Characteristics and Effects of Contaminated Sediments

During a survey of polynuclear aromatic hydrocarbon (PAH) contamination of ocean sediments (Anderson and Gossett 1987), several offshore sites (sewage and sludge outfalls) and harbor locations were sampled and found to have PAH concentrations high enough to have potential effects on marine organisms. To gather additional information about the extent of chemical contamination and biological effects at some selected sites, a multidisciplinary extension study was conducted by Steven Bay, Bruce Thompson, and Jack Anderson for the California State Water Resources Control Board.

The information collected during this study has helped to create a data base of chemical and biological effects measurements, and to provide an examination of the inter-relationships among the various indicators of sediment quality. The toxicity studies conducted for this project are noteworthy because they include long-term exposures of indigenous organisms to sediments.

Methods

Sediment samples were collected by Van Veen grab in September and November in 1987 from 10 sample sites (Figure 1). Eight of these sites had contaminated sediments (as determined by previous research) or were located adjacent to potential sources of contaminants. These stations included three sites adjacent to large municipal wastewater/sludge outfalls offshore of Orange County (OC), Palos Verdes (PV), and Santa Monica Bay (SMS). Five harbor stations were also sampled, including three in San Diego Bay (SDC, SDN, SD7), one in Los Angeles Harbor (LAH), and one located near the mouth of the Los Angeles River in Long

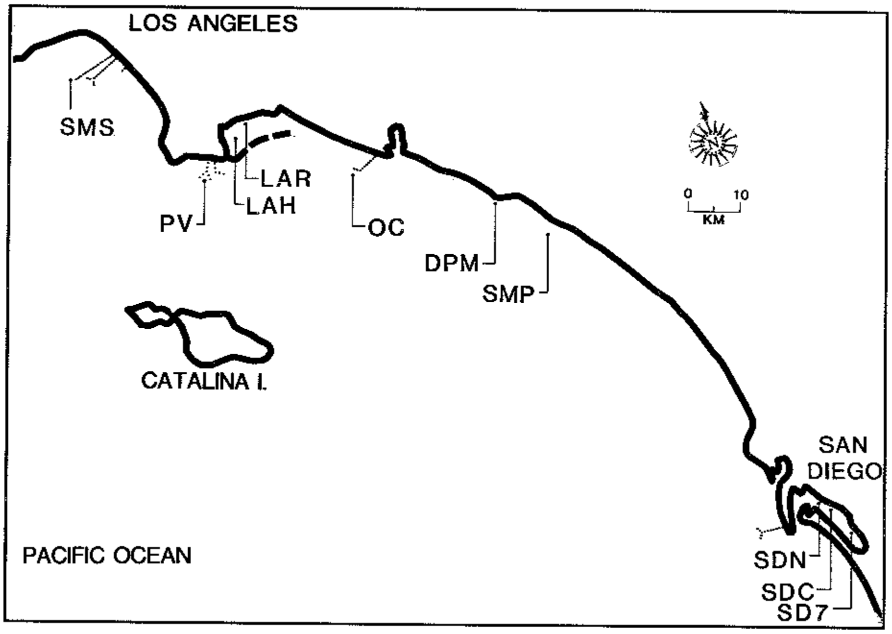


Figure 1. Location of the 10 sediment sampling sites. Site abbreviations are identified in the text.

Beach Harbor (LAR). Two additional stations were also sampled; these sites were determined to be relatively uncontaminated and served as reference sites to make statistical comparisons of the data collected. One of these reference sites, located offshore of San Mateo Point (SMP), was representative of uncontaminated conditions at outfall depths. The other site was located inside the Dana Point Marina (DPM) and served as a shallow water macrofauna reference for comparison with the other five harbor sites.

Jack Anderson deploys a Van Veen Grab to collect a sediment sample.

