RC. 677

GEOLOGICAL SURVEY CIRCULAR 677

A Review of Benthic Faunal Surveys in San Francisco Bay

A Review of Benthic Faunal Surveys in San Francisco Bay

By Frederick H. Nichols

GEOLOGICAL SURVEY CIRCULAR 677

Washington 1973

United States Department of the Interior
ROGERS C. B. MORTON, *Secretary*

Geological Survey
V. E. McKelvey, *Director*

Free on application to the U.S. Geological Survey, Washington, D.C. 20244

CONTENTS

	Page
Abstract	1
Introduction	1
Surveys of benthic organisms in San Francisco Bay	2
Historical review	2
Summary	9
Inadequacies of existing data	11
Sampling methodology	11
Species identifications and life history studies	13
Effect of pollutants on benthic animals—the diversity index	13
Proposed directions of future research	15
References	17

ILLUSTRATION

	Page
FIGURE 1. Sketch map of San Francisco Bay estuary	3

TABLE

	Page
TABLE 1. Summary of methods used in surveys of the benthic organisms of San Francisco Bay, arranged alphabetically by author	11

A Review of Benthic Faunal Surveys in San Francisco Bay

By Frederic H. Nichols

ABSTRACT

During the past 60 years, considerable effort has been expended in studies of the relations of the biotic community and physicochemical characteristics of San Francisco Bay water. In very recent years these studies have emphasized the relations between the "state of health" of bottom-living invertebrates (the benthos) and the levels of pollutants in the bay. Benthic organisms, generally sessile, are unable to escape deleterious environmental changes, and they reflect these changes in alterations of normal species composition of assemblages and species abundance. Data that expands understanding of these relations in urbanized areas such as San Francisco Bay are critical. Because of the implications of such data in control of water quality, the U.S. Geological Survey undertook a review of the results and major conclusions of San Francisco Bay benthic surveys.

The size and species composition of faunal assemblages are largely controlled by the salinity of the water, the texture of the bottom sediments, and locally by wastes discharged into the bay. Efforts to describe the structure and function of benthic communities of the bay and to quantify the effects of waste discharge on them have been hampered by inconsistent and often faulty sampling methodology and species identification. Studies made show a lack of information on the normal life processes of the organisms concerned. The diversity index (a mathematical expression of the number of kinds of organisms present at a location), commonly used to describe the "health" of the benthic community, has been employed without regard for the need for standardizing methodology and species identifications or for understanding natural biological processes that affect such mathematical indices. There are few reliable quantitative data on the distribution of benthic organisms in San Francisco Bay with which future assessments of the "health" of the benthic community might be compared. Methods for study of the benthos must be standardized, identifications of species verified by trained taxonomists, and new field and laboratory studies undertaken before we can expect to obtain an accurate description of the benthic fauna and its relations with the environment.

INTRODUCTION

Prior to the mid-19th century, the San Francisco Bay area was rich in fish and shellfish, providing food and livelihood for inhabitants of the region. The late 1800's brought about intensive commercial exploitation of these fisheries; for example, in 1880, 21 salmon canneries processed 10 million pounds of salmon, and in 1892 nearly 3 million pounds of crab and more than 5 million pounds of shrimp were caught (Skinner, 1962). Seafood harvested in 1899 included 1 million pounds of striped bass and nearly 3 million pounds of oysters, many species of which were introduced by man in the latter half of the 19th century (Skinner, 1962). These bountiful harvests began to decline before the beginning of this century owing to overfishing, pollution, and siltation, in part from hydraulic gold mining in the drainage area above the bay (Skinner, 1962). The bay was not only a primary source for man's food but was becoming his waste receptacle as well. The decrease in productivity of the fisheries resources of the bay was so rapid that in 1912 a major scientific investigation, the *Albatross* Expedition, was launched to study the causes. The inhabitants of the bay area clearly understood that man was having a deleterious effect on the biota of the bay and that the bay was in a state of declining "health."

Since the time of the *Albatross* Expedition of 1912–13, the concern of scientists and laymen has led to numerous investigations of the biota of the bay and the relations between the characteristics of the aquatic environment (natural and man-made) and the biota. Recently, large-scale surveys have been conducted at considerable public expense to determine how waste discharges affect the biota, to establish the means by which the obvious decline of the fishery resources might be reversed, and to suggest ways to improve water quality in the bay.

Many legislative decisions affecting the control of San Francisco Bay water quality are now being made or soon will be. It is critical to examine what is understood about the biological processes of the bay and to carefully decide what ought to be known before establishing realistic long-range goals. That fishery resources have been drastically reduced by man's use and misuse of the bay is clear; the precise cause and nature of this reduction is not clear. Even less clear is the specific nature of the means necessary to reverse the trend. In this report an attempt is made to point out wherein past efforts to answer these questions have been unsatisfactory and to emphasize the need for more appropriate investigations into the causal relations between the "health" of the biota and the environment in which it must exist.

This report is restricted in scope to a critical summary of the methods, results, and general conclusions of those biological surveys conducted in the bay concerned with the macroinvertebrate organisms (organisms larger than some finite size, for example, 0.5 mm) living at the bottom of the bay (the benthos). Macrobenthic organisms are generally sessile (live most of their lives in the same location) and longlived (several months to several years) and as such are unable to escape deleterious environmental changes. They are therefore indicators of the "health" of the bay; that is, any group or assemblage of species reflects the cumulative effect of exposure to the environment, recording by changes in species composition or abundance the effects of both short- and long-term changes in the environment.

This review does not include a summary of those studies concerned with marine boring and fouling organisms (animals that bore into or encrust pilings, wharfs, ship bottoms; see for example, Hill and Kofoid, 1927, and the studies cited therein; Graham and Gay, 1945; Filice, 1954a) or those concerned with salt-pond organisms (Carpelan, 1957). Nor does it review very recent studies that evaluate local effects of individual waste discharges on the nearby biota, for the results of these studies, required by California State law (see California Water Resources Control Board, 1972b) and conducted by private firms, are not yet readily available to the general public.

I greatly appreciate the helpful criticism of Dr. Karl Banse, Department of Oceanography, University of Washington; Dr. Joel W. Hedgpeth, Department of Oceanography, Oregon State University; James T. Carlton, Department of Invertebrate Zoology, California Academy of Sciences; and my colleagues of the U.S. Geological Survey. J. T. Carlton has been especially helpful in locating some of the material discussed herein.

SURVEYS OF BENTHIC ORGANISMS IN SAN FRANCISCO BAY

HISTORICAL REVIEW

The first major investigation of the biology of the bay began in 1912 under the auspices of the Federal Bureau of Fisheries. Scientists participating this investigation aboard the research vessel *Albatross* collected samples of the bottom fauna, water, and sediments at stations throughout the bay during 1912 and 1913 to estimate the existing and potential market value of the commercial fisheries and to obtain knowledge concerning the biological and physical conditions upon which the fisheries depend. These scientists were especially interested in explaining the decline of the oyster industry during the decade prior to this survey. Benthic animals were collected in many "qualitative" dredge samples taken during the 14-month study and in a few (43) "quantitative" orange-peel grab samples (Sumner and others, 1914) taken between December 1912 and February 1913. (In this report grab is used as in Thorson (1957) to denote those samplers that take a point sample, as distinguished from a dredge, which is dragged on the bottom for some distance, taking an integrated sample.) Some of the bay mollusks (clams and oysters), at least partly because of their commercial value, received the most thoroughly quantitative study (Packard, 1918a and b). Packard noted that the distribution of molluscan species was in part regulated by salinity, for most marine species were found only below Carquinez Strait (fig. 1). Because salinity was low above the strait, only a meager fauna existed in the brackish water. But the most significant environmental influence on molluscan distribution appeared to be the texture of bottom sediments (particle size, shape, and arrangement). Sediment composed of mixed mud, sand, and (or) gravel (central bay) sup-

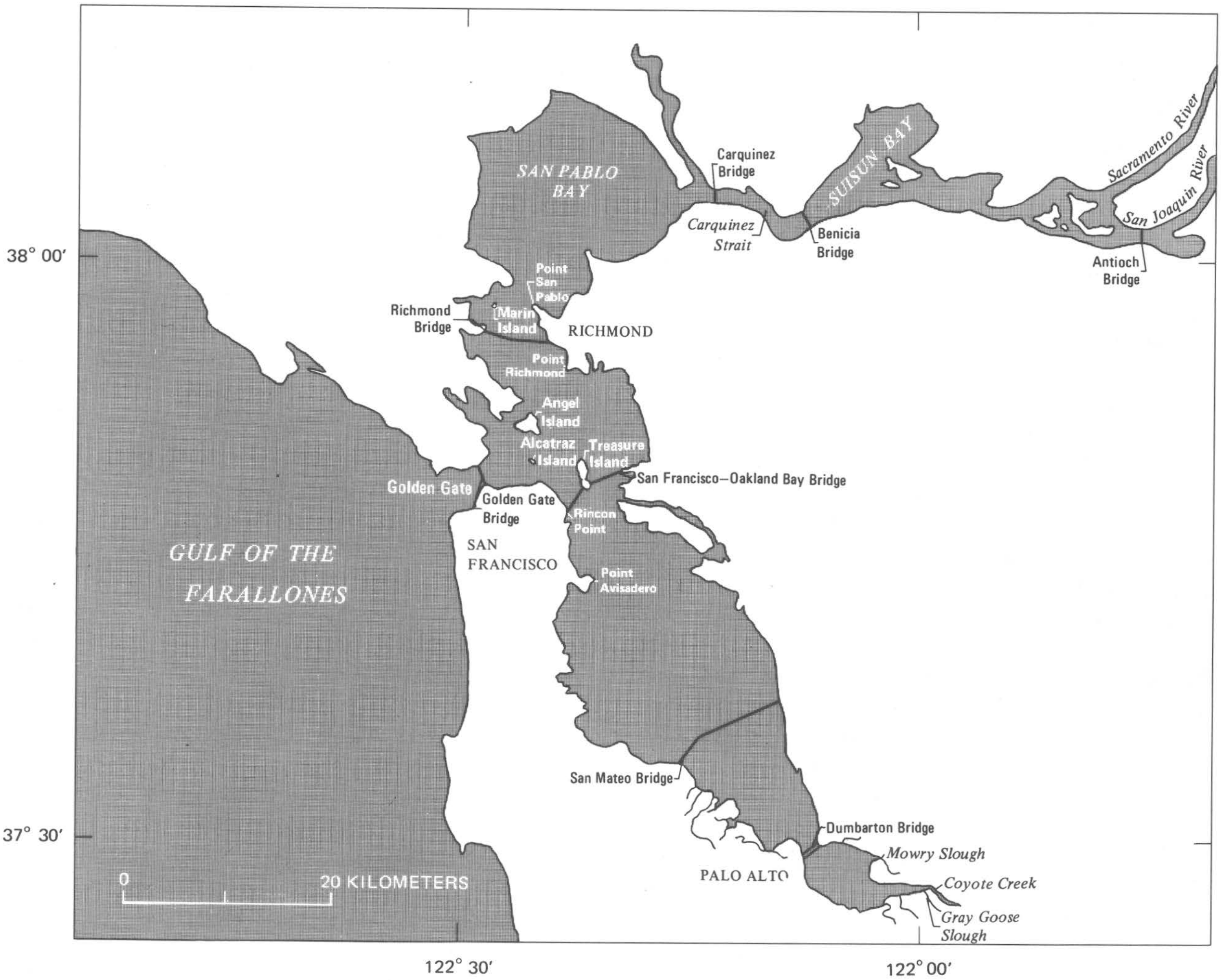

FIGURE 1.—San Francisco Bay estuary.

ported the greatest number of species, mud (San Pablo and south bays) fewer species but a greater number of individuals.

