SONAR MAPPING IN THE CALIFORNIA CURRENT AREA: A REVIEW OF RECENT DEVELOPMENTS

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ABSTRACT

Some developments in the use of sonar to study pelagic fish schools are reviewed. Techniques for counting the number of fish schools per unit area, measuring their horizontal dimensions, determining their biomass, sizing individual fish within a school, and distinguishing northern anchovy, *Engraulis mordax*, schools from all others are discussed briefly. Acoustic observations of the distribution, behavior, sizes, and packing density of anchovy schools are reviewed.

INTRODUCTION

It is the intent of this paper to review the use of horizontally directed echo ranging devices (sonar) to study pelagic fish schools off the coast of California. Research objectives are reviewed and several papers by biologists at the California Department of Fish and Game (CDFG) and the Southwest Fisheries Center (SWFC) are discussed as they relate to a development of sonar research.

Sonar mapping is the process by which a sample transect of the upper mixed layer of the ocean is insonified by a ship proceeding at 9 to 12 knots. Echo returns are recorded or digitized for detection of aggregations of organisms thought to be mostly fish shoals. The primary measurements are the location of each school in the horizontal plane and the diameter of the school on an axis perpendicular to the direction of travel of the survey vessel (Figure 1). The method was first discussed by Smith (1970) and later by Mais (1974) and Hewitt, Smith and Brown (1976). Collectively the measurements yield the number of fish schools per unit area, the geographical distribution of fish schools within the survey area, and the relative proportions of the fish school sizes.

Other measurements of the acoustic return have been demonstrated to be of use in estimating the biomass of a school, the size of the fish in a school, and in identifying schools of the northern anchovy, *Engraulis mordax*, in a mixture of fish schools. Unfortunately these measurements have not yet been feasible from a ship underway at full speed.
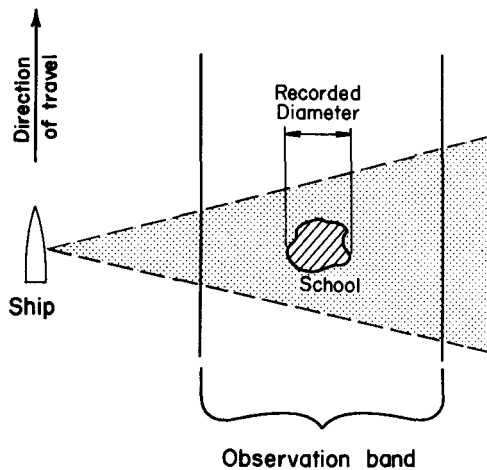

FIGURE 1. Plan view of the sonar mapping technique. Transducer is fixed at 90° to the ship's head rather than swept from side to side as in searching patterns.

RESEARCH STRATEGY

The ultimate intention of the program to detect and determine fish schools by sonar is to develop a tool for pelagic fish stock assessment and to describe its precision. A secondary goal is to investigate the nonrandomness (or patchiness) of the spatial distribution of fish schools, particularly its similarity to distributions encountered when studying other life stages of the same group of animals; e.g., pelagic fish eggs and fish larvae.

In 1968, with these goals in mind, the development of the following capabilities were established as objectives of the research program:

1) To count the number of fish schools per unit of sea area,
2) To measure the horizontal dimensions of detected fish schools,
3) To estimate the fish biomass of any detected school,
4) to estimate the size of individuals constituting a school,
5) To distinguish northern anchovy schools from all other aggregations.

Progress toward the accomplishment of these objectives may be most clearly described with the use of a simple matrix which considers the five objectives, in terms of measurement capabilities, and

the degree to which these capabilities may be considered practical operations (Table 1).

TABLE 1

Objectives of the Research at the Southwest Fisheries Center and the Degree to Which These Objectives have been Attained, as of 1975.

Objective	Phase I develop theory technique	Phase II demonstrate test feasibility	Phase III practical operation from a ship underway at 9-12 knots
1. Count fish schools per unit area	Accomplished	Accomplished	Automated and corrected for known biases
2. Measure horizontal school dimensions	Accomplished	Accomplished	Automated and corrected for known biases
3. Determine school biomass	Accomplished	Direct methods shown to be feasible indirect methods currently being calibrated	
4. Determine individual fish size	Accomplished	Acoustic techniques demonstrated as feasible	
5. Distinguish northern anchovy	Accomplished	Acoustic techniques demonstrated as feasible	

Counting Fish Schools and Measuring Their Horizontal Dimensions

The technique for determining the number of fish schools per unit area and their horizontal dimensions has been developed into a practical method and automated with a shipboard computer. All known biases have been investigated and proper corrections applied to the technique (Hewitt, Smith, and Brown, 1976).

A significant source of potential bias, encountered when enumerating schools with sonar, is the variation in effective range caused by internal waves. Temperature and salinity variations, due to internal waves, cause changes in the magnitude of sound velocity. While investigating the expected tidal period of these waves, Smith (1973) noted that variations of equal amplitudes occurred with periods as short as 5 minutes. The implication of short range spatial variations and the infeasibility of collecting coherent sound velocity profiles, led Smith to suggest a statistical approach to the estimation of a probable effective range.

Smith assembled long term hydrographic data for several subregions of the California Current area by month. He then assumed that no fewer than two sound velocity profiles per month-region stratum would be taken and sampling activities were allocated among regions and seasons to reduce the

standard error of the mean sound velocity gradient to a uniform value. To illustrate the idea, a portion of his "allocation" table is reproduced here (Table 2).

TABLE 2

An Allocation of Sound Velocity Profiles Among Inshore Areas (0–80 miles from coast) by three regions and 4 months.

	Southern California inshore	Northern Baja California	Southern Baja California
January	2*	2*	3*
April	6	4	5
July	25	14	36
October	23	11	17

* The numbers indicate the number of profiles necessary to equalize the standard error of the mean sound velocity gradient in the upper 30 m.

Table 2 describes the number of sound velocity profiles required to equalize the standard error of the sound velocity gradient among regions and months. It may also be used to determine the optimum time of the year to conduct a sonar mapping survey in a particular region in terms of reducing the variability in effective range caused by thermal changes.

Smith further proposed the construction of a probability diagram to apply corrections to the numbers of targets received at various ranges and depths (Figure 2).
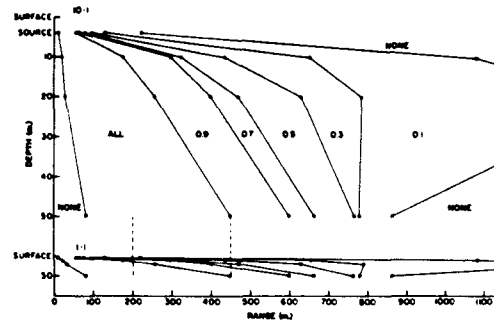

FIGURE 2. A pooled summary of 38 ray trace analyses of limiting range by depth by the probability of detection of −30 db targets (from Smith, 1973). Sound velocity profiles were obtained in October 1972 off the southern California coast.

Mais (1974) discussed, in some detail, his observations from enumerating and measuring fish schools, particularly those composed of northern anchovy. Mais reports the bulk of detected anchovy schools within 50 nautical miles of the coast and the most seaward school ever detected at 165 miles from shore. The north-south range is characterized by an ill-defined limit in northern California to a more abrupt southern limit 100 miles north of the southern tip of Baja California, with the bulk of detected schools off southern California and northern Baja California.

