MAMALA BAY STUDY

PROJECT MB-10
ENVIRONMENTAL IMPACTS ON RECEPTORS AND RESOURCES

Part III
EFFECTS OF EFFLUENT FROM THE BARBERS POINT AND SAND ISLAND OUTFALLS ON THE MAMALA BAY ECOSYSTEM

Principal Investigators:

William J. Kimmerer
Romberg Tiburon Center,
San Francisco State University

Joseph M. O'Connor
Kinnetic Laboratories Inc.
Santa Cruz, CA

1 August 1995
EFFECTS OF EFFLUENT FROM THE BARBERS POINT AND SAND ISLAND OUTFALLS ON THE MAMALA BAY ECOSYSTEM

Table of Contents

Executive Summary

1.0 Introduction ................................................................. 1
  1.1 Conceptual Model ..................................................... 1
  1.2 Data Sources ........................................................... 3
2.0 Water Quality ............................................................ 5
  2.1 Approach ................................................................. 5
  2.2 Results ................................................................. 7
    2.2.1 Nutrient Concentrations ...................................... 7
    2.2.2 Particulate Matter .............................................. 8
  2.3 Discussion ............................................................ 8
3.0 Sediment Chemical Composition ........................................ 10
  3.1 Results ................................................................. 12
    3.1.1 Oxidation-Reduction Potential .............................. 12
    3.1.2 Oil and Grease ................................................ 14
    3.1.3 Total Organic Carbon ...................................... 14
    3.1.4 Total Kjeldahl Nitrogen ..................................... 15
  3.2 Discussion ............................................................ 15
4.0 Sediment Supply to the Benthos ......................................... 17
  4.1 The Model ............................................................. 17
  4.2 Discussion ............................................................ 19
4.3 Model Results .......................................................... 19
5.0 Benthic Composition and Abundance ..................................... 22
  5.1 Data sources .......................................................... 23
  5.2 Analytical Approach ................................................. 24
  5.3 Results ................................................................. 26
    5.3.1 Abundance of Major Groups ................................ 27
    5.3.2 Diversity Patterns ............................................. 28
    5.3.3 Species Abundance Patterns: Molluscs .................... 29
    5.3.4 Species Abundance Patterns: Polychaetes ................. 32
  5.4 Discussion ............................................................ 35
6.0 General Discussion and Conclusions .................................. 36
7.0 Recommendations ....................................................... 38

References

List of Tables followed by Tables

List of Figures followed by Figures
EFFECTS OF EFFLUENT FROM THE BARBERS POINT AND SAND ISLAND OUTFALLS ON THE MAMALA BAY ECOSYSTEM

Executive Summary

This report presents results of analyses of existing data on chemical and biological conditions in Mamala Bay to determine the ecological effects of sewage discharge from the Sand Island and Barbers Point outfalls based on existing data. Sewage affects coastal ecosystems through several pathways: nutrient and organic enrichment, sediment loading, and toxicant input. The first two are discussed in this report. A wide variety of effects has been reported for sewage discharges in other localities including enrichment of sediments, inundation of benthic populations by sediment loading, alteration of sediment chemistry, stimulation of opportunistic benthic and pelagic species and suppression of sensitive species, reduction of diversity, and degradation of coral reefs.

We examined available data to assess the degree to which each of these effects could be occurring in Mamala Bay. We used data on sediment chemistry and benthic abundance collected for several years in the vicinity of both outfalls, City and County of Honolulu water quality data, published reports, and other reports from the Mamala Bay study to make our assessment. The analysis focused on water quality, sediment quality, sediment loading to the bottom, and benthic species abundance and composition.

The discharge of sewage in Mamala Bay results in measurable increases in nutrient concentrations in the immediate vicinity of the outfalls. These nutrient levels decline rapidly with distance from the outfalls. Because of initial dilution and subsequent mixing, there is little chance that coral reefs would be affected by the slight elevations in nutrient concentrations near the outfalls. Phytoplankton growth is presumably stimulated by these nutrients, but probably over a long time scale relative to mixing; there was no elevation of chlorophyll concentration in the vicinity of either outfall.

Routine measurements of sediment quality at both sites include oxidation-reduction potential (ORP), oil and grease (OG), and total organic carbon as a percentage of the weight of sediments (TOC). Low ORP can indicate reducing conditions in the sediments brought
on by excessive organic loading. ORP was high at both sites, and there was no spatial
gradient in ORP with distance from the outfalls, nor was TOC elevated near the outfalls. OG
was also invariant with distance from the outfalls; this variable is indicative of sewage input
to sediments.

A simple model of plume dispersal was used to estimate rates of organic flux to the
sediments under several assumptions. Rates calculated using this model were lower than rates
measured in Mamala Bay. This indicates that little, if any, effect on the sediments or benthic
communities should occur.

Analyses of diversity and abundance of benthic species near both outfalls showed little
pattern attributable to sewage. Diversity patterns were examined separately for molluscs and
for polychaete worms. Diversity varied among stations, but not in a way that suggested either
enhancement or suppression by sewage.

Abundance of several major taxonomic groups was examined for differences
attributable to sewage discharge. Total abundance was examined for bivalves, gastropods,
polychaetes, oligochaetes, nematodes, copepods, and amphipods. Only gastropods and
nematodes varied among stations at Barbers Point, and these variations were not related to
distance from the outfalls. At Sand Island, all but amphipods varied among stations;
oligochaetes and copepods were much more abundant near the outfall than far from it; and
bivalves increased with distance from the outfall.

Abundance patterns of common species of molluscs and polychaetes, and of indicator
polychaete species, were examined using graphical and statistical techniques. There was a
tendency for some species of molluscs to be more abundant near the Barbers Point outfall
than far from it, but the same species were not more abundant near than far from the Sand
Island outfall. Since the loading rate and apparent effect of the Sand Island outfall is greater
than Barbers Point, we expected more of an effect on species distributions at Sand Island;
thus, the mollusc distributions at Barbers Point may be related to factors other than sewage
discharge.

Polychaete abundance patterns were much more variable from year to year than the
molluscs, which had surprisingly little interannual variation. Polychaete abundance generally
varied among stations, but few were related to distance from the outfall. Only Ophryotrocha
sp. A and *Capitella capitata* were significantly more abundant near both outfalls than at control stations. Two other species were somewhat more abundant near than far from the Sand Island outfall, and one was more abundant far from the outfall; these species were unrelated to distance from the Barbers Point outfall.

Conclusions of this study are:

1. The Mamala Bay outfalls apparently do not provide sufficient loading of organic matter to overwhelm the processes of dissipation and oxidation in Mamala Bay.
2. The effects on benthic fauna are minor and localized, and probably confined to portions of the soft-bottom communities within ca. 500 meters of the outfalls.
3. The effects are even less prominent at Barbers Point than Sand Island.
4. Effects on bulk chemistry of sediments are nearly unmeasurable.
5. Differences in benthic community composition among sampling stations are generally much larger than the differences explainable by proximity to the outfalls, implying that the outfall effect is minor.
6. There is probably no effect of sewage discharge on coral reefs in Mamala Bay.
1.0 Introduction

The purpose of this report is to present results of analyses of existing data on chemical and biological conditions in Mamala Bay. The objective of these analyses was to determine whether ecological effects of sewage discharge from the Sand Island and Barbers Point outfalls could be discerned in the data, and the severity of any effects.

1.1 Conceptual Model

The influence of sewage discharge on coastal ecosystems is well known. Sewage affects coastal ecosystems through several pathways: nutrient and organic enrichment, sediment loading, and toxicant input. The first two are discussed in this report.

In most cases the effect of sewage discharge on the water column is a stimulation of primary and secondary production and an enhancement of biomass at most or all trophic levels (e.g., Smith et al. 1981; Figure 1). At high levels of discharge, this stimulation can result in the dominance by a few opportunistic pelagic species. At still higher levels, elevated oxygen consumption by heterotrophs and by autotrophs near the bottom or at night can reduce or eliminate dissolved oxygen from the water column. This makes both the water column and the benthos unsuitable as habitat for most organisms.

Changes in biota near the outfall may provide a more sensitive indicator of sewage stress than chemical measurements, since the biota integrate effects over time. In addition, effects on biota are of more immediate concern than small effects on water quality. Typically, benthic populations appear more sensitive than to sewage effects than pelagic populations because most benthic species have limited ability to move in and out of the area affected by sewage. In addition, their relatively long lives make them useful as integrators of ambient conditions over a long time (weeks to months). Variations in the direction of the plume, discharge rates, and dilution should be averaged out over this time scale.
The best-described example of the enrichment of a tropical coastal ecosystem by sewage is Kaneohe Bay, Oahu (Smith et al. 1981, Maragos 1985, Taguchi and Laws 1987). In the study by Smith et al. (1981) the discharge of sewage was terminated, providing an opportunity to examine its effects. Among the effects were elevations in all of the pools and fluxes of organic matter and nutrients measured, including dissolved and particulate organic and inorganic N and P, organic carbon, phytoplankton, zooplankton, primary production, and nutrient fluxes out of the sediments. The studies of Kaneohe Bay did not examine effects on benthic communities except for the metabolic activities reflected in the nutrient fluxes.

Coral reefs are susceptible to sewage pollution in several ways; Some pathways of impact are illustrated in Figure 1. Some coral species are sensitive to sediment loading and are excluded from areas of high sediment input from sewage (Pastorok and Bilyard 1985). High levels of organic matter and nutrients can stimulate algae that overgrow corals, or phytoplankton that shade them (Maragos 1985). In addition, elevated levels of phosphate can reduce calcification rates of corals (Kinsey and Davies 1976), which could ultimately result in erosion and degradation of the reef.

Sediment loading, from sewage or from particulate matter produced on nutrients in sewage, can have an influence on soft-bottom benthic communities (Figure 1). Sediments in the vicinity of an outfall can become enriched with organic matter including petroleum products and toxicants (Swartz et al. 1986). The organic matter can stimulate the growth of benthic populations, particularly of certain opportunistic species (Pearson and Rosenberg 1978). Species sensitive to toxins or to high organic loading can be suppressed. At high loading rates, deposition of organic-rich sediments can cause eutrophication, anoxia, and suppression of species near the outfall (Pearson and Rosenberg 1978, Swartz et al. 1986).

No evidence has come to light that eutrophication has occurred in Mamala Bay. The reports of several years of benthic monitoring and sediment analysis have concluded that no effect of sediment enrichment has been observed in the sediments or in the benthic communities (Nelson et al. 1994a-c and references). However, these results have not yet been
compared rigorously across years to determine whether some effects might be evident in the combined data.

This report examines the effects of nutrient and organic loading from the sewage outfalls on Mamala Bay. Data used include benthic monitoring and sediment data (Nelson et al. 1994a-c and references), water quality data from the City and County of Honolulu, and data on effluent characteristics. This report analyzes the effects of sewage discharge in the following ways:

Section 2: Examine data on concentrations of nutrients, chlorophyll, and other water quality measurements for evidence of a potential effect on pelagic ecosystems or reefs.

Section 3: Examine data on sediment composition near the outfalls for evidence of a sewage "signal" in several commonly-measured indicators, including the percentage organic carbon in sediments, oil and grease, and oxidation-reduction potential.

Section 4: Calculate expected sediment loading rates to the bottom based on sewage input, assumed settling rate, and a simple analytical model.

Section 5: Examine benthic species composition and abundance of selected species for evidence of spatial relationships that might be attributed to sewage effects.

1.2 Data Sources

All the data used herein were taken with the sewage outfalls in operation. There are no data from before outfall construction. This is unfortunate because spatial patterns in the data cannot be unequivocally attributed to effects of sewage. Control sites were chosen far enough from the outfalls to be unaffected by the discharges, but this also meant that they may have been in different environments with respect to depth, current patterns, sediment characteristics, and proximity to reefs and major nonpoint sources of materials. In other words, without pre-discharge data there is no way to evaluate how representative the control stations are.
Annual benthic monitoring near each of the two outfalls provided most of the data analyzed here (Nelson et al. 1994a-c, and references). Samples at Barbers Point were taken in the zone of initial dilution (ZID), at four locations along the (presumed) ZID boundary, and 3600 m east and 3700 m west of the ZID station (Figure 2a). At Sand Island samples were taken in the ZID, at three ZID-boundary stations, and approximately 1600 m east and 2000 and 2700 m west of the ZID station (Figure 2b). At both locations the stations roughly followed the depth contours at which the diffuser is located, so they nominally occur at about the same depth. However, even within stations, depth variation has been large because of navigational uncertainties (Tetra Tech 1987).

Replicate samples were taken at each station using a Van Veen grab sampler. Subsamples were taken for analysis of grain size distribution and several chemical components of the surficial (top 2 cm) sediments, and for several categories of benthic fauna in 5 cm deep subcores. Replicate data were retained for the analysis of chemical variables, but the mean of the replicates was used for most of the analyses of benthic fauna in Section 5.

Tetra Tech (1987) evaluated the benthic monitoring program conducted at Barbers Point in 1986 and made many comments, some of which led to improvements in the program. This report examines three aspects of the series of reports produced since then: sediment composition, benthic species composition, and abundance of selected benthic taxa. We assume that methods of sample collection and analysis were applied correctly, consistently, and without bias, so that differences among stations can be taken as real differences rather than methodological artifacts.

