MAMALA BAY STUDY

IMPACT OF POINT AND NON-POINT SOURCE POLLUTION ON CORAL REEF ECOSYSTEMS IN MAMALA BAY

PROJECT MB-9

Principal Investigator:

Richard W. Grigg

Department of Oceanography

1000 Pope Road

University of Hawaii

Honolulu, HI 96822

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1 EXECUTIVE SUMMARY

The effects of both point and non-point sources of pollution on coral reef ecosystems in Mamala Bay were studied at three levels of biological organization; the cell, the population and the community. The results show a uniform lack of negative environmental impact. Calcification and growth show no relation to point or non-point sources of pollution within the bay. Neither do species abundance patterns, diversity or community structure. Changes in water quality caused by rainfall and wave events are too small and too short lived to affect coral reef ecosystems in the bay. Species abundance patterns and community structure of coral ecosystems in the bay appear to be related to the effects of large hurricane wave events in 1982 (Iwa) and 1992 (Iniki). Recovery of coral reef ecosystems in Mamala Bay is now taking place from damage sustained during and after these storms, and from an earlier period of severe environmental degradation prior to 1977 when raw sewage was discharged into the bay at 13 m depth off Sand Island. Not withstanding future disturbances, existing sources of point and non-point source pollution are not expected to interfere with the recovery process now ongoing in Mamala Bay, and long-term biological processes should eventually return the coral ecosystem to a more mature successional stage.

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2 INTRODUCTION

The purpose of the Mamala Bay Study is to develop an Integrated Coastal Management Plan in order to protect the environment and public health of this unique embayment off leeward Oahu in the Hawaiian Islands. Having resulted from a Consent Decree of the United States District Court in Honolulu, Hawaii, the study called specifically for: 1) An analysis of point and non-point source discharges into Mamala Bay, 2) A determination of the effects of these discharges on water quality, ecosystems and public health, and 3) A management plan to reduce pollution and improve water quality in the bay. The study was divided into twelve sub-projects. This report presents the results of one part of MB-9 which dealt with ecosystem response and was charged with identifying pollution impacts on target or receptor aquatic species in the water column and benthic environments.

Coral reef ecosystems were chosen for study in this project for the following reasons:

1) Coral reef ecosystems are known to be sensitive to environmental stress and therefore serve as excellent indicators of pollution as well as natural environmental variability (Brown and Howard, 1985). Corals are particularly sensitive to excess nutrient loading, suspended sediment, turbidity and sedimentation (Pastorok and Bilyard, 1985).

2) Coral reef ecosystems are present, although not uniformly, all along the shallow nearshore insular shelf bordering Mamala Bay from Diamond Head to Barber's Point (AECOS, 1979). Their nearshore location helped to evaluate potential impact from non-point source pollutants contained in land runoff, and the degree to which outfall plumes might reach and affect nearshore environments.

3) Corals are foundation species that support the overall benthic reef ecosystem including numerous resources of economic and recreational importance.

4) Because corals are sessile and long lived, their growth and survival serve as an integrated measure or proxy of environmental impact over long periods of time (decades).

Hence, the aim of this study is to use coral reef ecosystems to quantify impacts, if any, caused by point source wastewater disposal off Sand Island and Ewa Beach and non-point source runoff from land and via Pearl Harbor and the Ala Wai Canal. The research was designed to complement other studies within MB-9 dealing with infaunal communities on soft bottoms, algal and fish communities, recruitment processes, water column communities, bacterial biomass, primary production and water quality.

2.1 Scope of work

This project was divided into two parts; one dealing with the potential impacts of point and non-point discharges on coral ecosystems in the bay at the present time (1993-94), and the other, with historical events (impact) during the past 30 years. The study of present coral communities consisted of a gradient analysis of coral abundance, community structure and growth of dominant species as a function of proximity or distance from sources of point and non-point discharges and a correlation analysis of water quality (salinity, PO_4, NO_3, NH_4, Si-SiO_3, turbidity, and chlorophyll-a) at the surface and bottom at all stations during normal (baseline) and episodic events (high waves, heavy rainfall and runoff). Sedimentation was also analyzed at representative stations.

The second part of the study was a retrospective analysis of the past 30 years using the growth rates and bioerosion rates of corals (Porites lobata) as a measure of potential point and non-point impacts. During this time frame, the existing sewage treatment plants at Sand Island and Honouliuli were built. In 1977, the discharge off Sand Island was diverted from about 13 m depth to 73 m and 2743 m offshore, and the treatment was changed from none (raw sewage) to advanced primary. The Sand Island discharge volume is presently about 70 MGD. The Honouliuli treatment plant was built

in 1982 and began discharging advanced primary treated effluent (~25 MGD) at a depth of 65 m in the same year. An attempt was made to find and collect coral colonies near these outfalls that exceeded the age of the outfalls, in order to determine if the initiation of the discharges had any effect on growth and bioerosion.

An existing data set collected off Sand Island by R.W. Grigg in 1975 before the raw sewage was diverted into deeper water was also used to interpret the results of the study. Other anecdotal observations regarding the impacts of Hurricanes Iwa and Iniki on coral reef ecosystems in Mamala Bay in 1982 and 1992, respectively, were also taken into account.

2.2 Objectives

The major objectives of this work are twofold; first, to quantify impacts or changes in coral ecosystem dynamics and water quality in Mamala Bay related to point source (sewer outfall discharges) and non-point (Pearl Harbor, Ala Wai Canal and land) sources of pollution, and second, to assess the effects of both natural and anthropogenic events on coral ecosystems in the bay during the past 30 years.

2.3 Project organization

Principal investigator - Richard W. Grigg, University of Hawaii, Department of Oceanography, responsible for design, organization, operation and completion of the study including writing of the final report.

Research Assistant- Brad Gould, Graduate Student, Department of Oceanography, University of Hawaii, responsible for collection and analysis of all water quality data, and completion of Master's Thesis Dissertation.

Dennis Pesch, Research Assistant, responsible for sclerochronology and densitometry of collected corals.

3 METHODS

3.1 Task Summary

Since the research design of the study was based on gradient analysis (effects of distance or time on data), the selection of stations was exceedingly important. This could have been done arbitrarily at regular and even distances away from point or non-point sources of pollution. However, other factors such as depth and substratum type are not uniformly or regularly distributed in Mamala Bay preventing this simple approach. Rather, an attempt was made to census the entire bay in order to obtain a qualitative understanding of the pattern of distribution of coral reefs and their condition, from Diamond Head to near Barber's Point. A tow survey was conducted in which a diver operated sled was used to census 24 kilometers of coastline at depths between 5 and 15 meters depth. Based on this survey, 16 stations were selected, 5 along the 6.5 m isobath

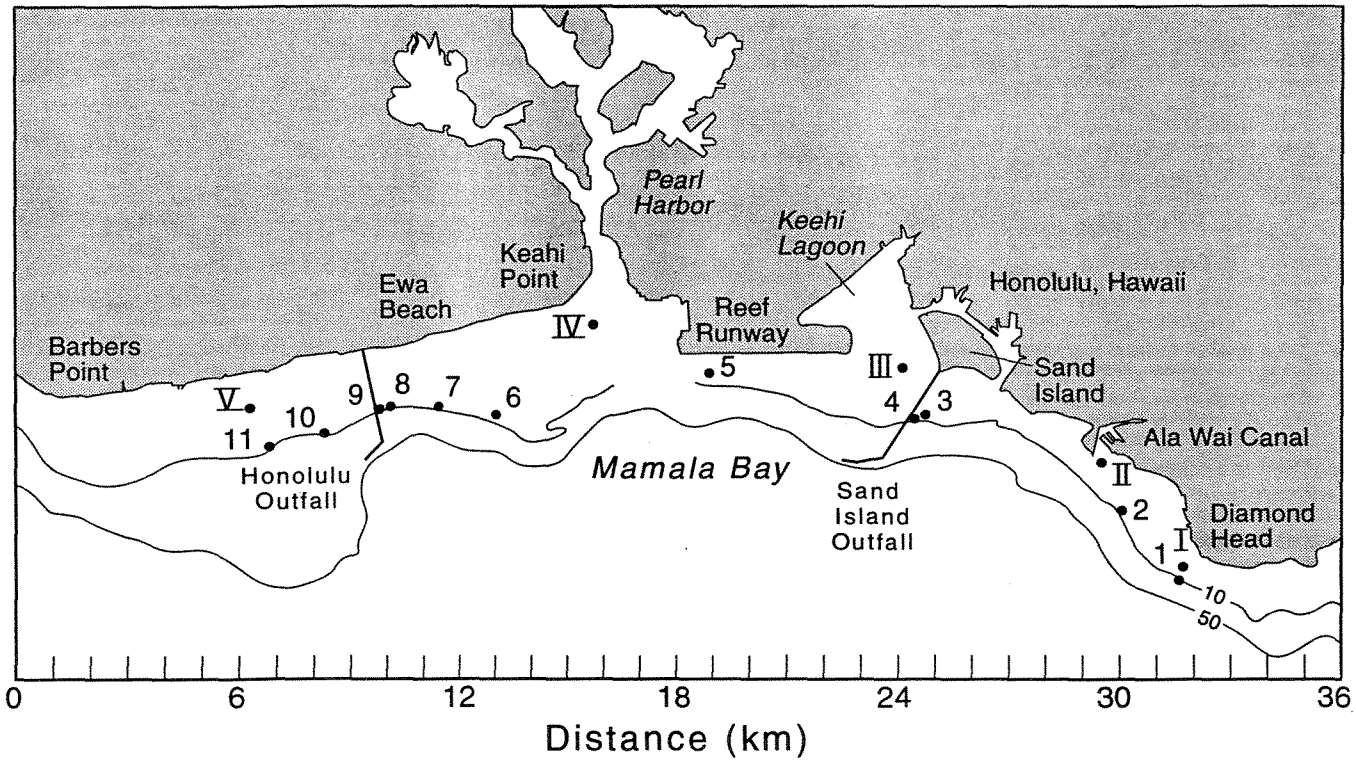


Figure 3.1 Map showing locations of all stations in Mamala Bay. Stations I-V are at 6m depth. Stations 1-11 are at 13m depth.

and 11 along the 13 meter depth contour. It turned out that hard bottom areas naturally fell into two categories; low relief (<1.0 m) with very low coral cover, and high relief (2-4 m) with relatively higher coral cover. For this reason, stations representing both categories were selected for study (4 low and 12 high relief stations). The stations spanned a distance of 26 km from Diamond Head to west Ewa Beach (Figure 3.1).

The following data were collected at every station; coral community structure (abundance and species composition), diversity of coral species, salinity, temperature, depth, phosphate, nitrate, ammonium, silicate, suspended solids, turbidity and chlorophyll-a. Sedimentation was measured at eight representative stations. Water quality data were collected on eight days at all stations; 3 collection dates were calm dry days (baseline), 3 were during significant wave events, and 2 were on significant wet (rain event) days. A more detailed description of how significant wave and rainfall events were defined can be found in Gould (1995). In brief, a significant event for both waves and rainfall was defined as the cut-off for the upper 5% of the data.

Coral colonies of P. lobata up to 30 years in age were also collected at every station for sclerochronological analysis in the laboratory. Colonies of P. lobata were also collected at 13 m depth in Hanauma Bay and off Sunset Beach to serve as controls.

3.2 Task Methodology

Coral abundance (cover) and species diversity measures were obtained by conducting 50 m line transects at every station. The method involves placement of a 50 m line, previously marked at 10 random points, on the bottom. A 0.7 m^2 quadrat is then placed over each random point and photographed. In the laboratory, photographic slides are projected on a grid and coral cover for each species present is recorded.

Water samples were collected at each station from the deck of a small vessel at the surface and one meter off the bottom with a messenger triggered Niskin open and closing bottle. Stations were relocated using a GPS (Global Positioning System) accurate to

within 20 meters. After retrieving Niskin bottles on deck, subsamples for nutrients and chlorophyll-a were filtered through a 0.45 mm GF/F glass microfiber filter and stored in double washed polyethylene bottles. These subsamples were chilled and transported to the University of Hawaii where they were analyzed in the SOEST Analytical Services Laboratory. Subsamples were also taken for suspended solids and turbidity and also analyzed at the ANS at SOEST. A more detailed account of the methods used to measure various water quality constituents can be found in Gould (1995). CTD casts were also taken at each station.

Sedimentation was measured by deploying sediment traps at fixed locations on the bottom. The traps were attached to a meter tripod frame and placed on the bottom such that the top of the traps were 1.5 meters off the bottom. Traps were designed in order to sample effectively within longshore or wave generated currents between 0-25 cm/sec. In order for turbulence caused by this flow to be dissipated within the trap, an aspect ratio (length to height) of 8:1 is required (US GOFS, 1989). Traps were designed with 3 inch PVC tubing cut into 24 inch lengths. This design would be expected to produce a tranquil layer at the bottom of the trap. Six small baffles (1' x 6") were inserted in the top of each trap to further damp turbulence around the mouth. A funnel with a removable test tube (volume calibrated vial) was affixed to the bottom of each trap. This allowed samples to be collected in situ at the end of the deployment periods by a diver without retrieving the whole trap. Deployment times averaged one week. NaCl was placed in the collection vials to serve as a fixative to prevent microbial activity. After collection, sediment samples were chilled and transported to the laboratory where sample wet volume, dry weight and percent organic weight were measured. Dry weight was determined after drying at 57 degrees Celsius for three days. Percent organic matter was determined by the difference in dry weight before and after combustion at 500 degrees Celsius for four hours.

