MARINE FARMING THE COASTAL ZONE: CHEMICAL AND HYDROGRAPHIC CONSIDERATIONS

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ABSTRACT

Hydrographic and marine chemical observations are reported in the vicinity of a pilot-scale kelp farm (0.1 hectare) that depends on artificial upwelling of nutrients in the Southern California Bight. Measurements of temperature, salinity, dissolved oxygen, phosphate, nitrate, silicate, and trace metals (Cu and Ni) were made from January 1979 to June 1980 as close as practicable to the facility moored near the 500-m isobath about 10 km SSW of Corona del Mar, California.

The hydrographic results complemented the historical record of conditions in the bight and disclosed several aspects of concern to coastal marine farming projects. The facility depended on nutrients artificially upwelled from a depth of 450 m. Nitrate and phosphate are critical nutrients for giant kelp *(Macrocystis pyrifera)* culture. They were found in abundant supply, averaging 35.3 and 3.00 μM, respectively, during the study period. Though not critical for kelp nutrition, silicate and oxygen concentrations were the most variable parameters in the deep water. Significant fluctuations in nutrient concentration were noted throughout the water column during upwelling events.

Profiles of total copper suggest that surface gyre circulation coupled with anthropogenic pollution in the Southern California Bight cause copper levels 2-5 times higher than those observed at offshore stations in the California Current by previous workers. Our observations confirm existing concepts of metal enrichment in nearshore marine environments relative to oceanic conditions, with implications for mariculture in the coastal zone.

RESUMEN

Observaciones hidrográficas y químicas marinas han sido reportadas en la vecindad de una granja experimental de algas (0.1 hectárea) en la Bahía del Sur de California que depende de la surgencia artificial de nutrientes. Medidas de temperatura, salinidad, oxígeno disuelto, fosfato, nitrato, silicato, y metales de bajas concentraciones (Cu y Ni) fueron hechas desde enero de 1979 hasta junio de 1980, lo más cerca posible a la instalación anclada cerca de la isóbata de 500 m localizada a una distancia aproximada de 10 km al sur-sudoeste de Corona del Mar, California.

Los resultados hidrográficos complementaron el registro histórico de condiciones en el área y revelaron varios aspectos de importancia para proyectos de granjas marinas costeras. La instalación dependía de nutrientes surgidos artificialmente desde una profundidad de 450 m. Nitratos y fosfatos son nutrientes absolutamente necesarios para el cultivo de *Macrocystis pyrifera.* Estos fueron encontrados en abundancia durante el estudio, con promedios respectivos de 35.3 y 3.00 μM. Aunque las concentraciones de silicato y oxígeno no son críticos para la nutrición de algas, dichas concentraciones fueron los parámetros más variables en la zona profunda. Se observaron fluctuaciones significativas en la concentración de nutrientes por toda la columna de agua durante la surgencia.

Los perfiles de cobre total sugieren que la circulación del giro superficial junto con la contaminación antropogénica en la Bahía del Sur de California aumenta los niveles de cobre de 2 a 5 veces más que en las estaciones de fuera de la costa en la Corriente de California observados por otros investigadores. Nuestras observaciones confirman los conceptos existentes acerca del enriquecimiento por metales en medio ambientes marinos cercanos a la costa relativo a condiciones oceánicas, con implicaciones para la maricultura en la zona costera.

INTRODUCTION

Increasing scarcity of critical natural resources has focused attention on developing the fertile coastal zone.

Marine scientists of diverse specializations are greatly concerned with the impacts of use and management of these areas. Coastal developments for mineral extraction, ocean-thermal energy conversion, desalination, fisheries management, or marine farming operations have recently progressed beyond planning to preliminary or pilot-plant stages. Site surveys utilizing the historical data base provide valuable information for initial designs. However, there are few

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coastal zones for which an adequate site-specific literature exists. The dynamics of the coastal environment, human population influence, proximity to shore installations, environmental impact, and the particular needs of a project are interrelated factors that must be considered for optimum site selection. The situation is further complicated for marine farming ventures because nutritional requirements are of paramount importance.

This study details chemical and hydrographic conditions in the vicinity of a pilot-scale marine kelp farm supported by artificial upwelling of deep nutrient-rich water in the Southern California Bight. Serial on-site monitoring of oceanographic conditions disclosed unique aspects of the region that were not evident from the past literature.

The giant kelp, *Macrocystis pyrifera,* is a brown alga with potential for large-scale nearshore farming to provide chemicals or energy via anaerobic digestion of its biomass. Kelp harvesting has been practiced for nearly 70 years in the natural beds off the California coast, and even longer elsewhere (Chapman 1970). Recently, the potential of kelp tissues as an alternative energy source has been investigated in a program known as the Marine Biomass Project. Field observations and experiments with juvenile plants and gametophytes have established minimum nutrient requirements for growth. Nitrogen appears to be the most critical nutrient (North 1980), and levels below 3 μM may be suboptimal. Availability of nutrient-rich deep water, together with logistic constraints, resulted in the choice of a site for a pilot-scale marine farm as noted in Figure 1.

