

Sediment Stress and Coral Reefs

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Abstract

The ecology of coral reef systems and changes in the community structure with respect to stress factors in the environment is one of the fundamental problems in environmental analyses. The reef community is a complex assemblage of organisms, but the response of the coral assemblage is the fundamental factor in survival or loss of the entire community under stress conditions; the resistance of the total community to environmental stresses cannot exceed the survival ability of the coral framework.

The forereef of a coral reef system is zoned vertically in relation to specific coral dominance. This zonation is related to the ambient light input. The reefs on the south coast of Puerto Rico can be divided into the following depth-related zones:

- **Acropora palmata zone**: 0 - 6 meters
- **mixed coral zone**: 5 - 10 meters
- **massive coral zone**: 9 - 24 meters
- **Agaricia - Montastraea zone**: 22 - 37 meters

In the wave sheltered, high sediment environment of a submarine canyon the 9 to 24 meter zone of massive coral is modified and becomes a mixture of this zone and the Agaricia – Montastraea zone.

The Guayanilla Canyon system has three tributary branches that offer an excellent opportunity to judge the effects of sediment stress on a coral reef system. The western most tributary, Punta Ventana canyon, is free of the pollution problems of Guayanilla Bay and has no ship traffic. Guayanilla and Tallaboa tributaries have no major chemical or bacterial pollution at the outer reaches of the shelf but do have constant ship traffic which introduces major sediment stress in the environment- Suspended sediment and Secchi readings in these tributaries are near or below survival levels, and the west sides of the canyons are no longer coral reefs.

Corals exist within limited variations of temperature, salinity and water clarity. Sediment load in the water is a major stress on the coral system and excessive sediment input can stress the reef system beyond the ability to survive. The death of a reef system under sediment stress proceeds in a series of steps.

- Lowered light input due to water turbidity causes shifts in the ecological pattern and depth of the more rapidly growing coral.
- Direct deposition on coral heads results in a selective loss of coral related to the tolerance of individual coral to sediment loading. This results in further shifts in the ecology.
- There is a definite loss of total coral cover and a shift to a slow growing, modified deeper-water coral assemblage.
- The dead coral areas are covered with an algal-sediment mat and the total available space for coral larvae attachment or asexual coral head expansion is reduced.
- Continued stress conditions result in changes in the cover from a norm for the massive coral zone of 30 to 40 percent down to less than five percent and changes in numbers of species from 12 to 15 down to less than five species. There is a marked increase in the dominance of *Montastraea cavernosa*.
Introduction

Geological studies were started at Guayanilla Bay in October 1978 to study the response of the coral reef system to sediment stress, and to map the sediment facies of the bay. The work presented in this paper is preliminary since much of the study is incomplete.

The extent of the investigation to date is shown in figure 1. About half of the available sediment samples have been analyzed, and another 30 samples need to be collected. Seismic lines have been run in all three canyons on a reconnaissance basis. This data will be used to develop a detailed sedimentary facies map for the coral reef study and for use in biological studies being conducted in Guayanilla Bay.

Ten coral reef study stations have been established. The data from these forms the basis of this paper. Sediment input is being measured by sediment trap collection (Fig. 2a), suspended sediment, and Secchi readings.
The ecology of the reef is examined by diver transects with notes (Fig. 2b) and by measurement from photo-transect mosaics.

Coral reefs form an important part of the marine environment. They

- are one of the most biologically productive and taxonomically diverse of any ecological community
- are an important part of the food chain and are a habitat for propagation of marine biomass
- significantly alter the physical, geological, and chemical environment
- offer protection to the shoreline from erosion and
- are important to the fisheries industry and are an important recreational asset.

The reef community contains representatives of every phylum of the animal kingdom and many members of the plant kingdom. Coral accounts for less than 25 percent of the total reef community (Fig. 3), but is essential for when the coral dies, the reef community degenerates due to death or migration of
the associated fauna. Because the reef ceases to grow, it is less resistant to wave action and actual physical deterioration is accelerated. The resistance of a reef community to environmental stresses cannot exceed that of the coral component.

