THE IMPACT OF WASTE-WATER DISCHARGE ON BIOLOGICAL COMMUNITIES IN SAN FRANCISCO BAY

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Recent improvements in waste treatment have resulted in improved water quality as far as organic loading and nutrient discharge into the Bay are concerned. However, problems with trace contaminants remain unsolved. Localized instances of biological contamination with toxic metals and trace organics equal those anywhere in the world. Indications of physiological stress in animals contaminated with trace toxicants have also been observed; and the toxicant tolerance in one species of bivalve suggests that adaptability to toxicant stress may be important for survival, at least in some parts of the Bay. Although most contaminant impacts are localized, the number of impacts may be large, because of the number of point-source dischargers and accidental spills. The result is an environment of unpredictable and variable suitability for the development of a complex ecosystem. Such environments tend to select against the larger, longer-lived species most valuable to man. The history of fisheries in the Bay reflects such a trend—away from larger, more valuable species and toward smaller species with greater adaptive flexibility.

We do not yet understand why eutrophication is not a problem in this nutrient-rich environment. Recent studies indicate that grazing by benthic invertebrates may limit phytoplankton biomass in South Bay. If so, damage to the benthic community (e.g. through an increase in trace contaminant stress) could have widespread impacts on the entire biological community of the Bay.

San Francisco Bay is the largest estuary along the west coast of the United States and represents a natural resource of immeasurable value (Fig. 1). The Bay serves as a passageway for adult salmonids and striped bass that spawn in upstream tributaries. It provides a nursery ground for juveniles of these species as well as for English sole and Dungeness crab. Pacific herring and anchovy spawn in the Bay. There is also active recreational fishing for striped bass. sturgeon, salmonids, and shad. The Bay historically has supported commercial fishing for shrimp and oysters (Jones and Stokes Assoc. 1977). Wong (1978) estimated that the Bay's potential shellfish resource alone could have an economic yield of S30 million annually. In addition, tidal marshes and mudflats provide habitat for wildlife and waterfowl (including 12 rare or endangered species). Half the migrating waterfowl (70% of all migrating shorebirds) along the Pacific Flyway use the Bay and its marshes during winter.

Given the Bay's natural resources. man is faced with conflicting desires to: (1) exploit these resources for economic and population growth; or (2) maintain a healthy and productive biological community in the Bay for esthetic. economic, ecological, and public health reasons. Of particular concern is our using San Francisco Bay as a receptacle for wastes, yet at the same time trying to minimize impacts on water quality and biota. Waste waters contain trace metals and organic compounds that are toxic, nutrients that may stimulate the nuisance growths of plants, organic matter that places a demand on dissolved oxygen, and/or pathogens that may threaten public health. Documentation of these deleterious impacts from waste discharge is difficult. except in extreme cases. Documenting impacts requires both a thorough understanding of the natural ecosystem. and

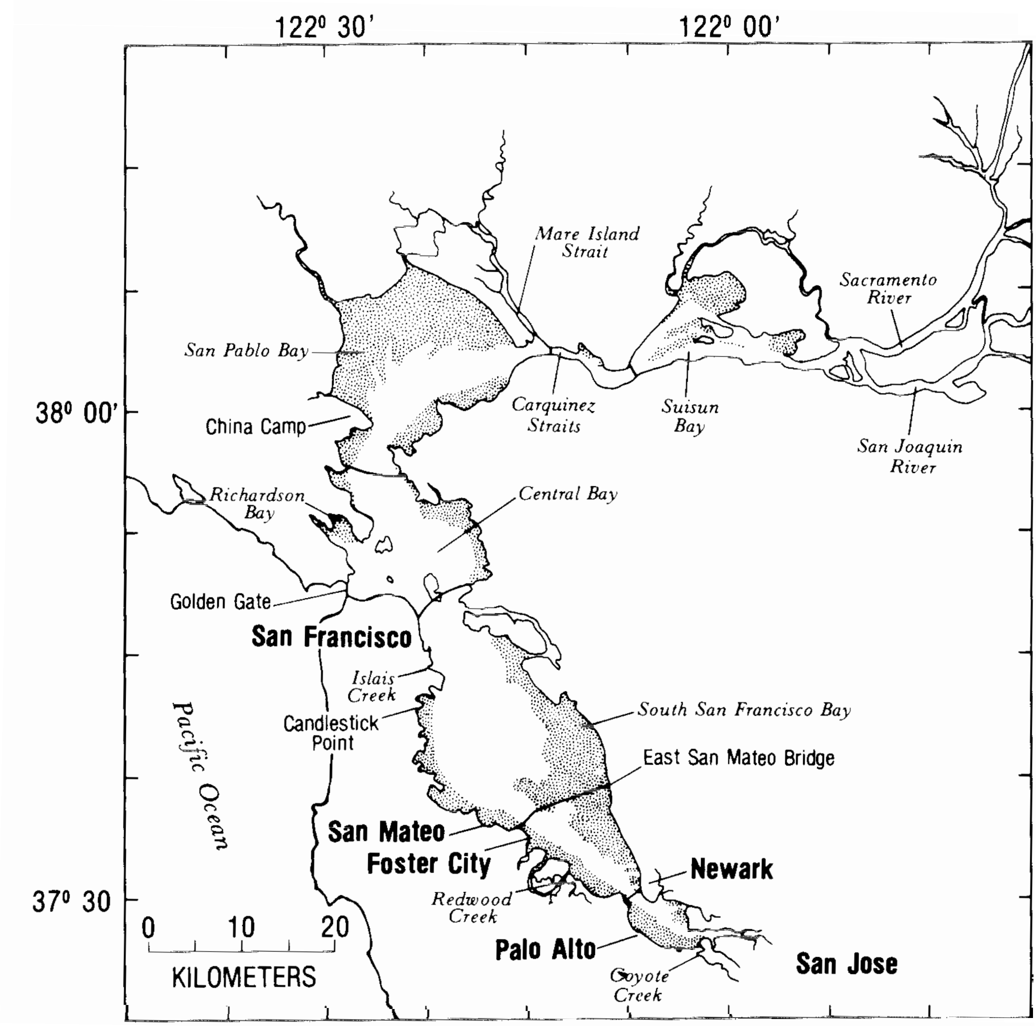

Fig. 1. San Francisco Bay, with relevant areas delineated.

data that describe historical changes coincident with accelerated waste inputs. For the Bay, both our understanding and the historical data are insufficient.

A major difficulty in specifically defining impacts from waste discharge is that, historically. increases in discharges have been accompanied by other biologically significant changes: (1) more than 95% of the original surrounding marshes have been destroyed by filling and diking (Atwater et al. 1979). Marshes assimilate organic matter and nutrients, and may trap heavy metals. Wastes discharged to the Bay today, therefore. may have a more immediate impact than in the historic past, (2) Heavy siltation from hydraulic mining in the Sierra Nevada during the last century greatly affected the bathymetry (and presumably hydrodynamics), sediment stability. and the quantity of suspended sediment in the water column (Gilbert 1917). (3) The quantity and quality of fresh water entering the Bay have been altered dramatically by water projects that divert flows of the Sacramento-San Joaquin rivers (Delta outflow) away from the Bay and return agricultural waste water. Fresh-water inflow to the Bay has been reduced to half the historical flow, thus reducing the capacity to dilute and flush wastes. (4) A variety of exotic species has been introduced. and has become established in the Bay since the mid-1800s (Carlton 1979).

Even when we can document historical changes in the Bay community, separating the influence of waste discharge from the influence of other changes is difficult. However, waste-water discharge does have some unique impacts. In this paper we will discuss the different types of waste-water discharges into San Francisco Bay. and analyze impacts unique to those discharges. We will then describe the biological community of the Bay. emphasizing characteristics of the community which might be affected by waste waters. Our analysis does not yield a clear picture of the role waste-water discharge has played in forming the biological community that exists today. However. it does provide useful information about the relative importance of different sources of waste-water discharge. It helps define the pollution-related issues which are of the greatest importance today. and which will be important in the future; it points to some profitable and unprofitable approaches to research in the Bay: and it summarizes what we see as important research needs.

CATEGORIES OF WASTE-WATER DISCHARGE

The quantity and composition of waste waters discharged to the Bay vary in several ways. Point-source discharges, such as municipal sewage or industrial wastes. may vary in composition or in quantity from day to day or hour to hour. However. if averaged over weeks to months. such discharges are relatively constant. representing a source of continuous pollution. Superimposed on the background of continuous waste input are the following two intermittent sources of waste waters: (1) storm runoff and fresh water inflows (rivers and streams) carry wastes which vary seasonally in quantity and composition: and (2) accidental spills. breakdowns of sewage-treatment plants. and dredging periodically subject the estuarine community to unpredictable and acute episodes of pollution.

In 1978, 52 municipal treatment facilities and 42 industrial facilities continuously discharged waste water into San Francisco Bay (Russell et al. 1981). These dischargers each released more than 0.1 mgd and 30 lb of pollutants per day. In all, 200 permits for industrial discharge have been granted (Gilbert Assoc. 1978). Among the municipal facilities. 42 provide secondary or advanced-level treatment and 10 provide primary-level treatment. The annual discharge of biological oxygen demand (BOD). total nitrogen, and total phosphorus from the municipal and industrial dischargers exceeds by twofold loadings from the tributaries of the Bay (Russell et al. 1981).