Packard's study of the molluscan fauna (1918a, b) provided the baseline for most benthic investigations that followed. His species lists and relative abundances of specimens for those species have formed the basis for qualitative judgements on long-term changes of the fauna of the bay, despite the fact that his samples were nonquantitative, as discussed in the section "Inadequacies of Existing Data."

Of the remaining benthic fauna collected during the *Albatross* Expedition, only the decapod crustaceans (shrimps, crabs) received comprehensive attention. Within a larger study of the decapod crustacea of California, Schmitt (1921) described the occurrence and geographic distribution of 47 species of decapods collected in the *Albatross* dredge and grab samples. He confirmed Packard's (1918b) findings that organisms were distributed according to salinity and sediment characteristics, not depth or water temperature. Although the samples from which the species of crustaceans were identified were generally nonquantitative (abundances not calculated on an areal basis), Schmitt's study, together with Packard's, provides the first thorough description of a portion of the benthic fauna of San Francisco Bay. The other benthic specimens from the *Albatross* Expedition have apparently been scattered among many museum or private collections, resulting in the publication of numerous short reports concerning the taxonomy of individual species or groups of species (for example, Hartman, 1954), of little use in the present context.

Interest in the relation between the decline of fishery resources and the deterioration of water quality in San Francisco Bay was not formally renewed until 40 years later, in the early 1950's, when Filice (1954a and b, 1958, 1959) investigated the effects of domestic and industrial waste on the composition and abundance of benthic organisms. Filice's study was based on sampling at 460 stations along the south margin of the waterway between Point San Pablo and the Antioch Bridge between April 1951 and April 1952. A small Ekman grab (Ekman, 1911) was used for sampling by hand in shallow water and a larger Petersen grab (Petersen, 1911) for deep water (neither of these samplers bites as deeply into the sediment as the orangepeel grab used in the *Albatross* Expedition). In addition to numbers of species and specimens, Filice measured biovolume, the volume of water displaced by preserved specimens. He observed that biovolume was lowest in sandy sediment and highest in gravel-rocky sediment, but he realized that such distributions were also related to salinity and proximity to waste outfalls, precluding the determination of true sediment preferences of most species on the basis of parameters measured.

Filice observed that industrial wastes were significantly more toxic than domestic wastes, for the fewest numbers of species and specimens were found at industrial outfalls and numbers increased with distance from the outfalls. A few more species were tolerant of domestic sewage at its source, but downstream a number of species were found in great abundance, apparently thriving on the organic matter from domestic sewage that provided a plentiful food source when diluted and adsorbed onto sediment particles. This was not so in areas marginal to industrial outfalls. That discharge of fresh water alone can have detrimental effects on estuarine organisms was disregarded as a possible reason for the scarcity of organisms near outfalls.

Filice concluded that because species distributions and abundances were somewhat similar to those reported from the *Albatross* Expedition (Packard, 1918a and b), whereas the samplers used and locations examined were different, there was little evidence of faunal change since the *Albatross* study.

At about the time (1953) of Filice's study, the engineering firm of Brown and Caldwell (San Francisco) was retained by the City of San Jose to survey the effects of untreated waste entering the south end of San Francisco Bay from Coyote Creek. In addition to samples for the chemical analysis of water and sewage collected five times during the year, samples for a description of the number and kinds of benthic invertebrates were collected in October 1953 at 27 stations in the area south of the Dumbarton Bridge with an Ekman grab and cursorily examined by the California Department of Fish and Game (Brown and Caldwell Engineers, 1954). Although the data on benthic organisms were limited, the scarcity of animals in Coyote Creek above Gray Goose Slough was suggested as evidence of a toxic environment.

With this modest undertaking, the study of the benthos of San Francisco Bay became the interest of local governments around the bay and signaled the beginning of public concern about short- and long-term effects of unregulated disposal of waste into the bay. Studies commissioned by these governments to determine the effects of local waste discharge have been conducted to the present.

A survey of the physical and chemical conditions of the bay bottom and associated benthos off Point Richmond was conducted in 1953 by M. L. Jones under the direction of the California Department of Fish and Game (California Department of Public Health, 1954). The study was intended as a baseline investigation prior to the operation of a sewage outfall in the area. Sixty-five stations were occupied during September 1953, and subsamples of those animals collected in a single Ekman grab sample per station were identified and counted. Physical and chemical factors associated with the water and sediments were measured at 25 of the stations. Because of the lack of replicate samples (by which one can judge how representative a single sample might be) and the few environmental and pollution parameters measured, the report could conclude only that waste discharge had little noticeable effect on the benthos near Point Richmond. Jones recommended that replicate samples be collected and that more physical and chemical factors be considered in future studies.

Jones resumed the Point Richmond survey in 1955 and 1956 (Jones, 1961). He was concerned not with pollution effects but with determining the effect of variations in sample size and number upon estimates of the dispersion characteristics of species populations. Jones studied the spatial distributions and life histories of the important species at four stations in the vicinity of Point Richmond by collecting 30 replicate core (glass tube, outside diameter=22 mm) samples and one Ekman grab sample at each station on 10 occasions between January 1955 and March 1956. Because of the small size of the core sampler used, the number of specimens recovered per species was in most cases very small. Nonetheless, Jones showed that some species were distributed as separate clumps of specimens, not randomly distributed as must be assumed when only one sample per station is taken. He confirmed that multiple samples of small size are preferable to single large samples when quantitative population data are to be interpreted correctly. Jones' work provides valuable details on seasonal changes in specimen size and abundance of some of the smaller species in the Point Richmond area.

In the following year, 1957, the California Department of Fish and Game examined the benthos of the bay region south of the Dumbarton Bridge to evaluate the effects of sewage effluent on fish, benthic invertebrates, and water quality during the canning season (Pintler, 1958). One sample was taken with an Ekman grab at each of 24 stations in September 1957. The animals and plants were sorted into major taxonomic groups, counted, and measured by volume. A total of 22 groups ("organisms") were identified in all samples, but only in a few cases did these groups represent individual species. The study attempted to relate the level of pollution, as defined by turbidity and oxygen concentration, to the number of kinds of organisms and biovolume at a given location. On this basis three zones were seen: the headwaters of the sloughs, where few or no "organisms" existed; the mouth of Coyote Creek, where a limited variety was found; and Mowry Slough, where bottom life was diverse in terms of number of different kinds of animals. The report suggested that the first two areas were in an "unhealthy" condition. The highest productivity (biovolume) occurred in the area of "recovery" at the mouth of Coyote Creek, in agreement with the findings reported by Filice (1954) of similar conditions in a creek (Castro Creek) near Point San Pablo; that is, a few species thrived in the zone downstream from the source of organic pollutants. Comparison with the 1953 data from the same area (Brown and Caldwell Engineers, 1954) was not possible because of differences in sampling locations and methods of faunal identification, although a similar lack of benthic animals in the upper reaches of Coyote Creek and the other sloughs was noted.

The most extensive study of the benthos of San Francisco Bay was conducted by the Sanitary Engineering Research Laboratory (SERL) of the University of California at Berkeley. This investigation (henceforth referred to as the SERL study) was carried out as part of an investigation "of the possible adverse effects of water pollution on the water quality characteristics and the fishery resources of San Francisco Bay" (from preface to Jenkins and others, 1965). Begun in 1958 as a pilot study of the bay south of the Dumbarton Bridge (Harris and others, 1961), the study eventually encompassed the entire bay as far north as the Antioch Bridge, with sampling every 2 months until June 1964. The findings were reported in four annual reports and eight final reports to the California State Water Pollution Control Board (as cited in Pearson and others, 1970). This study provides the most data on San Francisco Bay invertebrates. Because of difficulties in methodology (both in sampling and species identifications), however, specimen counts and biovolume data must be considered qualitative and used with great caution in comparing with data of subsequent benthic surveys.

The results of the SERL study suggest, in concurrence with Packard's findings (1918a, b), that in species composition benthic assemblages are roughly similar throughout most of the bay between the Dumbarton Bridge and Carquinez Strait except for the predominance of strictly marine species near the Golden Gate. Different assemblages are found in Suisun Bay because of the depressive effect of brackish water on the number of species and below Dumbarton Bridge presumably because of the toxic effect of waste discharges that are little diluted in the shallow, restricted water. Similar conclusions were reached by Brinkhurst and Simmons (1968) after some of the oligochaetes (fresh- or brackish-water segmented worms) collected in the SERL study during 1961 and 1962 were reidentified.

