

AN ABSTRACT OF THE THESIS OF

Jose Ruben Lara-Lara for the Master of Science
(Name) (Degree)

in Oceanography presented on November 21, 1978
(Major) (Date)

Title: Variability and Tidal Exchange of Ecological Properties in a

Coastal Lagoon

Redacted for privacy

Abstract approved: Lawrence F. Small

Sea level, current velocity, temperature, salinity, oxygen, inorganic phosphate, chlorophyll a, seston, phytoplankton species abundance, particulate organic carbon and nitrogen, and primary productivity time series were generated for the mouth of San Quintin Bay, Baja California, for 18 days during the summer of 1977. This was done to elucidate the main factors that cause variability of these ecological properties and to frame some generalizations about the overall direction and magnitude of the fluxes that couple the bay and the offshore waters during the summer season. San Quintin Bay is of considerable interest because of its developing mariculture potential.

Alternation of upwelling events was the main cause of variability for all properties except temperature. Semidiurnal tides were the main cause of variability for temperature. Conservative variables such as temperature and salinity had a semidiurnal component greater than the diurnal one. Most non-conservative variables (chlorophyll a and

phosphate concentrations, for example) had equal diurnal and semidiurnal variability components, due to biological processes that strongly depend on the solar radiation cycles. The relationship between variability components for oxygen was intermediate to those relationships for the conservative and non-conservative variables. Seston variability was mainly due to turbulence induced by winds and tidal currents. Lack of correlation between particulate organic carbon and nitrogen, and the wide range of C:N ratios in particles, indicate that bay-derived seston of widely varying organic content represents most of the suspended particulate matter. Up to 99% of the organic particulate matter is detritus, produced mainly from the degradation of sea grasses. Upwelling is responsible for the high chlorophyll a and inorganic phosphate concentrations that appear in the bay.

Only during the second upwelling event (the last seven days of the sampling period) did there appear to be significant export from the bay, as shown by mean fluctuation fluxes for temperature, oxygen and chlorophyll a. For all other variables and during other segments of the sampling period there were no significant mean fluctuation fluxes. The fact that only one station was occupied at the bay mouth makes assessment of fluctuation fluxes difficult, however.

Diatoms were always the most abundant phytoplankton group. Primary productivity was always greatest at the surface, with a mean value of $27 \text{ mgC m}^{-3} \text{ hr}^{-1}$ through the sampling period. Maximum surface productivity values were obtained for the upwelling relaxation period (up to $44 \text{ mgC m}^{-3} \text{ hr}^{-1}$). A mean value of $122 \text{ mgC m}^{-2} \text{ hr}^{-1}$ was found for the entire water column during the 18-day period. These values are comparable to the productivity maxima of other upwelling areas. The

mean surface assimilation ratio was 6.6 mgC (mgChla⁻¹) hr⁻¹, which indicates nutrient-rich waters.

Variability and Tidal Exchange of Ecological
Properties in a Coastal Lagoon

by

Jose Ruben Lara-Lara

A THESIS

Submitted to

Oregon State University

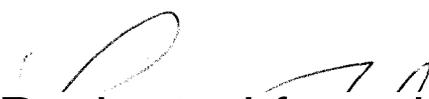
in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed (November 21, 1978)

Commencement June 1979

APPROVED:


Redacted for privacy

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Date thesis presented November 21, 1978

Typed by Rebecca Rakish for Jose Ruben Lara-Lara

To my wonderful family

For their patience and encouragement, and for providing a peaceful, agreeable home environment. I love them and thank them.

My wife and daughter

XOCHITL and MARLENE LARA.

With love, respect and gratitude to my parents

JOSE and AUDELIA LARA.

ACKNOWLEDGMENTS

I thank my major professor, Dr. Lawrence F. Small, for his valuable help throughout my graduate work. His time, guidance and suggestions will be specially remembered. I also want to thank the Director of the Center of Scientific Investigation of Ensenada, Baja California (CICESE), Dr. Saul Alvarez-Borrego for his friendship, his help, and his personal influence in many aspects of my academic life. To Antoine Badan-Dangon, I thank sincerely for his time and valuable suggestions during my work; I owe to him in many ways my own understanding about time series analysis.

I also want to express my thanks to the "Consejo Nacional de Ciencia y Tecnologia" of Mexico for their support while working on my M. S. program.

Without the time and effort that my fellow Manuel Acosta-Ruiz, Gilberto Gaxiola-Castro, Roberto Millan-Nunez, Jose A. Zertuche-Gonzalez, Vidal Huitron-Barajas, Juan M. Rodriguez-Osuna, Eduardo Millan-Nunez and Josue Alvarez-Borrego spent during the sampling period and Sila Najera de Munoz, Elsa Gil de Gaxiola and Carolina Morales-Zuniga during the analysis of phytoplankton, salinity and oxygen samples, this work would not have been possible. I am very grateful to them.

I want to thank, also to the different CICESE groups that supported this work. My thanks also to the captain of the R/V Sirius I, Mr. Leonardo Lopez. Special thanks to Mr. Alfonso Vela who permitted us to use his motel for laboratory purposes.

I also want to express my thanks to Argelia Luviano and Maria de Jesus de la Cerda for their time in typing the first version of this thesis. Special thanks to all those who in many ways are responsible for the completion of my degree.

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VARIABILITY AND TIDAL EXCHANGE
OF ECOLOGICAL PROPERTIES IN A
COASTAL LAGOON

INTRODUCTION

During the last five years, there has been an increased interest in developing maricultures in the coastal lagoons of the Baja California peninsula. The main interest has been concentrated on oyster culture. Very successful experiments with Crassostrea gigas, the Japanese oyster, and Ostrea edulis, the European oyster, have been carried out in most of the coastal lagoons of the peninsula's Pacific coast. Most of these coastal lagoons are very much in their natural state. But, as development goes on from the two ends of the peninsula, human activities are making an impact upon their ecology. Some of the northern and southern lagoons are already suffering changes due to urban and touristic development, besides the effects of irrational fishing on (mainly) crustaceans and molluscs. There is still a unique opportunity to carry on basic ecological studies in some of these coastal lagoons before significant changes are done by man's activities. These studies can give us the background ecology against which the situations of the future may be compared. Also, the studies can be designed to gain useful information that might be applied to make rational decisions as maricultures are developed. For example, it is important to know the spatial and temporal ranges of important ecological variables as temperature and salinity; the relative food availability in different

lagoons; the mechanisms that are responsible for greater or less fertility of some lagoons with respect to others and with respect to the open ocean; and the water exchange rate between the lagoons and the adjacent ocean.

GENERAL DESCRIPTION OF THE STUDY AREA

The present study was carried on in San Quintin Bay. This is a coastal lagoon located between $30^{\circ}24'-30^{\circ}30'N$, and $115^{\circ}57'W-116^{\circ}01'W$, on the pacific coast of Baja California, Mexico (Fig. 1). The bay is some 300 km south of the Mexico-U.S.A. border. The bay is "Y" shaped with a single permanent entrance at the foot of the Y. It has a north-south orientation, and an area of about 41.6 km^2 . The lagoon is extremely shallow, and at lower low tide some portions of the bottom are exposed to the air. There are narrow channels that rarely exceed 8 meters in depth. The western arm is named Falsa Bay and the eastern arm is called specifically San Quintin Bay (Barnard, 1962). The continental shelf is very narrow off San Quintin Bay and the wave energy is very high on the open coast (Lankford, 1976).

The climate is arid along the coast and in the mountains. The small amount of annual precipitation (5-10 cm) comes mostly in winter. The relatively cool California Current offshore of San Quintin Bay is partly responsible for the benign climate of the region. Upwelling occurs in the open ocean immediately off the mouth of the bay during spring and summer (Dawson, 1951), a result of northwesterly winds during these seasons. The upwelling process accounts for the presence of fog off the bay in spring and summer.

Except for flood runoff, occurring sometimes in winter, there are no flowing streams coming into the bay. The westernmost seaward edge of the bay is a long sandpit connecting two cinder cones (Fig. 1), the southern of which marks the entrance to the bay. The south shore on the open sea trends east and west, being formed of a sandspit (Punta Azufre)

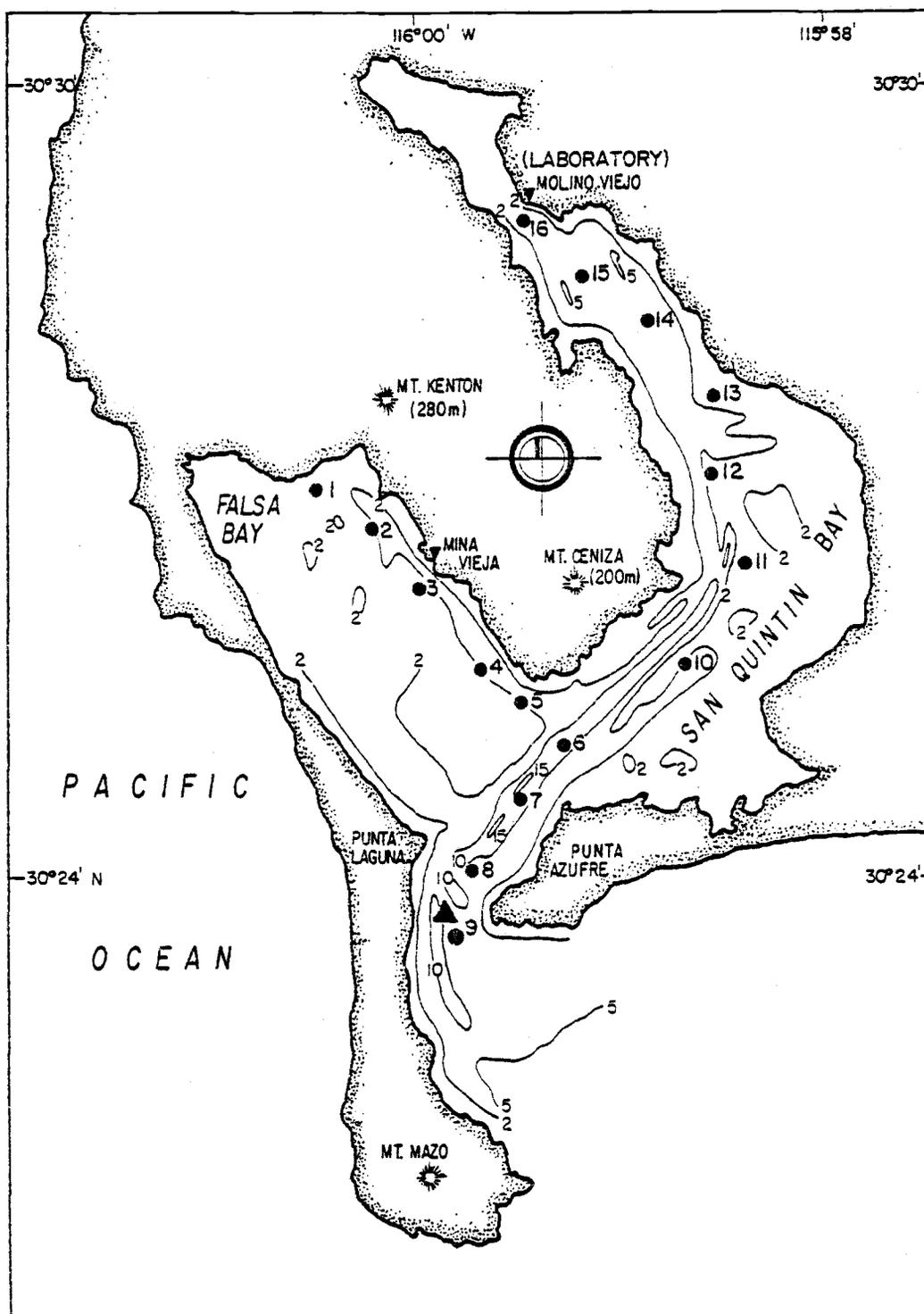


Figure 1. San Quintin Bay. Time series (anchor) station location (▲). Station locations for spatial distributions (●). Bathymetry in meters.

protecting bayward marshes. The two northward trending arms of the bay are split by two prominent cones, Mt. Ceniza and Mt. Kenton and most of this middle peninsula is formed of volcanic materials (Barnard, 1962).

The mainly shallow mud-flat character of the bay provides for two kinds of dominant vegetation. One is a marine flora consisting of eelgrass, Zostera marina, which forms broad, dense strands occupying the greater part of the muddy bottom of the lagoon. The other is a salt marsh flora of extensive development along nearly half of the low-lying margins of the lagoon subjected to tidal flooding (Dawson, 1962).

GENERAL OCEANOGRAPHY

Due to shallow depths and the turbulence caused by tidal currents there are no significant vertical gradients in the different seawater properties. In general, all the year around, there are horizontal salinity and temperature gradients, with values increasing from the mouth to the extrema of the lagoon. Sometimes during winter, with cold air temperatures (0-4°C), the seawater temperature gradient reverses, with values near 15°C at the mouth and near 12°C at the extrema of the bay. The lowest surface temperatures at the mouth have been recorded during summer, with values sometimes below 12°C. These low temperatures are the result of upwelling events during summer, in the adjacent oceanic area. Surface temperatures in the extrema may be higher than 23°C during summer, due to solar radiation input. San Quintin Bay, the eastern arm, has greater salinity values than Falsa Bay, with a difference of about 1‰. This is due to a greater residence time of water in the former location. Salinity may be higher than 37‰ in the extrema of the eastern arm, and lower than 33‰ at the mouth. Average surface salinities for the whole lagoon do not change significantly from winter to summer. Tidal and solar radiation cycles cause big diel changes of the different water properties in all areas of the lagoon, so that any graph showing the spatial distribution of a seawater property is only a first approximation because sampling can not be really synoptic (Chavez-de Nishikawa and Alvarez-Borrego, 1974; Alvarez-Borrego, Ballesteros-Grijalva and Chee-Barragan, 1975).