Annual growth of Porites lobata colonies was determined using sclerochronology and densitometry (Buddemeier et al, 1974). Using a rock saw, coral colonies were cut into 4 mm cross sections across the central axes of growth. Cross sections were then x-rayed in the laboratory. This procedure produced high quality contact x-radiographic negatives from which positive prints were developed. Annual growth rate was calculated by measuring the linear distance (extension) between annual bands (alternating couplets of porous and dense layers) in the skeleton. X-ray negatives were scanned using a densitometer in order to determine the average density of the skeleton within each annual growth band. Six values of density were recorded for every millimeter of growth on the contact negatives. Hence, the density value obtained for each year of linear growth (about 7-8 mm) was on the order of 40 to 50 readings. Linear extension for each year, multiplied by the average density of the skeleton corresponding to that year, produced estimates of gross calcification in units of Kg $CaCO_3/m^2/yr$. In total, 118 colonies of P. Lobata were analyzed in the above manner, representing in total 910 years of growth. One hundred forty five of those years represented control colonies collected at Hanauma Bay and Sunset Beach on the north shore of Oahu.

Bioerosion for each colony of P. lobata was calculated by measuring the ratio of excavated area to total area of each cross section. This was accomplished using a hand operated electronic planimeter (Planix Model 7, Tamaya Digital Planimeter), on positive photographic contact prints.

4 RESULTS

4.1 Coral community structure in 1993-94

Two patterns of coral abundance were found at stations selected for study in Mamala Bay in 1993-94 (Figure 4.1). At high relief stations, coral cover was relatively high, averaging 29% +15% with the dominant species being P. lobata. In contrast, at low relief stations, coral cover was low, averaging only 6.6 % + 5% with the dominant species being Pocillopora meandrina. At no station was coral species diversity particularly high although higher values were generally more common in areas of low abundance (Figure 4.2). This was due to high equitability or evenness. No pattern of coral abundance was found to exist relative to the location of point sources (outfalls) or non-point sources of pollution (Pearl Harbor and the Ala Wai Canal).

At all stations, the predominance of coral rubble was high. This was particularly true at low relief stations, where extensive low mounds of dead coral rubble and cobbles were commonplace. Many rubble piles were about 10-15 m long and elliptical in shape, oriented perpendicular to the shoreline (Figure 4.3). Typically, rubble piles were two to three times longer than they were wide. During summer months, rubble piles were often covered by an extensive growth of brown algae, primarily of the genus, Dictyopterus.

4.2 Calcification, growth and bioerosion

Similar to patterns of coral abundance across Mamala Bay, there was no spatial relationship found between calcification and growth with point or non-point sources of pollution (Figure 4.4 and 4.5). Analysis of over 109 colonies of P. lobata representing collectively 765 years of growth at 14 stations in Mamala Bay produced an average rate of calcification of 12.0 + 2.3 kg $CaCO_3/m^2/yr$ (Figure 4.5). This rate of calcification can be compared to the control stations in Hanauma Bay and Sunset Beach where rates of calcification were 11.47 + 2.5 and 9.5 + 1.0 kg $CaCO_3/m^2/yr$, respectively. The differences between the means in Mamala Bay and the control stations were statistically

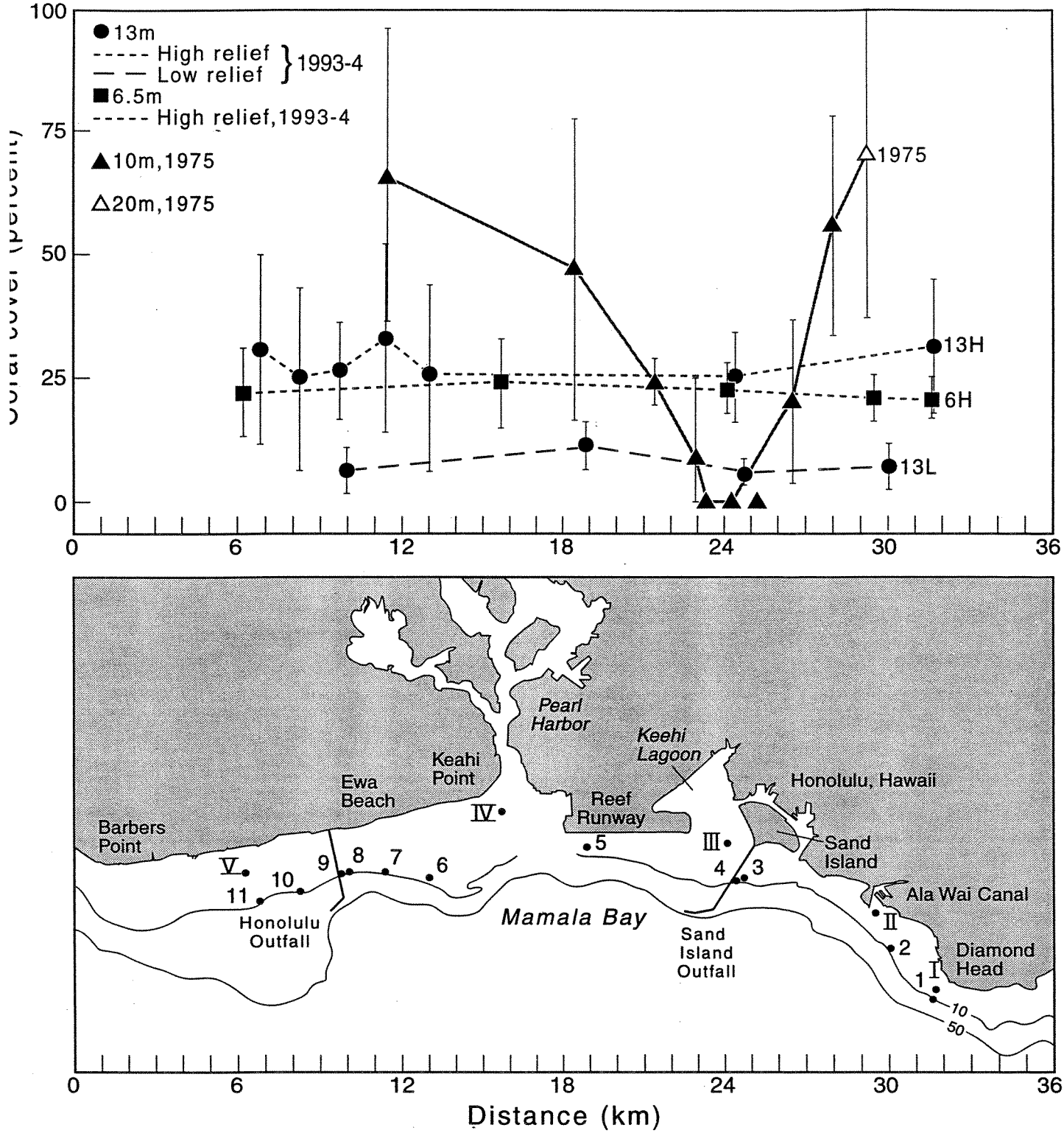


Figure 4.1 Percent coral cover at all stations

Dashed lines connect data collected in 1993-94. The solid line connects data collected in 1975.

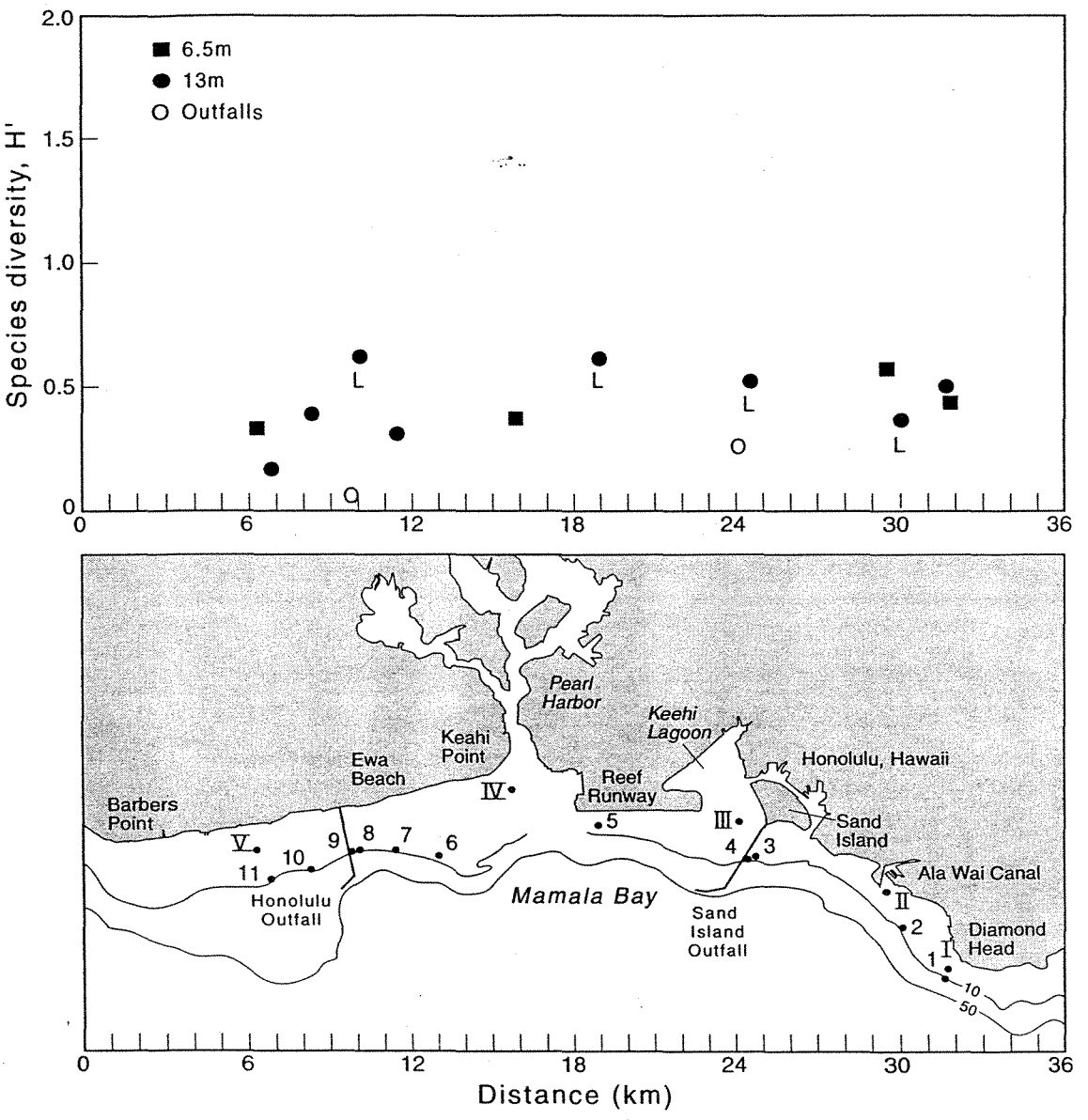


Figure 4.2 Coral Species diversity (H') at all stations in Mamala Bay

$$H' = p_i(\ln p_i) \text{ where } p_i = \frac{\text{cover of the } i^{th} \text{ species}}{\text{total coral cover}}$$

insignificant (t-test, $p = 0.13$) although the rate at Sunset Beach was somewhat low. Also, there was no significant difference in calcification rate of P. lobata between shallow (6.5 m) and deep (13 m) stations, $p < 0.12$, Figure 4.5. Calcification at outfall stations 3, 4, 8 & 9 was also the same ($p = 0.68$) as other stations throughout Mamala Bay (Figure 4.5). Finally, there was no statistical difference between calcification at low versus high relief stations ($p = 0.93$). Overall the pattern of calcification and growth of P. lobata at all stations in Mamala Bay and Hanauma Bay is one of uniformity in response, and no relation to point or non-point sources of pollution is evident.

Perhaps the most revealing indication of the lack of effect of sewage discharge at point source stations on growth is a plot of cumulative growth (linear extension) versus colony age for P. lobata at stations at or adjacent to Honouliuli Outfall (Figure 4.6). It is evident from Figure 4.6 that while colonies exhibit slow, medium and fast patterns of growth, their growth rates are consistent over time. The Honouliuli Outfall was constructed and became operational in 1982. The growth of all eight colonies analyzed that were living at or near the Honouliuli Outfall (+ 2 km) in 1982 show no change in extension rate in 1982 or thereafter. Had there been a slowdown or halt in growth, this would clearly show up in this analysis. Not even the slightest hint of change is evident in 1982 (Figure 4.6).

A similar analysis for the outfall off Sand Island is more difficult to make. In 1977, the sewage discharge at Sand Island was diverted offshore and the treatment was changed from raw to advanced primary. In 1993-94, only one colony was found within several kilometers of the outfall that was old enough to have been in place in 1977. This colony (SI-83) did not show any change in growth during the 1977 year of growth, however, other colonies in the area at that time are known to have died (See Section on Historical considerations).

