitrogen may prevent the development of this condition, but the potential remains and if additional nitrogen were introduced in the upper slough, undesirable conditions could develop.

Tidal variations were the single most important factor in determining the instantaneous solute distribution. The area above the tidal prism (about 4.8 km inland) is essentially isolated from offshore influence and develops its own chemical identity. In this area, significant diurnal variations occur in the dissolved oxygen concentrations, and to a lesser extent, in phosphate levels. A net production rate of about 50 mg-at O_2-O/m^2 hr were estimated from these observations in March and August, respectively. Even though this area is highly productive, judging from the annual phosphate and oxygen distributions, the upper slough appears to be dominated by respiration or decomposition. This is reasonable considering the quantity of detrital organic material contributed by the adjacent marsh areas.

To adequately predict the consequences of the proposed enlargement of Moss Landing Harbor on residence time and water quality of Elkhorn Slough, further study is indicated. An increase in the volume of the lower slough would decrease the penetration of the tidal prism and thereby increase the residence time for waters in the upper slough. Some apparent paradoxes in the distribution of phosphate and nitrogen have been pointed out. These differences have been observed in other systems, and further study of a semi-closed system such as Elkhorn Slough might allow a more detailed determination of the sources, sinks and rates necessary to maintain these distributions in shallow waters. The study of spatial and seasonal distributions of plant and animal communities would provide important data on biochemical rates that would help to complete our understanding of this complex system.

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APPENDIX 1

Time and Distance Smoothed Salinities Used in Eddy Diffusion Model

APPENDIX 1

Salinity

Distance Inland (km)	May 31	June 29	July 29	Aug. 28	Sept. 27
1	33.50	33.50	33.50	33.50	33.50
2	33.50	33.50	33.51	33.51	33.50
3	33.51	33.54	33.55	33.53	33.51
4	33.52	33.56	33.60	33.64	33.54
5	33.55	33.73	33.88	33.89	33.64
6	33.63	34.00	34.29	34.28	33.89
7	33.78	34.46	34.91	34.88	34.30
8	34.13	34.98	35.52	35.51	34.88
9	34.40	35.53	36.17	36.15	35.50
10	34.77	35.95	36.63	36.62	35.96

APPENDIX 2

Eddy Diffusion Constant K from Equation (3)

APPENDIX 2

$K(10^4 cm^2/sec)$

Distance Inland (km)	May 31- June 29*	June 29- July 29	July 29- Aug. 28	Aug. 28- Sept. 27	Mean
1	∞	∞	∞	∞	∞
2	1100	410	320	570	430
3	180	160	100	130	130
4	100	54	45	57	52
5	41	23	21	19	21
6	17	12	12	14	12
7	9.4	7.7	7.8	8.0	7.8
8	6.5	6.2	6.5	6.0	6.2
9	5.2	6.1	6.2	5.6	5.9

*May 31 - June 29 Neglected in computation of mean because equilibrium conditions had not yet stabilized.

APPENDIX 3

Time Series Observations Collected
at Sandholt Bridge, Highway 1 Bridge and
Kirby Park on March 27-28 and August 16-17, 1971

Kirby Park
March 27-28, 1971

APPENDIX 3 (CONTINUED)

TIME hr	TEMP °C	SALINITY ppt	SIGMA T	OXYGEN ml/l	AOU μg-at/l	SAT %	PHOSPHATE	NITRATE	NITRITE	AMMONIA	SILICA
							μg-atoms/liter				
900	14.0	30.750	22.9	4.01	159	69					
930	13.7	31.100	23.3	3.84	176	66					
1000	13.7			4.03			2.33	6.5	.31	6.2	26
1100	14.0	31.950	23.9	4.33	117	77	2.50	7.1	.49	7.2	30
1230	15.0	31.280	23.1	4.88	69	86					
1300	15.2	30.720	22.7	5.38	24	95					
1330	17.0	30.030	21.7	5.72	- 21	104					
1400	18.0	29.540	21.1	6.25	- 76	116	1.79	6.5	.31	2.8	18
1430	17.8	28.670	20.5	5.65	- 18	104					
1500	18.0	28.140	20.1	5.89	- 39	108					
1530	18.0	27.750	19.8	5.98	- 46	110					
1600	18.0	27.250	19.4	5.98	- 45	109	1.86	10.2	.55	2.7	23
1630	18.0	27.020	19.2	6.01	- 47	110					
1700	18.2	26.900	19.1	6.24	- 69	114					
1800	17.4	27.720	19.9	5.93	- 36	107	1.98	11.6	.55	2.5	24
1900		28.910		5.69							
2000	16.3	30.380	22.2	4.44	98	80	2.32	5.2	.35	4.7	38
2100	15.5	31.550	23.2	3.54	183	63					
2200	14.6	32.120	23.8	4.64	91	82	2.19	6.8	.43	7.2	21
2300	13.8	32.570	24.4	2.90	254	51					
2400	13.6	32.460	24.3	5.02	67	87	2.32	5.9	.35	6.5	103
100		32.180		5.00							
200		30.750		4.04			2.73	6.5	.37		34
300	14.4	28.880	21.4	3.71	188	64					
400	14.8	27.880	20.6	3.37	217	58	2.82	10.3	.57	5.4	49
500	14.5	27.680	20.5	3.32	226	57					
600		27.640		3.28			2.81	12.2	.70	4.1	53
700	14.2	27.990	20.8	3.22	237	55					
800	14.2	28.340	21.0	3.68	194	63	2.72	10.9	.67	3.8	50
900	14.4	29.150	21.6	3.53	203	61	2.76	11.2	.61	3.8	44

