ECOLOGICAL RESPONSE OF BENTHIC COMMUNITIES TO RELAXATION OF SEWAGE STRESS OFF SAND ISLAND, O'AHU

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ABSTRACT

From 1935 to 1977, the largest domestic sewage outfall in Hawaii discharged 62 mgd of raw sewage in 10 m of water approximately 1 000 m off Sand Island, Oahu. Results of an ecological field study conducted in 1975 of epibenthic communities near Sand Island show clear patterns of community change associated with both sewage impact and relaxation of this stress: negative community effects attributable to sewage input decreased and degree of recovery of community structure increased with distance from the point source of discharge. Sewage discharge had an impact up to 5 800 m west and 1 900 m east of the outfall. This elliptical area of influence is asymmetrical to the west due to the prevailing current pattern which carried the sewage-laden plume to the south-west.

Within this area of influence two distinct zones of impact are distinguished by the degree of physical degradation of the benthic reef structure. An acute impact zone extending some 500 m east and 1 000 m west of the outfall is now characterized by a complete biochemical reduction of the reef structure to a pitted, flat carbonate pavement presently covered with sediment-bound algal turf. Prior to outfall termination the acute impact zone was characterized by high biomass and low diversity from domination by sewage-dependent species. Following sewage abatement biomass is low and diversity higher due to limited colonization of the newly exposed substrata.

In the zone of intermediate impact the old reef framework is largely intact, though devoid of most living corals. Instead a veneer of encrusting coralline algae covers most of the reef framework. During sewage discharge, the zone of intermediate impact showed increases in diversity compared with both control and high impact stations due to the presence of both normal species and species associated with the outfall. Following sewage abatement, diversity increased even further since the new colonizers are a more varied assemblage than the relatively few species that disappeared with the removal of sewage stress; no single species is yet dominating the community. The degree of response by benthic organisms in both the acute and intermediate impact zones is correlated with the degree of physical destruction of the reef framework.
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INTRODUCTION

Waste water discharge from domestic sewage outfalls may significantly affect the biological and physical composition of benthic coral reef communities in a variety of ways. The major environmentally significant aspects of the delivery of organic matter (sewage) is nutrient loading and consequent cultural eutrophication of the ecosystem (Smith 1977). The accumulation of organic-laden sediments emanating from outfall discharge or from passage through the food chain can modify or cover substrate causing them to become unsuitable for settlement by many epibenthic species (Grigg and Kiwala 1970). Increases in organic-laden sediments can also lead to domination of hard bottom substrates by epifaunal filter feeders dependent on the high organic loads. These filter feeders may successfully outcompete "normal" reef species for space and light. Increases in turbidity from both increased organic particulates, and stimulated autotrophic production in the water column may decrease light energy available for benthic photosynthetic activity. The discharge of sewage can also depress the abundance of species sensitive to toxins in the effluent and low oxygen levels associated with eutrophication (Rastetter and Cooke 1979). Changes in biological processes, notably competition and predation, associated with effluent loading may also affect community structure. It is possible that all, or some of these effects may simultaneously influence the distribution and abundance of the benthos, and some effects are synergistic (Grigg 1978). However, since most of these factors change in a similar fashion as a function of distance from the pollution source, separation of each effect requires a high

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degree of control on the variables, a condition not easily achieved in field
studies (Rastetter and Cooke 1979).

However, predictable and quantifiable technological events may provide op-
portunities to apply an experimental approach to the investigation of inter-
actions between ecosystem stress and subsequent response once the stress is
eliminated. The diversion of sewage from an existing outfall of longstanding
duration can provide such an opportunity to observe, monitor, and quantitatively
assess the recovery of a benthic community following cessation of the forcing
variable.

The present investigation was designed to document the effects of dis-
charge of raw sewage for 22 years on a shallow reef community off Sand Island,
Oahu, Hawaii and to evaluate quantitatively and observationally the environ-
mental response to the abrupt and virtual total elimination of this sewage dis-
charge after 18 months. From this assessment of "before-and-after" change, it
may be possible to gain some ability to predict ecosystem response and thus
speculate whether, or to what extent, communities are returning to prestressed
conditions.

Benthic organisms are particularly well suited for studies designed to
evaluate the effects of waste water discharge on aquatic or marine systems be-
cause their sessile habitat selection and/or low mobility often cause them to
be directly affected by exogenous inputs of materials. Components of the ben-
thos must either tolerate the surrounding conditions within limits of adapta-
bility or die (Reed 1978). Likewise, benthic species can also be expected to
recolonize a stressed area only when conditions have returned to within their
range of tolerance. Therefore, changes in the composition of the benthos is
one measure of the effects of both long-term exposure and the removal of en-
vironmental stress.
The focal point of this study, the Sand Island Sewage Ocean Outfall, is the largest sewer outfall in Hawaii, handling approximately one-half the domestic sewage on Oahu, and servicing an area from Niu Valley to Moanalua. From 1955 to mid 1977 this sewage was discharged "raw" from a shallow outfall which extended 1097 m (3600 ft) from shore and terminated at a depth of 11 m (35 ft) (Fig. 1). Prevailing winds and water currents usually caused the elliptical sewage plume to be held close to shore and attenuated to the west, toward Pearl Harbor. This plume was readily discernible by a dark brown discoloration of turbid water, as well as a strong odor.