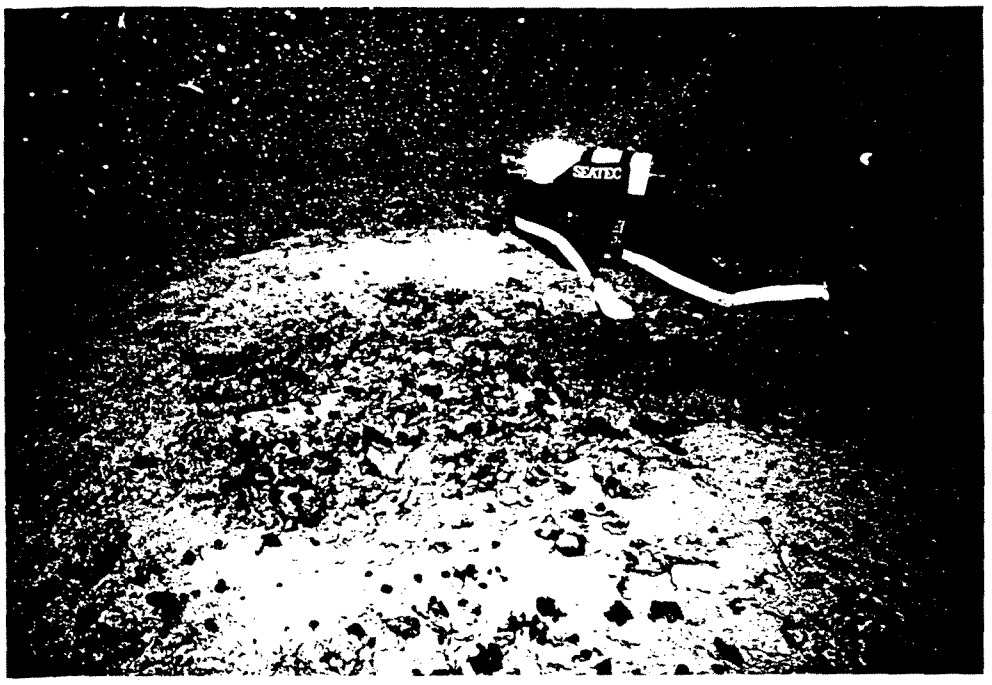


Figure 4.3 Elongate piles of coralline rubble in Mamala Bay
These are particularly abundant on low relief areas of hard substratum. Rubble piles were first observed after Hurricane Iwa in 1982l

Figure 4.4 Annual growth rings
(couplets of low and high density skeleton) are present in and were used to measure annual linear extension and rates of calcification. Bioerosion was measured as the ratio of excavated area to total area of P. lobata cross sections. (See results and Figure 4.8)

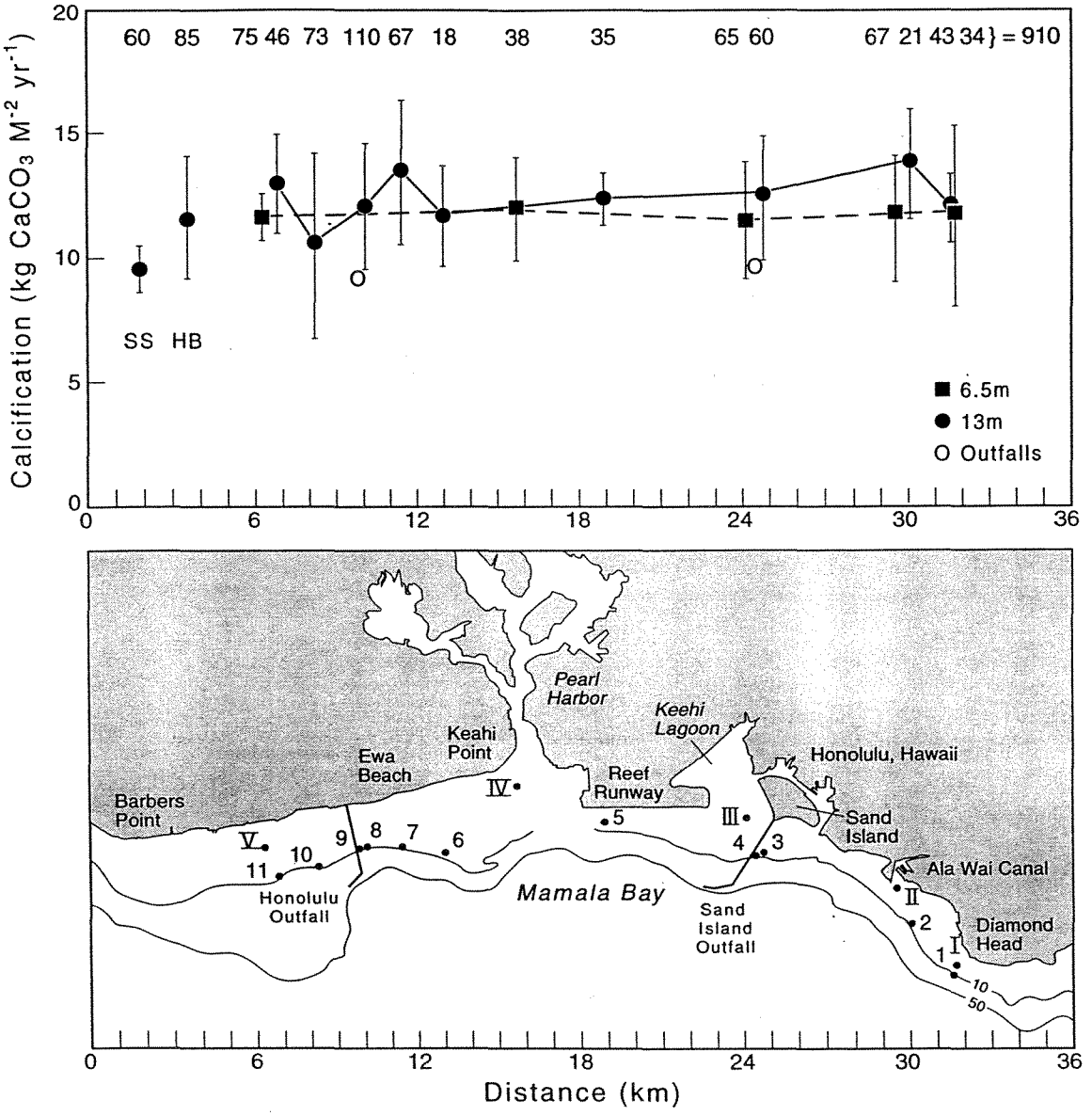


Figure 4.5 Annual rates of calcification of P. Lobata (linear annual growth x density) at all stations in Mamala Bay, Hanauma Bay (HB) and Sunset Beach (SS). Numbers at the top refer to number of years on which the mean annual growth rate is based.

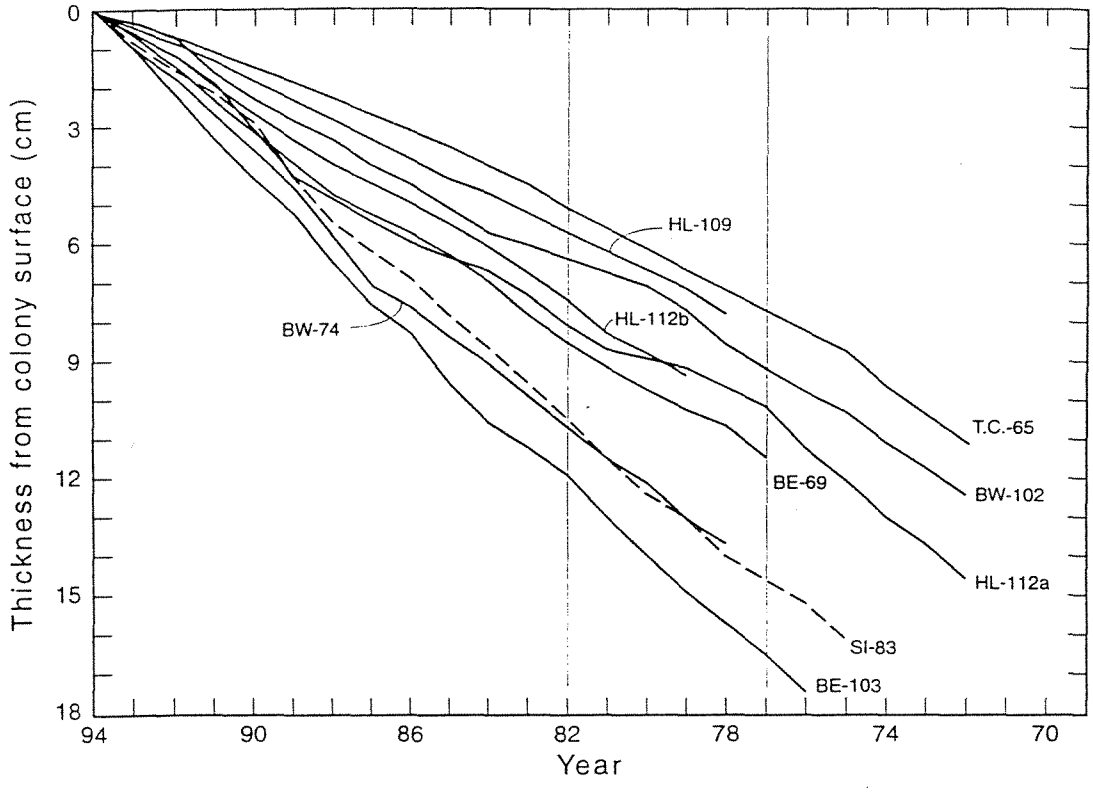


Figure 4.6 Cumulative linear extension of P. Lobata colonies living near Honouliuli outfall (solid lines) and Sand Island outfall (dashed line) during the past two decades. Vertical lines in 1977 and 1982 depict years when Sand Island and Honouliuli outfalls were constructed.

The growth rate of all colonies of P. lobata analyzed was found to have no relationship to age (Figure 4.7). In other words, over the time span of zero to about 30 years, growth is indeterminate. Hence, there is no age effect to remove from the data.

While calcification and growth of P. lobata were found to be uniform within the bay regardless of depth or location, this was not true for bioerosion. At 13 meter stations, bioerosion was insignificant ranging from only 1.72% at Sand Island to 4.52% at Station 11. Bioerosion at 6.5 m stations was also low (<5%) at stations east of Pearl Harbor, however, at Pearl Harbor and the shallow station off Ewa Beach, toward the west, bioerosion was 9.74% and 6.38%, respectively, almost double that of any other stations (Figure 4.4 and 4.8). Bioerosion at these stations was due to primarily the boring of bivalves, polychaetes and sponges.

4.3 Water Quality

During baseline conditions (trade winds 10-20 mph, waves < 2.0 m, and rainfall, 1.25 cm/day) all measures of nutrients and other chemical parameters remained relatively constant at both surface and bottom stations in Mamala Bay (Table 4.1 , figures 4.9-4.15). Ranges for each parameter are given in Table 4.1. Even though sampling spanned an entire year, only small deviations in all parameters were encountered. Salinity ranged between 34.5 and 34.6 ppt; PO_4, NO_3 and NH_4 values ranged between undetectable levels and 0.15 μM; turbidity ranged between 0.25 and 0.37 ntu and chlorophyll-a ranged between 0.07 and 2.44 μg/L. Only silicate exhibited much variation and that was limited to the nearshore station near the Ala Wai Canal. A small but significant ($p < 0.01$, Spearman Rank Correlation) trend of increasing ammonium from east to west was also observed.

Sedimentation was measured during a baseline condition over a period of one week during the summer (July 11- 17, 1994). The results show a gradient of volume flux and dry weight, high near Diamond Head decreasing almost monotonically toward the

east except for one high value at the Reef Runway Station (Figure 4.16). Organic carbon showed the opposite trend, increasing steadily from east to west (Figure 4.16). All values were exceedingly low.

During significant wave events (height >2.0 m, period > 14 seconds) many chemical variables were unaffected by the waves and basically remained baseline in character (Table 4.2). This was true for salinity, silicate, chlorophyll-a and turbidity although turbidity was increased slightly. The ranges for all variables are given in Tables 4.1, 4.2 and 4.3 and Figures 4.9 - 4.15. Two notable exceptions to this pattern were observed. On one hand, phosphate decreased consistently and significantly at all stations surface and bottom ($p < 0.01$), while on the other, nitrate and NH_4 were both found to increase significantly over baseline values (t-test, $p<0.01$), and showed a trend of slight increase from east to west in the bay. Levels of nitrate increased exponentially with relative wave energy ($r^2 = 0.90$, Figure 4.17).

Rainfall events produced the largest changes in water quality, particularly near non-point sources at Pearl Harbor and Ala Wai Canal and particularly at surface stations (Table 4.3, Figures 4.9 - 4.15). Changes were magnified (non-linear) by larger rainfall events. The greatest changes were surface salinity and silicate at Ala Wai and Pearl Harbor. The nutrients NO_3 and PO_4 were also high at the surface off Ala Wai, but interestingly this was not true at Pearl Harbor where they remained low. Conversely, chlorophyll-a was very high at the surface off Pearl Harbor. Longshore gradients away from Pearl Harbor and the Ala Wai Canal for all chemical variables trended to the east along the shore toward Diamond Head. This was associated with strong westerly Kona winds which accompanied all significant rainfall events studied.

