

Ecological changes in the Southern California Bight near a large sewage outfall: benthic conditions in 1980 and 1983

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ABSTRACT: The structure of the macrobenthic community, sediment toxicity, and sediment contamination changed greatly between 1980 and 1983 along a pollution gradient from the Los Angeles County Sanitation Districts' (LACSD) sewage outfalls on the Palos Verdes Shelf, California, USA to a reference site in northern Santa Monica Bay. Stimulation of the species richness, biomass, and density of the benthos along the 60 m contour 5 to 11 km from the outfalls was significantly reduced in 1983 when compared to 1980. The clam *Parvilucina tenuisculpta* and the polychaete *Tharyx* sp. A were the numerically dominant species in the area of benthic stimulation in both years. Stations 1 to 3 km from the outfalls in 1980 were occupied by a depauperate fauna strongly dominated by the opportunistic polychaete *Capitella* spp. In 1983 species richness and biomass significantly increased close to the outfalls, *Capitella* spp. was much less abundant, and the assemblage was dominated by ostracods of the genus *Euphilomedes* that are characteristic of background conditions or areas only slightly affected by wastewater discharges. At the reference site in Santa Monica Bay there were no significant changes in species richness, biomass, or density between 1980 and 1983, and the brittlestar *Amphiodia urtica* remained the dominant species. Sediment contamination by most measured chemicals and parameters of organic enrichment decreased on the Palos Verdes Shelf, but not at the reference station, between 1980 and 1983. Sediments collected within 3 km of the outfalls in 1980 were acutely toxic to the phoxocephalid amphipod *Rhepoxynius abronius*. There was no significant toxicity associated with any sediment from the Shelf in 1983. These ecological changes correspond with the reduction in the mass emission of BOD and chemical contaminants from the LACSD outfalls between 1980 and 1983. Severe storms in the winter of 1982–83 may also have contributed to improvements in sediment quality and the partial recovery of the macrobenthos.

INTRODUCTION

The marine macrobenthos responds in a consistent pattern to changes in the level of sediment organic enrichment (Pearson & Rosenberg 1978). Benthic assemblages near major sources of organic material contain no macrofauna or only a few pollution-tolerant, opportunistic species that may be very abundant. At sites further from the enrichment source, the opportunists are replaced by an assemblage of greater species richness and biomass that gradually changes into the community characteristic of the unpolluted environment. The Pearson & Rosenberg (1978) model applies to successional patterns that occur in both time and space in response to increasing or decreasing sediment organic enrichment. The model is consistent with benthic spatial distributions near sewage outfalls and the temporal response of the benthos to the initiation or

elimination of sewage discharges in open coastal waters (Smith 1974, Anger 1975, Smith & Greene 1976, Bascom 1978, 1982, LACSD 1981, Mearns & Word 1982, Swartz et al. 1985a, Stull et al. 1986). However, little is known about benthic responses to incremental changes in the mass emission of organic material and specific chemicals. We have, therefore, examined sediment contamination, sediment toxicity, and benthic community structure near a major sewage outfall during a period of gradual reduction in the mass emission of many effluent constituents.

The Los Angeles County Sanitation Districts (LACSD) discharge approximately 5×10^{11} l yr⁻¹ of municipal wastes on the Palos Verdes Shelf, California, USA (Schafer 1984). Sufficient particulate material accumulates on the seabed to greatly increase the sediment concentration of chemical contaminants and organic matter. These sediment changes have substan-

tially altered the macrobenthos in a pattern predicted by the Pearson & Rosenberg (1978) model (Swartz et al. 1985a). Since at least 1971, benthic species richness, biomass, and density over a large area of the Shelf have been significantly greater than background conditions (SCCWRP 1973). At sites closer to the outfalls there have been significant reductions in these parameters and a strong numerical dominance by the opportunistic polychaete, *Capitella* spp.

Since 1971 there has been a gradual decline in the mass emission of suspended solids and most chemical contaminants from the LACSD outfalls (LACSD 1981, Stull et al. 1986). Between 1977 and 1980 the average reduction in the emission of the 22 effluent components monitored by Schafer (1978, 1980, 1984) was 14.2 % and from 1980 to 1983 the average reduction was 18.6 %.

In 1983, we repeated the survey conducted in 1980 (Swartz et al. 1985a) of the macrobenthos, sediment toxicity and chemical contamination on the Palos Verdes Shelf. Our objective was to determine if the reduction in mass emissions from the outfalls resulted in a reduction in sediment contamination and a recovery of the macrobenthos. We examined *a priori* predictions, related to the Pearson & Rosenberg (1978) model, of ecological changes that would occur in response to improved sediment quality: (1) the abundance, richness, and biomass of the benthos at the site of maximum stimulation in 1980 (Stn 6) would be reduced; (2) the site of maximum benthic stimulation would move closer to the outfalls; (3) tolerant, opportunistic species would disappear or become less abundant at sites closest to the outfalls; (4) less tolerant species would appear or be more abundant at sites closer to the outfalls; and (5) the slight sediment toxicity detected in 1980 near the outfalls would be reduced or eliminated. The relative tolerance of benthic species to sediment organic enrichment was based on Word's (1978, 1980) classification of 45 taxa according to their distribution near sewage outfalls in the Southern California Bight.

MATERIALS AND METHODS

Sediment and macrobenthos samples were collected on the Palos Verdes Shelf and Santa Monica Bay, California on 13 to 15 May 1980 at Stns 1, 2, 3, 4, 6, 8 and 9, and on 27 to 29 June 1983 at Stns 1, 3, 4, 5, 6, 7, 8 and 9 (Fig. 1). Stn 2 was not occupied in 1983 because benthic conditions there were very similar to those at Stn 1 in 1980 (Swartz et al. 1985a). Stns 5 and 7 were added in 1983 to provide better spatial coverage of ecological changes on the Shelf. The LACSD outfalls discharge at a water depth of approximately 60 m on the southeast portion of the Shelf. The first 8 stations

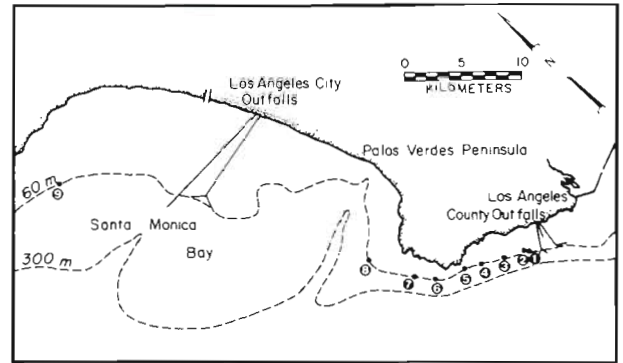


Fig. 1. Location of benthic stations on the Palos Verdes Shelf and Santa Monica Bay, California

were located along the 60 m contour at increasing distances of 1 to 15 km to the northwest of the outfalls in the direction of predominant benthic deposition of sewage particles (LACSD 1981, Hershelman et al. 1981). Stn 9 was 47 km from the outfalls at a water depth of 60 m in northern Santa Monica Bay. This reference station is the closest site to the study area that is representative of background benthos conditions in the southern California Bight (Word & Mearns 1978, Bascom 1978). The Los Angeles City sewage outfalls in Santa Monica Bay have little or no influence on the pollution gradient (1 to 8) or reference (9) stations (Bascom et al. 1978).