In recent years the dramatic increase in awareness of the problems of sewage impact has been reflected in the Federal Water Pollution Control Act of 1972, which states as its objective "...to restore and maintain the...biological integrity of the Nation's waters." In response to this Federal mandate the City and County of Honolulu completed construction in February 1978 of a new sewage treatment plant and outfall off Sand Island. The new outfall discharges partially primary treated sewage approximately 2743 m (9000 ft) offshore at a depth of 61 to 73 m (200-240 ft). Since completion, the new deep-water outfall has been the sole source of sewage discharge in the Sand Island area, thereby removing the stress of sewage effluent from the shallow hard-bottom communities.

In 1975, during the period of shallow outfall operation, Dr. Richard Grigg of the Hawaii Institute of Marine Biology conducted a survey of the Sand Island area as part of the Sea Grant Coral Reef Management (CORMAR) program. The purpose of this survey was to document the extent and degree of the effect of sewage discharge on the hard-bottom benthos in the vicinity of Sand Island. The results of this survey serve as the data base for the "before" aspects of the present investigation.
FIGURE 1. LOCATIONS OF OLD AND NEW SAND ISLAND SEWAGE OUTFALLS
METHODS

The field study period ran from 12 December 1978 to 15 March 1979. Several methods were employed in the collection of qualitative and quantitative data from the Sand Island Outfall area. Qualitative reconnaissance surveys covering the entire study area were conducted by towing, at slow speed, a diver holding a line behind a small boat. These surveys were useful in making relative comparisons between areas, identifying any unique or unusual biotic resources, and providing a general picture of the benthic assemblages occurring throughout the region of study.

Benthic Transect Methods

Quantitative surveys were conducted using SCUBA apparatus from an anchored 5 m (18-ft) boat provided by the City and County of Honolulu. These surveys consisted of line transects at three different depths (5, 10, 20 m) at each of nine stations. An additional transect was studied at the old outfall site, for a total of 28 transects. Station locations and transect depths were selected to correspond as closely as possible to locations surveyed in the 1975 pre-abatement study, in order for the data to reflect as accurately as possible changes occurring in the same microenvironment. Stations within the area of observable change associated with the outfall were located off Kewalo Basin, Sand Island (east and west ends), Kalihi Channel, and the reef runway off Honolulu International Airport. Control stations located beyond the apparent area of disturbance were situated off Magic Island and Oneula Beach Park (Fig. 2).

The transecting method in this study used a replicating technique, i.e., information was recorded both photographically and by visual estimation in situ. At each location, a 50-m transect line was placed over the reef substrata as close to the specified depth as topography allowed, and parallel to the shoreline. A 1 x 0.7-m aluminum rectangular quadrat (same proportion as a 35-mm
FIGURE 2. STATION LOCATIONS, TRANSECT NUMBERS AND DEPTHS, 1975 AND 1979, SAND ISLAND SEWAGE OUTFALL, O'AHU.
transparency) with a Nikonos camera and electronic strobe light supported by four legs at a fixed distance from the center of the quadrat, was sequentially placed on the reef surface over 10 random points on the transect line. At each of these points a color photograph of the substrate enclosed by the quadrat frame was taken. The term photo-quadrat refers to a photograph of a given area of the benthos. In addition, a diver with knowledge of resident species visually estimated the areal coverage of all organisms larger than approximately 2 cm within each quadrat. These estimates also included the number of echinoids and other motile invertebrates, as well as the presence of various macrothalloid algae. Algal abundance estimates were limited to presence-absence. No quantitative data on algae were collected in the 1975 survey, and therefore only qualitative comparisons of algal occurrence (with the exception of calcareous encrusting species) were possible.

Following investigation, the quadrat photographs were projected on a grid with dimensions similar to the quadrat frame, and the units of bottom cover of each species and substrata type were summed for each transect. This information was applied to the in situ cover estimates and the combined assessments provided the data base for the benthic community structure analyses.

Benthic cover values are directly related to successful competition for substrate space, photosynthetic area, and exposure to planktonic food resources. It may also avoid biases which numbers bestow to small individuals and which biomass bestows to larger or heavier organisms (Bohnsack 1979).

The practical advantages to photo-quadrat sampling are numerous: the methodology requires little field or laboratory training or experience; most species can be easily and accurately identified from transparencies; and the color transparencies provide permanent records which are easily duplicated and quickly and accurately analyzed without extraneous factors inherent in field tabula-
tions, stored in a small amount of space, and easily sorted and catalogued. Sampling speed is rapid and efficient with respect to time and data collected—an important consideration under conditions where underwater time is restricted by cost, depth, and exposure. Photo-quadrats contain much more information than could possibly be recorded by divers in a similar time span. In most cases, the sampling does not disturb the organisms present—a valuable asset in studies where documentation of temporal changes of the same space is necessary (Bohnsack 1979).