The range of field conditions (temperature, nitrate-ammonia, phosphate, etc.) that are associated with a "healthy" status among coastal kelp beds is fairly well defined. Relations between many of these physical-chemical parameters and kelp growth have been studied in the laboratory. Because oceanic surface waters are typically low in N and P, it is clear that plants on a marine farm would have to be fertilized. The need for maintaining a positive energy balance dictates that only artificially upwelled deep water can be used for fertilizing marine farms. Cost considerations indicated that an experimental farm moored in water several hundred meters deep would be the cheapest method of obtaining the large volumes of deep water needed.

The present study deals primarily with chemical micronutrient and trace element distributions in the vicinity of a marine farm moored at the 500-m isobath off the coast of southern California. This study assessed the available nutrient supply via artificial upwelling, emphasizing extreme conditions that might be obstacles to year-round farming. Results are presented so as to complement the historical data base, focusing on actual site conditions as contrasted to regional averages.

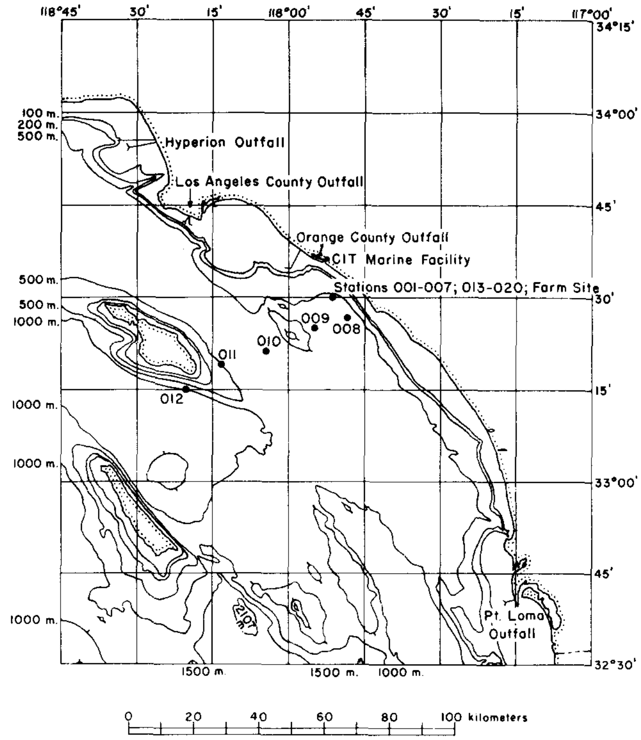

Figure 1. Locations of transect stations and of the moored test farm.

MATERIALS AND METHODS

The study involved standard oceanographic techniques; unless otherwise indicated, guidelines of the U.S. Naval Oceanographic Office (1968) were followed for each station. Fifteen serial hydrographic stations were occupied at the farm site (Figure 1) between January 1979 and June 1980. Station locations were as near as practicable to the moored facility, between the 500-m and 600-m isobaths at the head of the San Diego Trough. The location was semiprotected by offshore islands. The late summer movement of the California Undercurrent has been tracked along the continental margin as far north as Oceanside, California (Tsuchiya 1976). A SW-NE transect of the area was therefore conducted in September 1979 to determine if such deepwater movements materially affected hydrographic conditions at the study site. Five stations were occupied on this transect. The geostrophic approximation was made to calculate the current regime using the computer program OCLDAT4 (NOAA, Ocean Chemistry Laboratory 1979). The deepest common depth between the stations (500 m) was chosen as the level of no-motion.

Acid-washed PVC "go-flo" Niskin bottles of 5-l capacity were used for water sampling. Salinity, dissolved oxygen, reactive phosphate, and silicate were determined within 48 hours on subsamples stored at 4°C. Analytical procedures and observed precision limits are shown in Table 1. Copper and nickel were determined in acid-preserved subsamples collected with rigorous precautions against contamination. These subsamples were taken from each Niskin bottle immediately after oxygen samples were drawn. Shipboard metal sampling procedures included rinsing the sampling valve with Milli-Q water, flushing the polyethylene transfer line (leading to a lucite-supported glove bag) with at least one liter of sample, rinsing the 250-ml polyethylene sampling bottle and cap (within the glove bag) twice, and finally taking the sample and adding 500 μl of G.F. Smith redistilled HC1 to preserve it for analysis. Analyses used a modification of the cobalt-APDC coprecipitation method described by Boyle (1976).