Ten 0.1 m² van Veen grab samples were collected at each station. The contents of 5 of the grabs were sieved through a 1.0 mm mesh screen to collect macrofauna. Material retained on the screen was preserved in buffered 10 % formalin, later transferred to 70 % ethanol, sorted to major phylogenetic group, and weighed (± 0.1 g) after blotting on absorbent paper. Specimens were counted and usually identified to the species level. Polychaetes identified by taxonomic keys as *Capitella capitata* are referred to as *Capitella* spp. because of the possible occurrence of sibling species in our collections (e.g. Grassle & Grassle 1976). Certain alphabetic codes for distinct species reflect assignments given by the Southern California Association of Marine Invertebrate Taxonomists, e.g. *Tharyx* sp. A. and *Myriochele* sp. M.

The structure of the benthic community was analyzed in relation to species composition, species richness (number of species, S, collected per 0.1 m² grab), density (number of individuals, N, per 0.1 m²), biomass (g per 0.1 m², wet weight), dominance, and Infaunal Index. The dominance index was defined as the minimum number (or fraction) of species whose combined abundance was equal to 75 % of the individuals in the sample. The dominance index is inversely related to numerical dominance. The Infaunal Index is based on the relative abundance of 4 groups of species

representing different stages of macrobenthic succession in relation to organic enrichment near sewage outfalls in the southern California Bight. Group I includes species that are dominant in background areas and decrease in abundance with increasing proximity to sewage outfalls (e.g. phoxocephalid and ampeliscid amphipods, ophiuroids). Species of Group II increase in abundance in areas slightly affected by sewage discharges (e.g. *Euphilomedes* spp., *Mediomastus* spp.). Species of Group III are present in moderately affected areas (e.g. *Parvilucina tenuisculpta*, *Macoma carlottensis*). Opportunistic species found in heavily affected areas are placed in Group IV (e.g. *Capitella* spp., *Schistomeringos* spp.). The complete list of species in each of the 4 groups and the index formula are given by Word (1978, 1980) and Mearns & Word (1982). Index values range from 0 when all individuals belong to opportunistic species of Group IV to 100 when all individuals belong to Group I.

Samples from the remaining 5 grabs were used for physical, chemical, and toxicological analyses. Methods are described in detail by Swartz et al. (1985a). The van Veen grab was equipped with hinged top plates that permitted sampling of the sediment surface. Redox potential (Eh) was measured by inserting a Pt/calomel electrode 1 cm beneath the sediment surface. Interstitial water was collected by suction into a syringe through a cellulose filter inserted into the sediment, and preserved for ammonia-nitrogen and free sulfide analyses. Cores (2 cm deep) were taken from the surficial sediment layer in each grab for analysis of (1) sediment toxicity, (2) total volatile solids and total organic carbon, (3) 5 d sediment BOD, (4) total oil and grease, hydrocarbon oil and grease, (5) total sulfide, (6) metals (Cd, Pb, Zn, Cr, Cu, Ni), (7) bis(2-ethylhexyl) phthalate (DEHP), and (8) 4,4'-DDE. DDE and DEHP were measured in only 2 grabs from each station during the 1980 survey. All other parameters were measured in 5 replicate grab samples from each station in 1980 and 1983. The bulk concentration of all chemicals in sediment is expressed on a dry weight basis. Sediment toxicity was determined by the survival of the phoxocephalid amphipod *Rhepoxynius abronius* after 10 d of exposure to Palos Verdes sediment (Swartz et al. 1985b). Sediment from the Yaquina Bay, Oregon, USA collection site of *R. abronius* was used as a reference for the sediment bioassays.

Statistical comparisons of differences in mean values between stations and between years for biological and chemical parameters were made by t-tests, analysis of variance, Student-Newman-Keuls multiple range test, and, when variance was heterogenous for transformed data, the Games and Howell method (Sokal & Rohlf 1981, Steel & Torrie 1960). F_{\max} was used to test for

homogeneity of variance. Log transformations were applied when variances were heterogenous. Dunnett's procedure was used to compare mean survival in sediment from the Palos Verdes Shelf with mean survival in the Yaquina Bay reference sediment (Steel & Torrie 1960). Unless otherwise noted, all statements about statistical comparisons are based on the $p < 0.05$ significance level.

The biological and chemical data sets were analyzed separately by numerical classification techniques to establish the relative similarity of individual grab samples without consideration of the station or year of collection. Samples were clustered on the basis of similarity in the composition and abundances of macrobenthic species or the presence and magnitude of chemical parameters. The Canberra metric dissimilarity coefficient and the flexible sorting strategy of Lance & Williams (1966) with $\beta = -0.25$ were used in the classification analyses (Boesch 1977). To reduce the biological data set to a manageable size, rare species represented by a total of less than 20 individuals in all samples were excluded from the classification. All measured chemical parameters except DDE and DEHP were included in the chemical classification. DDE and DEHP were excluded because they were analyzed in only 2 samples from each station in 1980.

RESULTS

Dominant macrobenthic species: 1980–1983 comparison

The composition and abundance of dominant species changed between 1980 and 1983 at stations close to the outfalls (Table 1). The 5 most abundant species at Stn 1 in 1980 were the polychaetes *Capitella* spp., *Nereis procerca*, *Nephtys cornuta franciscana*, *Eumida sanguinea*, and *Schistomeringos longicornis*. All of these species disappeared or declined in abundance at Stn 1 in 1983. The proportion of individuals belonging to *Capitella* spp. decreased at Stn 1 from 85.2 % in 1980 to 10.8 % in 1983. The dominants at Stn 1 in 1983 included the ostracod *Euphilomedes* spp., the polychaetes *Tharyx* sp. A, *Capitella* spp., and *Mediomastus californiensis*, and the pelecypod *Tellina modesta*. In 1980, all of these species except *Capitella* spp. had densities $< 1 \text{ 0.1m}^{-2}$ at Stn 1 and were more abundant at stations further from the outfalls. Temporal changes at Stn 3 were similar to those at Stn 1. The proportion of individuals belonging to *Capitella* spp. declined from 56.2 % in 1980 to 0.1 % in 1983. With the exception of the pelecypod *Parvilucina tenuisculpta*, the 5 most abundant species in 1980 were less abundant in 1983, and the 1983 dominants were

rare in 1980. In 1983, 4 of the 5 most abundant dominants were the same species at both Stns 1 and 3.