Three methods were used to measure the quality of surface sediment collected from the 10 sample sites: 1) each sample was analyzed for concentrations of trace metals, organotin, chlorinated hydrocarbons (DDT, PCBs), polynuclear hydrocarbons (PAHs), and dissolved sulfide; 2) benthic macrofauna living in the sediment at each location were identified and counted, and the sediment quality was described in terms of the animal community present; and 3) sediment quality was assessed by conducting laboratory toxicity tests with three marine species - measuring interstitial water (water from wet sediment) toxicity with bacteria (*Photobacterium phosphoreum*) using the Microtox analysis system, and measuring bulk sediment toxicity in amphipods (*Grandidierella japonica*) and sea urchins (*Lytechinus pictus*).

The parameters measured in this project were similar to those used in previous studies with the exception of the sediment toxicity tests. These toxicity tests have been used infrequently in southern California, and this is one of the first instances in which long-term exposures have been used to assess sediment toxicity.

Sediment samples were stored at 5°C for up to 9 d before toxicity tests were initiated. Interstitial water samples were centrifuged in preparation for Microtox analysis. Bacterial luminescence was measured with a Microtox 2055 analyzer following a 30 min exposure to 1 ml of interstitial water.

The amphipod toxicity tests were conducted in 1 l beakers containing a 2 cm layer of sample sediment. Two separate experiments were conducted simultaneously on each set of sediment samples. One experiment measured the effects on amphipod survival and reburial ability for a duration of 10 d at 15°C. The second experiment measured amphipod growth (the change in body length) and survival during a long-term exposure of 35 d at 19°C.

The sea urchin test consisted of a long-term exposure (35 d at 15°C) in 10 l containers containing a 2 cm layer of sample sediments. Daily measurements were taken of sea urchin survival and sediment preference during each experiment. At the end of the exposure period the urchin diameters and wet weights were measured, and the urchins were dissected to measure gonad weight and contaminant concentrations of trace metals, DDT, and PCB.

Another important feature of this study was our method of data analysis. We used multivariate statistics (principal components and principal coordinates analysis) to identify patterns in the data and to indicate relationships among different indicators of sediment quality. This statistical method was used because a large volume of data was generated and many of these data were highly intercorre-