All subsequent sample transfers and digestions were conducted in a clean hood flushed with HEPA-filtered laboratory air. Possible contamination from the hydrowire was checked by taking surface samples from a rubber raft at least 100 m upswell from the research vessel in carefully cleaned one-liter polyethylene bottles. Samples were split for duplicate determinations by the technique described above. Flameless atomic absorption measurements were made on digested concentrates using a Varian AA-6 instrument with graphite furnace atomization capability. Oxygen-free filtered nitrogen or argon provided an inert atmosphere for the dry, char, and atomization steps. Instrument settings used to optimize sensitivity differed little from those reported by Boyle (1976), Boyle et al. (1977),

TABLE 1
Analytical/Sampling Errors of Hydrographic Parameters

Parameter (method)	Symbol	(N)*	Mean ± 2 (standard deviations)	Percent deviation
Salinity (A)	S‰	(170)	34.922 ± 0.004	0.01
Temperature	T (°C)		(Traceable to NBS standard thermometers, reading error ±0.05C°)	
Oxygen (B)	O_2 (mL/L)	(85)	2.50 ± 0.03	1.2
Phosphate (C)	PO_4 (μM)	(40)	1.60 ± 0.16	10
Silicate (D)	$Si(OH)_4^=$ (μM)	(40)	50.0 ± 0.75	1.5
Nitrate (E)	NO_3^- (μM)	(40)	20.0 ± 0.8	4
Nickel (F)	Ni (nM)	(13)	5.0 ± 0.61	12.2
Copper (F)	Cu (nM)	(11)	7.5 ± 0.79	10.5

*N = Number of duplicate standards run during the project period.
Methodology covered in *Hydro-Lab Procedure Manual* of the Kelp Habitat Improvement Project.
A —High-precision induction salinometry, Beckman RS-7C.
B —Iodometric titration, Carpenter modification (1965).
C,E —Strickland and Parsons (1972) 2nd edition.
D —Fanning and Pilson (1973).
F —Boyle (1976).

and other workers (Bruland et al. 1979).

Sampling was performed from the R/V *Osprey* and R/V *Ms. Acrylic* of the California Institute of Technology. Several stations were occupied from the R/V *Westwind*, a commercial vessel.

RESULTS AND DISCUSSION

Hydrography of the Farm Site

Hydrographic results (Figures 2 and 3) for the eighteen-month period from January 1979 to June 1980 included monthly data for stations CIT-001→007 and 013→020. Average oceanographic conditions at the site were similar to those previously reported (Reid et al. 1958). Holm-Hansen et al. (1966) have fully discussed biological implications of these chemical distributions for a station off the California coast. Seasonal variations in the thermohaline properties of the water column were considerable. Upwelling is a regular occurrence off the west coast of the Americas and is most intense in the Southern California Bight in the spring. It was observed to compress the base of the shallow thermocline from 100 to 40 meters and increased the slope (C°•m^{-1}) from −0.06 to −0.25.

Apart from upwelling events, temperature and salinity distributions at the site were similar to "California shelf" water described by Emery (1960). This

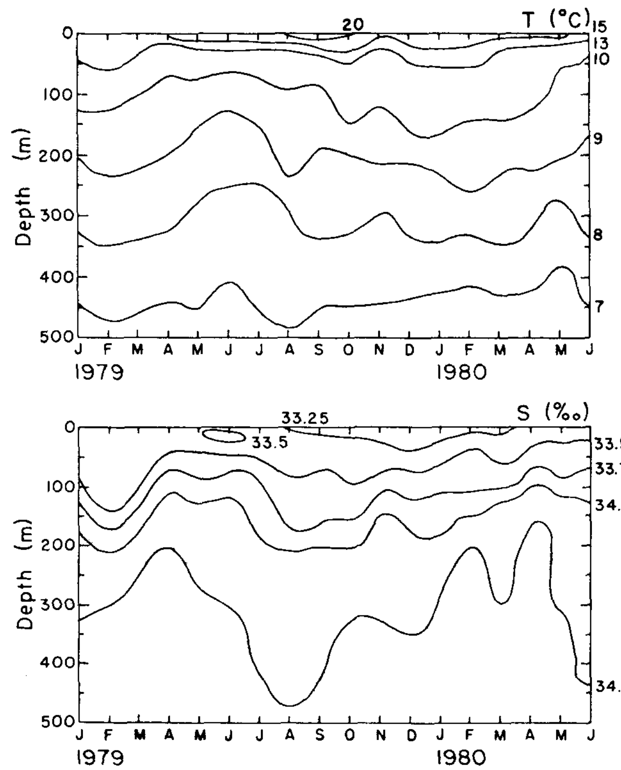

Figure 2. Annual distributions of temperature (T, °C) and salinity (S, ‰) in the water column at the study site.

water type results from mixing of Subarctic and Equatorial water masses carried into the area by the California Current from the north and subsurface countercurrents from the south (Reid et al. 1958). Analysis of the historical record (CalCOFI cruise reports 1963-1971) and the records of the National Oceanographic Data Center from 1970 to 1978 (NODC 1978) revealed that all our temperature and salinity profiles fell within two standard deviations of the historical means.