Corals are limited by physical factors in the environment, but often exist in areas where conditions are close to the limit. The reef is a sensitive indicator of environmental stresses because of its response to the stresses. Beyond this, the reef can give us a look in time at former baseline conditions where we do not have data in an area before development has occurred. As the environment degrades, mobile organisms leave or die and are buried, but the coral is frozen in place as a permanent record. The presence of a dead reef complex implies a specific range of conditions once existed, or the reef would not have developed (Fig. 4). The coral can be dated and individual corals studied to determine when changes occurred that caused the death of the reef. The reef is a time machine which will allow us to make interpretations of the prior environment.
Geological and Oceanographic Setting

The Guayanilla canyon system occupies an indentation of the insular shelf between Guanica and Playa de Ponce (Fig. 5). The shelf is only three kilometers wide in comparison to about ten kilometers on either side of the canyon system. This is also an area of concentration of river systems, and the canyon heads are generally opposite modern or ancient river channels. The three canyons compared in this study are tributaries of the main channel, Guayanilla Canyon (Fig. 5).

Figure 5. Guayanilla submarine canyon system – includes the Guanica, Guayanilla, Tallaboa and Ponce Canyons.

The bathymetry (Fig. 6) was mapped from NOS-NOAA smooth sheets, the Guayanilla harbor map and data recorded with a Raytheon fathometer. The shelf gradually deepens seaward to 16 to 20 meters at a grade of 1:160 (0.3°). The irregularities of the surface are related to subaerial erosion and development of the canyons, a karst topography, and subsequently to the growth of reefs on this topography as sea level came back up some ten thousand years ago. The shelf is cut into the Miocene limestone that outcrops in the Guayanilla area. There is a thin veneer of sands and some patches of coral over the shallow platforms, and fine sands and muds on the canyon floors and the inner bays of Guayanilla and Tallaboa. Most of the hard bottom is covered with soft coral, gorgonians, alcyonarians, sponges, and algae. Low mounds of massive coral and encrusting coralline algae are common.

Figure 6. Bathymetry of the Guayanilla Canyon.
The shelf break and the break into the outer reaches of the canyon occurs at about 15 to 18 meters depth. The slope gradient is between 1:4 and 1:2 (14° to 27°). The submarine canyon walls have gradients between 1:4 and 1:6 (14° to 9°). The floor of the canyons are a mixture of fine to silty sand and sandy silts and muds that are both terrigenous and carbonate shell material. There is a fairly deep accumulation of sediment on the floors of the canyons, but the walls are limestone covered with dead coral and coralline algae, living coral, and a thin veneer of sediments (Fig. 5).

**Figure 5. Texture map for Guayanilla**

The sediments on the canyon walls are fine grained sands, silts, and clays with Foraminifera tests, mollusca fragments, and fragments of corals, coralline algae, *Halimeda*, spicules, and planktonic Foraminifera tests. This is a fine sediment that is being winnowed from the shelf and deposited in the quiet water of the canyon. Since the movement of these sediments is westward with the current and wave patterns, there is more material dumped on the reefs of the eastern walls of the submarine canyons.

Wind driven and tidal currents operate in the canyon areas, setting up a dominant northwest current pattern. Because of the wind pattern and diurnal tide system, the currents should be stronger during the day, which coincides with the movement of ship traffic in Guayanilla and Tallaboa canyon tributaries. Dye traces and drogue movements showed definite net movement in a northwest direction at Punta Ventana (Fig. 6). The absence of a sea land breeze means that the movement will tend to be unidirectional throughout a 24 hour period. Hernandez found no stratification of the water column and no salinity variations of significance in Punta Ventana Canyon. The water column can be considered a thoroughly mixed layer at least to 20 meters.
The dominant direction of wave approach is from the southeast. This has a strong effect on the transport of sediments into the canyons and on the reef sediment stress pattern. Most of the wave power is expended along the 10 meter contour at the edges of the canyons. The eastern walls of the canyons are leeward and receive little of the energy compared to the western walls (Fig. 7).