While the potential of quantitative photographic sampling is tremendous, the procedure nonetheless has several drawbacks. The best photographic results depend on relatively flat surfaces. When the three-dimensional reef surface is examined on a two-dimensional photographic plane, estimates of abundance are biased in favor of flat or encrusting species. Other problems are that cryptic and inconspicuous individuals, as well as smaller organisms and infaunal and nocturnal species, are usually underestimated. Some species also require actual specimens for exact taxonomic identification. Another source of error is failure to observe timorous species which may leave the area at the approach of the quadrat frame and diver (the scare factor). An excessive canopy in areas of high relief can conceal an understory, although this may be corrected by removing the canopy and then sampling. A final drawback is that the effectiveness of the photographic method is reduced in areas of excessive turbidity, often a factor in the vicinity of sewage outfalls.

Other Field Methods

Sediment samples were collected at each transect location for analyses of micromolluscan assemblages by Dr. E. A. Kay.

Water quality and physical oceanographic data referred to in this study were gathered by consultants to the City and County of Honolulu and appear in
an in-house publication, "Water Quality Program for Oahu with Special Emphasis on Waste Disposal" (Dept. of Public Works, City and County of Honolulu 1970).

Numerical Analysis Methods

The information generated by transect analyses provided estimates of (1) number of species present, (2) density, and (3) percent bottom cover of each species and substrate type. By using estimates of species diversity, evenness, and similarity coefficients, it is possible, from measurements made, to evaluate the effects of waste discharge, and discharge abatement on benthic communities. Species diversity is equated with the degree of uncertainty that exists regarding the species of an individual (colony) selected from a population. The Shannon-Wiener index of diversity is sensitive both to the number of species (species richness) and to the degree of equal apportionment of the individuals among the species (equitability). The Shannon-Wiener index of diversity is represented by

\[
H_\text{C}^I = \sum_{i=1}^{s} p_i \ln p_i,
\]

where \( p_i \) is the proportion of cover by the \( i \)th species in the population and \( s \) is the number of species (Pielou 1966).

In order to compare the "before and after" effect on community composition at Sand Island, Sorenson's similarity index was used (Mueller-Dombois and Ellenberg 1974). This index in effect measures the redundancy of species from one spatial community to another or, in this case, from one point in time to another. The equation for the index is

\[
SI = \frac{2C}{(A + B)}
\]

where \( A \) = number of species in 1975 transects, \( B \) = number of species in the 1979 transects and \( C \) = number of species in common.

Mueller-Dombois and Ellenberg (1974) suggest that an index of 50% (.50) represents a threshold value; that is, if the index value exceeds 50%, the similarity is great enough to indicate that the species are a part of the same association or community.
RESULTS

Preabatement Results

To evaluate the response of the marine communities off Sand Island to relaxation of sewage stress, it is first necessary to have a clear idea of community structure and pattern of response during the period of environmental impact by sewage discharge. Following is a summary of the physical conditions, community structure, and species composition of the benthos compiled in the preabatement studies off Sand Island.

Grigg (1975) found that, although the nature of change varied with depth and proximity to the outfall terminus, in all cases the effects were asymmetrical, extending more to the west, in the direction of the predominant current.

With regard to spatial distribution of organisms, Grigg found that in relation to the outfall there were at least four patterns of abundance: species which are unaffected, species which are enhanced, species which are depressed, and species which are sparse near the outfall but more abundant than normal at various distances from the outfall. A complete tabulation of all species present on all transects may be found in the forthcoming WRRC Tech. Rep. No. 124, "Ecological Response of Marine Communities to Relaxation of Sewage Stress off Sand Island, O'ahu," by S. J. Dollar. Three zones of influence were apparent: a zone of acute impact, intermediate impact, and no impact or control zone (Fig. 3). In 1975, reef corals were among the species with a depressed pattern of abundance, and were nonexistent within 400 m of the outfall terminus (Figs. 4-5, Table 1). Extensive mounds of an arenaceous polychaete, *Chaetopterus* sp. were found in this area. Reed (1978) also reported extensive benthic cover of *Chaetopterus* mounds in the vicinity of the outfall within these mounds characteristically reaching heights of up to 1 m and diameters of 2 to 3 m. The large increase in total benthic macroinvertebrate cover, of between 35 and
FIGURE 4. PERCENT CORAL COVER FROM TRANSECT DATA, 1979, SAND ISLAND SEWAGE OUTFALL, O'AHU.
FIGURE 5. NUMBER OF CORAL SPECIES ON TRANSECTS, 1975 AND 1979, SAND ISLAND SEWAGE OUTFALL, O'AHU.
### TABLE 1. 1975 PREABATEMENT MACROINVERTEBRATE ABUNDANCE (IN PERCENT COVER) AND DIVERSITY AT SAND ISLAND SEWAGE OUTFALL O'AHU