We also analyzed the water quality data from the City and County of Honolulu's monitoring program. This data set includes several years of data, and includes the benthic sampling stations and additional stations close to and far from the outfalls. The data appear to be of high quality; values from control stations far from the outfalls have similar values to those previously reported for open-ocean waters near Oahu (see below). However, different stations were visited each year, so the analysis could not be based on a factorial model as for the sediment data (Section 2). Only data available in electronic format were analyzed.
This report focuses on differences among stations attributable to the influence of sewage. However, we also compared results between sites (Barbers Point and Sand Island) and years to attempt to explain the patterns observed within each site. We also looked for relationships with grain size of sediments, which is often related to chemical contamination.

2.0 Water Quality

The ocean waters surrounding Oahu are highly oligotrophic, meaning that nutrient concentrations in these waters are very low and often undetectable by the best routine analytical techniques available. One consequence of this is that the endemic phytoplankton community may be extremely nutrient-limited but still capable of rapid growth (Laws et al. 1984). Adding nutrients to this water may result in rapid uptake by the phytoplankton, so that the nutrients are stripped from the water fairly rapidly (see Laws and Ziemann 1995). Therefore, nutrient addition to these waters may manifest itself as increased chlorophyll concentration rather than increased nutrient concentration per se, except in the immediate vicinity of the outfall.

2.1 Approach

We focused on ammonium as a tracer of inorganic nutrients in the sewage plume. Ammonium is typically high in primary or secondary sewage and low in oligotrophic waters; nitrate is more characteristic of runoff and upwelling sources. Phosphate can be more useful than nitrogen species for tracing inputs, but it was measured only at Barbers Point and not as often as ammonium. Therefore we estimated phosphate concentrations from ammonium based on their ratio in samples with elevated ammonium near the outfall (see below).

Data analysis included graphical and analytical techniques. The goal of this analysis was to determine whether stations close to the diffuser had higher nutrient concentrations than stations far from the diffuser. First we plotted the data vs. distance from the diffuser using box plots to examine the apparent trend in median and spread with distance.
The second approach was designed to detect extreme values. The upper quartiles (75th percentiles) of all the data for each year were determined. The frequency at which each station contributed values exceeding the upper quartiles for all stations was examined for differences among stations. For example, if the ZID station had two samples in the upper quartile in 1990, one in 1991, and none in 1992-93, then it contributed three samples to the upper quartile. The expected value for each station is 25% of the total values from that station, under the assumption that extreme values do not occur more often at one station than another.

The proportion of samples in the upper quartiles of all stations was plotted against distance from the outfalls to test for increases in water quality parameters by sewage discharge. We also examined measures of particulate matter including total organic N and P, extinction coefficient, and chlorophyll. Most of the measures of particulate matter were rather invariant with distance from the outfalls.

Chlorophyll concentrations were examined using various graphical and regression techniques. In this and subsequent sections, diagnostic plots of residuals from regressions were used to insure that the data met the criteria for regression analysis. In particular, we examined the residuals for signs of a nonlinear term or heterogeneous variances. The expected concentration of chlorophyll as a function of dilution was calculated from the nutrient input of the sewage outfalls, assuming that all inorganic N was converted to phytoplankton with a Redfield C:N molar ratio of 106:16 and a carbon:chlorophyll ratio of 50.
2.2 Results

2.2.1 Nutrient Concentrations

Ammonium concentrations varied in time, distance from the outfalls, and sample depth. The spatial trend at each of the sites is illustrated by Figure 3. The box plots show that stations close to the outfalls had more frequent high values of ammonium than stations further than 1000 meters away, particularly for the deep samples. However, the median values do not look particularly different. In fact, if the values over 1 μg-at/l are removed, the median values from the stations near the outfall were lower than those from the distant stations.

Because the difference in ammonium among distance categories was apparently confined to the extreme values, and the data are obviously heteroscedastic and asymmetrically distributed, parametric tests of differences among means were neither warranted nor suitable. Instead, we focused on the extreme values as represented by the upper quartiles for each year.

The proportion of samples in the upper quartiles decreased with distance from the diffusers (Figure 4). This relationship was apparently unrelated to direction from the outfall; slopes are not significantly different for eastern and western stations (analysis of covariance, p>0.1).

Ammonium values greater than 0.6 μg-at/l were rare in the stations more than 1000m from the outfalls. Any measured values greater than 0.6 μg-at/l were taken as plume values. The proportion of values from near-ZID stations 30 meters or deeper that were more than 0.6 μg-at/l was 14% for Barbers Point and 26% for Sand Island. That is, the plume can be detected at about those frequencies at the stations near the outfall. The median elevation of ammonium in the plume where it occurred was 0.8 μg-at/l at Barbers Point and 1.1 μg-at/l at Sand Island.

Phosphate data from Barbers Point also showed some elevated values (Figure 5), but the influence of the sewage discharge was not as clear. The median molar ratio of ammonia-N to phosphate-P was two in all samples, and four in samples with elevated ammonium and phosphate (i.e. over 0.6 μg-at/l and 0.2 μg-at/l). This ratio can be used to calculate a plume...
value of phosphate of 0.2 and 0.3 µg-at/l at the Barbers Point and Sand Island. Total N and P (most of which is dissolved) show similar patterns at both outfalls (Figure 6), with somewhat more high values close to the outfall. Applying the upper-quartile method to TN and TP, however, revealed a significant (negative) slope only for TP at Sand Island (linear regression, p<0.05).

2.2.2 Particulate Matter

Particulate matter was represented by total suspended solids (SS), turbidity, chlorophyll and, at Sand Island, extinction coefficient. Turbidity showed no pattern with distance from the outfall, but was generally higher inshore (Figure 7). SS was nearly invariant and low (Figure 7). Extinction coefficient was generally low with high values only at inshore stations.

No trend in chlorophyll with distance from the outfalls was detected by either graphical or regression techniques (Figure 8). At Sand Island, but not at Barbers Point, stations at distances of 1000-3000 meters had a somewhat greater proportion of high values of chlorophyll than distant or near-ZID stations.

Inspection of time trends of chlorophyll indicates substantial interannual variability not associated with sewage flow, the physical environment, or any obvious meteorological events. Values were higher in 1990-1992 than in earlier years. In addition, different groups of stations were sampled in each year. The interannual variation, together with shifts in the stations visited in each year, accounts for most of the variation in chlorophyll with station.

2.3 Discussion

The mean concentration of ammonium in the two sewage discharges was estimated from data in Stevenson et al. (1995), which gives flow and loading from each plant. These concentrations are 1000 µg-at/l NH₄ at Sand Island and 1300 µg-at/l NH₄ at Barbers Point. This translates to dilutions of about 900 at Sand Island and 1800 at Barbers Point. Initial dilutions calculated by the near-field modeling averaged about 600 (Roberts, 1995).
Ammonium concentrations calculated for the effluents were 6000-7000 times higher than background (the median concentration at the control stations). A similar calculation for other nutrients for which data are available gives ratios of 60-80 for nitrate plus nitrite, 210-290 for total nitrogen, and 2100-2900 for total phosphorus. Thus, nutrient elevation due to sewage should be most readily detected in ammonium (even accounting for differences in detection limits among these nutrients).

At the dilutions necessary to eliminate the excess ammonium signal, ca. 2000, the salinity signal should be undetectable (at ca. 0.015 psu) in field data gathered over a period of time. Indeed, there was no relationship between distance from the outfall and salinity. A slight relationship between ammonium and salinity was statistically significant but had no explanatory power (p<0.0001, r²=0.03, linear regression), and inspection of graphs did not suggest a sewage origin of this relationship.

Based on the nutrient results, the sewage plume could bring excess concentrations of ammonium (>1 μg-al/l) and phosphate (~0.25 μg-at/l) to the bottom within 500 meters of the outfalls about 25% of the time. These results can be used to determine whether a hazard exists to coral reefs in the vicinity due to elevated nutrient concentrations. The sampling stations were along the same depth contours as the outfalls, and the plume probably does not extend across the contours to as great an extent. Nevertheless, if we assume that the sewage plume visits stations within 500 m in any direction at about one time in four, we can estimate the range of impacts conservatively. A distance of 500m from either outfall is at about the 20 meter depth contour. This is deeper than most corals in the Hawaiian Islands, mainly because of poor light penetration to this depth. In addition, Mamala Bay is not known for extensive coral reefs, perhaps because of strong currents and wave action (see Grigg 1995).

There is little information on the effect of elevated nutrient concentrations on coral reefs. Smith et al. (1981) presented an extensive data set on nutrient concentrations in Kaneohe Bay, Hawaii, along with some data on reef responses to the cessation of sewage input to the bay. In the northern and central reaches of the bay, where coral growth on some patch reefs was luxuriant, ammonium and phosphate concentrations averaged 0.6 and 0.2 μg-
at/l respectively before sewage discharge was terminated, and 0.4 and 0.1 μg-at/l after, with frequent excursions to twice the mean values (Smith et al. 1981 Figures 20-21). This does not rule out an influence of nutrients on the reefs, but if it existed it must have been subtle. Maragos (1985) has described the extensive recovery in the south bay several years after sewage discharge was terminated; in 1985-86, ammonium concentrations averaged around 0.5 μg-at/l and phosphate 0.2 μg-at/l (Taguchi and Laws 1987).

Kinsey and Davies (1979) reported calcification of corals was reduced by 50% after three-hour periods of exposure to a concentration of 2 μg-at/l phosphate. This is about eight times higher than the calculated plume values for Mamala Bay. Again, this does not rule out effects on calcification rates, but given the relatively low levels of phosphate within 500 m of the outfall, and the occurrence of corals mostly in shallower waters than this, significant effects of elevated phosphate on Mamala Bay reefs are extremely unlikely. Grigg (1995) reported no difference in calcification rates of corals that could be attributed to the outfalls.

Laws and Ziemann (1995) conducted bioassays that showed growth of Mamala Bay phytoplankton nearly doubled within 24 hours after enrichment by sewage diluted to 1 μg-at/l ammonium. Presumably this occurs in Mamala Bay, so that over a span of one to several days the ammonium would be converted to phytoplankton biomass. The plume ammonium concentrations referred to above, about 1 μg-at/l, translate to a chlorophyll concentration of about 1-2 μg/l, assuming complete conversion. This concentration is higher than the oceanic values presented above or by Laws and Ziemann (1995). However, in the time it would take for such a bloom to develop, the plume would have dispersed and the chlorophyll diluted to the point where it would be undetectable. This conclusion is supported by the studies of Laws and Ziemann (1995), which showed that phytoplankton pigment composition in bioassays using diluted sewage was different from that in samples taken near the Sand Island outfall.

3.0 Sediment Chemical Composition

Samples were taken at each benthic station at Sand Island during August 1987 and 1990-1993 for oxidation-reduction potential (ORP, mv, also taken in 1987), total oil and
grease (OG, mg/kg), weight percent total organic carbon (TOC, 1991-93 only), and total Kjeldahl nitrogen (TKN, mg/kg). At Barbers Point samples were taken in January of 1990-1994 for ORP, OG, and TOC. Grain size distribution was determined at each station.

Analysis of the data was exploratory, using graphical representation of the data to reveal patterns, then applying suitable statistical tests to the data where appropriate. Parametric statistical tests were unsuitable for the analysis because:

- Variances were heterogeneous and distributions sometimes skewed
- For all of the variables, significant interactions existed between station and year; thus, significance tests for differences between station means across all years would be difficult to interpret using an analysis of variance model
- Generally the extreme values were of as much interest as the means, because the sewage effect could be episodic and patchy. Therefore special statistical methods were required.

The goal of this analysis was to determine whether stations close to the ZID had higher values for the various measurements (lower for ORP) than stations far from the ZID and, if possible, to determine possible causes of any differences observed. Two general approaches were used to detect differences. These approaches were designed to minimize assumptions, and to minimize effects of the sometimes large interannual variability in the data. The first approach was designed to examine differences among median values. For each variable, medians were calculated from each year's data set and ranked, then the ranks were summed across all years. Sums of ranks were then examined for differences among stations that might result from sewage input. In addition, Friedman's test was applied to the medians to test for differences in rank among stations.

The second approach was to compare extreme values among stations for nutrients. For each variable, the upper quartiles (lower for ORP; see below) of all the data for each year were determined. These were tested for rank-order using Friedman's test. In addition, the frequency at which each station contributed to the upper quartiles of all years was used to examine for differences among stations. For example, if the ZID station had two samples in
the upper quartile in 1990, 1 in 1991, and none in 1992-93, then it contributed three samples to the upper quartile. The expected value for each station is 25% of the total value from that station.

3.1 Results

Initial examination using correlation coefficients and graphical analysis showed no apparent relationships among the chemical variables used in the analysis. Therefore each was treated as a separate entity for examining the possible effect of the outfalls. Table 1 gives the median values and the number of samples reported for each station in each year.