TABLE 3

Summary of Mais' (1974) Observations on Anchovy Schools and Their Constituents by Three Geographic Regions.

	Northern and central California	Southern California and northern Baja California	Central and southern Baja California
Distribution............	5% of all detected schools. Bulk of schools within 0.5 miles of shore.	70% of all detected schools. Bulk of schools within 85 miles of shore; largest concentrations within 20 miles of shore.	25% of all detected schools. Bulk of schools within 15 miles of shore.
School types* encountered	I—most common, all seasons III—rare	I—most common, all seasons. II—encountered most frequently in the northern inshore portion of the bight, in the fall. III—encountered most frequently in the southern portion of the bight, in the spring. IV—rare. V—encountered year round in the inshore flats between Santa Barbara and Ventura. VI—encountered rarely in the late summer and fall in the inshore flats between Santa Barbara and Ventura. VII—encountered in the summer.	I—most common, all seasons. V—prevalent school type encountered in the summer and fall. III—encountered in the northern portion of region in the spring.
Age and length..........	Largest fish—most rapid growth	Slightly smaller fish than north and central California. Moderate growth—larger fish offshore, smaller inshore.	Slowest growth—shortest lived least maximum length.

* See text for explanation of school types.

Mais (1974) also reported a mean vertical school dimension of 12 m and both Mais and Hewitt et al. (1976) reported a median horizontal school diameter of 30 m. Mais further identified and described seven school patterns observed for the northern anchovy. The school types are briefly described below and summarized by region and occurrence (Table 3).

Type I: The most common school type encountered was 5 to 30 m diameter, 4 to 15 m thick (vertical dimension) and 9 to 18 m from the surface. These schools were the dominant type year-round but were detected most frequently during late winter and early spring. The schools were well delinated during the day, dispersing into a thin scattering layer at dusk. This was the only school type found to contain actively spawning fish. These schools were usualy wary and difficult to approach.

Type II: Large schools measuring 25 to 100 m in diameter, 12 to 40 m thick, and 0 to 55 m from the surface were encountered fall through winter over deep water basins and channels adjacent to the coast. These schools dispersed into a coarse scattering layer at dusk and reformed into distinct schools after midnight attaining their densest structures slightly before dawn. Time of schooling reformation occurred progressively later until January or February when it occurred after dawn. These schools were not wary and easy to approach.

Type III: Moderately large and dense schools, highly visible at the surface, and measuring 10 to 100 m in diameter and 12 to 40 m thick were encountered during spring and early summer over basins and channels within 20 miles of the coast. Samples from these schools suggested that the fish were in a postspawning stage.

Type IV: Large and dense schools were infrequently encounted at depths of 120 to 220 m along canyons and excarpments within 5 miles of the coast. These schools were observed to rise to the surface at dusk and form a heavy scattering layer. After midnight, surface schools would reform and submerge to daytime depths at dawn.

Type V: A loose and extensive scattering layer was occasionally observed during all seasons in the shallow flats (< 100m) between Santa Barbara and Ventura, California, and in the summer and fall off central Baja California. The scatter was near bottom during daylight hours and formed a thin surface layer at night.

Type VI: Infrequently dense schools were observed in the shallow flats between Santa Barbara and Ventura during the summer and fall. these schools would form a scattering layer at dusk and regroup after midnight.

Type VII: A loose and extensive scattering layer was occasionally observed offshore of southern California during the

summer months. Such concentrations were observed during daylight hours and over deep water.

Estimating Biomass

The determination of fish biomass contained in a school cannot at present be considered a practical operation; however, some progress has been made toward developing this capability. Anchovy school biomass is assumed to be a function of schooling densities. A theoretical model of school compaction has been developed to describe the maximum variability one may expect in school densities; two direct methods of sampling school compaction have been employed; and work is continuing with the aim of correlating direct and indirect measures of school compaction.

To gain an idea of school structure and resulting densities, an idealized model may be employed which can be used to compute the space required for a single fish when separated from its neighbors by a specified distance. The inverse of the resulting volume yields the number of fish which may occupy a unit volume for a given interfish spacing.
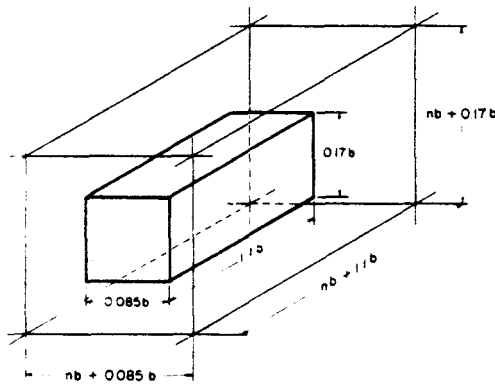

FIGURE 3. Idealized volume required by a single fish of standard length b in a school whose packing density is expressed by an interfish distance of nb.

The standard length, b, of an anchovy is used as the basic measurement. The fish is idealized as a rectangular solid whose dimensions are fractions of b. School structure is idealized by assuming that the fish's six nearest neighbors lie equidistant from the centers of the rectangle's six faces. If the interfish spacing is specified as some multiple of body length, nb, then the required volume for a single fish may be described (Figure 3). The volume, V_n, may be expressed:

$$V_n = (nb + 0.085b) = (nb + 1.1b)(nb + 0.17b)$$
$$= (nb)^3 + 1.355n^2b^3 + 0.2950nb^3 + 0.0159b^3$$

School density, D_n, is the number of fish which may

occupy a unit volume for an interfish spacing of nb. D_n may be expressed:

$$D_n = (V_n)^{-1}$$

Using a standard length of 12 cm as typical of anchovy school constituents detected by sonar (Mais, 1974), a range of school densities may be calculated. The minimum spacing which may be attained without interference from the tail beat of adjacent fish is assumed to be 0.2b. The maximum spacing observed to be necessary to retain school integrity under ideal conditions is 10b. Densities have been determined using these maximum and minimum values and three intermediate points (Table 4). A maximum variation in anchovy school compaction of approximately 8,000 fold was estimated using this approach. While the model may be an oversimplification of school structure, it does provide an estimate of the scale of the parameter we are trying to measure.

TABLE 4

Interfish Spacing and Corresponding School Densities as Calculated from an Idealized Model

Interfish spacing in body lengths (nb)	Density fish (meter)$^{-1}$ (D$_r$)
10	0.51
7	1.41
4	6.66
1	217.08
0.2	4,219.40

Graves (1974) analyzed *in situ* photographs of anchovy schools in order to estimate various schooling parameters, including school density. Three-dimensional analysis of 10 photographs yielded school densities ranging from 50 to 366 fish/m³. Although this represents only a small portion of the possible range of anchovy school compaction, Graves estimates that the technique may be useful over a range of 1,000 fold, i.e., 0.5 to 500 fish/m³ (pers. comm.).