<table>
<thead>
<tr>
<th>Transect No.</th>
<th>km from Outfall</th>
<th>Depth m</th>
<th>Macroinvertebrate Cover</th>
<th>Coral Cover</th>
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<td></td>
<td></td>
<td>Cover %</td>
<td>No. of spp.</td>
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<td>23.4</td>
<td>13</td>
</tr>
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<td>5</td>
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<td>6</td>
</tr>
<tr>
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</tr>
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<td>4.2</td>
<td>2</td>
</tr>
<tr>
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<td>5</td>
<td>2.6</td>
<td>3</td>
</tr>
<tr>
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<td>62.4</td>
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Source: Grigg (1975).
75% at 10 and 20 depths (Stas. 8, 9, 10) near the outfall in 1975, was almost exclusively due to the presence of Chaetopterus mounds (Fig. 6, Table 1). Although species cover was high in this area, the number of species was very low (Fig. 7, Table 1), with only two species present at transects 8 and 10 nearest the outfall. Grigg observed that, in many areas near the outfall, areas of substrate up to several hundred square meters were totally covered by the polychaete mounds. At the 5-m depth transects (Nos. 4, 7, 11) inshore from the outfall, (1975) Chaetopterus abundance was greatly reduced; patches of the worms that did occur appeared to be associated with Pocillopora meandrina colonies. Frequently the worms seemed to be in the process of smothering these coral colonies.

Although this annelid was observed in vast quantities off Sand Island, it is presently an undescribed species* and little is known of its habitat. The worm appears to be a deposit feeder and is obviously favored by the enriched environment associated with the outfall. The polychaete mounds, which may be considered bioherms, are made up of thick masses of entangled parchment tubes and entrapped sand. Present within these masses was an enormously rich infauna consisting of nematodes, other polychaetes, ostracods, and amphipods. For example, the density of nematodes was estimated to be as great as 100,000 individuals/m² (Engineering-Science 1970).

Moving away from the outfall discharge point, Grigg (1975) found a relatively barren zone about 600 m shoreward of the outfall terminus (Transects 7, 11). The shortspined sea urchin, Tripneustes gratilla was the only unusually abundant species, but small mounds of Chaetopterus and occasional colonies of Pocillopora meandrina also occurred (Fig. 6, 7). Some of the dense aggregations of motile echinoids may have been due to relocation or migration out of

*J. Bailey-Brock 1978: personal communication.
FIGURE 6. PERCENT COVER OF ALL INVERTEBRATE SPECIES, 1975 AND 1979, SAND ISLAND SEWAGE OUTFALL, O'AHU.
FIGURE 7. NUMBER OF INVERTEBRATE SPECIES, 1975 AND 1979, SAND ISLAND SEWAGE OUTFALL, O'AHU.
the Chaetopterus zone since there were no uncovered substrate surfaces left on which to feed.

Beyond this entire area of acute impact, termed the "Chaetopterus Zone," a region of intermediate impact extended on either side of the outfall. This zone was approximately 4,000 m wide to the west of the outfall, commencing about 2,000 m west of the outfall and extending to 6,000 m. To the east, this zone commenced about 500 m from the outfall and extended to about 2,000 m from the discharge terminus. At its inner periphery, Grigg found this zone to be relatively barren of macroscopic invertebrates. For example, at Transects 11, 12, and 14 there were only traces of sponges, polychaetes (Chaetopterus sp., Salmocina sp.), and the alcyonarian, Anthelia edmondsoni. Several echinoids (Echinocardia diadema and Tripneustes gratilla) were present, while occasional newly-settled, small patches of the stony corals Leptastrea purpurea, Porites lobata, and Montipora verrucosa were found (Table 1). The overall structure of the substrata in this area was a flat, pitted limestone pavement covered with a short, but very dense, algal turf. No large skeletons of recently dead corals were present.

Toward the middle of the intermediate zone, species associated with both the outfall and "normal" environments coexisted, a factor which accounted for the high peaks in species diversity and evenness on both sides of the outfall, especially at 10 and 20 m (Figs. 8, 9). This zone can be considered an ecotone between polychaete- and coral-dominated communities. While no species were consistently dominant in the mid-intermediate zone, several appeared with high frequency. The zoanthid Palythoa tuberculosa was particularly characteristic, as were several stony corals. Many of these coral colonies occurred in small patches which appeared to be remnants of much larger colonies, most of which had died. The dominant substrate in this mid-intermediate zone was a consoli-
Figure 8. Shannon-Wiener diversity index ($H'_C$) for coral cover, 1975 and 1979, Sand Island sewage outfall, O'ahu.
Figure 9. Shannon-Wiener diversity index ($H'_2$) for all macroinvertebrates, 1975 and 1979, Sand Island sewage outfall, O'ahu.
dated, but highly eroded, limestone reef covered with a low algal turf that entrapped a layer of silt and particulate organic matter.