3.1.1 Oxidation-Reduction Potential

If sewage-derived particulate organic matter is deposited in substantial concentrations, oxidation can reduce oxygen supply or cause anoxia in subsurface sediments near the outfall. If so, ORP would be lower at sites nearest the outfall. Therefore this analysis examined the data to detect low rather than high values from stations near the outfall.

Figure 9 shows box plots of ORP for each of the stations within each of the two areas, arranged by distance from the ZID station from west to east. Box plots are useful for examining the central tendency of the data as well as the extreme values. These results can be examined in two stages: first by comparing the ZID station with the three or four ZID-boundary stations, and second by comparing the stations in or near the ZID with the distant stations.

The only apparent pattern in the medians in Figure 9 is that the far-field stations (HB1 and HB7) at Barbers Point appeared to have slightly higher medians, indicating more oxidized sediments, than the stations in and near the ZID. Conversely, the only station at Sand Island with a substantially different median is Station B4, where the median is elevated. However, Friedman's test did not indicate a significant difference among medians (p>0.1).

The values of the lower quartiles likewise did not differ among stations (p>0.07). However, the frequency of values in the lower quartiles for each year is a more powerful
statistic. At Barbers Point, the distant stations had significantly fewer values in the lower quartile than stations closer to the outfall \((p<0.01, \text{chi-square test})\), but near the ZID no pattern was apparent. By contrast, the distant stations at Sand Island had significantly more of the lower-quartile values \((p<0.01)\), while two stations close to the ZID (B4 and B5) had no values in the lower quartiles for any year.

Comparison of the results for the two areas revealed slightly lower medians and a wider spread, with a few negative values, at Sand Island (Figures 9, and 10). Negative values occurred only in three samples in 1987, and were clearly different from other replicates from the same stations. These measurements were probably erroneous, but the Sand Island stations still had more low values than the Barbers Point stations (Figure 10). Possible explanations for the difference between areas are differences in temperature, sediment grain size, water motion, or terrigenous loading.

Seasonal differences could arise because samples were usually taken at Barbers Point in January-February (but twice in summer), and at Sand Island in August. The temperatures during these periods were 24.5°C and 26.5°C (median of all data from each station from City and County of Honolulu samples; temperature stratification was usually small). The difference of 2°C does not seem sufficient to account for the difference in ORP at the two sites. Furthermore, since increasing temperature would increase rates of both oxidation and reduction reactions, it is not clear in which direction ORP would go as temperature increased. However, seasonal differences in runoff or other environmental variables may contribute to the difference. On the other hand, data taken at Barbers Point in summer on two occasions did not differ from data gathered in winter.

ORP was not correlated with median grain size of sediments, either within each site or between sites (linear regression, \(p>0.1\), and inspection of scatter plots). Median grain size did not differ among individual stations by more than 1 phi unit (factor of two in diameter), and there was no consistent difference in grain size between the two areas. Overall median grain size was phi 3.1, which is medium sand. The proportion of silt and clay in the samples had a median value of 4%, and only 3% of samples had a silt and clay proportion larger than...
10%. Thus, the sediments can be characterized for all stations as medium sand with little fine sediment. Sediments of this size range are not normally associated with reducing conditions. Variation in sediment grain size is discussed further in Section 5 in connection with potential effects on benthic populations.

3.1.2 Oil and Grease

Oil and grease measurements showed large differences between sites (Figure 11), but no apparent effect of the sewage outfalls (Tables 1-3; Friedmans test on medians and upper quartiles, p>0.1). Data from Barbers Point were fairly uniform, with all stations having medians ranking near the upper and lower ends of the range of medians in different years (Table 2), and an even frequency of values in the upper quartile (Table 3). Data from Sand Island were more variable in space and time: values from 1992 were much higher than any of the other values. Although stations differed in rank order of their median values (Table 2) and the frequency of values in the upper quartile (Table 3), these differences were not significant, nor did they suggest a sewage effect.

The reason for the high values from Sand Island in 1992 is unknown. Possible explanations of such a widespread elevation in oil and grease include a methodological error, an oil spill in the area, or a widespread bloom of phytoplankton that subsequently was deposited in the sediment. Data on chlorophyll in the vicinity of the Sand Island outfall (City and County of Honolulu monitoring data) do not show particularly high values during late 1991 or early 1992.

3.1.3 Total Organic Carbon

The percentage of total organic carbon (TOC) measured in the sediments was greater at Barbers Point than it was at Sand Island (Figure 12); medians overall were 0.26% in samples from Barber’s Point and 0.12% for samples from Sand Island, respectively. This difference is opposite from those seen for ORP (Figure 10) and oil and grease (Figure 11). Differences among stations are variable (largely because of low sample size at Sand Island;
Tables 1-3), but none were significant (Friedman's test, p>0.1). The medians and upper quartiles of the ZID and near-ZID stations do not suggest a sewage influence.

The discrepancy in results between TOC and ORP could be due to several factors, but without synoptic sampling at the two locations a seasonal or temperature effect cannot be ruled out. In either case, the values of TOC are very low, consistent with the location of these samples in an oligotrophic environment with little organic matter input to the sediments. There is no evidence in the chlorophyll data of significant blooms that could have affected sediment organic carbon or O&G.

3.1.4 Total Kjeldahl Nitrogen

The concentration of total nitrogen (TKN) was measured only at Sand Island. Box plots (Figure 13) show a tendency for more extreme values in and near the ZID, as does the summary of upper quartile values (Table 3). This effect was confined to 1990. In other years there was no relationship between distance from the ZID and TKN, and the medians and upper quartiles did not differ among stations (p>0.1, Friedman's test).

During 1990, three of the highest four values were from station Z, and eight of the highest 10 from the ZID and near-ZID stations. Median values were 251, 282, and 368 mg/kg at far-field, ZID boundary, and ZID stations respectively. The median for the ZID station in 1990 differed from that of all other stations (p=0.014, Mann-Whitney U test), while that of the stations within 1000m of the ZID station differed from that of all other stations (p=0.001). Even in view of the multiple testing implicit in the exploratory data analysis conducted here, the latter value indicates a strong probability that the near-ZID stations were indeed higher in TKN than the far-field stations, possibly suggesting a sewage effect. However, this effect did not appear in the other measures of sediment chemistry, and was confined to a single year.

3.2 Discussion

Sediment chemical composition in the two areas showed considerable spatial and interannual variability. However, almost none of that was explained by sewage input. The
single exception was for TKN in 1990, which was somewhat elevated at and near the ZID station. This general lack of clear gradients in sediment chemistry with distance from the outfalls could arise for several reasons:

1. Rates of input of sewage-derived material from the outfall are too low to produce a gradient in deposition rates with distance from the outfall.

2. A gradient in deposition rates of organic matter exists, but benthic oxidation of organic matter is so rapid that a gradient in organic matter concentration cannot be detected.

3. The spatial scale of sampling is too small: either the ZID station is outside the area of influence of the outfall, or the far-field stations are substantially affected by effluent.

4. Sampling or analytical techniques are not sensitive enough to detect a sewage effect.

These possibilities are addressed in the Discussion section of Section 4. Briefly, some evidence shows an effect of sewage inputs on sediments near the outfall, but the flux of sewage-derived sediment to the bottom is small and the benthic oxidation of these sediments seems to be rapid.

High values of some of the variables occurred at all stations at a site in one year, but never in both areas in the same year. This suggests that much of the variability is either seasonal or irregular in time. Without further information on the spatial and intra-annual variability in these data, the cause of the variability cannot be determined.

It is tempting to suppose that the difference between sites in ORP may be due to differences in exposure to terrigenous inputs. The Barbers Point outfall is on an area of open coast with the only major nearby source of terrigenous matter being Pearl Harbor. By comparison, the Sand Island outfall is close to several major streams with only limited areas for settling of sediments (e.g., Ala Wai Canal, Honolulu Harbor, Keehi Lagoon). Thus there could be a slightly greater terrigenous component of sediments at Sand Island that contribute to a somewhat more reducing sedimentary environment. However, this finding seems to be contradicted by the higher proportion of total organic carbon in the sediments at Barbers Point.
4.0 Sediment Supply to the Benthos

The purpose of this section is to analyze the rate at which sediment is supplied to the benthos. In particular, we are concerned with the rate of deposition of organic matter and the effects that this material may have on the benthos.

4.1 The Model

We constructed a simple analytical model of particle flux to the bottom to examine the extent to which suspended sediments might affect the benthos in the vicinity of the Barber’s Point and Sand Island outfalls. The model was based on a single measurement of settling rate distributions made on effluent from Sand Island. The structure of the model is depicted in Figure 14.

Assumptions of the model are:

1. The single experimental measurement is reasonably representative (see below for sensitivity analysis).

2. Most of the particle settling rates are small, and the distribution of settling rates for the more rapidly settling particles decreases exponentially with increasing settling rates.

3. The plume is subjected to a net (i.e., tidally-averaged) velocity U with direction that varies randomly on time scales of days.

4. Sediments settle evenly over the area affected by the plume.

5. Turbulence, stratification, flocculation, and shear effects on particle settling are ignored.

6. Particles are not resuspended once they reach the bottom.

Assumption 2 was based on examination of the data, and results in a model that approximates the form of the data. Assumptions three to five represent a simplification of the model necessary to make it analytically tractable. Assumption three is equivalent to assuming that the plume is equally likely to flow in any direction, and the frequency of visitation of any point is averaged over time. This model gives a higher sediment flux at the edges of the plume.
than would be expected, and is therefore conservative. Assumption six is probably not correct (Zapka and Krock 1983) but is also conservative.

The data consist of one set of six measurements of settling rates. Effluent was mixed with seawater (1 part in 40), then poured into cylinders 35 cm high and allowed to settle for various periods. The water was then siphoned off and the particulate matter was weighed. The results (Figure 15) show that after four hours 17% of the weight of sediments had settled.

Under assumption 2 above, the settling rate can be modeled as a probability density:

$$ P = A e^{-bW} $$

where $W$ is settling velocity, $PdW$ is the proportion of particles with settling velocities between $W$ and $W + dW$, and $A$ and $b$ are positive parameters.

We applied this model to the experimental data to obtain the equation:

$$ S = \frac{At}{35b^2} \left(1-e^{-\frac{35b}{t}}\right) $$

where $S$ is the proportion of mass that settled to the bottom of the cylinder by time $t$. This equation was solved for $A$ and $b$ using a nonlinear curve-fitting procedure to give values of $A=17.5$, $b=106$ (for velocities in cm/s). Equation 1 with these parameters gives a value of 6% of the particles settling faster than 0.01 cm/s, and 0.004% settling faster than 0.1 cm/s (Figure 15). Values of $b$ between 89 and 154 produce curves that include all but one data point (Figure 15).

Under assumptions three and four, the sediments either settle out within some distance from the outfall, or they remain suspended. The distance from the outfall is equal to the
distance the mean flow takes the particles in the time it takes them to settle. In other words, particles must have a minimum settling velocity $W_0$:

$$W_0 = \frac{HU}{r}$$

(3)

where $H$ is the depth below the plume and $r$ is the distance from the outfall. Under assumption four the sediment flux to the bottom within the distance $r$ is given by:

$$\Phi = \frac{\alpha}{r^2} e^{-\frac{\beta}{r}}$$

(4)

Where $\Phi$ is the settling flux ($g \ m^{-2}$), $\alpha=LA/(b\pi)$, and $\beta=bHU$, where $L$ is the mass loading rate (grams) from the outfall.

4.3 Model Results

The settling flux $\Phi$ has a maximum value in the radius $r$ that can be determined by differentiating equation 4 with respect to $r$ and setting the result to 0. Maxima in $\Phi$ for various conditions are given in Figure 16, assuming a loading rate $L$ of $1.6 \times 10^6$ grams/day of suspended sediments (the upper 95% confidence limit for monthly means at Sand Island). All values fall below a sediment flux of $10 \ g \ m^{-2}$, and most are less than 1% of that value.

4.2 Discussion

Sedimentation rates have been obtained using sediment traps in the vicinity of the outfalls on several occasions. M&E Pacific (1984) reported sedimentation rates of organic material of $2-3 \ g \ m^{-2} \ d^{-1}$ at sites within 25 m of the Sand Island outfall, compared with $1 \ g \ m^{-2} \ d^{-1}$ at a control site. However, the sediment traps were on the bottom and affected by sedimentation: carbonate material made up 94.3% of the trap material at the control site and
94.5% at the outfall sites (M&E Pacific 1984, Table IV-18). This material originates from resuspension or deposition of biogenic material from reefs and sand. The proportions of organic matter in the sediments collected at the control and outfall stations were very similar (2.8% at diffuser sites, 2.7% at the control site), suggesting that nearly all of the difference between control and diffuser sites was due to the deposition of biogenic carbonate material. Therefore most of the difference between the control and outfall sites was probably due to differences in the background sedimentation rather than the sewage discharge.