The composition of the dominant species at stations 5 km or more from the outfalls did not change greatly between 1980 and 1983. *Tharyx* sp. A, *Parvilucina*

tenuisculpta and *Mediomastus californiensis* were consistently among the 5 most abundant species at Stns 4, 6, and 8 in 1980 and 1983 and at Stns 5 and 7 that were sampled only in 1983 (Table 1). Although they remained strong dominants, these 3 species were

Table 1. Mean densities of the 5 most abundant species at at least 1 station on the Palos Verdes Shelf and Santa Monica Bay, California in 1980 or 1983. Five replicate 0.1 m² grabs were taken at each station

Species	Year	Station								
		1	2	3	4	5	6	7	8	9
<i>Eumida sanguinea</i> (PO)	1980	7.4	15.2	0.6	0	nd	0	nd	0	0
	1983	0	nd	0.2	0	0.4	0.8	1.6	0.4	0
<i>Schistomeringos longicornis</i> (PO)	1980	6.6	8.6	1.4	0	nd	0	nd	0	0
	1983	0	nd	0	0	0	0	0	0	0
<i>Nephtys cornuta franciscana</i> (PO)	1980	7.8	3.8	0.8	0.2	nd	0.2	nd	0.6	0
	1983	1.6	nd	1.2	0.2	0.8	0.4	0.2	0.2	2.8
<i>Capitella</i> spp. (PO)	1980	316.6	579.2	172.6	4.2	nd	9.6	nd	0.2	0.2
	1983	34.4	nd	0.2	0.8	1.0	0.8	0	0	1.0
<i>Euphilomedes</i> spp. (OS)	1980	0.2	0.4	0.2	0.6	nd	10.2	nd	74.2	2.2
	1983	84.6	nd	19.6	35.8	48.6	54.2	107.6	3.0	1.2
<i>Tharyx</i> sp. A (PO)	1980	0.2	0.6	0.2	42.4	nd	1194.0	nd	113.8	0.8
	1983	34.6	nd	46.8	24.4	268.6	394.0	509.6	30.0	1.4
<i>Macoma carlottensis</i> (PE)	1980	2.4	8.8	10.6	0.2	nd	4.2	nd	0.4	0
	1983	3.4	nd	3.2	1.2	2.0	2.8	1.0	0.4	0.4
<i>Nereis procera</i> (PO)	1980	10.6	6.0	11.4	5.2	nd	26.8	nd	6.4	0.2
	1983	0	nd	0.8	2.6	1.4	5.2	5.8	2.4	0.8
<i>Notomastus</i> sp. A (PO)	1980	0	0	0.2	17.8	nd	27.6	nd	2.6	0
	1983	0.6	nd	4.6	15.8	9.8	19.4	15.0	1.4	0.2
<i>Parvilucina tenuisculpta</i> (PE)	1980	3.6	2.6	12.2	335.4	nd	1498.6	nd	155.0	33.4
	1983	15.0	nd	27.4	98.6	384.0	807.6	270.4	30.6	3.2
<i>Listriolobus pelodes</i> (E)	1980	0	0	28.6	6.0	nd	45.2	nd	24.4	0.8
	1983	1.0	nd	2.0	0.8	1.8	11.0	5.0	2.2	0
<i>Tubulanus</i> spp. (N)	1980	0	0.2	0.6	15.2	nd	56.8	nd	12.2	0.6
	1983	2.6	nd	1.8	4.4	14.8	19.2	12.2	8.4	3.6
<i>Mediomastus californiensis</i> (PO)	1980	0	0.2	0.2	83.8	nd	529.4	nd	81.6	7.6
	1983	26.6	nd	21.2	52.0	128.2	47.6	41.4	7.4	25.2
<i>Tellina modesta</i> (PE)	1980	0.6	2.4	2.4	2.2	nd	3.6	nd	44.4	3.8
	1983	21.4	nd	21.8	8.4	16.0	11.2	8.8	6.6	4.4
<i>Spiophanes missionensis</i> (PO)	1980	0	0	1.8	2.8	nd	67.6	nd	74.2	39.2
	1983	3.6	nd	5.4	15.2	28.8	58.4	76.8	46.8	42.2
<i>Axinopsida serricata</i> (PE)	1980	0	0	0	0.4	nd	15.8	nd	95.4	21.0
	1983	0.4	nd	10.8	2.0	3.4	4.0	13.2	20.6	9.6
<i>Pectinaria californiensis</i> (PO)	1980	0	0	1.8	22.0	nd	51.2	nd	52.6	15.2
	1983	1.0	nd	13.4	7.4	10.4	14.6	19.2	24.4	29.4
<i>Minuspio cirrifera</i> (PO)	1980	0	0	0.2	0.4	nd	0.4	nd	3.8	1.0
	1983	5.4	nd	6.2	0.6	0.4	0.8	0.2	1.8	46.6
<i>Myriochele</i> sp. M (PO)	1980	0	0	0	0	nd	0	nd	0.8	53.0
	1983	0	nd	0	0	0	0	0.2	0	1.6
<i>Amphiodia urtica</i> (OP)	1980	0	0	0	0	nd	0	nd	0.2	131.0
	1983	0	nd	0	0	0	0.2	0	0	89.4
<i>Rhepoxynius bicuspidatus</i> (A)	1980	0	0	0	0	nd	0	nd	0	23.0
	1983	0	nd	0	0	0	0	0	0	5.4

nd: no data
 PO = polychaete; PE = pelecypod; E = echiuroid; N = nemertean; OS = ostracod; OP = ophiuroid; A = amphipod

always less abundant in 1983 than in 1980 at Stns 4, 6, and 8. The polychaete *Spiophanes missionensis* and *Euphilomedes* spp. were usually ranked among the 5 most abundant species at Stns 4 through 8 in 1983.