At the outer periphery of the intermediate impact zone, the only conspicuous feature was the relatively low coral cover at the 10- and 20-m transects, apparently due to high percentages of dead, but intact, _Porites compressa_ colonies. Other than this, species composition at the outer periphery of the intermediate impact zone was not much different from stations located beyond the influence of the outfall discharge. Normal, or control, reefs existed on both sides of the outfall, approximately 3000 m east and 6000 m west of outfall terminus. It is noteworthy that diversity values of both total benthic living cover and living coral cover are generally less at stations representative of normal areas and acutely impacted areas, compared to stations in the intermediate zone (Figs. 8, 9).

This same pattern has also been documented for other environments subjected to sewage stresses. In general, highly enriched waters are characterized by a few "tolerant" species, notably mud-tube dwelling fauna (Nair 1962; McNulty 1970; Rastetter and Cooke 1979), and mats of blue-green algae, diatoms, and sulfur bacteria (Barnard 1968; Golubic 1970; Littler and Murray 1975). Biotic diversity usually increases where pollution is less severe (Mor et al. 1970), and decreases in nutrient-poor areas. Biomass is high in areas of high enrichment and decreases as nutrient levels fall off (Long 1972; Rastetter and Cooke 1979).

Postabatement Results

Abundance, species diversity, species composition, and similarity coefficients of the benthos approximately 18 months after sewage abatement are presented in Table 2 and the distribution of these parameters on the transects is shown in Figure 4 to 11. Qualitative and quantitative descriptions of the physical and biological setting of the Sand Island area indicate that the three
### TABLE 2. 1979 POSTABATEMENT MACROINVERTEBRATE ABUNDANCE (IN PERCENT COVER) AND DIVERSITY AT SAND ISLAND SEWAGE OUTFALL, O'AHU

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<tr>
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<th>Coral Cover</th>
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Source: Dollar (1979).
FIGURE 10. INDEX OF SIMILARITY FOR CORAL SPECIES, FISH SPECIES AND TOTAL BENTHIC MACROINVERTEBRATES, 1975 AND 1979 SURVEYS, SAND ISLAND SEWAGE OUTFALL, O'AHU.
Figure 11. Percent cover of calcareous encrusting algae, 1975 and 1979, Sand Island Sewage Outfall, O'ahu.
zones of influence described in 1975 (acute impact or *Chaetopterus* zone, intermediate zone of biological change, and control or unaffected zone) are still clear and consistent patterns associated with the outfall. However, some of the boundaries and dominant features of these zones have changed in the time between the surveys. The major factor distinguishing these zones is the degree of degradation of the primary reef framework; in the acute impact zone the entire reef structure has been reduced to a pitted flat limestone pavement by biological and/or chemical erosional activity. In the intermediate zone the reef structure is obviously stressed and many of the primary framework builders are dead, but the structure is recognizable to be at least partially intact. Beyond these zones of effect, there are no apparent alterations to the physical or biological community structure. This region serves as the control zone. Distinct patterns of biotic response, in terms of before-and-after comparisons within the zones of effect are described below.

**Acute Impact-Chaetopterus Zone**

The most conspicuous difference between the pre- and postabatement surveys was that the *Chaetopterus* worms which had dominated the benthos within 500 m of the outfall had entirely disappeared from the area in 1979. During the approximately 50 hr spent underwater conducting this field survey, not a single worm or remnant of a parchment tube was observed. It appears that, with the cessation of the enriched, organic particulate rain emanating from the outfall, the deposit-feeding worms were no longer able to dominate or even exist near the outfall. Instead, the substrata in this zone of impact is presently a pitted limestone pavement covered with a ubiquitous mat of fine filamentous algae and entrapped sand grains. Interspersed in this carbonate pavement are patches of soft sediment, predominantly coarse white sand. This dramatic difference in bottom cover is graphically shown in Figure 7 where the peaks in percent cover,
representing preabatement *Chaetopterus* cover of 31.5% and 74.9% at 10 and 20 m respectively, are totally lacking in the postabatement benthic macroinvertebrate cover.

The present pitted structure of the limestone pavement may be a result of bioerosional activity of the boring sea urchins, *Echinometra mathaei* and *Echinostrephus aciculatus*. The abundance of these organisms is relatively low (less than .4 individuals per m²) in the acute impact zone (Fig. 9) both before and after outfall termination, and the pitted area is several thousand square meters in extent and has a uniform degree of eroded relief. Thus, the data indicate that other eroding factors are also responsible for the substrate appearance. These factors may include bioeroding cryptofauna and endolithic algae, as well as possible biochemical dissolution of the substrate due to sewage input. The most likely event leading to this extensive erosion is the creation of an anaerobic milieu close to the reef surface due to the dense overlying *Chaetopterus* mounds. Biological activity of bacteria in this layer would lower the pH, which could result in chemical dissolution of the calcium carbonate framework. It appears that reefs close to the outfall may have been exposed to such high levels of sewage-rich waters that corals and coralline algae were quickly killed and that biological or chemical erosion proceeded at such a rate that now, approximately 22 years after outfall initiation, the only remaining remnant of the reef is the pitted limestone surface.