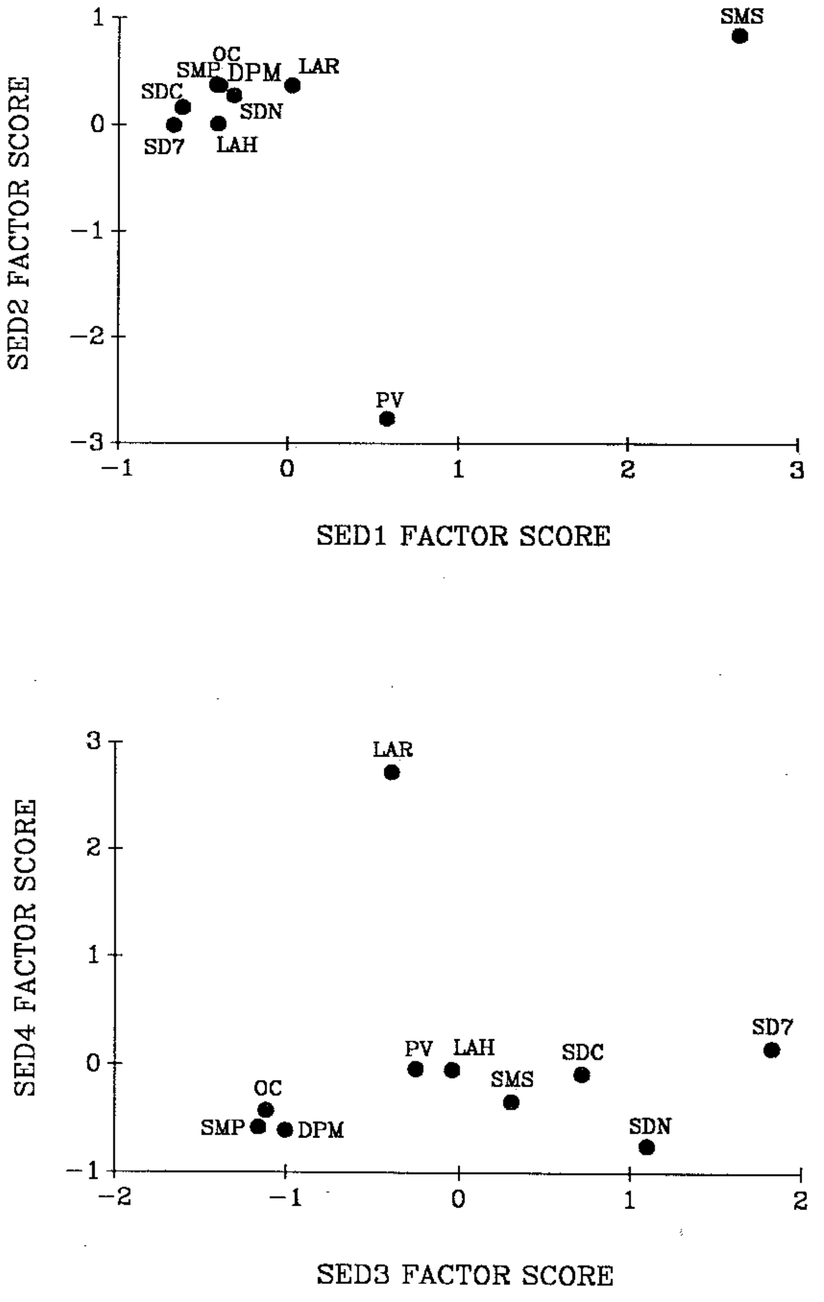


Figure 2. Plot of PCA factor scores for combined contaminant data. Scores are standardized values with a mean of zero and a standard deviation of one unit. Increasing concentrations are indicated by larger scores for SED1, SED3, and SED4. For SED2, lower scores (ie. negative scores) indicate increasing concentrations.

lated, making the identification of toxicity and contaminant relationships difficult.

Results

High levels of contamination were found at many of the sample sites. The Palos Verdes (PV) and Santa Monica Bay sludge (SMS) outfall sites generally had the highest concentrations of trace metals, chlorinated hydrocarbons, and total PAHs. The highest level of DDT compounds was present in PV sediment (6,000 ppb dry wt). The PV site also had the highest concentration of PCB compounds (1,500 ppb). Total concentrations of PAH were highest at SMS (20,000 ppb), although high levels were also found in the five harbor stations (4,700-12,100 ppb).

Principal components analysis (PCA) was used to reduce the chemistry data matrix to a set of composite variables that were statistically uncorrelated with one another. Each of the new variables (factors) represented a weighted combination of the original chemistry parameters. PCAs were first calculated for the contaminants within each of three major groups (inorganic metals, chlorinated hydrocarbons, and PAHs). A set of two or four composite variables was obtained with PCA for each of the contaminant groups.

Two factors were obtained after PCA of the inorganic metals data. The first factor, MET1, was highly correlated with the concentration pattern of Sn, Cd, As, Cr, Ni, Ag, and Cr. MET2 was highly correlated with the Pb and Zn values.

Two factors were also

obtained when the chlorinated hydrocarbon group was analyzed by PCA. One group (DDTF) was highly correlated with DDT compounds, while the second group (PCBF) was most highly correlated with the distribution pattern of PCB compounds.

Four factors resulted from PCA analysis of the PAH group. Two major factors were obtained; PAH1 represented petroleum compounds and was most highly correlated with low molecular weight PAHs, while the PAH2 factor was highly correlated with higher molecular weight PAHs characteristic of fossil fuel combustion. The remaining two PAH factors were correlated with only a few compounds and reflected distinctive contamination patterns at single sites.

