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The 1987–1989 Phytoplankton Bloom in Kaneohe Bay

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Abstract: A remarkable bloom of phytoplankton occurred in the southeast sector (SE) of Kaneohe Bay from 1987 through 1989. During the bloom, concentrations of chlorophyll *a* at the former site of the Kaneohe municipal wastewater treatment plant outfall averaged a little more than 2 mg m^{-3} for a period of 40 months. The increase of chl *a* was accompanied by a roughly twofold increase in the percentage of chl *a* accounted for by cells retained on a 35-micron filter, a drawdown of silicate concentrations from roughly 10 µM to 3–4 µM, an increase of nitrate concentrations from roughly 0.5 to more than 3 µM, and an increase of phosphate concentrations from roughly 0.2 to 0.5 µM. Extraordinarily heavy rains on 31 December 1987 led to flooding and land runoff that briefly raised chl *a* concentrations in the bay to as high as 17 mg m^{-3}, but the bloom in question developed more than one year before the 1987 New Year's Eve flood. It was not caused by unusually heavy rainfall: the average rainfall during 1987–1989 was only 10% above the long-term average. Instead, the bloom appears to have been caused by a leak in the sanitary sewer line that was previously used to discharge secondary treated sewage into Kaneohe Bay. Ultimately, leaks in the sanitary sewer lines maintained by the City and County of Honolulu led to legal action and a consent decree that required upgrading and the renovation of the wastewater collection system.

Keywords: phytoplankton; Kaneohe Bay; bloom; nutrients; sewage

1. Introduction

Discharges of sanitary sewage into coastal waters have led to cultural eutrophication problems in both freshwater [1,2] and marine systems [3,4]. The impacts typically involve excessive growths of algae that create aesthetic problems [5], release toxic substances into the water [6], and cause oxygen depletion problems when the algae decompose [7]. Corrective actions have included tertiary treatment to remove a limiting nutrient [8], discharging the treated wastewater elsewhere [4,9], and installing primary treatment or upgrading from primary to secondary treatment [3]. In all cases, there has been a need for continued monitoring of water quality in the receiving system because changes that occur on a timeframe of one year (for example) may be followed by delayed or long-term responses that are not easily anticipated [1,10]. In some cases, changes unrelated to the initial reduction in nutrient loading may enhance [11] or confound [12] the short-term effects of diverting or treating the wastewater.

Kaneohe Bay, a coastal embayment on the northeast side of the island of Oahu in the Hawaiian Islands (Figure 1), is a good example of a marine ecosystem that has been adversely affected by discharges of sanitary sewage. From 1951 until May 1978, the southeastern (SE) sector of the bay received increasing amounts of treated sewage that stimulated the growth of plankton and benthic filter feeders. Although the bay had once been the site of a flourishing coral reef community [13], a study by Maragos [14] revealed that 99.9% and 87% of the corals in the SE and central sectors of the bay had died or been destroyed by 1971. The sewage discharges were consequently diverted from the

SE sector of the bay in December 1977 and May 1978, and the coral reefs made a remarkable recovery as the abundance of plankton and benthic filter feeders declined [4]. In this paper and in the study by Smith et al. [4], the years 1976–1977 are referred to as the pre-diversion period and May 1978 to May 1979 as the post-diversion period.
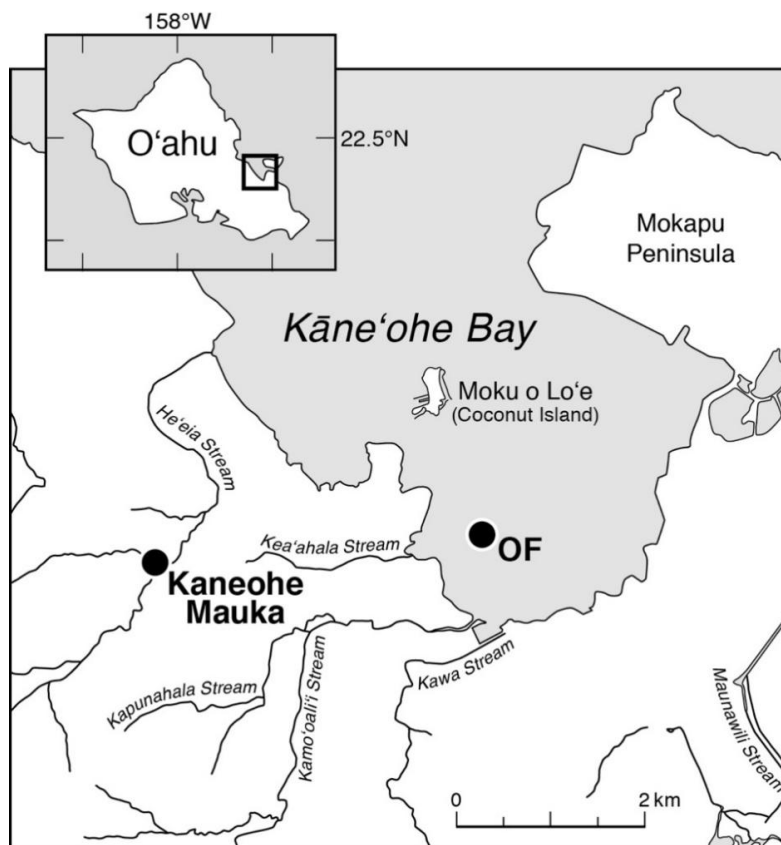
Figure 1. The location of the sampling site (OF) in the southeast sector of Kaneohe Bay and of the U.S. Weather Bureau Kaneohe Mauka rain gauge.