Another direct method of sampling school compaction was reported by Hewitt, Smith, and Brown (1976). Horizontal dimensions of 49 anchovy schools were measured acoustically and subsequently captured by commercial purse seiners. Assuming the school vertical dimension to be constant, a horizontal school area to biomass conversion factor was calculated by dividing the weight of the school by its detected area. Hewitt, Smith, and Brown (1976) used the mean of a distribution of this factor (Figure 4) to convert detected horizontal school area to fish biomass on a sonar mapping survey of the Los Angeles Bight. Assuming a vertical school dimension of 12 m and an individual fish weight of 20 g, these factors may be converted to school densities with a range of 0.52 to 533 fish/m³.
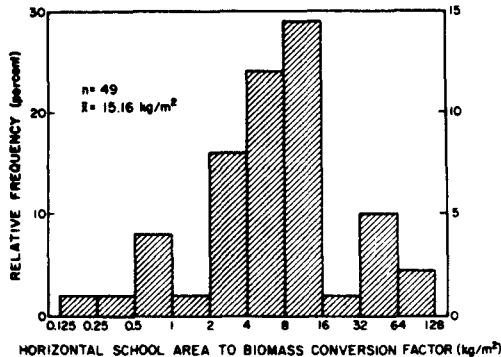
FIGURE 4. Distribution of horizontal school area to biomass conversion factors obtained from the charter boat experiment (from Hewitt, Smith, and Brown, in press).

The ideal method would be to correlate an indirect school measurement, in this case an acoustic parameter, with direct estimates of school compaction and thus establish a remote sensing technique for determining school density. Target strength, the ability of an object to reflect a sound wave, is an acoustic parameter easily measured with proper system calibration and signal digitizing equipment. When recording a peak value of target strength for each school, Hewitt, Smith, and Brown (1976) were able to describe a distribution range of 30 db (1,000 fold).

There are, however, several problems to consider when attempting to relate school target strength with school density. The target strength of a single fish has been shown to vary considerably with aspect by several experimenters (Cushing, 1973). One may expect this condition to exist in an aggregation of fish sharing a common directivity. Secondly, a fish school is neither a solid object nor a point source as considered in classical acoustic theory. Attenuation or absorption of the sound wave in a school must be considered as a complex function of fish aspect, reflection between fish and school density. Lastly, since target strength is measured by sampling a continuous variable (echo power), the calculation of a single value for each school is a function of the sampling frequency and averaging method employed.

Work is ongoing, at the SWFC, with the aim of correlating direct measures of fish school compaction (using camera and capture methods) with indirect measures (target strength). Schools are being insonified from several directions in an attempt to detect school aspect dependence of target strength estimmates. Target strength estimates are being made, using a variety of methods, from echoes which have been digitized at the smallest significant interval. The resulting distributions will be

compared in a search to find the most meaningful one. The strategy is not to attempt to describe the interaction of a sound wave and an aggregation of fish, but to define an acoustic measurement, if any, which most accurately represents the school.

Sizing Individual Fish; Distinguishing Northern Anchovy

Holliday (1972, 1973, 1974) approached these related problems from an acoustician's point of view and demonstrated to biologists that meaningful information may be obtained by the application of acoustic theory. He investigated the frequency domain of echoes from pelagic fish schools by examining the resonance structure of echo returns (1972), and by studying the Doppler spread in echo energy (1974).

Using broad-band explosive acoustic sources and narrow-band spectral analysis, Holliday (1972) observed significant resonant structure in five schools. The schools were subsequently sampled and theoretical predictions for the resonant swim bladder response compared with the experimentally observed resonances. Correlation was made (Figure 5), and a method established for remotely determining the presence of swim bladders in an aggregation of pelagic organisms. A relationship between fish size and resonance frequency also was demonstrated. Holliday further suggested that the technique may be used for acoustic determination of weight or length distributions within a species and age determinations within a population.

The resonant frequency technique was modified and extended to underway operation at ship speeds up to 5 knots and described by Holliday in 1973. A towed arcer source, similar to those used for seismic profiling, and a towed hydrophone array were employed to detect significant frequency structure
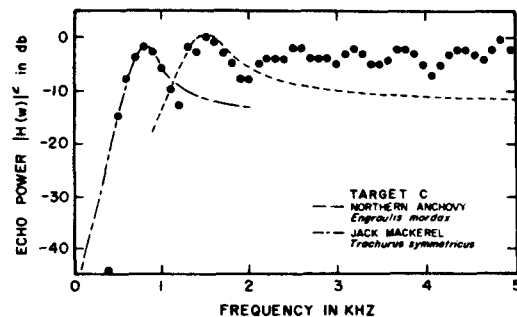

FIGURE 5. An example of the comparison between predicted and observed frequency structure in four echoes from a mixed school of jack mackerel and northern anchovy. The dashed lines represent predicted swim bladder resonance response and the dots represent observed values. The difference between the predicted curve and experimental points above 2 kHz is attributed to scattering from scales, bones, and flesh (Holliday, 1972).

in fish school echo returns (Figure 6). The structure was explained by resonant scattering from fish swim bladders.
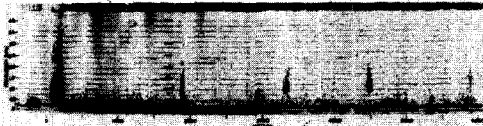

FIGURE 6. Frequency structure in fish schools echoes obtained from an underway survey vessel. Distance along the survey track is displayed on the abscissa; frequency is displayed on the ordinate; and echo energy is displayed as marking intensity (light marks representing less energy than dark marks).

In 1974, Holliday published a study of Doppler energy spread detected in echoes from pelagic fish schools. From the Doppler shift of side aspect echoes, the tail beat velocities of school constituents were calculated. Using Bainbridge's (1960) equation relating swimming speed, length, tail beat amplitude, and tail beat frequency, Holliday calculated the corresponding body lengths. These lengths agreed well with average fish lengths computed from observed school cruising speeds. When examining the Doppler spread from head and tail aspect echoes, Holliday was able to detect swimming behavior characteristics, particularly the accelerate-and-glide swimming behavior associated with northern anchovy and jack mackerel. By knowing the individual fish length and swimming behavior, it may be possible to distinguish northern anchovy from other common pelagic schooling organisms in the California Current area.

The two techniques described above are potentially valuable tools to the fisheries biologist. Additional work must be performed before they can be considered fully developed. In the case of resonance structure, information on the acoustical and physical properties of gas filled swim bladders as a function of depth, season, and geographic location

must be obtained. With regard to Doppler structure, additional experimentation and confirmation of results is necessary.

Visual species identification is also possible by examining photographs taken with a free-fall camera* described by Graves (1974). The camera and method for quantifying photographs of fish obtained with it are valuable tools for confirming and calibrating remote sensing techniques.

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* The camera system, commonly called the Isaac-Brown free-fall camera, was designed and built by John Isaacs and Daniel Brown at Scripps Institution of Oceanography.

CALIFORNIA UNDERCURRENT IN THE SOUTHERN CALIFORNIA BIGHT

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ABSTRACT

In September 1974 hydrographic measurements were made to study the California undercurrent in the Southern California Bight. Three sections, extending 10 to 15 miles offshore from Del Mar, Oceanside, and Dana Point, were occupied with closely spaced STD stations. The observed distributions of properties suggested that an undercurrent (100–400 m) with a width of only a few miles was present at 5 to 10 miles from the shore.