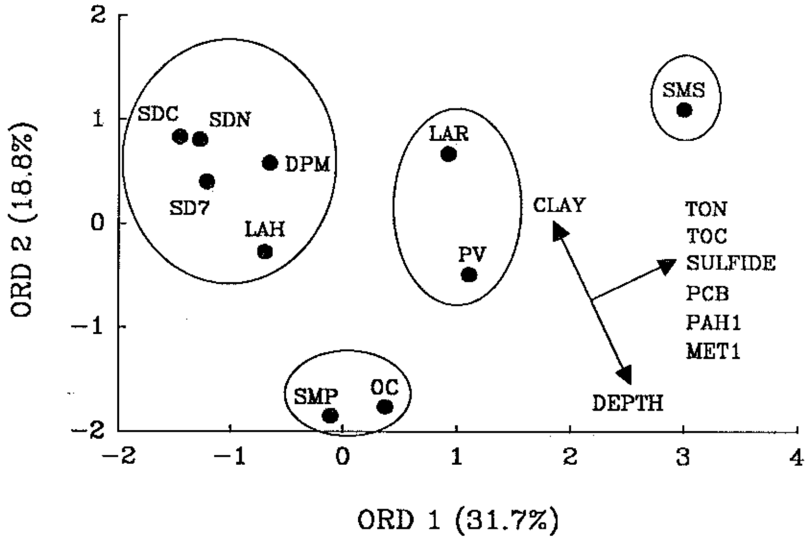


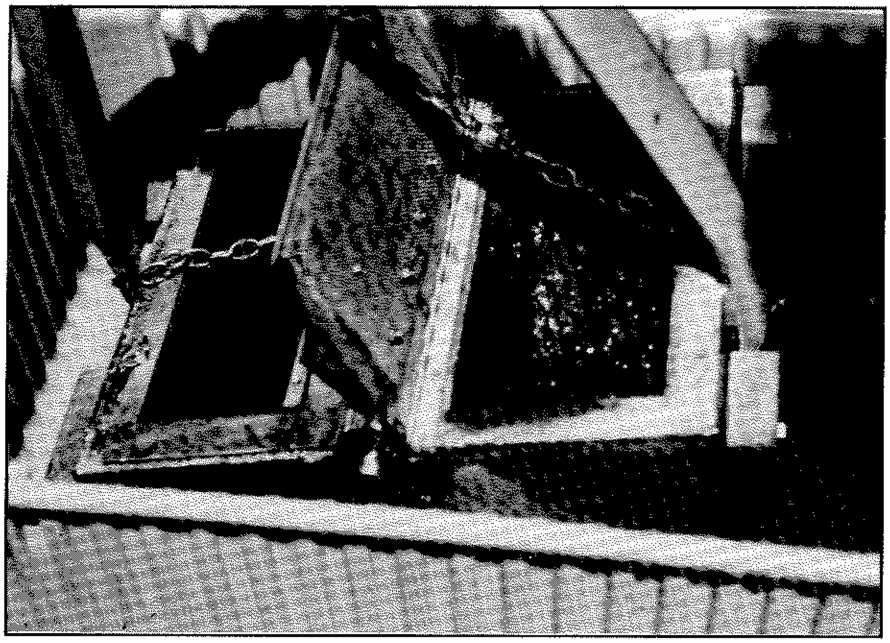
Figure 3. Plot of infaunal ordination scores for the two dominant principal coordinates analysis axes. Percentages show the amount of variation accounted for by each axis. Vectors show increasing concentrations of abiotic factors strongly correlated with the scores.

Scores for each of the above factors were calculated for each sample site, then combined with the other chemistry data (sulfide and organotin), and re-analyzed by PCA to determine the overall patterns of contaminant distribution. This analysis produced four factors, each of which represented a distinct pattern of contaminant distribution. Each factor was composed of a group of metals and hydrocarbon contaminants with distribution patterns among the sample sites that were too similar to one another to consider individually.

The relative values of the four factors, plotted for each sample site in Figure 2, indicate the contamination characteristics of each site. One factor group (SED1) represented the combined distribution pattern of PCBs, petroleum PAHs, most metals, and dissolved sulfide. The SMS sludge outfall site dominated this contamination group. The second group (SED2) reflected DDT and several PAH compounds; this group was dominated by the PV site. The LAR site also had a contamination pattern that dominated one of the PCA factors (SED4); this pattern was most highly correlated with several PAH compounds, Pb, and Zn. Combustion PAH, Pb, Zn, and organotin formed another group (SED3), having similar distribution patterns; scores for this PCA group were highest for the San Diego Bay sites and also produced the greatest separation of all the sites, reflecting the high prevalence of these contaminants in most areas.