The data from the SERL study were later used (Storrs, Pearson, Ludwig, Walsh, and Stann, 1969) to further investigate the relations between physical and chemical parameters of the water and sediment and species diversity (the number of kinds of organisms) found at different locations in the bay. Using a diversity index derived from information theory (see section "Effect of Pollutants on Benthic Animals—the Diversity Index") species diversity was computed for all samples taken in the SERL study. It was found that water chlorosity (salinity) and sand content of the sediment accounted for most of the variation in diversity among stations (median values per station were used in this analysis, that is all data from one station lumped) and that diversity generally decreased with distance from the mouth of the bay toward the northern and southern extremities of the bay. Lower-than-predicted values of diversity at stations near waste outfalls, especially in the south bay, the region below the San Francisco–Oakland Bay Bridge, led to the suggestion that the diversity index might be a valuable tool in assessing the toxicity level of the environment. The inappropriateness of this suggestion is discussed in the section on diversity indices.

The species composition of the benthic fauna of the San Francisco waterfront was determined from samples collected by Dederian (1966) between Rincon Point and Point Avisadero within 1,000 meters of the shoreline. In fall and winter of 1961, Dederian collected single samples at 147 stations with a "modified" Petersen grab from which all organisms were identified (after removal of 500 cm^3 of sediment for particle-size analysis) and the distribution of individual species described. His study provides useful information on the relative abundance and sediment preference of the most common species. Dederian suggested, from comparisons with the work of Filice (1958) and Jones (1961), that the San Francisco waterfront supported the richest fauna (numbers of species and biovolume) in the estuary. He could not, however, give precise reasons for this finding.

In 1963, as part of a 3-year biological survey of San Francisco Bay by the Marine Resources Operations Laboratory of the California Department of Fish and Game, benthic samples were collected monthly at six stations between Richmond and a location south of the Dumbarton Bridge (Aplin, 1967). At each, one sample was collected with a small orangepeel grab, and the contained species identified, counted and measured, and the seasonal abundance of dominant species for each station noted. The value of benthic invertebrates as a resource was stressed in this report, but no comparisons between this and previous studies were made.

In 1961 the Delta Fish and Wildlife Protection Study (Kelley, 1966) was organized to investigate the effects of future water development on the fauna of the Sacramento–San Joaquin River estuary. As part of this investigation, the benthos of the San Pablo and Suisun Bay area was investigated in 1963 (Painter, 1966). Two or three Petersen grab samples were collected monthly at each of 27 stations arranged in eight transects. All animals were counted identified, and their volumes determined. Sediment particle size and cholorinity (salinity) were roughly determined. In examining the relations between the distribution of 11 of the 40 species recognized and bottom type, depth, and chlorinity, it was found that the effects of sediment and depth were difficult to differentiate and that the chlorinity regime (low concentrations in Suisun Bay, higher in San Pablo Bay) seemed to be dominant in regulating the distribution of many of the species. This coincides with the findings of all previous workers (for example, the faunal break at Carquinez Strait described by Filice, 1958). Seasonal fluctuations in species abundances were observed, but relations between mean animal size and abundance (that is, descriptions of life histories of these species) were not determined.

Bottom-sediment samples collected by Moore (1965) in June 1964 at 50 stations just outside the Golden Gate in a study of sediment transport on the central California continental shelf were used to describe faunal communities of the area (Yancey and Wilde, 1970). These samples, collected with a pipe dredge (a pipe opened at one end that is dragged along the bottom to scour surface sediments), were dried and stored for several years prior to the examination of the fauna contained. Yancey and Wilde screened the dried samples to separate the remaining hard parts of the benthic organisms. They identified these hard parts and attempted to estimate and compare the biological "productivity" (the percentage by weight of hard parts in each sample) of the stations. The loss of soft-bodied organisms was not considered critical to the outcome of this study, although in the adjacent area of central San Francisco Bay, the SERL study found that soft-bodied organisms made up 55 percent of the total number of species (Storrs and others, 1965, table 6–4, p. VI–6, 7). Moreover, whether the mollusks were living or dead at the time of collection apparently was disregarded.

Because of these limitations and omissions, the descriptions of faunal communities and comparisons of their levels of productivity are virtually useless. Nevertheless, these data were presented as part of a more recent study of the ecological conditions of the area outside the bay as these conditions relate to waste disposal (Brown and Caldwell Engineers, 1971).

Vassallo (1969a, 1971), in May and June of 1967, collected benthic samples on an intertidal mudflat on the east side of San Francisco Bay just north of the San Mateo Bridge, using a reinforced ½-gallon milk carton as a sampling device (Vassallo, 1969b) to collect one sample at each of 63 stations along three 700-m transects extending outward from the shoreline. Her reports describe the distribution of several of the dominant species with regard to tide level and water currents, as well as the vertical distribution of the organisms within the sediment, and conclude that distribution of the dominant species on the mudflat resulted at least in part from competition and food availability. The effects of man are not mentioned.

To evaluate short- and long-term effects of dredging and spoils disposal associated with maintenance of the ship channel of north San Francisco and San Pablo Bays (preliminary investigations pertaining to the U.S. Army Corps of Engineers' John F. Baldwin Navigation Channel Project), personnel at the Tiburon Marine Laboratory examined the demersal (bottom-living) fish and invertebrate fauna of the area (U.S. Fish and Wildlife Service, 1970). Seventeen stations were visited monthly between September 1967 and August 1969. Benthic invertebrates, however, were not collected until January 1968 at 12 of the stations, and later at the five remaining stations. The stations were selected to include dredged areas, disposal areas, unspoiled or nondredged areas, as well as shallow and deep areas. Laboratory studies were made to determine the gross effects of turbidity on certain fishes. The method of collection of benthic animals was unspecified, but all organisms (other than polychaetes and small gastropods) larger than 0.5 millimeters were counted and identified. These investigators could find no significant differences in number of species between the dredged and nondredged deep stations but indicated that there were more species at the deep stations than at the shallow ones. The omission of polychaetes from the analyses is unfortunate, as these organisms were shown in the SERL study to make up nearly half of the species in the San Pablo area (Storrs and others, 1964). Nonetheless, species diversity was computed, as for the SERL data, for each season at each station. The Fish and Wildlife Service found the same trends in diversity associated with depth and salinity as previous workers but was unable to show significant differences between spoil and nonspoil areas. It did report that at two stations near Marin Island spoils disposal significantly reduced the number of specimens and species, and recovery over the next 14 months was slow. At two other spoil sites near the ship channel in San Pablo Bay, no effects were observed. It was suggested that significant effects of spoils disposal on biological populations are short termed (less than 6 years) and vary with method of dredging and disposal, geographic location, depth, and season. The omission of the polychaete and gastropod data may affect the validity of these conclusions.

Public demand for better water quality in San Francisco Bay resulted in authorization by the State Legislature in 1965 of the San Francisco Bay–Delta Water Quality Control Program. Coordinated by Kaiser Engineers (Oakland), this program was established to determine the effects of waste collection and disposal and to develop plans for the control of water pollution (Kaiser Engineers, 1969). In addition to reviews of existing data regarding benthic invertebrates of the bay (Kaiser Engineers, 1968a; California Department of Fish and Game, 1968), this program incorporated an investigation of the diversity of the benthic fauna at stations throughout the bay for comparison with the data of the earlier SERL study (Kaiser Engineers, 1968b). In March 1968, two to four samples were taken at each of 20 stations with a small orangepeel dredge for computation of animal numbers, biovolumes, and diversity indices. Despite differences in sampling and subsampling procedures and the fact that the 1968 data represented only one point in time, Kaiser Engineers considered the diversity data from the two studies to be comparable. The data from the 1968 survey revealed trends similar to those reported in the SERL study (lower diversity away from the bay mouth toward the north and south) with similar values in all but the south bays where the 1968 diversity values were somewhat lower. Kaiser Engineers (1969) concluded that diversity had decreased significantly in the south bay in the intervening years. By implication, the continued introduction of toxic substances was suggested as the primary cause of the decrease.

Another survey of the Coyote Creek area was undertaken by Allen (1971) to determine whether the benthic fauna had changed since the SERL study of the same area in 1961 and 1962. Using an Ekman grab, Allen collected replicate samples at 12 stations (with two exceptions, in Coyote Creek or its tributaries) in a preliminary survey conducted between March and June 1970 and at 11 stations (all in Coyote Creek or tributaries) in the main survey conducted between September 1970 and February 1971. Presumably because of the coarseness of the screen upon which the samples were washed, Allen found only 14 species or faunal groups. He measured biovolume and determined diversity from his species and specimen count data using the formula

$$d=(S-1)/\ln N,$$

where d is the index of diversity, S the number of species, and N the total number of specimens. After recomputing species diversity for the SERL data (less the data concerning faunal groups not found in the later study) using the preceding formula, Allen compared by station the two sets of biovolume and diversity data. He concluded that biovolume had increased at some locations since the 1961–62 study but that diversity had not changed in the Coyote Creek area in the 10 years between studies.

In 1969 the City of San Francisco engaged the engineering firm of Brown and Caldwell to make necessary investigations into the design and location of submarine waste outfalls in order that the city might comply with State and Federal water quality regulations. Ecologic conditions in the marine environment adjacent to the City of San Francisco (Brown and Caldwell Engineers, 1971) were a part of the study. Of most concern were the proposed disposal sites in the channel between the City of San Francisco and Alcatraz Island and on the continental shelf seaward of the Golden Gate (Gulf of the Farallones). Between April and October 1970, five stations were visited in each of the two areas. At least two samples were collected (and combined) at each station with a Petersen or an orangepeel grab, and the contained organisms generally identified only to phylum or family. Most of the benthic data presented in the final report were reprinted from species lists reported by Yancey and Wilde (1970) (described previously). Despite the crudeness and omissions of the two sets of data, four faunal communities were described: shelf, near reef, bar, and bay communities, distinguished by bottom-sediment type and exposure to wave action and current. The comparisons of biological productivity, because they were based principally on the dried samples described by Yancey and Wilde (1970), have little validity. The comparison of species diversity estimates for each community type is equally questionable because species identifications were incomplete.

Included in the Brown and Caldwell investigation were field studies in which divers made qualitative and semiquantitative observations of the large dominant forms of fauna at locations along nearshore transects and intertidal areas in the vicinity of the Golden Gate. The most useful contribution of the biological studies associated with this project was the laboratory investigation into survival rates of selected planktonic and benthic invertebrates subjected to varying dilutions of domestic waste. This study revealed that at higher concentrations (dilution ratio of effluent to sea water less than 1:20) waste materials could alter or stop normal biologic processes within 96 hours of initial exposure. These results cannot be considered definitive, however, because the workers failed to demonstrate clearly that specimen handling and experimental methodology were not responsible for at least some of the mortality (especially with regard to the larval invertebrate experiments). This failure prevents proper interpretation of differences between experimental and control tests. Additionally, the most realistic experiments, the continuous flow bioassays, did not include study of organisms found at the specific disposal sites, nor were the experiments of sufficient duration to measure true toxicity effects.