While no living corals were observed in the *Chaetopterus* Zone during the preabatement study, infrequent, small, scattered living corals are presently encountered on the predominantly barren substrate (Figs. 4, 5; Table 2). Percent coral cover on these transects ranges from 0 to 1.35%. These corals consist of four species: *Pocillopora meandrina*, *Leptastrea purpura*, *Porites lobata*, and *Montipora verrucosa*. The most common species *Pocillopora meandrina*,
a fugitive species, is the first to settle newly created, or newly cleared, substrata (Grigg and Maragos 1974). This seems to be the case in the high impact zone off Sand Island where numerous colonies not present in 1975 now occur. The most dense aggregations of these colonies occurred on the outfall diffuser structure and the surrounding boulders where eleven small P. meandrina colonies were counted on one diffuser pipe. This same pattern of P. meandrina colonization has been noted on sewer pipes off Wai'anae, O'ahu (Reed et al. 1977) and Mōkapu Point, O'ahu (Russo et al. 1979). The coelenterates Anthelia edmonsoni and Palythoa tuberculosa are also colonizing these outfall structures.

Thus, while the total percent coral cover remains less than 1.4% on Transect 7 to 14 in the postabatement survey (Fig. 4), the relative equality of distribution of the colonizing species results in relatively high diversity (maximum $H^2_C = 1.38$ at Transect 10) values (Figs. 8, 9).

As in the preabatement survey, echinoids are presently one of the dominant benthos components in the barren acute impact zone. Numerous Tripneustes gratilla are present in the sandy areas, and Echinosthrix diadema is abundant on the limestone pavement, apparently browsing on the algal turf. Relatively few Echinometra mathaei are observed on the limestone pavement. The peak in E. mathaei abundance of 5.9 individuals/m², encountered in the preabatement survey at Transect 7, was reduced to 2.9 individuals in the postabatement survey. Few other macroinvertebrates, with the exception of the sponges, Iotrocha protea, Dysidea sp. and Spirastrella vagabunda, are present in the acute impact zone. Also conspicuous by their absence are leafy algal species. However, small encrustations of Porolithon onkodes and Peyssonella rubra as well as Halimeda discoidea were seen on the limestone pavement. Within the area of acute impact, up to 1 km east and west of the outfall site, similarity coefficients (Fig. 10) comparing the preabatement to postabatement coral and total
invertebrate communities are all below the .5 threshold level. This indicates that changes over time since relaxation of sewage stress has resulted in distinctly different community assemblages in the acute impact zone.

Intermediate Impact Zone

The intermediate impact zone is distinguished from the acute impact zone by the degree of degredation of the reef structure. In the intermediate impact zone at least part of the reef framework is still intact even though the primary framework builders, primarily corals and coralline algae, may be destroyed.

In the preabatement survey the co-occurrence of species associated with the effluent discharge and normally occurring species accounted for the peaks in species diversity on both sides of the outfall in the area termed the intermediate impact zone. However, following sewage abatement and the subsequent disappearance of species associated with the outfall, species diversity has remained high within the intermediate zone due to the replacement of species associated with the outfall by new colonizers that have moved into the area following the disappearance of the outfall-associated stress. While the two species of annelid worms associated with the outfall, *Chaetopterus* sp. and *Salmacina* sp., contributed to the species counts in the intermediate zone in the 1975 study, a fairly numerous array of new colonizing species of sponges, echinoids, corals, and algae were encountered in the 1979 survey (Fig. 6, 7; Table 2). Similarity indices of less than .5 (Fig. 10) between the pre- and postabatement benthic assemblages indicate that the community structure of all stations from 1 300 m east to 1 950 m west of the outfall is different before and after outfall termination. This entire area, from the west Sand Island station to the east reef runway station corresponds to the zones of high and intermediate impact where species associated with the outfall were present during the preabatement period. At the west reef runway station, (Transects 18-20) where
definite effects of the outfall showed but where outfall-associated invertebrates were not present in 1975, the similarity indices indicate that the community assemblages are the same in pre- and postabatement periods (Fig. 10). As in 1975, this zone of impact is asymmetrically shaped, extending further to the west. For this reason, the zonal gradations to the east of the outfall are very compressed compared to the western attenuated zonation.

In the inner areas of the intermediate impact zone (Transects 11-14) conditions are very similar to the high impact area; the major benthic feature is a pitted limestone pavement covered with a mat of algal turf and sparsely populated with small coral colonies, sponges, and grazing echinoids. The frondose algae, *Asparagopsis taxiformis* and *Ulva* spp. also occur in this area. The only difference between this inner periphery, intermediate, and the high impact zone is that some older, large, dead reef coral fragments remain in the former area.