Nitrate, dissolved oxygen, reactive silicate, and phosphate distributions showed considerable variability induced by coastal upwelling events in the spring (Figure 3). The well-oxygenated surface waters were generally depleted of nitrate (<10 μM) and phosphate (<1 μM) despite the 50-100-m rise of the deep water isopleths during upwelling. Upwelling is primarily an inshore phenomenon in the region, and little increase in surface values was expected at the offshore farm site. Nitrate, a critical nutrient below 3 μM (North 1980), dipped to a winter minimum at 450 m of 31.5 μM in 1980. Within the analytical uncertainty of ±0.8 μM, the minimum available supply of nitrate in the upwelled water seems more than adequate. No significant nitrite (NO_2^-) was observed at any time during the study period.

Similarly, deep phosphate levels fluctuated very little (<5 percent as compared to the analytical uncertainty of ±10 percent), and the supply seems sufficient for good kelp growth (North 1980). Salinity and temperature showed seasonal changes related to upwelling events, as mentioned above. The calculated density at 450 meters deviated only ±0.14 percent from the mean value of 1.02694 kg•l^{-1}.

The dissolved oxygen distribution varied significantly during the study period. The lack of a defined oxygen minimum below the photic zone was due presumably to mixing in the nearshore waters.

Oxygen and silicate levels in the deep water showed variability that may be related to an intermittent influx of intermediate or bottom water. Samples low in oxygen and high in silicate were encountered during the first half of 1979, extending beyond the spring upwelling event. In 1980, however, values near the 18-month mean were observed during the first half of the year; after upwelling the silicate levels fell as oxygen levels increased. Upwelling combined with variable wind force and direction may contribute to nearshore