Rivers and streams are the major sources of both fresh water and suspended solids. Because of seasonal differences in river loadings. the rivers are also a more important source of nitrogen in winter than are sewage treatment facilities (Horne and McCormick 1977). Loadings of heavy metals in both river discharge and storm runoff exceed loadings from continuous waste sources. The high metal loadings in river discharge indicate that metals are associated with suspended solids. Based on mass balance calculations, concentrations of metals per unit of suspended solids are six times greater in sewage discharges than in river discharges. Metal concentrations in the suspended solids of storm runoff are 2.5 times greater than in sewage.

No reliable estimates are available as to the quantity of waste released annually to San Francisco Bay by accidental spills. Overflows from combined sewer and storm runoff systems (as in San Francisco) could contribute significant discharges of untreated waste. Even where systems are separate. overflows or bypasses at treatment plants may occur as much as 10% of the time during the peak of the rainy season because of seepage into sewerage (Regional Water Quality Control Board. Oakland. CA. unpublished data).

Five different State and Federal agencies are responsible for counting spills of hazardous substances. but because of overlaps in their jurisdiction, the number of spills per year is not certain (Table 1). Several statistics, however. illustrate the magnitude of the problem. Data reported by the Coast Guard alone indicate that an average of one spill occurs per day in the Bay

TABLE 1. OIL AND CHEMICAL SPILLS REPORTED IN THE BAY AREA ANNUALLY (adapted from Jackson 1980)

Reporting Agency	Average No. of Spills/Year[a]	Percent Composition Oil	 Hazardous Materials	 Non-hazardous Materials	 Unknown Substance
Coast Guard	360	98	2[b]	–	-
Environmental Protection Agency	200	60	24[c]	5	11
State Department of Fish and Game	127	58	21[d]	9	12
Caltrans	160	4	17	78	1
State Office of Emergency Services	170	nda	nda	nda	nda

[a] Due to overlapping jurisdictions, spill counts from each agency should not be added together to give a total annual count for the Bay Area.

[b] Hazardous materials, defined by Title 49 CFR, Part 172. list of 1260 materials.

[c] Hazardous substance?, defined by Title 40 CFR, Part 117. list of 299 materials.

[d] In practice, DFG considers any substance potentially hazardous to waterways. However, the California Administrative Code. Title 22, Division 4, Chapter 30, Article 8, identifies 791 materials as hazardous.

nda = no data

Area (Jackson 1980). The true frequency is undoubtedly higher. as some agency estimates include spills not reported by the Coast Guard. Furthermore. many estimates depend upon reports from the spillers themselves.

Oil is the most common single substance spilled. accounting for 200-300 of the spills reported to the Coast Guard per year (Cushing. Inc. 1980). Four percent of the oil transported in the world is refined on the shores of San Francisco Bay (Riseborough et al. 1977). For every 100 transfers of oil from ship to shore, or vice versa. 2.3 spills occur (Cushing, Inc. 1980). For every million barrels refined. five barrels are spilled in the Bay. By far the largest number of spills (both of oil and other hazardous substances) are small. but several major spills occur each year.

The mass of pollutants released in accidental discharges is probably only a fraction of that released from continuously discharging and seasonally variable sources. However, the potentially toxic nature of many of the spills and their high frequency suggest that they might have localized impacts and so could contribute to the overall impact upon the biological community of the Bay.

Waste discharges into San Francisco Bay. then. are characterized by a high background level of continuously discharged pollutants: a significant seasonally variable input of pollutants: and a series of unpredictable discharges. most of which result in localized releases of pollutants.

IMPACTS OF WASTE DISCHARGES

Waste discharges have several impacts which can be separated from those caused by other types of stress. These include (1) contamination of biota with trace toxicants: (2) biological changes centered on discharges that are localized in space or time: (3) indications of physiological stress in organisms: and (4) changes in water quality in conjunction with changes in waste treatment. We will first discuss toxicant contamination in organisms, then some possible results of that contamination.

Toxicant Contamination

Toxicant *concentrations.* Toxicant concentrations in organisms are often used as indicators.. of biologically significant releases of contaminants, Toxicant surveys conducted world-wide are sufficient to provide some perspective on the data from the Bay.

In general, concentrations of metals in shellfish within the Bay are higher than in the same species from nearby coastal embayments (Table 2; Bradford and Luoma 1980; Anderlini et al. 1975), or from other California bays, such as Humboldt Bay, Elkhorn Slough, or Morro Bay (Stephenson et al. 1980). When metal concentrations in these organisms are averaged Bay-wide, extreme contamination is not evident. However, concentrations show much spatial variability.

TABLE 2 CONCENTRATION[a] OF HEAVY METALS IN MUSSELS AND CLAMS FROM SAN FRANCISCO BAY COMPARED TO CONCENTRATIONS IN THE SAME SPECIES FROM NEARBY COASTAL STATIONS[b,c]

	Ag	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Se	Zn
Mytilus edulis												
Tomales Bay	1 3	5 5	6 4	<1	7 5	73	0 26	6 3	1 2	0 9	5 4	82
n=1	(0 5)	(0 9)	(1 1)		(1 1)	(5)	(0 01)	(1 7)	(0 5)	(0 3)	(0 5)	(11)
San Francisco	0.43	7.1	5.3	–	8.0	287	0.38	29.6	2.2	3.3	4.5	170
Bay: n=20	(.33)	(1.5)	(3.0)		(2.3)	(312)	(0.19)	(30.5)	(1.2)	(4.9)	(2.5)	(58)
Macoma nasuta												
Bodega Bay	0.9				20.0							200
n=1												
San Francisco	6.5				37.0							182
Bay n=5	(3.5)				(13)							(84)
Tapes japonica												
Princeton Harbor	0.7				5							41
n=1												
San Francisco	17				17							80
Bay; n=7	(22)				(10)							(50)

[a] μg/g dry weight.
[b] Numbers in parentheses are standard deviations
[c] n=number of stations sampled.

For nearly every toxic metal, there are several locations where concentrations approach, or exceed, the highest concentrations reported for similar species in world-wide surveys of contamination. The following examples can be cited:

(1) Concentrations of copper (Cu) and silver (Ag) in tellenid clams (*Macoma* balthica) are high throughout South Bay (Bradford and Luoma 1980). At the southern end of South Bay, concentrations of Cu and Ag exceed any reported for such clams in surveys of 37 European estuaries characterized by a variety of pollutant inputs (Luoma and Cain 1979: Bryan et al. 1980).

(2) Concentrations of cadmium (Cd) and Ag in mussels (*Mytilus edulis* or *Mytilus californianus*) from South Bay are as high as those observed in any of the 63 locations surveyed on the east and west coasts of the U.S. (Coldberg et al. 1978).

(3) Concentrations of nickel (Ni) reported by Anderlini et al. (1975) in *Macoma* balthica from Mare Island Strait substantially exceed concentrations reported by Bryan et al. (1980) from any of ten estuaries in England. which include several heavily industrialized areas. Concentrations of Ni in mussels from Carquinez Strait, Islais Creek near San Francisco, and Redwood Creek

in South Bay (Riseborough et al. 1977) exceed any reported in the 63 stations sampled by Goldberg et al. (1978). or in the extensive literature review of Riseborough et al. (1977). except for one case of extreme contamination in Sicily.

(4) Concentrations of lead (Pb) in mussels from Central Bay (Albany Hill, Islais Creek, and Oyster Point [Girvin et al. 1975]) are higher than any found in extensive surveys in the United States (Goldberg et al. 1978; Leland et al. 1978) and Australia (Phillips 1976). In the 33 surveys reviewed from the international literature by Riseborough et al. (1977), Pb concentrations in mussels which exceed those from Central Bay were found in only three instances.

(5) Analyses of mercury (Hg) in mussels (Girvin et al. 1975) indicate that high concentrations. compared to elsewhere in the world, occur at several locations in South Bay. Concentrations in mussels from Redwood Creek exceed any values found in 12 surveys of waters in Europe. Asia, and the U.S. (Riseborough et al. 1977), or in the St. Lawrence Estuary (Bourget and Cossa 1977).

Riseborough et al. (1977) conclude that Bay-wide contamination with trace metals is not a significant problem. If the Bay is considered as a homogeneous system, characterized by a single mean concentration for each metal. this conclusion is valid. However, if the spatial heterogeneity that characterizes metal distributions in organisms is considered, extremes of contamination for Ag, Cu, Cd, Hg, Ni. and Pb equal to those found anywhere in the world are readily evident.

Surveys of toxic trace organic compounds have included analyses of polychlorinated biphenyls (PCB) and hydrocarbons derived from petroleum products. Although these data are not extensive, trends in concentrations in organisms appear similar to those observed for trace metals. Concentrations of PCB in mussels are spatially heterogeneous. and are 10 to 250 times greater in Bay mussels than in mussels from more pristine coastal locations (Table 3). The highest concentrations of PCB observed in Bay mussels are equivalent to the highest concentrations observed in other surveys world-wide (Riseborough et al. 1976, 1977, 1980: Goldberg et al. 1978; Hagl and Thuinstra 1978; Young et al. 1976). PCB contamination is also found in species other than mussels. Stevens (1981) reported mean PCB concentrations of 5.49 μg/g in the muscles of 22 striped bass in 1972. and 0.41 μg/g in nine striped bass collected in 1976. (The sample sizes in this study are too small to confirm any apparent decline in PCB concentrations since 1972. However.

