EFFECTS OF BUN-OFF, SILTATION AND SEWAGE

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Introduction

Run-off, siltation, and sewage are impacts which are all more pronounced on fringing reefs than they are on outer shelf or oceanic reefs; Based on my work with coral reefs over the last 25 years I believe that, contrary to some' popular opinion, reefs are quite tolerant to stress. However, there is a sharp threshold beyond which their collapse can be quite dramatic. In the case of fringing reefs, fresh water is 'probably the major "killer" in situations not. subjected to extreme anthropogenic stresses. It is likely that terrigenous sediment most usually constitutes a chronic stress though it may ultimately become a "killer" if the reef is subjected to actual burial. Sewage, also, most usually constitutes chronic stress but inevitably leads to a progressive degradation of the community, though not necessarily to its total destruction.

The example which I will discuss today is that of Kaneohe Bay, on Oahu, Hawaii. This is one of the most complete case histories available. The fringing reefs in Kaneohe Bay are very well developed., They 'have, in recent decades, been subjected to well developed and well defined stresses exhibiting convenient'gradients from one end of the bay to the other. The responses of the reefs have been well studied. Since 1978 there has also been a detailed study of the recovery of the fringing reef system since the diversion at that time' of a major domestic sewage outfall. The Bibliography lists a number of publications which summarise most of, the information available concerning those aspects of Kaneohe Bay considered: in this paper.

The setting and the stresses

Kaneohe Bay is one of the more spectacularly beautiful parts of the island of Oahu., It certainly has the best developed fringing reef structures in a low to moderate energy environment, and (at, least 'in the past) 'high, coral cover. This combination of a high aesthetic profile, well developed reefs, and a well-protected environment suitable forrecreational activity' has led to the bay assuming a very high importance in human values and to

a great deal of attention being given to its fate. For a long period of time, and certainly pre-dating European occupation, some degree of agricultural activity has occurred in many parts of the bay. The greatest emphasis on agriculture has been, and still is, towards the northwestern end of the bay, and this has resulted in significantly increased terrigenous sediment run-off over extended time. There is no immediate suggestion of a cessation of this type of activity though hopefully somewhat greater control is now being exercised.

In more recent times there has been general residential development along the bay and an intensive suburban development in the Kaneohe City area. The population has increased from 5,000 in the 1920s to some 60,000 by 1980. This development has resulted in very large amounts of disruption to the land surfaces to facilitate building and road making, and this, in turn, has caused a very large degree of terrigenous sediment input particularly to the southeastern end of the bay.

Thus, northwest and southeast Kaneohe Bay have been subject to substantial sediment input; however, the central bay typically has been subject to very little in the past or in the present. The northwest bay also has been subject to some input from agricultural fertilisers and other materials associated with agricultural activity.

Fresh water run-off into the bay also is principally concentrated in the northwest and the southeast. The major run-off is from the Waikane and Waiahole streams in the northwest. The run-off into the southeast bay has been associated only with very small local streams. Recent urbanisation has led to substantial increases in run-off because of surface sealing and discontinuation of water conservation practices. Most of the sediment input is carried to the bay by the various stream systems.

Figure 1 indicates the approximate configuration of the bay, the location of the fresh water streams, the general tide/wind driven circulation, and the distribution of fringing reefs within the bay. The reefs in the central region have been consistently in quite good condition throughout history (except for occasional episodic kills as discussed below). Coral cover here is generally good.