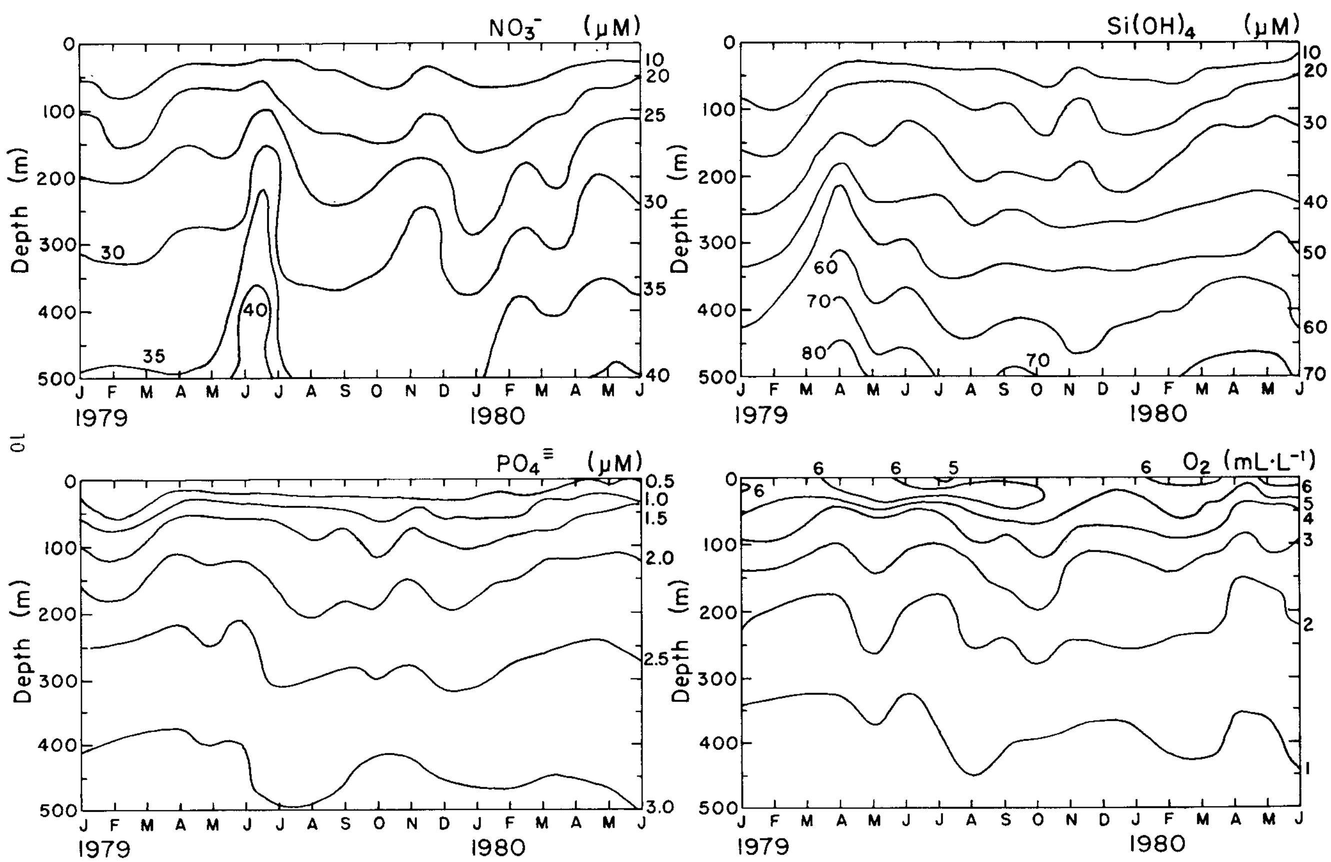

Figure 3. Annual distributions of nitrate (NO_3^-, μM), silicate ($Si(OH)_4$, μM), phosphate ($PO_4^{\equiv}$, μM), and dissolved oxygen (O_2, mL•L^{-1}) at the study site.

surface current reversals, incomplete mixing, and an unstable water column. Temperature inversions were frequently noted throughout the water column in biweekly XBT traces during this period. The apparent instabilities occurred well into midsummer. Our sampling frequency makes further comment speculative.

Nearshore Circulation

A five-station transect was executed during late summer 1979 in order to define regional transport better. The northward movement of the California Undercurrent, a warm nutrient-rich flow, was of particular interest. This feature is best developed near shore during August and September (Tsuchiya 1976). Hydrographic characteristics of the undercurrent were quite similar to those encountered at the farm site. There were no obvious offshore trends evident in the subthermocline chemical distributions. Results of the geostrophic flow calculations are shown in Figure 4 as flow contours along the ENE-WSW transect line. Results for the 011-012 station pair were questionable because of the proximity of the Catalina Island landmass. However, the results from these stations have been included in the contours for the sake of completeness. The general flow regime agrees quite well with previous results representative of this time of year (Reid et al. 1958; Hendricks 1977). The inshore surface flow bears NNW at 10-15 cm•sec^{-1}, while the offshore southerly California Current flows at somewhat greater speeds—~20 cm•sec^{-1}. This is manifest evidence of a counterclockwise eddy in the Southern California Bight, which tends to restrict exchange and extends the residence time of its waters. Subsurface geostrophic flows were very weak (at or below the noise level) at the inshore stations, and there is little evidence of northward countercurrent flow of equatorial water at the core depth range of 200-300 meters (Tsuchiya 1976). Absence of a high salinity bulge (>34.30 ⁰/₀₀) in the dashed region of the temperature-salinity plot (Figure 5) further supports this conclusion (Wooster and Jones 1970).

Much of the recent literature deals with circulation as it affects the mixing and residence time of municipal sewage effluents in shelf waters. Hendricks (1977) has pointed out that coherency in shallow, subthermocline motions can occur at distances of <35 km from shallow water outfalls. Directions of these currents frequently oppose those of surface water motions at speeds averaging 3 cm•sec^{-1}. Hendricks observed longshore and offshore components that mix effluents with deeper waters, aided by bottom currents with speeds up to 20 cm/sec. Because the study site lay less than 15 km from the Orange County Sanitation District sewage outfall and heavily trafficked Newport Harbor, pollutant transport to the farm site had to be considered. In fact, the farm was at the deep end of the Newport Submarine Canyon. When the dominant surface flow is to the NNW, one would expect some return flow along the canyon's contours in the direc-

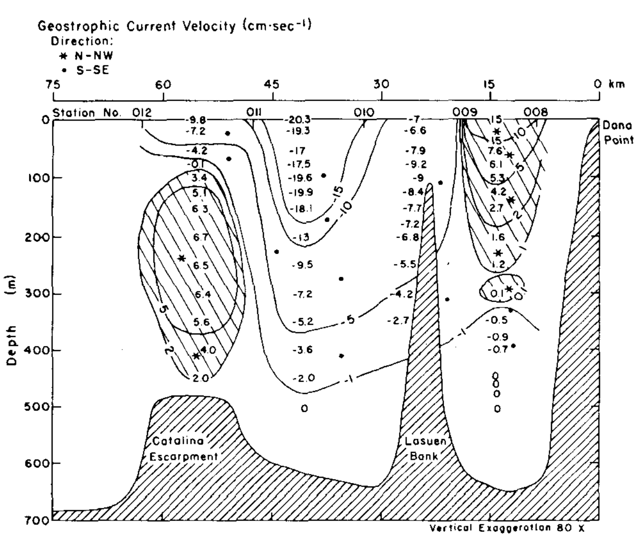

Figure 4. Geostrophic currents calculated from hydrographic observations on east-west transect of study region (CIT stations 008-012, September 1979).