The brittlestar *Amphiodia urtica* was the most abundant species at the reference station (9) in 1980 and 1983 (Table 1). *A. urtica* was rare or absent at all other stations. This is also true of 2 other abundant species at Stn 9 in 1980, the amphipod *Rhepoxynius bicuspidatus* and the polychaete *Myriochele* sp. M. However, most of the other dominants at Stn 9 were usually found on the Palos Verdes Shelf. Dominants as close to the outfalls as Stn 3 were sometimes among the 5 most abundant species at Stn 9, e.g. *Parvilucina tenuisculpta* in 1980 and *Mediomastus californiensis* in 1983.

Changes in the distribution of dominant species on the Palos Verdes Shelf near the LACSD outfalls between 1980 and 1983 can be classified as follows:

Less abundant near outfalls

Polychaetes

Eumida sanguinea
Schistomeringos longicornis
Capitella spp.
Nereis procera

Closer to or more abundant near outfalls

Polychaetes

Tharyx sp. A
Notomastus sp. A
Mediomastus californiensis
Spiophanes missionensis
Pectinaria californiensis
Minuspio cirrifera

Bivalves

Parvilucina tenuisculpta
Tellina modesta
Axinopsida serricata

Ostracods

Euphilomedes spp.

Community structure

Macrobenthos species richness, biomass, and density increased above background levels on the Palos Verdes Shelf in both 1980 and 1983 (Fig. 2). In both years the maximum values for these parameters occurred at Stn 6, about 9 km from the outfalls, and then decreased progressively at stations closer to the outfalls. Although this between-station spatial pattern was similar in both years, there were significant changes between 1980 and 1983 in the structure of the benthos at most stations (Table 2). At Stn 1 there were

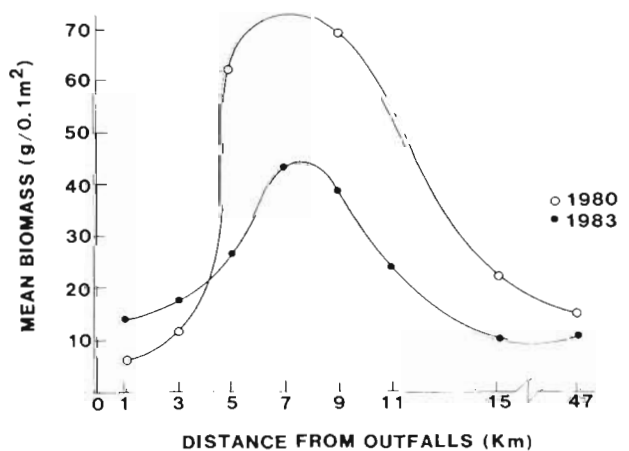
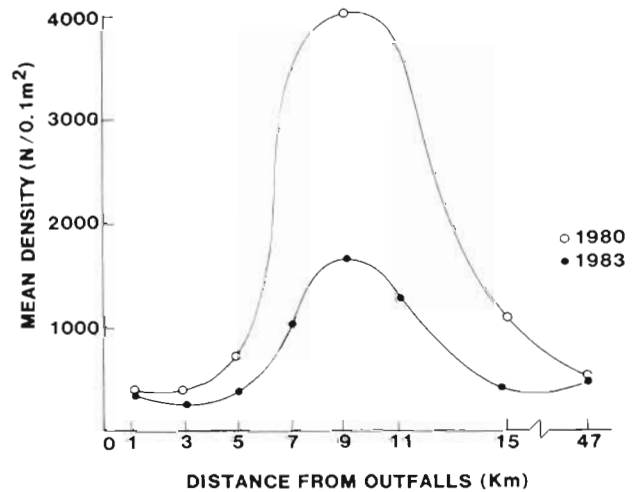
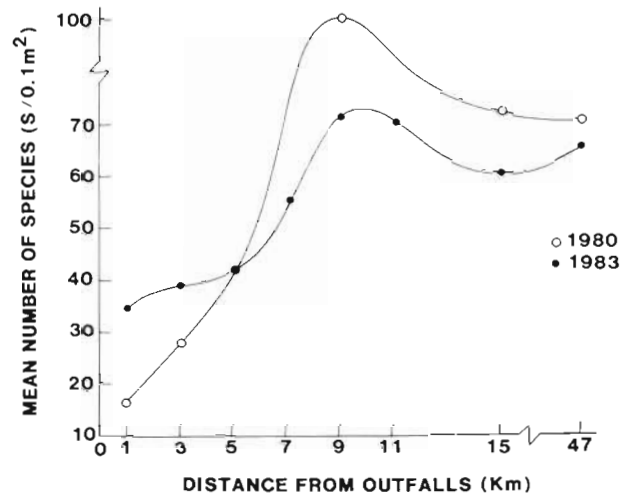


Fig. 2. Spatial changes in species richness ($S/0.1m^{-2}$), density ($N/0.1m^{-2}$), and biomass ($g/0.1m^{-2}$), of the macrobenthos near the Los Angeles County sewage outfalls in 1980 and 1983

significant increases in 1983 in species richness, biomass, and the Infaunal Index. Numerical dominance decreased significantly and amphipods were present at Stn 1 in 1983, but not in 1980. Macrobenthos density in 1983 at Stn 1 was not significantly different from 1980. Changes between years at Stn 3 were similar to those at Stn 1; there were significantly more species, higher Infaunal Index, and lower numerical dominance. Biomass at Stn 3 increased by 79 % in 1983, but the difference from 1980 was not significant.

The greatest quantitative changes in the benthos of the Palos Verdes Shelf occurred at Stns 4, 6, and 8 where density and biomass decreased significantly between 1980 and 1983 (Table 2). Infaunal Index increased significantly in 1983 at Stns 4 and 8, but did not change at Stn 6. Phoxocephalid amphipods were present at Stn 4 in 1983, but not in 1980. The abundance of phoxocephalids and all amphipods decreased significantly at Stns 6 and 8 in 1983.

The benthos changed less at the reference station (9) than at any other station. There were no significant differences there between 1980 and 1983 in density, species richness, dominance, Infaunal Index, or

biomass (Table 2). However, phoxocephalid amphipods and other amphipod densities declined in 1983.