TABLE 3. CONCENTRATIONS OF PCB AND PETROLEUM HYDROCARBONS (PHC) IN MUSSELS FROM DIFFERENT COASTAL AREAS WORLD-WIDE

Location	PCB	PHC (μg/g)
Northern California Coast	6-66[a,b]	9±4[a]
Southern California Coast	88-130[a]	64±68[a]
Goleta Point (natural oil seep)		410±230[a]
San Diego Harbor	360-1700[a,c]	220[a]
Los Angeles Harbor	270[a]	270[a]
Los Angeles County Outfall	230-780[d]	
Narragansett Bay	300-626[a]	
Boston Harbor	635[c]	
Dutch Coast	70-330[e]	
French Coast	200-1100[d]	
San Francisco Bay	250-1500[b]	180[a]

[a] Riseborough et al. 1980

[b] Riscborough et al. 1977

[c] Goldberg et al. 1978

[d] Riseborough et al. 1978

[e] Hagl and Thuinstra 1978

such a decline is consistent with data from coastal environments [Riseborough et al. 1980]). Concentrations of PCB in over 100 samples of striped bass collected in 1976 from Chesapeake Bay averaged 0.23 μg/g, with a range of 0.00–0.58 μg/g (Eisenberg et al. 1980). In the Hudson River estuary, concentrations in fish muscle exceed 100 μg/g near a PCB manufacturing plant (Horn et al. 1979).

PCB concentrations of 500 μg/g are found in the blubber of adult Harbor seals from Richardson Bay (Riseborough et al. 1977). In South Bay (Mowry Slough), PCB concentrations in the blubber of seal pups range from 16 to 120 μg/g; and 140 μg/g PCB was observed in an adult seal. Concentrations of PCB in blubber from seals collected along the California coast are considerably lower. ranging from 4.5 to 21 μg/g in pups and 17 to 27 μg/g in adults. PCB concentrations of 56 to 140 μg/g in the blubber of adult ringed seals in the Baltic Sea–concentrations similar to those observed in the Bay were thought to be the cause of reproductive failures observed in the seals (Helle et al. 1976a,b).

Contamination by petroleum hydrocarbons (PHC) is also evident in organisms from San Francisco Bay (Table 3). although published evidence is limited to mussels. Concentrations in mussels from San Francisco Bay are 20 times higher than in mussels on the Northern California coast: only slightly less than observed in San Diego or Los Angeles harbors; and only two times less than concentrations observed in mussels living near a natural oil seep at Goleta Point (Riseborough et al. 1980). Preliminary data indicate that PHC contamination is much greater in striped bass from San Francisco Bay than from Coos Bay in Oregon (J. Whipple, NMFS).

Little or nothing is known about distributions in the Bay of potentially toxic organic compounds other than PCB or petroleum hydrocarbons. Such compounds might include pesticides, specific carcinogens (such as polynucleated aromatic compounds found in oil), low-molecular-weight organic materials (such as benzene from oil or oil-refining wastes), or compounds formed by the chlorination of sewage.

The use of most pesticides that are highly persistent was banned in the 1970s, and aquatic environments have responded accordingly. DDT concentrations at California coastal stations have declined consistently since the ban in 1972 (Riseborough et al. 1980). Concentrations of DDT (and its metabolites) in mussels from San Francisco Bay were low in 1978. compared to other California locations (Riseborough et al. 1980). Many of the pesticides currently in use would not be expected to accumulate in aquatic biota. because they are readily degraded or are immobilized in the environment. Adequate methods for analyzing the concentrations have not been developed for other pesticidies and organic compounds which might constitute persistent environmental problems.

Pathogenic bacteria and viruses are also contaminants associated with the discharge of waste waters. Coliform bacteria are used as indicators of the presence of pathogenic bacteria in waters and shellfish. National water quality standards suggest that total coliforms in water suitable for shellfish harvesting should not exceed 70 organisms per 100 ml on the average or 230 organisms per 100 ml in more than 10% of the samples. A median of 240 organisms per 100 ml is the total coliform standard for water-contact sports.

Coliform bacteria levels in the Bay vary spatially but are generally surprisingly low. In 1977 median total coliforms were 4 organisms per 100 ml in the channels of both South Bay and North Bay, and 240 per 100 ml in Carquinez Strait and Suisun Bay (California Water Quality Control Board 1977). Coliform levels over the shoals are higher and more sporadic than in the channel, and are considerably higher in winter than in summer. Summer coliform values over the shoals met the Federal standards for shellfish at half the stations sampled in 1980 during a study of the feasibility of harvesting shellfish in the Bay (Johnson 1980). During wet weather, coliform levels exceeded the standard. Creek and storm drain runoff was the primary source of coliform contamination.

Coliform concentrations in clams (Mya *arenaria* and Tapes *japonica*) tend to be approximately ten times higher than concentrations in sea water. In the 1980 survey of shellfish beds.

viruses were surprisingly uncommon in clams, although. in several scattered instances, polio viruses were found (Johnson 1980).

Sources of Contamination. Quantitatively. river discharge and storm runoff provide most of the metal contaminants entering the Bay. However, other sources appear to control concentrations of at least some of the metals in organisms. In a study of spatial gradients of trace-metal concentrations in organisms and sediments over a 10-km transect near Palo Alto in South Bay, Thomson et al. (in prep.) showed that: (1) despite secondary treatment, the local sewage outfall was a major source of extreme Cu and Ag contamination at all times of year (Fig. 2); (2) storm runoff, the Palo Alto yacht harbor. and contaminated ash in a local landfill were not significant sources of either Cu or Ag compared to the sewage outfall; (3) storm runoff was a source of zinc (Zn), but the bioavailability of Zn in the runoff was lower than in the sewage; and (4) the distributions of contaminants changed dramatically over distances of less than 1 km. High levels of contamination

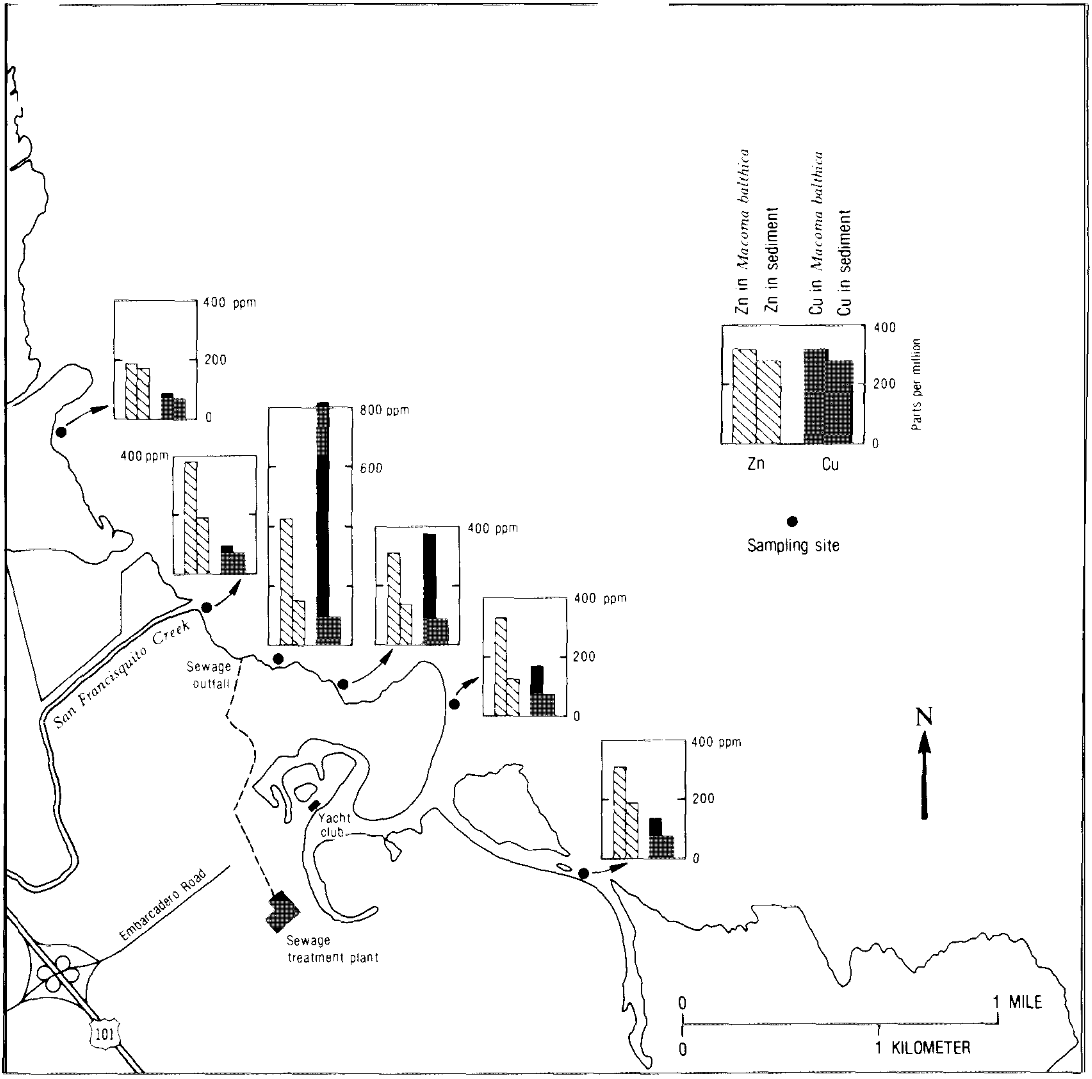

Fig. 2. Concentrations of Cu and Zn in sediments and clam tissues along a 5-km transect near the shoreline in the vicinity of the Palo Alto sewage outfall and San Francisquito Creek, a source of urban runoff. All samples were collected in April 1980.

extended at least 3 km south of the outfall, but less than 0.5 km north of the outfall, apparently because of the prevailing circulation patterns.