INTRODUCTION

The California undercurrent, sometimes called the California countercurrent, is a narrow northward flow that is present below about 200 m and that extends along the coast from Baja California to Cape Mendocino (40°N) or farther north (Reid, Roden and Wyllie, 1958). Water transported by this current is of equatorial origin and characterized by high temperature, high salinity, low oxygen, and high nutrients as compared to California Current water farther offshore. On the temperature-salinity diagram undercurrent water is indicated by a high-salinity bulge centered near 150 cl/t of thermosteric anomaly (Wooster and Jones, 1970). Therefore, the distribution of the California undercurrent can be studied by mapping salinity on the 150 cl/t isanosteric surface. The 150 cl/t surface is 250–300 m deep and probably close to the core depth of the undercurrent. The area of the undercurrent indicated by high salinity (above 34.3°/oo) on this surface varies considerably from cruise to cruise (Wooster and Jones, 1970). Nevertheless, south of about 29°N (slightly north of Punta Eugenia) it has generally a large offshore extent (>200 miles) and is characterized by a distinct vertical maximum of salinity centered at about the depth of this isanosteric surface. North of 29°N the area of high salinity is limited to a very narrow strip next to the coast, and the vertical distribution of salinity does not exhibit a well defined maximum. (A similar distribution can be seen on the maps of the monthly mean salinity at 150 m prepared by Wyllie and Lynn, 1971.) Subsurface drogue measurements made by Reid (1963) off northern Baja California also indicate that the northward flow is narrow and found only within about 50 km of the coast. Because of the narrowness of the feature, it can easily escape from the network of the routine CalCOFI observations.

Recently, Wooster and Jones (1970) studied the undercurrent off Punta Colnett (31°N) with an array of closely spaced stations. Their measurements indicate that the northward undercurrent is only 20 km wide and bound to the continental slope.

STUDY AREA AND METHODS

In September 1974 the northward extension of this flow into the Southern California Bight, where the bottom topography is more complex, was investigated from the E. B. SCRIPPS during her first Southern California Bight study cruise (SCBS-1). Three sections, 20 miles apart, were occupied off Del Mar, Oceanside, and Dana Point (Figure 1). The station intervals were about 1 mile over the steep bottom slope from 100 m to 600 m and 3 to 4 miles in deep water farther offshore. On each station an STD was lowered nearly to the bottom. On seven stations oxygen samples were collected from Nansen bottles attached to the STD cable. No effort was made to directly observe the current velocity.

RESULTS

Property curves are plotted for two stations (Figure 2). Station 9 represents the distribution outside the undercurrent, and Station 7 represents the distribution in the undercurrent. There are clear differences in the distribution between the California Current and the undercurrent. At temperatures between 7°C and 10°C (depth 100–400 m), salinity at Station 7 is much higher and exhibits a well defined maximum centered near 150 cl/t of thermosteric anomaly. In the same temperature range, oxygen at Station 7 is about 1 ml/l lower than at Station 9.

The distributions of temperature and salinity are illustrated for the southernmost section off Del Mar (Figure 3). The shallow salinity minimum in the thermocline is derived from the California Current and is present everywhere on the section. The salinity maximum at about 300 m is associated with the northward undercurrent. The maximum is evident at Stations 10, 11, and 12, but Station 9 (shown in Figure 2) does not show any evidence of the undercurrent. The width of this high salinity water appears to be only 3 to 4 miles. On the temperature section, the isotherms for 8° and 9°C slope down toward the shore and suggest a northward geostrophic flow with its maximum speed at a depth of about 150 m, where isotherms are nearly level.
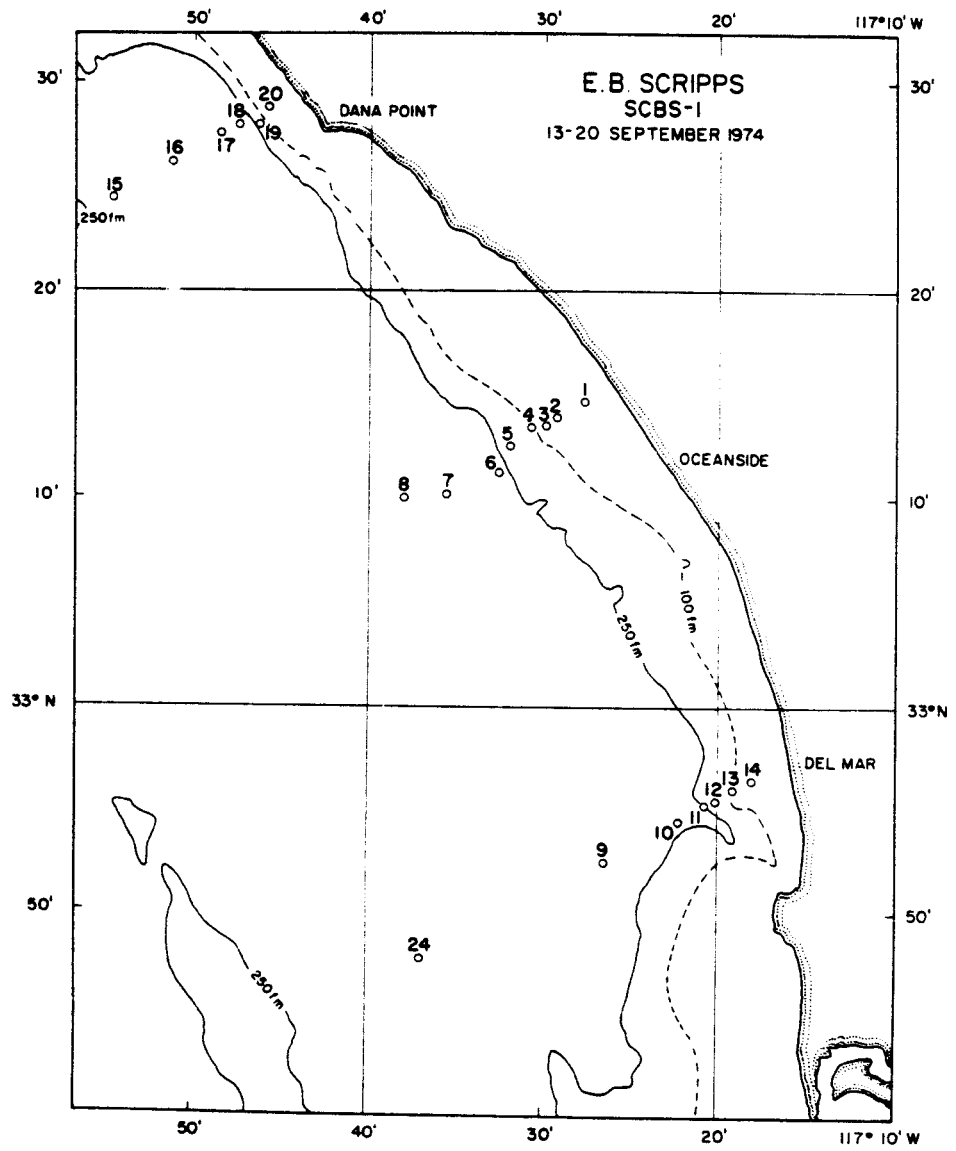
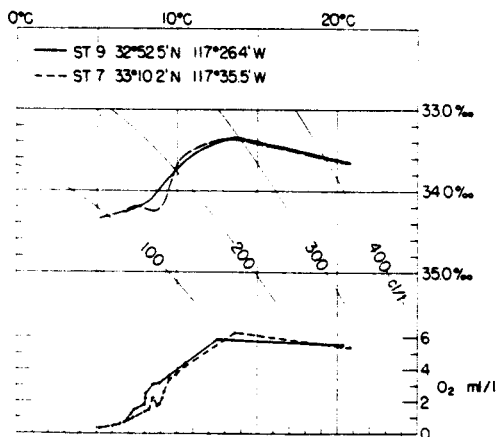FIGURE 1.   Station positions.