APPENDIX 3

Highway 1 Bridge
March 27-28, 1971

TIME hr	TEMP °C	SALINITY ppt	SIGMA T	OXYGEN ml/l	AOU µg-at/l	SAT %	PHOSPHATE	NITRATE	NITRITE	AMMONIA	SILICA
							µg-atoms/liter				
1100	11.4	33.610	25.6	7.13	-101	119	.76	2.6	.20	1.8	11
1300	11.3	33.590	25.6	6.86	- 75	114					
1400	12.1	33.520	25.4	2.71	286	46	1.23	7.5	.27	3.0	24
1500	12.8	33.320	25.2	2.47	300	42					
1600	13.0	31.710	23.9	2.91	264	50	3.57	26.2	1.58	18.0	29
1700	13.2	31.840	23.9	5.64	18	97					
1800	12.3	33.460	25.4	5.83	5	99	1.75	12.4	.30	4.1	16
1900	10.7	33.710	25.8	5.29	71	87					
2000	10.9	33.680	25.8	5.27	70	87	1.61	21.6	.19	1.8	20
2100	11.1	33.630	25.7	6.04	0	100					
2200	11.2	33.590	25.7	6.53	- 45	108	.75	7.5	.09	.6	25
2300	10.9	33.430	25.6	6.49	- 37	107					
2400	10.9	33.520	25.7	6.36	- 26	105	.88	7.1	.10	1.6	6
100	11.1	33.490	25.6	6.02	2	100					
200	11.0	33.570	25.7	5.38	60	89	1.37	11.8	.07	2.3	
300	11.8	33.260	25.3	4.85	99	81					
400	12.6	32.930	24.9	4.70	104	80	2.39	10.4	.35	7.0	24
500	12.6	30.310	22.9	4.77	108	80					
600	12.4	31.820	24.1	4.50	132	75	3.74	18.9	1.18	11.0	32
700	10.6	32.470	24.9	4.81	120	78					
800	9.6	33.400	25.8	3.65	232	58	1.69	18.3	.29	2.6	19
900	9.8	33.390	25.8	5.96	23	96					

APPENDIX 3 (CONTINUED)