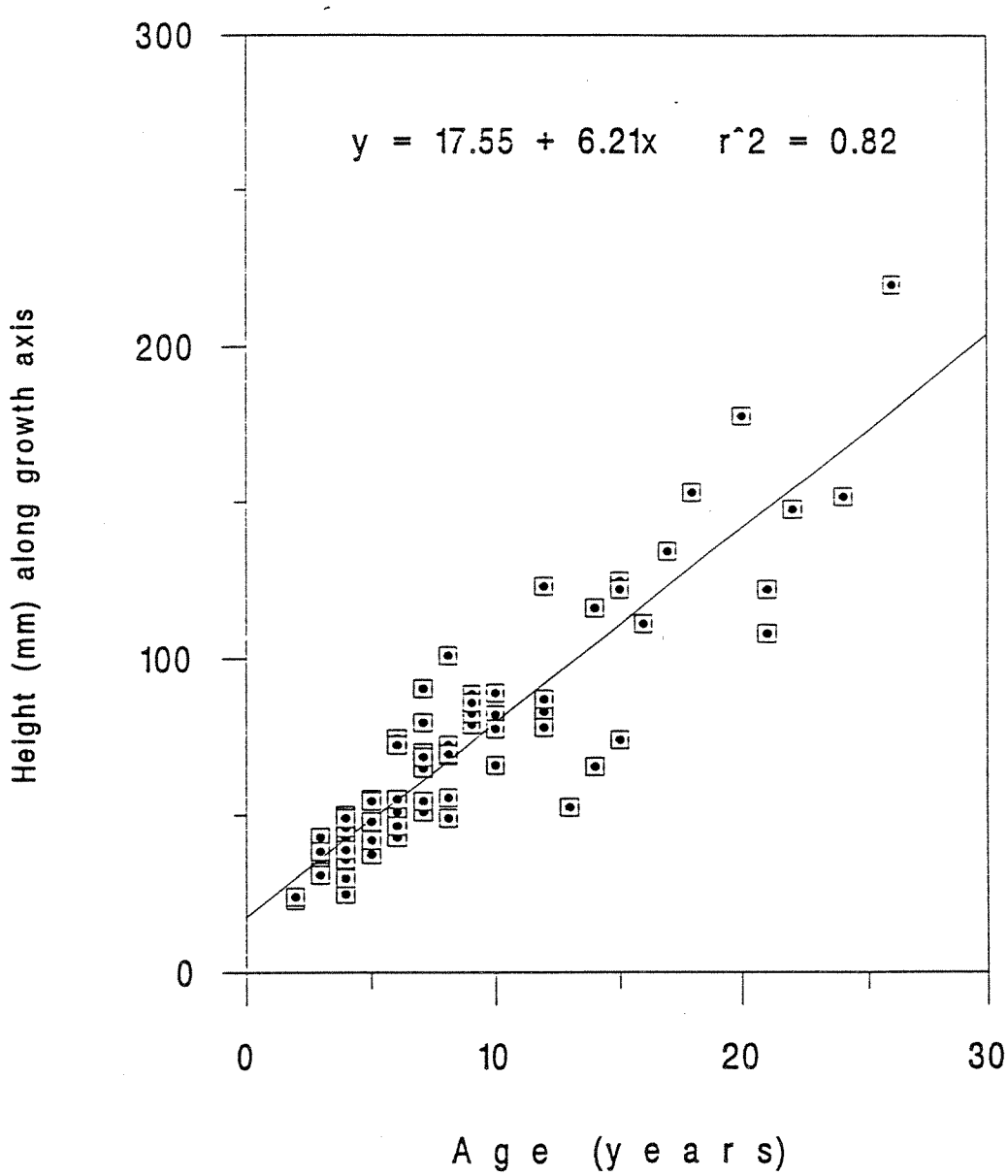


Figure 4.7 Height versus age in P. Lobata
The linear fit to the data shows that growth is indeterminate, at least from 0-30 years.

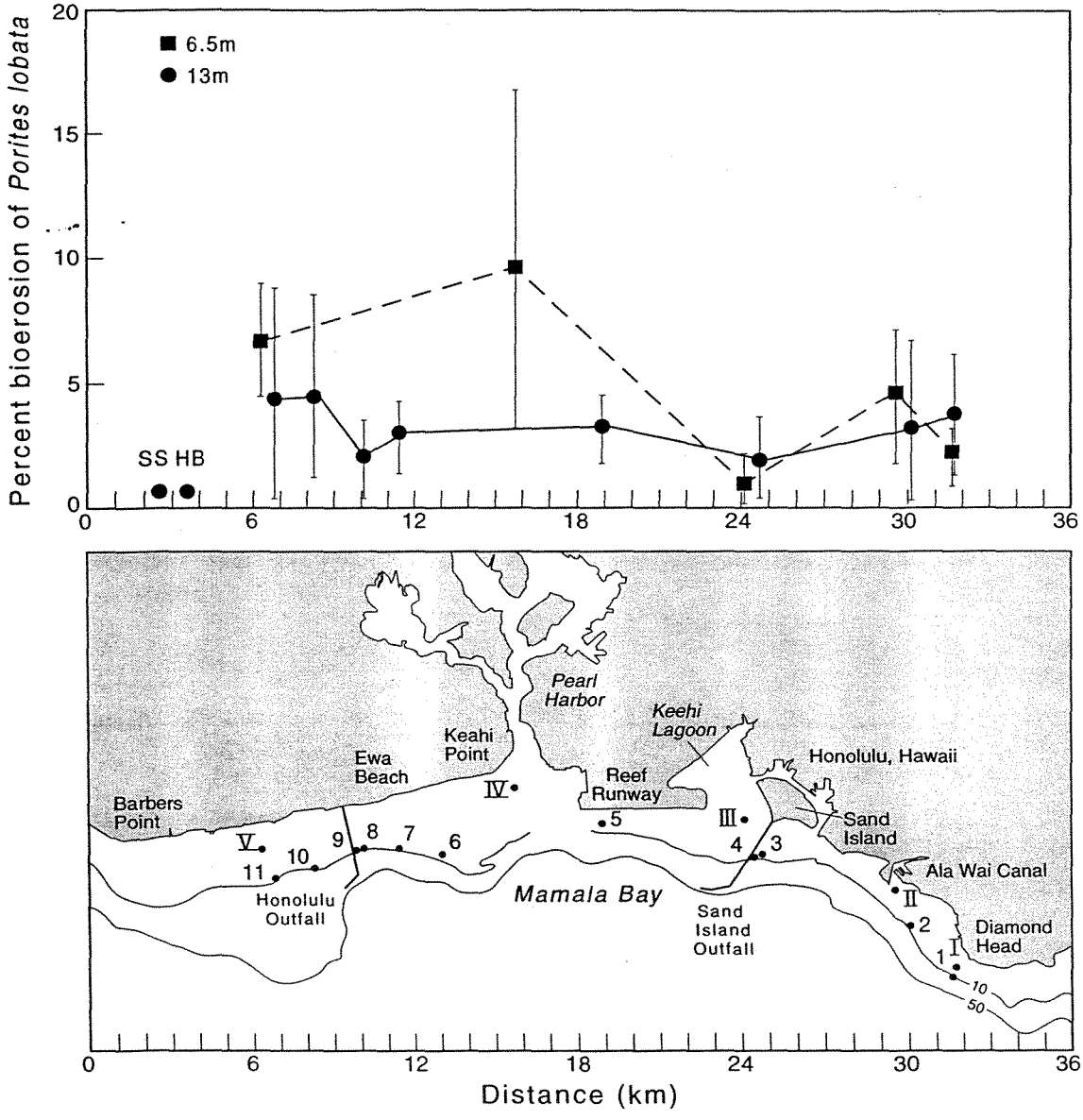
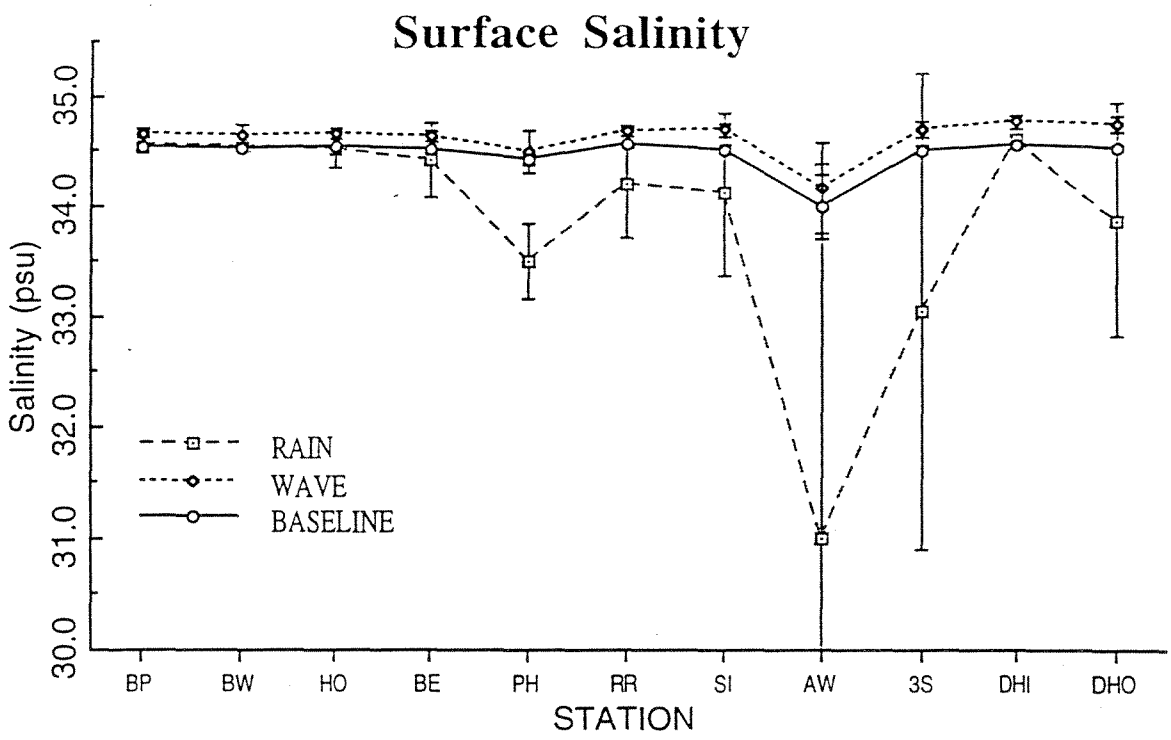


Figure 4.8 Bioerosion of P. Lobata at all stations in Mamala Bay and at the control stations, Hanauma Bay (HB) and Sunset Beach (SS).



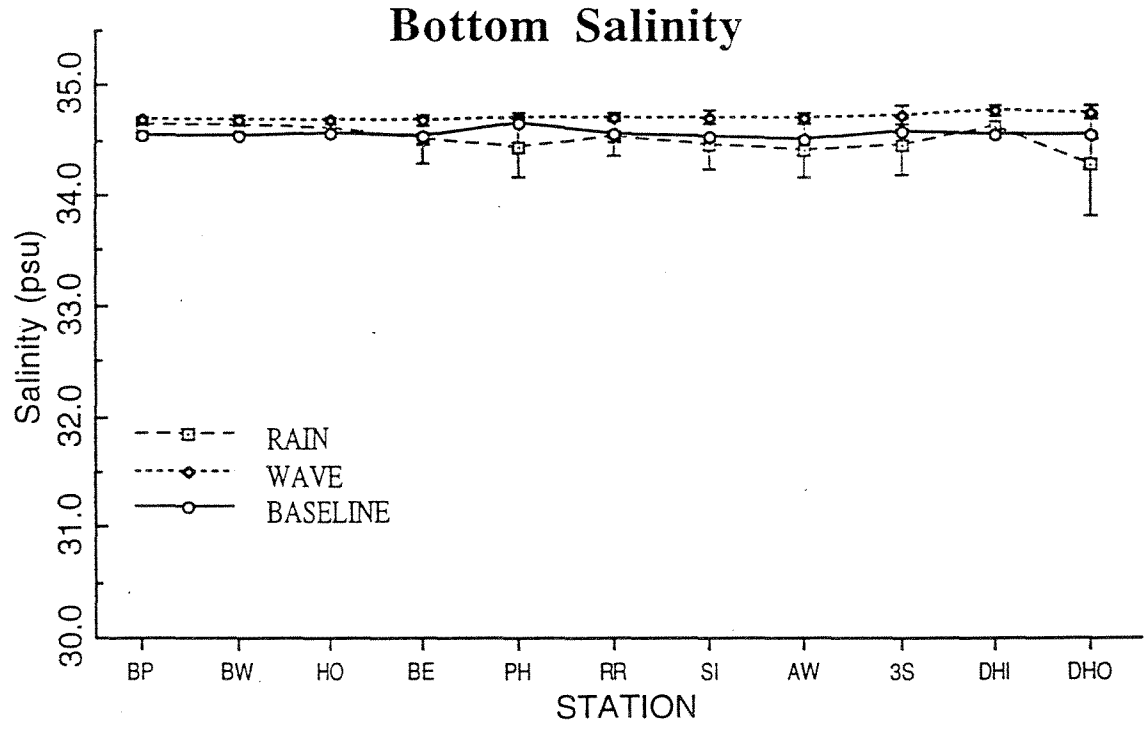
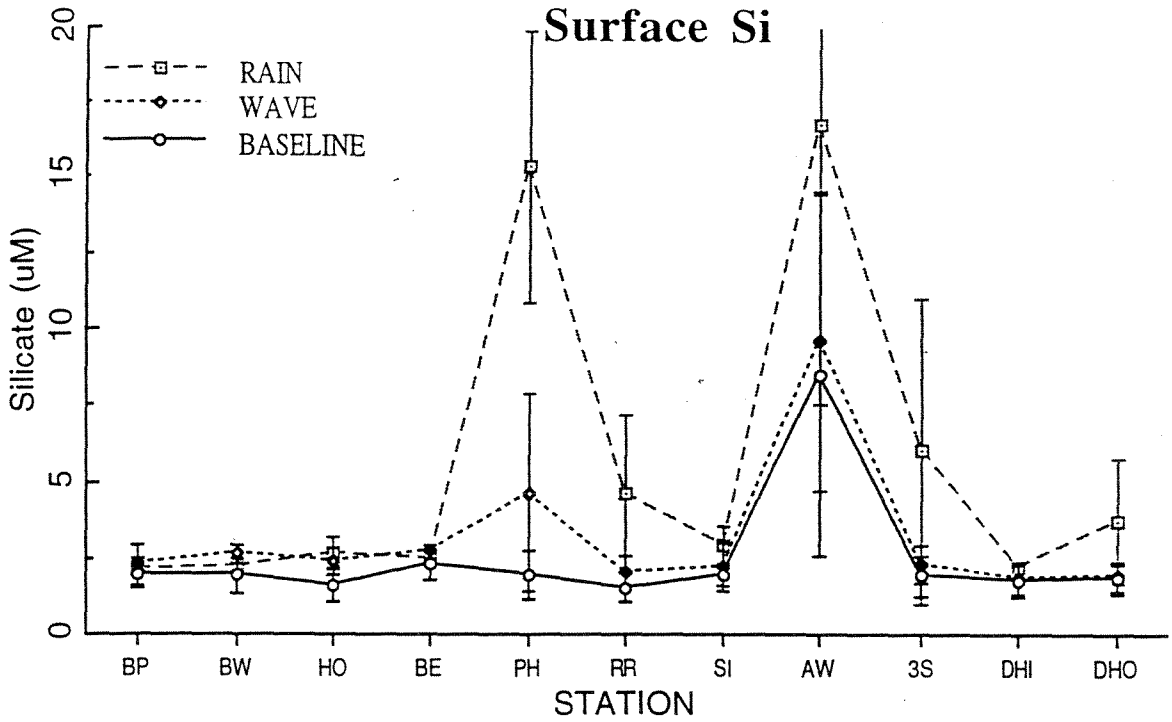


Figure 4.9 Surface and bottom salinity at all stations in Mamala Bay during normal (baseline) conditions and during significant wave and rainfall events.