Data on the distribution and abundance of the benthic macrofauna species were analyzed by principal coordinates analysis, in addition to routine calculations of abundances of indicator taxa, measurements of biomass, and calculations of various diversity indices. Principal coordinates analysis produced four main independent axes which accounted for 71% of the macrofauna variance among the sites. Four groups of sample sites, each with similar species composition and abundance characteristics, were identified when the scores for these axes were plotted (Figure 3).

The macrofauna at the harbor sites, except LAR, were similar to those at DPM (the embayment reference); these stations constituted one of the four assemblage groups.



Sediment grab.

The LAR and PV outfall sites were grouped together, indicating that the macrofauna assemblages at these two stations were most similar to each other. The similarity of the LAR and PV sites was unexpected because there were large differences in depths and contamination patterns between these sites. Similar levels of dissolved sulfide and organic carbon were found at these sites, suggesting that the fauna at the LAR site represented a transition between organic enrichment and contamination effects.

Greater macrofauna assemblage differences were found among the open sea sites than among the harbor sites. The macrofauna assemblage at SMS was very different from any other site, resulting in an isolated position for this station in the ordination plot. Only the presence of *Capitella capitata* linked this site with the other contaminated open sea sites. Of the five species collected at SMS, most of the individuals belonged to three undescribed species of the polychaete genus *Ophyrotrocha*, which are only found in the most contaminated areas off southern California. The OC outfall site formed a group with the open coastal reference site, SMP, indicating the relative similarity of the assemblages at these two stations. OC cannot be considered a reference site, however, as it was inhabited by species that are characteristic of impacted areas - the polychaete *C. capitata*, and the pelecypod *Parvilucina tenuisculpta.* The ophiuroid *Amphiodia urtica* was the most abundant species at SMP and is characteristic of reference sites; this species was present in low abundance at OC.

The grouping pattern identified for the stations based on ordination of the macrofauna data shared some similarities with those derived by PCA for the chemistry data. Both analyses identified the SMS, PV, and LAR stations as very distinct from the DPM and SMP reference sites. In addition, both analyses indicated the SMP and OC sites were relatively similar to one another.

The nature of the relationships between macrofauna changes and sediment chemistry were investigated further by using additional PCA and correlation analyses. PCA of the macrofauna ordination scores with the contamination scores indicated the presence of several similar patterns. Sediment characteristics constituting SED1 (sulfides, petroleum PAHs, PCBs, and MET1) had a strong correlation with the first ordination axis. An association was also indicated for the fourth ordination axis, which best reflected the macrofauna pattern of the embayment sites, and the contaminants dominating the SED3 group (combustion PAHs, Pb, Zn, and organotin).

Other environmental characteristics important to benthic organisms, such as depth, sediment grain size, and organic carbon, were not included in the PCA calculations. Additional analyses indicated that variations in depth and sediment organic material were correlated with the second ordination axis, reflecting the importance of environmental characteristics unrelated to contamination in the distribution and abundance of benthic animals.

Laboratory toxicity tests usually identified harmful effects at more sample sites than macrofauna analysis. A summary of the principal results for each of the toxicity tests is presented in Figure 4. All three of the test methods identified the same site, SMS, as most the most toxic site; these three test methods also showed a similar degree of response for the SDC station.