Phosphate and silicate surface values increase in general from the mouth to the extrema. These increases indicate that the lagoon has a mechanism to concentrate inorganic nutrients. Alvarez-Borrego and Chee-Barragan (1976) have suggested that the inorganic nutrient distributions may result from high concentration of sea grasses in the lagoon bottom. The grasses act to trap the suspended material that is carried from the adjacent oceanic zone into the lagoon by the tidal currents. This trapping action causes a high deposition of organic material, which is then remineralized to inorganic compounds and finally redistributed in the water by tidal currents and wind-induced turbulence. During spring and summer, in addition to the above mechanism, the system receives impulses of inorganic nutrients from the adjacent oceanic area during upwelling events. This causes nutrient concentrations at the mouth to be greater during summer than during winter. Reported ranges for phosphate for the whole bay have been 1.5 to 2.9 μM for summer and 0.7 to 2.0 μM for winter; and for silicate, 13 to 18 μM for summer and 5 to 35 μM for winter. Alvarez-Borrego and Lopez-Alvarez (1975) reported for the mouth a phytoplankton total biomass (wet weight) of 42 $\mu\text{g l}^{-1}$ in July and 17 $\mu\text{g l}^{-1}$ in January, with diatoms dominating in July and dinoflagellates in January. Phytoplankton biomass decreases toward the extrema, especially toward the head of the eastern arm, where values are an order of magnitude smaller than the mouth.

Lara-Lara and Alvarez-Borrego (1975) studied the surface distribution of photosynthetic pigments in San Quintin Bay during one annual cycle. They found the lowest concentrations in winter (average chlorophyll a concentration of 1.5 mg m^{-3}), increased amounts in spring (average chlorophyll a concentration of 2.0 mg m^{-3}), and highest values

in summer (average chlorophyll a concentrations of 3.0 mg m^{-3}). Highest chlorophyll a concentrations were always found in the area between the mouth and the vertex of the "Y". Here, summer maximum values of 8.0 mg m^{-3} and winter maximum values of 3.5 mg m^{-3} were found.

In order to elucidate the ocean-lagoon relationships, including diel variations of the physico-chemical and ecological parameters and their inter-relationships through tidal and solar radiation cycles, Alvarez-Borrego, Lara-Lara and Acosta-Ruiz (1977) and Alvarez-Borrego, Acosta-Ruiz and Lara-Lara (1977) generated 26-hr time series of salinity, temperature, oxygen, phosphate, nitrate, chlorophylls and meteorological variables, once every season at the mouth of the bay. However, these investigators have realized that sampling for such short periods is like looking at reality through slits, and general conditions can not easily be separated from irregular or episodic conditions. Some of the factors that can cause irregular variations of the seawater properties are: non-uniform heating and evaporation in the interior of the lagoon due to an irregular bathymetry; the presence of long-shore currents at the exterior; changing oceanic conditions at the bay mouth such as those produced by upwelling events; changes in the wave regime, a greater turbulence and therefore greater homogeneity of the water column during ebb flow (Alvarez-Borrego, Acosta-Ruiz and Lara-Lara, 1977), and the fact that the tide is semi-diurnal and the solar radiation is diurnal, which causes an asymmetry between the temperature and salinity maxima and minima (Zertuche-Gonzalez and Alvarez-Borrego, 1978).

OBJECTIVE OF THIS WORK

The objective of this work was to study San Quintin Bay with a sampling intensity and duration such that reliable generalizations could be made about the overall direction and magnitude of the fluxes that couple the bay and the offshore waters during the summer season. Following Wastler (1969), if San Quintin Bay is treated as a "black box", it becomes very difficult and complex to state precisely what is happening in this black box; however, it is possible to measure what goes in and what comes out, and from these measurements deduce a little about what is happening in the black box. Some of the measurements made to determine fluxes include the following: 1) salinity (S°/oo), temperature ($T^{\circ}\text{C}$) and oxygen (O_2) time series; 2) export and import of particles and dissolved nutrients between the lagoon and the adjacent ocean (in terms of phytoplankton abundance, chlorophyll a, total inorganic phosphate, total seston, organic and inorganic fractions of the seston, and nutritional aspects of the particles, such as carbon and nitrogen content) 3) phytoplankton primary productivity, to assess changes in a convenient and useful instantaneous rate measurement; 4) phytoplankton total abundance and by gross taxonomic groups; and 5) tides and tidal currents, to assess their effect on export-import of materials. A major analytical device is time series analysis of the measured quantities, to help elucidate interrelationships between the physical, chemical and biological features of the system.

DATA COLLECTION AND ANALYSIS

To accomplish the above objectives a time-series sampling was carried out at an anchor station at the mouth of San Quintin Bay (Fig. 1), between 20 June and 7 July 1977. In addition, the spatial distributions of the different properties throughout the lagoon were measured at 16 stations (Fig. 1) twice during the sampling period (once during flood-flow, July 6, and the other during ebb-flow, July 7). These two latter 16-station samplings had a duration of 2 to 3 hours, the first starting at 1030 hours from Falsa Bay (Station 1), and the second starting at 1415 hours from the mouth (Station 9).

At the mouth a 9.5 m length boat was used as a sampling platform. Every hour a Nansen bottle cast was made to furnish data on salinity, water temperature, dissolved oxygen and inorganic phosphate. Samples were only collected at surface due to the homogeneity of the water column (usually 8 to 10 meters deep). At the same time a Van-Dorn sampler was used to collect surface water for analysis of chlorophyll a. Out of this bottle, every 3 hours, samples were taken for analysis of seston and particulate carbon and nitrogen; and twice a day, once at ebb-flow and once at flood-flow, samples were taken for phytoplankton species abundance estimates.

Every day, and sometimes twice a day, from 21 June to 2 July, carbon-14 incubation experiments were carried out. Incubations were done at 0.4, 3, and 6 m for 1.5 to 5.0 hours, using essentially Steeman-Nielsen's (1952) method. The vials containing the filtered samples were transported to the Oregon State University's School of Oceanography phytoplankton laboratory, where the radioactivity of the samples were

determined in a scintillation spectrometer. Conversion of radioactivity to carbon productivity was done as indicated by Strickland and Parsons (1972), but following Morris, Yentsch and Yentsch's (1971) suggestion not to subtract the dark fixation.

Water temperatures were read off standard reversing thermometers. Salinity was analyzed at a shore-based laboratory (Fig. 1) with a conductivity salinometer (Beckman, 118WA 200). Oxygen was analyzed at the shore laboratory by the micro-Winkler titration method. Pigment samples were obtained using 0.45 μm pore-sized Millipore filters. Filters were frozen to be transported to the laboratory at Ensenada and analysis was done basically by the SCOR-UNESCO (1966) method, but with some modifications. Second readings at 665, 645, and 630 nm were done after acidification following Lorenzen (1967). A 1-to-1 volume solution of 90% acetone and dimethyl sulfoxide was used as a solvent to improve the pigment extraction (Shoaf and Liem, 1976). Spectrophotometric equations developed by Millan-Nuñez and Alvarez-Borrego (1978) were used to estimate concentrations of chlorophyll a. The equation for chlorophyll a is exactly the same as that of Lorenzen (1967) due to the chlorophyll b:phaeopigment b and chlorophyll c:phaeopigment c ratios at 665 nm being equal to one.

Two drops of a saturated solution of HgCl_2 were added to each phosphate sample immediately after collection. Then samples were frozen to be transported to the laboratory. They were analyzed by the method described by Strickland and Parsons (1968). Both pigments and phosphates were determined utilizing a Bausch & Lomb spectronic 210-UV Spectrophotometer. Seston, as the total dry weight of particulate matter, was

determined by the gravimetric method described by Krey (1950), using 47 mm diameter and 0.8 μm pore size Nuclepore filters. Filters were then treated to discriminate between organic and inorganic particulate fractions, according to the method described by Peterson (1977). This method, in general, relies on oxidation of the material collected on the filter by an 18% solution of reagent grade hydrogen peroxide, with heating to about 60°C for 1/2 hour. After this wet ashing, the filter plus remaining material is re-weighed. Then by weight differences the organic and inorganic fractions are calculated. Particulate organic carbon (POC) and particulate organic nitrogen (PON) were determined with a Carlo-Erba elemental analyzer, model 1100 at Oregon State University's School of Oceanography phytoplankton laboratory. Phytoplankton abundance was determined by the Utermohl (1958) inverted scope technique using an American Optical Model 1810 inverted microscope.

Tide height was measured at the mouth of the bay by a Kahlsico Model 310WA420 limnigraph, and at Molino Viejo (Fig. 1) by a Fisher and Porter Model 1550 digital tide gauge. The limnigraph functioned only during two days. The results obtained during this period were used to calculate the phase lag between the mouth and Molino Viejo, and subsequently back-calculate the tides for the mouth based on data from Molino Viejo. Surface currents at the mouth were measured only at the anchor station in the bay mouth (Fig. 1), using a Braincon HCM type 1381 current meter.

STATISTICAL ANALYSIS

To estimate the fluxes of the different properties at the mouth of the bay, the following expression was used:

$$E(t) = q(t) \cdot v(t) \quad (1)$$

where $E(t)$ is the time-dependent exchange, $q(t)$ is a seawater property, and $v(t)$ is the velocity of the flow along the principal axis of flow (see later for analysis of principal flow axis). We can express $q(t)$ and $v(t)$ as the sum of a mean plus a time-dependent fluctuation about that mean, according to Platt and Conover (1971), as follows:

$$E(t) = [\bar{q} + q'(t)] \cdot [\bar{v} + v'(t)] \quad (2)$$

where \bar{q} and \bar{v} are the means defined for the period of observation. The mean exchange, obtained by temporally averaging equation (2) becomes:

$$\overline{E(t)} = \bar{q}\bar{v} + \overline{q'(t)v'(t)}$$

where $\overline{E(t)}$ is the mean total exchange for the total time period, $\bar{q}\bar{v}$ is the mean transport for the time period, and $\overline{q'(t)v'(t)}$ is the mean transport due to the fluctuations for the time period. Since currents were measured only at one point at the bay mouth, the transport terms were only computed per unit cross area and per unit time to test for significance of net exports or imports. The assumption was that the single station in the bay mouth yielded representative fluxes for the total cross-sectional area of the bay mouth.

The principal axis of the flow at the mouth of San Quintin Bay differs substantially from the actual north-south direction. Figure 2

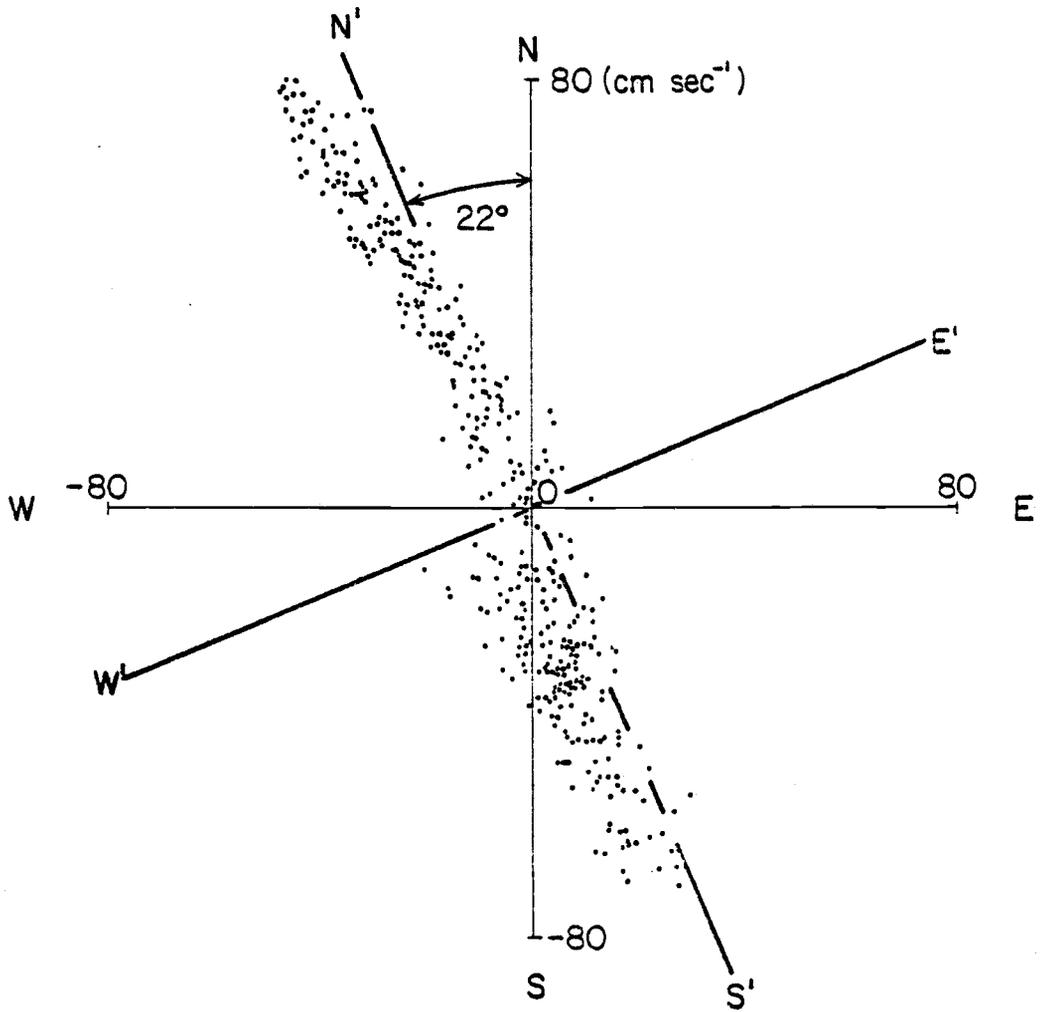


Figure 2. Orientation axes for geographical and natural coordinate systems.

shows graphically the generalized orientation of the geographical and natural coordinate systems. N and E are the north-south and east-west axes for the geographical system while N' and E' are the respective axes in the natural or principal system, rotated by the angle $\theta = 22^\circ$. The angle θ was obtained from the following expression

$$\tan 2\theta = \frac{2 \overline{u'v'}}{\overline{u'^2} - \overline{v'^2}}$$

where u' and v' are the fluctuations about the mean of the original orthogonal components of the current velocity, that is, under the "true" N-S coordinate scheme. The velocity components transform under a coordinate rotation according to the relations

$$u_m = u' \cos \theta + v' \sin \theta$$

$$v_m = -u' \sin \theta + v' \cos \theta$$

This results in maximizing one of the components (in this case, v_m) while minimizing the second (u_m). When the system is strongly directional as is the case here, this procedure in effect causes one of the components (u_m) to be negligible. The maximized component (v_m) thus represents most of the flow field (Fofonoff, 1969). Following from this transformation, $\overline{q\bar{v}}$ and $\overline{q'(t)v'm(t)}$ are the mean transport and the mean fluctuation transport along the principal axis of flow.