Faunal homogeneity within stations was consistently high relative to homogeneity between stations or between years. Numerical classification of the macrobenthos data always placed replicate grab samples from the same station in the same year within the same cluster (Fig. 3). The dendrogram reflects strong spatial and temporal biological gradients. Larger station clusters are evident in Fig. 3. Replicates within these large clusters were pooled for statistical comparisons of biological conditions (Table 3). Stns 1, 2, and 3 in 1980 form a distinct cluster at one extreme in the biological gradient. All samples from Stn 9 in both 1980 and 1983 group to form a cluster representing background conditions at the other extreme of the gradient. The background assemblage had the highest Infaunal Index of any cluster, relatively low biomass and density of individuals, and very low numerical dominance. Echinoderms and amphipods were abundant. The most abundant species was the brittlestar *Amphiodia urtica*. Two clusters in Fig. 3 are associated with an apparent

Table 2. Structural comparison of the macrobenthic community on the Palos Verdes Shelf and Santa Monica Bay, California in 1980 and 1983. Data are mean values for 5 replicate 0.1 m² grabs taken at each station

Variable	Year	Station					
		1	3	4	6	8	9
Density (N 0.1 m ⁻²)	1980	371.8	307.0	720.2	4086.0	1082.0	528.6
	1983	320.0	292.7	334.2	1656.2	354.6	489.6
		NS	NS	- ***	- **	- ***	NS
Species richness (S 0.1 m ⁻²)	1980	15.8	28.2	41.2	96.2	71.8	70.4
	1983	34.8	39.3	41.2	70.4	59.8	66.6
		+ **	+ *	NS	- *	- *	NS
Dominance index (S 75% N ⁻¹)	1980	1.02	4.6	2.8	2.6	10.8	11.8
	1983	7.30	9.6	6.0	3.1	16.6	13.8
		+ ***	+ *	+ ***	NS	+ ***	NS
Amphipod density (N 0.1 m ⁻²)	1980	0.0	2.4	1.6	46.0	52.2	65.4
	1983	9.4	4.3	2.2	21.2	20.8	20.8
		+ **	NS	NS	- *	- ***	- ***
Phoxocephalid density (N 0.1 m ⁻²)	1980	0.0	0.0	0.0	30.6	40.8	31.4
	1983	0.0	0.0	0.4	11.6	12.6	9.4
		NS	NS	NS	- **	- ***	- ***
Echinoderm density (N 0.1 m ⁻²)	1980	0.0	0.2	0.0	0.0	0.2	136.0
	1983	0.2	0.2	0.0	0.4	0.2	93.4
		NS	NS	NS	NS	NS	NS
Infaunal Index	1980	4.5	18.4	37.1	51.9	63.5	81.0
	1983	52.8	58.6	52.8	50.6	68.3	79.6
		+ ***	+ **	+ ***	NS	+ *	NS
Biomass (g 0.1 m ⁻²)	1980	6.5	9.9	61.6	68.7	20.8	14.4
	1983	14.3	17.7	27.2	39.4	10.2	11.5
		+ *	NS	- **	- **	- *	NS

NS: not significant; - decrease between years; + increase between years
 * P < 0.05; ** P < 0.01; *** P < 0.001

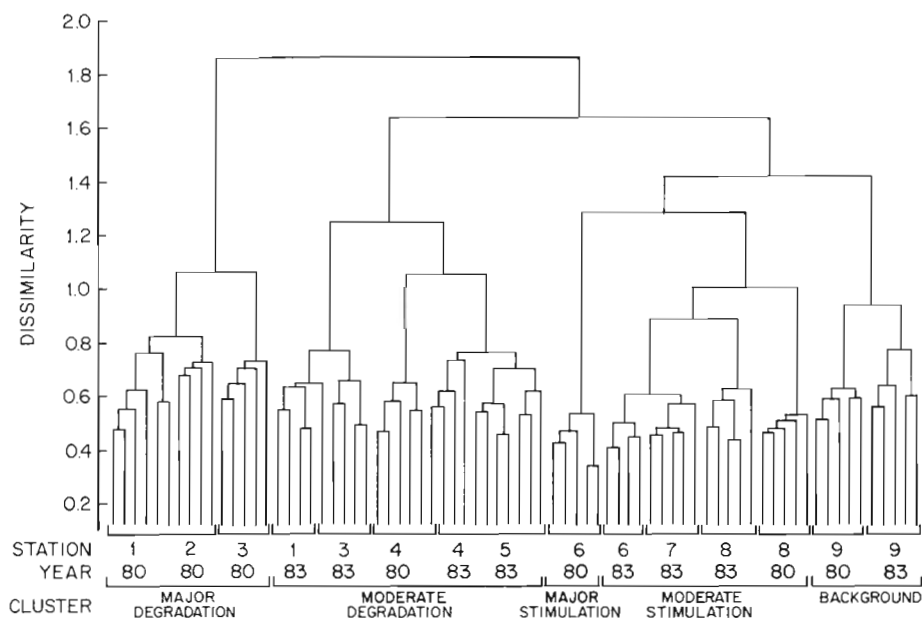


Fig. 3. Numerical classification of macrobenthos samples. Primary clusters include replicate grab samples from each station/year combination. Description of secondary clusters is based on faunal changes (Table 3)

stimulation of the benthos as reflected by significant increases in density or species richness from the background cluster mean. The 'moderate stimulation' cluster includes samples from Stns 6, 7, and 8 in 1983 and Stn 8 in 1980. The dominant species in this cluster was *Parvilucina tenuisculpta*. Amphipods were abundant, but echinoderms were rare. Species richness was not significantly different from the reference assemblage, but density of individuals was twice as great. Replicates from Stn 6 in 1980 form a unique cluster of major benthic stimulation because there were significantly more species, biomass, and individuals than in the reference assemblage. In the 2 clusters associated with

a degradation of the benthos there were fewer species and individuals and lower biomass than in the condition of stimulation. Echinoderms and amphipods were rare. Samples from Stns 1, 3, 4, and 5 in 1980 and 4 in 1980 are included in the cluster of moderate degradation. The major degradation at Stns 1, 2, and 3 in 1980 is different from moderate degradation because of the greater dominance of *Capitella* spp. and significantly lower values of Infaunal Index, species richness, and biomass.

Both spatial and temporal gradients are evident in the numerical classification (Fig. 3). For either year the hierarchical arrangement of macrobenthic sample clus-

Table 3. Structural characteristics of macrobenthic communities at station clusters on the Palos Verdes Shelf in 1980 and 1983. Station clusters are defined by numerical classification (Fig. 3). All data are mean values per 0.1 m² for all grab samples pooled within each station cluster. Means followed by different letters within the same column are significantly different ($p < 0.05$). (The letters have no purpose other than to indicate the results of the multiple range test)