FIGURE 2. Temperature-salinity (top) and temperature-oxygen (bottom) curves (For station positions, see Figure 1).
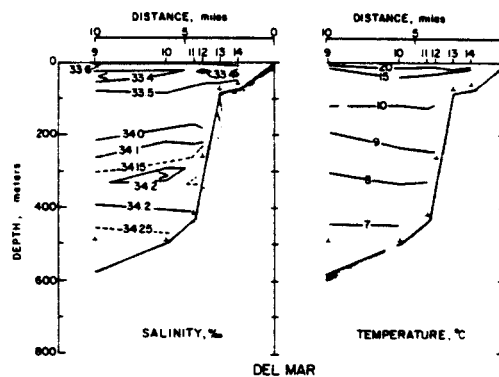

FIGURE 3. Vertical sections of temperature and salinity off Del Mar.

On the Oceanside section (Figure 4) 20 miles farther north, the salinity maximum is again apparent at Stations 7 and 8. The slope of the isotherms for 8° and 9°C between these stations is consistent with a northward geostrophic flow. The offshore portion of the undercurrent may have escaped from this section. Farther inshore, there is no evidence of the undercurrent except that isolated warm high salinity water is found at the bottom 30 m of Station 5 (not revealed by the isopleths in Figure 4).

On the northernmost section off Dana Point (Figure 5) there is no indication of high salinity water of equatorial origin. All stations show temperature-salinity and temperature-oxygen

curves characteristic of the California Current.

In summary, the distributions of properties observed in September 1974 suggest that a northward undercurrent only a few miles wide was present at 100–400 m in the southern half of the study area. It was located at distances 5 to 10 miles from the coast. However, in view of the fact that Station 23, made 50 miles off Del Mar, and Station 24 (Figure 1) indicated the presence of high salinity water of equatorial origin, the main flow or a branch of the undercurrent may have occurred farther offshore. Clearly, more field work is needed to obtain a clear picture of the California undercurrent in the Southern California Bight.
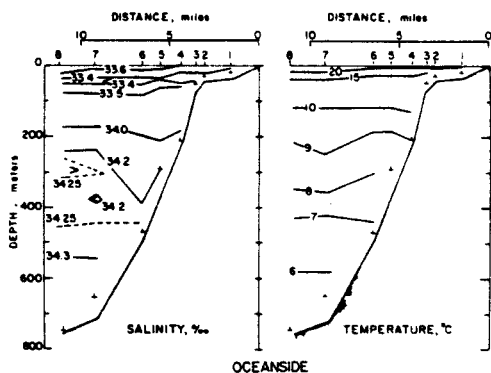

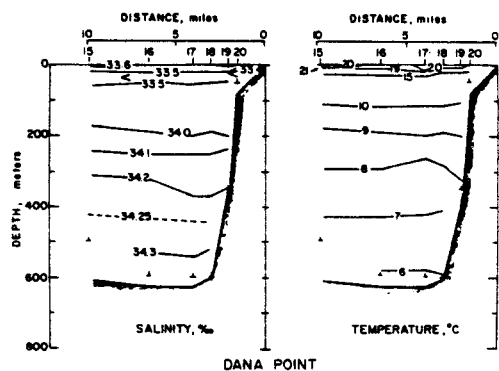FIGURE 4. Vertical sections of temperature and salinity off Oceanside.

FIGURE 5. Vertical sections of temperature and salinity off Dana Point.

ACKNOWLEDGMENTS

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SEDIMENT TRAP APPLICATIONS IN THE NEARSHORE REGION *

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ABSTRACT

The impact of a major sewage sludge discharge to Santa Monica Submarine Canyon off the Southern California coast has been studied using sediment traps to collect settling particulate matter in the vicinity of the discharge. The samples collected by the sediment traps revealed that both the fallout rates and the organic content of settling particulates are greatly influenced by the sludge discharge, but only in the immediate vicinity of the outfall. The particulate fallout rates and organic content were found to approach natural levels rapidly within a few kilometers of the discharge point. The discharged sludge was found to contribute less than 20% of the total particulate fallout and about 40% of the organic fallout to the Santa Monica Canyon ocean bottom.

INTRODUCTION

Coastal population centers have traditionally used the ocean as a disposal site for treated municipal wastewaters and, in some cases, for treatment plant sludges as well. The wastewaters and sludges contain a complex mixture of organic and inorganic substances in both dissolved and particulate phases. In general, a major portion of the wastewater constituents considered to be potential pollutants (heavy metals, chlorinated hydrocarbons, and oil and grease) are associated with the particular matter in the discharges. Consequently, a knowledge of the relatively immediate physical fate of the waste particulates is essential to an evaluation of the effects of wastewater discharges to the ocean. The use of sediment traps to collect samples of the settling particulate matter in the vicinity of wastewater outfalls is one method currently being used to gain such knowledge.

SAMPLING AND ANALYTICAL PROCEDURES

The sediment trap being used at the Coastal Water Research Project was designed by Andrew Soutar of Scripps Institute of Oceanography and consists of an inverted cone with a 0.05m² collecting surface at the top and a removable sample container at the bottom. The entire device is supported on a tripod frame which holds the collecting surface approximately 2m above the ocean bottom. In 1974, four sediment traps were used to collect 29 samples at 22 stations over a period of about 7 months. The sampling period at each station ranged from 14 to 39 days and averaged 24 days.

* Contribution 34 of the Coastal Water Research Project.

The samples were refrigerated once on board ship and frozen upon arrival at the Project's laboratory the same day (samples that were to be analyzed the next day were kept refrigerated overnight). We determined the total amount of particulate solids in the samples and the organic content of the solids, using procedures described below. In the future months, we also will analyze the collected solids for chemical oxygen demand, oil and grease, trace metals, and chlorinated hydrocarbons.

Total particulate solids procedure

The samples were first centrifuged to concentrate the solids. The centrate was decanted and the wet solids transferred to a tared drying dish and weighed. The solids were dried at 80°C for 24 hours and weighed again. The sea salt content of the dry solids was estimated from the moisture loss, and this amount was subtracted from the weight of the dried solids (this correction ranged from negligible to 22%, depending upon the characteristics of the solids).

Solids organic content procedure

A small subsample of the dried solids was redried and weighed. This sample was then ashed at 550°C for 1 hour, cooled in a dessicator, and reweighed. The value for the weight lost in ashing was adjusted for the weight lost from combustion of the volatile components of the sea salts present. The adjusted weight loss was considered to be due to the combustion and volatilization of the organic matter present in the sample and was used as a measure of the organic matter.

STUDY DESCRIPTION AND RESULTS

The region selected for this study was the Santa Monica Canyon in Santa Monica Bay, California. The City of Los Angeles Hyperion Sewage Treatment Plant discharges 5 million gallons per day of a mixture of treatment plant sludges and secondary effluent at the head end of the canyon. About 131 metric tons of dry particulate solids per day are discharged through this system, and the organic content of these solids is usually between 60 and 70%. The objectives of the Coastal Water Project's study were to determine: (1) the rates of fallout of the discharged particulates at selected stations in the canyon region, and (2) the physical and chemical properties of the settling particulates at each station (limited to data on organic content at this time).
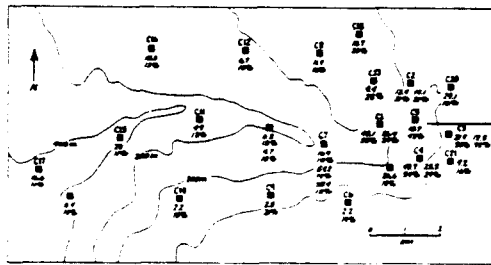
FIGURE 1. Santa Monica Canyon sediment trap stations, observed sedimentation rates (gm/m²/day), and organic content of trapped solids (%).