Conditions in the bay appeared to stabilize in the first few years after the sewage diversion, but a torrential rainfall from 31 December 1987 to 1 January 1988 dropped as much as 58 cm of rain over a 24-h period in some windward Oahu locations [15]. The runoff from that event stimulated a phytoplankton bloom, and chlorophyll *a* (chl *a*) concentrations in the bay reached as high as 17 mg m^{-3} within one week of the storm.

Under dry-weather conditions, the phytoplankton biomass in the bay is limited by the availability of dissolved inorganic nitrogen (DIN) [16], but runoff from storms deliver DIN and dissolved inorganic phosphorus (DIP) in molar ratios of 25–29, which are high compared to the Redfield ratio of 16 [17]. The phytoplankton blooms that occur in the SE sector of the bay following these runoff events draw down the concentrations of DIN and DIP but consistently exhaust the DIP before the DIN. Ringuet and Mackenzie [18] have concluded that the phytoplankton in the SE sector tend to become limited by dissolved inorganic phosphorus (DIP) after storms, particularly in the vicinity of stream mouths. However, they point out that these perturbations are transient events and that the system rapidly recovers to pre-storm conditions during dry weather. Microscopic examinations and high-performance liquid chromatographic pigment analyses have indicated that the composition of the phytoplankton community changes during the post-storm blooms. The abundance of phytoplankton in the picoplankton (0.2–2.0 μm) category [19] remains essentially constant. Large pennate and chain-forming diatoms, however, become as much as 10 times more abundant during post-storm blooms [18].

Here we report the results of a retrospective analysis that has revealed that increases of inorganic nutrients and chl *a* concentrations preceded the 1987/1988 New Year's Eve storm by roughly one year. Furthermore, those concentrations remained elevated for several years after the storm. Conditions in the bay did not begin to return to normal until the latter half of 1989. We hypothesize that this two-year bloom of phytoplankton was caused by a leak in a sanitary sewer line with a long history of poor maintenance.

2. Materials and Methods

Samples were collected on a weekly basis from June 1982 through June 1992 at one station (Figure 1) from a depth of ~0.1 m using a Nalgene bottle that was opened only after submersion. The station was located directly over what had previously been the outfall of the Kaneohe municipal wastewater treatment plant (KMWTP) and corresponded to the station designated OF by Smith, Kimmerer [4]. The water depth at that location is 5 m. Samples of net phytoplankton were collected in a vertical haul using a 35-μm mesh net with a 30-cm diameter opening from 2 m above the bottom [20]. The efficiency of the net (53.7%) was estimated with a TSK flowmeter (Tsurumi-Seiki, Japan) that was attached at the mouth of the net. The chl *a* concentration in the <35 μm size fraction was equated to the difference between the total chl *a* concentration in the water collected with the Nalgene bottle and the net phytoplankton chl *a* concentration. All samples were prescreened through 183-μm Nytex netting, except in January 1988, when there was a large phytoplankton bloom following the New Year's Eve flood. In that case, a 35-μm mesh net was used to filter large cells. Subsamples were filtered onto Whatman GF/C filters (nominal pore size, 1.2 μm) from June 1982 to December 1985 and Whatman GF/F filters (nominal pore size, 0.7 μm) from January 1985 to September 1989. In previous studies in Kaneohe Bay, both GF/C filters [4,18] and GF/F filters [16,21] have been used for chl *a* analyses and to separate particulate matter from dissolved substances. We assume that GF/C and GF/F filters produce equivalent results in Kaneohe Bay. All filters were immediately stored in dark bottles with 100% acetone at -20 °C. Chl *a* analyses were performed on a Turner Model III fluorometer following the procedure of Holm-Hansen, Lorenzen [22]. Nitrate, phosphate, and silicate concentrations were analyzed using colorimetric methods with an Autoanalyzer [23]. Temperature and photosynthetically active radiation (PAR, mol photons m^{-2} d^{-1}) were obtained from the weather station on the roof of the Hawaii Institute of Marine Biology on Coconut Island. Rainfall data were taken from the U.S. Weather Bureau Kaneohe Mauka station 781.