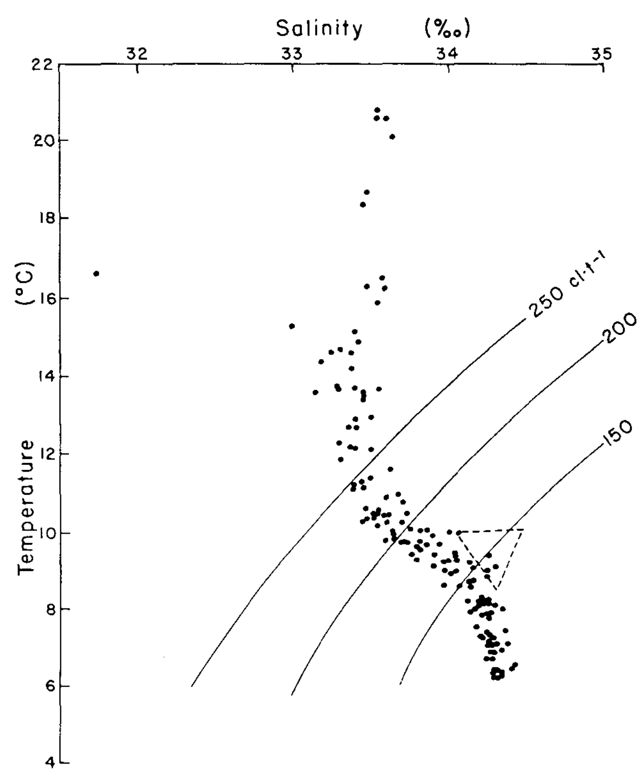

Figure 5. Temperature-salinity diagram for sixteen serial stations occupied at the study site. Values of the isanosteric anomaly are contoured in 50 cl•t^{-1} increments. The triangular region denotes zone of T-S properties indicative of countercurrent water.

tion of the farm. Bascom et al. (1978) noted "changed" sediment conditions judging from a sediment "Infaunal Trophic Index" over an 11-12-km^2 area near the sewage outfall. Patches of "changed" conditions were reported to the SSW near Newport Harbor and Dana Point. The potential for impact at the moored farm and the elevated water column levels of copper near the site prompted closer examination of anthropogenic influences.

Copper and Nickel Distributions in the Study Area

The trace metal data show an influence of human activities on the marine chemistry of the bight. Figure 6 depicts the hydrographic profiles of copper and nickel for five stations taken at the site from April 27, 1979, to August 13, 1979. The data show significant variability over the four-month period of intense upwelling. Copper was found to vary from 3.2-15.6 nM in the upper 100 m. Surface and subthermocline data sets were not significantly different at the 90 percent confidence level. Thus the possibilities of controlling atmospheric or sediment-related inputs were discounted. The variability for nickel was somewhat less than copper and agreed generally with the data of Boyle (1976) and Bruland et al. (1979).

Overall copper levels were 2-5 times higher than those at similar depths reported by the above workers for stations considerably more distant (>90 km) from shore. They observed total copper levels ranging from 2-4 nM using essentially identical analytical methods. In Figure 7, the envelope of our data set is compared with the profiles of previous workers. The nearshore levels were clearly elevated over their results. Further, our surface values were also higher than those reported by Windom and Smith (1979) for samples off the southeastern coast of the United States. Circulation in the Southern California Bight is characterized by a counterclockwise eddy, which tends to limit communication with open ocean waters. Thus it was necessary to examine the available trace-metal data for inshore stations near the study area.

Young's results (1979) are most comparable to our data, because his sampling and analytical methods were nearly identical to ours. He observed copper levels in Newport Harbor ranging from 139-35 nM. His surface value at the offshore station (9.4 nM) shows excellent agreement with our observed mean surface value of 8.98 ± 3.51 nM (N = 15), with a range of 5.01-18.6 nM. Results from Zirino et al. (1978), though not strictly comparable because they