Localized instances of contamination, from point-source discharges. may have Bay-wide significance in determining levels of Cu contamination. In clams (*M. balthica*) collected over several years from five mudflats (each within 2 km of sewage outfalls), concentrations of Cu correlated strongly (r=0.85) with the Cu discharge from the sewage treatment facility nearest each sampling station (Fig. 3). The concentration of Cu in clams from a given mudflat reflected local discharges near that mudflat more than any characteristic value for the Bay system as a whole. Concentrations of Cu in the sediments at these stations are not particularly high compared to other estuarine systems (Bradford and Luoma 1980), suggesting that discharges of Cu are not excessive. In contrast, concentrations of Cu in clams are very high compared to other systems. indicating an unusual biological vulnerability to Cu contamination, perhaps stemming from undefined physicochemical characteristics of the Bay which enhance the biological availability of Cu (Bradford and Luoma 1980).

Exceptional Ag contamination in South Bay is reflected in both sediments and animals. Inefficient Ag removal by one or more sewage treatment facilities in the southern end of South Bay appears to be the cause (Bradford and Luorna 1980). The patchy distributions of Ni, Cd, and Cr also suggest that inefficiently treated, localized discharges of waste water control the concentrations of these metals in animals.

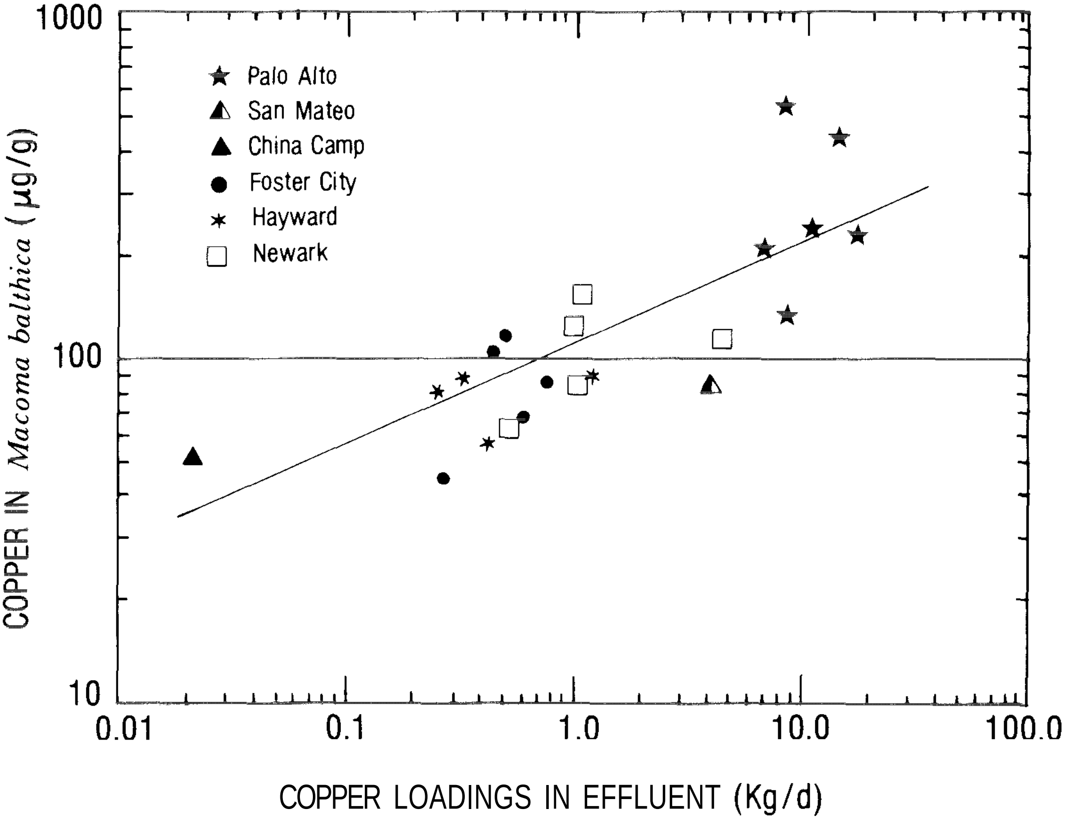

Fig. 3. Correlation of Cu in soft tissues of the clam *Macoma balthica* at six different mudflats in San Francisco Bay, as a function of Cu loadings from the sewage treatment plant nearest the mudflat. Several stations were sampled several times over a three-year period. Cu loadings were determined at the time of sampling.

Waste-water discharges may also contribute to Pb and Hg contamination. However. the major inputs of these metals appear to be legacies of the past. The unusual Pb contamination in Central Bay is in an area contaminated by a smelter which has subsequently ceased to operate. Pb toxicity in terrestrial animals was observed in this area when the smelter was in operation. Similarly. Hg contamination in South Bay could reflect runoff (or historical sediment contamination) from old Hg mines in the watersheds of South Bay creeks (George Parks, Stanford University. pers. comm.).

Too little is known about contamination by PCB's, petroleum hydrocarbons, or other organic materials, to determine its sources. Detailed infoimation about the distribution of trace organic contamination. similar to that available for trace metals. could aid greatly in identifying major sources of contamination.

Localized contaminant impacts would have little significance in the Bay if there were only a few sources of contamination. However. 94 major outfalls discharge industrial and municipal waste. and there are numerous inputs from storm runoff and smaller outfalls. Historical sources of contamination appear to retain their effects for long periods after inputs cease. The great spatial heterogeneity observed in surveys of contaminant concentrations is not surprising. The Bay is not a single homogeneous system in terms of trace contaminants, but resembles a fine-grained spatial mosaic of localities contaminated to different degrees with different toxicants. A single median value is meaningless in describing toxicant contamination in a spatially heterogeneous system. Toxicant concentrations, and impacts, at any given locality are functions of the nature of the nearest source of toxicant and the distance from that source. The overall impact on the system is determined by the sum of the many localized impacts.

Hydrologic Influences. The biological impacts of pollutants are not solely a function of pollutant loadings. Chemical interactions may affect biological availability (Luoma and Bryan 1978. 1979). Seasonally variable hydrologic processes may disperse. chemically alter. or add to the influence of continuous pollutant discharges. In the Bay, seasonal variations in hydrologic parameters may produce substantial fluctuations around the background level of contamination provided by continuously discharging sources. For example, within any year. concentrations of trace metals in the indicator clam, *M. balthica.* show consistent fluctuations. Throughout the Bay. metal concentrations in clams are highest in winter (during the rainy season) and lowest in summer (Fig. ***3)***. Near Palo Alto, the onset of the annual winter increase in concentrations of Ag and Cu in the clams coincided with the onset of rainfall in each year from 1975 through 1980 (Luoma and Cain 1979: Luoma et al. unpublished data). Urban runoff is not a direct source of these metals. but changes associated with the onset of the rainy season certainly influence the annual fluctuation in biologically available Cu and Ag.

Temporal fluctuations in metal concentrations in *M. balthica* in South Bay are highest in the relatively stagnant southern reach. and decline progressively toward Central Bay (Fig. 4). A fivefold difference between maximum and minimum concentrations of Cu occurs annually near Palo Alto. Near the northern end of South Bay. variations seldom exceed an amplitude of twofold within a year. Unlike the enclosed head of South Bay, the northern end is mixed with coastal and North Bay waters by tidal currents. and is flushed by non-tidal currents driven by Delta outflow. Where mixing and flushing are less effective, biologically available metals build up to higher levels in the clams, and have greater seasonal variations in concentration.

Annual differences in pollutant concentrations also may be influenced by flushing. McCulloch et al. (1970) showed that. during a year of low Delta outflow, concentrations of phosphate in South Bay waters greatly exceeded those observed during years of high outflow. They concluded that the rate of phosphate turnover in South Bay was strongly influenced by the rate of Delta outflow. Luoma and Cain (1979) found that concentrations of Ag and Cu in clams from two stations in South Bay increased more rapidly and to higher concentrations in the early winter. in years when fresh-water discharge was low. Their statistical analysis showed no correlation