The calculated sedimentation rates ranged from 2.2 to 107 g dry solids m²/day, with the higher values occurring near the discharge point (Figure 1, Table 1). We took more than one sample at several of the stations to get an idea of the sedimentation rate variation from one sampling period to another: Five stations, C1, C2, C3, C4, and C10, were sampled twice, and one station, C7, was sampled three times. The observed deviations ranged from 2.5 to 54% of the mean station values, with an average deviation from the mean of 18%. As the quality and characteristics of the particulate matter discharged are fairly constant, these variations are probably due to changes with time in the water movement

patterns in the canyon area. Variations in currents in the study area could change the speed and direction of discharged particulate transport and the quantity of resuspended surface sediments collected at any sediment trap station.

Current measurements were made at only one station, C17. Bottom currents at that station were recorded every 15 minutes for a period of 3 weeks in September 1974. The predominant currents recorded were downcanyon, with a net speed of 5.5 cm/sec. The highest current speed recorded was 32 cm/sec, and all currents greater than 25 cm/sec were downcanyon.

To compare the sedimentation rates obtained with the amount of solids discharged on the basis of mass per unit time, we assigned areas to each of the stations and estimated the total mass flux over the study area (69 km²). The estimated total solids fallout of 825 metric tons per day was 6.3 times the particulate solids discharge rate of 131 metric tons per day. The estimated organic solids fallout of 203 metric tons per day was 2.4 times the discharge rate of 85 metric tons per day.

The fact that there appeared to be much more particulate matter falling to the bottom of the canyon than was discharged at the head end may be the result of many factors. The sedimentation of marine particulate matter naturally occurring in the study area certainly accounted for some of the excess. No data have been found in the literature regarding sediment accumulation rates in submarine canyons. Emery (1960) studied sediment accumulation rates at several locations off the southern California coast and reported a net sediment accumulation rate of 3.4 g/m²/day for a station in Santa Monica Basin, his sampling station closest to the Santa Monica Canyon. This number corresponds closely with the sedimentation rates measured in this study at stations distant from the outfall. Andrew Soutar (Scripps Institution of Oceanography, pers. comm.) has measured the fallout rates of particulate matter in eight basins off southern California, using sediment traps similar to those used in this study. The rates he recorded range from 0.23 to 2.44 g/m²/day, with an average of 0.74 g/m²/day. His value for Santa Monica Basin is 0.69 g/m²/day, a factor of five lower than Emery's estimate.

It must be noted that the sediment traps collect falling matter. Thus, we are measuring particulate matter fallout rates, which may be quite different than sediment accumulation rates. Transport mechanisms such as bottom scour, which resuspends sediment and may greatly affect the sediment accumulation rate, are not operative within the sediment traps. The collection of resuspended sediments by the sediment traps is an unknown that could be significant. The speed of the canyon currents that we measured (9% of the observations

TABLE 1
Sediment Trap Data Summary 1974

Station	Sampling period	Total Solids		Organic content (%)
		Sample size (g)	Fallout rate (g/sq m/day)	
C1	5 Jun to 19 Jun	31.6	45.1	26.4
	19 Jun to 23 Jul	98.0	57.6	28.9
C2	5 Jun to 19 Jun	9.4	13.4	30.7
	19 Jun to 23 Jul	23.9	14.1	20.6
C3	5 Jun to 19 Jun	15.3	21.9	49.7
	19 Jun to 23 Jul	32.0	18.8	41.5
C4	5 Jun to 19 Jun	30.6	43.7	53.5
	19 Jun to 23 Jul	44.0	25.9	29.0
C5	23 Jul to 7 Aug	80.0	107.0	42.3
C6	15 Aug to 29 Aug	1.5	2.2	18.5
C7	4 Oct to 25 Oct	17.7	16.9	15.3
	25 Oct to 19 Nov	67.7	54.2	13.5
	19 Nov to 12 Dec	44.2	38.4	15.1
C8	23 Jul to 29 Aug	22.0	11.9	16.2
C9	29 Aug to 12 Sep	1.7	2.5	20.7
C10	4 Oct to 25 Oct	7.1	6.8	12.7
	25 Oct to 19 Nov	5.8	4.7	14.6
C11	29 Aug to 4 Oct	8.9	4.9	12.8
C12	29 Aug to 12 Sep	4.7	6.7	15.2
C13	29 Aug to 12 Sep	4.5	6.4	13.8
C14	12 Sep to 4 Oct	2.4	2.2	18.4
C15	4 Oct to 25 Oct	29.4	28.0	11.0
C16	12 Sep to 4 Oct	11.3	10.3	12.3
C17	12 Sep to 4 Oct	18.2	16.6	11.2
C18	4 Oct to 25 Oct	14.4	13.7	20.0
C19	12 Dec to 3 Jan	40.5	36.6	17.9
C20	12 Dec to 3 Jan	32.0	29.1	16.3
C21	25 Oct to 3 Jan	17.9	9.2	16.2
C23	19 Nov to 12 Dec	10.8	9.4	24.9

were greater than 20 cm/sec) are sufficient to cause scour and resuspension of unconsolidated sediments (Hjulstrom 1939; Southard, Young, and Hollister, 1971). In the future, we plan to compare the sedimentation rates with estimated sediment accumulation rates since 1960, when the waste discharge began, to get an estimate of the importance of scour and resuspension as a transport mechanism in the study area.
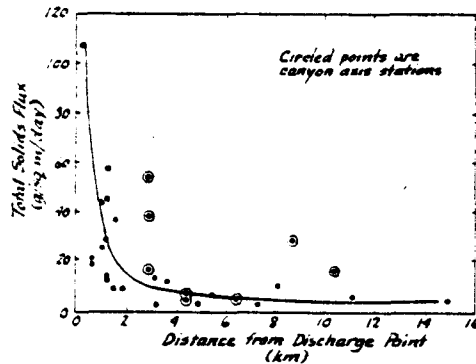

FIGURE 2. Observed sedimentation rates vs. location.

Most of the waste particulates discharged at the head of Santa Monica Canyon fall to the bottom within a few kilometers of the discharge point (Figure 2). A line indicating the trend of the data has been fitted by eye. The data are scattered about this proposed trend for a number of reasons, and some of this scatter appears not to be random. Beyond 2 km from the discharge point, the four obviously high data points are from canyon axis stations (C7, C15, and C17), and the three lowest points represent the three stations along the southern lip of the canyon (C6, C9, and C14). The influence of the outfall discharge on the flux of particulates to the bottom appeared to be greatest at or near the point of discharge and decreased rapidly within a distance of 2 to 3 km. Assuming a net current downcanyon of 5 cm/sec, this distance represents approximately 11 to 17 hours residence time in the water column for the settling wastewater particulates.