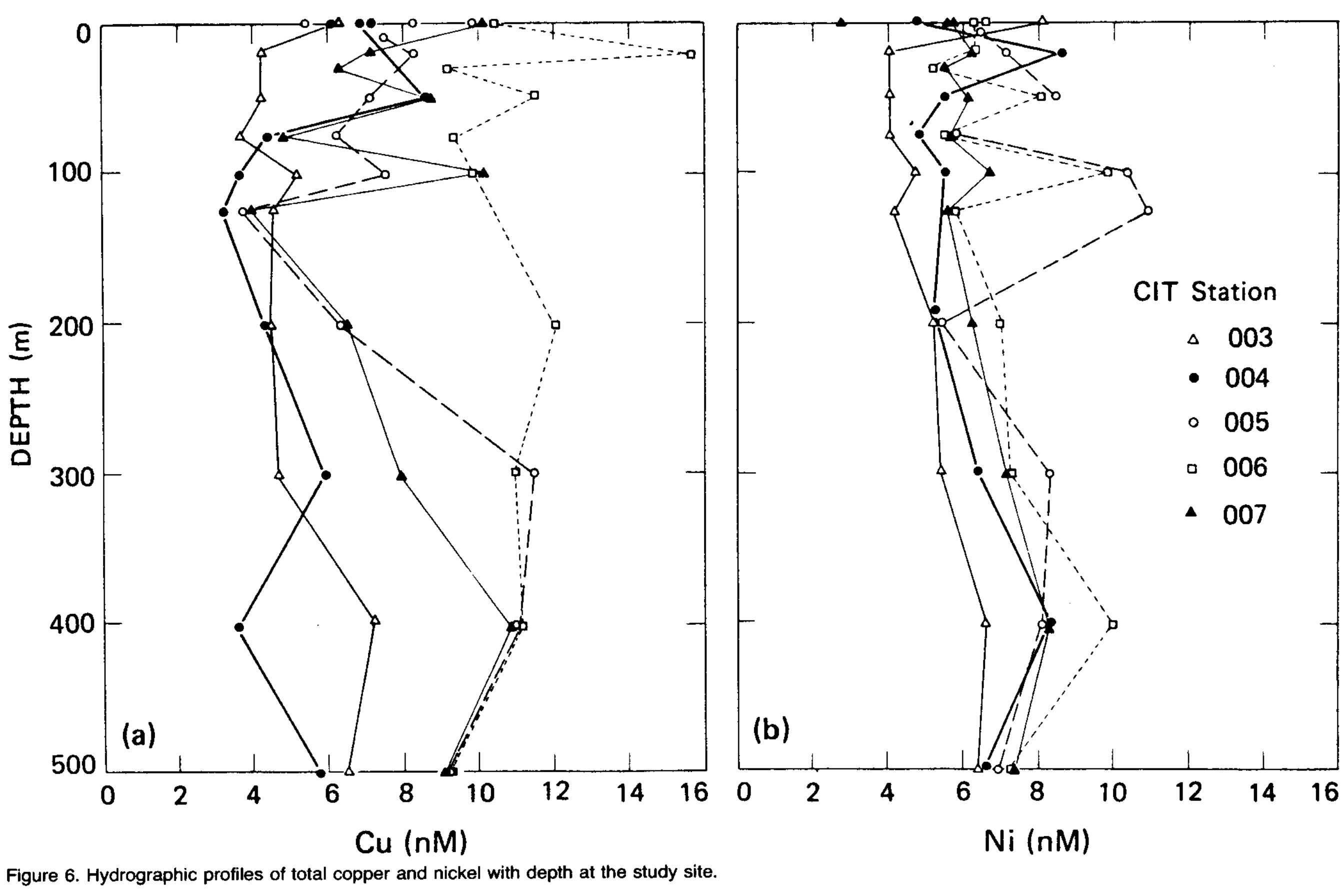

Figure 6. Hydrographic profiles of total copper and nickel with depth at the study site.

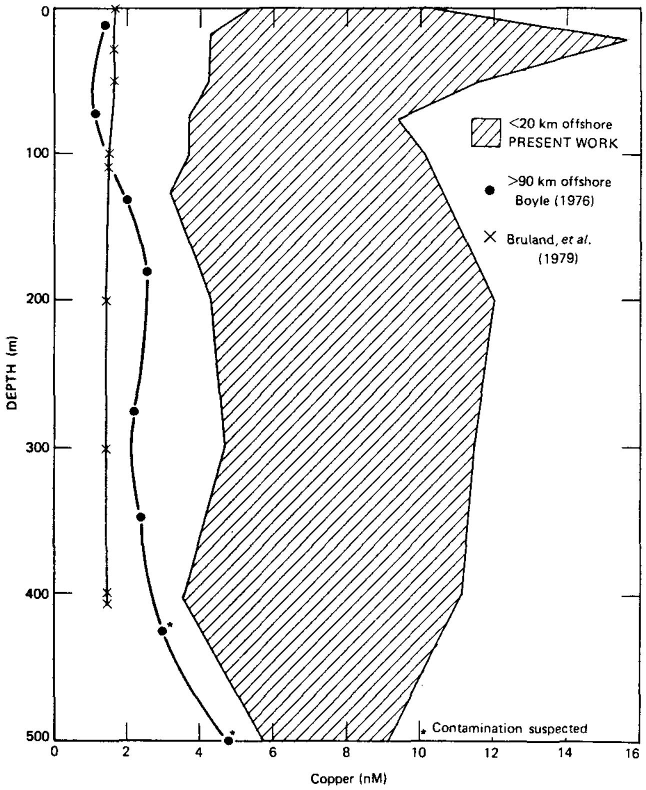

Figure 7. Envelope of nearshore total copper levels versus depth contrasted with offshore results.