Smith and Dollar (1986) reported organic sedimentation rates of 25 and 12 mmole C m$^{-2}$ d$^{-1}$ near the Sand Island outfall, 17 and 16 at Barbers Point, and 12 and 8 at two control sites in 1984 and 1985, respectively. Particulate nitrogen sedimentation rates were 1.8 and 1.1 at Sand Island, 1.2 and 1.0 at Barbers Point, and 0.2 in both years at the control site. Sediment traps were placed 10, 70, and 140 m from the diffusers, and data were combined from the three distances. Differences between Sand Island values and controls for carbon, and between both sites and controls for nitrogen, were significant in each year (p<0.05, analysis of variance; Smith and Dollar 1986), comprising about 13 and 4 mmole C m$^{-2}$ d$^{-1}$ in each year. Smith and Dollar (1986) discussed the possibility of variation in background sedimentation rates between their sites and the controls. Based on the C:N ratios in the organic sediments they concluded that most of the excess organic sediment in the traps near the outfalls was of sewage origin. This contrasts with the conclusion drawn above on the basis of ratios of organic to inorganic matter.

A sedimentation rate of 10 mmole C m$^{-2}$ d$^{-1}$ due to sewage inputs is equivalent to about 0.3 g m$^{-2}$ d$^{-1}$ of organic sediment assuming that carbon comprises about 40% of the dry weight of the sediment. This falls within the envelope of values for sedimentation rates based on particle settling rates (Figure 16). However, the rate calculated from trap data is for stations very close to the outfalls, and sedimentation rates should decline with distance from the outfalls.

Organic sediment settling to the bottom will be resuspended, oxidized, or eventually buried. Resuspension is probably frequent given the strength of currents in the region (Zapka
and Krock 1983), but is ignored here as intractable (which makes calculations conservative). The chemical composition and N isotope ratios of sediments in profiles through the upper 3-4 cm suggest that no component of the sediment is buried (Smith and Dollar 1986). Therefore, we assume that all of the sediment deposited in the vicinity of the outfalls is oxidized.

The portion of organic matter that is oxidized contributes to an upward flux of nutrients and dissolved inorganic carbon (DIC), and a downward flux of oxygen, at the bottom. Smith and Dollar (1986) determined the fluxes in nutrients, DIC, and oxygen into and out of the bottom near and far from the outfalls. Fluxes did not differ by direction or distance from the outfall within 140 meters at Sand Island, although there was an increasing trend to the northwest at Barbers Point. Significant differences were found in fluxes of all materials between controls and the Sand Island site in 1984, and in fluxes of some materials between controls and Sand Island in 1985 and Barbers Point in both years.

The calculated DIC fluxes near the outfalls exceeded the controls by 8-27 mmoles C m⁻² d⁻¹. This range of values is in rough agreement with the data from sediment traps, and also in accord with the sediment flux model presented above. In addition, comparisons of fluxes of different materials gave results consistent with a sewage source of the material near the outfalls, and predominantly aerobic metabolism of the sediments.

Analysis of pore-water concentrations of nutrients also suggested an aerobic environment and lack of long-term net burial of organic sediments (Smith and Dollar 1986). Furthermore, the sediments were poor in organic carbon (see Section 3), and there was no spatial trend in the percentage organic carbon in bulk sediments.

The model demonstrates the inverse relationship between the sediment flux and the distance over which that flux is felt. Because of the low settling velocities of most of the sediment particles, only a small percent of them actually reach the bottom. Smith and Dollar (1986) estimated that only about 1% of the organic material reaches the sediment near the outfalls, and that essentially all of that is remineralized in the top few cm of sediment. Based on the model calculations above, about 1% of the sediment reaches the bottom within about 400 meters, and 10% reaches the bottom within about 2 km (except where sediment drifts...
into deeper water). Thus, the bulk of the sediment discharged by the sewage outfalls leaves Mamala Bay in suspended form.

It is arguable, though, to what extent the finer materials transported away from the outfalls reach the bottom in the form in which they were discharged. The settling rates of the more slowly settling particles are poorly known. However, the currents in Mamala Bay are sufficient to mobilize sand grains at times. Since there is apparently no location in Mamala Bay where fine sediments aggregate to produce well-packed sediments, it is reasonable to expect the finer sediments to be mobilized as well. Even measurements taken with sediment traps are misleading in this regard, since they include an unknown proportion of resuspended material. Thus, the estimates above for sediment impacts should be viewed as upper limits.

5.0 Benthic Composition and Abundance

Changes in biota near the outfalls may provide a more sensitive indicator of sewage stress than chemical measurements, since the biota integrate effects over time. In addition, effects on biota are of more immediate concern than small effects on water quality. Typically, benthic populations appear more sensitive to sewage effects than pelagic populations because most benthic species have limited ability to avoid areas affected by sewage. In addition, their relatively long lives make them useful as integrators of ambient conditions over a long time (weeks to months). Variations in the direction and depth of the plume, discharge rates, and dilution should be averaged out over this time scale.

Effects of sewage effluent on benthic community structure are well-described (Section 1.1). Effluent has high concentrations of organic matter, which can stimulate secondary production around the outfall. Secondary production and biomass of sensitive species can be reduced by toxic materials in the effluent or by rates of organic matter deposition sufficient to cause anoxia in sediments. Thus, diversity can be reduced either through stimulation of one or a few opportunistic species, or through elimination of sensitive species (Figure 1).

The traditional model of effluent effects on the benthos (Pearson and Rosenberg 1978) holds that sewage results in reduced benthic diversity. An alternative model (Swartz et al.
1986) holds that at intermediate levels of discharge (or distance from the outfall), disturbance is sufficient to alter dominance of the most abundant species, but not to eliminate species. In that case both biomass (or productivity) and diversity increase relative to values at undisturbed sites. Only near the outfall and at high rates of sewage loading does diversity and, eventually, biomass decline. An assumption underlying all these models, borne out by field data (Swartz et al. 1986), is that distance from the outfall is a surrogate for the level of influence of sewage; thus, stations close to the outfall would be more affected than distant stations.

The hypotheses tested in this analysis were:

1. Total abundance of benthos (as a surrogate for biomass) differs among stations
   1a Total abundance is related to distance from the outfall
   1b Total abundance is related to other factors

2. Benthic diversity differs among stations
   2a Diversity patterns are related to distance from the outfalls
   2b Diversity patterns are related to other factors (e.g., depth, sediment grain size)

3. Abundance of common species differs among stations
   3a Abundance of common species is related to distance from the outfall
   3b Abundance of common species is related to other factors

Total abundance is taken to mean abundance of major taxonomic groups, such as bivalves, polychaetes, and amphipods. Diversity is considered within two major groups for which considerable effort has been spent identifying large numbers of species: molluscs and polychaetes.

5.1 Data sources

and 1990-1993 [Sand Island] and 1987 and 1990-1994 for Barbers's Point). Samples were taken in February in most years at Barbers Point (but in July 1991 and June 1993), and August at Sand Island. See those reports and the general introduction above for a complete description of methods of sampling and sample analysis. Data are presented in appendices to those reports as numbers of each taxon in subsamples of replicate grab samples.

Data are reported separately for each site, with a discussion comparing the two sites below. This report also distinguishes between micromolluscs and other fauna (predominantly polychaete worms) to follow the source documents. These two "taxa" were separated from the samples and examined by different teams of taxonomic experts. In the case of both micromolluscs and other taxa, there is evidence that faunal differences can arise from disturbance (Swartz et al. 1978, Kay 1980).

5.2 Analytical Approach

We expected that any sewage effect would be detectable either in diversity patterns or altered abundance of particular species near the outfalls. Therefore we examined how these patterns varied among sampling stations and with distance from the outfalls.

We chose to concentrate on the more common species in the samples. There are three reasons to do this. First, concentrating on the common species enhances the statistical power of any tests applied; that is, the numbers are more robust than for rare species and differences due to sewage are easier to detect. Second, different numbers of samples were taken at different stations in different years; to examine patterns for rare species would require that the effort be equalized by eliminating samples from the analysis. This is undesirable because of the loss of power. Third, the importance of rare species to the ecosystem is unknown, but unlikely to be high. For example, the common species are more likely to provide substantial food to higher trophic levels. However, we also examined total number of species per replicate sample (within the molluscs and polychaete) as a way of including the rarer species.

We analyzed the means of the replicated samples to avoid most of the problems due to variable numbers of replicates. Thus, we have a single value for each species (or higher
taxonomic level) for each combination of station and year, referred to here as a sample. Since we were interested in differences among stations, analysis of the underlying replicates was not warranted. Data analyzed were either raw or log$_{10}$(N+1)-transformed numbers of each taxon per grab sample.

For each site, we first examined total abundance patterns of major taxonomic groups including polychaetes, oligochaetes, nematodes (four years of data only), amphipods, copepods (four years of data only), bivalves, and gastropods. Data were examined graphically, and differences among stations were tested using the Friedman two-way nonparametric analysis of variance. In cases where significant differences existed, graphical and regression analyses were used to detect dependencies of log abundance on distance from the outfalls, distance along an east-west transect, sample depth, and sediment grain size. The latter were parameterized as the proportion of sediments larger than Phi=2 following exploratory analysis using graphical techniques and principal component analysis; this is close to the median grain size in all the data.

Diversity is a measure of the number of species in a sample, and the degree to which their abundances are evenly distributed. Traditional diversity indices are an attempt to encapsulate these characteristics in a single index, but in doing so they may lose information. Therefore we analyzed species abundance curves using graphical techniques and principal component analysis (PCA). First we plotted the relative abundance of species in each sample in order of declining relative abundance averaged over all samples. Nearly all of the patterns in these curves are contained in the mean; i.e., the differences among the individual curves were small. In addition, the variation among samples was concentrated in the most abundant taxa. Therefore we log-transformed the relative abundance values, then subtracted the mean of log-transformed values from all samples, to arrive at a series of residual curves that depicted the variation among samples.

Patterns of diversity were examined by principal component analysis on these residual curves. This gave two principal components whose values could be interpreted from their scores and plots of representative curves from the original data (Jones and Rice 1994). Box
plots of the principal component scores were then used to examine differences among stations.

The diversity figures described above do not take into account the identity of the species on each curve; for example, the most abundant species at one station may not be the same at another. To examine how the species were distributed among stations, we constructed plots of abundance of the 15 most abundant species of molluscs, and 25-30 most abundant species of polychaetes. These included most species comprising over 5% in more than one sample. Data were sorted by decreasing abundance of the mean value for all samples within a site, which gave plots similar to Figure 17. We then applied principal component and cluster analysis along with various data visualization techniques (Cleveland 1994). For molluscs, these techniques resulted in a relatively small number of variables (3-4) taken to represent the abundance of different groups of species. These variables were then examined for their proximity to the outfalls and water depth. For polychaetes, principal components were less readily interpretable, and loaded on fewer species. We therefore also examined abundance of species selected for their high abundance or because they had been identified as indicator species for sewage effects (e.g., Bailey-Brock 1995).

5.3. Results

Sample depth varied among stations and also among years at a given station (Figure 18). In particular, station 3 at Barbers Point was deeper than the other stations, while Sand Island stations were split between those with medians near 62 meters and those with medians near 73 meters; as shown below, these differences are related to some differences in organism abundance.

Sediment grain size, as indicated by the percentage of weight larger than 2 Phi units, also varied among stations and years (Figure 19). At Barbers Point, the westernmost station (7) usually had coarser sediments than the other stations. At the Sand Island site there was a trend from fine sediments toward the west to coarser sediments toward the east.
5.3.1 Abundance of Major Groups

Total abundance was examined for bivalves, gastropods, polychaetes, oligochaetes, nematodes, copepods, and amphipods (Figures 20-26). Table 4 shows the significance of Friedman tests of differences among stations, and dependence of these groups on depth, sediment grain size, distance along an east-west transect, and distance from the outfalls. Two of the groups differed significantly among stations at Barbers Point and six at Sand Island. Bivalves did not differ among stations at Barbers Point, but increased with distance from the outfall at Sand Island (Figure 20). Gastropods differed among stations at Barbers Point, but only because they were more abundant at station 1 to the east (Figure 21). Gastropod abundance declined with depth and was highest at station 2 at Sand Island; although distance from the outfall was significant in a linear model, diagnostic plots revealed this was not an appropriate model because station 1, furthest from the outfall, had a similar gastropod abundance to the near-ZID stations. Polychaetes did not differ among Barbers Point stations, or among Sand Island stations except for station 6 to the east (Figure 22). Oligochaetes were more abundant near the Sand Island outfall than far from it (Figure 23). Nematodes decreased with depth and with increasing grain size at Barbers Point. Nematodes were more abundant at the stations at and west of the ZID station at Sand Island than at the two easternmost stations, but a linear relationship did not give a good representation of this relationship. Tree-based regression split the data into two groups, one east of the outfall and the other at and west of the outfall (Figure 24; \( p<0.0001, r^2 = 0.68 \), tree regression). Copepods (Figure 25) did not vary among stations at Barbers Point, but were much more abundant near the Sand Island outfall than far from it. Amphipods (Figure 26) did not differ among stations at either site.

In summary, the patterns of abundance of some of these groups show a response to distance from the outfall at Sand Island, but in some cases the response is confounded with differences in location, depth, and sediment grain size. Oligochaetes and copepods were more abundant near the outfall than far from it, and bivalves were more abundant away from the outfall. No patterns emerged with respect to distance from the Barbers Point outfall.
5.3.2 Diversity Patterns

Figures 27-30 show the first two principal component (PC) scores for molluscs and polychaetes at the two sites. Interpretation of the PCS is somewhat different in the various figures, but the figures have been scaled so that high values on each figure represent high diversity. In all cases PC1 represents a contrast between relative abundance of the three most abundant species and relative abundance of the remaining species, especially 10-20. PC2 represents the relative abundance of species of intermediate rank, around 5-8.