The organic content of the trapped solids decreases rapidly with distance from the discharge point (Figure 3). A line indicating the trend of the data has been fitted by eye. The shape of this curve is remarkably similar to that in Figure 2. The major influence of the discharged waste particulates, which average about 65% volatile solids, in determining the character of the particulate fallout was limited to an area within about 2 km of the discharge. If the effects of the waste particulates approach zero with increasing distance from the outfall, then the organic

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content of the collected particulates should approach that of natural marine fallout. We can estimate the probable range for the organic content of natural fallout to be 10 to 15% (Figure 3). Two samples collected with sediment traps placed in Catalina Canyon were analyzed for organic content according to the procedures already described. The values for the these were 11% and 12%, numbers which fit well with the hypothesis that most of the particulate matter collected by the sediment traps more than 2 km from the outfall is natural to the study area. Additional analyses of the chemical characteristics of the samples will be helpful in evaluating this interpretation of the data.
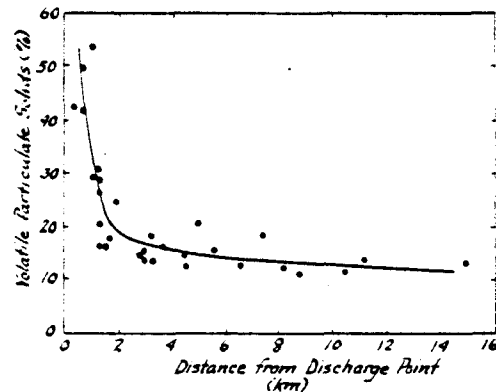

FIGURE 3. Organic content of settling particulates vs. location.

CONCLUSIONS

Although much of the data from this study are not yet available, the following preliminary conclusions have been made, based upon data presented in this paper.

1. Sediment traps are useful devices for the collection of settling particulate matter in the ocean.

2. Most of the waste particulates discharged at the head of Santa Monica Canyon fall to the bottom within a distance of 2 km of the point of discharge.

3. Natural fallout in the Santa Monica Canyon is in the range of 2 to 20 g/m²/day, with an organic content of 10 to 15%. High deposition rates occur aperiodically, primarily along the canyon axis; these probably result from resuspension and transport of the sediment by strong bottom currents.

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TRACE ELEMENT ANOMALIES IN MARINE ORGANISMS OFF SOUTHERN CALIFORNIA *

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ABSTRACT

Large quantities of DDT and trace metals are released annually to the coastal marine ecosystem off southern California via municipal wastewaters discharged through five major submarine outfall systems. Samples of the California seamussel, *Mytilus californianus*, and the Dover sole, *Microstomus pacificus*, were collected from throughout the Southern California Bight to determine if, around these local point sources, contamination of the nearshore biota had occurred. Highest DDT levels in seamussels were observed in specimens collected from the vicinity of a major outfall which, in the past, discharged effluents containing industrial wastes from the manufacture of this pesticide. Copper levels were significantly higher in urban seamussels than in either rural or island control specimens. In contrast, cadmium concentrations were significantly lower in the urban samples. Lead appears to be a wide spread contaminant of the southern California coastal region. Concentrations of chromium were highest in rural seamussels and silver concentration were highest in urban specimens. No significant differences in the nickel and zinc levels were observed between seamussels from any of the three regions. Similarly, no significant enhancements in the trace metal concentrations measured in Dover sole livers were observed despite the close association of the specimens with highly contaminated sediments.

INTRODUCTION

In recent years there has been increasing concern about pollution of coastal marine ecosystems. One aspect of this concern that has received considerable attention is the possibility that trace elements released to this environment through man's actions are being accumulated by organisms to unnatural levels that endanger both their health and their usefulness as seafood. Here we report results of studies into anomalous concentrations of 11 trace elements in two very different marine organisms, an intertidal mollusc, the California seamussel, *Mytilus californianus*, and a nearshore flatfish, the Dover sole, *Microstomus pacificus*, found off the densely populated coastal plain of southern California.

Approximately 11 million persons, or 5% of the Nation's population, inhabits the region between Point Conception and the U.S. Mexico border

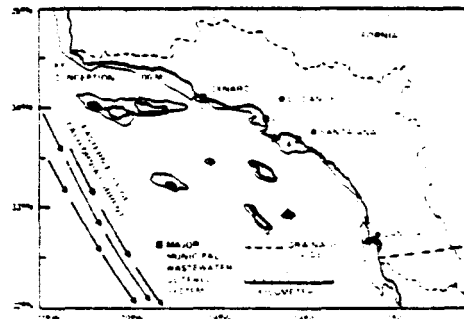* Contribution 39 of the Southern California Coastal Water Research Project

FIGURE 1. The Southern California Bight. Outfall systems are (1) Oxnard City, (2) Hyperion, Los Angeles City, (3) Joint Water Pollution Control Plant (JWPCP), Los Angeles County, (4) Orange County, and (5) San Diego City.

(Figure 1). Most of these people live in the Los Angeles/Orange County Basin * or near San Diego. The municipal wastewaters from these communities in large part are discharged from submarine outfalls a few kilometers offshore, generally at depths shallower than 100 m. Such discharges now total more than 1 billion gallons per day (approximately 1.4×10^{12} l/yr), comparable to the 1941-70 median annual flow of 1×10^{12} liters from surface runoff (United States Geological Survey, 1974). Approximately 95% of this municipal wastewater passes through five major treatment plants, where it generally undergoes only primary settling of solids

* Centered around the cities of Los Angeles and Santa Ana

TABLE 1

Average trace element concentrations (mg/dry kg) in two types of particulates in the Bight *

Trace element	Percent associated with wastewater particulates	Wastewater particulates	Natural nearshore marine sediments
Silver	88	100	1.0
Cadmium	93	130	0.4
Chromium	54	1500	46
Copper	91	1600	16
Mercury	90†	4†	0.04
Nickel	58	350	14
Lead	94	610	8.5
Zinc	92	3000	63

* After Galloway, 1972a and Young et al., 1973.
† Estimates for Joint Water Pollution Control Plant (JWPCP) effluent only.

before release (Southern California Coastal Water Research Project, 1973).

Young, Young, and Hlavka (1973) have summarized the importance of these wastewaters as sources of trace metals to the coastal ecosystem. For a number of metals, discharges from these systems contribute either a majority or a significant fraction of the estimated total input from the coastal plain. In collaboration with J. Galloway (University of California, San Diego), we found that most of these metals are associated with filterable particulates, and that the concentrations on such effluent solids are often two orders of magnitude above natural levels for bottom sediments found around the submarine outfalls (Table 1).

DDT AND TRACE METALS IN CALIFORNIA SEAMUSSELS

It has been shown that at least one chemical constituent of municipal wastewater can significantly contaminate the marine biota over a wide area. During summer 1971, we collected intertidal California seamussels, *M. californianus*, from coastal and island stations throughout the Southern California Bight. The whole soft tissues of specimens 4 to 6 cm in length were analyzed for chlorinated hydrocarbons by B. de Lappe and R. Risebrough at Bodega Marine Laboratory. Data on resultant DDT concentrations illustrate the striking effect one outfall system has had on residue levels of this pesticide in an intertidal invertebrate (Figure 2). Values decreased by factors of 50 to 100 in five directions away fromPalos Verdes Peninsula, the site of the outfalls of County Sanitation Districts of Los Angeles County. The source apparently was industrial DDT wastes released in very large quantities from a manufacturer of the pesticide over an undetermined period. During 1971, 20 metric tons of this waste were carried to the sea via effluent discharged from the Joint Water Pollution Control
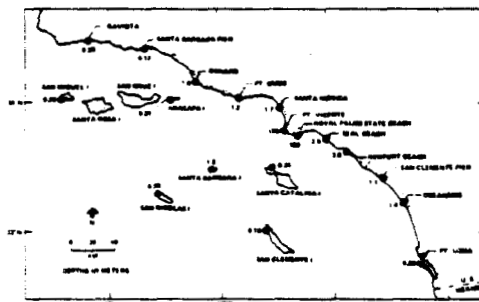
FIGURE 2. Total DDT concentrations (mg/dry kg) in whole soft tissues of California seamussel, *Mytilus californianus*, 1971. Average wet to dry weight ratio for these samples was 4.4 (Analyses by B. de Lappe and R. Risebrough).