used electrochemical techniques, were of the same order of magnitude (10-39 nM-Cu) and demonstrated the strong tidal variations noted in copper levels in the harbors.

The highly industrialized, densely populated southern California coast provides numerous pollutants to the coastal waters. The study site lay within 125 km of three major sewer outfalls discharging more than $3 \times 10^9 l \cdot day^{-1}$ of primary and secondary treated effluent (Schafer 1978). Copper, nickel, chromium, and lead are important toxic metals identified in these discharges. In coastal areas of restricted circulation, total metal levels probably reflect the influence of all sources.

The history of trace-metal inputs to the coastal zone has been studied in the sedimentary record by Bruland et al. (1974) and Bertine and Goldberg (1977). These authors demonstrated recent enrichment of several trace metals in the coastal basins within 30 km of the shore. Bruland et al. (1974) further pointed out that about 1.9 percent of the discharged copper associated with wastewater alone could account for its observed enrichment in nearshore sediments. Thus, a substantial fraction of the total copper discharged remains available for transport in coastal waters. Estimates were made of the annual inputs of copper from various

TABLE 2
Estimated Copper Inputs to the Study Area

Activity	Mass input rate (metric tons/yr) Cu
Discharge of municipal waste waters (Orange County)	87
Boat maintenance (Newport Bay)	40
Storm runoff (Santa Ana River, San Diego Creek)	1.8
Aerial deposition	1.6
Dredging (slip maintenance)	1.3
Discharge of power plant cooling waters	0.44
Total estimated annual input	132.0

Sources: SCCWRP 1978; Schafer 1978.

sources in the immediate vicinity (<30 km) of the site (SCCWRP 1978; and Schafer 1978). These inputs are shown in Table 2 for various source categories. Sewage discharge is clearly the dominant anthropogenic input. Correcting the annual copper input for a 0.1-1 percent loss from rapidly settling particles (Herring and Abati 1978), and using a water residence time of 3-4 months, we find it conceivable that a 2-5 nM increase in total copper in the nearshore water column could occur. Such an increase would be sufficient to account for the high total copper levels observed in this study.

Our investigation suggests the potential for anthropogenic impact at an offshore farm site. Observed copper levels were elevated over oceanic conditions. A severe impact on kelp plants is not expected because natural inshore beds flourish close to significant sources of the metal; examples are the Point Loma beds near the San Diego municipal discharge and those at Palos Verdes near the Los Angeles County outfall.

North (1980) observed little enrichment of copper in kelp tissue at dissolved copper levels below 50 nM under batch culture conditions where media were renewed every other day. Slight reduction of specific growth rate first occurred at copper supplements of 100 μM, where 400 μM additions led to strong growth inhibition and greening of blade tissues within a few days. Considerably lower copper concentrations would be required under flowing conditions to achieve comparable adverse effects. Probably continuous exposure to 10 μM copper alone would not damage *Macrocystis*. Problems might appear at 20 to 30 μM.

One should also be aware of the potential impact of chronic plant exposure to various metals at "low" concentrations. Though no single metal may be present at "toxic" levels, the combination of nickel, lead, and copper exposures, for example, could prove stressful to the organisms. Any kelp farming operation, coastal or oceanic, should avoid sites lying immediately downcurrent from major sources of toxic elements.

SUMMARY AND CONCLUSIONS

Eighteen months of hydrographic measurements at an offshore (~8 km) 0.1-hectare marine farm have delineated the variability in certain chemical factors related to mariculture of the giant kelp, *Macrocystis pyrifera*. The results complement the historical record and demonstrate the variability of deep water (450 m) available for artificial upwelling. Nutrient supplies of nitrate and phosphate were more than adequate for kelp production within the prototype design limitations. Estimates of current flow using the geostrophic approximation agree with reports of average conditions within the Southern California Bight.

The facility's proximity to coastal sources of pollution led to total copper levels intermediate between typical values for inshore kelp beds and oceanic levels. Such exposures are not expected to affect growth of kelp. Future developers of marine mariculture in the nearshore waters must consider the influence of coastal pollution.

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