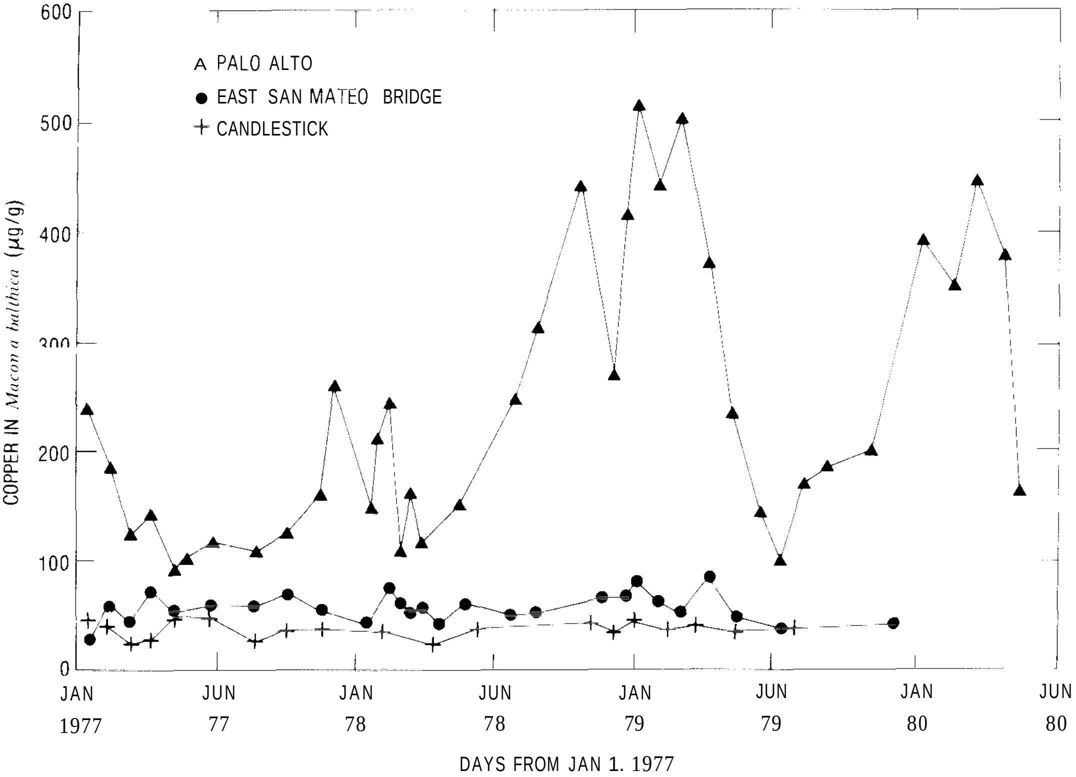

Fig. 4. Fluctuations in concentrations of Cu in the soft tissues of *Macoma balthica* from Candlestick Point near the mouth of South Bay, the East San Mateo Bridge in Central South Bay, and Palo Alto Yacht Harbor near the enclosed southern end of South Bay.

between local stream discharge rates and the buildup of metals in the animals. However. metal buildup showed a strongly significant inverse correlation with Delta outflow. They concluded that fresh-water flushing (perhaps driven by Delta outflow) somehow reduced the concentration of biologically available Cu and Ag in sediments and/or water, even in the southernmost extremity of South Bay.

The possibility that Delta outflow could influence pollutant availability as far south as Palo Alto is given further credence by more recent data on temporal patterns of Ag and Cu contamination in South Bay animals. Spatial distributions indicate that the Ag contamination near Palo Alto originates from the sewage outfall. The minimum concentration of Ag observed in clams at Palo Alto has been different each summer since 1975. The lowest value observed was 7 μg/g in June 1975; the highest was 117 μg/g in July 1978. These differences are not solely related to differences in Ag discharge. However, if Ag discharge is normalized to summer rates of Delta outflow, a very distinct correlation is observed (Fig. 5). The very high Ag concentrations observed in animals in 1978 coincided with a high rate of Ag discharge from the sewage plant[1] and a "normal" summer rate of Delta outflow. Discharge of Ag from the sewage plant in June 1980 was also unusually high. More moderate concentrations of Ag in clams in May and June 1980 than in 1978 coincided with high rates of Delta outflow. In June 1975, unusually high rates of Delta

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[1] The values for Ag discharge were obtained from quarterly analyses of plant effluent provided courtesy of Steve Hayashi and Doris Maez of Palo Alto Municipal Sewage district. The relatively infrequent sampling could provide some margin of error.

outflow occurred for that time of year. and Ag concentrations in clams were the lowest ever observed at the Palo Alto station. In late spring and summer. local stream discharge in South Bay does not correlate well with Delta outflow. It also seems unlikely that other events could have correlated with Delta outflow in summer in recent years. Statistical correlations do not prove cause and effect. especially in a system as complex as San Francisco Bay. A precise understanding of the role Delta outflow plays in pollutant interactions throughout South Bay awaits further study. However. the evidence collected to date indisputably emphasizes the important influence on waste-water impacts of hydrologic processes which control flushing.

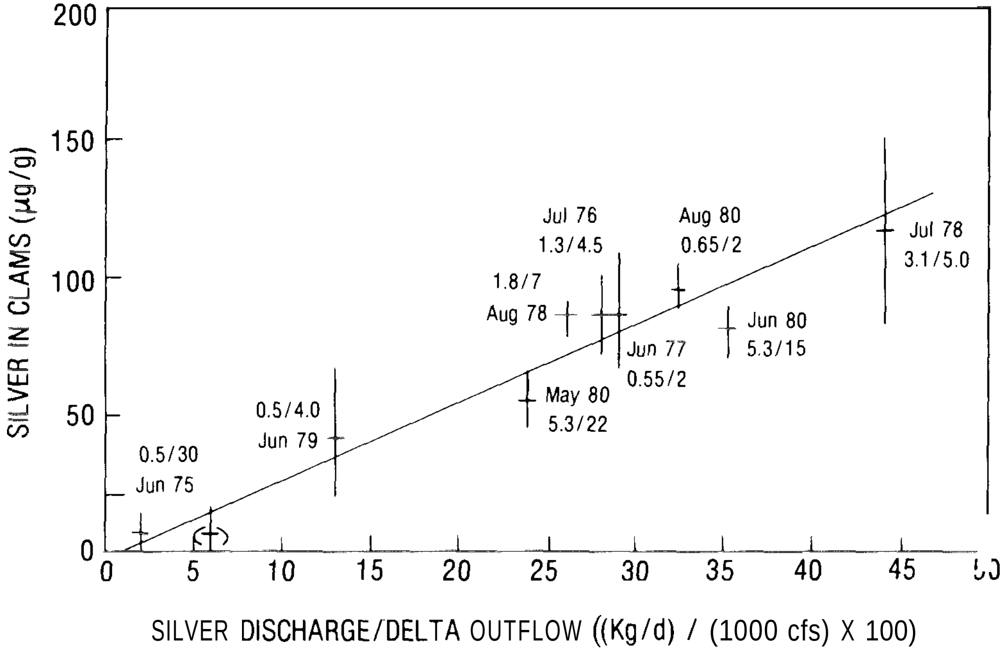

Fig. 5. Relationship of the minimum Ag concentration observed in *Macoma balthica* in each summer between 1975 and 1980 with the Ag discharged by the Palo Alto sewage treatment plant normalized to Delta outflow. Date of sample and ratio of Ag discharge to Delta outflow as shown for each data point. Ag discharge in June. 1975, is estimated from previous loadings to fall between 0.5 kg/d and 1.5 kg/d. Data point for the latter value is shown in parentheses. Vertical bars are standard errors for Ag concentrations in clams.

Continuous pollutant discharge. then. appears to control the background level of trace-metal contamination in benthic organisms. Spatial and temporal differences in hydrodynamics and/or physicochemical variables in the Bay superimpose seasonal and annual variability on those background levels. The spatial mosaic that characterizes metal distributions in benthic organisms in the Bay appears to be accompanied by a temporal variability, apparently driven by changes in freshwater inputs from the watershed of the system.

Localized Changes in Biological Communities

Localized impacts on the benthic community around municipal and industrial outfalls were first documented by Filice (1959). who noted consistent patterns around sources of waste discharge. An absence of macrofauna was evident near municipal and industrial outfalls. High biomass and a reduced number of species occurred at intermediate distances from municipal outfalls. and low biomass and a large number of species (typical of unaffected areas) occurred at greater distances. Biomass did not increase at intermediate distances from industrial outfalls; and. in general, changes in the benthic community around industrial outfalls were more dramatic than near municipal outfalls.

No acceptable studies of changes in benthic communities around sources of waste discharge have been conducted since the late 1950s. The work that has been accomplished has been deficient in sample design and species identification, and has not always had a sound scientific approach (Nichols 1973). The difficulty in demonstrating conclusively the presence (or absence) of impacts around point sources of discharge is due. at least partly, to the extreme temporal and spatial patchiness of both species diversity and benthic biomass in the Bay. For example, in one recent benthic survey (Jones and Stokes Assoc. 1980), three replicate grab samples were collected at each of five stations at four times in one year around a sewage outfall in Central Bay. Less than two individuals per 0.05 m^2 of surface sediment were recorded for most species. Numerically dominant species changed with both time and space. Jones and Stokes Assoc. (1980) concluded that changes caused by effluent discharge could not be separated from the extremes of natural fluctuations in community characteristics. Results such as these suggest that impact studies which are limited in either time or space will be of little value in evaluating all but the most severe effects of waste discharge on the benthic community. This difficulty will continue until the basic processes governing the heterogeneity of the benthic community are better understood.

Some indirect biological evidence points to possible impacts on biological communities near point sources of discharge. Populations of clams (*M.* balthica) living in locations with a large amount of Cu and Ag enrichment are more tolerant to metal toxicity than are populations inhabiting less contaminated locations (Luorna et al., in prep.). These clams appear to possess a wide range of genetic or physiological adaptability which permits the species to persist in extremely contaminated environments (although the development of such tolerance occurs at some expense to a population since the tolerance disappears in less contaminated locations). M. balthica typifies organisms which inhabit continually perturbed environrnents. It is small, grows rapidly (Nichols and Thompson. in press). and produces large numbers of pelagic larvae. In general, such reproductive and growth "strategies" enhance the adaptability of a species. facilitating its survival in stressful types of habitat. Many species lack the plasticity of *M.* balthica. The tolerance to metals in *M.* balthica in specific localities is an indication that adaptive plasticity is necessary for survival. The existence of tolerance indicates a stressful environment. and may suggest that contaminants limit the suitability of the locality for complex biological communities by eliminating species lacking adaptability (Luoma 1977).