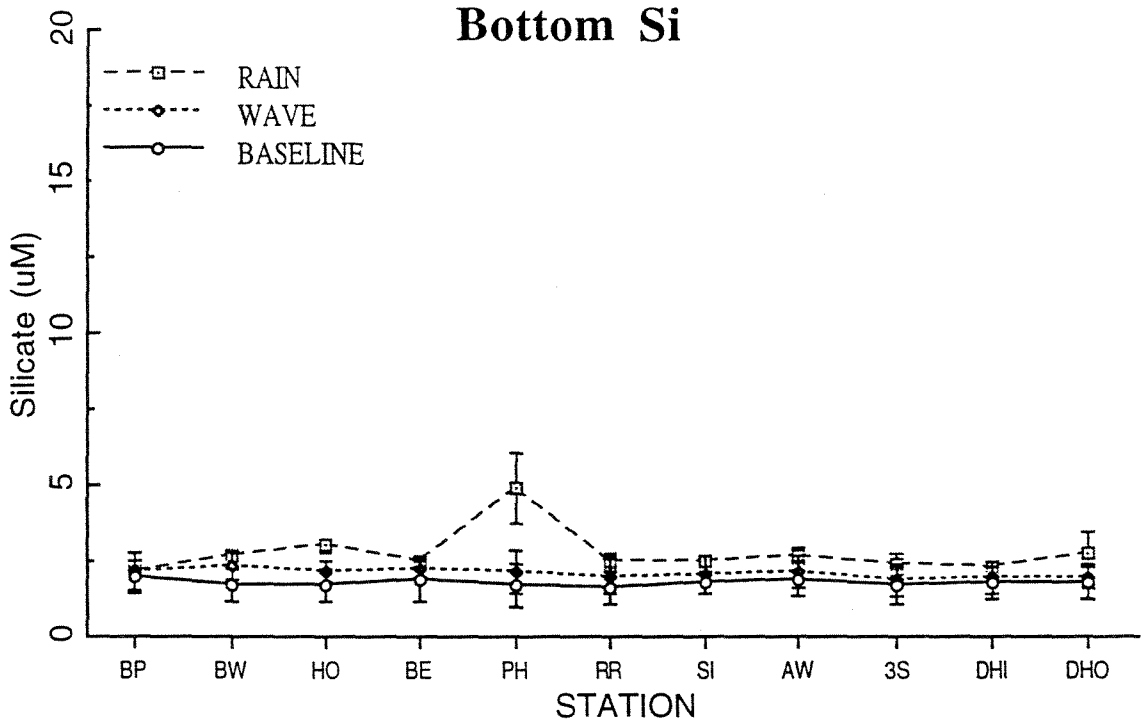
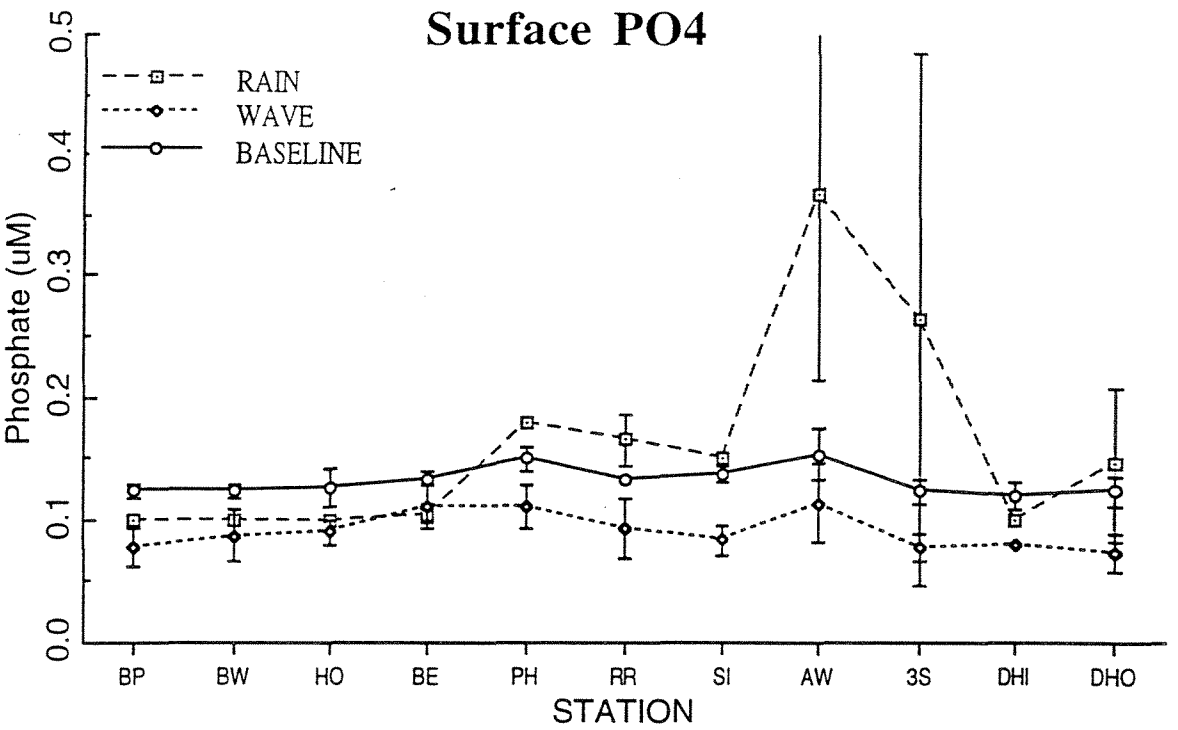


Figure 4.10 Surface and bottom silicate at all stations in Mamala Bay during normal (baseline) conditions and during significant wave and rainfall events.



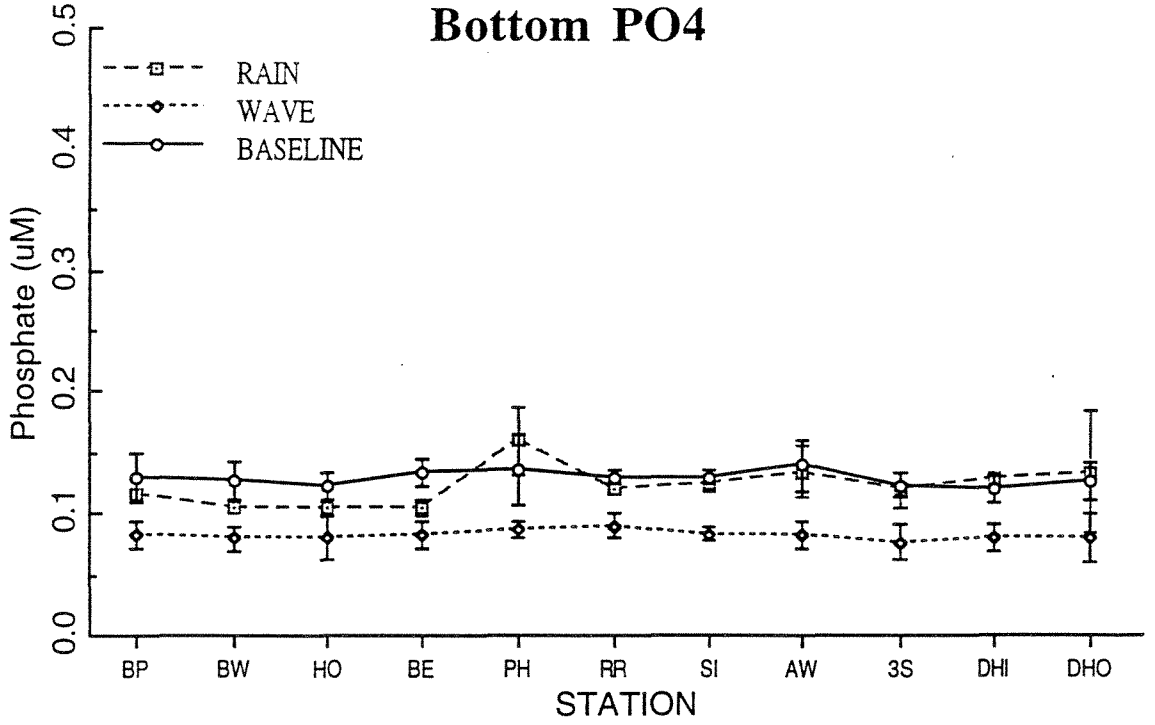
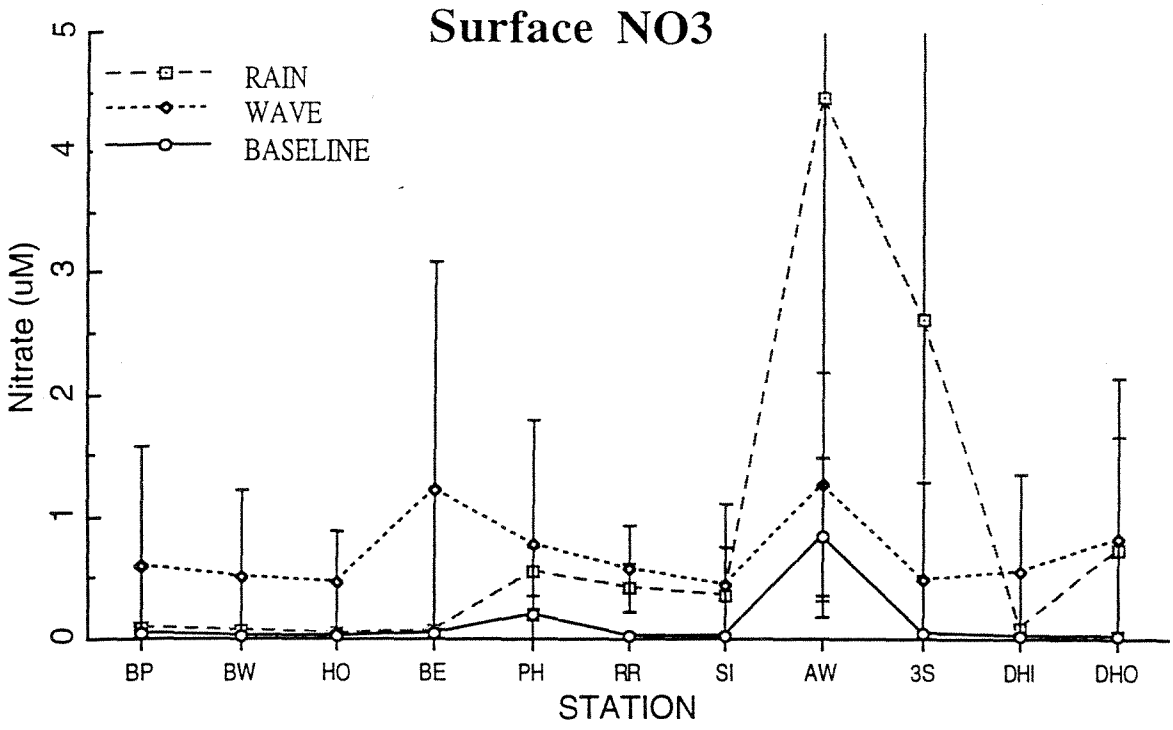


Figure 4.11 Surface and bottom phosphate at all stations in Mamala Bay during normal (baseline) conditions and during significant wave and rainfall events.