Nonetheless, the conclusion drawn from all biological investigations in the Brown and Caldwell study (but based primarily on the laboratory bioassay studies) was that the biota would not be adversely affected by waste discharge given proper location of outfalls and dilution of waste material.

To obtain a more quantitative assessment of the depressive effects of toxic substances in waste discharges, the State Water Resources Control Board began a more detailed study in 1970 (California Water Resources Control Board, 1972a).

Six restricted areas, waste dispersion zones in proximity to waste outfalls, were selected around the bay for a detailed comparison of toxicity levels and benthic diversity. Four replicate samples were collected with a Ponar grab (Powers and Robertson, 1967) at 8–14 stations within each area on one or two occasions between September 1970 and April 1971, and species diversity of the contained specimens correlated with the level of toxicity (biological oxygen demand and concentrations of suspended solids, grease and oil) of receiving waters. In general, species diversity decreased with increasing toxicity within each area. Again, it was reported that diversity had decreased since the SERL study, but this conclusion was considered tentative because of the differences in sampling techniques used.

Burton (1972) examined the relation between the sulfide content of sediments and the diversity of benthic organisms south of the Dumbarton Bridge. He took five Ekman grab samples between July and September 1971 at each of 45 stations throughout the region, including the shallow mudflats not normally sampled in benthic surveys. One-liter subsamples were taken from each grab sample, the animals identified and counted, and diversity computed as in previous studies. Additional sediment samples were collected for the analysis of sulfides. Thirty species were identified in this study, six more than found by the SERL study for the same area, but there was little evidence of a faunal change since the earlier study. The abundance of organisms was greater and the point of maximum specimen abundance had apparently moved southward to a point near the mouth of Coyote Creek. Burton suggested, contrary to the conclusions of the San Francisco Bay–Delta Water Quality Program report (Kaiser Engineers, 1969), that as abundance and diversity had increased near Coyote Creek, toxicity had decreased in the area. Burton found a positive correlation between species diversity and sediment sulfide content, in contradiction to that predicted by Storrs, Pearson, Ludwig, Walsh, and Stann (1969), the highest values of both parameters measured being along the shallow west margin of the bay near Palo Alto.

Other small-scale regional studies of benthic organisms, conducted primarily by engineering firms under contract to various municipal and private organizations, are being made to assess the effects of domestic and industrial waste disposal on water quality and marine life. Most are concerned with actual or potential changes in the diversity of the biota associated with increased toxicity of the water for comparison with the data from previous investigations (for example, Jenks and Adamson Engineers, 1971). The problems inherent in such comparative studies are discussed subsequently.

SUMMARY

The results of 60 years of benthic sampling, despite varying capabilities of workers involved, differences in methods used, and diversity of objectives sought, reveal basic patterns in the distribution and abundance of organisms living at the bottom of San Francisco Bay. A diverse, strictly marine fauna similar to that found on the continental shelf of central California extends through the Golden Gate into the deeper, central part of the bay (the area east of the Golden Gate to Angel and Treasure Islands, including the narrow passage to the north of Angel Island). Because they are dependent on high salinity and low temperatures, these species are not found in the shallower reaches of the bay. At the extreme ends of the bay, a meager fresh- or brackish-water fauna exists, restricted to the river and stream inlets because of its affinity to fresh water. Between Carquinez Strait to the north and below Dumbarton Bridge to the south is a fauna composed of organisms with a tolerance for wide fluctuations in temperature and salinity. These species populations are maintained in the estuary by water circulation patterns characteristic of all estuaries (Carriker, 1967; McCulloch and others, 1970); they belong to genera that are found in most estuaries of the world. Much evidence indicates that this is at least in part the result of intentional or accidental introduction of many of these species into the bay by man (James T. Carlton, California Academy of Sciences, oral commun., 1972). During the past 125 years, for example, the importation of oyster populations and the dumping of ship ballast into the bay provided the means by which numerous species were transported from estuaries around the world to San Francisco Bay. These species thrive in the bay but are often not found outside the bay on the open coast of California.

Within the major faunal groups determined by salinity are subgroups composed of organisms with specific depth and sediment preferences: Species that are found most commonly in intertidal or shallow subtidal mudflats at the margins of the bay, or in the deep muds, sands, or gravels of the channels and bars. Packard (1918a and b) and the authors of the SERL study (Storrs and others, 1966b) found that faunal assemblages at stations between Carquinez Strait and the Dumbarton Bridge having similar depth and sediment characteristics contained many of the same species. The actual constitution of the assemblage at any location, however, is distinct because of the extremely variable combinations of local physical, chemical, and biological factors. It is the relation between local benthic-community structure and naturally occurring environmental factors that many of the workers attempted to define (Packard, 1918a, b; California Department of Public Health, 1954; Filice, 1958; Jones, 1961; Dederian, 1966; Painter, 1966; Aplin, 1967; Vassallo, 1969a, 1971). These workers made little or no attempt to describe recent changes in the communities studied, but instead accepted the patterns in their observations as reflecting natural (cyclical or steady-state) phenomena. Their studies were too discontinuous in both time and space to provide a cohesive picture of the structure and function of the entire benthic community of San Francisco Bay, but they do provide generally reliable qualitative descriptions of the major components of the fauna and the associated physical and chemical environments.

The normal benthic assemblages described are altered by the usually depressive effects of man's waste disposal first noted in the bay by Filice (1954a); many species are eliminated because they are unable to tolerate a polluted environment. In areas subjected to concentrated wastes, a few tolerant species survive and, in the absence of competition for food and space, thrive in great numbers (Filice, 1959), depending on the type and dilution rate of the waste material. A short distance away from the source of waste material, however, changes in normal biologic processes brought about by changes in the physicochemical environment (for example, increased toxicity of the water) are difficult to recognize and measure. Nevertheless, in appraising man's impact on the environment of large areas, authors of pollution-oriented studies have often interpreted their observations in terms of pollution effects, and volumes of data on the San Francisco Bay estuary have resulted from efforts to quantify these observations, primarily by relating the diversity of organisms to specific criteria for water or sediment quality (Storrs and others, 1966b; Kaiser Engineers, 1968b; U.S. Fish and Wildlife Service, 1970; Burton, 1972; California Water Resources Control Board, 1972a). Unfortunately, we still understand little of the precise physiological mechanisms that maintain these patterns; that is, how water quality or sediment characteristics affect individual organisms. But, all the surveys provide information useful in formulating research projects designed to help define these mechanisms. For instance, from the species lists provided in the reports of the SERL study (see Storrs and others, 1966b), we can choose those species that because of their size or abundance might be best suited to detailed studies of population biology, that is life histories, rates of birth, growth, and mortality, and mechanisms and rates of the uptake and release of pollutants. The data we now have allow us to predict where these species might be found; further study presumably will reveal the reasons for nonpredictable distributions.

However, despite the extensive sampling of the benthos of San Francisco Bay and the publication of the numerous reports described herein, there are actually few reliable quantitative data on the numerical abundance and biomass distribution of the benthic fauna with which future data might be compared. Quantitative baseline data, collected with rigorous attention to reproducible sampling methodology and data analysis, are necessary if we are to detect changes in the species composition of benthic communities and to relate these changes in a cause-effect manner to changes in water quality.

Methods for the collection and processing of samples have varied widely from survey to survey and generally also have been nonquantitative; in addition, species identifications have been in many cases incomplete or erroneous, and data analysis and interpretation, without exception, have been limited by lack of precision and statistical validation. Further, because the samples from many of the earlier studies were not retained (James T. Carlton, California Academy of Sciences, oral commun., 1972), reanalysis of those data is impossible. As Hedgpeth (1969, p. 384) commented, "The critical, comprehensive study of the benthos of San Francisco Bay * * * still remains to be done." An understanding of the limitations of past benthic investigations is important if future studies are to provide the information necessary for assessing man's impact on the estuary.

INADEQUACIES OF EXISTING DATA

SAMPLING METHODOLOGY

Quantitative benthic sampling methods were developed in Europe more than 60 years ago when the need arose for estimating, on an areal basis, the potential food supplies of fish populations (Petersen, 1913). Devices that collect bottom samples of known dimensions (for example, 0.1, 0.2, or 0.5 m^2) have been used since that time (Thorson, 1957), and data collected worldwide are comparable on that basis. Sampling of the benthos of San Francisco Bay has been done with little regard for such standardization (table 1), as exemplified by the change of methodology dur-

TABLE 1.—*Summary of methods used in surveys of the benthic organisms of San Francisco Bay, arranged alphabetically by author*