Station cluster	Year: stations	Number of species	Number of individuals	Number of amphipods	Number of echinoderms	Biomass (g)	Dominance index	Infaunal Index	Dominant species
Major degradation	1980: 1, 2, 3	20.2 ^D	447 ^A	0.8 ^C	0.1 ^B	9.4 ^A	2.2 ^C	8.5 ^D	<i>Capitella capitata</i>
Moderate degradation	1980: 4 1983: 1, 3, 4, 5	42.8 ^C	566 ^A	4.4 ^B	0.1 ^B	34.2 ^C	5.4 ^B	50.3 ^C	<i>Parvilucina tenuisculpta</i>
Major stimulation	1980: 6	96.2 ^B	4086 ^C	46.0 ^A	0.0 ^B	68.7 ^D	2.6 ^C	51.9 ^C	<i>Parvilucina tenuisculpta</i>
Moderate stimulation	1980: 8 1983: 6, 7, 8	67.8 ^A	1095 ^B	31.4 ^A	0.3 ^B	23.6 ^{BC}	8.6 ^{AB}	60.6 ^B	<i>Parvilucina tenuisculpta</i>
Background	1980: 9 1983: 9	68.5 ^A	509 ^A	43.1 ^A	114.7 ^A	13.4 ^{AB}	12.8 ^A	80.3 ^A	<i>Amphiodia urtica</i>
Statistical comparison		F = 20.9 p < 0.001	F = 110.7 p < 0.001	F = 74.2 p < 0.001	F = 640.7 p < 0.001	F = 17.2 p < 0.001	H = 38.4 p < 0.001	F = 150.1 p < 0.001	

Table 4. Chemical characteristics of sediment from the Palos Verdes Shelf and Santa Monica Bay, California in 1980 and 1983. All bulk sediment concentrations are expressed on a dry weight basis. Data are mean values for 5 replicate grabs taken at each station in each year

Parameter	Year	Station					
		1	3	4	6	8	9
Eh, mV	1980	-85	-29	89	219	363	321
	1983	44	132	210	114	310	251
		NS	+ **	NS	NS	NS	NS
Total volatile solids, %	1980	17.5	15.0	14.2	15.2	9.5	4.0
	1983	12.1	11.4	11.8	10.6	6.9	6.6
		- ***	- *	- *	- ***	- ***	NS
Total organic carbon, %	1980	4.1	3.7	3.8	3.2	2.2	0.9
	1983	3.1	3.3	3.0	2.4	1.4	1.3
		- *	NS	NS	- *	- *	NS
Ammonia-N, mg l ⁻¹	1980	2.4	1.4	0.40	0.34	0.56	0.44
	1983	2.0	1.5	1.3	0.50	0.53	1.6
		NS	NS	+ *	NS	NS	NS
Free sulfide, mg l ⁻¹	1980	11	6.7	0.49	0.65	0.41	0.33
	1983	1.2	1.5	0.37	0.27	1.2	0.37
		- **	NS	NS	- *	NS	NS
Total sulfide, mg kg ⁻¹	1980	2520	2370	1310	443	121	24
	1983	1838	1349	1532	572	157	226
		NS	- *	NS	NS	NS	NS
5 d BOD, mg kg ⁻¹	1980	13800	10600	7160	4390	1740	660
	1983	3990	4540	3250	2100	880	680
		- ***	- ***	- ***	- **	- *	NS
Total oil/grease, mg kg ⁻¹	1980	20600	9950	6180	3620	1020	338
	1983	6860	5280	5060	1620	610	516
		- ***	- *	NS	- ***	- *	NS
Hydrocarbon oil/grease, mg kg ⁻¹	1980	10800	7020	4920	2270	645	144
	1983	6180	4500	4590	1290	503	291
		- ***	NS	NS	- **	- **	NS
Cadmium, mg kg ⁻¹	1980	32	26	22	8.9	2.4	2.4
	1983	26	14	18	4.5	1.8	0.7
		NS	- *	NS	- **	- *	NS
Lead, mg kg ⁻¹	1980	338	293	252	150	57	33
	1983	193	140	147	45	31	47
		- ***	- *	- **	- ***	- **	NS
Zinc, mg kg ⁻¹	1980	853	584	709	339	130	95
	1983	873	531	577	171	107	129
		NS	NS	NS	- ***	NS	NS
Chromium, mg kg ⁻¹	1980	821	481	720	305	101	62
	1983	664	439	478	180	152	94
		- **	NS	NS	- *	+ *	NS
Copper, mg kg ⁻¹	1980	691	450	547	309	96	52
	1983	328	235	248	74	51	45
		- ***	- *	- ***	- **	- **	NS
Nickel, mg kg ⁻¹	1980	95	99	85	61	26	61
	1983	76	63	70	42	29	42
		- ***	- **	NS	- ***	NS	NS
Bis (2-ethylhexyl) phthalate, µg kg ⁻¹	1980 ^a	12730	8800	7200	5120	1010	140
	1983	13960	8460	9310	1820	450	440
		NS	NS	NS	- **	NS	NS
4,4'-DDE, µg kg ⁻¹	1980 ^a	5610	5920	7830	1460	970	60
	1983	6990	4970	7510	2790	1050	110
		NS	NS	NS	NS	NS	NS
Number of parameters decreasing between 1980 and 1983		14	16	14	13	11	3

^a Only 2 replicates were analyzed for DDE and phthalate in 1980
NS: not significant; - decrease between years; + increase between years
* p < 0.05; ** p < 0.01; *** p < 0.001

ters is consistent with a hypothesis of a spatial biological gradient from the stations closest to the outfalls to the reference station. Temporal changes between 1980 and 1983 are shown by shifts in the location of stations from one cluster to another. Stns 1 and 3 moved from the major degradation cluster in 1980 to the moderate degradation cluster in 1983. Stn 6 moved from the major stimulation cluster in 1980 to the moderate stimulation cluster in 1983. Samples from Stns 8 and 9 farthest from the outfalls remained in the same clusters (moderate stimulation and background, respectively) in 1980 and 1983.

The 'background' and 'major degradation' clusters represent the extremes within this data set of biological conditions on the spatial-temporal pollution gradient associated with the LACSD outfalls. The 2 clusters differ greatly in species composition, species richness, dominance, Infaunal Index, and the presence/absence of indicator taxa like amphipods, echinoderms, and *Capitella* spp. (Table 3). Despite these qualitative differences, there are no significant differences between these clusters in the density or biomass of the benthos.

Sediment contamination

The concentration of most sediment contaminants declined significantly on the Palos Verdes Shelf between 1980 and 1983 (Table 4). Among 85 temporal comparisons of 17 contaminants at 5 stations on the Shelf, 44 showed significant decreases in sediment concentration. There were only 2 instances in which sediment concentrations increased significantly: ammonia-N at Stn 4 and chromium at Stn 8. (The sig-

nificant increase in Eh at Stn 3 is evidence of decreasing sediment organic enrichment.) Four parameters decreased significantly at every station on the Shelf: total volatile solids, sediment BOD, lead, and copper. In contrast, there were no significant changes in sediment concentrations of any parameter at the reference Stn 9 in Santa Monica Bay.