Sometimes it is necessary to study the relationship between two processes with possibly different scales of measurement or different

variances. In this situation it is necessary to define the cross-correlation function:

$$R_{12}(L) = \frac{S_{12}(L)}{S_1 S_2}$$

where S_1 and S_2 are the sample standard deviations of series 1 and 2, respectively, S_{12} is the covariance of series 1 and 2, and R_{12} is the correlation coefficient between series 1 and 2. The symbol L is the number of "lags" or time units that one series is displaced with respect to the other (Jenkins and Watts, 1969). In this work, L is the number of either one-hour or three-hour lags (depending upon sampling intensity) to obtain the maximum correlation coefficient between two data sets. One application of lagged cross-correlation is in the measurement of time delay between two processes. The cross-correlation of two series at zero lag is simply the linear correlation. The cross-correlations presented in this work were computed through application of a standard algorithm (Ochs et al., 1970).

From Platt and Denman (1975), spectral analysis of a series of data may be regarded as an analysis of variance in which the total variance of a variable or property fluctuation is partitioned into contributions arising from processes with different characteristic time scales. The essential point is that the sizes of these partial variances are related in a simple way to the sizes of the characteristic time scales. Thus, spectral analysis of a record of observations results in a sorting of the total variance of the record into its component frequencies. The spectral estimates presented here were computed with

a fast Fourier transform algorithm. The output presents the frequency components in cycles per data interval.

RESULTS

Description of time series of seawater properties

Tidal height and tidal current velocity time series at the bay mouth are shown in Fig. 3. These tidal features showed a semidiurnal behavior. The tidal height range was about 3 m. The velocity (V_m) extrema were 92 and -76 cm sec^{-1} , with positive numbers meaning flow into the bay. The mean velocity (\bar{V}_m) for the sampling period was 5.7 cm sec^{-1} . The fact that \bar{V}_m was not zero, but a positive number, indicated that at positions in the bay mouth other than the anchor station, ebb-flow must have been greater, on average, than flood-flow. Evaporation loss could not have balanced the net flux into the bay measured at the anchor station.

Temperature and salinity at the bay mouth also had a semidiurnal behavior, with high values corresponding in general with low tides and vice versa (Fig. 4). The temperature series showed clearly a long wave with a period of about two weeks and maximum values on the eighth sampling day. The salinity series did not show the long wave. The oxygen concentration time series (Fig. 5) was well coupled to the temperature series showing the long wave feature. Phosphate possibly showed the long wave feature, but in an inverse fashion and much more irregularly (Fig. 5). Lower temperatures in general corresponded to higher phosphate and lower oxygen levels. The long wave through these data series was due to upwelling events at the beginning and at the end of the sampling period. The oxygen and phosphate time series, but not necessarily the temperature series, suggested that the second upwelling event was less intense than the first (the O_2 values were higher, and the PO_4 values

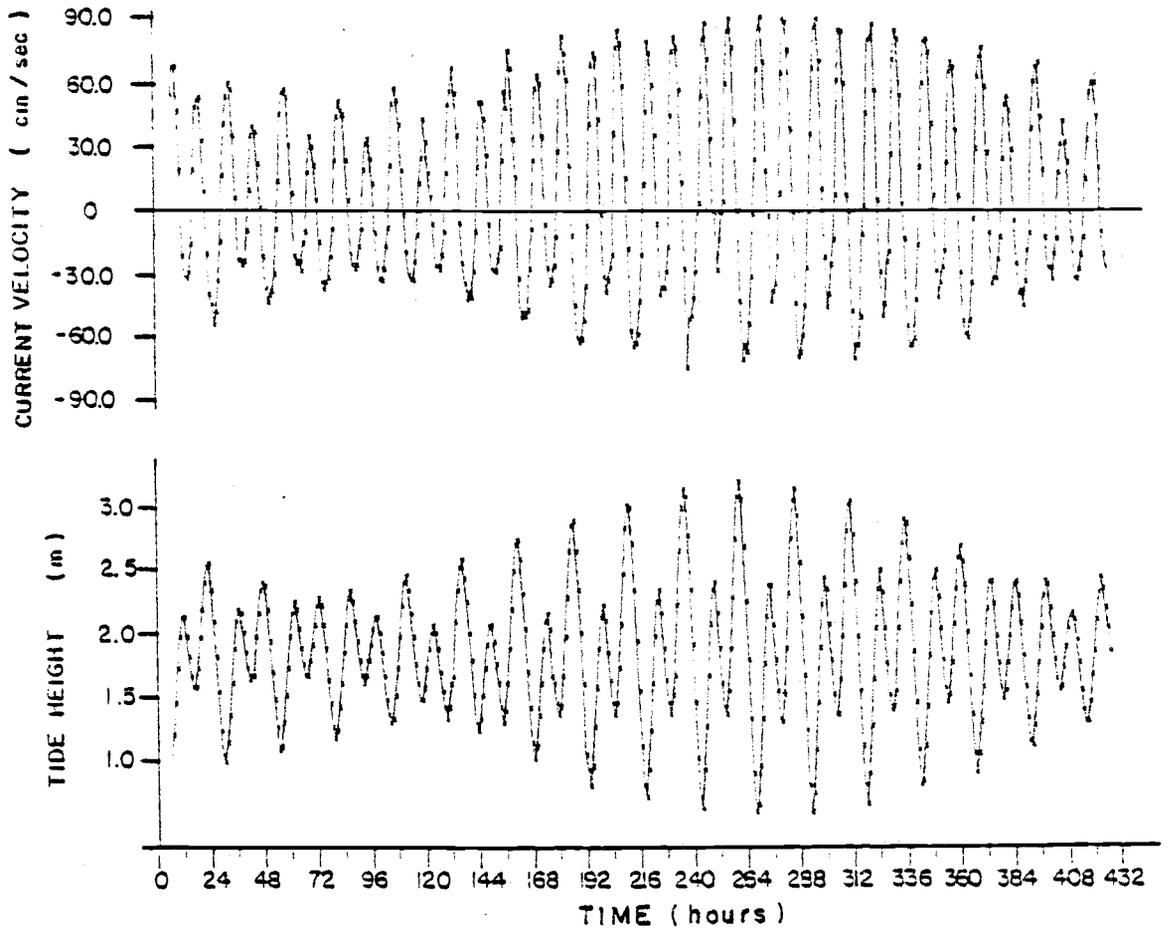


Figure 3. Current velocity and tidal height time series. Numbers mark midnight.

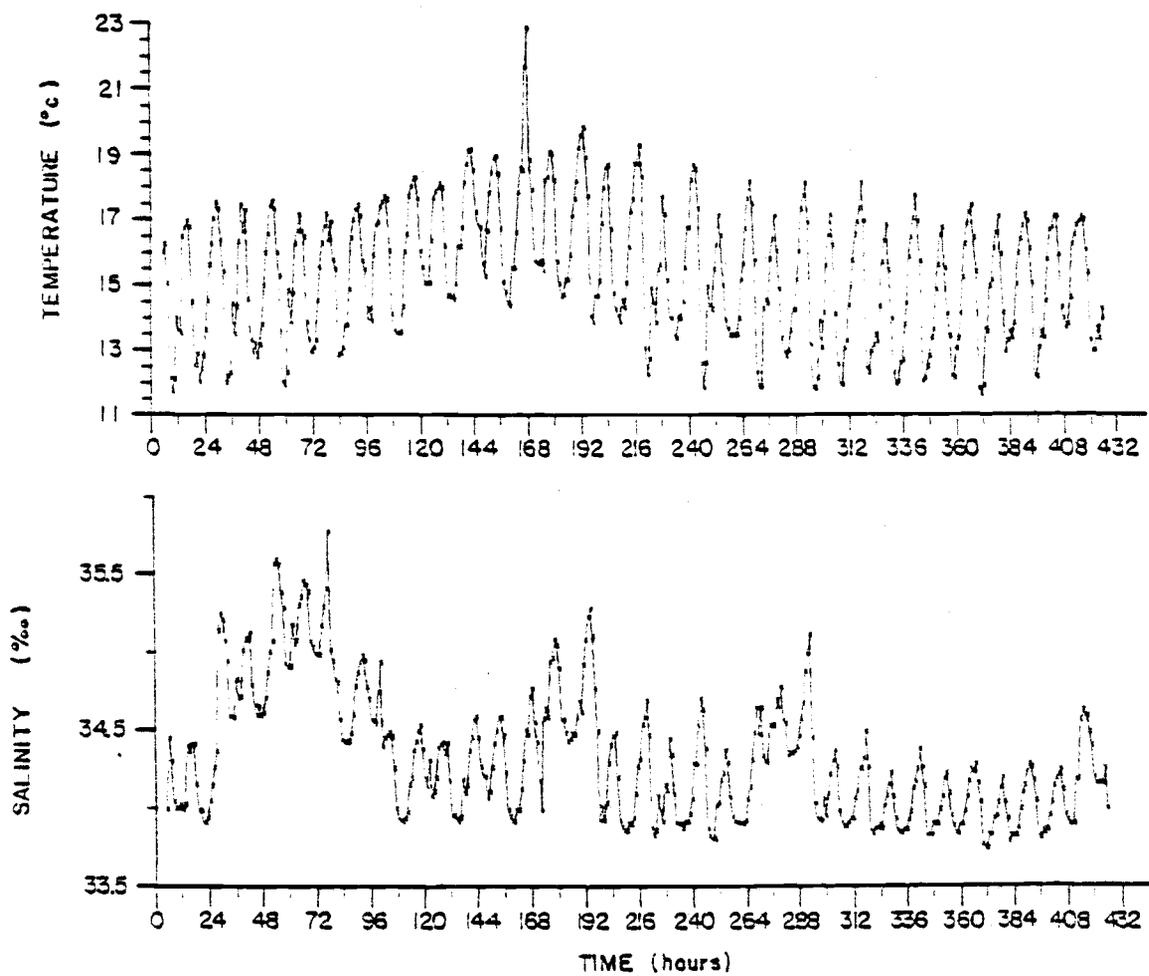


Figure 4. Temperature and salinity time series. Numbers mark midnight.

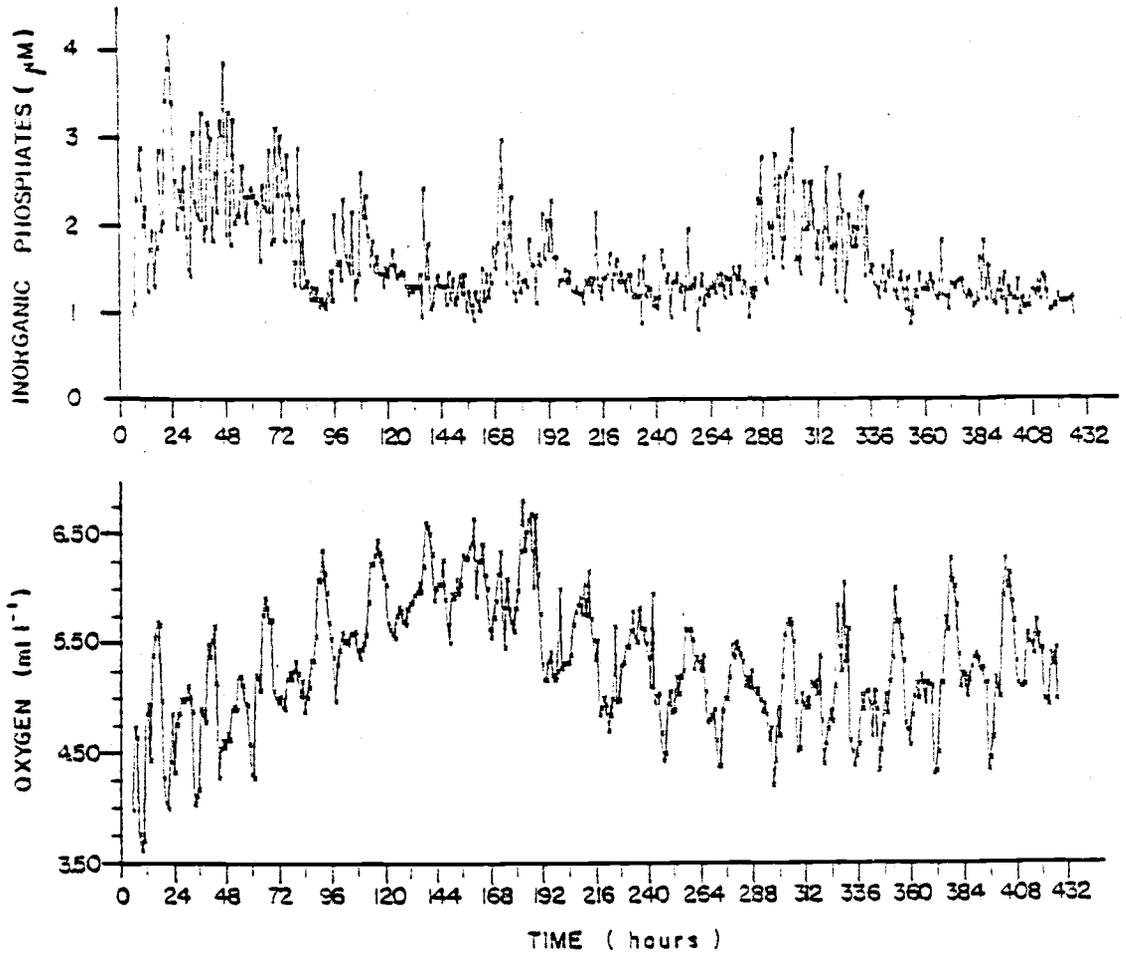


Figure 5. Phosphate and oxygen time series. Numbers mark midnight.

lower at the end of the series compared to the beginning). The ranges of T, S, O₂, and PO₄ were 11.65°C to 22.93°C; 33.75‰ to 35.78‰; 3.6 ml O₂ L⁻¹ to 6.8 ml O₂ L⁻¹ and 0.7 μM PO₄ to 4.4 μM PO₄, respectively.