Sandholt Bridge
March 27-28, 1971

TIME	TEMP	SALINITY	SIGMA T	OXYGEN	AOU	SAT	PHOSPHATE	NITRATE	NITRITE	AMMONIA	SILICA
hr	°C	ppt		ml/l	µg-at/l	%	µg-atoms/liter				
900	12.1	32.690	24.8	5.47	42	92	5.14	16.5	1.02	.0	25
1000	12.4	31.850	24.1	5.41	47	91	4.95	24.9	1.77	.6	32
1100	12.2	31.410	23.8	5.38	54	90	3.98	26.2	1.93	1.1	29
1200	12.3	32.130	24.3	5.50	39	93	4.36	27.4	2.04	1.0	32
1300	12.9	31.840	24.0	5.59	26	95	4.46	25.3	2.17	26.0	34
1400	13.0	31.230	23.5	5.67	20	96	5.56	33.3	2.81	32.0	40
1500	12.9	30.170	22.7	5.71	21	96					
1600	13.9	28.970	21.6	5.52	31	94	8.73	51.0	4.40	52.0	54
1700	13.9	30.030	22.4	5.65	16	97					
1800	13.9	30.030	22.4	5.68	13	97	7.49	43.8	4.02	45.0	49
1900	13.3	30.580	22.9	5.66	19	96					
2000	12.4	31.900	24.1	5.76	16	97	4.14	22.2	1.94	22.0	30
2100	12.1	31.960	24.2	5.07	81	85					
2200	12.1	32.620	24.8	5.43	46	91	3.21	20.6	1.33	14.0	28
2300	11.8	31.140	23.7	5.68	33	94					
2400	12.1	32.590	24.7	5.05	80	85	3.43	20.7	1.31	14.0	28
100	11.8	31.740	24.1	5.42	54	90					
200	12.1	31.840	24.1	6.21	- 20	104	6.30	34.8	.49	28.0	47
300	12.1	31.730	24.1	5.33	58	89					
400	11.7	31.490	23.9	5.32	65	88	3.67	37.9	2.16	9.8	17
500	11.9	28.890	21.9	4.75	123	78					
600	11.9	29.510	22.4	4.77	119	78	4.57	23.9	1.90	20.0	33
700	11.8	28.740	21.8	4.68	131	76					
800	11.7	31.560	24.0	3.79	201	63	4.33	25.4	2.02	20.0	36
900	10.6	32.720	25.1	4.95	106	81					

APPENDIX 3 (CONTINUED)

Kirby Park
August 16-17, 1971

TIME hr	TEMP °C	SALINITY ppt	SIGMA T	OXYGEN ml/l	AOU µg-at/l	SAT %	PHOSPHATE	NITRATE	NITRITE	AMMONIA	SILICA
							µg-atoms/liter				
1200	20.7	35.611	25.1	4.56	34	92	2.81	.7	.11	.1	21
1300	21.0	35.656	25.0	4.89	2	100					
1400	21.9	35.755	24.8	5.97	-101	124	2.70	.6	.09	.4	20
1500	21.6										
1600	21.6	34.976	24.3	6.07	-106	124	2.66	.6	.08	.7	20
1700	21.6	34.677	24.1	6.42	-136	131					
1800	20.7	34.390	24.1	5.73	- 67	115	2.50	.8	.22	1.5	16
1900	19.6	34.048	24.2	5.50	- 36	108					
2000	18.7	33.815	24.2	6.29	- 99	121	1.94	.8	.27	1.4	14
2100	17.6	33.690	24.4	6.06	- 68	115					
2200	18.9	34.122	25.2	4.95	15	97	2.62	1.4	.37	2.2	19
2300	19.6	34.743	24.7	4.54	47	90					
2400	19.8	35.802	25.4	4.01	89	80	2.61	.3	.14	.3	15
100	20.1	36.175	25.6	3.70	113	74					
200	19.9	36.342	25.8	3.40	141	68	3.18	.1	.14	.0	23
300	19.7	36.381	25.9	3.10	170	62					
400	19.6	36.370	25.9	3.05	175	61	3.25	.3	.15	.2	14
500	19.3	36.290	26.0	3.00	182	60					
600	19.1	36.165	25.9	3.02	182	60	3.29	.0	.17	.3	21
700	19.2	36.014	25.8	1.42*	325	28					
800	19.1	35.700	25.6	1.41*	327	28	2.88	.3	.13	.1	18
900	18.9	35.340	25.3	1.89*	287	37					
1000	18.7	34.993	25.1	3.59	138	70	3.07	.9	.23	1.6	22
1100	19.2	34.965	25.0	3.79	116	74					
1200	19.6	35.347	25.2				2.81	.0	.10	.7	19
1300	20.7	35.571	25.0								
1400	21.6	35.647	24.8				2.42	.1	.08	.2	15

* questionable data

APPENDIX 3 (CONTINUED)