The numerical classification of the chemical data set produced a dendrogram similar to that for the macrobenthos (Fig. 4). Spatial gradients in sediment contamination are evident in the arrangement of clusters from A, containing the most contaminated samples from Stns 1, 2, and 3 in 1980, to F, containing most samples from the least contaminated, reference Stn 9. Temporal changes in sediment chemistry are indicated by the complete separation of replicates from Stns 1, 3, and 6 into different clusters depending on the year of collection. In 1983 all replicates from Stns 1, 3, and 6 were placed in clusters representing less contaminated sediment conditions than in 1980. Within-station heterogeneity in sediment characteristics in 1983 is evident in the appearance of replicates from Stns 3, 4, and 9 in adjacent clusters. The heterogeneity at Stn 9 in 1983 may be due to the presence in some grabs of large quantities of terrestrial plant leaves and twigs. This material was not found at any other station.

Sediment toxicity

Mean survival of *Rhepoxynius abronius* was significantly less than the Yaquina Bay sediment in 1980 at Stns 1, 2, and 3 (Table 5). All other sediment samples

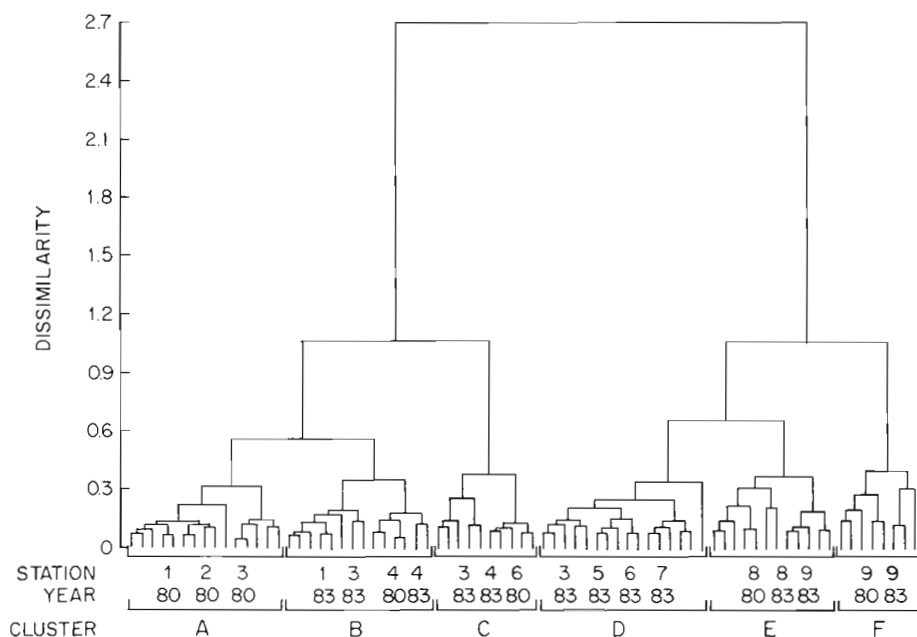


Fig. 4. Numerical classification of sediment chemistry samples. Alphabetically-coded clusters include one or more replicate grab samples from each station/year combination

Table 5. *Rhepoxynius abronius*. Mean survival in sediment from the Palos Verdes Shelf and Santa Monica Bay, California. Twenty amphipods were added to 5 replicate sediment samples from each station in each year. Means underlined are not significantly different from survival in Yaquina Bay, Oregon reference sediment ($p < 0.05$)

Year	Station									Yaquina Bay reference
	1	2	3	4	5	6	7	8	9	
1980	15.4	16.0	16.0	<u>18.4</u>	NT	<u>16.8</u>	NT	19.4	<u>19.0</u>	19.6
1983	<u>18.2</u>	NT	17.2	19.2	18.2	<u>16.6</u>	18.6	19.4	18.2	19.4

NT: not tested

collected from the Palos Verdes Shelf and Santa Monica Bay in 1980 and 1983 were not significantly different from the reference sediment.

DISCUSSION

Benthic conditions improved on the Palos Verdes Shelf between 1980 and 1983. The level of organic enrichment and the concentration of most measured contaminants decreased at all stations on the 60 m contour except the reference station in Santa Monica Bay. Four of 5 predictions concerning changes in the macrobenthos in response to the decline in sediment contamination were confirmed. Benthic abundance at Stn 6, the site of maximum stimulation in 1980, declined in 1983. With the exception of infaunal echinoderms, more sensitive species generally appeared closer to or became more abundant near the outfalls in 1983. The most pollution-tolerant species either disappeared or became less abundant near the outfalls in 1983. Evidence for acute sediment toxicity at stations within 3 km of the outfalls in 1980 was not found in 1983. The prediction that was not confirmed concerned an expected movement toward the outfalls of the area of maximum benthic stimulation. Instead, the site of maximum benthic species richness, density and biomass remained at Stn 6, about 9 km from the outfalls in 1980 and 1983.

Characterization of species that became much less abundant at stations close to the outfalls as 'tolerant' is supported by Mearns & Word's (1982) grouping of species for the Infaunal Index. *Capitella* spp. and *Schistomeringos longicornis* were dominants at Stns 1, 2, and 3 in 1980 and became much less abundant in 1983. Both species were placed by Mearns & Word (1982) in Infaunal Index Group IV that includes species most abundant in areas heavily affected by sewage discharges.

Species that were found closer to or became more abundant near the outfalls in 1983 typically belong to Infaunal Groups II (*Euphilomedes* spp., *Mediomastus californiensis*, *Axinopsida serricata*) or III (*Parvilucina*

tenuisculpta). Infaunal groups II and III are abundant in areas under slight or moderate influence of the discharges (Mearns & Word 1982).

Some sensitive taxa, especially *Amphiodia urtica* and other infaunal echinoderms, were rare at all stations on the Shelf in both 1980 and 1983. Amphipods were more abundant near the outfalls in 1983, while their density declined significantly at sites further away on the Shelf and in Santa Monica Bay. Although the cause of this decline is uncertain, the similarity in amphipod density fluctuations at the reference station and at sites 9 to 15 km from the outfall suggests the changes occurred over a relatively large spatial scale.

Ecological changes close to the outfalls represent only a partial recovery of the benthos. Infaunal Group I dominates natural assemblages at 60 m in the southern California Bight (Mearns & Word 1982). Species from this group were rarely collected near the outfalls. Although the structure of the benthic assemblage close to the outfalls improved in 1983, species richness, numbers of amphipods and echinoderms, numerical dominance, and Infaunal Index were significantly less there in 1983 than at the reference station. We therefore characterize conditions near the outfalls as changing from a major degradation in 1980 to a moderate degradation in 1983 (Table 3).