The chlorophyll a time series showed the long wave feature (Fig. 6), but maximum values were in the middle of the series, slightly out of phase with temperature and oxygen. The chlorophyll a range was 0.8 to 15.7 mg m⁻³. Total seston (Fig. 6), and particularly the organic fraction of the seston (Fig. 7), also tended to show a long wave in the time series. As with chlorophyll a there tended to be larger values in the middle of the series. The ranges were 0.4 to 14.8 mg L⁻¹ for total seston, and 0.2 to 7.6 mg L⁻¹ for the organic fraction. The inorganic fraction of the seston (Fig. 7) did not show a long wave, but displayed a spike in abundance between about 250 and 310 hours. The large spike can also be observed in the total seston series (Fig. 6), was undoubtedly related to the spike in inorganic phosphate. This spike will be discussed later. Values ranged between 0.0 and 11.6 mg L⁻¹ for the inorganic particulate fraction.

The particulate organic nitrogen (PON) time series, despite its high variability, also tended to show a long wave similar to the chlorophyll a series, and possibly a spiking event between about 300 to 360 hours (Fig. 8). No long wave or spiking event was discerned in the particulate organic carbon (POC) data (Fig. 8). The particulate carbon-to-nitrogen ratio (C:N) failed to elucidate any further features in the C and N data (Fig. 9). The ranges for POC, PON and C:N were respectively: 0.7 to 6.2 mg L⁻¹, 0.04 to 0.32 mg L⁻¹, and 3.0 to 81.8. The means were 2.0 mg L⁻¹, 0.13 mg L⁻¹, and 18.0 mg L⁻¹, respectively.

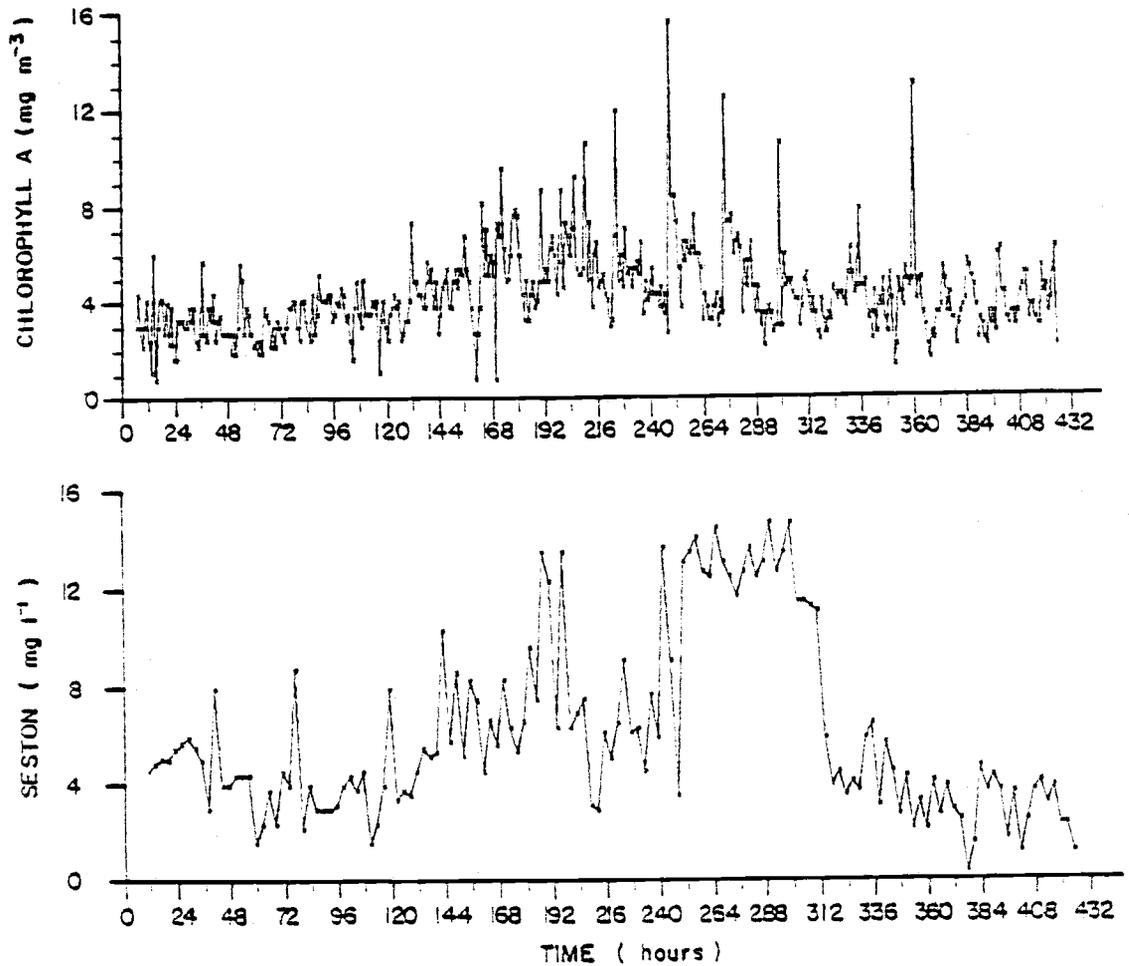


Figure 6. Chlorophyll a and seston time series. Numbers mark midnight.

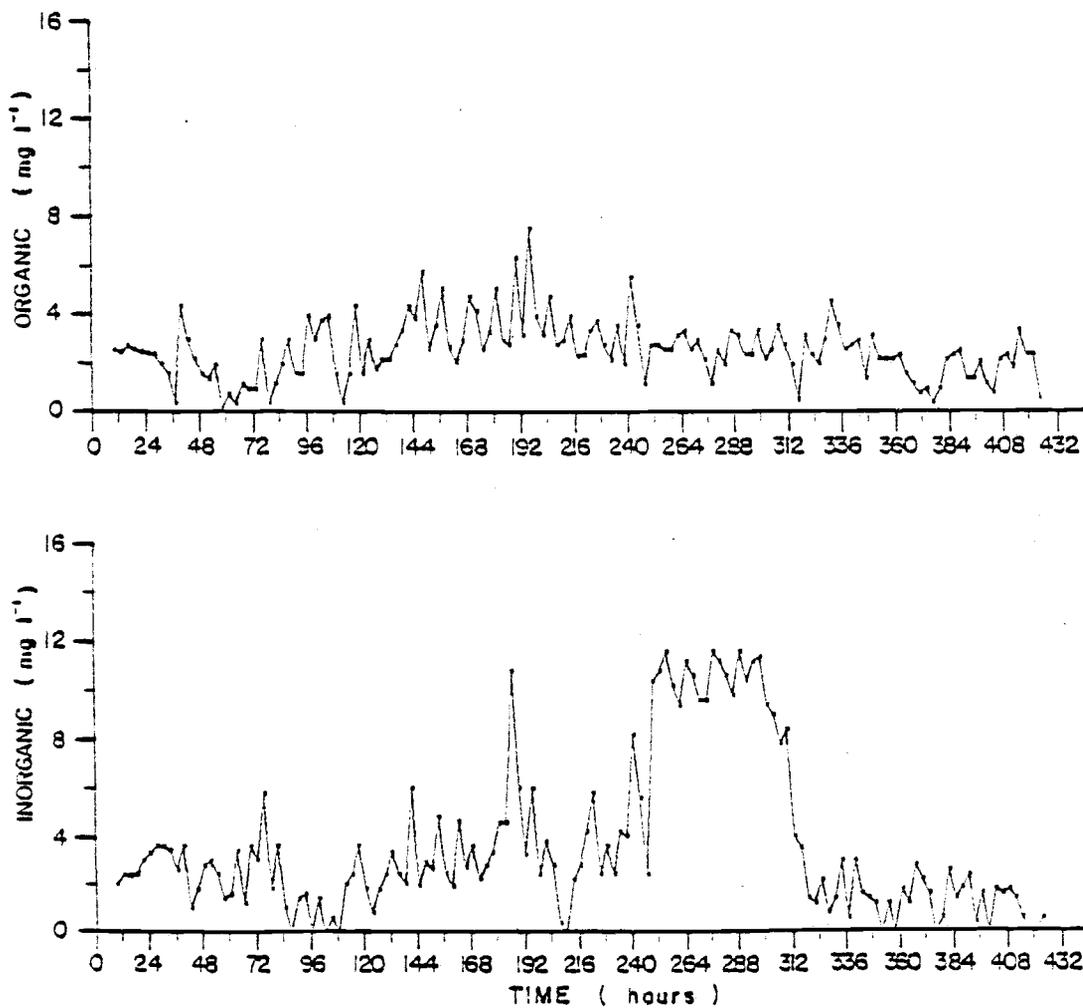


Figure 7. Organic and inorganic particulate matter time series. Numbers mark midnight.

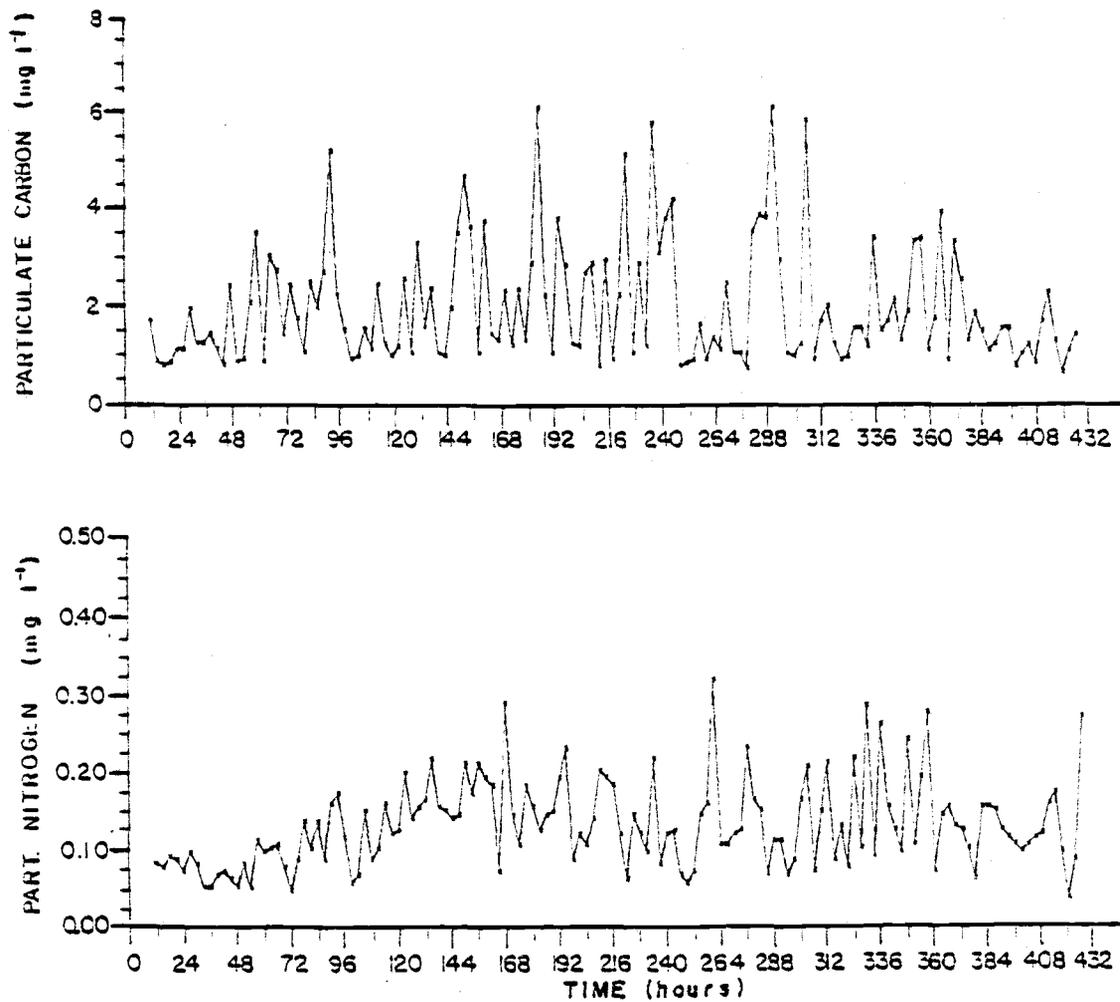


Figure 8. Particulate organic carbon and nitrogen time series. Numbers mark midnight.

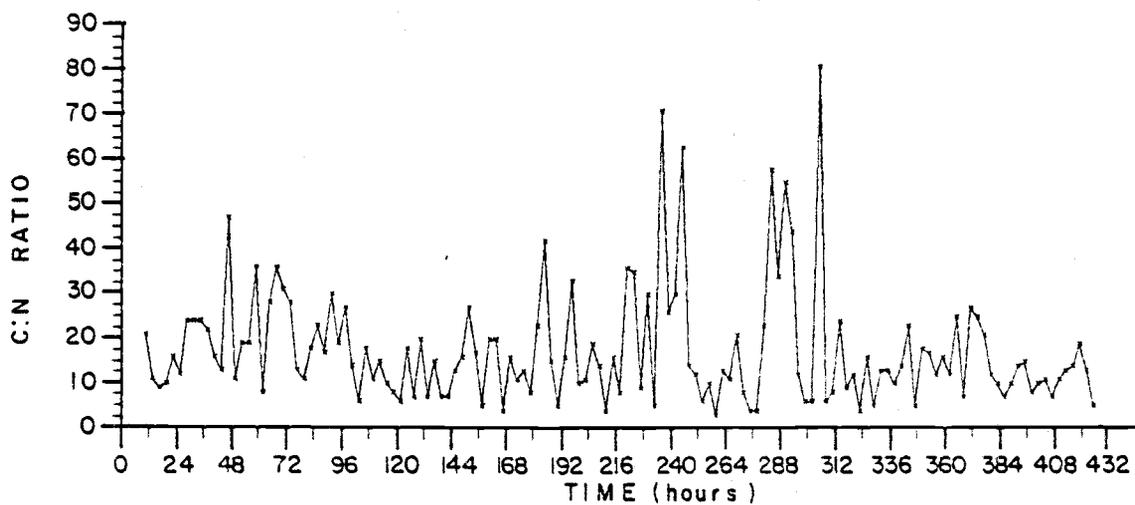


Figure 9. Particulate organic carbon-to-nitrogen ratio time series. Numbers mark midnight.