Moving away from the outfall, the center of the intermediate impact zone differs from the inner periphery in that the substrate is less reworked by bioturbating forces. Rather, the substrate in this area is recognizable as former *Porites*-dominated reefs that are now largely dead, but intact, skeletal structures. A fine layer of silt covers much of this dead reef and reef rubble. Living corals in this area are very sparse, and the few that do remain appear to be older colonies growing off the reef surface on dead, pedestal-like bases. Patches of *P. compressa* with only the terminal branch tips remaining alive are also common at the 20-m transects in this subzone. Newly settled colonies are very sparse in this area, apparently due to the silt cover. Sponges, as well as grazing and burrowing echinoderms, are the only other dominant macrobenthos in this area of high silt deposit. No frondose algae were observed in this area.

The outer periphery of the intermediate impact zone exhibited the most in-
teresting example of postabatement colonization. The bottom composition off
the west reef runway stations (Transects 18-20) is recognizable as old *Porites*
reefs, with the dominant species *P. lobata* at the 5- and 10-m depths and
*P. compressa* at the 20-m depth. While this primary reef framework is still
recognizable to the species level, a very small percentage of living coral re-
 mains. Rather, the framework is almost totally covered with a solid veneer of
red, encrusting calcareous algae, predominantly *Porolithon onkodes*, *Peysonnel-
lia rubra*, *Sporolithon erythraeum*, *Tonearea tessellatum*, and the crustose melo-
besioids. This calcareous algal cover accounts for 23% to 75% of the substra-
tum at west reef runway transects. The major coral components of this area
are the encrusting species *Pavona varians* and *Montipora* spp., which are growing
interstitially within the reef framework. The skeletal structure of the reef
framework is extremely friable and easily broken, evidence that the structure
has been extensively reworked by bioeroding organisms.

Samples of the reef framework from this outer periphery of the interme-
diate impact zone which were sectioned in the laboratory revealed thick depo-
sits of up to 3 cm. of calcareous algae covering the dead coral skeletons, and
extensive working of the interior by bioeroding sponges, mollusks and annelids.
Thickness of encrustations and bioeroding activity varied inversely with dis-
tance from the outfall. Infauna contained in the sections from the central
runway station consisted primarily of gastropods and sipunculids, while there
was very little evidence of activity of boring sponges. Janet White, a PhD.
candidate at the University of Hawaii currently examining the bioerosion asso-
ciated with sewage input into Kane' ohe Bay, speculates that bioeroding and en-
crusting activity near the east runway station, closer to the outfall, has been
in progress for a period on the order of 20 yr while off the central runway
this activity may have only been occurring for approximately 5 yr. Although
calcareous algae were recorded at these same stations in 1975 during outfall operation (maximum cover 24.5% at Transect 19), their abundance was markedly less than in 1979, following sewage abatement (maximum cover 74.7% at Transect 19) (Fig. 11). This indicates that termination of sewage stress is a factor responsible for the present high cover values of the algal encrusters. Similarly, at the 5-m transect (No. 18) in 1979 living benthic cover is dominated by the anthozoan Palythoa tuberculosa (30.5% total bottom cover) (Fig. 4). Although this species was present in the 1975 survey, it did not dominate the substrata as it does today with a bottom cover of only 2.5%. This species is adapted to the high surge of the shallow, 5-m transect site and appears to have proliferated following sewage abatement.

A rather unexpected observation in the outer periphery of the intermediate impact zone was a large aggregation of crown-of-thorns starfish, Acanthaster planci, on the calcareous algal reef. This aggregation had an approximate density of 1 individual/10 m². The preferred prey species of Acanthaster in Hawaii, Pocillopora meandrina and Porites spp. (Branham et al. 1971) were entirely absent from this area. Overturning these individuals indicated that none were feeding on the limited live coral cover of the area.

In the 1975 survey, the outer periphery of the intermediate impact zone off Pearl Harbor was characterized by extensive areas of dead Porites compressa (Fig. 4; Table 1). This was not the case in the 1979 survey when transect data off Pearl Harbor showed benthic assemblages very similar to control transects, with no large areas of dead coral (Table 2; Fig. 4). It is possible that the degree of sewage stress reaching Pearl Harbor during the preabatement period was of a level to cause death to much of the delicate P. compressa, but not to other, harder species. Following sewage abatement, when water conditions returned to a normal state, the rapidly growing P. compressa recolonized the in-
tact reef framework so that conditions today are similar to an unstressed community. Indeed, reefs off the Pearl Harbor entrance channel at the extreme western end of the reef runway presently show no apparent negative effects to benthic community structures.

DISCUSSION

The community structure of the benthos in the vicinity of the old outfall and predominant wind and current patterns provide convincing evidence that the cause of stress can be attributed to effluent related factors. Nevertheless, other sources of pollution, such as discharge of waters from Honolulu and Pearl Harbor, periodic channel dredging with resulting siltation, and construction of the reef runway, may have or are exerting some influence on the benthos and related communities off Sand Island. If so, these communities may not be comparable to the areas that lie to the east or west. However, since these sources of stress appear to be relatively insignificant in the Sand Island region now, it is assumed that patterns of benthic community structure were not significantly different than control stations prior to outfall operation.