Reference	Number of stations; number of samples at each station	Sampler (area)	Screen mesh size (mm)	Count data	Identification level	Biomass estimate
Allen (1971)	23;3–7	Ekman ($\sim$0.02 m^2).	1.5	All species	All species	Biovolume of species.
Aplin (1967)	6;1	100 in.^{3} orange-peel ($\sim$0.07 m^2).	Not given	All but small organisms.	Dominant species.	None.
Brown and Caldwell Engineers (1954).	27;1	Ekman ($\sim$0.02 m^2).	do	None	Faunal types (crude).	Do.
Brown and Caldwell Engineers (1971).	10;2, samples combined.	Petersen (0.5 m^2) or orangepeel (?).	do	All species	All species	Do.
Burton (1972)	45;5	Ekman ($\sim$0.02 m^2).	1.0	do	do	Do.
California Department of Public Health (1954).	65;1	do	.42	All large; subsamples of small.	do	Biovolume of species.
California Water Resources Control Board (1972a).	6 areas, 8–14 stations per area; 4.	6.4-1 Ponar ($\sim$0.05 m^2).	.6	All species	do	Dry weight of species.
Dederian (1966)	147;1	Petersen ($\sim$0.1 m^2).	1.6	do	do	Biovolume of total sample.
Filice (1954a, b, 1958, 1959).	460;3, samples combined (shallow).	Ekman ($\sim$0.02 m^2).	$\sim$1.0	do	do	Do.
	1 (deep)	Petersen (?)	$\sim$1.0	do	do	Do.
Jones (1961)	4;30	22-mm corer ($\sim$3 cm^2).	.417	All species	All species	Biovolume of species.
	4;1	Ekman ($\sim$0.02 m^2).	.417	do	do	Do.
Kaiser Engineers (1968b).	20;2–4, samples combined and inconsistently subsampled.	100 in.^{3} orange-peel ($\sim$0.07 m^2).	.5	All species in subsamples.	All species in subsamples	Biovolume of phyla.
Packard (1918b)	27;1 or 2	2.5 ft^3 orange-peel ($\sim$0.7 m^2).	$\sim$1.0	All large; subsamples of small.	All species of mollusca.	None.
Painter (1966)	27;2 or 3	Petersen ($\sim$0.09 m^2).	.6 or .3	All species	All species	Biovolume of selected species.
Pintler (1958)	24;1	Ekman ($\sim$0.02 m^2).	.6	Major faunal "components."	Major faunal "components."	None.
Storrs, Pearson, and Selleck (1966a).	[1958–59] 10;2.	100 in.^{3} orange-peel ($\sim$0.07 m^2).	1.3	All species sample data combined.	All species	Biovolume of species.
	[1960–61] 28;2.	do	$\sim$1.0	do	do	Do.
	[1961–62] 28;2.	do	.5	do	do	Do.
	[1962–63] 29;2, samples halved and combined.	220 in.^{3} orange-peel(?); 300 in.^{3} Petersen (0.065 m^2) for sand stations.	.5	All species	do	Do.
	[1963–64] 18;2, samples halved and combined.	do	do	do	do	Do.
U.S. Fish and Wildlife Service (1970).	17;(?)	Not specified	.5	All species except polychaetes and small gastropods.	All species except polychaetes and small gastropods.	None.
Vassallo (1969a, 1971).	63;1	Box corer (94 cm^2).	.297 or .500	All large; subsamples of small.	All species	None.
Yancey and Wilde (1970).	50;1	Pipe dredge	.5	All hard parts.	All hard parts.	Dry weight.

ing the course of the SERL study, in which two sizes of orangepeel grab and a Petersen grab and at least two sizes of screen mesh for separating animals from the sediment were used on different occasions. Without proper attention to sampling methodology and standardization, possible changes in the composition of faunal assemblages between surveys go undetected.

Unfortunately, samples obtained during the first major benthic survey in the bay, the *Albatross* Expedition, were collected with the roughly circular, but nonquantitative, orangepeel bucket sampler; its use undoubtedly influenced later workers in their choice of sampler. (See, for example, Harris and others, 1961.) Thorson (1957) pointed out that this sampler was designed primarily for retrieving submerged pipes and caissons and for reconnaissance work and was not suitable for sampling that would make possible a critical evaluation of the distribution of benthic fauna. The orangepeel grab collects variable amounts of sediment, depending on substrate hardness (a fact recognized by the participants of the SERL study midway in their program), and it may overflow and be subject to washing action as it is brought to the surface, causing loss of the surface sediments and the associated fauna. Yet its use is still recommended for surveys of benthic fauna (American Public Health Association and others, 1971, p. 764).

The small Ekman grab and hand corers, convenient for intertidal or shallow-water sampling from a small skiff, provide a sample generally too small for statistical comparison with the data obtained with more conventional large deepwater samplers, especially a comparison of data concerning the larger, more widely dispersed animals. The small samplers do retrieve without loss quantitative samples that can be compared with other samples of similar size.

Because the area sampled by the grab commonly was not known, data from different surveys could not be normalized and compared on that basis. Abundance and biomass were most commonly expressed as functions of volume of sediment sampled, despite evidence that depth (and volume) sampled varied with sediment hardness. This is especially critical when one considers that most organisms live on or near the sediment surface; that is, the number of organisms found does not necessarily increase with depth of sediment sampled. Estimates of volume of sediment sampled, therefore, have little meaning in comparing samples from regions of different sediment types.

The need for replicate samples in biological investigations has been well demonstrated (Jones, 1961; Storrs and others, 1966a; Lie, 1968), not only for use in statistical analyses of sampling error and patterns of animal distributions but also to obtain complete lists of species present. Ideally the number of samples to be collected is based on the size and dispersion patterns of the animal populations to be studied as determined from a reconnaissance survey. In studies of the benthic fauna of San Francisco Bay, the number of samples taken at each location and sampling period varied (generally only one or two samples per station), and the number taken was determined, apparently, by the amount of time (and cost) required to process each sample. There is some indication that "replicate" samples did not always represent the same assemblage (for example, Storrs and others, 1964), a situation that could arise if the survey vessels were not anchored while the samples were being collected. In none of the reports reviewed (table 1) is the use of an anchored vessel mentioned. In an area such as San Francisco Bay, where winds and tides can act strongly to cause ship drift, replicate samples taken minutes apart from an unanchored vessel can represent widely differing habitats, for the species composition of benthic assemblages can change significantly over short distances where the sea floor is not level (Nichols, 1970).

The size range of organisms collected is largely determined by the mesh size of the screen upon which the sample is washed. Because small organisms are usually the most abundant, slight changes in screen mesh size will greatly affect the total number of organisms retained, if not the biomass (Reish, 1959b; Birkett and McIntyre, 1971). Use of screen mesh of different sizes makes comparisons of abundance data impossible. In bay studies screen size has varied from the 1.6-mm mesh used by Dederian (1966) to the 0.297-mm mesh used by Vassallo (1969a), and as mentioned, screen size was changed several times in the SERL survey (Storrs and others, 1963).

Filice (1958) observed that differences in sampling equipment and techniques prevent detection of changes in the composition of faunal assemblages between surveys. Kaiser Engineers (1968b) were not as cautious when comparing their data with that of previous studies. Whatever the methods employed, the generally nonquantitative nature of the sampling in the bay (that is, inadequate equipment and improper sampling techniques) will make it difficult to compare past results with those of future studies.

SPECIES IDENTIFICATIONS AND LIFE HISTORY STUDIES

In checking selected samples from several of the major studies discussed, it has become evident that many of the identifications are erroneous and specimen counts invalid (James T. Carlton, California Academy of Sciences, oral commun., 1972). Improper identifications seem to result from inexperience of personnel employed as taxonomists, as well as from the use of highly incomplete taxonomic keys. In the only long-term study of the benthos of the bay, the SERL study, species identifications apparently changed from year to year; for example, whereas in 1960–61, 12 species or genera of polychaetes were recognized in the region south of the San Mateo Bridge, at least 21 were recognized at the same stations in 1961–62. This problem is compounded by the recent introduction of species new to this part of the world (Hanna, 1966): many of the references commonly used for the identification of San Francisco Bay invertebrates are based on taxonomic studies conducted prior to these introductions.

An aspect of the study of benthic animals of San Francisco Bay that has been neglected is that of the biology of the individual species themselves. In none of the surveys reviewed here have the phenomena of normal reproduction, growth, and mortality been considered in detail, and only a few of the workers considered seasonal changes in specimen numbers and biomass to be reflections of natural biological processes.

A consequence of discontinuous sampling in time and space is often that natural baywide seasonal changes are interpreted as geographic differences between stations. In the reports of those surveys during which fixed locations were resampled (Jones, 1961; Painter, 1966; Storrs and others, 1966b; Aplin, 1967), only Jones considered the seasonal age structure of individual species populations. During any given year of the SERL study, only two or three of six subareas within the bay were studied; no single subarea was sampled continuously throughout the 4-year program. For this reason, no attempt could be made to characterize the distribution of individual species populations on a baywide basis or long-term changes in the species composition of faunal assemblages found at each station that could provide information on the changing nature of the physicochemical environment. And no attempt was made to relate seasonal variability in biovolume with differences in the size (age) structure of the species populations. Only counts and total biovolumes for each species were computed. Other workers leave seasonal variations in numbers and biomass unexplained or imply a relation to physical factors. Because of the time and effort required to measure the size of individual specimens, such information is lacking for nearly all invertebrate species in the bay. Jones (1961) emphasized that simple estimates of numbers of organisms, total biomass or biovolume, and species diversity are limited in value without accurate measurements of the spatial and temporal fluctuations in these parameters and an assessment of the dispersion pattern of each species relative to the size of the sampler used. Except for the study by Jones, there are no data of this type on the benthos of San Francisco Bay, and even Jones' study is limited by the very small size of the sampler used (that is, only a few specimens of small, abundant species were recoverable in the 22-mm corer) and the very small area studied. No truly quantitative estimate of the structure of the benthic community and the relation of this structure to environmental quality can be made until a great deal more is known about the normal life cycles of the organisms.

EFFECT OF POLLUTANTS ON BENTHIC ANIMALS—THE DIVERSITY INDEX

The complexity of the estuarine environment requires that one proceed systematically in the study of the relation between animals and their habitats. Studies of the life cycle of individual species must be combined with measurements of the tolerance of these species to natural variations in temperature, salinity, oxygen concentration, depth, and sediment particle size before the consequences of water pollution can be fully determined. But it is clear that the wastes discharged into waterways do have disastrous effects on aquatic organisms; attempts to assess these effects are numerous.

One commonly investigated waste-disposal problem is the effect of trace elements and pesticides on benthic animals. Many papers report levels of various trace elements and pesticides in the tissues of plants and animals. With consistency in methodology, it is relatively easy to monitor such substances in both space and time. (See, for example, Butler, 1971.) There is much literature (for example, Brown and Caldwell Engineers, 1971) reporting toxic levels of substances for individual species, usually determined as the concentration of pollutant required to kill a fixed percentage of test organisms within a certain (usually short) period. It is quite another problem to ascertain the effects of chronic low levels of toxic substances.

The extent to which pollutants entering the marine environment are detrimental to the organisms varies greatly, depending in part on the variety and concentrations of the pollutants, the flushing characteristics of the receiving waters, and the tolerances of individual organisms. The relative toxicity of a given pollutant varies from species to species for any given concentration (Pringle and others, 1968; Bryan, 1971; Butler, 1971) and for a given species with temperature, body size, and degree of starvation (Portmann, 1968). When concentrations of pollutants are low, there can be uptake by some species without obvious detrimental effects (Butler, 1971). With long-term chronic exposure to pollutants, some species may gradually disappear from a habitat (regressive species), while other, more tolerant species replace them at the original site (transgressive species) (Leppäkoski, 1968; Tulkki, 1968, O'Sullivan, 1971). Low, sublethal levels of some pollutants may affect the morphology (structure, color, taste, and so on), reproduction, growth, larval development, and behavior of certain animals without causing immediate death but lead to the eventual decline of the species within the polluted area. High concentrations of pollutants may cause immediate death, often the first indication that there is a pollution problem.