Since Punta Ventana Canyon will be used as an ecological model for comparison to the Guayanilla and Tallaboa canyon reef systems, the quality of the environments compared is important. Caribe-Tech Laboratory reported no coliforms, no Kjeldahl nitrogen, low nitrate, low phosphorous, and absence of chemical or bacteriological contaminants except for mercury which was 0.35 ~g/g in the
canyon sediments. There was no evidence of petroleum hydrocarbons. Data from Lopez shows similar mercury values near the site of the Guayanilla tributary transects, and extreme low values of petroleum hydrocarbons in the nearest measured samples. It is probable that chemical and bacteriological pollutants do not reach the transect sites and are not a factor in the coral reef ecology, based on the available data.

Coral Reef Systems

The coral reef is a complex system developed in relation to a coral framework. The system is wave resistant, actively building, and creates a topographic relief that significantly modifies the environment. Modern reefs developed on a surface that was exposed less than 15,000 years before present and have grown upward with a change of sea level of more than 120 meters (Fig. 8). The forereef, or wave facing part of the reef, is zoned in terms of coral assemblages with water depth. Reef zonation and coral diversity are responses to natural stresses and energy inputs. Reef growth and vertical zonation with depth are related to light input in turn a function of water clarity/turbidity (Fig. 9).

Logan developed a zonation based on a community concept, defining a community as:
"...a group of organisms dominated by certain abundant and functionally important components which are consistently associated throughout a bio-geographic region."
Figure 9. Relationship between water clarity and coral reef zonation – modified from Hallock & Schlager, 1986

Table 1. Reef zonation

<table>
<thead>
<tr>
<th>Coral Zone</th>
<th>Mixed Coral zone</th>
<th>Massive Coral zone</th>
<th>A. agaricia-M. annularis zone</th>
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<tbody>
<tr>
<td>Acropora palmata</td>
<td>Montastrea annularis</td>
<td>Montastrea cavernosa</td>
<td>A. agaricia</td>
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<tr>
<td>Mixed Coral zone</td>
<td>Acropora coccidina</td>
<td>A. coccidina</td>
<td>M. annularis</td>
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<td>Montastrea annularis</td>
<td>P. porites</td>
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<td>Siderastrea siderea</td>
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<tr>
<td>Montastrea cavernosa</td>
<td>D. labyrinthiformis</td>
<td>D. labyrinthiformis</td>
<td>Solenastrea app</td>
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<td>P. porites</td>
<td>Montastrea cavernosa</td>
<td>A. agaricia</td>
<td>A. fragilis</td>
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<td>P. porites</td>
<td>Siderastrea siderea</td>
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<tr>
<td>P. porites</td>
<td>Montastrea cavernosa</td>
<td>S. fragilis</td>
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<td>D. labyrinthiformis</td>
<td>Montastrea cavernosa</td>
<td>D. coccidina</td>
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<td>Teuthotheca simons</td>
<td>Montastrea cavernosa</td>
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<td>Dendrogyra spiculosa</td>
<td>Montastrea cavernosa</td>
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<td>Diploria labyrinthiformis</td>
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<td>Montastrea cavernosa</td>
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</table>

- **Table 1.** Reef zonation
  - **High cover, low diversity**
    - moderate cover
    - low cover
  - **0 to 6 meters**
    - 5 to 10 meters
    - 11 to 24 meters
  - **Very abundant octocoral becomes hard ground at**
    - many areas
    - bare areas, sediment fill between heads
  - **Less slope, almost a terrace**
    - drop-off, fairly steep slopes
    - fairly high angle slope
  - **Scattered, small heads, still abundant branching**
    - massive, interlocking heads
    - platy, fragile forms, isolated heads
These communities are distinguished by the over-all biologic composition. The discussion of components and zones from Logan, 1969 Newell and Rigby, 1959 Rogers, 1977 Goreau and Goreau, 1973 and transects made as a part of this study have been used to develop a concept of zonation of the reef systems on the south coast of Puerto Rico (Table 1).