Impacts of accidental waste-water discharges can be determined from localized changes which coincide with the discharge. For 22 days in September 1979. the large sewage treatment facility at San Jose-Santa Clara malfunctioned. During this time. primary-treated sewage (1.5×10^7 m^3) was continuously released to a region of South Bay with poor circulation. During the spill. dissolved oxygen in waters in the vicinity of the outfall (within Coyote Creek) was low, as were oxidized forms of nitrogen (Cloern and Oremland, in prep.). Concentrations of particulate organic carbon. dissolved methane. and coliform bacteria were increased. Shrimp, previously fished commercially for bait, disappeared. as did recreationally important species such as sturgeon and shark (W. Dahlstrom, Calif. Dept. of Fish and Game. pers. comm.). Within two weeks of cessation of the discharge. water quality parameters had returned to levels characteristic of unaffected South Bay localities. and coliform bacteria counts had dropped 1000-fold (Cloern and Oremland. in prep.). Within one month, shrimp were again being harvested in the area, and recreational fishing was possible: juvenile sharks and rays had not reappeared two months after the spill.

The rapid biological recovery from the stress of this large sewage spill reflects the simplified nature of the biological community, and the resilience of South Bay. The biological community of this area of the Bay is dominated by opportunistic species. characteristic of the early stages of ecological succession (Nichols 1979), and well suited to life in perturbed environments.

Reproductive strategies. extensive migration, and physiological plasticity aid the survival of such species and permit rapid recovery when die-offs occur. Despite the massive volume of sewage spilled, adverse impacts were localized because of the substantial diluting capacity available (Cloern and Oremland, in prep.). Thus. migrant organisms were available in abundance from adjacent environments once the suitability of the affected environment was restored. The apparent lack of high levels of persistent toxicants also contributed to the rapid biological recovery.

Extensive fish-kills also occur in the Bay every year. Some kills coincide with known spills of hazardous substances. Others are of unknown cause, although it is generally thought that many of these are associated with discharge or spillage of wastes (Wong 1977). Between 1963 and 1976, 225,000 dead fish were counted in the Bay and its tributaries in 313 separate incidents (Wong 1977). This number undoubtedly reflects only a small proportion of the actual deaths. Some of the fish-kills resulted from the annual die-off of striped bass which has occurred for at least 25 years (Stevens. in press). The cause of these die-offs has not been determined. Other kills involve a simultaneous die-off of more than one species (44 different species have been involved). Where several species are included in a fish-kill. a "natural" die-off seems unlikely.

Other than indirect indications from fish-kills and the study of the failure of the San Jose sewage treatment plant. virtually nothing is known about the impacts of the frequent acute and/or accidental discharges of waste. Together with documented localized impacts around continuously discharging sources. acute discharges may add to the heterogeneity of the Bay community at any one time. These series of localized impacts may result in a community which is continuously and contiguously in different stages of recovery from stress, as the suitability of specific habitats changes with space and time.

PHYSIOLOGICAL INDICATORS OF STRESS

Environmental stress may be reflected in a degradation in the morphological or physiological condition of individuals. Tumors, parasitism, reduced reproductive capabilities and tissue anomalies all may be induced by exposure to the chemical contaminants of waste waters (Sinderrnann 1979). Such physiological anomalies seem to occur more frequently in polluted than in unpolluted environments, although evidence linking these anomalies to pollutant exposures in nature is more circumstantial than direct.

Physiological indications of stress have been observed in a number of species from the Bay. Epidermal papillomas (skin tumors) were reported in 12% of nearly 16.000 English sole collected in the late 1960s (Cooper and Keller 1969). Individual fish had as many as 33 tumors. In contrast. papillomas did not exceed 0.1% in English sole collected in coastal waters distant from cities (Sindermann 1979). The maximum incidence of these tumors reported in the literature for English sole from polluted environments is 58% (Sindermann 1979).

Histopathological analysis indicated that mussels from the Bay were in poor physiological condition compared to mussels at many of 63 other coastal stations sampled in the United States (Yevich and Barazcz in Goldberg et al. 1978). Animals from both North Bay and South Bay had poorly developed reproductive systems and a variety of tissue anomalies indicative of stress. Three mussels from North Bay had cancer-like neoplastic tumors—the only tumors found in mussels in the nation-wide survey. Tissue concentrations of at least one toxicant (most commonly PCB or Cd) were very high at nearly every location where mussels were found to be in poor condition. In the animals from the Bay. Ag. Cd and PCB values all were among the highest observed in the survey.

Recently. physiological indications of stress have also been observed in striped bass (J. Whipple, NMFS, pers. comm.). Parasitic damage to organs was observed in 37R of 300 striped bass collected in 1978-80. and body lesions were observed in 35%. The proportions of physiological anomalies greatly exceeded the number of anomalies in striped bass from Coos Bay in Oregon.

Blood studies indicated abnormally low numbers of lymphocytes. and high numbers of granulocytes were common in striped bass from the Bay. Poor physiological condition was often accompanied by reproductive immaturity and high concentrations of trace metals, petroleum hydrocarbons, and/or PCB's.

INFLUENCE OF SEWAGE TREATMENT

In recent decades. facilities for treating municipal and industrial wastes have expanded in San Francisco Bay (Russell et al. 1982). Few specific comparisons of biological communities are available before and after these improvements in sewage treatment. However, several lines of evidence suggest that improved waste-water treatment has resulted in some improvements in the quality of Bay waters.

First, with the onset of improved waste treatment, BOD concentrations in South Bay have declined (Horne and McCormick 1977). The decline in BOD has been accompanied by a detectable improvement in levels of dissolved oxygen in the southernmost end of South Bay where circulation is poor. A comparison between surveys in the early 1960s (Storrs et al. 1966) and more recent studies (Smith et al. 1979) shows measurable increases in the availability of dissolved oxygen in lower South Bay (and particularly in Coyote Creek) since the San Jose-Santa Clara sewage treatment plant was upgraded to secondary treatment (Fig. 6). Since oxygen is crucial to most macrofauna, it seems likely that improvements in the biological community of lower South Bay have accompanied the improvements in oxygen levels. The biologically destructive effects of the temporary reversion to primary treatment by the San Jose plant during the breakdown in 1979 substantiate this conclusion.

Second, the bacteriological quality of the Bay has improved substantially with improved sewage treatment (California Water Quality Control Board 1977). Total coliform counts averaging 800 organisms per 100 ml were observed in South Bay in 1964. In 1977, coliform counts at similar stations averaged four organisms per 100 ml (Table 4). Improvements of a similar magnitude were also observed in North Bay and Carquinez Strait over this period.

Finally, between the 1960s and the 1970s there was a trend toward fewer fish-kills in the Bay and its tributaries. Furthermore, a decreasing proportion of the kills occurred in the Bay itself (Wong 1977), suggesting an improvement in some causes of fish toxicity.

Improvements in the treatment of sewage entering the Bay have. apparently, more than kept pace with the increasing volume of sewage discharged in terms of organic loadings, dissolved oxygen. and pathogenic bacteria. The biological community has undoubtedly benefited from these improvements. However, physiological suggestions of stress in organisms and instances of substantial contamination with trace toxins indicate that significant waste-water discharge problems remain unsolved. In fact, these problems may be growing. If so, substantial past investments in the treatment of sewage to improve water quality may be negated as contaminant impacts replace the impacts of discharging organic wastes.

THE BIOLOGICAL COMMUNITY OF SAN FRANCISCO BAY

Anthropogenic changes and the natural stresses of estuarine processes have undoubtedly combined to shape the characteristics of the biological community of the Bay. We are not certain if waste discharge has permanently affected, Bay-wide. any major components of the biological community. However, a review of community characteristics consistent with impacts expected from waste-water discharge is relevant.

Despite the massive inputs of nutrients to San Francisco Bay from sewage discharge, river discharge, and storm runoff, the Bay does not exhibit classical symptoms of eutrophication. Algal blooms, with associated depletions of dissolved oxygen. are uncommon (Horne and McCormick