Diversity of molluscs at Barbers Point differed significantly among stations for both PC1 (p<0.01) and PC2 (p<0.05). PC1 showed high diversity at control station H7 (Figure 27), but there was no apparent relation to proximity to the outfall. PC2 showed similar diversity at all stations except H1, where diversity was low.

Diversity of molluscs at Sand Island was much more heterogeneous among stations (Figure 28), and the variability persisted through years: both PCS differed significantly among stations (Friedman test, p<0.001). Stations to the east had higher values of PC1 than stations to the west, indicating reduced dominance of the most abundant species. PC2 indicates that the relative abundance of intermediate-rank species was high at B4, low at B6, and about the same at remaining stations.

Polychaete data were more heterogenous among stations and years, so that the spread of the data was greater than for molluscs. At Barbers Point (Figure 29), differences among stations were not significant, and there is no significant trend with distance for either PC. At Sand Island (Figure 30), PC1 varied significantly among stations (p<0.01), mainly because diversity at station B3 was low; PC2 did not vary significantly (p>0.1). Again, there is no apparent trend with regard to distance from the outfall.

Diversity, in terms of number of species per replicate, also did not differ in a way suggesting a sewage effect. Friedman tests showed significant differences among stations at each site in number of mollusc species (p<0.01 for both sites). There was a significant trend with distance from the outfall at Barbers Point (Figure 31; p<0.01, linear regression, $r^2 = 0.28$), but not at Sand Island, where there was a weak relationship with position along the
east-west transect \((p=0.03, r^2 = 0.11)\). The number of species was highest at station H1 at Barbers Point, and at the three easternmost stations at Sand Island including the ZID station. The result for Sand Island is similar to that for PC1 (Figure 28), suggesting a general trend toward more species and higher relative abundance of the less abundant species at these stations.

The diversity of polychaetes, as measured by number of species, varied more among years than did the number of species of molluscs. Number of polychaete species did not differ among stations at Barbers Point (Figure 32; \(p>0.1\), Friedman test), a result that was in basic agreement with the results from principal component analysis, above. At Sand Island there was a significant difference among stations \((p=0.0001\), Friedman test\). As with the principal component analysis, much of the difference among stations was due to low diversity at B3. Although a linear regression on distance from the outfall was significant \((p<0.01)\) it explained only 4% of the variance, while an analysis of variance with station as independent variable explained 32% of the variance. In either case, variances were heterogeneous so the regression results were not useful in modeling the variability in polychaete species at Sand Island.

Summary Diversity, as measured by principal component analysis on the species abundance curves or number of species, shows significant differences among stations, particularly at Sand Island. However, there is little to suggest a substantial effect of sewage discharge on diversity of either molluscs or polychaetes.

5.3.3 Species Abundance Patterns: Molluscs

Abundances at all stations within a site (Barbers Point or Sand Island) were compared using cluster analysis of the mean values of the 15 most common mollusc species for each station, and principal component analysis on the species abundances. The species abundance curves generally looked like that in Figure 17; since we were interested in the variation rather than the mean trend, we subtracted the mean trend for each site before applying principal component analysis. Of the 15 most common mollusc species at the two sites, the first eight were the same at both sites, although the rank order of abundance was slightly different.
Barbers Point: Cluster analysis of the 15 most common mollusc species (Figure 33) shows that the two most remote stations at Barbers Point were similar to each other and dissimilar from the other stations. Principal component analysis yielded four components that explained 82% of the variance in the 15 species; these are plotted against distance from the outfalls in Figure 34. The first of these was very abundant at the near-ZID stations and low at stations far from the outfall. This component was closely correlated with the abundance of *Finella pupoides*, which is considered an indicator of anaerobic conditions (Kay 1980). However, note that reducing conditions have not been found near the outfall (see section 3.1.1). The remaining components had significant spatial gradients, but were not related to proximity to the sewage outfall. Grain size and water depth were not significantly related to any of these components.

All of the top 12 species varied significantly among stations. Of these, 11 were significantly related to distance from the outfall (linear regression); three were more abundant near the outfall, and eight more abundant far from it. Although in some cases this relationship was confounded with differences in grain size, distance from the outfall was the most important independent variable for eight species.

Sand Island: In contrast to the pattern at Barbers Point, the cluster analysis for molluscs at Sand Island did not show clear separation of control and near-ZID stations (Figure 33). Rather, station B1 was very different from other stations, but most similar to B5 and Z, the ZID station.

The first four principal components explained 88% of the variance in species abundance. The first component declined from west to east and was significantly related to depth, grain size, and position along an east-west transect (p<0.001, r²=0.76, linear regression, Figure 35). This component had its greatest loading on *Finella pupoides*, which was very abundant only at station B1 to the west; several other species were either unusually abundant or rare at station B1. This result for *F. pupoides* appears to contradict that from Barbers Point, in that this species was not abundant near the Sand Island outfall (see below). The second component, highest at station B2 and moderate to low elsewhere, loaded heavily
on the three most abundant species (*Diala scopulorum, Cerithidium perparvulum, and Scaliola spp.*). Components 1 and 2 incorporate most of the separation among stations in the cluster analysis in Figure 33. The remaining components had no significant spatial gradient.

Abundance of individual species in the most-abundant group generally did not vary with distance from the outfall, or, if they varied significantly, the explanatory power of a linear model was poor (see below). Inspection of residual plots revealed violation of assumptions of linear fits to distance from the outfall. This was because, for many species, abundance differed more among stations B1, B2, and B6 than between those and the ZID stations. Furthermore, distance along an east-west transect gave a better fit than distance from the outfall, especially for those species loading heavily on PC1, above. Where slopes with distance from the outfall were significant, they were of opposite sign to that for the same species at Barbers Point.

**Common species** Several of the most common species are plotted vs. distance from the outfall in Figures 36-39. *Diala scopulorum* (Figure 36) had a significant spatial gradient and was more common near the outfall at Barbers Point, but was not significantly different near the ZID than far from it at Sand Island. In addition, abundance at the Barbers Point outfall stations was about the same as that at all Sand Island stations. *Cerithidium perparvulum* (Figure 37) was more abundant far from the Barbers Point outfall but least abundant at the most remote station at Sand Island. *Scaliola spp.* (Figure 38) had a similar pattern to *C. perparvulum*. *Finella pupoides* (Figure 39) was most variable among stations, having its highest abundance at the Barbers Point near-ZID stations and the western control station at Sand Island. For these species, examination of the data from Barbers Point, but not Sand Island, would lead one to suspect a sewage effect.

The results for molluscs appear somewhat conflicting: a strong apparent sewage signal is visible in some species (PC1) at Barbers Point, but not at Sand Island, which had larger spatial variation in abundance. Yet, Sand Island should be more heavily influenced by sewage, judging from the higher loading, lower dilution, weaker currents, clearer effect on other taxonomic groups (oligochaetes and copepods in particular; also some polychaetes, see
below), and more detectable plume (Smith and Dollar 1986, Roberts, this volume, and this report). The apparent signal at Barbers Point may be merely an artifact of the choice of sample stations, since the stations differ somewhat in depth and grain size (Figures 18 and 19), and possibly in other characteristics. This issue is discussed further below.

A remarkable result of this analysis is the coherence of spatial patterns of abundance across years. For example, *Scaliola* spp. (Figure 38) varied among stations by a factor of 16, but among years by less than two.

5.3.4 Species Abundance Patterns: Polychaetes

**Barbers Point:** The 25 most abundant species of polychaetes included all but one species comprising 5% in at least two samples; this species, *Ophryotrocha* sp. A, is discussed under indicator species below. Cluster analysis of median abundance of species by station (Figure 40) showed that station 7, the westernmost station, was the least similar to other stations; station 4 and Z, the ZID station, were similar, and station 1, the easternmost station, was similar to station 6, at the west end of the ZID.

Principal component analysis on log abundance of species showed that the first six components explained only 77% of the variance in polychaete log abundance, in contrast to the results for molluscs, above. Of these components, only the first two varied significantly among stations (Friedman test, $p<0.01$). The first component was highly loaded on *Euchone* sp. B, while the second was negatively loaded on three species, and positively loaded to a lesser extent on *Euchone* sp. B. The differences among stations for component 1 do not suggest a relationship with distance from the outfall (Figure 41). Component 2 varied significantly with distance from the outfall ($p<0.02$, $r^2 = 0.13$, Figure 41), but analysis of variance explains much more of the variance ($r^2 = 0.48$), implying that a linear model with distance as the independent variable is not suitable. In other words, for both components, there is variation among stations that is largely unexplained by distance from the outfall.

Among the 12 most abundant species, seven had abundances that differed significantly among stations (Friedman tests, Table 5). Few of these appeared to be related to spatial
gradients. The log abundance of *Synelmis acuminata* decreased from the westernmost to the easternmost station, while that of *Euchone* sp. B was low at station 7, as suggested by the principal component analysis. *Augeneriella dubia*, which loaded heavily on PC2, was most abundant near the outfall, but regression on distance from the outfall was not significant (p>0.1), and abundance at stations near the outfall was highly variable. Phyllodocidae sp. F was less abundant near the outfall than far from it, but this relationship was confounded by a dependence on sediment grain size; that is, the spatial variation could be explained about equally well by either distance or grain size.

**Sand Island** The 30 most abundant species included all but three species making up 5% in two or more samples. These three species were uncommon or absent except on a few occasions, and are not discussed further. Cluster analysis of median abundance of species by station (Figure 40) showed that the ZID station and the station immediately west of it (3) clustered together, while the more remote stations were further separated in terms of species composition. Station 5, at the eastern boundary of the ZID, was moderately close to 1, 2, and 6, and dissimilar to the ZID station.

Principal component analysis on species gave a similar result to that on Barbers Point polychaetes, with the first six components explaining 80% of the variance. The first four components differed significantly among stations (Friedman test, p=0.02 to <0.0001; Figure 42). The first component was positively loaded on three species (*Synelmis acuminata*, *Myriochele oculata*, and *Augeneriella dubia*), the second positively on *Euchone* sp. B and negatively on *Ophryotrocha* sp. A, the third negatively on Phyllodocidae sp. A and *Augeneriella dubia*, and the fourth negatively on *Euchone* sp. B and *Ophryotrocha* sp. A. Thus, component 2 represents a contrast between the latter two species while component 4 represents their common pattern.

PC1 was low at stations to the west and some near the ZID, and was positively correlated with depth (p<0.001, r² = 0.26, linear regression). Component 2 increased with distance from the outfall (p<0.0001, r² = 0.67, linear regression). PC3 was somewhat related to distance from the outfall, but this relationship differed among years, and diagnostic plots
revealed numerous negative outliers. With data from 1986 eliminated, the regression was highly significant with $r^2=0.41$; robust methods (bisquare regression, which reduces the influence of outliers) confirmed a strong relationship with distance from the outfall, with 38% of the variance explained with 1986 eliminated. Component 4 increased on a transect from west to east, and was about equally related to sediment grain size ($p=0.001$, $r^2 = 0.24$).

Among the 12 most abundant species, only Augeneriella dubia did not differ among stations (Friedman tests, Table 6). Of those with significant differences among stations, four were related to distance from the outfall (discussed below). Four species had some dependence on depth, and three had some on grain size, although at Sand Island, grain size is correlated with distance from the outfall so the effects cannot be separated.

Indicator species Bailey-Brock (1995) discusses several polychaete species as potential indicators of sewage effects. These species include Pionosyllis heterocirrata, Euchone sp. B, Capitella capitata, Ophryotrocha sp. A, and Neanthes arenaceodonta. In addition, Podarke angustifrons was reported varying between control and outfall sites in winter. Analyses were presented for Sand Island; here we compare the sites for evidence of sewage effects, as opposed to effects of grain size or other variables; we also include Phyllocodidae sp. F, which varied significantly with distance from both outfalls (Tables 5 and 6).

Of these species, Ophryotrocha sp. A and Capitella capitata showed clear signs of higher abundance near both outfalls, particularly Sand Island (Figures 43 and 44). Differences between the ZID and near-ZID stations were examined using tree regression to split the data into two parts, followed by Mann-Whitney U tests to test for significant differences. At Sand Island tree regressions split the data into values closer than or further than 1140 meters from the outfall, i.e., the control stations. Differences were significant for Ophryotrocha sp. A ($p<0.0001$) and Capitella capitata ($p=0.031$). At Barbers Point the split was at 321 meters for both species, and the differences were significant for both species ($p=0.01$). Pionosyllis heterocirrata was uncommon at the Barbers Point site, and common only in 1986 at Sand Island (Figure 45); thus, this cannot be considered an indicator of sewage pollution.
Podarke angustifrons was correlated with distance from the Sand Island outfall but not Barbers Point (Figure 46; p<0.0001, linear regression). Euchone sp. B was suppressed near the Sand Island outfall. The station at Barbers Point with the lowest median abundance was HB7, the western control station, while abundance of this species was generally higher near the outfall (Figure 47). Phyllodocidae sp. F at both stations was related to grain size and distance from the outfall (1986 appears to be an outlier, Figure 48), but the relationship was different between the two sites. When data from the two sites were combined and 1986 data from Sand Island removed, the dependence on grain size remained (p<0.0001, $r^2 = 0.33$).