Below the reef crest, which is dominated by Millipora, four distinct reef zones can be distinguished on the La Parguera reefs. The Acropora palmata zone is restricted to relatively clear water with moderate to strong wave energy. The zone disappears or is represented by such limited remnants in high sediment input areas that it is not considered for comparison in this study. The mixed coral zone is dominated by Montastraea annularis and Acropora cervicornis. Acropora cervicornis may form a sub-zone between the Acropora palmata and mixed coral zones in which it is more than 50 percent of the total coral cover. The mixed coral zone occupies a more level part of the forereef, and can be mapped by bathymetry in many instances. There is abundant octacoral and soft organisms associated with this zone and in places the assemblage approaches more of a hard ground facies than a reef environment.

The massive coral zone is dominated by Montastraea, Porites and Diploria species. The Diploria were rare in our transects of the upper part of the massive coral zone, but have been observed in more abundance toward the lower depth limits of the zone. There is generally a break in slope between the mixed coral and the massive coral zones, with the massive coral growing on a relatively steep slope. At La Parguera this zone forms the lower part of the shelf barrier reefs and is the upper part of the shelf edge submerged reef.

At about 22 meters, the composition of the reef changes enough that a fourth community can be distinguished. This is the Agaricia-Montastraea zone. Because of the depth, this is found only on the shelf edge reef face. Although Agaricia species are common in all of the other zones, there is a distinct change to dominance and there is also a change from Montastraea annularis to Montastraea cavernosa as the most common coral.

Below 37 meters, there is almost no coral (Fig. 10) and an assemblage of Gypsina plana and Lithothamnium species similar to that described by Logan < 1969 at Alacran takes over on the lower slope. The two lower zones have been studied by photo-transects and diver observations so that more details were observed than in the grab sample surveys at Alacran.

Figure 10. Deep slope at La Parguera

With an increase in depth, there is a distinct change from more rapid growing branching coral to the massive coral types. With respect to light, the mixed zone is a more favorable environment than the
deeper reef slope. However, there is less cover in the mixed zone and more of the space is occupied by octacorals. Light is the primary energy source for the reef and the slope of course gets less under normal conditions. On a wider shelf there may be a freedom from sediment turbidity that reduces this difference. There is a reduction in coverage, smaller colonies with more separation, and general absence of branching forms as we approach the deeper limits of coral growth.

Effects of Sediments

Individual species of coral have resistance to sediment stress up to certain critical levels. There are differences in tolerances and these have been reported in a number of papers. These differences should be directly reflected in the changes in ecology of a stressed reef, and are to a certain extent. Sediments are a natural part of the reef environment and reef corals have adapted to this, but above a low input of sediment there is energy drain and the coral is stressed.

Temperature, salinity, wave regime, ambient light, and relatively pure water quality are requisites for reef growth. Reefs have developed primarily in low sediment input areas, and although some are found near river outlet environments, those reefs are existing at a toleration limit. Some of the problems associated with the influx of sediment into a reef system are

- smothering of the reef by sediment
- scouring of the reef by sediment laden waters
- loss of bottom area suitable for settlement of larvae and
- reduced light intensity due to turbidity

The latter problem results in shifting of the zonation and an upward migration of depth limitations. The loss of light is more critical to the deeper coral assemblages and a chronic increase in turbidity can be expected to reduce coral growth in deeper water and cause changes in the species dominance. Farther shifts in the ecology result from the differences in toleration to direct sediment application by the different corals.

A change in the environmental parameters beyond tolerable limits or even to a point of adjustable stress will shift the entire ecosystem and a new and less competitive Coral assemblage may result which has less chance of survival if threatened by other problems. In studies of the recovery of coral reefs from extreme siltation, oil pollution, hurricane damage, etc. there has been recovery only where the faster growing, shallow water types of coral were present.

One of the major problems of sedimentation is the reduction of potential for future establishment of coral. As the old coral surface dies, it is covered with algae, including the filamentous greens that trap and hold sediment to form an algal mat. This is a completely unsuitable surface for colonization.

Submarine Canyon Reefs

At La Parguera coral growth virtually ceases below 37 meters and the *Agaricia-Montastraea* zone has very low coral cover. Living coral is found to a depth of 80 meters. At Mayaguez and Guayanilla submerged shelf edge reef areas, the limit of coral growth is closer to 25 meters. Both of these areas are closer to shore and receive coastal waters with a higher sediment load. These are more typical of the reefs described by Macintyre as Caribbean submerged shelf edge reefs. There is a reduction in total coral coverage and less variety of species.