Cross correlation among variables

Table I shows the cross correlation coefficients and the number of lags (lag unit equal to one hour) between V_m , tide, $T^{\circ}C$, $S^{\circ}/_{\infty}$, O_2 , PO_4 , and chlorophyll a at the anchor station. The highest cross correlation coefficients were for V_m - tide (0.86), V_m - $T^{\circ}C$ (-0.77), and tide - $T^{\circ}C$ (-0.76), as expected. Cross correlation coefficients were lower among non-conservative variables. Those coefficients between phosphate and tide, and phosphate and V_m , were the lowest. Because of the high number of observation (> 400), cross correlation coefficients higher than 0.20 and 0.25 were statistically significant respectively, at the 95% and 99% confidence levels; however, such low coefficients indicated that only a small fraction of the variability of the dependent variable could be accounted for by linear relationship with the independent variable.

Table II shows the cross correlation coefficients and the number of lags (lag unit equal to three hours) between V_m , seston, organic and inorganic fractions, and POC and PON. The highest correlations were between total seston and its inorganic and organic fractions (0.94 and 0.50, respectively). There was low correlation between organic particulate matter and PON (0.21). All other correlation coefficients were not significant at the 95% confidence level. Of particulate interest was the lack of correlation between POC and PON, and between POC and the organic fraction of the seston.

Multiple regression analysis was applied to the data, but non-significant results were obtained when the physical-chemical properties

	Vm	TIDE	T°C	S‰	O ₂	CHl _g	PO ₄
Vm		(3) ⁺⁺ 0.86	(3) ⁺⁺ -0.77	(3) ⁺⁺ -0.51	(2) ⁺ -0.24	(5) ⁺ 0.22	(3) 0.08
TIDE			(0) ⁺⁺ -0.76	(1) ⁺⁺ -0.54	(4) ⁺⁺ 0.31	(7) ⁺ -0.22	(5) -0.05
T°C				(0) ⁺⁺ 0.53	(0) ⁺⁺ 0.54	(7) ⁺⁺ 0.26	(1) -0.16
S‰					(5) -0.14	(2) -0.18	(4) ⁺⁺ 0.36
O ₂						(4) 0.19	(1) ⁺⁺ -0.34
CHl _g							(4) -0.18

Table I. Cross correlation coefficients and number of lags (in parentheses) needed to maximize the correlation coefficients. The time series of the variables in the column at left are moved forward in time the number of lag units as indicated in each case. Lag unit equal to one hour. ++ = significance at the 99% confidence level. + = significance at the 95% confidence level.

	Vm	Seston	Org. part.	Inorg. part.	POC	PON
Vm		(0) 0.10	(0) -0.10	(0) 0.10	(1) -0.09	(1) 0.11
Seston			(0) ⁺⁺ 0.50	(0) ⁺⁺ 0.94	(0) 0.16	(1) 0.12
Org. part.				(0) 0.19	(1) 0.17	(1) ⁺ 0.21
Inorg. part.					(0) 0.15	(1) 0.06
POC						(0) 0.09

Table II. Cross correlation coefficients and number of lags (in parentheses) needed to maximize the correlation coefficients. The time series of the variables in the column at left are moved forward in time the number of lag units as indicated in each case. Lag unit equal to three hours. ++ = significance at the 99% confidence level. + = significance at the 95% confidence level.

were used as independent variables in an attempt to explain the variation in each biological property (as a dependent variable).

Spectral analysis of time series

Tidal velocity (V_m), temperature, salinity, oxygen, phosphate, and chlorophyll a variances had components basically at four frequency bands (Fig. 10). The lowest frequency component (~ 0.0025 cph) was due to the alternation of neap and spring tides, for V_m , and probably to both the alternation of upwelling events and spring and neap tides for the rest of the variables. However, upwelling events may also have occurred at frequencies different than those shown in Fig. 10 because such events are not totally predictable temporally.

The two next lowest, very prominent, frequency components were the diurnal and semidiurnal ones (~ 0.041 and 0.083 cph, respectively). The conservative variables (V_m , $T^\circ\text{C}$ and $S^\circ/\text{‰}$) showed the semidiurnal component higher than the diurnal one. This was due to the tidal effect being stronger than the effect of the solar radiation cycle on conservative variables. In the case of V_m , both the diurnal and semidiurnal components were higher than the component of lowest frequency, and in the case of $T^\circ\text{C}$, the semidiurnal component was higher. In all other cases the lowest frequency component was the highest. The non-conservative variables (O_2 , PO_4 , Chl a) showed a diurnal component equal or nearly equal to the semidiurnal one. This was due to biological processes, mainly photosynthesis and respiration, that strongly depended on the solar radiation cycle.

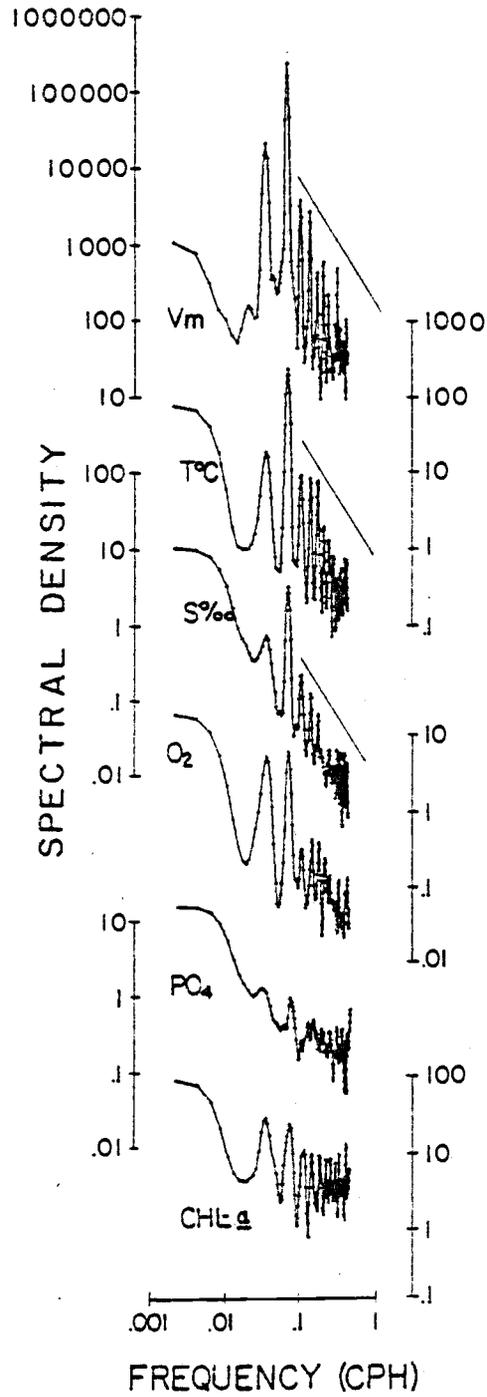


Figure 10. Spectral density of V_m , $T^{\circ}C$, $S^{\text{‰}}$, O_2 , PO_4 , and chlorophyll a. CPH = cycles per hour.

At frequencies higher than the semidiurnal one (>0.100 cph) the spectral density for V_m , $T^{\circ}C$, and $S^{\circ}/_{\infty}$ decreased with increasing frequencies. The slope was near $-5/3$, which might indicate the effect of turbulent processes as suggested by Platt (1972). The inorganic phosphate and chlorophyll a spectra yielded a zero slope in this frequency range, suggesting either 1) that these two variables were not affected by turbulent processes at the mouth of San Quintin Bay, or 2) if they were affected by turbulence, other processes such as metabolism and excretion offset the turbulence effect. The intermediate slope for the O_2 spectra in the high frequency range suggested the semi-conservative nature of O_2 ; i.e., O_2 concentrations were affected both by physical diffusion and mixing, and by biological metabolism.

Spectral analysis did not show any dominant periodicity for seston or its organic and inorganic fractions nor for particulate organic carbon and nitrogen (not illustrated). Not even the diurnal and semi-diurnal components were clear, a fact which will be discussed later.

Fluxes of properties

Only the mean fluctuation fluxes of temperature and oxygen were significantly different from zero at the 95% confidence level, which means that at the anchor station, input was equal to output over the total time interval for all properties except temperature and oxygen (Table III). Both the temperature and O_2 fluxes for the complete series were negative, which indicated export from the bay. To explore the possibility of flux differences between strong and weak upwelling

Variable	Units	F L U C T U A T I O N F L U X E S				MEAN TRANSPORT
		Strong Upwelling	Weak Upwelling	Strong Upwelling	Complete Series	Complete Series
T °C	°C·cm sec ⁻¹	- 4.91 (12.48)	-10.17 (12.74)	-14.66 (12.24)	-10.90 (7.97)	88.24
S ‰	‰·cm sec ⁻¹	0.51 (3.52)	1.67 (2.30)	0.30 (1.96)	0.46 (1.60)	196.69
O ₂	ml l ⁻¹ ·cm sec ⁻¹	-3.74 (3.82)	- 2.55 (3.50)	-3.90 (2.98)	-3.24 (2.43)	30.68
PO ₄	μM·cm sec ⁻¹	0.56 (4.48)	- 0.41 (2.44)	0.016 (3.46)	-0.50 (2.15)	9.43
Chl <u>g</u>	mg m ⁻³ ·cm sec ⁻¹	1.65 (6.38)	- 7.11 (11.04)	-9.97 (9.95)	-5.66 (6.42)	24.68
Seston	mg l ⁻¹ ·cm sec ⁻¹	-10.46 (18.56)	1.78 (36.42)	11.39 (65.60)	5.43 (30.81)	38.10
Org part.	mg l ⁻¹ ·cm sec ⁻¹	- 2.63 (11.34)	10.32 (17.62)	0.82 (11.24)	4.42 (9.62)	15.87
Inorg part.	mg l ⁻¹ ·cm sec ⁻¹	-6.74 (13.64)	- 8.74 (28.32)	10.62 (61.36)	1.15 (27.93)	22.23
POC	mg l ⁻¹ ·cm sec ⁻¹	1.47 (11.38)	7.81 (12.66)	-0.64 (16.76)	3.29 (8.56)	12.05
PON	mg l ⁻¹ ·cm sec ⁻¹	-0.14 (0.34)	-0.11 (0.62)	-0.32 (0.66)	-0.15 (0.37)	0.79

Table III. Fluctuation fluxes and mean transport for the complete time series, and fluctuation fluxes for the three upwelling related portions of the time series. Positive numbers mean fluxes into the bay. Numbers within parentheses are the errors at the 95% confidence level. Thicker numbers are the only significant ones.

events, the times series for each variable were partitioned into three time segments, using the temperature variation as a guide (Fig. 4). The first and third segments, which corresponded to strong upwelling events, were defined by those time intervals over which the diurnal temperature minima could be represented by a straight line with zero slope. The middle segment, which represented a weak upwelling event or a relaxation period, was the one where the diurnal temperature minima rose significantly. The first segment was taken from the beginning of the sampling to 2200 hours on June 23 (0 to 87 hours), the second to 1400 hours on June 30 (88 to 247 hours), and the third to the end (248 to 419 hours). Only during the third segment of the time series were there significant mean fluctuation fluxes, and only for temperature, oxygen and chlorophyll a. These mean fluctuation fluxes were all negative, suggesting export from the bay. The mean chlorophyll a fluctuation flux was barely significant.

Even though some mean fluctuation fluxes were negative, mean transports for the complete time series were all positive (Table III) due to a positive mean tidal velocity of 5.7 cm sec^{-1} calculated at the anchor station. Mean transports should be balanced at other points in the bay mouth which had negative mean velocities. The mean transports for the bay mouth cross-section should be essentially zero. The calculated non-zero (positive) mean transport might have had some effect on the negativity of the fluctuation fluxes calculated for $T^{\circ}\text{C}$, O_2 , and Chl a, but this effect, if any, could not be assessed.

Spatial distribution of the properties within the bay

Water properties were measured at different surface sampling locations inside the bay on July 6 and 7, as mentioned above (Fig. 1). Although no generalizations can be made out of single spaced samples, this was the first time that data had been obtained successively at ebb and flood flow throughout the whole of San Quintin Bay, and we gained some insight by comparing both conditions. As had been reported before (Chavez-de-Nishikawa and Alvarez-Borrego, 1974; Alvarez-Borrego, Ballesteros-Grijalva and Chee-Barragon, 1976), temperature and salinity increased from the mouth to the extrema of the bay (Table IV). Chlorophyll a had a general tendency to decrease from the mouth to the extrema. Phytoplankton abundance (cells ml⁻¹) throughout the bay were only determined during flood-flow on July 6, but in general, the total number of cells also decreased from the mouth to the extrema (Fig. 11). Cell counts up to 800 cells ml⁻¹ were obtained for the mouth stations, while for the extrema 100 cells ml⁻¹ were determined. Also, it was interesting to note the predominance of diatoms at the mouth stations, while the dinoflagellates and microflagellates were in greater abundance toward the extrema stations.