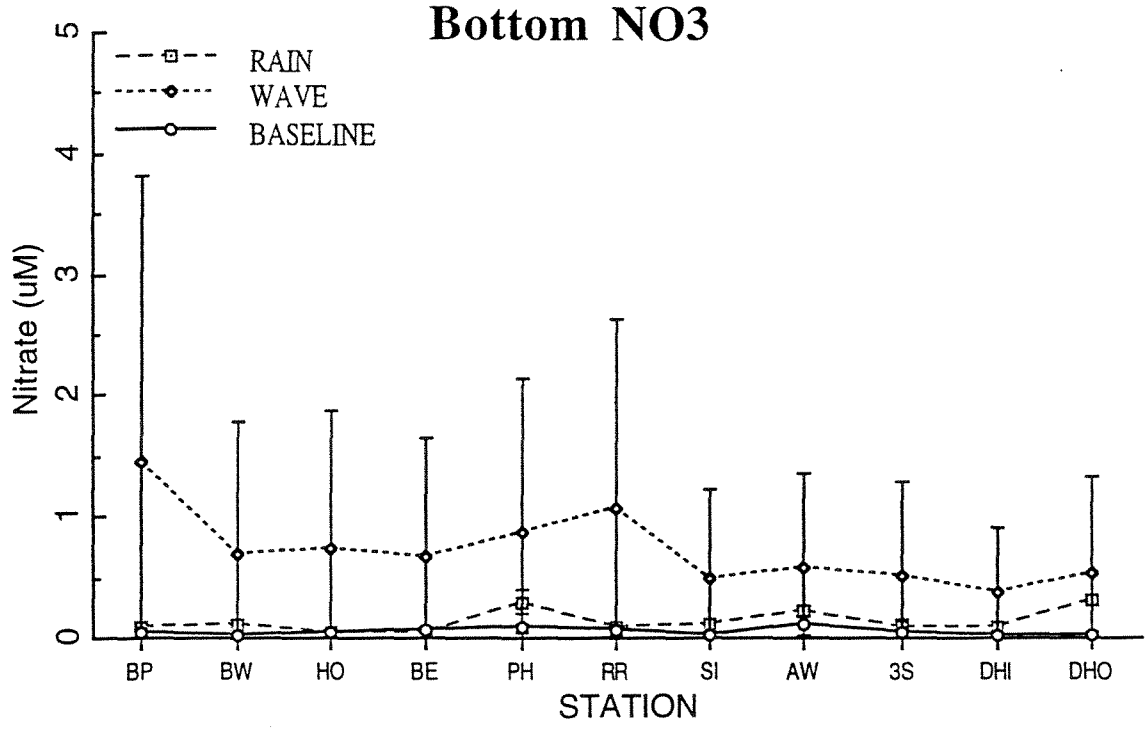
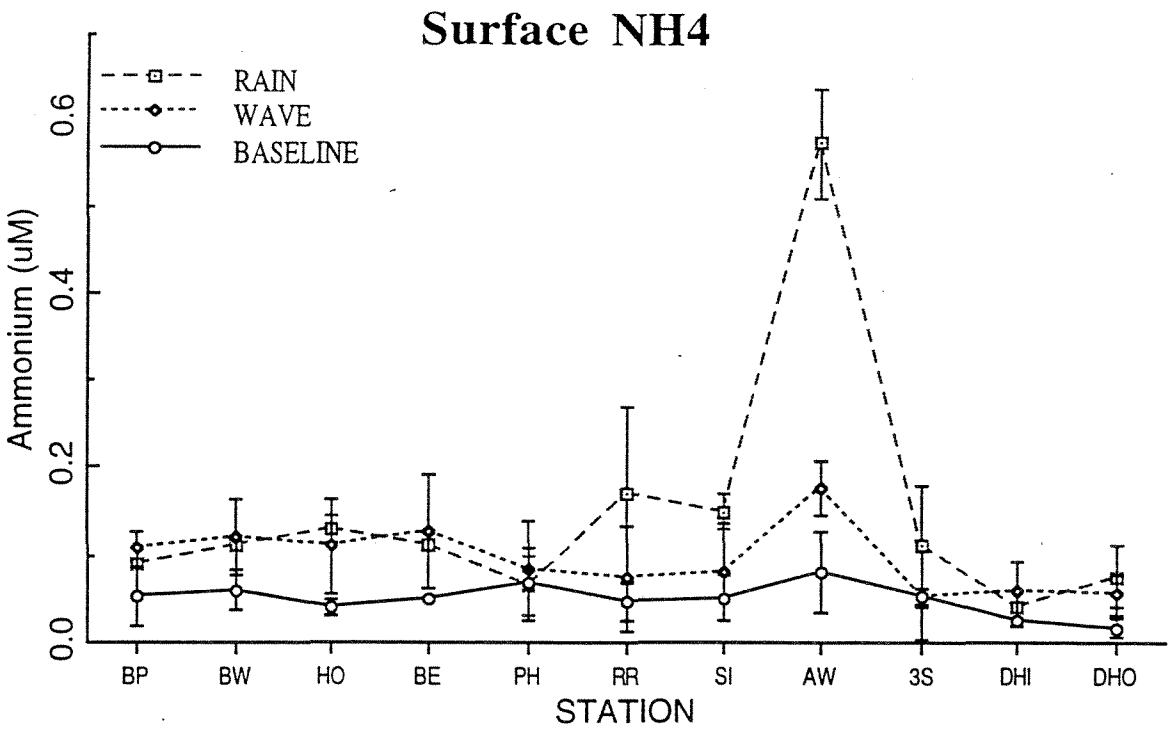


Figure 4.12 Surface and bottom nitrate at all stations in Mamala Bay during normal (baseline) conditions and during significant wave and rainfall events.



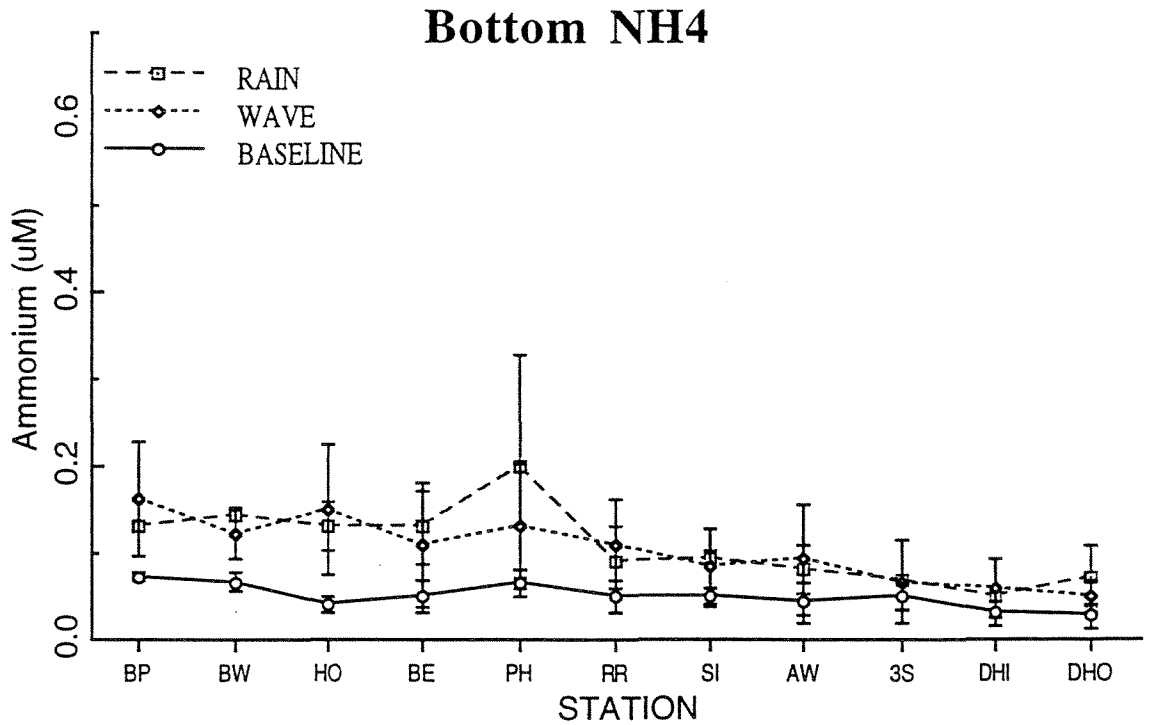
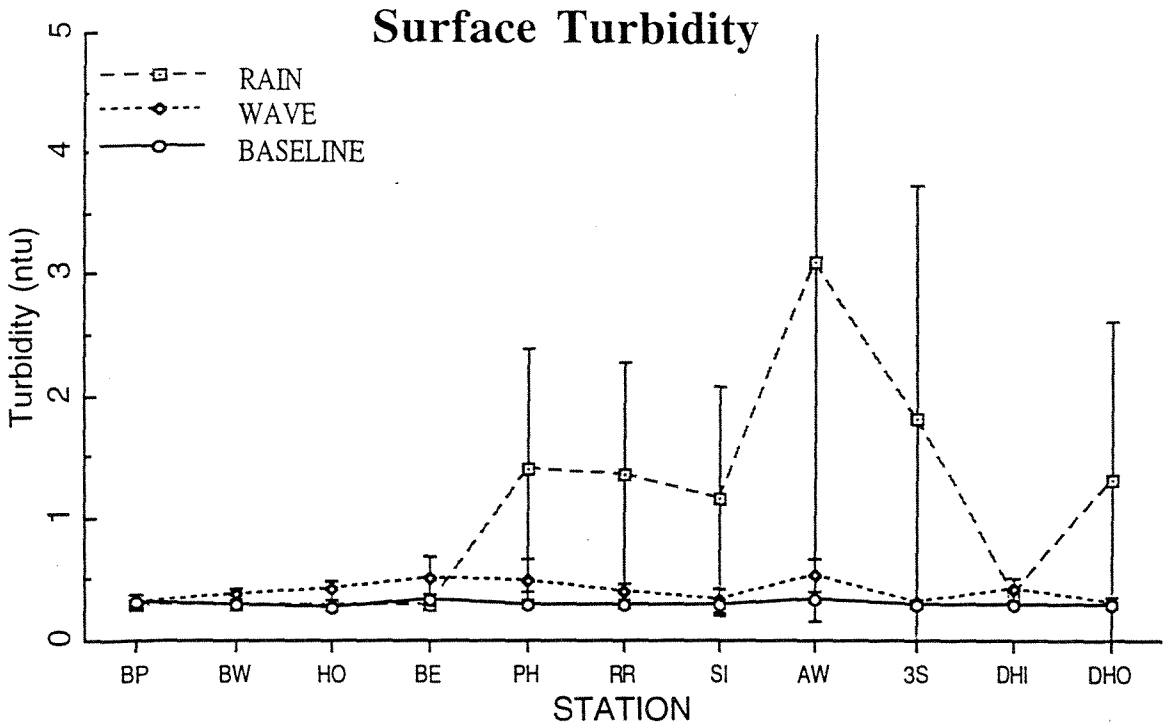


Figure 4.13 Surface and bottom ammonium at all stations in Mamala Bay during normal (baseline) conditions and during significant wave and rainfall events.



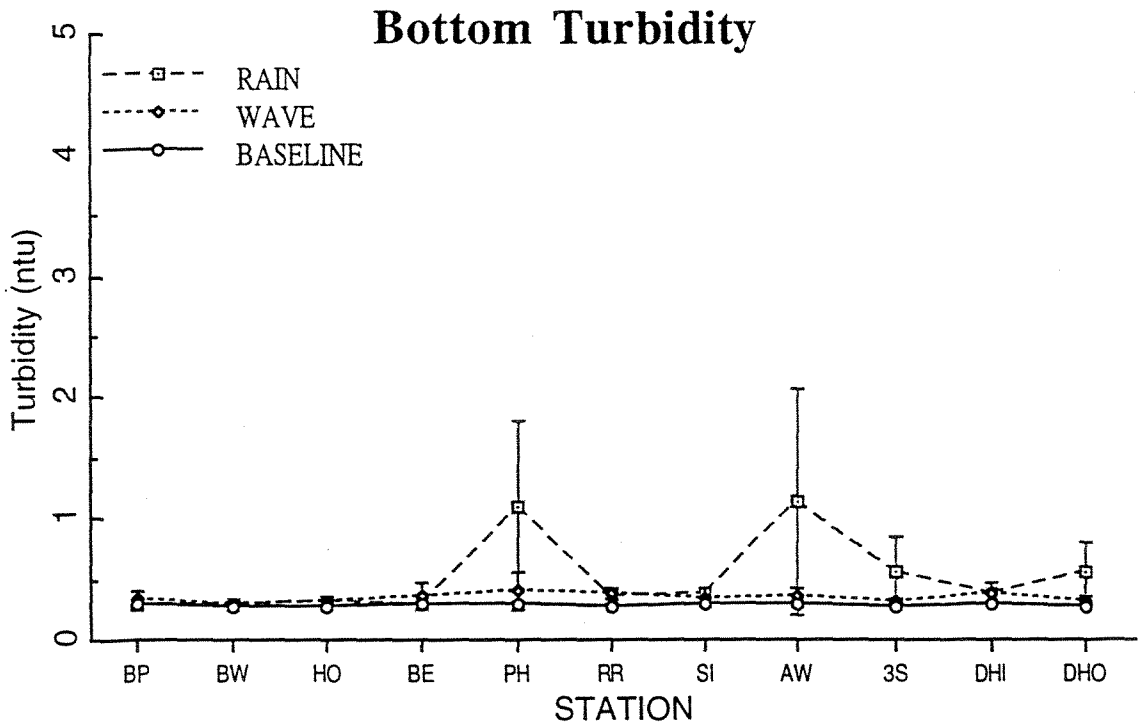
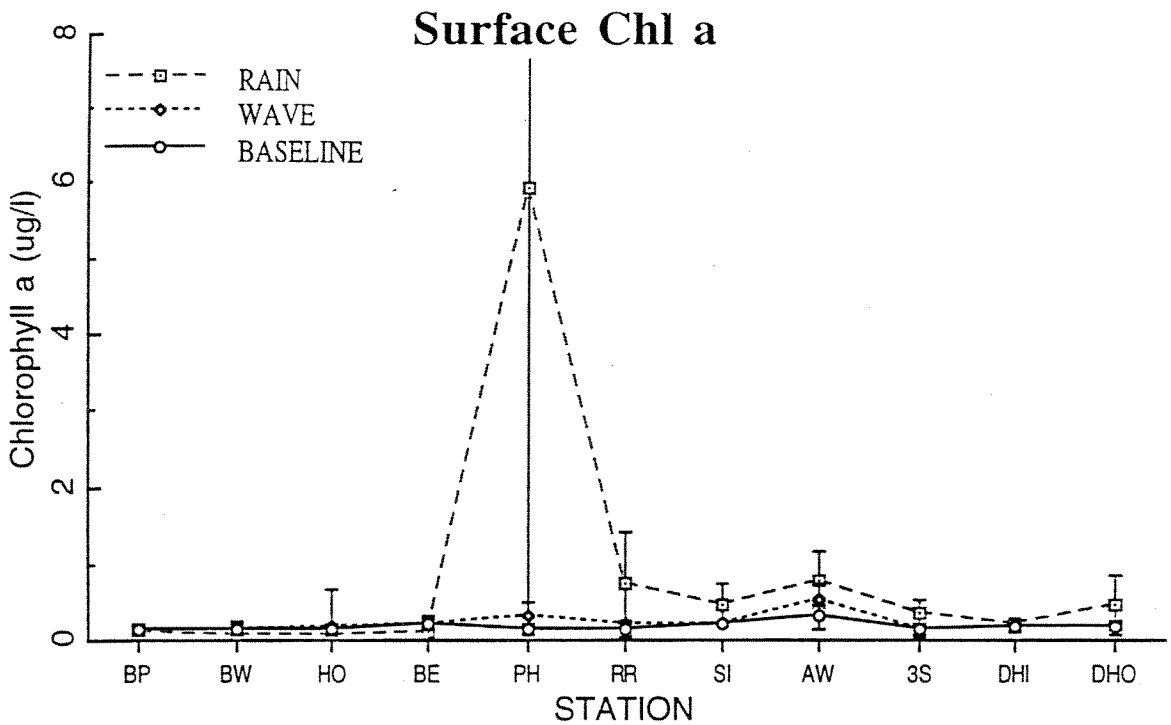


Figure 4.14 Surface and bottom turbidity at all stations in Mamala Bay during normal (baseline) conditions and during significant wave and rainfall events.