The submarine canyon reefs present a farther change in conditions and ecology. These receive a higher direct sediment input and reduced light levels due to water turbidity. The coral coverage is slightly to
moderately reduced from the nearer shore shelf edge submerged reefs, and the coverage and ecology is influenced by the relationship of the canyon trend to prevailing wave and current conditions (Table 2). Since the reefs studied at Guayanilla are of this type, a submarine canyon reef type has been developed as a control or standard, to use rather than directly applying the criteria developed at La Parguera.

Table 2. Reef coral assemblages

<table>
<thead>
<tr>
<th>Punta Ventana Canyon</th>
<th>Guiana Canyon</th>
</tr>
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<tbody>
<tr>
<td>Montastrea cavernosa</td>
<td>Montastrea cavernosa</td>
</tr>
<tr>
<td>Montastrea annularis</td>
<td>Montastrea annularis</td>
</tr>
<tr>
<td>Siderastrea siderea</td>
<td>Agaricia agaricites</td>
</tr>
<tr>
<td>Meandrina meandrites</td>
<td>Siderastrea siderea</td>
</tr>
<tr>
<td>Porites spp.</td>
<td>Porites porites</td>
</tr>
<tr>
<td>Solenastrea bourdoni</td>
<td>Diploria labyrinthiformis</td>
</tr>
<tr>
<td>Diodonocemia stokesi</td>
<td>Mycetophylla lamarcki</td>
</tr>
<tr>
<td>Meandrina meandrites</td>
<td>Agaricia fragilis</td>
</tr>
</tbody>
</table>

The canyon wall assemblages were measured between 12 and 17 meters, which is in the depth range of the massive coral zone. The environment is different, however. There is a higher sediment load, resulting in reduced light levels and direct sediment stress on the coral; there is less wave action and reduced circulation. There is a distinct difference in the geomorphology of these reefs as opposed to the shelf barrier reefs of La Parguera. The latter reefs rise upward from a platform of about 18 meters. Sediment moved from the bottom by wave action must be carried upward to the reef, and with continued wave action will be removed quickly. The canyon walls lie below a 10 to 12 meter surface and sediments are dropped from above by wave action, a decidedly disadvantageous situation. The relatively quiet wave environment of the canyon requires that the coral remove the sediment without wave assistance.

There are some distinct changes in the ecology and the submarine canyon reefs show elements of the massive coral zone and the Agaricia-Montastrea zone. The dominant coral is now Montastrea cavernosa and Montastrea annularis is second in abundance. There is an increase in Siderastrea abundance, and the shape and growth of Agaricia is modified. These changes reflect sediment stress and lowered light level adaptations of the community. The coral system is now living close to the limits of tolerance. This is the system that is probably the most susceptible to increased levels of sediment in the waters and is the least studied of the coral reef types.

**Sediment Input at Guayanilla**

During heavy rainfall conditions (Hurricane Eloise, 1975; June 1979 flooding, October 1978 floods) there is a heavy discharge of sediment into the coastal waters, and high turbidity conditions exist beyond the shelf edge. These conditions may persist for several weeks, but represent intermittent acute stress rather than a chronic condition and are less damaging to coral growth. There is generally higher level of sediment turbidity due to the narrow shelf at Guayanilla. Two rivers enter the bays, but both carry a low sediment load normally.

The values of sediment input and light transparency measured thus far at Guayanilla offer an interesting contrast (Table 3). The suspended sediment is relatively high in relation to La Parguera and higher in Guayanilla and Tallaboa tributaries than in Punta Ventana, but still below critical levels. The material collected in the sediment traps at Guayanilla is low in quantity. This is probably related to the low river input and the limited area of shelf platform. The Secchii disk readings are within tolerable levels for Punta
Ventana Canyon, but are at or below levels for successful reef growth over Guayanilla and Tallaboa tributaries. This seeming contradiction in values indicates that the problems of sediment generation may be related to ship traffic through the Guayanilla and Tallaboa tributaries.