These results are somewhat confounded by the correlation of distance from the outfall and grain size. At Sand Island, the lower abundance of Podarke angustifrons and Phyllodocidae sp. F and higher abundance of Euchone sp. B at stations west of the outfall could have been due to a greater proportion of fine sediments at station B1. This is supported by the regression results above, and by the relatively high abundance of the first two species and low abundance of the third at station 7 at Barbers Point, with the lowest proportion of fine sediments. Only Ophryotrocha sp. A and Capitella capitata appear have an unambiguous response to the sewage outfalls.

5.4 Discussion

There was no significant trend in sediment chemistry that could be explained as a sewage effect. However, there was an apparent effect on some taxonomic groups. Total oligochaetes and copepods were elevated, and bivalves reduced, near the Sand Island but not near the Barbers Point outfall. A few species of polychaete were more abundant near both outfalls. Several species of molluscs were elevated near the Barbers Point outfall, but comparison of their patterns with those at Sand Island, where sewage impacts should be more prominent, suggest that the somewhat higher abundances near the outfall may be due to background variability. There were also several effects of depth, sediment grain size, and distance along an east-west transect that make it difficult to determine whether sewage was having an effect.
Swartz et al. (1986) documented changes in benthic abundance and diversity near an outfall in southern California, accompanied by substantial changes in sediment chemistry. The trends in benthic species abundance in Mamala Bay are far more subtle than those observed by Swartz et al. (1986). The low coherence of species in Mamala Bay, as indicated by the relatively low explanatory power of principal components of bivalve and polychaete abundance, (Section 5.3.4), means that there is little similarity in how different species in Mamala Bay respond to different aspects of their environment. Some of these aspects are known, including distance from the outfall, depth, and sediment grain size, but in many cases large, persistent differences in abundance of different species among stations cannot be explained with the available data. Proximity to the outfall appeared to be important in relatively few cases (see previous paragraph). This implies that the sewage outfalls are having a relatively minor effect on the benthos of Mamala Bay, and that this effect is extremely localized. As expected, the effect of the outfall is considerably greater at Sand Island.

Smith and Dollar (1986) reported large microbial mats on and near the Sand Island outfall. These mats were presumably growing on nutrients and organic matter in the sewage, and in turn providing a highly localized carbon source to the benthos. This could be the source of organic matter stimulating oligochaetes, copepods, and several common species of polychaete including several indicator species. If so, it implies settling of fine organic particles discharged from, or growing on nutrients from, the sewage (Figure 1) may not be the major pathway for enrichment of the benthos. In turn that would mean that the effect of the sewage on the benthos is extremely localized.

6.0 General Discussion and Conclusions

Sediment loading to the benthos can alter the function or structure of the benthic communities in the vicinity of sewage outfalls (Swartz et al. 1986). The structure of these communities in Mamala Bay has been altered slightly; the function in terms of nutrient and carbon cycling has hardly been affected (Section 2 and Smith and Dollar 1986). Although nutrient and oxygen fluxes differ between outfall and control stations (Smith and Dollar
1986), there is no evidence of a buildup of organic sediments on the bottom, and no evidence that anaerobic metabolism in sediments is more common close to, rather than far from, the outfalls. The soft-bottom benthic community appears to be able to absorb the excess organic matter without undergoing qualitative changes in metabolism, as are seen in eutrophication.

Figure 1 showed our conceptual model of the likely pathways for sewage effects on the ecosystem of Mamala Bay. Figure 49 shows the pathways that probably operate, although at a minimum level and mainly at Sand Island. Sewage discharge enriches the water column with nutrients (Section 2.2.1). This stimulates phytoplankton growth and biomass (Laws and Ziemann 1995), but not measurably (Section 2.3). Suspended sediment increases, resulting in a slight enrichment of the sediments near the outfall with organic matter; although this is not measurable as total organic carbon or oxidation-reduction potential (Section 3), it can be observed sometimes in elevated benthic fluxes of nutrients (Smith and Dollar 1986). A handful of taxonomic groups is stimulated by the localized increase in organic loading.

Most other effects are ruled out by the analyses reported here. One exception is potential effects on pelagic animals. However, such an effect would be extremely minor and unmeasurable, given that no increase in chlorophyll concentration could be found. Effects on resident demersal communities in the vicinity of the outfalls might be found, but these would probably be overshadowed by the effects of the physical structure (see Brock 1995).

The ecosystem of Mamala Bay is far from pristine, but the causes of degradation are not the existing outfalls. Freshwater runoff, non-point source inputs, waves, storms, and purposeful and inadvertent human alteration of habitat all probably have a much greater effect on this ecosystem.

Thus, our conclusions are:

1. The Mamala Bay outfalls apparently do not provide sufficient loading of organic matter to overwhelm the processes of dissipation and oxidation in Mamala Bay.
2. The effects on benthic fauna are minor and localized, and probably confined to portions of the soft-bottom communities within ca. 500 meters of the outfalls.
3. The effects are even less prominent at Barbers Point than Sand Island.
4. Effects on bulk chemistry of sediments are nearly unmeasurable.

5. Differences in benthic community composition among sampling stations are generally much larger than the differences explainable by proximity to the outfalls, implying that the outfall effect is minor.

6. There is probably no effect of sewage discharge on coral reefs in Mamala Bay.

7.0 Recommendations

No alteration of either of the outfalls or sewage treatment plants is justifiable on the basis of ecological effects.

Since the outfalls appear benign with regard to ecological effects in Mamala Bay, there is little point in devoting much further effort to extensive monitoring of these effects. Subject to regulatory requirements, the City and County should reduce its monitoring program to a series of measurements of sediment characteristics and eliminate benthic faunal analysis from its program. The frequency of sampling for benthic chemistry should be increased to quarterly or semiannually to permit events (e.g., violations or natural occurrences) to be detected.

A major flaw in previous benthic monitoring is that the resulting data have not been kept in electronic format. For the purpose of this report we had to do considerable data entry and manipulation, duplicating previous efforts supported by the City and County. Furthermore, there has been very little synthesis of the information gathered each year at the two sites. Each annual report refers to the others, but generally there has not been much analysis; thus, much of the value of the data has been lost. Future contracts for monitoring should include requirements for archiving data in electronic format, preferably at the City and County, as well as thorough analyses of the data so that rational decisions can be made about environmental effects, and about whether to continue monitoring.
List of Tables

1. Medians and (numbers of values) of sediment chemistry variables by station and year for Barbers Point and Sand Island stations.

2. Sum and range of ranks of median values for each station among all stations within each area.

3. Percentage of samples from each station that are in the upper quartile (lower quartile for oxidation-reduction potential) of the data for each area.

4. Abundance of major taxonomic groups in Barbers Point and Sand Island samples, with significance levels of Friedman tests of differences among stations and significant (p<0.05) dependency on environmental variables for those variables that differed among stations.

5. Twelve most abundant species of polychaete in Barbers Point samples, with significance levels of Friedman tests of differences among stations and significant (p<0.05) dependency on environmental variables for those variables that differed among stations.

6. Twelve most abundant species of polychaete in Sand Island samples, with significance levels of Friedman tests of differences among stations and significant (p<0.05) dependency on environmental variables for those variables that differed among stations.
Table 1. Medians and (numbers of values) of sediment chemistry variables by station and year for Barbers Point and Sand Island stations.

**Barbers Point stations**

<table>
<thead>
<tr>
<th>Year</th>
<th>HB1</th>
<th>HB2</th>
<th>HB3</th>
<th>HB4</th>
<th>HB6</th>
<th>HB7</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxidation-reduction potential (mv)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>99 (3)</td>
<td>64 (3)</td>
<td>115 (3)</td>
<td>93 (3)</td>
<td>79 (3)</td>
<td>108 (3)</td>
<td>73 (3)</td>
</tr>
<tr>
<td>1991</td>
<td>82 (3)</td>
<td>42 (3)</td>
<td>103 (3)</td>
<td>60 (3)</td>
<td>43 (3)</td>
<td>153 (3)</td>
<td>48 (3)</td>
</tr>
<tr>
<td>1992</td>
<td>109 (5)</td>
<td>112 (3)</td>
<td>29 (3)</td>
<td>53 (3)</td>
<td>61 (3)</td>
<td>75 (3)</td>
<td>74 (3)</td>
</tr>
<tr>
<td>1993</td>
<td>115 (5)</td>
<td>45 (5)</td>
<td>78 (5)</td>
<td>72 (5)</td>
<td>52 (5)</td>
<td>92 (5)</td>
<td>54 (5)</td>
</tr>
<tr>
<td>1994</td>
<td>113 (5)</td>
<td>203 (5)</td>
<td>110 (5)</td>
<td>58 (5)</td>
<td>67 (5)</td>
<td>85 (5)</td>
<td>131 (5)</td>
</tr>
<tr>
<td>Oil and grease (mg/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>259 (3)</td>
<td>369 (3)</td>
<td>169 (3)</td>
<td>184 (3)</td>
<td>128 (3)</td>
<td>238 (3)</td>
<td>412 (3)</td>
</tr>
<tr>
<td>1991</td>
<td>286 (3)</td>
<td>408 (3)</td>
<td>216 (3)</td>
<td>187 (3)</td>
<td>206 (3)</td>
<td>405 (3)</td>
<td>278 (3)</td>
</tr>
<tr>
<td>1992</td>
<td>342 (3)</td>
<td>326 (4)</td>
<td>245 (3)</td>
<td>174 (4)</td>
<td>129 (4)</td>
<td>160 (3)</td>
<td>169 (5)</td>
</tr>
<tr>
<td>1993</td>
<td>134 (5)</td>
<td>142 (5)</td>
<td>197 (4)</td>
<td>178 (4)</td>
<td>270 (4)</td>
<td>252 (3)</td>
<td>158 (4)</td>
</tr>
<tr>
<td>1994</td>
<td>184 (3)</td>
<td>106 (3)</td>
<td>185 (3)</td>
<td>339 (3)</td>
<td>262 (3)</td>
<td>296 (3)</td>
<td>179 (3)</td>
</tr>
<tr>
<td>Total organic carbon (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>0.14 (1)</td>
<td>0.26 (2)</td>
<td>0.08 (1)</td>
<td>0.33 (1)</td>
<td>0.16 (1)</td>
<td>0.04 (1)</td>
<td>0.24 (1)</td>
</tr>
<tr>
<td>1991</td>
<td>0.25 (3)</td>
<td>0.12 (2)</td>
<td>0.22 (3)</td>
<td>0.16 (2)</td>
<td>0.22 (3)</td>
<td>0.21 (3)</td>
<td>0.20 (2)</td>
</tr>
<tr>
<td>1992</td>
<td>0.3 (3)</td>
<td>0.46 (3)</td>
<td>0.44 (3)</td>
<td>0.16 (3)</td>
<td>0.36 (3)</td>
<td>0.44 (3)</td>
<td>0.38 (3)</td>
</tr>
<tr>
<td>1993</td>
<td>0.97 (3)</td>
<td>1.1 (3)</td>
<td>0.63 (3)</td>
<td>0.8 (3)</td>
<td>1.5 (3)</td>
<td>0.6 (3)</td>
<td>0.90 (3)</td>
</tr>
<tr>
<td>1994</td>
<td>0.3 (3)</td>
<td>0.3 (3)</td>
<td>0.19 (3)</td>
<td>0.18 (3)</td>
<td>0.24 (3)</td>
<td>0.12 (3)</td>
<td>0.16 (3)</td>
</tr>
</tbody>
</table>