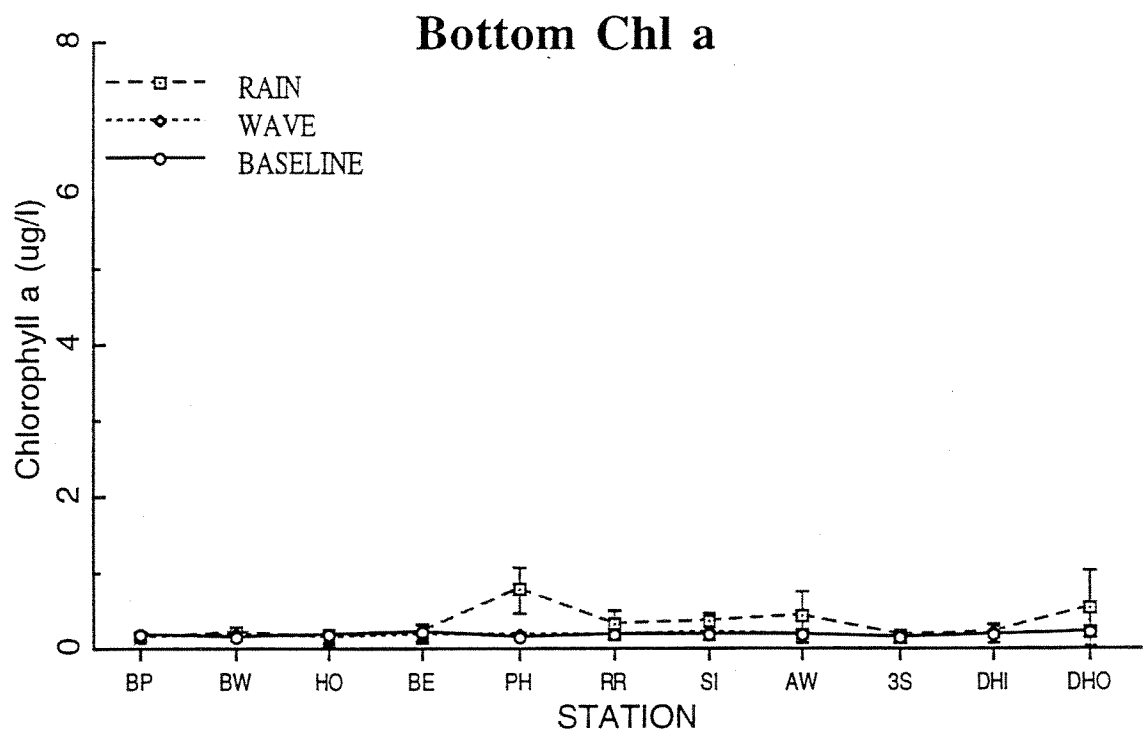


Figure 4.15 Surface and bottom chlorophyll-a at all stations in Mamala Bay during normal (baseline) conditions and during significant wave and rainfall events.

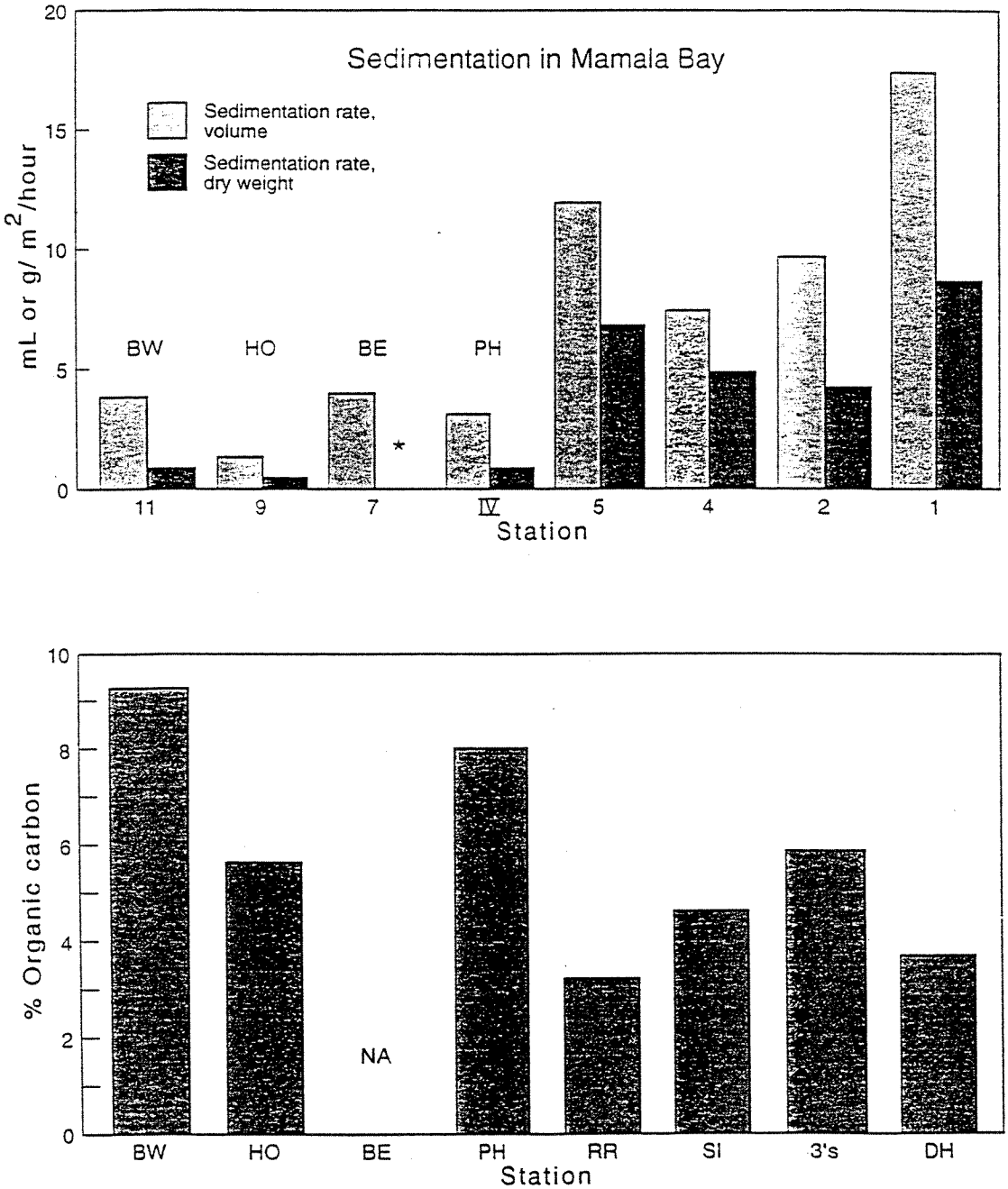


Figure 4.16 Sedimentation at all stations in Mamala Bay
(top: volume and dry weight; bottom: percent organic carbon)

Table 4.1 Offshore stations' baseline parameters

BASELINE	SURFACE		BOTTOM	
Parameter	Mean	Range	Mean	Range
Salinity (ppt)	34.55 ± 0.03	34.48 - 34.60	34.55 ± 0.02	34.52 - 34.61
Phosphate (μM)	0.13 ± 0.01	0.11 - 0.15	0.13 ± 0.01	0.11 - 0.15
Nitrate (μM)	0.03 ± 0.02	0.01 - 0.07	0.04 ± 0.02	0.00 - 0.08
Ammonium (μM)	0.04 ± 0.02	0.00 - 0.07	0.05 ± 0.02	0.01 - 0.08
Silicate (μM)	1.87 ± 0.48	1.08 - 2.68	1.76 ± 0.46	1.04 - 2.25
Turbidity (ntu)	0.29 ± 0.03	0.25 - 0.37	0.28 ± 0.02	0.25 - 0.32
Chlorophyll a (μg/l	0.16 ± 0.14	0.09 - 0.24	0.17 ± 0.06	0.07 - 0.24

Table 4.2 Offshore stations' wave event parameters

WAVE EVENT	SURFACE		BOTTOM	
Parameter	Mean	Range	Mean	Range
Salinity (ppt)	34.70 ± 0.07	34.59 - 34.83	34.72 ± 0.06	34.63 - 34.83
Phosphate (μM)	0.09 ± 0.02	0.06 - 0.11	0.08 ± 0.01	0.06 - 0.10
Nitrate (μM)	0.63 ± 0.86	0.02 -3.38	0.72 ± 1.04	0.02 - 4.17
Ammonium (μM)	0.09 ± 0.05	0.01 - 0.22	0.10 ± 0.06	0.02 - 0.22
Silicate (μM)	2.30 ± 0.55	1.25 - 2.98	2.09 ± 0.45	1.28 - 2.75
Turbidity (ntu)	0.37 ± 0.10	0.27 - 0.70	0.34 ± 0.06	0.27 - 0.48
Chlorophyll a (μg/l	0.18 ± 0.07	0.06 - 0.28	0.17 ± 0.07	0.01 - 0.30

Table 4.3 Offshore stations' rain event parameters

RAIN EVENT	SURFACE		BOTTOM	
Parameter	Mean	Range	Mean	Range
Salinity (ppt)	34.13 ± 0.88	31.53 - 34.41	34.51 ± 0.21	33.97 - 34.60
Phosphate (μM)	0.15 ± 0.09	0.10 - 0.42	0.12 ± 0.02	0.10 - 0.17
Nitrate (μM)	0.61 ± 1.36	0.01 - 5.15	0.11 ± 0.13	0.01 - 0.53
Ammonium (μM)	0.11 ± 0.05	0.04 - 0.24	0.11 ± 0.04	0.04 - 0.16
Silicate (μM)	3.51 ± 2.14	2.11 - 9.55	2.52 ± 0.30	2.13 - 3.35
Turbidity (ntu)	0.93 ± 0.96	0.28 - 3.20	0.39 ± 0.16	0.29 - 0.77
Chlorophyll a (μg/l	0.32 ± 0.34	0.03 - 1.23	0.27 ± 0.20	0.13 - 0.89

4.4 Discussion

Ecosystem response, the central goal of Project MB-9, was investigated at three levels of biological organization in the study. Growth and calcification are under physiological control at the level of the 'cell'. Patterns of species abundance depend on 'population' processes; recruitment, survival and mortality. Community structure is controlled by 'ecosystem' processes including competition, predation, primary and secondary production, energy flow and trophic structure. This three level research design and the use of corals as indicator organisms, established an inherent sensitivity within the analysis. Even so, the results failed to provide any evidence of significant negative environmental impact caused by point source or non-point source pollution within Mamala Bay. Patterns of growth, calcification, species composition and abundance and community structure of coral ecosystems showed no spatial relation to point source discharges or non-point source runoff. The only indication of an environmental change produced by the study is a small increase of about 5% in bioerosion in P. lobata that was found at the 6.5 m stations off Pearl Harbor and west Ewa Beach. While coral abundance is slightly lower (~7%) at Pearl Harbor and the shallow station off Ewa Beach compared to other high relief stations, a corresponding increase in biodiversity would exist at stations with higher bioerosion. This relation has probably reached steady state since non-point outflow at Pearl Harbor is a natural age-old process. Any detriment to the reef in areas of slightly increased bioerosion should be offset by an enhancement in biodiversity.