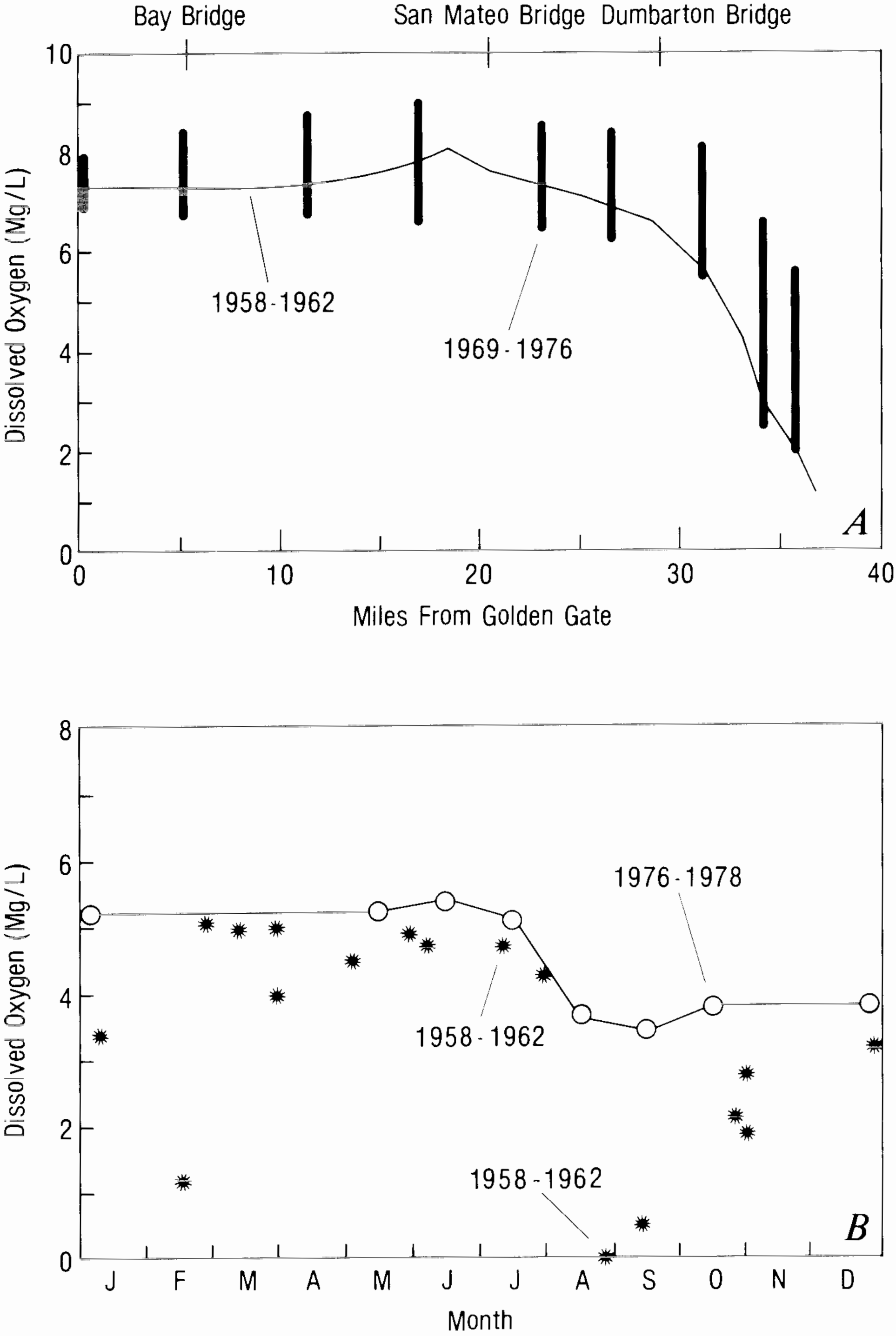

Fig. 6. Dissolved oxygen concentrations measured between 1958 and 1962 (Storrs et al. 1966) compared to dissolved oxygen observed between 1969 and 1976 (Smith et al. 1979). (A) A profile of measurements throughout South Bay. Vertical bars are the range of values observed by Smith et al. (1979). Solid line is mean of values observed by Storrs et al. (1969). (B) Seasonal changes in dissolved oxygen in the southern extremity (near the mouth of Coyote Creek) of South Bay during the two periods.

TABLE 4. BACTERIOLOGICAL QUALITY OF OFFSHORE WATERS IN SAN FRANCISCO BAY SYSTEM. (Comparison of data for years indicated from California Water Quality Control Board. 1977.)

	Median Total Coliform (MPN/100 ml)			
Section	1977	1976	1973	1962-1964
South Bay	4	8	10	809
North Bay	4	6	30	785
Above San Pablo Bay	240	94	1550	2665

1977). Red tides (blooms of toxic dinoflagellates that poison shellfish) are seen in coastal waters near San Francisco Bay, but do not occur inside the Golden Gate.

Phytoplankton biomass can be high in North Bay, particularly in the shallows of San Pablo Bay (during spring) and Suisun Bay (during spring or summer), where chlorophyll a concentration often exceeds 50 μg/L (Alpine et al. 1981). However: these blooms do not lead to deterioration of water quality. In fact, high phytoplankton biomass appears to be desirable since the dominant forms are diatoms which support zooplankton productivity and, ultimately. fishery resources. Orsi (1980), for example, has found a significant correlation between chlorophyll concentrations and the abundance of zooplankton including *Neomysis mercedis*, a preferred food source for juvenile striped bass.

In South Bay, phytoplankton biomass is usually low, especially in summer when chlorophyll a concentration is less than 5 μg/L (Alpine et al. 1981), and is usually dominated by microflagellates (Wong and Cloern 1981). The absence of dense algal populations. especially during periods of low turbidity, is surprising given the high nutrient availability (Conomos et al. 1979), slow circulation (Conomos 1979), and measured rates of photosynthesis, which indicate a potential for rapid population growth (B. E. Cole pers. comm.). Dense populations of benthic suspension-feeders occur locally in South Bay, and could control phytoplankton biomass there. Calculations based upon biomass values reported by Nichols (1979) indicate that benthic invertebrates may filter the volume of South Bay at least once daily. If the benthic species exert primary control over algal biomass, then phytoplankton population dynamics would usually be independent of nutrient availability. Changes in nutrient discharges would have little impact on the phytoplankton in such an instance. But, if the benthic species are selectively disturbed and their control is removed. then the possibility exists for dense algal blooms in South Bay.

The poor coupling between nutrient availability and phytoplankton growth in the Bay has long been recognized (Horne and McCormick 1977). However, the possibility that benthic organisms may be responsible for the uncoupling is a new hypothesis that requires substantiation.

Horne and McCormick (1977) suggested that benthic algae were the most likely members of the plant community to exhibit signs of eutrophication if excessive nutrient enrichment occurred. Localized nuisance blooms of benthic algae have periodically covered small areas of mudflats in the Bay. For example, a bloom of red algae (*Polysiphonia* sp.) covered the mudflat near Palo Alto with more than 8 cm of decaying organic matter in August 1975. The decaying algae killed nearly all the benthic niacrofauna in the area (Nichols 1979; Luoma unpublished data). Epifauna began to reappear several months after the algal mat disappeared, but many infaunal species did not reach their earlier densities for several years.

In summer 1979. a massive bloom of benthic green algae, *Cladophora*, occurred in North Bay. The extent of the bloom was unprecedented. From Suisun Bay to Candlestick Point, economic damage was attributed to the massive algal mats which fouled fishing gear, obstructed industrial influent pipes, and caused both esthetic and odor problems on the shorelines. The bloom did not return in 1980. The cause of the 1979 *Cladophora* bloom remains an unsolved problem. It seems most likely that some uncommon combination of environmental events and Bay characteristics produced conditions optimal for algal growth. Although unsubstantiated, it seems unlikely that such an extensive bloom would have occurred without the high background of nutrient concentrations provided by continuous inputs from municipal outfalls. The 1979 bloom could be the first overt sign of a potential for large-scale eutrophication, at least of macroflora uncontrolled by biological processes. Defining the causes of the bloom, the contribution of waste discharges, and the probability of recurrence should be given high priorities in future research in the Bay.

Relatively few species are present in the benthic cornmunity compared to other estuarine systems (Nichols. Luoma unpublished data), in part because the benthos is subjected to a variety of biotic and abiotic stresses (Nichols 1979). These stresses. both natural and man-induced, result in continuing disturbance of the benthic environment, a situation to which few species adapt. Comparisons of benthic species present today with species found in shell middens from thousands of years ago do not indicate that any major extinctions of edible species have occurred in the Bay during modern times (Nichols pers. comm.), although such data say nothing about relative abundances, or the fate of inedible species. There is no conclusive evidence that demonstrates Bay-wide impacts from waste discharge on the benthic community. As we have mentioned, evidence of physiological stress in mussels and evidence supporting some localized impacts around sewage outfalls is available. The patchiness of the benthic cornmunity could also indicate localized stress as well as habitat heterogeneity. In general, however, we understand very little about the dynamics of the benthos Bay-wide, and even less about the impacts of different environmental changes upon that community. If the benthos is the key to the lack of eutrophication, at least in South Bay, then a better understanding of spatial and temporal patterns within this segment of the ecosystem is essential.

In contrast to our lack of measured changes in the benthic community, many changes have been documented in the fisheries of San Francisco Bay. Major fisheries of the Bay have included striped bass, shad, white sturgeon, salmon. Dungeness crab, oysters, bait shrimp, anchovy, and herring. Only the last three have supported commercial fishing in recent years.

Commercial fishing of sturgeon was prohibited in the early 1800s after intense exploitation and/or environmental perturbation (probably heavy siltation) greatly reduced populations (Smith and Kato 1979). Commercial fishing of striped bass was prohibited in 1935 and commercial harvesting of Chinook salrnon inside the Bay was prohibited in 1957. Striped bass supported a fishery in excess of 900.000 kg (Stevens in press) annually and salrnon 3.22 million kg annually (Smith and Kato 1979) at their peaks. Populations of both species had declined prior to the prohibition of commercial fishing. Shad fishing was prohibited in 1957. primarily to protect striped bass and salmon. Sturgeon. shad, salmon, and striped bass continue to be important recreational fisheries.

Between 1963 and 1977, populations of striped bass declined steadily (Stevens in press). Between 1959 and 1977, the numbers of young striped bass could be predicted from a correlation with Delta outflow. The declining population was explained by a general increase in the diversion and consumption of fresh water for agriculture. However. since 1977. the abundance of young bass has fallen more than 30% below the level predicted by Delta outflow (Cannon 1982). An undefined source of stress has affected the population since 1977, and questions have even been raised about the survival of this vaiuable resource.

Dungeness crabs are not harvested commercially in San Francisco Bay, but migration into the Bay is a crucial step in the early stages of their life cycle. The Dungeness crab fishery off San Francisco Bay collapsed in 1961 from a high of more than 5 million kg annually to less than 250,000 kg annually. Recent evidence suggests that parasitism of eggs may have contributed to the low level of the fishery (Wickham 1979), but the underlying causes of the collapse of this resource have not been established conclusively.