While the effect of pollutants as a cause of the depletion of benthic animals near waste outfalls is generally recognized, the effect of unpolluted fresh water on estuarine or marine animals near such outfalls is commonly overlooked, primarily because it is difficult to distinguish. Fresh-water effects can be extremely severe, resulting in major changes in the structure of the community (Golubić, 1971).

Field studies utilizing accurate and consistent sampling methodology may show a cause-effect relation between a detected change in the environment and an unexplained change in the biology of a species or the species composition of the community. But only when the suspected factor is tested under laboratory conditions, where other variables are controlled, can a relation be confirmed (Waldichuk, 1969). This complex, costly, and time-consuming process is now undertaken for only a few commercially exploited species of fish or shellfish (for example, Butler, 1971). Thus, shortcut methods for assessing the effects of pollutants on the biota have great appeal where immediate answers are needed for social or economic problems.

A commonly used measure of the effects of extreme pollution is the index of diversity. The index takes a number of forms, the simplest being counts of number of species and the most complex being mathematical functions of the distribution of specimens among species. The number of species usually decreases when the environment becomes uninhabitable for the more sensitive species (Wilhm, 1967; Tulkki, 1968). Near sewage outfalls, this effect is readily seen (Filice, 1954a; Reish, 1959a). Away from the waste source where the pollutants have been diluted, the relations between pollutant concentrations and diversity are much more difficult to determine.

The index used in nearly all studies concerned with diversity in San Francisco Bay is one derived from information theory (Margalef, 1958; Pielou, 1967):

$$H' = -\sum_i p_i \log p_i,$$

in which H' is the diversity and p_i the proportion of number of specimens of species i to the total number of specimens (N_i/N). To use this index, one must count and accurately identify all species within the sample as well as have a clear indication of the homogeneity of samples or community for which diversity is measured (McIntosh, 1967; Pielou, 1967). This index is affected by the method of collection, the identification of component groups, the size of the space sampled, and the population biology of the species themselves (Margalef, 1969). McIntosh presented a table 1967, table 5, p. 400) giving the maximum and minimum values of the information-theory diversity index for a sample of 100 individuals divided among varying numbers of species. For example, if 100 specimens are identified as representing 10 species, the possible range of indices is 0.50–2.30, depending on the distribution of the specimens among the 10 species. If 20 species are identified, the range is then 1.04–2.98; if 50 species, 2.60–3.90. The ability of the worker to distinguish similar-looking or closely-related species and to properly assign all specimens is critical to the final determination of diversity. Two workers with different abilities in taxonomy can easily arrive at quite different estimates of diversity. The chances for error by semiskilled workers are further compounded by the similarity of several species of many genera of benthic organisms at any given locality.

Despite the likelihood of error in determining such an index of diversity, recent studies of pollution in San Francisco Bay have placed much emphasis on the information-theory index as a measure of the toxicity of the environment. In using data from the SERL study to relate diversity in unpolluted parts of the bay to water chlorosity (salinity) and sediment sand content, values lower than predicted by the chlorosity-sand relation were found in regions of suspected environmental toxicity (Storrs, Pearson, Ludwig, Walsh, and Stann 1969).

Because the trends observed by Storrs, Pearson, Ludwig, Walsh, and Stann (1969, fig. 2, p. 905) were derived from diversity data lumped by station over a period of 4 years without regard for seasonality (during which time sampling methodology and identification levels changed), the degree of statistical confidence around any given data point shown is low. The limits of confidence shown in their figure 2 (20th and 80th percentile values of diversity) indicate that 40 percent of the observations of diversity at each station fell outside these limits. Although the trend toward greater diversity near the seaward entrance of the bay is probably real, the overall estimates of diversity for particular locations can be accepted only as being very crude. Yet in a followup assessment of benthic diversity by Kaiser Engineers in March 1968 as part of the San Francisco Bay–Delta Water Quality Control Program (Kaiser Engineers, 1968b), it was concluded that diversity had decreased in the southern part of the bay since the SERL study. This conclusion was drawn despite the fact that seasonal population fluctuations would be expected to reduce benthic diversity in the spring (Lie, 1968) and that the methods used were different (in subsampling routine) from those of the earlier study. In view of these complications and the evidence that some of the species identifications and specimen counts reported are erroneous, it becomes clear that the specific conclusions of the Kaiser study relating to decreased species diversity are invalid. Because no reliable baseline measurements of benthic diversity in San Francisco Bay exist, such comparisons with existing data are nearly meaningless regardless of methods used in subsequent data collection and analysis.

As a result of the program sponsored by the State Water Resources Control Board in which diversity indices were determined for samples taken in 1970 at several locations near waste outfalls (California Water Resources Control Board, 1972a), the Department of Fish and Game, while acknowledging the limitations of the data of the earlier studies, concluded that diversity had decreased since the SERL study. Again, this conclusion is not quantitatively justified whether there has been a change or not. Burton's opposite finding (1972) of increased diversity in south bay since the SERL study probably reflects differences in sampling methods and species identifications rather than significant faunal changes and serves to point up the problems inherent in such analyses.

The diversity index, being sensitive to seasonal, spatial, and methodological variation, can be used only as a crude tool for attempting to assess the "health" of an ecosystem. Only very gross changes in the physical and chemical nature of an environment as complex as an estuary can be directly correlated with diversity changes, for the statistical error involved in making a single estimate of species diversity at one location through even a short time is great. Far more must be known about the dynamics of individual components of the system before this tool will be useful. Crude estimates of diversity similar to those determined in the studies evaluated can be used only when methodology is consistent from year to year and normal seasonal and spatial variations are considered.

PROPOSED DIRECTIONS OF FUTURE RESEARCH

We have gained little insight into the effects of man on the biota of San Francisco Bay since Filice (1954a) observed the depression of the numbers and kinds of animals near waste discharges in the area of Point San Pablo. It is true that evidence gathered for the bay as a whole supports his conclusions, but we have failed to clearly demonstrate further deterioration of the biota (although it may have occurred) as a result of continued waste disposal into the bay except in the near vicinity of waste outfalls. More important, we do not have sufficiently reliable data with which future data might be compared. We are therefore unable to judge with certainty whether we have succeeded or failed in recent attempts to lessen man's impact on the biota. Nor can we decide, with the evidence at hand, what steps need be taken. Studies that will form the bases for these decisions must be undertaken now.

Clearly, much of the fault of previous studies of the benthos of San Francisco Bay has been the lack of standardization and repeatability of sampling methods even where identification of genera or species may have been accurate. There is no single procedure to be followed in studying the benthos, but certain basic practices are generally accepted (see Holme and McIntyre, 1971) that are statistically valid and provide ecologically relevant results.

With a dependable quantitative grab or core sampler, depth and area of bite can be determined and there is no loss of sample during recovery. Of the many types of large samplers, the van Veen (Thorson, 1957), Ponar, and Smith-McIntyre (Smith and McIntyre, 1954) grab samplers seem to be the best. Lie and Pamatmat (1965) and Nichols (1972) have found that the van Veen is useful in protected waters (waters not subjected to deep-ocean swells, which tend to cause pretripping); it is simple to operate, and it takes a rectangular bite deep enough to collect all but the large, deep-dwelling forms. In certain types of substrate, deep-dwelling organisms may contribute more biomass than is generally the case (Smith and Howard, 1972); the errors inherent in use of the shallower samplers must be taken into account when summarizing count and biomass data. Ideally the size of the sampler depends on the size, abundance, and spatial distribution of the organisms studied. Whereas a small-diameter corer from which the whole sample is returned to the laboratory for sorting may be appropriate for studying small but numerically abundant amphipods or immature stages of other species of the bay, the grab sampler is necessary for study of the larger, more widely dispersed but less abundant species. But within a size group, methodology must remain constant throughout the study period. Birkett and McIntyre (1971) discussed the effect of varying the screen mesh size, suggesting that a 0.5-mm screen be used where possible. As it is tedious to wash a large sample over so fine a screen as 0.5 mm and subsequently sort large numbers of vary small animals under a sorting lens, a screen size of 1.0 mm has been more commonly used to separate the macrofauna from the sediment (Mare, 1942; Lie, 1968). Smaller core samples washed through fine screens can be use to collect the smaller forms in sufficient numbers with considerable saving of time aboard ship (Nichols, 1972). This eliminates the need for subsampling, a statistically questionable operation when done by hand aboard ship.

The time frame of a benthic sampling program must be based on the lifespan of the organisms studied if we are to obtain accurate estimates of the parameters of population biology—birth, growth, and mortality rates. To separate natural from unnatural variations confidently, the dynamics of natural populations must be monitored for at least several lifespans (Preston and Wood, 1971). In addition, replicate samples need to be taken at each location for accurate measurement of sampling error and dispersion characteristics of the organisms (Elliott, 1971).

There are numerous approaches to the study of benthic communities, each depending on the intended use of the resulting data. One is to make an intensive areawide survey of the kinds and numbers of species at locations throughout the bay at one point in time. Through factor or multivariate analysis (for example, Lie and Kelley, 1970), species composition and abundance can be correlated with environmental factors and the underlying causes for general patterns of distribution interpreted (Waldichuk, 1969). This approach, roughly similar in concept to that of the original *Albatross* Expedition, would provide not only information regarding environmental factors, but also baseline data with which later similar surveys could be compared (using identical sampling techniques and at comparable times of year). To assess the general state of "health" of an area such as San Francisco Bay, a baseline study could be compared with one made under similar circumstances in other bays in less-urbanized areas. This type of comparative study would provide, relatively quickly, a measure of the extent of changes brought about by urbanization.

In view of the nonquantitative nature of existing data, such a baseline study remains to be made.