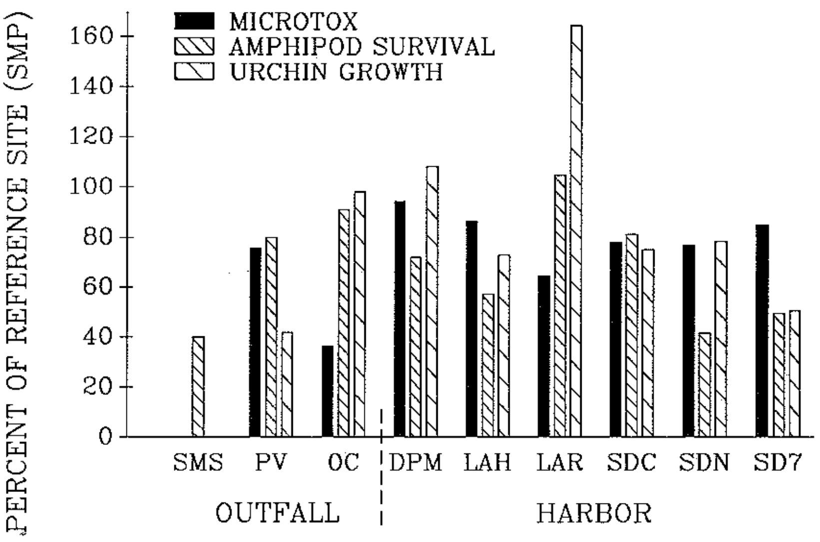


Figure 4. Relative responses of three toxicity tests to sediment or interstitial water from each sample site. Data are expressed as a percentage of the San Mateo Point reference site response.

Aside from the similarities noted above, there was little agreement among the three test methods regarding the extent of toxicity at the sample sites. The Microtox test identified significant interstitial water toxicity at all sample sites except the two reference sites. This was the only test that identified the OC and LAR stations as toxic. The results of the 10 d amphipod survival test identified sediments at one outfall (SMS) and all harbor sites except LAR as toxic. The amphipod test was the only method that identified the harbor site DPM as toxic. Growth of sea urchins after a 35 d exposure to the test sediments identified three sites, SMS, PV, and SD7, as toxic. The urchin test was the most sensitive of the three toxicity tests to sediment from PV.

PCA of the toxicity test results revealed that each of the principal test endpoints (bacteria luminescence, amphipod survival, and sea urchin growth) were correlated with different factors, indicating that each test method had different overall response patterns to the sediment samples. Scores resulting from the contamination and toxicity PCAs were combined and analyzed by PCA to identify potential relationships between these two measures of sediment quality. These results indicated that the Microtox analysis and the amphipod survival tests responded to different groups of contaminants. The Microtox data were highly correlated with the sediment contamination factor representing contamination from PCBs, petroleum PAHs, most metals, and sulfides (SED1). Amphipod survival scores correlated most strongly with the contamination factor representing combustion PAHs, Pb, Zn, and organotin (SED3).

The sea urchin growth data did not show a strong correlation with any one contaminant group, suggesting that these responses may have been elicited by a greater variety of contaminants than the other tests. These results may also indicate that urchin growth was strongly affected by sediment factors other than contamination (eg. total organic carbon [TOC] levels) at some sites, producing a more variable contaminant-response relationship.

The different response patterns exhibited by each toxicity testing method emphasize the necessity of using multiple species and different test strategies to accurately assess sediment toxicity. The differences in the response of each test type were probably related to the methods used, in addition to differences in the species' sensitivity to contaminants. The Microtox test was a measure of interstitial water toxicity and was probably most affected by contaminants with high water solubilities, such as sulfide and low molecular

Pat Hershelman and Skip Westcott processing sediment samples.

weight PAHs. The differences in response between the amphipod and sea urchin tests may also reflect methodological differences (eg. exposure length, degree of contact with sediment). For example, exposure to PV sediment for 10 d did not produce significant mortality in amphipods or sea urchins, but longer exposures of 28 d (amphipods) or 35 d (sea urchins) resulted in reduced growth for both species.

Discussion

Three different approaches to sediment quality assessment (chemical analysis, macrofauna examination, toxicity testing) were used in this study. Each of these methodologies should correlate well with each other under ideal circumstances, but, as demonstrated here, this is seldom the case. Thus, chemical analysis, macrofauna analysis, and sediment toxicity tests all provide important, but different, information about sediment quality.