At Sand Island the most obvious response to relaxation of sewage stress is the complete disappearance of Chaetopterus and other epifaunal filter feeders dependent upon suspended organic materials in the water column. This rapid disappearance of the annelid bioherms and the lack of sediment accumulation have caused an abundance of substrate to be made available for settlement by species either intolerant of sewage stress or formerly smothered by Chaetopterus mounds. At the present stage of recovery this new substrata is covered by a sediment-bound algal turf; a fact which probably accounts for the limited colonization of corals, coralline algae and associated epibenthos species. In contrast, the outfall structure itself and the surrounding boulder bottom is supporting the recolonization of a more abundant and diverse community than the surrounding
reef bench. The difference in colonization rates on these artificial surfaces and the natural reef substrate indicates that there is a qualitative difference between the two surface types. Post-settlement mortality from predation by small infauna of the reef platform and interference with larval settling from the unconsolidated sediment-bound algal turf may be major reasons for lack of new colonization in the acute impact area. Harrigan (1972) found that the most favorable surface for coral planlar settlement is a flat growth of green algae, diatoms, and bacteria. If this film is thicker than approximately .5 cm young corals were smothered or could not attach directly to the underlying hard substrate. It is possible that the dense mat of filamentous algae as well as the unconsolidated bound sediment which rapidly covered the pitted limestone pavement following disappearance of the Chaetopterus mounds is responsible in part for low rate of settlement of epibenthic macroinvertebrates. Harrigan (1972) also found that pieces of worn, dead coral which had lain in water long enough to acquire a patina of green algae contained small crustacean and annelid predators which devoured newly settled primary polyps during the night. This predation by small infauna appears to be a major source of mortality among newly settled polyps. A combination of lack of predators, elevation off the reef surface and vertical surfaces, which would reduce the amount of bound sediment, may account for the higher settlement rates on inorganic surfaces compared to natural reef rock.

Whether by introduction of toxins or increased turbidity that reduced available light energy, sewage introduction into the intermediate zone of impact resulted in a very high level of coral reef destruction. However, this destruction, as well as the recolonizing response, is very different than that found in the acute impact zone. The most important difference in the mode of destruction is that the reef substrate is still intact in the intermediate
zone; biochemical erosion is less a destructional factor than in the acute im-
 pact zone.

In terms of response to sewage abatement, coralline algae rather than fila-
mentous algae is the dominant re-colonizer. Recolonization by hermatypic corals
which are recognizable as former primary framework builders of this area has
yet to become widespread. The most obvious explanation for the lack of coral
colonization is that planulae do not settle on encrusting algal surfaces. How-
ever, views of this explanation are conflicting. Harrigan (1972) reports that
planulae of *Pocillopora damicornis* do settle directly on coralline algae, while
Keumen (1950) believed that corals would not grow on coralline algae. However,
Harrigan states that "...settlement on a particular substratum does not ensure
that the organism will be able to survive and grow on it. But so much calca-
reous algae is found on reefs that it would seem an adaptive advantage for the
planulae to settle and survive on it." Continued observations of the Sand Is-
land area over a regular time interval would provide a unique natural experi-
ment on the settlement behavior of coral planulae and other forms of benthos,
as well as on the successional changes of the calcareous algal community.

Differences in community structure on the Pearl Harbor transects before
and after sewage abatement also illustrate differences in recolonizing response
as a function of mode and degree of environmental destruction. The Pearl Harbor
transect appeared to be at the outer periphery of the area of influence and
transect data and qualitative observations in 1975 showed that during the pe-
riod of sewage stress one of the factors detrimental to coral growth affected
*Porites compressa* abundance but not that of other species. Since sewage abate-
ment, the *P. compressa* communities on the 1979 Pearl Harbor transects have al-
ready fully recovered and are at the same level of abundance as unstressed com-
munities.
In summary it appears that community responses to abatement of the multi-factored perturbation of sewage discharge are extremely variable depending on both the mechanism and extent of destruction to the reef framework. In zones where biochemical processes have completely reworked the reef complex, recolonization is limited compared to areas where biological but not physical environmental changes occur. The results of this survey indicate that recovery of the reef system in proximity to Sand Island is in the early phases. However, the pattern of recovery is not sufficiently well-established to indicate the timescale of response for the entire community to reach predischarge structure. For this, surveys at several year intervals will be necessary. Thus, while "before and after" sampling is a valuable tool to determine change over a given time span, repetitive sampling programs are necessary in order to judge the stability of the observed assemblages, and the differences in time scale of response by individual species. Thus, the results of this survey will be useful, hopefully in designing future studies which may explain the specific processes and causal effects for the restoration of biological integrity of perturbed ecosystems.

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