The significant reductions in benthic density and biomass at Stns 4, 6, and 8 also represent a partial recovery of the benthos relative to the reference station (Table 3). This decline in benthic stimulation was evident for most dominant species in the assemblage (Table 1). The only major exception was the increased abundance of *Euphilomedes* spp. Although the densities of *Parvilucina tenuisculpta* and *Tharyx* sp. A decreased by about 60 % in 1983, they remained the dominant species. The size of both individuals and populations of *P. tenuisculpta* is related to the degree of sediment organic enrichment near sewage outfalls (Fabrikant 1984).

The 1980 to 1983 reduction in sediment contamination on the Palos Verdes Shelf was correlated with macrobenthos alterations that are generally consistent with predictions based on the Pearson & Rosenberg

(1978) model. However, the expected spatial shift of the area of maximum benthic stimulation toward the outfalls did not occur in 1983. The concentration of most sediment contaminants at Stns 1, 3, and 4 in 1983 was greater than at the site of maximum benthic stimulation in 1980 (Stn 6, Table 4). Thus, the improvements in sediment quality may not have been sufficient to allow a major benthic stimulation at stations close to the outfalls in 1983.

We have used the terms stimulation and degradation to classify benthic conditions according to significant changes in species richness, number of individuals and biomass relative to a reference site (Table 3). This classification reflects the unimodal pattern of the biological gradient on the Palos Verdes Shelf (Fig. 2). In contrast, the chemical gradients on the Shelf typically show monotonic decreases with increasing distance from the outfalls (Table 4). The quantitative values of community parameters associated with different degrees of stimulation and degradation may be site-specific, and perhaps time-specific, and should not be applied uncritically to other situations.

Although benthic stimulation results in more species, individuals, and biomass, these changes are not necessarily desirable from a management perspective. Differences in species composition between the stimulated assemblage on the Shelf and the reference assemblage may affect benthic coupling with pelagic segments of the ecosystem. The benthos of areas of the Christiaensen Basin in the New York Bight affected by sewage wastes is dense and productive, but little of the productivity is transferred to higher trophic levels (Boesch 1982). Also, the stimulated benthic assemblage is associated with a variety of sediment contaminants that have the potential for adverse ecological effects (Table 4).

The elimination of acute sediment toxicity, as determined by the phoxocephalid amphipod bioassay, at Stns 1 and 3 between 1980 and 1983 provides additional evidence of the improvement of ecological conditions on the Shelf. However, the absence of acute sediment toxicity does not demonstrate the absence of benthic degradation (Swartz et al. 1985b). Although some amphipods were found at Stn 1 for the first time in 1983, phoxocephalid amphipods were no closer to the outfalls than Stn 4 (Table 2).

Substantial reductions in the mass emission of organic materials and chemical contaminants from the LACSD outfalls are consistent with the improvement in sediment quality on the Palos Verdes Shelf. The benthic accumulation of chemicals released from sewage outfalls is affected by many physical and biogeochemical processes. Exactly proportional changes in effluent and sediment concentrations should not be expected. However, with the exceptions

Table 6. Comparison of changes between 1980 and 1983 in the mass emission of materials from the Los Angeles County sewage outfalls and sediment concentrations at Stn 1 on the Palos Verdes Shelf, California. Mass emission data from Schafer (1982, 1984)

Parameter	Percent change	
	Mass emission	Stn 1 sediment
BOD	-20.0	-71.1
Oil & grease	-18.0	-66.7
Ammonia	-3.0	-16.7
Cadmium	-28.0	-18.8
Chromium	-56.1	-19.1
Copper	-36.8	-52.5
Nickel	-38.0	-20.0
Lead	-35.5	-42.9
Zinc	-18.1	+2.3
DDT	-66.2	+19.7*

* Change calculated for DDE, the major DDT metabolite at Stn 1

of DDT and zinc, there were corresponding reductions in the LACSD mass emission and Palos Verdes sediment concentration of most parameters for which comparative data are available (Table 6). Most of the DDT and its metabolites on the Shelf were introduced prior to source control in 1970 when the annual mass emission was about 100 metric tons (LACSD 1981). By 1980 the annual emission rate was reduced to 542 kg (Schafer 1980). The further 66.2% reduction to 183 kg DDT yr⁻¹ in 1983 apparently had little influence on the sediment concentration of previously discharged DDT and its metabolites.

Two other factors that have been cited as possible causes of improvements in sediment contamination near large southern California sewage outfalls are sediment bioturbation and sediment scouring by bottom currents or wave action (Greene 1976a, b, Stull et al. 1986). Burrowing, feeding and respiratory activities of the echiuran worm *Listriolobus pelodes* may have caused a reduction in the areal extent of anaerobic sediment on the Palos Verdes Shelf from 1974 to 1977 (Stull et al. 1986). *L. pelodes* dominated the benthic biomass on the Shelf during that period. This worm was present at our stations in 1980 and 1983, but ranked among the 5 most abundant species only at Stn 3 in 1980 (Table 1).

Unusually severe storms affected the southern California coastal zone several times during the winter of 1982-83 (Dayton & Tegner 1984, Gunnill 1985). These storms occurred during an El Niño warm-water period whose impact on the productivity of the southern California Bight could also have affected the benthos of the Palos Verdes Shelf. The storm waves had heights exceeding 3 m and periods exceeding 20 s

(Seymour & Sonv cited by Dayton & Tegner 1984). Such waves are capable of resuspending sediments at 60 m and could account for a reduction in contaminant concentrations in the surficial sediment layer (W. P. Muellenhoff pers. comm.). The occurrence of terrestrial plant debris at the reference Stn 9 may have resulted from stormwater runoff into Santa Monica Bay. Although this debris may have affected sediment chemistry, it had no obvious impact on the macrobenthos or sediment toxicity.

Reductions in BOD and chemical mass emissions from the LACSD outfalls, El Niño, and the 1982-83 winter storms may have all contributed to benthic improvements on the Palos Verdes Shelf. If the decline in mass emissions was the dominant factor, these improvements should persist in the future. If the El Niño or storms were responsible, the partial recovery of the Shelf benthos may be a temporary phenomenon.

Acknowledgements. We thank Don Baumgartner, Henry Lee, Jerry Pesch, Steve Ferraro, and Bob Whitlatch for their reviews of the manuscript; George Ditsworth, Kathy Sercu, Janet Lamberson, and Jill Jones for technical support; and the crew of the R/V *Marine Surveyor* for assistance during the field collections.

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This article was presented by Professor J. Gray; it was accepted for printing on April 2, 1986