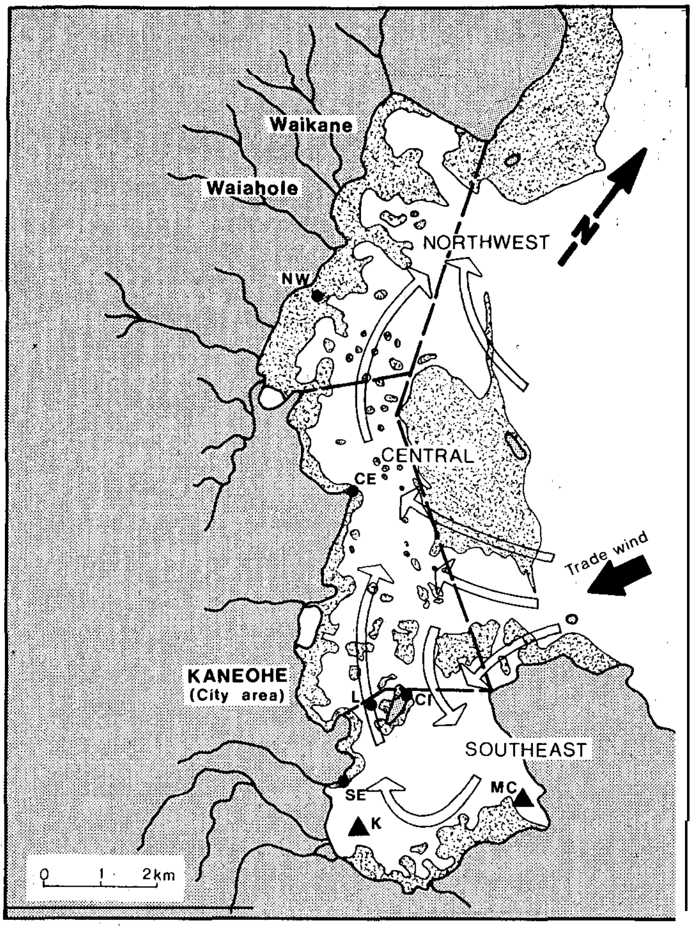

FIGURE 1. Kaneohe Bay on the island of Oahu, **Hawaii.** Principal watershed streams and all major patch-reefs and fringing **reefs are** shown. The bay is **semi-**enclosed by a substantial barrier-reef/sand-bar **struc-**ture and is considered functionally in **three** indicated zones: northwest, central, and southeast. The two sewage'outfalls, in use' to the end of 1977, are indicated A . K is the Kaneohe city outfall and MC is the smaller Marine Corps base outfall.' Reef-flat sites,, referred to **in** the **paper** are indicated • . General patterns of tide/' wind driven circulation are also indicated.

As far as we can tell from old records, kills of the fringing reefs in Kaneohe Bay have occurred periodically, and have been caused by major storm events. Reef-flat community destruction has been caused primarily by the build-up of fresh water in the upper levels of the water-column. Historically, sediment run-off associated with these heavy rainfall periods, while **obvious,** probably has not been sufficiently concentrated or persistent to be particularly destructive to the reef and, almost, certainly, recovery from these storm events by the corals and.other reef organisms has been quite good. The reefs have been able to survive this cycle, we assume, throughout much of the Holocene, though the **frequency of** severe run-off events is likely to have been increasedwith the effects of **urbanisation** discussed previously. Similar cycling of fringing 'reef environments has been reported from elsewhere in the world and almost certainly has been seen in various parts of the Great Barrier Reef Region.

Table 1 indicates some basic parameters of the Kaneohe Bay system and **also** indicates the potential impact of the watershed in discharging fresh water , into the bay. As can clearly be seen, even 20% of, the 'average annual rainfall occurring in one major storm could cause as much as one **metre** of

overlying fresh water if most of the water ran-off into the bay, and if the storm were not accompanied by major wind turbulence or other mixing effects. In so far as the reef-flats in Kaneohe Bay rarely have more than a metre of water over them, because of the small tides, it can readily be seen that a single storm of this magnitude could subject all of the reef-flat surfaces to fresh water. This would cause nearly total destruction of hermatypic corals and many other fauna, and probably flora.

TABLE 1

General information relating to Kaneohe Bay

Kaneohe Bay		
	reef-flat area	$9 km^2$ at average depth 1m
	lagoon area	$19 km^2$ at average depth 15m
	total area	$28 km^2$
	water volume	$270 x 10^6 m^3$
	flushing time	approx. 13 days
Water-shed		
	area	$90 km^2$
	average rainfall	$1.7 m.y^{-1}$
Freshwater input to bay		$6 m.y^{-1}$

During the years 1920-77, and particularly in the last two decades of that period, there has been appreciable input of domestic sewage to the southeastern end of Kaneohe Bay with the principle outfalls being those indicated in Figure 1. By 1977, $20000 m^3.d^{-1}$ of domestic sewage was discharged into the bay. This material contained 550 kg BOD. However, the more functionally important inputs associated with this sewage were dissolved nitrogen and phosphorous nutrients, and these were, effectively, from one major point source (Kaneohe outfall, $14000 m^3.d^{-1}$) and one minor point source (Marine Corps outfall, $5000 m^3.d^{-1}$) both in the southeast bay. The stream inputs also included significant dissolved nutrients but these were more diffuse.