Inorganic particulate matter was in greater concentration in the eastern arm of the bay than in the western (not shown). All other measured properties did not show any clear tendency. Differences between flood and ebb values for July 6 and 7 were calculated separately for each sampling location, for all measured properties. The means of these differences were only significant (at the 95% confidence level) in the cases of salinity, phosphate, chlorophyll a, PON, and C:N ratio (Table IV). The mean values of these latter properties showed that

Sampling station	T°C		S‰		O ₂		PO ₄		Chlorophyll		Seston		ORG. PART. matter		INORG. PART. matter		POC		PON		C:N ratio	
	ebb	flood	ebb	flood	ebb	flood	ebb	flood	ebb	flood	ebb	flood	ebb	flood	ebb	flood	ebb	flood	ebb	flood	ebb	flood
1	19.3	18.5	34.82	34.45	5.73	6.30	1.18	0.98	1.30	3.65	12.4	7.6	4.3	1.8	8.8	5.8	1.56	0.96	0.23	0.20	6.7	4.8
2	19.0	18.2	34.67	34.37	5.68	5.86	1.21	1.19	1.70	3.01	20.0	7.6	12.8	0.4	7.2	7.2	2.50	2.63	0.24	0.29	10.4	9.0
3	17.8	17.9	34.56	34.29	5.68	5.30	1.25	0.83	1.40	3.77	8.1	8.6	2.1	4.0	5.9	4.6	2.28	1.29	0.09	0.07	25.3	18.4
4	17.8	18.9	34.57	34.35	5.68	5.73	1.39	0.79	2.90	3.48	10.5	9.6	5.6	3.8	4.8	5.4	2.00	1.95	0.07	0.11	28.5	17.7
5	17.0	17.5	34.52	34.24	5.70	5.70	1.15	1.01	2.00	3.74	7.8	11.9	2.7	10.5	5.1	1.3	1.56	1.03	0.06	0.09	26.0	11.4
6	15.6	17.3	34.36	34.21	5.70	5.58	1.32	0.98	2.30	4.17	9.1	7.8	3.7	5.8	5.4	2.0	1.48	1.42	0.05	0.08	29.6	17.7
7	13.8	16.5	34.20	34.15	5.69	5.11	1.32	1.15	4.40	5.80	11.3	10.4	5.4	6.0	5.9	4.4	1.16	1.95	0.07	0.09	16.5	21.6
8	14.3	14.3	34.18	33.96	5.69	5.22	1.60	1.45	5.00	3.57	11.6	18.4	4.5	12.8	7.0	5.6	1.75	1.69	0.38	0.33	4.6	5.1
9	13.5	13.0	34.08	33.82	5.73	4.87	1.40	1.41	4.30	6.03	5.9	18.4	0.3	7.6	5.6	10.8	0.90	1.29	0.35	0.31	2.6	4.1
10	17.3	17.3	34.52	34.26	5.78	6.10	1.08	1.16	4.60	3.71	8.9	16.0	4.3	7.2	4.5	8.8	2.45	2.28	0.15	0.19	16.3	12.0
11	18.5	17.9	34.72	34.29	5.57	6.30	1.03	1.03	3.10	4.14	11.6	16.4	3.2	7.6	8.4	8.8	1.42	1.23	0.05	0.15	28.4	8.2
12	19.0	18.0	34.80	34.33	5.68	4.29	0.99	1.10	2.00	3.71	9.2	15.6	2.4	7.6	6.8	8.0	2.30	2.21	0.10	0.14	23.0	15.8
13	19.3	19.5	34.81	34.72	5.60	5.29	1.50	1.24	2.30	3.48	14.0	14.4	3.2	6.0	10.8	8.4	0.90	1.03	0.06	0.12	15.0	8.6
14	19.5	19.3	34.95	34.61	5.55	5.02	1.32	1.30	2.90	3.25	10.4	18.4	4.0	7.6	6.4	10.8	1.75	1.56	0.04	0.08	43.7	19.5
15	20.1	20.0	35.22	34.85	5.62	5.07	1.39	1.13	1.60	2.81	13.6	18.4	1.6	5.2	12.0	13.2	1.16	1.95	0.07	0.09	16.6	21.6
16	20.8	20.1	35.33	34.96	5.70	5.30	1.43	1.28	1.60	4.48	10.0	16.8	0.4	4.8	9.6	12.0	1.85	1.56	0.19	0.24	9.7	6.5
\bar{X}	17.6	17.7	34.64	34.37	5.67	5.46	1.28	1.12	2.71	4.55	10.5	13.4	3.7	6.1	7.0	7.3	1.68	1.62	0.13	0.16	18.9	12.6
\bar{X}'	+0.10		-0.27		-0.21		-0.16		+1.84		+2.90		+2.40		+0.30		-0.06		+0.03		-6.30	
E	0.51		0.06		0.28		0.10		1.08		3.20		2.60		1.50		0.23		0.02		4.17	

Table IV. Surface values for variables at each sampling location (for sampling locations see Figure 1). \bar{X} = mean; \bar{X}' = mean of differences between flood and ebb stage (positive numbers indicate higher mean surface values at flood tide). E = error at the 95% confidence level. Thicker numbers are the only significant ones.

salinity, phosphate, and C:N ratio were greater during ebb-flow (negative mean differences), but chlorophyll a and PON were greater during flood-flow (positive mean differences). Taking the temperature data from the two arms of the bay (stations 1-4 and 10-16) separately from those of the region adjacent to the mouth, a difference mean of 0-34°C was calculated, with a standard error of 0.13°C. This mean was significant at the 95% confidence level, and indicated warmer water during ebb-flow during the July 6-7 period. Temperature differences near the mouth were not significant because sampling during ebb-flow was initiated at the mouth immediately after high tide, and because there was a heavy fog at the mouth due to upwelling. No other differences between arms of the bay for other properties were found.

Phytoplankton abundance and primary productivity at the anchor station

As shown earlier (Fig. 11), total phytoplankton, and particularly diatoms, were in great abundance at two stations (8 and 9) on either side of the anchor station at 1200 hours on July 6, during flood tide. However, relatively low total phytoplankton abundance was determined at the anchor station on the same date during flood tide, but two hours earlier (Fig. 12). This disparity in abundance suggested that extreme phytoplankton patchiness was affecting the sampling, and perhaps little should be made of any single sample at a given location and particular time.

The mean for total phytoplankton abundance at the anchor station was 130 cells ml⁻¹ (with a range of 20 to 405 cells ml⁻¹), and diatoms were always the most abundant group, followed by dinoflagellates and

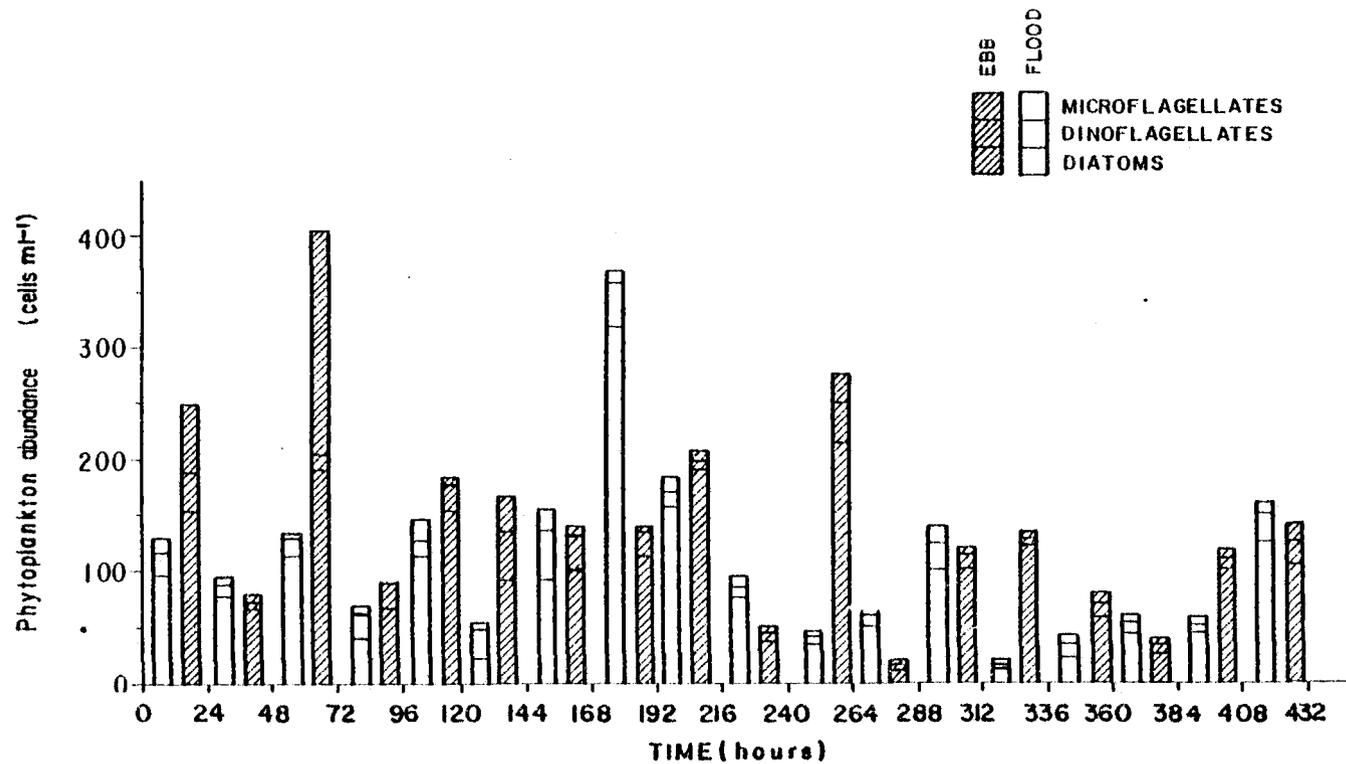


Figure 12. Phytoplankton abundance by major taxa and tidal stage at the anchor station.

microflagellates (Table V and Fig. 12). There were no significant differences between flood and ebb-flow means, at the 95% confidence level (Table V), indicating that high and low cell concentrations were spread randomly through the two tidal phases. This apparent randomness is observed in Fig. 12. Since there were only two estimates of phytoplankton abundance per day at the anchor station, times series analysis was not applied to the data. Although there was no clear variation tendency, the data (with the four highest concentration spikes removed) generally suggested somewhat less abundance during the first four and the last eight days of the sampling period (Fig. 12), with a pattern somewhat similar to patterns of chlorophyll a, oxygen, and temperature (Figs. 4, 5, and 6).

Primary productivity ($\text{mgC m}^{-3}\text{hr}^{-1}$) at the anchor station was always greater at the surface, with values decreasing regularly with depth except on June 22 (Fig. 13). Some of the primary productivity variations were due to tidal conditions and incubation times being different; e.g., the low values on June 29 (circled values) were likely due to incubations carried on during the early morning (0800), and were probably not representative of the general trend in productivity. In general, values at corresponding depths were four times greater during the upwelling relaxation period than during the upwelling events, in reasonable correlation with oxygen and chlorophyll a concentrations (Figs. 5 and 6). Productivities were somewhat lower during the first upwelling period than during the second, a fact also borne out by the plot of productivities integrated over depth ($\text{mgC m}^{-2}\text{hr}^{-1}$). The differences between surface-to-depth (0-6 m) productivity values were much greater, on average, during non-upwelling than during upwelling.

T AXONOMIC GROUP (cell ml ⁻¹)	\bar{X}	\bar{X}'	E	Max.	Min.
Diat. - f	88	-26	46	322	14
Diat. - e	114			216	11
Dino. - f	19	2.0	6.4	44	7
Dino. - e	17			65	1
Mflag. - f	5	-19	24	18	0
Mflag. - e	18			205	0

Table V. Phytoplankton abundance by gross taxonomic groups at the anchor station. \bar{X} = mean; \bar{X}' = mean of differences between flood and ebb stage. f and e = flood and ebb flow estimates, respectively, and E = error at the 95% confidence level.

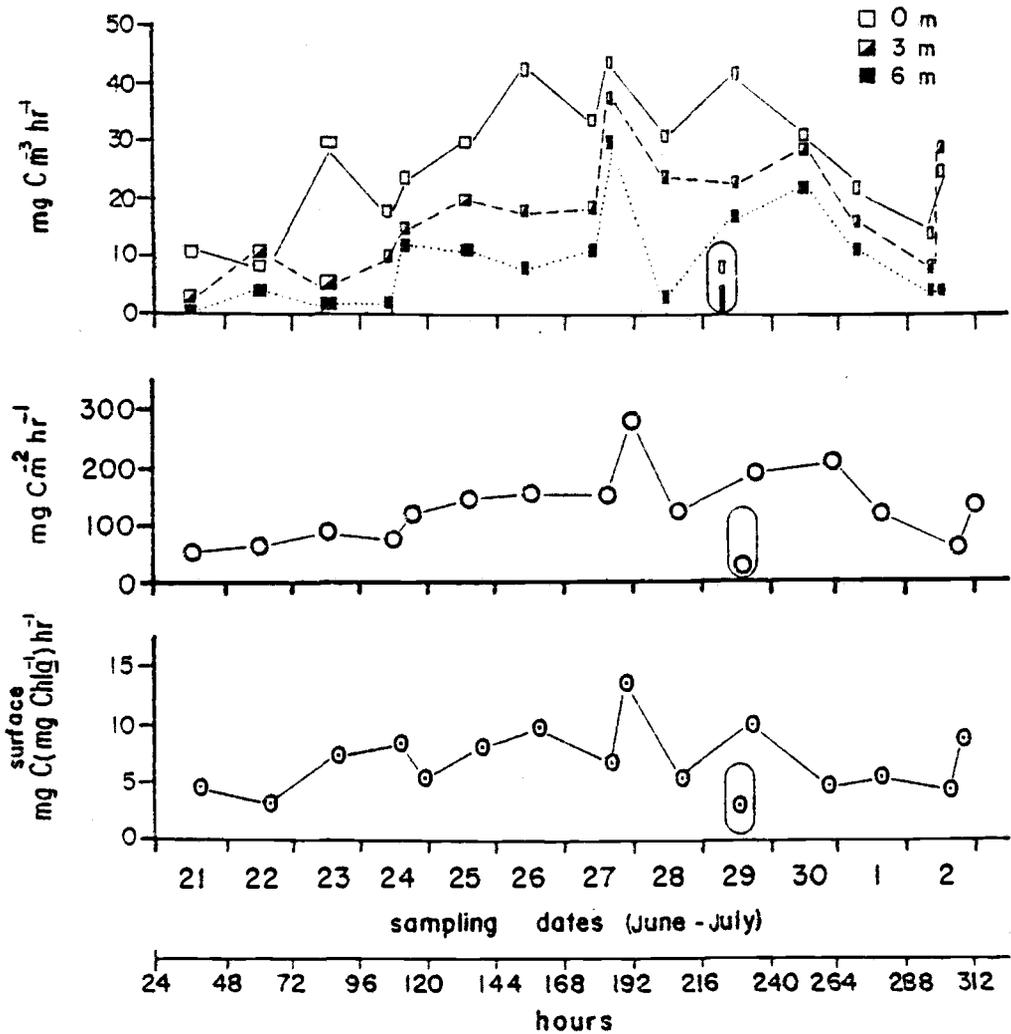


Figure 13. Primary productivity of the three sampling depths ($\text{mgC m}^{-3}\text{hr}^{-1}$) and as integrated productivity ($\text{mgC m}^{-2}\text{hr}^{-1}$), plus the maximum (surface) assimilation ratio ($\text{mgC mgChla}^{-1}\text{hr}^{-1}$), all at the anchor station. Square thicknesses indicate incubation periods. Circled values were likely due to incubations carried on during early morning (0800), and were probably not representative of the general trend in productivity.