**Sand Island stations**

<table>
<thead>
<tr>
<th>Year</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>B5</th>
<th>82</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxidation-reduction potential (mv)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1987</td>
<td>115 (3)</td>
<td>100 (3)</td>
<td>25 (3)</td>
<td>125 (1)</td>
<td>61 (1)</td>
<td>48 (3)</td>
<td>60 (3)</td>
</tr>
<tr>
<td>1990</td>
<td>24 (3)</td>
<td>31 (3)</td>
<td>58 (3)</td>
<td>43 (1)</td>
<td>45 (1)</td>
<td>40 (3)</td>
<td>41 (3)</td>
</tr>
<tr>
<td>1991</td>
<td>36 (3)</td>
<td>22 (3)</td>
<td>43 (3)</td>
<td>44 (1)</td>
<td>50 (1)</td>
<td>52 (3)</td>
<td>44 (3)</td>
</tr>
<tr>
<td>1992</td>
<td>72 (3)</td>
<td>52 (3)</td>
<td>98 (3)</td>
<td>117 (3)</td>
<td>150 (3)</td>
<td>132 (3)</td>
<td>107 (3)</td>
</tr>
<tr>
<td>1993</td>
<td>65 (3)</td>
<td>134 (3)</td>
<td>154 (3)</td>
<td>161 (3)</td>
<td>98 (3)</td>
<td>58 (3)</td>
<td>82 (3)</td>
</tr>
<tr>
<td>Oil and grease (mg/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>329 (3)</td>
<td>378 (3)</td>
<td>326 (3)</td>
<td>285 (1)</td>
<td>338 (1)</td>
<td>285 (3)</td>
<td>320 (3)</td>
</tr>
<tr>
<td>1991</td>
<td>75 (3)</td>
<td>182 (3)</td>
<td>219 (3)</td>
<td>219 (1)</td>
<td>222 (1)</td>
<td>226 (3)</td>
<td>340 (3)</td>
</tr>
<tr>
<td>1992</td>
<td>793 (3)</td>
<td>1000 (3)</td>
<td>1280 (3)</td>
<td>961 (1)</td>
<td>812 (1)</td>
<td>814 (3)</td>
<td>1220 (3)</td>
</tr>
<tr>
<td>1993</td>
<td>188 (3)</td>
<td>222 (3)</td>
<td>426 (3)</td>
<td>214 (1)</td>
<td>254 (1)</td>
<td>396 (3)</td>
<td>222 (3)</td>
</tr>
<tr>
<td>Total organic carbon (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1991</td>
<td>0.02 (3)</td>
<td>0.09 (3)</td>
<td>0.05 (3)</td>
<td>0.07 (1)</td>
<td>0.18 (1)</td>
<td>0.02 (3)</td>
<td>0.02 (3)</td>
</tr>
<tr>
<td>1992</td>
<td>0.14 (3)</td>
<td>0.56 (3)</td>
<td>0.53 (3)</td>
<td>0.41 (1)</td>
<td>0.46 (1)</td>
<td>0.23 (3)</td>
<td>0.28 (3)</td>
</tr>
<tr>
<td>1993</td>
<td>0.13 (3)</td>
<td>0.08 (3)</td>
<td>0.08 (3)</td>
<td>0.11 (1)</td>
<td>0.1 (1)</td>
<td>0.17 (3)</td>
<td>0.26 (3)</td>
</tr>
<tr>
<td>Total Kjeldahl nitrogen (mg/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>242 (3)</td>
<td>266 (3)</td>
<td>282 (3)</td>
<td>327 (1)</td>
<td>282 (1)</td>
<td>243 (3)</td>
<td>368 (3)</td>
</tr>
<tr>
<td>1991</td>
<td>236 (3)</td>
<td>238 (3)</td>
<td>228 (3)</td>
<td>301 (1)</td>
<td>178 (1)</td>
<td>160 (3)</td>
<td>252 (3)</td>
</tr>
<tr>
<td>1992</td>
<td>243 (3)</td>
<td>271 (3)</td>
<td>261 (3)</td>
<td>251 (1)</td>
<td>322 (1)</td>
<td>257 (3)</td>
<td>247 (3)</td>
</tr>
<tr>
<td>1993</td>
<td>197 (3)</td>
<td>212 (3)</td>
<td>205 (3)</td>
<td>180 (1)</td>
<td>245 (1)</td>
<td>184 (3)</td>
<td>192 (3)</td>
</tr>
</tbody>
</table>
Table 2. Sum and range of ranks (1 is smallest) of median values for each station among all stations within each area. The expected value for the sum of ranks is the total number of values at the bottom of each column; a high value for the sum of ranks indicates that the median value for that station was frequently higher than those for other stations. Note that high values may be associated with sewage impacts except for ORP, for which low values would indicate sewage effects.

<table>
<thead>
<tr>
<th>Station</th>
<th>Distance from Outfall (meters)</th>
<th>Oxidation-Reduction Potential</th>
<th>Oil and Grease</th>
<th>Total Organic Carbon</th>
<th>Kjeldahl Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barbers Point</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HB7</td>
<td>-3802</td>
<td>28 (5-7)</td>
<td>21 (1-7)</td>
<td>23.5 (2-7)</td>
<td></td>
</tr>
<tr>
<td>HB6</td>
<td>-798</td>
<td>17 (1-7)</td>
<td>22 (1-7)</td>
<td>26.5 (1-7)</td>
<td></td>
</tr>
<tr>
<td>HB4</td>
<td>-299</td>
<td>23 (1-7)</td>
<td>19 (2-5)</td>
<td>19 (2-6)</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>0</td>
<td>15 (1-4)</td>
<td>19 (1-7)</td>
<td>16 (1-7)</td>
<td></td>
</tr>
<tr>
<td>HB3</td>
<td>57</td>
<td>12 (2-3)</td>
<td>16 (1-7)</td>
<td>24.5 (3-7)</td>
<td></td>
</tr>
<tr>
<td>HB2</td>
<td>343</td>
<td>27 (3-7)</td>
<td>24 (2-6)</td>
<td>12.5 (1-6)</td>
<td></td>
</tr>
<tr>
<td>HB1</td>
<td>3733</td>
<td>18 (2-6)</td>
<td>19 (2-7)</td>
<td>18 (2-5)</td>
<td></td>
</tr>
<tr>
<td>Number of values</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand Island</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>-2657</td>
<td>13 (1-6)</td>
<td>8 (1-5)</td>
<td>8 (1-5)</td>
<td>10 (1-4)</td>
</tr>
<tr>
<td>B2</td>
<td>-2032</td>
<td>14 (1-5)</td>
<td>17.5 (2-7)</td>
<td>14.5 (2-7)</td>
<td>20 (3-6)</td>
</tr>
<tr>
<td>B3</td>
<td>-642</td>
<td>20 (1-7)</td>
<td>21.5 (4-7)</td>
<td>11.5 (2-6)</td>
<td>17.5 (3-5)</td>
</tr>
<tr>
<td>B4</td>
<td>-560</td>
<td>28.5 (5-7)</td>
<td>11 (2-4)</td>
<td>13 (4-5)</td>
<td>17 (1-7)</td>
</tr>
<tr>
<td>BZ</td>
<td>0</td>
<td>27 (4-7)</td>
<td>18 (2-6)</td>
<td>15 (3-7)</td>
<td>20.5 (2-7)</td>
</tr>
<tr>
<td>B5</td>
<td>551</td>
<td>19 (1-7)</td>
<td>16.5 (2-6)</td>
<td>10 (2-6)</td>
<td>9 (1-4)</td>
</tr>
<tr>
<td>B6</td>
<td>1639</td>
<td>18.5 (3-5)</td>
<td>19.5 (3-7)</td>
<td>12 (2-7)</td>
<td>18 (2-7)</td>
</tr>
<tr>
<td>Number of values</td>
<td>20</td>
<td>16</td>
<td>12</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Percentage of samples from each station that are in the upper quartile (lower quartile for oxidation-reduction potential) of the data for each area. The expected value in all cases is approximately 25%. Differences were significant (p<0.01) for redox potential at both areas where data were aggregated into 3 subareas: <100m, 100-1000m, and >1000m from the diffuser. Differences for other variables were not significant (Chi-square test, p>0.1)

<table>
<thead>
<tr>
<th>Distance from Outfall (meters)</th>
<th>Station</th>
<th>Oxidation-Reduction Potential</th>
<th>Oil and Grease</th>
<th>Total Organic Carbon</th>
<th>Kjeldahl Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Barbers Point</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HB7</td>
<td>-3802</td>
<td>5%</td>
<td>18%</td>
<td>38%</td>
<td></td>
</tr>
<tr>
<td>HB6</td>
<td>-798</td>
<td>47%</td>
<td>44%</td>
<td>46%</td>
<td></td>
</tr>
<tr>
<td>HB4</td>
<td>-299</td>
<td>16%</td>
<td>19%</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>0</td>
<td>26%</td>
<td>17%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>HB3</td>
<td>57</td>
<td>42%</td>
<td>18%</td>
<td>17%</td>
<td></td>
</tr>
<tr>
<td>HB2</td>
<td>343</td>
<td>47%</td>
<td>24%</td>
<td>31%</td>
<td></td>
</tr>
<tr>
<td>HB1</td>
<td>3733</td>
<td>11%</td>
<td>33%</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td><strong>Number of samples</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>15-18</td>
<td>12-13</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sand Island</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>-2657</td>
<td>67%</td>
<td>8%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>B2</td>
<td>-2032</td>
<td>53%</td>
<td>0%</td>
<td>33%</td>
<td>33%</td>
</tr>
<tr>
<td>B3</td>
<td>-642</td>
<td>27%</td>
<td>50%</td>
<td>11%</td>
<td>17%</td>
</tr>
<tr>
<td>B4</td>
<td>-560</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>50%</td>
</tr>
<tr>
<td>BZ</td>
<td>0</td>
<td>13%</td>
<td>33%</td>
<td>33%</td>
<td>42%</td>
</tr>
<tr>
<td>B5</td>
<td>551</td>
<td>0%</td>
<td>0%</td>
<td>33%</td>
<td>50%</td>
</tr>
<tr>
<td>B6</td>
<td>1639</td>
<td>33%</td>
<td>25%</td>
<td>22%</td>
<td>8%</td>
</tr>
<tr>
<td><strong>Number of samples</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9-15</td>
<td>4-12</td>
<td>3-9</td>
<td>4-12</td>
<td></td>
</tr>
</tbody>
</table>
Table 4. Abundance of major taxonomic groups in Barbers Point and Sand Island samples, with significance levels of Friedman tests of differences among stations and significant ($p<0.05$) dependency on environmental variables for those variables that differed among stations.

<table>
<thead>
<tr>
<th>Taxonomic group</th>
<th>Friedman p value</th>
<th>Dependencies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Barbers Point</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bivalves</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Gastropods</td>
<td>0.004</td>
<td>Easternmost station higher than the others; no significant difference among the other stations</td>
</tr>
<tr>
<td>Polychaetes</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Oligochaetes</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Nematodes</td>
<td>0.03</td>
<td>Depth, grain size</td>
</tr>
<tr>
<td>Copepods</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>Amphipods</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td><strong>Sand Island</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bivalves</td>
<td>0.003</td>
<td>Increase with distance from outfall, $r^2 = 0.32$</td>
</tr>
<tr>
<td>Gastropods</td>
<td>$&lt;0.001$</td>
<td>Decline with depth, $r^2 = 0.23$; most of the variance among stations unexplained</td>
</tr>
<tr>
<td>Polychaetes</td>
<td>0.005</td>
<td>Easternmost station lower than the others; no significant difference among the other stations</td>
</tr>
<tr>
<td>Oligochaetes</td>
<td>0.007</td>
<td>Decline with distance from outfall, $r^2 = 0.42$</td>
</tr>
<tr>
<td>Nematodes</td>
<td>0.008</td>
<td>Distance along transect, tree regression, $r^2 = 0.68$</td>
</tr>
<tr>
<td>Copepods</td>
<td>0.004</td>
<td>Declines with distance from outfall, $r^2 = 0.43$</td>
</tr>
<tr>
<td>Amphipods</td>
<td>0.06</td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Twelve most abundant species of polychaete in Barbers Point samples, with significance levels of Friedman tests of differences among stations and significant (p<0.05) dependency on environmental variables for those variables that differed among stations.

<table>
<thead>
<tr>
<th>Species</th>
<th>Friedman p value</th>
<th>Dependencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synelmis acuminata</td>
<td>0.005</td>
<td>Declines west to east, $r^2 = 0.18$</td>
</tr>
<tr>
<td>Myriochele oculata</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>Phyllodocidae sp. F</td>
<td>0.02</td>
<td>Grain size or distance from outfall, $r^2 = 0.17$</td>
</tr>
<tr>
<td>Prionospio cirrobranchiata</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Podarke angustifrons</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Euchone sp. B</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>Nereimyra sp. A</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Prionospio cirrifica</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>Augeneriella dubia</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Fabricia sp. A</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Nereis sp. B</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Amphicteis gunneri</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>
Table 6. Twelve most abundant species of polychaete in Sand Island samples, with significance levels of Friedman tests of differences among stations and significant (\(p<0.5\)) dependency on environmental variables for those variables that differed among stations.