Table 2 indicates the approximate nature and amounts of the nutrient inputs associated with both the sewage and the stream sources.

TABLE 2

Nutrient inputs **to Kaneohe Bay in 1977 (mole** per day)

	Total dissolved nitrogen,	ammonium nitrogen	nitrate nitrogen	total dissolved **phosphorus**	**inorganic** phosphorus
Sewage	30000	16000		3300	3000
Streams	7000		5000	320	200

Note: Sewage inputs are oontinuous and point-source
Stream inputs are episodic and rather diffuse

The effects

The **priciple** effect associated **with** the sediment input to the'bay through, time has been the 'imposition of a chronic stress on the reef systems in' both the northwestern and southeastern ends of the bay. However, in more recent times, the stress on the inner northwestern reef-flats (site NW) has become critical, resulting in the complete destruction of any residual "normal" reef-flat communities.

The chronic stress condition is caused by a coating of much of the living surfaces by sediments, with sufficient frequency to cause physiological **disadvantage,** and, in the case of the autotrophs, a substantial reduction in light intensity.

'Actual killing of the inner reefs in the northwest has been caused by total burial of the reef surface. In this critical condition, **the** environment of the reef-flat shifted progressively from the normally balanced **trophic** state of a coral reef environment (community, photosynthesis being equal to community respiration) **towards** extreme autotrophy. The reason for this is simply that the bommunity shifted towards total algal dominance. A contributing factor was the eventual lack of availability of hard substrate **caused** again by the burial with sediment. This in turn resulted in the inability of most' reef-flat organisms to find any **appropriate** place to settle and develop.,

In the. southeastern end of the bay, I believe it is **true** to say that sediment has primarily been only a chronic stress.

The effects of sewage are quite different to those of sediment and probably quite different to those' most commonly assumed. When sewage is discharged, more or less continuously, from a point source, into a semi-enclosed, flowing body of water, phytoplankton will readily exhibit a chemostat-like response, resulting in the localiseh consumption of the point source nutrient input, and the formation of a plume of phytoplankton. Thus, the reefs do not have the opportunity to respond fully to the nutrient input as the bulk of the nutrients have been immediately assimilated. The overall result in Kaneohe Bay was a tidal and wind-driven plume of phytoplankton and associated zooplankton, with only moderately enhanced dissolved nutrient levels. This plume ran from the sewage discharge points in the southeast bay towards the central and northern parts of the bay where it swung out into the open ocean (see fig. 1). Plankton and residual nutrient levels fell with distance from the outfalls because of mixing, consumption, and some sedimentation. However, the residual dissolved nutrient levels were probably the. most significant factor by the time the plume reached the central bay reefs.

The plankton flow had two principal effects on the fringing reefs in the southeast bay (sites SE, L, CI). The first was to cause a substantial light reduction. The second was to subject the reefs to a significant organic loading of assimilable material. Thus, the overall reef response to both of these effects was to shift strongly towards heterotrophy. There was a decline in many algae, a serious decline in coral and coralline algae cover, and a favouring of the development of organisms which utilise filter feeding such as sponges, barnacles, zooanthids, etc. Because many filter feeding organisms are also infaunal, another effect of the sewage was to lead to very extensive substrate boring and eventually, in the main outfall areas (site SE), to total substrate collapse. Thus, unlike sediment input, which merely causes passive prevention of the maintenance and calcification of the substrate, sewage input leads to positive destruction of the substrate.

It was apparent that much of the observed degradation of the southeastern reef-flats was not caused by the sewage or sediment stress alone. The mechanism, rather, seemed to involve episodic kills by fresh water followed by a failure of the normal community to reoover under the influence of the chronic stress imposed by the effects of sewage (and sedimentation in some cases). This was dramatically demonstrated by the

reef slopes in many areas of the southeast bay. Here, the corals and other coral reef biota were quite persistent below the immediate influence of 'the surface. These organisms were surviving notwithstanding very low light levels and being subjected to substantial plankton input. The adjacent reef-flat communities were totally modified. Similar persistence of "normal"communities below surface layers is dramatically evident on many reefs in highly polluted Jakarta Bay in Indonesia.