Surface assimilation ratios [$\text{mgC}(\text{mgChl}_a)^{-1}\text{hr}^{-1}$] seemed to follow the same tendency, with somewhat lower values in freshly upwelled water (Fig. 13). However, there was no discernible difference in assimilation ratios during the two upwelling periods. The maximum assimilation ratio was coincident with the maximum surface productivity value ($13.8 \text{ mgC}(\text{mgChl}_a)^{-1}\text{hr}^{-1}$ and $44 \text{ mgC m}^{-3}\text{hr}^{-1}$, respectively). The mean surface productivity was $27 \text{ mgC m}^{-3}\text{hr}^{-1}$, with a standard error of 3.2, the mean surface assimilation ratio was $6.6 \text{ mgC}(\text{mgChl}_a)^{-1}\text{hr}^{-1}$, with a standard error of 0.7, and the mean integrated productivity was $122 \text{ mgC m}^{-2}\text{hr}^{-1}$.

DISCUSSION

In summer, upwelling off the mouth of San Quintin Bay is largely responsible for the high average inorganic nutrient and chlorophyll a concentrations in the bay. Estero de Punta Banda, a coastal lagoon inside Todos Santos Bay some 60 miles south of the U.S.-Mexican border is far away from an upwelling zone and has maximal summer inorganic phosphate and chlorophyll a concentrations of $1.3 \mu\text{M}$ and 2.6 mg m^{-3} , respectively (Alvarez-Borrego, Lara-Lara and Acosta-Ruiz, 1977), compared with the maxima of $4.4 \mu\text{M}$ and 15.7 mg m^{-3} for San Quintin Bay reported here. Estero de Punta Banda has a very dense marine grass community very similar to that of San Quintin Bay; therefore, differences in inorganic nutrients and chlorophyll a concentrations cannot be explained in terms of the relative abundance of sea-grasses. At the mouth of San Quintin Bay during winter with no upwelling, Lara-Lara and Alvarez-Borrego (1975) reported 3.5 mg m^{-3} of chlorophyll a. Parra-Valdez (1976) reported chlorophyll a diel variations in the bay for February, with a maximum chlorophyll a concentration of 3.4 mg m^{-3} . These values are 20% of the maximum reported herein for summer. Glooschenko, Curl and Small (1972) studied diel chlorophyll a variations for Oregon coastal waters. They reported maxima of 9.0 mg m^{-3} at 10 m for July, and 30.0 mg m^{-3} at 25 m for September. Huntsman and Barber (1977) reported values of chlorophyll a up to 9.0 mg m^{-3} for the Cap Blanc area off northwest Africa during May. Beers, Stevenson, Eppley and Brooks (1971) found maximum values of 8.5 mg m^{-3} for chlorophyll a off the Peru Coast in June. Chlorophyll a concentrations at the mouth

of San Quintin Bay during summer were comparable to those of other upwelling regions.

Rates of primary productivity in San Quintin Bay mouth (Fig. 13) were about 2 to 3 times greater than average rates in the Gulf of California (Zeitzschel, 1969), in the upwelling areas off the west coast of Baja California (SIO, Data Report, 1969), and off Oregon (Curl and Small, 1965). However, Small and Menzies (in prep.) have found narrow high-productivity bands in the nearshore Oregon upwelling system. Productivity rates in these bands were similar to the rates of the mouth of San Quintin Bay, and may be more comparable than rates averaged over broad upwelling zones. Similar high rates have been reported by Beers, Stevenson, Eppley and Brooks (1971), and Barber, Dugdale, MacIsaac, and Smith (1971) for the Peru upwelling zone; and by Huntsman and Barber (1977) and Smith, Barber and Huntsman (1977) for the Northwest Africa upwelling zone.

The assimilation ratios for the mouth of San Quintin Bay (Fig. 13) were comparable to those obtained by Curl and Small (1965) off the Oregon coast during upwelling (principally during the strong upwelling year of 1962). The Oregon mean value was 8.6, with a standard error of 0.6. This value indicated nutrient rich waters. In other years off Oregon, including some weak upwelling years, the mean assimilation ratios for different conditions ranged from 3.1 to 6.7 (Small, Curl and Glooschenko, 1972), representative of the values in San Quintin Bay during the two upwelling events. Huntsman and Barber (1977) reported assimilation ratios from 2.5 to 8.0 $\text{mgC}(\text{mgChl}_a)\text{hr}^{-1}$ for the northwest Africa upwelling region, and other upwelling regions experienced about the same ranges.

The generation of time series to study the variability of seawater properties is a relatively old technique. Legendre (1908) explained the oxygen, temperature, salinity and density variations in the coastal zone of Concarneau, France, in terms of tidal and solar radiation cycles by generating time series as long as 22 days. He concluded that photosynthesis was the most important variation factor for the oxygen concentration, and aereation by wind-induced turbulence was secondary. However, the application of proper mathematical techniques for time series analysis is relatively new in marine ecology (Platt and Denman, 1975; and others cited therein).

Spectral analysis of salinity, temperature, oxygen, phosphate and chlorophyll a time series showed that their variability, at the mouth of San Quintin Bay was mainly caused by three factors during summer: upwelling events and tidal and solar radiation cycles. During winter, upwelling is two orders of magnitude weaker than during summer (Bakun, 1973); thus, tidal and solar radiation cycles should be the two most important variation factors in winter. At frequencies higher than the semidiurnal one (~ 0.1 cph) the spectral density for tidal velocity, temperature and salinity showed a decreasing slope of about $-5/3$ (Fig. 10), indicating the effect of turbulent processes on these variables. However, contrary to Platt's (1972) results for the Gulf of St. Lawrence, chlorophyll a did not show a slope in spectral density at high frequencies, suggesting that at the mouth of San Quintin Bay, the turbulent effects on chlorophyll a distribution may have been masked by the predominance of biological processes. The biological processes were in turn affected by the occurrence of upwelling events. Low chlorophyll a

concentrations at the beginning and at the end of the full time series (Fig. 6) were the result of recently upwelled water which had not yet experienced high phytoplankton production. At the middle of the sampling period, surface water, probably charged with nutrients from the previous upwelling, had a greater residence time off the bay mouth. The somewhat longer residence time of upwelled water in the lighted zone would present ideal culture conditions for phytoplankton growth. Perhaps the new water was "conditioned" in the sense of Barber and Ryther (1969); that is, certain unavailable micronutrients in the freshly upwelled water became available through chelation as the water aged, and phytoplankton populations responded by growing rapidly. The productivity time series (Fig. 13) verified the faster growth during this non-upwelling period. Whatever the exact mechanism for initiating increased production, the nutrients were more effectively used during this period, and chlorophyll a, as a measure of living biomass in the water column, increased (Fig. 6).

The phosphate series (Fig. 5) tended to support the suggestion of greater nutrient utilization during the period of greater residence time of surface water off the bay mouth. Even though much of the phosphate at the bay mouth could conceivably have originated from remineralization in the bay interior (see later), the decrease in phosphate levels after about 80 hours (Fig. 5) coincided reasonably well with the onset of chlorophyll a and primary productivity enhancement. The spectral distribution of phosphate at high frequencies (Fig. 10) matched that of chlorophyll a fairly well, which could be construed as further evidence that phosphate levels were influenced heavily by biological activity.

Disregarding the spike of inorganic phosphate between 288 and 336 hours for the moment (Fig. 5), there was no general increase in phosphate level during the second upwelling period, that was concomitant with declining chlorophyll a and productivity values. This lack of reciprocal adjustment might suggest that upwelling events in adjacent ocean waters did not totally control phosphate concentrations near the bay mouth. If upwelling intrusions were largely responsible for chlorophyll and phosphate distributions in the bay mouth, phosphate levels would be expected to be high when chlorophyll a levels were low, and vice versa. Interestingly, salinity values for the second upwelling period did not increase over the preceding non-upwelling period, either (Fig. 4) implying that bay-mouth salinity also was not always directly influenced by an upwelling event in the adjacent ocean. It appears that the intensity of upwelling events might be significant in determining concentrations of properties at the bay mouth. If the second upwelling event was not as intense as the first, relatively low bay-mouth phosphate levels and salinity levels (probably near-surface levels in adjacent ocean water) conceivably could have occurred simultaneously with relatively low primary productivity and biomass levels. The higher oxygen levels during the second upwelling event, relative to the first event (Fig. 5) also suggested a shallower source water for the bay mouth during the second event.

The most striking feature in the phosphate series during the last upwelling period was the spike of high inorganic phosphate in the water between 288 and 336 hours (Fig. 5). This spike was preceded slightly by a large seston spike between about 250 and 310 hours (Fig. 6). The

inorganic fraction of the seston was responsible for the total seston spike (Fig. 7). These spikes were caused by intensified winds which stirred the bottom sediments into the water column. Sediments are easily trapped by the bottom sea-grass beds during calm periods, and just as easily resuspended when the wind stress increases. Even though spectral analyses of the time series of total seston and its organic and inorganic fractions showed the effect of upwelling events (not illustrated), semi-diurnal and diurnal cycles were completely obscured by the sporadic wind-induced suspension of sediments. It appeared that particles controlled from the oceanside of the bay (i.e., chlorophyll a) showed well-defined spectra, but particles subjected to sporadic releases from the bay (seston, and its fractions) showed no short-frequency spectral components.

Phosphate was undoubtedly released from the sediments during these wind events, to add substantially to the dissolved load in the water column. The fact that the phosphate spike lagged somewhat behind the inorganic seston spike might indicate time lag in remineralization of dissolved inorganic phosphate from the particulate seston load once it is in the water column.

Carbon and nitrogen contents of the organic fraction of the seston (POC and PON, respectively) were not related to much of anything, including each other (Fig. 8, Table II). This indicated that the organic fraction of the seston was a heterogenous mixture in space and time of mostly detrital material. Unfortunately phytoplankton biomass was not determined, but it can be grossly estimated to be only 1-2% of the suspended particulate organic matter. A high proportion of the detritus

might always be generated by decay of the sea-grasses themselves. Odum and de la Cruz (1967) estimated that 95% of the detritus of a Georgia salt marsh originated from decaying Spartina grass, for example.

The C:N ratio of the suspended particles had a very wide range (3.0 to 81.8, with a mean of 18.0, Fig. 9). The C:N ratio by weight in healthy phytoplankton, under conditions of nutrient sufficiency, should theoretically be in the range of 6.0 to 7.0, despite slight species differences (Redfield, Ketchum and Richards, 1963). Because the phytoplankton was a very small fraction of the particulate organic matter in San Quintin Bay, the factor that most frequently regulated the C:N ratio undoubtedly was the detritus and the bacterial activity on the detritus. Harrison and Mann (1975) reported a C:N ratio of 20 for Zostera marina, while McIntire and Dunstan (1976) found C:N ratios for Spartina alterniflora from 23.0 to 63.0 in summer, and Knauer and Ayers (1977) reported mean C:N ratios for Thalassia testudinum in Florida of 17.9. All have concluded that increasing bacterial populations tended to increase the nitrogen content of the detritus. Otherwise, the C:N ratios might have been much higher. The lowest C:N values in the above studies and in San Quintin Bay might have arisen from phytoplankton or highly bacterized organic particles, or both.

During the sampling period in San Quintin Bay, no significant export of total seston (or its organic and inorganic components) to the open ocean was detected (Table III). Export of T[°]C, O₂, and Chl a was detected during the second upwelling event (June 30-July 7), but it was felt that this export might have been an artifact caused by single-station sampling at the bay mouth. Most of the data indicate that the two ecosystems, the lagoon and the adjacent open ocean, have very similar values for the

measured seawater properties. Conceivably, much of the water that goes out from the lagoon during ebb-flow comes back into the lagoon during flood-flow. This phenomenon can happen if there are relatively weak net horizontal currents in the adjacent ocean; however, there are no data to support this. With data on tides and the bathymetry of San Quintin Bay, a rough estimate of the water volume at low tide ($15 \times 10^6 \text{m}^3$) and at high tide ($75 \times 10^6 \text{m}^3$) indicates that up to 80% of the water from the bay may go out. Velocities during ebb-flow were lower than those of flood-flow, but ebb-flow lasted longer. The 410 data points for each variable measured at the anchor station were composed of 213 ebb-flow values and 197 flood-flow values. This asymmetrical temporal pattern of flow has been reported for marshes (Boon, 1975; Valiela, Teal, Volkman, Shafer and Carpenter, 1978).