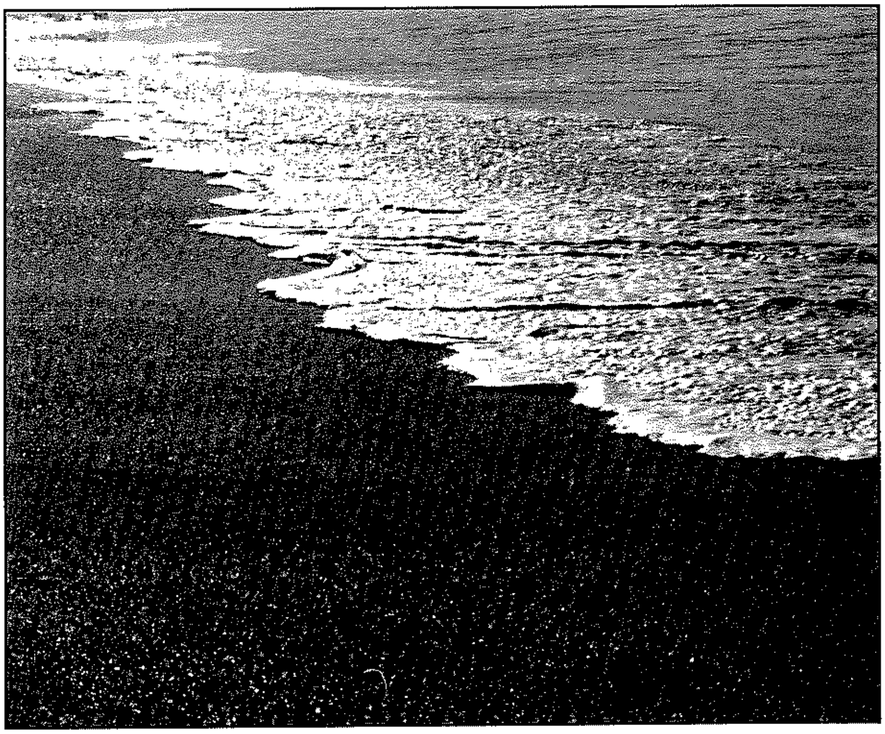
Several correlations between contamination groups, macrofauna, and toxicity patterns were found, indicating some of the observed biological effects were probably due to the presence of sediment contamination. Because the components of each contaminant group were highly correlated with one another, and because each of the three toxicity tests exhibited a different pattern of response to the contaminants, it is not possible to identify which specific contaminants affected toxicity most overall. Rather, these results indicate potential relationships between contaminants and test organisms that should be explored in future laboratory studies.

A significant correlation between biological effects and contamination was not identified for DDT compounds, which was surprising given the extremely high concentrations of DDT compounds at PV. This finding may illustrate a limitation of the statistical techniques used to identify relationships in this study. PCA identified patterns that accounted for the majority of the variation in the data. In the case of DDT, high concentrations were found only at PV, in the presence of many other contaminants that were more widely distributed among the other sites. The experimental data from this study indicated that the DDT compounds at PV were bioavailable to sea urchins and, therefore, a likely source of toxicity. However, the PCA method may have been unable to identify this relationship because it was a relatively small component of the overall pattern of sea urchin toxicity present.

More extensive field studies of sediment toxicity and macrofauna effects should be conducted in southern California. A large data base of sediment chemistry and macrofauna information exists for some areas in southern California, but sediment toxicity studies have been much more limited in scope. The current study focused on highly contaminated "hot spots" and found many effects. Future studies should include several sites spanning a gradient of contamination (and toxicity) in various locales. More precise effects threshold concentrations for some contaminants could then be estimated and compared with similar values derived from laboratory studies and predictive models.

Additional laboratory toxicity studies using spiked sediments should also be conducted. The complex nature of contamination of the ocean environment in southern California and other urban areas makes it impossible to determine cause and effect relationships of individual contaminants from field sampling alone. Controlled laboratory experiments are needed to confidently determine the effects of specific contaminants. Hydrogen sulfide, though not a contaminant in the strict sense, should be included in these studies because it was identified as an important factor in this study. Emphasis should also be placed on studying compounds with different chemical forms so structure-activity relationships can be identified and applied to other untested forms.

The complete results of this study appeared in an unpublished report to the California State Water Resources Control Board (Anderson et al. 1988). Portions of the toxicity test results were presented in the 1987 SCCWRP Annual Report, and an overview of the study was presented at Oceans 1989 in Seattle (October 1989).



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