<table>
<thead>
<tr>
<th>Species</th>
<th>Friedman p value</th>
<th>Dependencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phyllodocidae sp. F</td>
<td>0.007</td>
<td>Distance from outfall and grain size, (r^2 = 0.40, 0.85) of 1986 eliminated</td>
</tr>
<tr>
<td><em>Podarke angustifrons</em></td>
<td>0.0001</td>
<td>Distance from outfall, (r^2 = 0.61)</td>
</tr>
<tr>
<td><em>Synelmis acuminata</em></td>
<td>0.006</td>
<td>Depth, (r^2 = 0.21)</td>
</tr>
<tr>
<td><em>Myriochele oculata</em></td>
<td>0.001</td>
<td>Depth, (r^2 = 0.35)</td>
</tr>
<tr>
<td><em>Prionospio cirrobranchiata</em></td>
<td>0.02</td>
<td>Grain size, (r^2 = 0.11)</td>
</tr>
<tr>
<td><em>Augeneriella dubia</em></td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td><em>Prionospio cirrifer</em></td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td><em>Nereimyra</em> sp. A</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td><em>Euchone</em> sp. B</td>
<td>0.0001</td>
<td>Distance from outfall (positive) and grain size, (r^2 = 0.65)</td>
</tr>
<tr>
<td><em>Ophryotrocha</em> sp. A</td>
<td>0.0002</td>
<td>Distance from outfall, (r^2 = 0.40), but better modeled as step function</td>
</tr>
<tr>
<td><em>Sphaerosyllis taylori</em></td>
<td>0.002</td>
<td>Depth, (r^2 = 0.24)</td>
</tr>
<tr>
<td><em>Naineris</em> sp. A</td>
<td>0.007</td>
<td>Depth, (r^2 = 0.10)</td>
</tr>
</tbody>
</table>
List of Figures and Figure Legends

Figure 1. Conceptual model of potential causative pathways for sewage effects on biota in Mamala Bay. Heavy boxes indicate pathways originating from sediment deposition on the bottom. Double boxes indicate pathways of potential effects on reefs, while single boxes represent effects in the water column. Heavy lines indicate pathways that clearly operate in Mamala Bay, dotted lines indicate pathways that clearly do not operate, and single lines indicate pathways that could operate, and that are considered in this report. Pathways involving anthropogenic toxicants are explicitly excluded.

Figure 2. Map showing sampling stations in relation to the outfall pipe at Barbers Point (panel a) and Sand Island (panel b).

Figure 3. Boxplots showing ammonium concentration at three depth ranges and four distance categories at Barbers Point (A-C) and Sand Island (D-F). Depth ranges are: A, D: 0-15 meters; B, E 25-30 meters; C, F 50-60 meters. Distance categories are 0-100, 100-600, 1000-4000, and 5000-7000 meters at Barbers Point and 0-100, 100-200, 1000-2000, and 5000 meters at Sand Island. Boxes show the median as a horizontal bar, and first and third quartiles are the ends of the box. Dotted lines connect boxes with points that are the closer to the median of the extreme value or 1.5 times the interquartile range. Points outside 1.5 times the interquartile range are indicated by horizontal lines.

Figure 4. Ammonium concentration data. Proportion of data from each station that was in the upper quartiles of data for each year, vs. distance from the diffuser (meters, log scale). The expected proportion overall is 0.25. Straight lines are linear regressions (both significant at p<0.0001); open symbols are for stations west of the diffuser, and solid symbols east of the diffuser.

Figure 5. Boxplots showing phosphate concentration at two depth ranges and four distance categories at Barbers Point. A, 0-15 meters; B, 25-30 meters.

Figure 6. Boxplots of total nitrogen (A, C) and total phosphorus (B, D) concentrations vs. distance and depth categories as in Figure 5.

Figure 7. Boxplots of turbidity (A, C) and suspended solid concentration (B, D) vs. distance and depth categories as in Figure 5.
Figure 8. Boxplots of chlorophyll concentrations vs. distance and depth categories as in Figure 5.

Figure 9. Boxplots of sediment oxidation-reduction potential (ORP) at stations in the two areas for all years. Stations are arranged geographically from west (left) to east (right).

Figure 10. Frequency histograms of oxidation-reduction potential for Barbers Point (top) and Sand Island (bottom) for all stations and years.

Figure 11. Frequency histograms of oil and grease in sediments from Barbers Point (top) and Sand Island (bottom) for all stations and years. Data from Sand Island for 1992 had a median of 965 and a range of 726-1370, and are represented by the single bar.

Figure 12. Frequency histograms of percent organic carbon by weight for Barbers Point (top) and Sand Island (bottom) for all stations and years.

Figure 13. Boxplot of total Kjeldahl nitrogen at stations in the Sand Island area for all years. Symbols as in Figure 2.

Figure 14. Diagram of simple model of sewage dispersal and sedimentation of fine particles. The plan view shows how the edge of the plume disperses in a time-averaged sense; the side view illustrates how particles settle out of the plume as it disperses.

Figure 15. Particle settling data and curves representing the best-fit model and alternative models with values of b that enclose most of the points.

Figure 16. Results of particle-settling model. The upper figure gives the distance from the outfall over which the particles settle at the flux shown in the lower figure, for the base model run and with several alternative values of parameters.

Figure 17. Abundance curve for Sand Island polychaetes. The line gives the mean log abundance of the 20 most abundant species in order of declining abundance; error bars display the range of values in all samples.

Figure 18. Boxplot of mean depths at stations at Barbers Point and Sand Island, arranged from west to east.
Figure 19. Boxplot of percent of sediments with grain size larger than Phi=2 at stations at Barbers Point and Sand Island, arranged from west to east.

Figure 20. Boxplots of abundance of bivalves at stations at Barbers Point and Sand Island, arranged from west to east.

Figure 21. Boxplots of abundance of gastropods at stations at Barbers Point and Sand Island, arranged from west to east.

Figure 22. Boxplots of abundance of polychaetes at stations at Barbers Point and Sand Island, arranged from west to east.

Figure 23. Boxplots of abundance of oligochaetes at stations at Barbers Point and Sand Island, arranged from west to east.

Figure 24. Boxplots of abundance of nematodes at stations at Barbers Point and Sand Island, arranged from west to east.

Figure 25. Boxplots of abundance of copepods at stations at Barbers Point and Sand Island, arranged from west to east.

Figure 26. Boxplots of abundance of amphipods at stations at Barbers Point and Sand Island, arranged from west to east.

Figure 27. Boxplot of first two principal component scores for diversity of molluscs at Barbers Point. The signs of both sets of scores have been reversed so that high values represent high diversity.

Figure 28. Boxplot of first two principal component scores for diversity of molluscs at Sand Island. The sign of PC2 has been reversed so that high values represent high diversity.

Figure 29. Boxplot of first two principal component scores for diversity of polychaetes at Barbers Point. The sign of PC2 has been reversed so that high values represent high diversity.

Figure 30. Boxplot of first two principal component scores for diversity of polychaetes at Sand Island.

Figure 31. Boxplot of mean number of mollusc species per replicate at Barbers Point and Sand Island.
Figure 32. Boxplot of mean number of polychaete species per replicate at Barbers Point and Sand Island.

Figure 33. Cluster diagrams showing Euclidean distance among stations based on mean values of log of 15 most abundant mollusc spp. Top, Barbers Point, bottom, Sand Island.

Figure 34. First 4 principal components of Barbers Point molluscs based on log abundance of top 15 species, plotted against distance from the outfalls. The line connects median values for each station.

Figure 35. First 4 principal components of Sand Island molluscs based on log abundance of top 15 species, plotted against distance from the outfalls. The line connects median values for each station.

Figure 36. Log abundance of the mollusc *Diala scopulorum* at Barbers Point and Sand Island, vs. distance from the outfalls. Distance has been jittered by the addition of a small random number to make all points visible.

Figure 37. Log abundance of the mollusc *Cerithidium perparvulum*. Distance has been jittered by the addition of a small random number to make all points visible.

Figure 38. Log abundance of the mollusc *Scaliola* spp. Distance has been jittered by the addition of a small random number to make all points visible.

Figure 39. Log abundance of the mollusc *Finella pupoides*. Distance has been jittered by the addition of a small random number to make all points visible.

Figure 40. Cluster diagrams showing Euclidean distance among stations based on mean values of log of 15 most abundant polychaete spp. Top, Barbers Point, bottom, Sand Island.

Figure 41. First 4 principal components of Barbers Point polychaetes based on log abundance of top 15 species, plotted against distance from the outfalls. The line connects median values for each station.

Figure 42. First 4 principal components of Sand Island polychaetes based on log abundance of top 15 species, plotted against distance from the outfalls. The line connects median values for each station.
Figure 43. Polychaete indicator spp: log abundance of *Ophryotrocha* sp. at Barbers Point and Sand Island, vs. distance from the outfalls. Distance has been jittered by the addition of a small random number to make all points visible.

Figure 44. Log abundance of the polychaete *Capitella capitata*. Distance has been jittered by the addition of a small random number to make all points visible.

Figure 45. Log abundance of the polychaete *Pionosyllis heterocirrata*. Distance has been jittered by the addition of a small random number to make all points visible.

Figure 46. Log abundance of the polychaete *Podarke angustifrons*. Distance has been jittered by the addition of a small random number to make all points visible.

Figure 47. Log abundance of the polychaete *Euchone* sp. B. Distance has been jittered by the addition of a small random number to make all points visible.

Figure 48. Log abundance of the polychaete Phyllodocidae sp. F. Distance has been jittered by the addition of a small random number to make all points visible.

Figure 49. Conceptual model of causative pathways for sewage effects on biota in Mamala Bay. This figure is identical to Figure 1 except that pathways known or believed to operate at some level are shown in black, while those that probably do not operate in Mamala Bay are shown in gray.
Stimulation of phytoplankton/heterotrophs

Stimulation of benthic algae

Reduction of reef calcification

Inundation of benthos including reefs

Enrichment of bottom sediments

Anoxia or hypoxia in water column

Shading or overgrowth of reef

Degradation of reef

Alteration of sediment chemistry

Suppression of all or most pelagic and benthic species

Stimulation of opportunistic species

Suppression of sensitive species

Stimulation of opportunistic species

Anoxia in surface sediment

Reduction in pelagic diversity

Reduction in benthic diversity

Suppression of most benthic species

FIGURE 1
FIGURE 2. MAMALA BAY SAMPLING SITES
Distance Category
Barbers Point

Distance from outfall (m)

Proportion of NH₄ data in upper quartile

Sand Island

Distance from outfall (m)
FIGURE 5

Distance Category

Phosphate (µg-at/l)

A

B
Barbers Point

Chlorophyll concentration (μg/l)

Distance Category

Sand Island

Distance Category

FIGURE 8
FIGURE 10

Oxidation-Reduction Potential, mv

Sand Island

Frequency

Barbers Point

Frequency
FIGURE 11

Barbers Point

Sand Island 1992

Frequency

Oil and grease, mg/kg

C:\ALL\MA\ EA\RPT\MB10WJK.PPT FIG 11
**FIGURE 12**

Barbers Point

Total organic carbon, weight %

Sand Island

Total organic carbon, weight %

C:\ALL\MAMEA\RPT\MB10WJK.PPT FIG 12
Sediment flux model

Plume expands at velocity $U$

Plume height $H$ above bottom

Outfall Pipe

Edge of plume

Plume diameter $r$

Particle settling

Plan View

Side View

FIGURE 14
FIGURE 15

Percent of mass settled vs. Time (s).

- Data
- Best-fit model, b = 106
- Model, b = 89
- Model, b = 154

Time (h) on a logarithmic scale from 0.0001 to 10.
Mean depth, meters

Barbers Point

Sand Island

Station

FIGURE 18
Percent Larger than 2 Phi

Station

Barbers Point

Sand Island

H7 H6 H4 HZ H3 H2 H1

B1 B2 B3 B4 Z B5 B6

FIGURE 19
Abundance (per sample)

Station

A

Station

B
Principal Component Loadings

B1 B2 B3 B4 B5 B6

PC1

B1 B2 B3 B4 B5 B6

PC2

Station

Station
Principal Component Loadings

PC1

PC2

Station
Principal Component Loadings

Station

PC1

PC2

FIGURE 30
Mean number of species

Station

Barbers Point

Sand Island

Figure 31
Barbers Point

Sand Island

Mean number of species

Station

H7 H6 H4 HZ H3 H2 H1

Station

B1 B2 B3 B4 Z B5 B6
FIGURE 33

Euclidean distance
Figure 34

Distance from Diffuser, Km

Principal Component Scores

PC1

PC2

PC3

PC4
Log$_{10}$ Abundance (per sample)

Distance (km)

Barbers Point

Sand Island

FIGURE 37
Figure 38

Sand Island

Barbers Point

Distance (km)

Log_{10} Abundance (per sample)
Barbers Point

Sand Island

Log$_{10}$ Abundance (per sample)

Distance (km)

Distance (km)
FIGURE 40

Euclidean distance
Barbers Point

Sand Island

\[ \log_{10} \text{Abundance (per sample)} \]

Distance (km)

Distance (km)

FIGURE 43
Sand Island

Barbers Point

Distance (km)

Log^{10} Abundance (per sample)
Barbers Point

Sand Island

Distance (km)

Distance (km)

Log_{10} Abundance (per sample)

FIGURE 45
**Figure 46**

- **Sand Island**
- **Barbers Point**

Log$_{10}$ Abundance (per sample) vs. Distance (km)
FIGURE 48

Barbers Point

Sand Island

Log$_{10}$ Abundance (per sample)

Distance (km) Distance (km)
Sewage discharge

- Nutrients/organic matter
  - Stimulation of phytoplankton/heterotrophs
    - Inundation of benthos including reefs
    - Enrichment of bottom sediments
  - Reduction of benthic algae
  - Reduction of reef calcification
- Suspended sediment
  - Alteration of sediment chemistry
- Degradation of reef
  - Suppression of sensitive species
  - Stimulation of opportunistic species
- Shading or overgrowth of reef
  - Suppression of all or most pelagic and benthic species
  - Stimulation of opportunistic species
- Anoxia or hypoxia in water column
  - Reduction in pelagic diversity
  - Suppression of most benthic species