Surprisingly little is known about the dynamics of individual species populations—normal seasonal and annual fluctuations in population parameters such as reproduction, growth, and mortality, without which little can be inferred about nonnormal fluctuations commonly attributed to unnatural environmental stresses (pollution). Detailed studies are needed at specific locations that are presumably geographically representative of larger areas. In order that possible relations between the presence of pollutants and alteration of the population parameters can be deduced and reproduced in the laboratory, studies in polluted locations (that is, near waste outfalls) should be complemented by similar studies in physically similar nonpolluted locations (Wass, 1967). It must be pointed out that there are probably no completely "natural" habitats left in San Francisco Bay. Comparisons with such environments require investigation of nonurbanized estuaries. Where emphasis is placed on the detrimental effects of pollutants, routine monitoring of waste discharges, bay water, and sediment quality through long periods should be accompanied by similar monitoring of suspected pollutants in the biota, not only by species, but by age (size) groups within species and by seasons. We need to know, for instance, when in the lifespan of a benthic organism it is most sensitive to the toxic effect of a pollutant. When the mechanisms and rates of uptake of pollutants by individual species have been determined in the laboratory by long-term bioassays designed to detect the effect of chronic low levels of pollutants (Tarzwell, 1971), the movement of these pollutants through individual species populations can be estimated and the role of the benthic ecosystem in the turnover of these substances delineated.

It is worth noting here that some of the dominant species found in the bay, such as for example, members of the amphipod genus *Corophium*, appear to withstand polluted conditions (Fraser, 1932; Reish, 1959a; Tulkki, 1968; Gamble, 1970). The usefulness of such indicator species in pollution studies has been well documented (Wass, 1967), and the discovery of large numbers of specimens of those species known to be tolerant of polluted conditions is good indication that such conditions might exist. The study of tolerant species might reveal not only the mechanisms by which they survive in a polluted environment, but also the biochemical processes, initiated by the introduction of pollutants, that lead to the elimination of less-tolerant species.

Identification of species by taxonomic specialists or persons trained by these specialists is critical in studies of the effects of water quality on a benthic community. Verification of the identification by such a specialist of a small fraction of animals collected does not insure validity of all identifications. Improper identifications, and especially the lumping of similar species into single categories for the purposes of data analysis, lead to erroneous conclusions about the structure and function of the community, especially diversity of species. There is clear evidence that the results and conclusions of past benthic surveys of San Francisco Bay are of limited value because of such errors. After proper identification, the specimens should be stored in permanent collection, preferably museums funded for the maintenance of such collections, where they can be found by interested persons months or years later possibly for reidentification, for finding attached parasites, or for determining size (age), sex, or internal structure of the specimens. At present, there is little regard for the value of such collections, and therefore funds and space for their storage and maintenance are not usually provided.

Funds for the support of environmental research are normally channeled without coordination into many small-scale investigations, producing results that vary widely in quality and usefulness. Benthic investigations are costly, complex, and timeconsuming, especially when there is need to draw conclusions of political or economic impact. Coordination not only eliminates needless duplication but, more important, insures that methodology and data reduction are compatible, especially in identifying the enormous number of specimens that must be collected in an adequate assessment of the benthos of San Francisco Bay.

REFERENCES

Allen, J. T., 1971, A survey of the macrobenthos in the Coyote Creek area of southern San Francisco Bay: California State Univ., San Jose, M.S. thesis, 126 p.

American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1971, Standard methods for the examination of water and wastewater [13th ed.]: Washington, Am. Public Health Assoc., 874 p.

Aplin, J. A., 1967, Biological survey of San Francisco Bay, 1963–66: California Dept. Fish and Game, Marine Resources Operations Lab., 131 p.

Birkett, L., and McIntyre, A. D., 1971, Treatment and sorting of samples, *in* Holme, N. A., and McIntyre, A. D., eds., Methods for the study of marine benthos: Internat. Biol. Programme Handb. 16 [Oxford, Blackwell], p. 156–168.

Brinkhurst, R. O., and Simmons, M. L., 1968, The aquatic Oligochaeta of the San Francisco Bay system: California Dept. Fish and Game, v. 54, p. 180–194.

Brown and Caldwell Engineers, 1954, Survey of the water condition in lower San Francisco Bay: Santa Clara County, Calif., Rept. prepared for the city of San Jose, 49 p.

———1971, Oceanographic and ecological base data acquisition and evaluation of alternative locations, pt. 1 *of* A predesign report on marine waste disposal: San Francisco, Brown and Caldwell Engineers, 214 p.

Bryan, G. W., 1971, The effects of heavy metals (other than mercury) on marine and estuarine organisms: Royal Soc. [London] Proc., ser. B., v. 177, p. 389–410.

Burton, A. G., 1972, Sediment sulfide concentrations in relation to estuarine benthic macroinvertebrates of south San Francisco Bay. California State Univ., San Francisco, M.S. thesis, 78 p.

Butler, P. A., 1971, Influence of pesticides on marine ecosystems: Royal Soc. [London] Proc., ser. B, v. 177, p. 321–329.

California Department of Fish and Game, 1968, San Francisco Bay–Delta water quality control program; Task VII-1B (DFG), Fish and wildlife resources of San Francisco Bay and delta—description, environmental requirements, problems, opportunities and the future: California State Water Quality Control Board, 338 p.

California Department of Public Health, 1954, Department of Fish and Game report, pt. 1 *of* Richmond shoreline investigation: California Dept. Public Health Rept. (Proj. no. 54–2–3), 84 p.

California Water Resources Control Board, 1972a, Current San Francisco Bay–Delta research, sec. 4 *of* San Francisco Bay–Delta water quality; research, rationale for regulations, control policies, and plans for water quality enhancement: California Univ., Berkeley Ext., Water Research Eng. Educ. Ser. 9.

———1972b, Water quality control plan—ocean waters of Calfornia; guidelines for the preparation of technical reports on waste discharges to the ocean and for monitoring the effects of waste discharges on the ocean: California Water Resources Control Board, 65 p.

Carpelan, L. H., 1957, Hydrobiology of the Alviso salt ponds: Ecology, v. 38, p. 375–390.

Carriker, M. R., 1967, Ecology of estuarine benthic invertebrates—a perspective, *in* Lauff, G. H., ed., Estuaries: Am. Assoc. Adv. Sci. Publ. 83, p. 442–487.

Dederian, S. L., 1966, A survey of benthic marine invertebrates along the San Francisco Waterfront. California State Univ., San Francisco, M.S. thesis, 117 p.

Ekman, Sven, 1911. Neue apparate zur qualitativen and quantitativen erforschung der bodenfauna der seen: Internat. Rev. Gesamten Hydrobiologie, v. 3, p. 553–561.

Elliott, J. M., 1971, Some methods for the statistical analysis of samples of benthic invertebrates: Freshwater Biol. Assoc. Sci. Pub., v. 25, p. 1–144.

Filice, F. P., 1954a, An ecological survey of the Castro Creek area in San Pablo Bay: Wasmann Jour. Biology, v. 12, p. 1–24.

———1954b, A study of some factors affecting the bottom fauna of a portion of the San Francisco Bay estuary: Wasmann Jour. Biology, v. 12, p. 257–292.

———1958, Invertebrates from the estuarine portion of San Francisco Bay and some factors influencing their distribution: Wasmann Jour. Biology, v. 16, p. 159–211.

———1959, The effect of wastes on the distribution of bottom invertebrates in San Francisco Bay estuary: Wasmann Jour. Biology, v. 17, p. 1–17.

Fraser, J. H., 1932, Observations on the fauna and constituents of an estuarine mud in a polluted area: Marine Biol. Assoc. United Kingdom Jour., v. 18, p. 69–85.

Gamble, J. C., 1970, Anaerobic survival of the crustaceans *Corophium volutator*, *C. arenarium* and *Tanais chevreuxi*: Marine Biol. Assoc. United Kingdom Jour., v. 50, p. 656–671.

Golubić, Stjepko, 1971, Biological indication of the pollution in marine coastal environment: Vie et Milieu, supp. 22, p. 293–298.

Graham, H. W., and Gay, Helen, 1945, Season of attachment and growth of sedentary marine organisms at Oakland, California: Ecology, v. 26, p. 375–386.

Hanna, G D., 1966, Introduced mollusks of western North America: California Acad. Sci., Occasional Papers, v. 48, p. 1–108.

Harris, H. S., Feuerstein, D. L., and Pearson, E. A., 1961, A pilot study of physical, chemical, and biological characteristics of waters and sediments of south San Francisco Bay (south of Dumbarton Bridge): California Univ. (Berkeley), Sanitary Eng. Research Lab. Rept., p. 1–257.

Hartman, Olga, 1954, The marine annelids of San Francisco Bay and its environs, California: Allan Hancock Found. Occasional Paper 15, 20 p.

Hedgpeth, J. W., 1969, The San Francisco Bay–Delta estuary, an ecological system—prepared statement, *in* The nation's estuaries—San Francisco Bay and Delta, Calif.; Pt. 2, Hearings, House subcommittee of the Committee on Government Operations: U.S. 91st Cong., 1st sess., p. 367–386.

Hill, C. L., and Kofoid, C. A., eds., 1927, Marine borers and their relation to marine construction on the Pacific coast: San Francisco Bay Marine Piling Comm. Final Rept., 357 p.

Holme, N. A., and McIntyre, A. D., eds., 1971, Methods for the study of marine benthos: Internat. Biol. Programme Handb. 16 [Oxford, Blackwell] 334 p.

Jenkins, D. G., Selleck, R. E., and Pearson, E. A., 1965, A comprehensive study of San Francisco Bay, Final report; I, Physical, chemical and microbiological sampling and analytical methods: California Univ. (Berkeley), Sanitary Eng. Research Lab. Rept., v. 67, no. 7, p. 1–64.

Jenks and Adamson Engineers, 1971, Wastewater management program South San Francisco–San Bruno Sub-region Area, proposed Phase I project, environmental impact statement: Palo Alto, Calif., Jenks and Adamson Engineers, 16 p.

Jones, M. L., 1961, A quantitative evalution of the benthic fauna off Point Richmond, California: California University Pubs. Zoology, v. 67, p. 219–320.

Kaiser Engineers, 1968a, San Francisco Bay–Delta water quality control program; Task IV–3, Study of water quality parameters: California State Water Quality Control Board, p. I–1–1 to V–3–5 with app.

———1968b, San Francisco Bay—Delta water quality control program; Task VII–1b (KE), Biologic-ecologic study: California State Water Quality Control Board, p. I–1 to VI–4, with app.