Statistically significant differences between flood-ebb values were obtained for some properties within the bay during two days of the second upwelling period, when all surface sampling stations (not just the anchor station) were examined (Table IV). Negative values for salinity, phosphate and C:N indicated greater contributions from the ebb tide. This finding suggested that, even during an offshore upwelling event (though probably a weak one), the bay taken as a whole could act as an evaporation basin and as a nutrient remineralization region and detritus trap. A strong offshore upwelling condition might have reversed the condition (higher salinity and phosphate concentrations on flood tide). Contrary to the salinity and phosphate data for the same two-day time

period, however, positive mean values for chlorophyll a and PON were recorded for the bay as a whole (Table IV). Positive values indicated net inputs of these properties on the flood tide. It must be remembered that negative (export) values for chlorophyll a were estimated at the anchor station for this third time segment, in apparent contradiction to the positive (input) chlorophyll values reported above. The positive values were derived from only two concurrent days of sampling the whole bay, the negative values from analysis of fluctuations from the mean chlorophyll value at the anchor station over an eight-day period. Conceivably there could have been net input over the two-day period, but net export over the eight-day period. It must be remembered that the error associated with the negative (export) value was large, almost equal to the value itself (Table III). The chlorophyll distributions must have been patchy in time to have such a large error. Some notion of patchiness at the anchor station can be gained from examination of the phytoplankton cell variability in Fig. 12. Of course the patchiness problem was just as real with the two-day, whole-bay sampling scheme (Table IV) as with the anchor station series. The mean difference between ebb and flood chlorophyll a values for the whole bay (1.84 mg m^{-3}) also had a large error term associated with it (1.05 mg m^{-3}). Any other two-day segment during the second upwelling period, or for that matter any other sampling hours during the same two-day period, could have yielded different results. Probably the major differences in properties in the bay are always going to be seen on time scales of upwelling events and greater, unless the sampling program is changed. Thus, seasonal

differences in properties can now be documented, and from the present study differences between upwelling events and relaxation of upwelling can be observed. Finer scale analyses must await finer resolution sampling.

GENERAL CONCLUSIONS

At the beginning of this work two main problems were addressed: first, to investigate which processes cause the variability of ecological properties at the mouth of San Quintin Bay, and second, to ascertain the fluxes of properties that couple this coastal lagoon and the adjacent oceanic area. These two questions were stated in the context of understanding more about the potential capacity of the lagoon as an aquaculture ecosystem. Again, the three main processes that cause variability of the different properties at the San Quintin Bay mouth are upwelling events and the cycles of tides and solar radiation. With high variability of properties, no significant net fluxes of materials were found during the sampling period, even though concentrations of materials were high in the lagoon. This led to the conclusion that San Quintin Bay is linked to a highly productive system off the bay mouth, and that upwelling events and the relaxation of upwelling mainly dictate the concentrations of properties at the bay mouth, in time scales of several days to weeks. There is some evidence that production can be somewhat different inside and outside the bay, with slightly different materials in ebb and flood tides. Even though variability was high, it appeared that the offshore system at times could contribute living phytoplankton biomass on the flood tide, and the interior of the bay could contribute phosphate, salinity, and particles with high C:N ratios. How often, how long, and under exactly what conditions these imbalances occur is not known at this time.

It is unquestionable that the marsh grasses in the bay contribute importantly to the fertility of the bay, in the sense of direct photosynthetic production and as traps for nutrients and small particles. As a result, the energy flow in the bay should follow a complex food-web pattern in which microbial enriched detritus from decaying marsh grass plays a major part. From the viewpoint of potential consumers, fertility is a matter of both suspended and sedimented particles (plankton and detritus). The water is muddy, but this so-called "mud" likely is full of food energy for those organisms which can filter it. To harvest this fertility one naturally thinks of both suspension and deposit feeders. All the above characteristics make San Quintin Bay a potential site for cultures of filter feeders. Oyster culturing already has begun in this ecosystem, with initially successful results. The challenge now is to determine how to use San Quintin Bay optimally; i.e., how far should, or can we go in promoting mariculture before the culturing itself begins to change the environment?

LITERATURE CITED

- Alvarez-Borrego, S., G. Ballesteros-Grijalva, and A. Chee-Barragan. 1975. Estudio de algunas variables fisicoquimicas superficiales en Bahia San Quintin, en verano, otoño e invierno (In Spanish). *Ciencias Marinas*, 2(2):1-9.
- Alvarez-Borrego, S., and C. Lopez-Alvarez. 1975. Distribucion de biomasa de fitoplancton por grupos taxonomicos en Bahia San Quintin, B. C. a traves de un ciclo anual (In Spanish). Reporte para I.N.P. de la S.I.C. y la Direccion de Acuicultura de la S.R.H. (Unpublished).
- Alvarez-Borrego, S., and A. Chee-Barragan. 1976. Distribucion superficial de fosfatos y silicatos en Bahia San Quintin, B. C. (In Spanish). *Ciencias Marinas* 3(1):51-61.
- Alvarez-Borrego, S., M. de J. Acosta-Ruiz, and J. R. Lara-Lara. 1977. Hidrologia comparativa de las bocas de dos antiestuarios de Baja California (In Spanish). *Ciencias Marinas*, 4(1):1-11.
- Alvarez-Borrego, S., J. R. Lara-Lara, and M. de J. Acosta-Ruiz. 1977. Parametros relacionados con la productividad organica primaria en dos antiestuarios de Baja California (In Spanish). *Ciencias Marinas*, 4(1):12-21.
- Bakun, A. 1973. Coastal Upwelling Indices, west coast of North America 1964-71, NOAA Technical report NMFS SSRF - 671, 103 p.
- Barber, R. T., and J.H. Ryther. 1969. Organic chelators: factors affecting primary production in the Cromwell Current upwelling. *Journal of Experimental Marine Biology and Ecology*. 3:191-199.
- Barber, R.T., R. C. Dugdale, J. J. MacIsaac, and R. L. Smith. 1971. Variations in phytoplankton growth associated with the source and conditioning of upwelling water. *Inv. Pesq.* 35(1):171-193.
- Barnard, J. L. 1962. Benthic marine exploration of Bahia de San Quintin, Baja California, 1960-1961. *Pac. Nat.*, 2(6):251-269.
- Beers, J. R., M. R. Stevenson, R. W. Eppley, and E. R. Brooks. 1971. Plankton populations and upwelling off the coast of Peru, June 1969. *Fishery Bull.* 69(4):859-876.
- Boon, J. D. III. 1975. Tidal discharge asymmetry in a salt marsh drainage system. *Limnol. Oceanogr.* 20:71-80.
- Chavez-de-Nishikawa, A. G., and S. Alvarez-Borrego. 1974. Hidrologia de Bahia San Quintin en invierno y primavera (In Spanish). *Ciencias Marinas*, 1(2):31-62.

- Cooley, J. W. and J. W. Tukey. 1965. An algorithm for the machine calculation of complex Fourier series. *Math. Comput.* 19:297-301.
- Curl, H. Jr. and L. F. Small. 1965. Variations in photosynthetic assimilation ratios in natural marine phytoplankton communities. *Limnol. Oceanogr.* 10, supp.:R67-R73.
- Dawson, E. Y. 1951. A further study of upwelling and vegetation along Pacific Baja California. *Jour. Mar. Res.* 10(1):39-58.
- Dawson, E. Y. 1962. Marine and marsh vegetation. Benthic marine exploration of Bahia de San Quintin. Baja California. 1960-1961. *Pac. Nat.* 3(7):275-280.
- Fofonoff, N. P. 1969. Spectral characteristics of internal waves in the ocean. *Deep Sea Res., Supp.*, 6:58-71.
- Glooschenko, W. A., H. Curl, Jr., and L. F. Small. 1972. Diel periodicity of chlorophyll a concentration in Oregon coastal waters. *J. Fish. Res. Bd. Canada* 29:1253-1259.
- Harrison, P. G. and K. H. Mann. 1975. Detritus formation from eelgrass (Zostera marina L.): the relative effects of fragmentation, leaching, and decay. *Limnol. Oceanogr.* 20:924-934.
- Huntsman, S. A. and R. T. Barber. 1977. Primary production off Northwest Africa: the relationship to wind and nutrient conditions. *Deep Sea Res.* 24:25-33.
- Jenkins, G. M. and D. G. Watts. 1969. Spectral analysis and its applications. San Francisco: Holden-Day. 525 pp.
- Knauer, G. A. and A. V. Ayers. 1977. Changes in carbon, nitrogen, adenosin triphosphate, and chlorophyll a in decomposing Thalassia testudinum leaves. *Limnol. and Oceanogr.* 22(3):408-414.
- Krey, J. 1950. Eine neue methode zur quantitativen bestimmung des planktons (In German). *Kieler Merresforsch.* 7:58-75.
- Lankford, R. R. 1976. Coastal lagoons of Mexico, their origin and classification. In M. Wiley (ed.), *Estuarine processes*. Academic Press.
- Lara-Lara, J. R. and S. Alvarez-Borrego. 1975. Ciclo anual de clorofilas y produccion organica primaria en Bahia de San Quintin, B. C. (In Spanish). *Ciencias Marinas*, 2(1):77-97.
- Legendre, R. 1908. Recherches océanographiques faites dans la région littorale de Concarneau pendant l'été de 1907 (In French). *Bulletin de L'Institut Océanographique.* 111:1-29.

- Lorenzen, C. J. 1967. Determination of chlorophyll and phaeo-pigments: spectrophotometric equations. *Limnol. Oceanogr.* 12:343-346.
- McIntire, G. L. and W. M. Dunstan. 1976. Seasonal measurements of carbon, nitrogen, ash, iron, carbohydrates, and pigments from geographically different Spartina alterniflora marshes in the southeast. Unpublished manuscript, MAREX Tech. Report 76-5.
- Millan-Nuñez, R. and S. Alvarez-Borrego. 1978. Ecuaciones espectrofotométricas tricromáticas para la determinación de clorofilas a, b, c y sus feofitinas (In Spanish). *Ciencias Marinas*, 5(1):47-55.
- Morris, I., C. M. Yentsch, and C. S. Yentsch. 1971. Relationship between light carbon dioxide fixation and dark carbon dioxide fixation by marine algae. *Limnol. Oceanogr.* 16(6):854-858.
- Ochs, L., J. A. Baughman, and J. Ballance. 1970. OS-3 ARAND SYSTEM: Documentation and examples, Vol. I. CCR-70-4. OSU Computer Center, OSU, Corvallis, Oregon. 158 pp.
- Odum, E. P., and A. A. de-la-Cruz. 1967. Particulate detritus in a Georgia salt marsh estuarine ecosystem, p. 383-388. In G. H. Lauff (ed.), *Estuaries*. Publ. Am. Assoc. Adv. Sci. 83.
- Parra-Valdez, E. 1976. Variaciones diurnas de clorofila a y estimaciones de productividad orgánica primaria en dos antiestuarios de Baja California, en Otoño e Invierno (In Spanish). B. S. Thesis. Escuela Superior de Ciencias Marinas, Universidad Autónoma de Baja California. Ensenada, Baja California. 42 pp.
- Peterson, R. E. 1977. A study of suspended particulate matter: Arctic Ocean and Northern Oregon Continental Shelf. Ph.D. thesis, Oregon State University, Corvallis. 122 pp.
- Platt, T. 1972. Local phytoplankton abundance and turbulence. *Deep Sea Res.* 19:183-187.
- Platt, T. and K.L. Denman. 1975. Spectral analysis in ecology. *Ann. Rev. of Ecol. and Syst.* 6:189-210.
- Platt, T., and R. J. Conover. 1971. Variability and its effect on the 24h chlorophyll budget of a small marine basin. *Mar. Biol.* 10(1):52-65.
- Redfield, A. C., B. H. Ketchum, and F. A. Richards. 1963. The influence of organisms on the composition of seawater. In M.N. Hill (ed.), *The Sea*. Vol. 2. John Wiley, London.

- SCOR-UNESCO. 1966. Determination of photosynthetic pigments. Monogr. Oceanogr. Methodol. 1-18 p.
- Shoaf, W. T., and B. W. Lium. 1976. Improved extraction of chlorophyll a and b from algae using dimethyl sulfoxide. Limnol. Oceanogr. 21(6):926-928.
- Scripps Institution of Oceanography. 1969. Cruise TO-64-1 and cruise TO-64-2. Data Report. University of California at San Diego, Scripps Institution of Oceanography Reference 69-4. 57 pp.
- Smith, W. O. Jr., R. T. Barber, and S. Huntsman. 1977. Primary Production off the coast of Northwest Africa: excretion of dissolved organic matter and its heterotrophic uptake. Deep Sea Res. 24:35-47.
- Steeman-Nielsen, E. 1952. The use of radioactive carbon for measuring organic production in the sea. J. Cons. Perma. Int. Explor. Mer. 18:117-140.
- Strickland, J. D. and T. R. Parsons. 1972. A practical handbook of seawater analysis. 2nd ed. Bull. Fish. Res. Bd. Can. 167.
- Utermöhl, H. 1958. Zur Vervollkommnung der quantitativen Phytoplankton-Methodik (In German). Mitt. int. Verein theor. angew. Limnol. 17,47.
- Valiela, I., J. M. Teal, S. Volkmann, D. Shafer, and E. J. Carpenter. 1978. Nutrient and particulate fluxes in a salt marsh ecosystem: Tidal exchanges and inputs by precipitation and ground-water. Limnol. Oceanogr. 23(4):798-812.
- Wastler, T. A. 1969. Spectral analysis: application in water pollution control. Federal Water Pollution Control Administration. U. S. Department of the Interior. Washington, D. C. 20242.
- Zeitzschel, B. 1969. Primary productivity in the Gulf of California. Mar. Biol. 3:201-207.
- Zertuche-Gonzalez, J. A. and S. Alvarez-Borrego. 1978. Series de tiempo de variables fisicoquimicas en las bocas de dos antiestuarios de Baja California (In Spanish). Ciencias Marinas, 5(1):91-103.