Highway 1 Bridge
August 16-17, 1971

TIME	TEMP	SALINITY	SIGMA T	OXYGEN	AOU	SAT	PHOSPHATE	NITRATE	NITRITE	AMMONIA	SILICA
hr	°C	ppt		ml/l	µg-at/l	%	µg-atoms/liter				
1200	13.0	32.909	24.8	6.23	- 36	107	3.23	5.4	.63	4.5	12
1300	14.8	33.197	24.6	5.78	- 16	103					
1400	14.5	33.172	24.7	6.09	- 40	108	2.43	2.9	.43	1.8	22
1500	15.6	33.556	24.8	6.47	- 86	118					
1600	16.0	33.630	24.7	7.37	-171	135	.63	.8	.10	.5	4
1700	15.2	33.645	24.9	7.78	-200	140					
1800	15.0	33.649	25.0	7.78	-198	140	.67	.8	.06	.6	3
1900	13.9	33.639	25.2	6.74	- 94	119					
2000	13.6	33.629	25.2	6.18	- 40	108	1.08	3.5	.20	1.0	7
2100	14.0	33.633	25.2	6.14	- 41	108					
2200	15.0	33.617	24.9	6.59	- 91	118	1.05	1.8	.14	1.3	7
2300	15.8	33.550	24.7	6.77	-115	124					
2400	16.9	33.468	24.4	4.36	90	81	2.21	2.8	.44	3.0	11
100	17.9	33.698	24.3	5.26	0	100					
200	18.4	33.892	24.4	4.88	29	94	2.27	1.4	.28	2.5	15
300	18.6	33.632	24.1	4.60	53	89					
400	18.6	33.827	24.2	4.50	61	87	2.90	1.6	.47	3.8	18
500	16.9	33.561	24.4	5.96	- 53	111					
600	16.2	33.582	24.6				.72	1.4	.09	.2	4
700	15.7	33.604	24.8	6.95	-130	127					
800	14.3	33.553	25.0	6.28	- 56	111	1.02	5.5	.18	.4	9
900	12.6	33.541	25.4	5.60	22	96					
1000	13.9	33.591	25.1	5.83	- 12	102	.81	4.1	.11	.2	7
1100	13.8	33.550	25.1	5.97	- 24	105					
1200	13.9	33.382	25.0	5.60	9	98	1.47	4.8	.22	1.8	8
1300	14.4	33.385	24.9	5.91	- 24	105					
1400	15.2	33.238	24.6	6.02	- 41	108	2.00	4.1	.55	2.2	12

Sandholt Bridge
August 16-17, 1971

APPENDIX 3 (CONTINUED)

TIME	TEMP	SALINITY	SIGMA T	OXYGEN	AOU	SAT	PHOSPHATE	NITRATE	NITRITE	AMMONIA	SILICA
hr	°C	ppt		ml/l	μg-at/l	%	μg-atoms/liter				
1200	15.8	32.990	24.3	5.56	- 5	101	3.62	7.0	1.13	6.6	20
1300	16.1	31.782	23.3	5.79	- 24	105					
1400	16.2	30.631	22.4	5.98	- 39	108	4.94	12.8	2.30	12.0	30
1500	16.2	31.743	23.2	5.78	- 24	105					
1600	16.3	32.499	23.8	6.21	- 66	114	3.55	5.9	.99	3.8	19
1700	16.3	32.535	23.8	6.29	- 73	115					
1800	15.4	32.667	24.1	6.54	- 88	118	3.56	5.6	.82	5.2	13
1900	15.9	32.608	24.0	6.42	- 81	117					
2000	15.7	32.918	24.2	6.70	-106	122	3.25	3.5	.88	3.9	14
2100	16.3	32.081	23.5	6.31	- 74	115					
2200	16.0	32.324	23.7	5.80	- 26	105	4.33	7.7	1.03	5.2	17
2300	15.8	32.242	23.7	4.84	61	88					
2400	15.9	23.541	17.0	5.36	43	92	28.00	26.6	11.10	69.0	69
100	18.6	12.490	8.0	6.81	- 79	115					
200	18.8	13.191	8.5	4.21	149	72	32.00	9.1*	9.07*	4.2*	47
300	18.3	6.914	3.9	3.12	271	51					
400	16.9	9.121	5.8	3.00	290	48	51.00	80.0	25.20	53.0	31
500	15.9	14.928	10.4	2.55	322	41					
600	15.9	28.257	20.6	3.13	226	55	16.00	21.3	6.70	23.0	45
700	15.9	29.169	21.3	3.83	161	68					
800	16.0	30.073	22.0	3.12	220	56	8.20	10.3	3.77	8.7	28
1100	15.8	31.972	23.5	3.02	225	55					
1200	15.7	32.051	23.6	2.97	230	54	5.31	5.6	1.62	7.3	18
1300	16.8	31.366	22.8	2.78	239	51					
1400	17.1	31.357	22.7	5.70	- 24	105	6.48	7.0	1.74	5.6	20

* questionable data