———1969, San Francisco Bay–Delta water quality control program; Final report, prelim. ed., to the state of California: California State Water Quality Control Board, p. I–1 to XXIII–17, with app.

Kelley, D. W., ed., 1966, Ecological studies of the Sacramento–San Joaquin Delta; I. Zooplankton, zoobenthos, and fishes of San Pablo and Suisun Bays, zooplankton and zoobenthos of the delta: California Dept. of Fish and Game, Fish Bull., v. 133, p. 1–133.

Leppäkoski, Erkki, 1968, Some effects of pollution on the benthic environment of the Gullmarsfjord: Helgoländer wiss. Meeresunters, v. 17, p. 291–301.

Lie, Ulf, 1968, A quantitative study of benthic infauna in Puget Sound, Washington, U.S.A., in 1963–1964: Fiskeridir. Skr. Ser. Havnder., v. 14, p. 229–556.

Lie, Ulf, and Kelley, J. C., 1970, Benthic infauna communities off the coast of Washington and in Puget Sound: identification and distribution of the communities: Canada Fisheries Research Board, v. 27, p. 621–651.

Lie, Ulf, and Pamatmat, M. M., 1965, Digging characteristics and sampling efficiency of the 0.1 m^2 van Veen grab: Limnology and Oceanography, v. 10, p. 379–384.

McCulloch, D. S., Peterson, D. H., Carlson, P. R., and Conomos, T. J., 1970, A preliminary study of the effects of water circulation in the San Francisco Bay estuary—some effects of fresh-water inflow on the flushing of south San Francisco Bay: U.S. Geol. Survey Circ. 637–A, 27 p.

McIntosh, R. P., 1967, An index of diversity and the relation of certain concepts to diversity: Ecology, v. 38, p. 392–404.

Mare, M. F., 1942, A study of a marine benthic community with special reference to the micro-organisms: Marine Biol. Assoc. United Kingdom Jour., v. 25, p. 517–554.

Margalef, D. R., 1958, Information theory in ecology: General systems, v. 3, p. 36–71.

———1969, Discussion [of Storrs, P. N., and others, Estuarine water quality and biologic population indices]: Advances in Water Pollution Research, Internat. Conf., 4th, Prague 1969, Proc., p. 911–912.

Moore, D. B., 1965, Recent coastal sediments—Double Point to Point San Pedro, California: California Univ. (Berkeley), Hydraulic Eng. Lab. Tech. Rept., v. 2, no. 14, p. 1–86.

Nichols, F. H., 1970, Benthic polychaete assemblages and their relationship to the sediment in Port Madison, Washington: Marine Biology, v. 6, p. 48–57.

———1972, Carbon and energy flow through populations of a numerically dominant macroinvertebrate, *Pectinaria californiensis* Hartman, in Puget Sound, Washington, with reference to larger, rarer coexisting species: Washington Univ., Seattle, Ph. D. thesis, 164 p.

O'Sullivan, A. J., 1971, Ecological effects of sewage discharge in the marine environment: Royal Soc. [London] Proc., ser. B., v. 177, p. 331–351.

Packard, E. L., 1918a, Molluscan fauna from San Francisco Bay: California Univ. Pubs. Zoology, v. 14, p. 199–452.

———1918b, A quantitative analysis of the molluscan fauna of San Francisco Bay: California Univ. Pubs. Zoology, v. 18, p. 299–336.

Painter, R. E., 1966, Zoobenthos of San Pablo and Suisun Bays: California Dept. of Fish and Game, Fish Bull., v. 133, p. 40–56.

Pearson, E. A., Storrs, P. N., and Selleck, R. E., 1970, A comprehensive study of San Francisco Bay, final report; VIII, Summary, conclusions and recommendations: California Univ. (Berkeley), Sanitary Eng. Research Lab. Rept., v. 67, no. 5, p. 1–85.

Petersen, C. G. J., 1911, Valuation of the sea; 1, Animal life of the sea-bottom, its food and quantity: Danish Biol. Sta. Rept., v. 20, p. 1–81.

———1913, Valuation of the sea; 2, The animal communities of the sea-bottom and their importance for marine zoogeography: Danish Biol. Sta. Rept., v. 21, p. 1–44.

Pielou, E. C., 1967, The use of information theory in the study of the diversity of biological populations. Symposium on Mathematical Statistics and Probability, 5th, Berkeley, Proc., v. 4, p. 163–177.

Pintler, H. E., 1958, Preliminary results and analysis of a fish population and bottom sampling survey south of Dumbarton Bridge, South San Francisco Bay, California, August-September 1957: California Dept. Fish and Game Rept., 35 p.

Portmann, J. E., 1968, Progress report on a programme of insecticide analysis and toxicity-testing in relation to the marine environment: Helgoländer wiss. Meeresunters, v. 17, p. 247–256.

Powers, C. F., and Robertson, A., 1967, Design and evaluation of an all-purpose benthos sampler: Michigan Univ., Great Lakes Research Div., Spec. Rept., v. 30, p. 126–131.

Preston, A., and Wood, P. C., 1971, Monitoring the marine environment: Royal Soc. [London] Proc., ser. B, v. 177, p. 451–462.

Pringle, B. H., Hissong, D. E., Katz, E. L., and Mulawka, S. T., 1968, Trace metal accumulation by estuarine mollusks: Am. Soc. Civil Engineers, Sanitary Eng. Div. Jour., v. 94, p. 455–475.

Reish, D. J., 1959a, An ecological study of pollution in Los Angeles–Long Beach Harbors, California: Allan Hancock Found. Occasional Paper 22, 119 p.

———1959b, A discussion of the importance of screen size in washing quantitative marine bottom samples: Ecology, v. 40, p. 307–309.

Schmitt, W. L., 1921, The marine decapod crustacea of California: California Univ. Pubs. Zoology, v. 23, p. 1–470.

Skinner, J. E., 1962, An historical review of the fish and wildlife resources of the San Francisco Bay area: California Dept. Fish and Game, Water Proj., Branch Rept., v. 1, p. 1–226.

Smith, K. L., Jr., and Howard, J. D., 1972, Comparison of a grab sampler and large volume corer: Limnology and Oceanography, v. 17, p. 142–145.

Smith, W., and McIntyre, A. D., 1954, A spring-loaded bottom sampler. Marine Biol. Assoc. United Kingdom Jour., v. 33, p. 257–264.

Storrs, P. N., Pearson, E. A., Ludwig, H. F., Walsh, R., and Stann, E. J., 1969, Estuarine water quality and biologic population indices: Advances in Water Pollution Research, Internat. Conf., 4th, Prague 1969, Proc., p. 901–910.

Storrs, P. N., Pearson, E. A., and Selleck, R. E., 1966a, A comprehensive study of San Francisco Bay, Final Report; II, Biological sampling and analytical methods: California Univ. (Berkeley), Sanitary Eng. Research Lab. Rept., v. 65, no. 8, p. 1–75.

———1966b, A comprehensive study of San Francisco Bay, final report; V, Summary of physical, chemical, and biological water and sediment data: California Univ. (Berkeley), Sanitary Eng. Research Lab. Rept., v. 67, no. 2, p. 1–140.

Storrs, P. N., Selleck, R. E., and Pearson, E. A., 1963, A comprehensive study of San Francisco Bay, 1961–62: California Univ. (Berkeley), Sanitary Eng. Research Lab. Rept. v. 63, no. 3, p. 1–221.

———1964, A comprehensive study of San Francisco Bay, 1962–63: California Univ. (Berkeley), Sanitary Eng. Research Lab. Rept., v. 64, no. 3, p. I–1 to IX–9.

———1965, A comprehensive study of San Francisco Bay, 1963–64: California Univ. (Berkeley), Sanitary Eng. Research Lab. Rept., v. 65, no. 1, p. I–1 to VII–7.

Sumner, F. B., Louderback, G. D., Schmitt, W. L., and Johnson, G. E., 1914, A report upon the physical conditions in San Francisco Bay, based upon the operations of the United States Fisheries Steamer *Albatross,* 1912–1913: California Univ. Pubs. Zoology, v. 14, p. 1–198.

Tarzwell, C. M., 1971, Bioassays to determine allowable waste concentrations in the aquatic environment: Royal Soc. [London] Proc., ser. B, v. 177, p. 279–285.

Thorson, Gunnar, 1957, Sampling the benthos: Geol. Soc. America Mem., v. 67, p. 61–73.

Tulkki, Paavo, 1968, Effect of pollution on the benthos off Gothenburg: Helgoländer wiss. Meeresunters, v. 17, p. 209–215.

U.S. Fish and Wildlife Service, 1970, Effects on fish resources of dredging and spoil disposal in San Francisco and San Pablo Bays, California: U.S. Fish and Wildlife Service Rept., 36 p.

Vassallo, M. T., 1969a, The ecology of *Macoma inconspicua* (Broderip and Sowerby, 1829) in Central San Francisco Bay; I, The vertical distribution of the *Macoma* community: Veliger, v. 11, p. 223–234.

———1969b, A benthic sampler suitable for field instruction in the ecology of intertidal muds and sand: Turtox News, v. 47, p. 238–239.

———1971, The ecology of *Macoma inconspicua* (Broderip and Sowerby, 1829) in central San Francisco Bay; II, Stratification of the *Macoma* community within the substrate: Veliger, v. 13, p. 279–284.

Waldichuk, Michael, 1969, Effects of pollutants on marine organisms; improving methodology of evaluation—a review of the literature: Water Pollution Control Federation Jour., v. 41, p. 1586–1601.

Wass, M. L., 1967, Biological and physiological basis of indicator organisms and communities: II, Indicators of pollution, *in* Olson, T. A., and Burgess, F. J., eds., Pollution and marine ecology: New York, Interscience, p. 271–283.

Wilhm, J. L., 1967, Comparison of some diversity indices applied to populations of benthic macro-invertebrates in a stream receiving organic wastes: Water Pollution Control Federation Jour., v. 39, p. 1673–1683.

Yancey, T. E., and Wilde, Pat., 1970, Faunal communities on the central California continental shelf near San Francisco—a sedimentary environmental study: California Univ. (Berkeley), Hydraulic Eng. Lab. Tech. Rept., v. 2, no. 29, p. 1–65.

GPO 793-611