Looking more closely at calcification, mean rates for all stations in Mamala Bay varied within a narrow range of 10.5 to 13.8 kg $CaCO_3$ m^2/yr. and averaged 12.0 kg $CaC0_3/m^2$/yr (Figure 4.5). No statistically significant differences were found related to depth, habitat relief or geographic proximity to point or non-point sources of pollution within the bay, nor were differences between Mamala Bay stations and the control stations at Hanauma Bay and Sunset Beach statistically significant. The slight depression

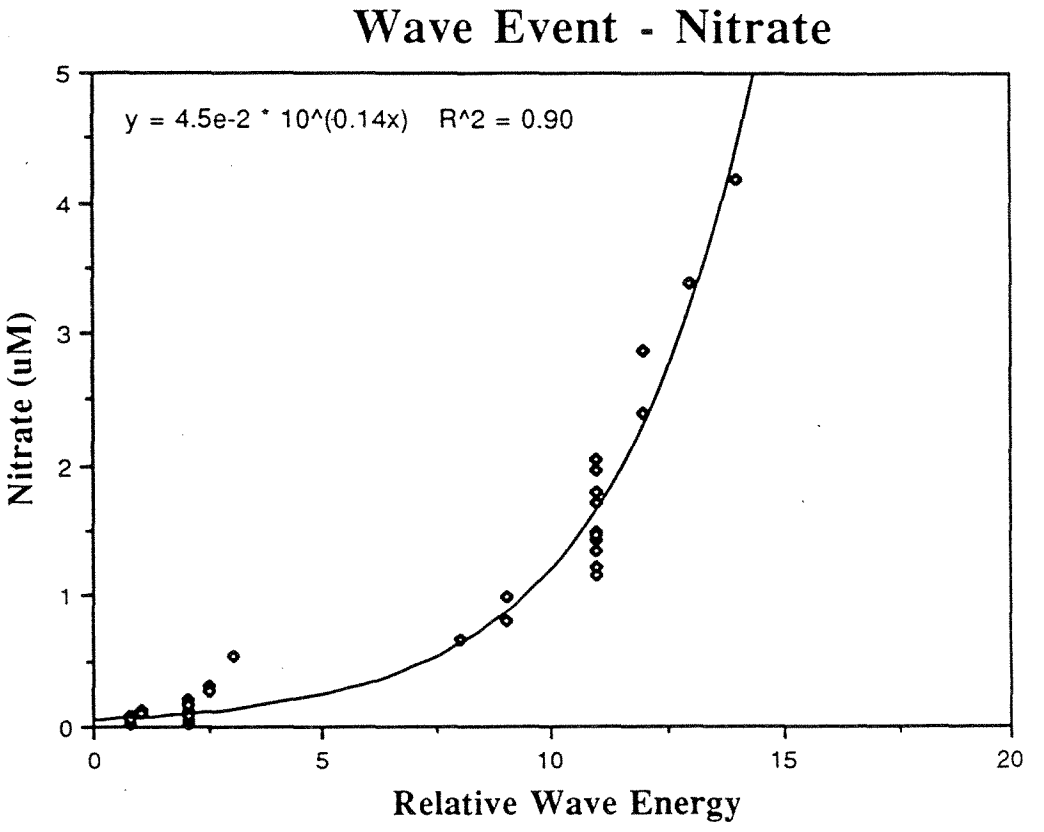


Figure 4.17 Nitrate versus wave energy during different magnitude wave events

(9.5 kg $CaCO_3/m^2/yr$) at Sunset Beach may be related to greater cloud cover associated with windward versus leeward shorelines in Hawaii and the greater turbidity caused by high winter surf on the North Shore. Interestingly, the highest rate of calcification in Mamala Bay was found at Station 2 off the Royal Hawaiian Hotel which consistently was characterized by the clearest water in the bay (Ed Parnell, personal communication). The Mamala Bay average of 12.0 kg $CaCO_3/m^2/yr$ gross calcification compares favorably with rates determined elsewhere in the Hawaiian Archipelago (Grigg, 1982) and the world (Barnes and Chalker, 1990).

Another convincing piece of evidence of the lack of environmental impact from the outfalls, is the continuous and uninterrupted records of growth of 9 colonies of P. lobata that were growing in place prior to the construction of the outfalls now present off Sand Island and Ewa Beach (Honouliuli) Figure 4.6. The rate of growth of these colonies was constant during and after the years that both outfalls were constructed (1977 and 1982).

The response at levels of population abundance (coral cover) and community structure also showed no relation to either point or non-point sources of pollution in Mamala Bay (Figure 4.1). The only pattern to emerge was a positive relation between coral cover and habitat relief. Coral cover at high relief stations was significantly higher than it was at low relief station; 29% versus 6%, t-test, $p<0.01$). The dominant species at high relief stations was P. lobata whereas the dominant species at low relief stations was Pocillopora meandrina. P. lobata is a massive species highly resistant to breakage, while P. meandrina is a pioneer or fugitive species (Grigg and Maragos, 1974) characteristic of early successional stages.

The lack of environmental impact at all levels of biological organization of coral ecosystems in Mamala Bay is not surprising given the results of water quality analyses during this study. During baseline conditions, the concentrations of all nutrients and other chemical parameters remained low and relatively uniform across the bay. The

slight increases in NH_4 from east to west may reflect inputs from either the outfalls or more likely non-point sources of runoff, but at values < 0.3 μMoles, they are too low to affect corals (Kinsey and Davis, 1979). Significant wave events also failed to produce nutrient levels that would be expected to affect corals.

Two changes in water quality, however, did occur during wave events that are of scientific interest. The systematic decrease in phosphate that was found (Figure 4.11) suggest that formation of insoluble precipitates possibly with iron ions (Fe+++) (Laws, 1993) or simply adsorption to ferric oxides and hydroxides may be favored by wave stirring. Conversely, NO_3 was found to systematically increase during wave events (Figure 4.12). This could also result from wave stirring possibly sufficient to stimulate the release of enriched interstitial pore waters in the sediment. Measures of sedimentation were taken during low waves, but nevertheless, showed high rates in areas exposed to waves and with high sediment; a result presumably due to wave stirring and resuspension (Diamond Head and the Reef Runway, See Figure 4.16). Sedimentation rates (dry weight) at all stations were less than 10 $g/m^2/hr$, values known to have no affect on corals (Pastorok and Bilyard, 1985).

Even during significant rainfall events, when the largest changes occurred at nearshore station off Pearl Harbor and the Ala Wai, nutrient values for PO_4, NO_3, NH_4 and silicate averaged less than 0.4, 5.0, 0.6 and 20 μMoles, respectively. Corals incubated at the Waikiki Aquarium have been shown to survive and rapidly grow in water of comparable nutrient enrichment (Atkinson and Carlson, in press). In the case of Mamala Bay, high values associated with significant rainfall events would be episodic and ephemeral in nature. High values were also confined to surface stations (Figures 4.9 - 4.15) and therefore may not come into direct contact with the benthos.

One interesting difference between the Ala Wai and Pearl Harbor stations during rainfall events was the relation between nutrients and chlorophyll-a. At Ala Wai, nutrients were high and chlorophyll-a was low, while at Pearl Harbor, nutrients were

relatively low and chlorophyll-a values were very high. This suggests that the water flushing out of Pearl Harbor is much richer in phytoplankton than water in the Ala Wai Canal. Gross primary production in the Ala Wai Canal is high (1,423 $g/m^2/yr$) but overall it has been found to be heterotrophic (Laws et al, 1994). Most phytoplankton in the Ala Wai Canal must recycle before they wash out into the ocean. Pearl Harbor, on the other hand, is 100 times larger than the Ala Wai Canal (Freeman, 1993) and must have a much longer residence time. This should enhance phytoplankton production and the rate of wash out into the ocean. The elevation in bioerosion near Pearl Harbor may in fact be a result of this subsidy in food supply. Many of the bioeroders such as bi-valves, polychaetes and sponges are filter feeders.

4.5 Historical considerations

The lack of environmental impact of point and non-point pollution on coral reef ecosystems in Mamala Bay in 1993-94 has not always been the case. Prior to 1977, most of the sewage discharged into Mamala Bay was untreated. In that year, sewage treatment was upgraded from raw to advanced primary and the outfall terminus was moved from a depth of 13 m to a depth of 73 meters, and 2743 meters offshore. In 1975, an extensive survey was conducted that ranged between 4 km to the east of the outfall and 13 km to the west of the outfall at Sand Island at depths between 5 and 20 m. Some of the results of this survey (Grigg, 1976) are replotted in Figure 4.1. In 1975, a large zone of impact existed around the old outfall, extending 2 km to the east and 4 km to the west, in which corals were either absent or severely depressed in abundance. The bottom area within 1 km of the outfall was completely dominated by Chaetopterus, a tube building polychaete that built thick (up to 0.5 m high) mounds or bioherms. Within the mounds, up to 100,000 nematodes/m^2 were found. Other species favored within the zone of impact were the algae, Ulva sp., sponges and the urchins Echinothrix diadema and Tripneustes gratilla. The urchins were exceedingly abundant and succeeded in bioeroding and

excavating virtually all living corals within the 6 km range. This accounts for lack of old colonies of P. lobata noted in the survey conducted in Mamala Bay in 1993-94.

By 1977, virtually the entire area within 6 km had been reduced to a flat hard plane of calcium carbonate with a benthic community dominated by species favored by the raw sewage. This community presumably replaced a normal coral reef ecosystem living in the area before the outfall was built in 1955. As such it represented a large scale phase shift in community structure (Hughes, 1994).

In 1978, one year after the outfall had been diverted into deeper water, another survey of the area was made (R.W. Grigg, Unpublished observations). At this time, all of the dominant species present in the zone of impact were now absent or very rare. The Chaetopterus bioherms had vanished. Urchins of both species were rare. Sponges and Ulva were absent. Another phase shift had occurred. The bottom was a hard pan barren limestone substratum with an abundance of cobbles and rubble and thin layers of sand. No coral recruitment was observed.

Then in 1982, huge waves generated by Hurricane Iwa devastated the entire coast of Mamala Bay (Borg et al, 1992). Anecdotal observations by R.W. Grigg, Gordon Tribble, Roger Pfeffer and many others, revealed that most of the reefs all across the bay, particularly those dominated by Porites compressa, the finger coral, were heavily disturbed. Many reefs formally supporting 60 to 100% coral cover were reduced to rubble. The only areas to "survive" were those where high relief existed and P. lobata was the dominant species. This explains the results of the 93-94' survey, that show that relative high coral cover exists only in high relief areas. By virtue of the complex morphology in high relief areas, they were little affected by scour and abrasion caused by transport and reworking of coralline rubble that occurs even during normal high waves every year in summer months.

Then in 1992, Mamala Bay was again hit by hurricane force waves, this time produced by Hurricane Iniki. Like Hurricane Iwa, waves from this storm were reported to be 25 feet or larger. In Hurricane Iwa, 30 foot waves were reported by the missile destroyer Goldsborough as it was leaving Pearl Harbor on November 23, 1982. Five crewmen were injured, one fatally, by waves that hit the ship (Chiu et al, 1983). The effects of Iniki were similar to those of Iwa in terms of scour and abrasion, however, coral breakage was not nearly so severe as with Hurricane Iwa since much of the vulnerable coral had already been heavily disturbed and little recovery had occurred. The dominant species to "weather" both storms was P. lobata and did so most successfully in areas of high relief.

In low relief areas in 1992, scour and abrasion was severe and the successional process was set back (Dollar, 1993). Piles of rubble were transported and reworked along the bottom (Figure 4.3). Only in areas relatively free of carbonate rubble, was there any evidence of substantial recovery and this was due to the recruitment and regrowth of P. meandrina since 1982. During the Mamala Bay 93-94' survey, all low relief stations were dominated by this pioneer species.

In summary, a historical perspective is necessary to interpret and understand the existing patterns of distribution and abundance of coral ecosystems in Mamala Bay. At the present time (1993-94), these ecosystems are virtually unaffected by both point and non-point sources of pollution in the bay. Distribution patterns appear to be related primarily to the effects of past episodic and severe storm events in 1982 and 1992. Today, the effects of these past intense and short lived physical events override the cumulative effects of long-term but slow biological processes such as recruitment, regrowth and succession. However, in the absence of intense future storms, biological processes should eventually return the ecosystem to a more mature successional stage. Unless significant changes occur in the nature of existing sources of point and non-point

source pollution, neither are expected to affect the long-term recovery of coral reefs in Mamala Bay.

5 CONCLUSIONS

1. Coral reef ecosystems in Mamala Bay are not significantly affected by point or non-point sources of pollution that presently discharge into the bay. This conclusion is based on the lack of demonstrated environmental impact at 3 levels of biological organization - the cell (growth and calcification), the population (survival and mortality) and the community (species composition, diversity and community structure).

2. Changes in water quality caused by rainfall and wave events are too small and too short lived to significantly affect coral reef ecosystems in the bay.

3. A historical perspective is necessary to interpret and understand the forces that control the community structure of coral reef ecosystems in Mamala Bay.

4. The structure of coral reef communities within Mamala Bay today appears to be primarily related to the effects of large hurricane wave events in 1982 and 1992. The effects of these events and associated secondary disturbances caused by scour and abrasion from coralline rubble, override long-term but slow biological processes of regrowth and recruitment.

5. Recovery of coral reef ecosystems in Mamala Bay is now taking place from damage sustained during the 1982 and 1992 hurricane events and an earlier period of serious environmental degradation prior to 1977 when raw sewage was discharged into the bay at 13 m depth off Sand Island.

6. High relief areas in Mamala Bay today, support higher coral cover because they appear to have been less affected by past hurricane damage as well as secondary disturbance associated with scour and abrasion from coralline rubble and sand. Massive species such as P. lobata, are favored over branching and encrusting forms.

7. Notwithstanding the effects of hurricane magnitude storm waves, natural biological processes should eventually return coral reefs ecosystems to a more mature succesional

stage in Mamala Bay. Point and non-point sources of pollution (unless altered from the present state) should not interfere with the recovery process.

6 RECOMMENDATIONS

1). The findings of this study which document the lack of environmental impact of point and non-point source pollution on coral reef ecosystems in Mamala Bay do not alone warrant any changes in existing waste water treatment practices for effluents discharged into Mamala Bay.

2) Future research is recommended and should include monitoring of coral reef ecosystems within Mamala Bay. Data should be collected at established stations in order to maintain continuity and create a long-term data base. Data should include at least those parameters measured in this study.

3). Should changes in growth, species composition or community structure occur due to such things as bleaching, disease or to other unforeseen events, a research protocol should be adapted to include these aspects in future studies.

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