The central site (CE) was subjected to marginally elevated,plankton and nutrient levels. At this level of enrichment, the community was not grossly modified. However, it is interesting to note the effect here was 'to encourage heavy development of an autotroph, the bubble alga Dictyosphaeria. Only limited increases in filter feeders (hetrotrophs) were noticeable. As the sewage effects became more extreme through time, Dictyosphaeria moved further north in the central bay, It 'clearly represented the major initial (or marginal) response to sewage input. It should be noted, however, that even though the conspicuous effect in the, centraal bay was the development of an "invading autotroph, the area nevertheless exhibitted a heterotrophic balance.

In summary, the southeast outfall site has been subjected to both sediment and sewage stresses. By 1977, it no longer had any remaining hard substrate, largely because of infaunal boring together with some' sediment burial. The site, therefore, had reduced standing stocks of even, the favoured heterotrophic filter feeders, The other southeast bay sites were subjected primarily. to sewage related stresses, but' still had. hard substrate overgrown with filter feeders. Normal reef organisms were at' low, or nil, standing stocks. The central site was subjected to marginal 'enrichment of sewage origin. It exhibited general enhancement' of all aspects of community function while retaining a reasonably normal reef community, somewhat overgrown, in patches, with both an invading alga and some, filter feeders. The northwest site was subjected to heavy sedimentation, had all hard substrate buried, and was dominated by algae. There was essentially no normal reef organisms. All 'of the sites are likely to have been subjected to increased, frequency of the episodic, critical stress associated with fresswater run-off.

The recovery

Over the period November 1977 to May 1978, all of the major sewage input from Kaneohe City and the Marine Corps base was diverted from the bay outfalls. The effects of this diversion, as might be expected, were quite dramatic. The most immediate effect was the clearing of the water column due to the virtually total cessation of the plankton production previously associated with the outfalls. This was followed quite rapidly, within the following six months, by a decline in' most of the more conspicuous filter feeders in the southeastern areas of the bay. Thus the sponges, zooanthids and barnacles largely ceased to be a feature of these reef-flats. Following these immediate effects, subsequent changes were much slower.

By 1982, most of the southeastern reef-flats, previously dominated by an overgrowth of filter feeding organisms, now showed the underlying hard substrate of earlier reef surfaces. Needless to say, this was not true in the outfall area where the reef-flat substrate had literally been destroyed by boring. All of these southeast reef-flats were also exhibiting a significant bloom of macro-algae (mostly reds). This phenomenon probably was the compound effect of increased light penetration and a continuing availability of non-point-source higher-than-normal nutrient levels. The latter resulted from remineralisation of the enriched lagoon floor sediments accumulated over the decades of sewage input. Little conspicuous recovery of any coral communities had occurred by this time.

By 1985, macro-algal blooms appeared to have declined, probably reflecting a general further decrease in the nutrient concentrations in the bay as a result of exhaustion of nutrient input from remineralisation of sediments. Also, by this time, there was evidence of good coral recovery over all of the hard reef substrate areas in the southeast bay and perhaps, suprisingly, even over much of the unconsolidated rubble of the degraded reef-flats near the outfall. Throughout all of this recovery period, the central bay exhibited no dramatic changes, though there was some decrease in the amount of Dictyosphaeria.

It now seems clear that something approaching total recovery of the central and southeast reefs of Kaneohe Bay will occur. In the case of the outfall site it seems likely that, notwithstanding some degree of

continuing chronic sediment stress caused by the **urbanisation** 'of the area (**local** regulations are now minimising this effect), that **there will** be a reconsolidation 'of the" reef 'surface and a redevelopment of coral fauna and coralline **algal cementation.**

It is, **however,** equally clear that the inner reef-flats in the northwestern end of the bay, already largely destroyed by sediment **burial,** will continue in their present state as none of the degradation of these reefs was associated with the sewage input., and nothing is occurring which is likely to cause a removal of the heavy sediment overload **already** existing. In fact, it seems probable that even a total cessation of agriculture would not be likely to result in the recovery of these reef-flats.

Conclusion

In conclusion, fringing reefs typically are quite tolerant of stresses. They may, however, reach a certain threshold beyond which their degradation is very rapid. I believe it is true that fresh water **is** the major killer of shallow fringing reefs in a short time frame. Sediment is usually a chronic stress but may at times kill by burial. Sewage is almost always likely to be a chronic stress and will result in progressive, slow environmental and community degradation. Chronic stresses ensure that recovery from a freshwater kill or other episodic catastrophe will not occur. However, it seems clear that recovery from an, almost totally degraded condition is possible in fringing reefs' once existing chronic stresses are removed.

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