Oysters (*Crassostrea virginica*) transported from the East Coast were successfully reared in

San Francisco Bay between 1869 and the early 1900s. The oyster fishery yielded 1.2 million kg of meat at its maximum in 1899 (Barrett 1973). In the early 1900s the fishery began to fail. Growth rates of animals declined. and tissues became thin and watery. Production in 1908 was down to 0.3 million kg annually and by 1923 was only 0.03 million kg per year. *Crassostrea gigas*, the Pacific oyster, planted in the Bay in the 1930s, also failed to grow properly (Bonnot 1935). Experiments in the 1970s suggest that *C. gigas* will grow rapidly on stakes (but not as well on sediments) in some parts of the Bay (W. Dahlstrom, California Fish and Game, pers. comm.). A successful re-establishment of an oyster fishery requires further study.

The most successful commercial fisheries in San Francisco Bay in the late 1970s were anchovy, herring, and bait shrimp. In general, the fisheries have been characterized by a shift from the more valuable. large, longer-lived, upper-trophic-level species to less valuable, smaller, more rapid reproducers from lower trophic levels (Fig. 7). A similar shift has been noted in the fisheries of the Great Lakes (Aaron and Smith 1971), the North Sea (Cushing 1975), the Baltic Sea (Thurow 1980), and other aquatic systems where intensive commercial exploitation has been coupled with changes in water quality. Changes in the type of fisheries reflect changes in the abundance of different species. Seldom can such changes be linked to any one specific cause.

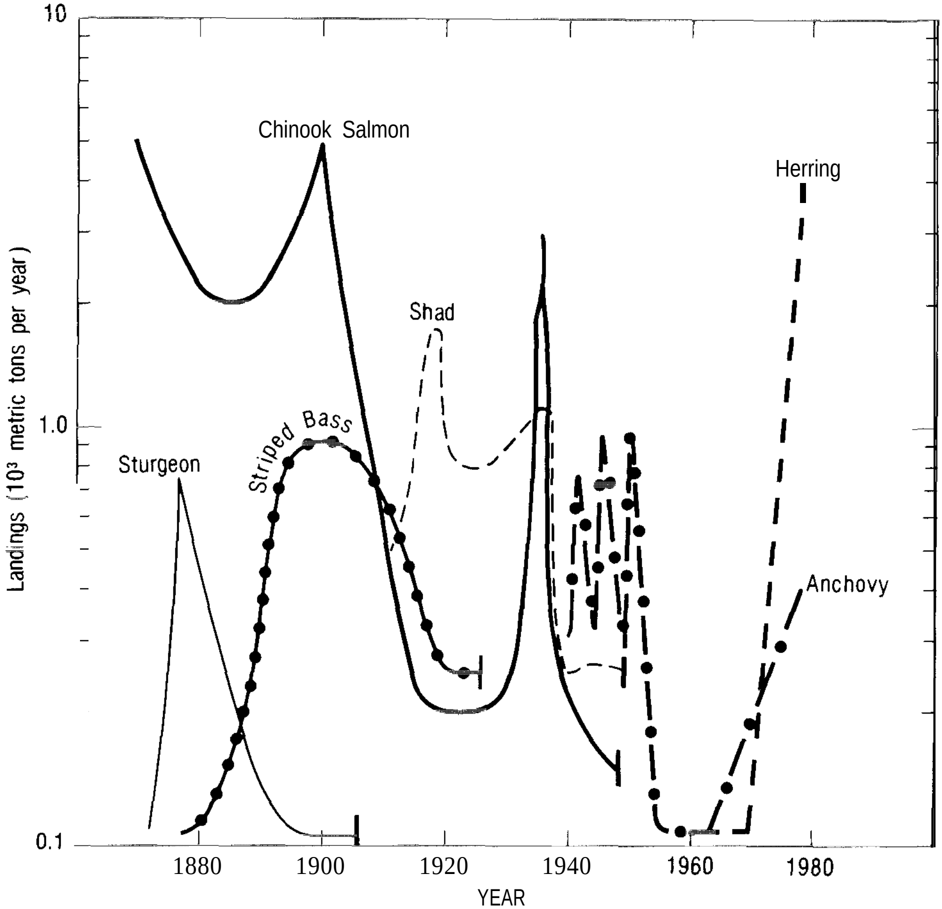

Fig. 7. General trends in several of the major fisheries of San Francisco Bay as observed between 1970 and 1978. Data for anchovy and herring are shown only from 1940 to 1978. Vertical bars signify when commercial fishing was prohibited. Catches less than 100 metric tons per year are not reported. Data are adapted from Smith and Kato (1979).

Larger. longer-lived species require larger and more consistent areas of suitable habitat than do smaller species with greater adaptability (Southwood 1977). Even if waste discharges have only localized impacts, the sum of those impacts has the possibility of playing a role in shifting the biological community away from more commercially valuable species and toward the adaptable species which best survive in a constantly changing spatial mosaic of habitat types. The possibility that waste discharge has played such a role in the deterioration of the fisheries of the Bay certainly deserves further investigation.

SUMMARY AND CONCLUSIONS

Available evidence supports several specific conclusions concerning the impacts of waste discharge into San Francisco Bay.

(1) Improvements in waste treatment since the 1960s have resulted in demonstrable improvements in some water-quality parameters. However, significant problems. particularly with trace contaminants, still exist. Pockets of extreme contamination of biota with toxic trace metals are evident. Also, contamination with toxic trace organic compounds (e.g., PCB's and petroleum hydrocarbons) occurs. at least in localized instances, and perhaps Bay-wide. Tolerance to trace toxins has been observed where contamination is severe. Physiological indications of stress consistent with trace contaminant impacts are observed in mussels. English sole. and striped bass.

(2) Most documented biological impacts of trace contaminants are localized. However. the number of such localized impacts may be large. given the number of point sources discharging urban runoff and waste waters from municipal and industrial facilities. The extremely high frequency of accidental spills, or short-term discharges of untreated wastes. adds to the heterogeneity of the Bay environment. If waste-water discharge has a general impact on the biological community of the Bay, it is through a subtle increase in this heterogeneity, creating a spatial mosaic of environments more or less suitable for complex biological communities.

(3) The major fisheries of the Bay have shifted from larger, longer-lived. less adaptable species toward smaller, rapidly reproducing species adapted to life in a perturbed environment. The precise causes of these changes have not been established. However. an increase in the temporal and spatial heterogeneity of the Bay environment could contribute to such a shift (Southwood 1977). Thus, the possibility that waste discharge has played a role in the decline of some Bay fisheries cannot be ignored.

(4) The impacts of waste-water discharge are influenced by flushing, dispersion, and general circulation. Also. the volume of the Delta outflow plays a major role in determining the influence of such impacts on biological communities, especially in South Bay.

(5) Despite massive discharges of nutrients, the Bay does not exhibit ongoing signs of eutrophication. The benthic community may contribute to the control of phytoplankton in South Bay and prevent nuisance blooms. If so, the benthos represents a poorly understood, but essential link that may be crucial to the maintenance of the biological community of the Bay in its present state. A recent large bloom of benthic macroalgae suggests that broad-scale nuisance blooms are possible in the Bay under the proper set of environmental conditions, further emphasizing the importance of maintaining biological controls on primary productivity.

In general, long-term intensive research and monitoring, focused on the processes (both anthropogenic and natural) controlling biological community structure could contribute to our understanding of the causes of stress in this complex system. Some work was begun in the 1970s. In the 1980s. changes in waste treatment, consolidation of treatment facilities, further reductions in fresh-water discharge, and further shoreline modifications seem likely. An extension of the research efforts of the past will be an essential step in preserving the complexity, and thus the important functions, of the biological community of San Francisco Bay.

The research needs of the future include the following: (1) Further improvements in waste-water treatment need to be made to remove trace contaminants. Expensive removal systems should not be proposed until the precise sources of specific trace contaminants are identified. however. Relatively inexpensive studies, using indicator organisins for in *situ* monitoring. have been used to identify a major source of Cu and Ag contamination in South Bay, and point to sewage treatment plants in general as a major source of Cu. Studies of the distribution of toxic trace contaminants in indicator organisms surrounding different types of waste-water outfalls could provide information about sources of contaminants; the extent of impacts from different types of waste, or different specific outfalls; the effectiveness of different levels of waste-water treatment: and the value of more intense treatment in reducing trace contaminants. Information about the distribution of PCB's. petroleum hydrocarbons. and other specific trace organics is especially needed.

(2) The conditions which uncouple phytoplankton and macroalgal productivity from nutrient availability, thus preventing eutrophication of the Bay, need to be defined. Relevant questions include: Do the benthos control phytoplankton productivity in South Bay. and under what conditions is that control lost? Is primary productivity always independent of nutrient availability, or do specific environmental conditions recouple the two?

(3) A Bay-wide study of the spatial and temporal features influencing the distribution and production of benthic species should be given high priority. Benthic surveys which are limited in time and space are presently of little value in identifying biological impacts because of the inherent patchiness of the communities. A comprehensive. long-term effort to understand the basic processes controlling patchiness. species distributions. and benthic productivity could eventually provide important information about vulnerabilities in the benthic community and the possibility of adverse impacts from waste-water discharge. The long-term benefit of such studies would be far superior to the minor benefits derived from continuing the type of short-term, poorly focused studies that have been carried out over the past 25 years.

(4) Evidence is accumulating that suggests that Delta outflow is a major variable controlling the impact of waste waters in South Bay. Information about the influence of Delta outflow on the hydrodynamics, chemistry, chemical-biological interactions, and the fate of pollutants in the channels. and especially on the shoals of the Bay is necessary.

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