Plant, and we found 200 metric tons in the bottom sediments of the Palos Verdes shelf the following year (McDermott, Heesen, and Young, 1974).

To determine if there was corresponding widespread contamination of the nearshore biota from anthropogenic inputs of trace metals, digestive glands of seamussels obtained from the 1971 collection were analyzed by G. Alexander utilizing optical emission spectroscopy at the University of California, Los Angeles. Composites of this tissue from three male and three female specimens were measured, and application of the Wilcoxon signed-rank test revealed no significant effect of sex on the resultant metal concentrations.

The results do not indicate dramatic copper contamination of the intertidal zone off Los Angeles and Orange Counties (Figure 3), despite the fact that we estimate more than 500 metric tons of this metal were discharged during 1971 via municipal
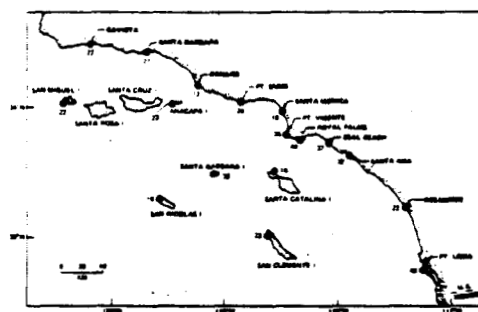
FIGURE 3. Copper concentrations (mg/dry kg) in digestive gland tissue of California seamussel, *Mytilus californianus*, 1971. Average wet to dry weight ratio for these samples was 3.8 (Analyses by G. Alexander).

wastewaters from the three largest submarine outfall systems * of the bight. In contrast, analyses of trace metals in surface runoff conducted in collaboration with J. Morgan, California Institute of Technology, indicated that only about 14 metric tons of copper were carried into the marine environment by storm runoff from these two Counties. While large gradients were not observed, there is a suggestion of somewhat elevated values in mussels collected between Palos Verdes Peninsula and Newport Beach, and off Point Loma in San Diego.

Although these higher concentrations found off the major urban areas might be attributed to municipal wastewater inputs, we recently have reported another potentially important source of copper to the coastal ecosystem (Young, Heesen, McDermott, and Smokler, 1974). Approximately 200 metric tons of this metal in antifouling paints are

* Hyperion Treatment Plant, City of Los Angeles: 340 mgd. JWPCP, County Sanitation District of Los Angeles County: 370 mgd. Orange County Sanitation District: 130 mgd.

applied annually to vessels in the Southern California Bight, with 120 metric tons being used at anchorages between Santa Monica and Newport Beach, and 50 metric tons being used at Mission and San Diego Bays near Point Loma. In contrast, San Diego municipal wastewater introduced only about 20 metric tons of copper off Point Loma during 1971. The highest copper concentrations (average: 68 ppm) found in the 1971 seamussel survey occurred on Point Loma between these two important San Diego anchorages, while the two next highest values (44 and 37 ppm) occurred to the north and south of San Pedro Harbor. Because the copper additives in antifouling paints are designed to effect marine invertebrates, such paints must be considered a candidate along with municipal wastewater as potential sources of the enhanced copper concentrations implied by the distribution found in *M. californianus.*

In addition to municipal wastewater discharges and vessel-related activities, there are other potentially important anthropogenic sources of trace metals to the coastal zone, such as aerial fallout from atmospheric pollutants and direct industrial discharges. Although they have not been adequately quantified to date, the impact of these and other inputs associated principally with major population centers were assessed by evaluating any significant differences in concentration levels of potentially toxic trace elements in the 1971 intertidal mussels collected from three distinct population regions.

We utilized a statistical test developed by Tukey (1953) which allows for multiple comparisons between an unlimited number of groups. The one restriction is that there must be an equal number of sample points per group. Therefore, we separated the intertidal stations into three distinct population groups with five station values for each of the metals analyzed. The urban coastal group included Palos

TABLE 2

Average trace element concentrations (mg/dry kg) in digestive glands of the California seamussel, *Mytilus californianus,* showing significant regional differences * off southern California.

Trace element	Urban vs Island	Urban vs Rural	Rural vs Island
Silver	U > I (26) (10)	--	--
Cadmium	U < I (14) (21)	U < R (14) (26)	--
Chromium	--	U < R (5) (15)	R > I (15) (2)
Copper	U > I (38) (20)	U > R (38) (22)	--
Nickel	--	--	--
Lead	U > I (18) (6)	--	R > I (21) (6)
Zinc	--	--	--

* 95% Confidence limit.

Verdes Peninsula, Santa Monica, Seal Beach, Newport Beach, and Point Loma. The Palos Verdes value was obtained by combining the concentrations from the Royal Palm and Pt. Vicente stations, which are located on the Peninsula near the JWPCP outfalls. The rural coastal group consisted of Gaviota, Santa Barbara, Oxnard, Point Dume, and Oceanside. Island control stations included San Miguel, Anacapa, San Nicolas, Santa Catalina, and San Clemente Islands. Santa Barbara Island was not included because the total DDT concentrations in mussels from this station were approximately five times that of the average for the other islands (Figure 2), suggesting an important influence of the JWPCP outfalls off Palos Verdes Peninsula.

The results of the analysis for the seven trace metals considered show that relatively constant values of about 20 mg/dry kg (ppm) lead were observed in both the urban and rural coastal zones, and that this level was significantly higher than the island mean of 6 ppm (Table 2). Only those differences between digestive gland concentrations which are statistically significant at the 95 percent confidence level are listed. This distribution may be a result, in part, of the large quantity (approximately 7000 tons) of tetraethyl lead burned annually in internal combustion engines and introduced via automotive exhaust to the coastal plain (Huntzicker, Friedlander, and Davidson, 1975).

Of the remaining six metals, the mean urban copper concentration (38 ppm) was significantly higher than both the rural and island means (22 and 20 ppm, respectively). For silver the urban mean (26 ppm) was significantly higher than the island mean (10 ppm), but not the rural mean (12 ppm). In the case of cadmium, the urban mean (14 ppm) was significantly lower than both the rural and island means (26 and 21 ppm, respectively). For chromium, the rural mean (15 ppm) was significantly higher than both the urban and island means (5 and 2 ppm, respectively). In the case of nickel and zinc, no significant differences between groups were observed; bight-wide averages for these two metals were 8 and 76 ppm, respectively.

Although individual results for these seven potential pollutants are quite varied, a general conclusion which may be drawn from this comparison is that there does not appear to be a pattern of dramatic urban enhancements of the trace metals analyzed in this intertidal invertebrate. Urban depressions as well as enhancements are observed, and regional group means generally agree within a factor of two or three. The biological implications of such variations are not yet well understood.

TRACE METALS IN DOVER SOLE

Following this regional survey, we conducted an intensive investigation into trace element