Table 3. Suspended sediment measured by trap.

The size of ships using the ports results in stirring of bottom sediments and regeneration of suspended sediment with each passing. This will affect the sediment trap in the same manner as the bottom, and the same sediment is apparently thrown into suspension repeatedly.

Coral Reef Photo Transects

Table 4. Coral reef cover by species
Ten locations have been picked for transects. These studies are only partially completed as each must be made under the best possible lighting conditions and within diver bottom time limitations, and with equipment that is still in transit. Three of the transects show the marked changes that occur with increased sediment stress beyond the normal canyon condition (Table 4 and Fig. 10). The eastern wall of Punta Ventana canyon shows a total coverage of 11.6 percent living coral. There has been a marked increase in the dominance of Montastrea cavernosa, compared to the same depth zone Turrumoteote Reef (La Parguera); it is 6.2 percent of the coral cover or 53 percent of the living coral present. This is the least advantageous of the two walls, and data for the Punta Ventana Canyon west wall gives an average of 19 percent total coral cover, with more species diversity and less dominance Montastrea cavernosa. The favorable west walls of Guayanilla and Tallaboa tributaries give values of 2 percent and 3 percent, respectively. The number of species has been reduced to less than five, with only three recorded on the transects. Only one coral species and one percent cover was measured at B#3g, a flat pinnacle.
Figure 11. Coral cover measured along vertical transects

Later work at Guayanilla and Punta Ventana was done with the transects along a depth i.e. 10 quadrats at 5, 10, 15 meters). The results are shown in the cover Figure 12.

Figure 12. Coral cover measured in horizontal transects at Guayanilla.

Conclusions

Corals can tolerate turbconditions and sediment stress to some extent; this was illustrated by Roy and Smith 1971 and other researchers. The zonation of the reef is however, dependent on light intensities and the corals have different susceptibilities to direct sediment cover. Rogers 1977 found that Acropora palmata was the most sensitive to application of silty sediment in field conditions (Acropora palmata has no cleaning capability) and that Agaricia agaricites, Porites asteroides and Acropora cervicornis had lower net productivity after application of silt than other corals. (Acevedo et al. 1989 and Morelock pers. comm. have found Porites asteroides to be relatively sediment resistant). This explains in part the depth zonation not only changes upward from an increase in turbid water, but the new reef assemblage is missing some of the deeper water corals and there has been a change in abundances and dominant species not explained by a simple response to light loss.
The marked difference between the coral reef cover and variety of species on the west wall of Tallaboa and Guayanilla canyons to the east wall of the same canyons and to the Punta Ventana reefs can only result from ship traffic. The western wall should be the better developed since the current system moves sediment onto the lee side (the east side) and the west wall would normally receive less sediment. The east wall in these canyons is comparable to the east wall of Punta Ventana Canyon, but the west wall is under extreme stress and is no longer a coral reef assemblage. It must be concluded that west moving currents and wave drift move the ship traffic generated sediment to the west, over these reefs. Although the sediment input is much less than that measured at Escollo Rodriguez at Mayaguez, the reef is in far worse shape, probably due to a chronic state of suspended sediment stress in contrast to the episodic condition at Mayaguez.

In the canyon environment, the coral is existing close to the limits for sediment-ambient light stress under natural conditions. The additional stress produced by ship traffic, excessive river discharge or other man-made factors is enough to destroy the system.

There is a generally accepted thesis that dredging, ship traffic, sand mining, waste disposal, chemical pollutants, etc. are harmful to the reef environment. Some field and laboratory measurements have been made to determine the response of coral to various stresses. There has been very little documentation and evaluation of the long term effect of a change in the environment to stress conditions on a coral reef system. The Guayanilla Bay area affords an opportunity to develop such a study, and to find definite answers. If we are to plan the continued development of our economy we must have reasonable knowledge of the effects of urban, agricultural and industrial development on reef systems. Only then can we intelligently make a cost evaluation of the value of the development versus the value of the reef environment - or find ways to make the two compatible.

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