3. Results

Concentrations of chl *a* from 1982 through September 1986 fell in the range 0.5–1.0 mg m^{-3} (Figure 2). To provide some context to these concentrations, we note that the mean chl *a* concentration in the year following diversion of the sewer outfalls from the SE sector (May 1978 to May 1979) was 1.38 mg m^{-3}. The chl *a* concentrations rose abruptly in October of 1986 and averaged 2.1 mg m^{-3} for the next 40 months. In February of 1990 they abruptly dropped below 1 mg m^{-3} and averaged 0.76 mg m^{-3} for the next 29 months. Changes in the fraction of chl *a* in the >35 μm size category (Figure 3A) and the reductions of silicate concentrations (Figure 3B) during the time of the elevated chl *a* concentrations were very consistent with the increase in abundance of large pennate and chain-forming diatoms during post-storm blooms documented by Ringuet and Mackenzie [18]. However, the years 1987–1989 were not associated with unusually heavy rainfall in the Kaneohe watershed (Figure 4). The annual rainfall at Kaneohe Mauka 781 during those three years averaged 209 cm, which is only about 10% higher than the long-term average of 190 cm at that station. Temperatures averaged 25.1 °C during the bloom, which was identical to the average water temperature from 1982 through September 1986. PAR during the bloom and during the two years preceding the bloom averaged 29 ± 6 and 36 ± 9 mol photons m^{-2} d^{-1}, respectively.
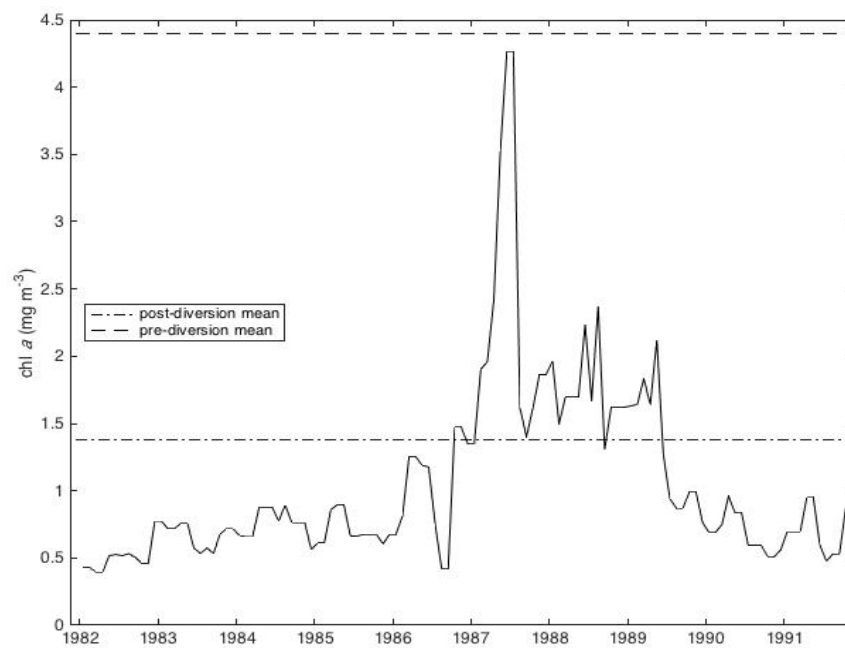
Figure 2. The three-month running means of chlorophyll *a* concentrations in the southeast sector of Kaneohe Bay from the middle of 1982 until the middle of 1992. Tick marks indicate the midpoint of the indicated year.
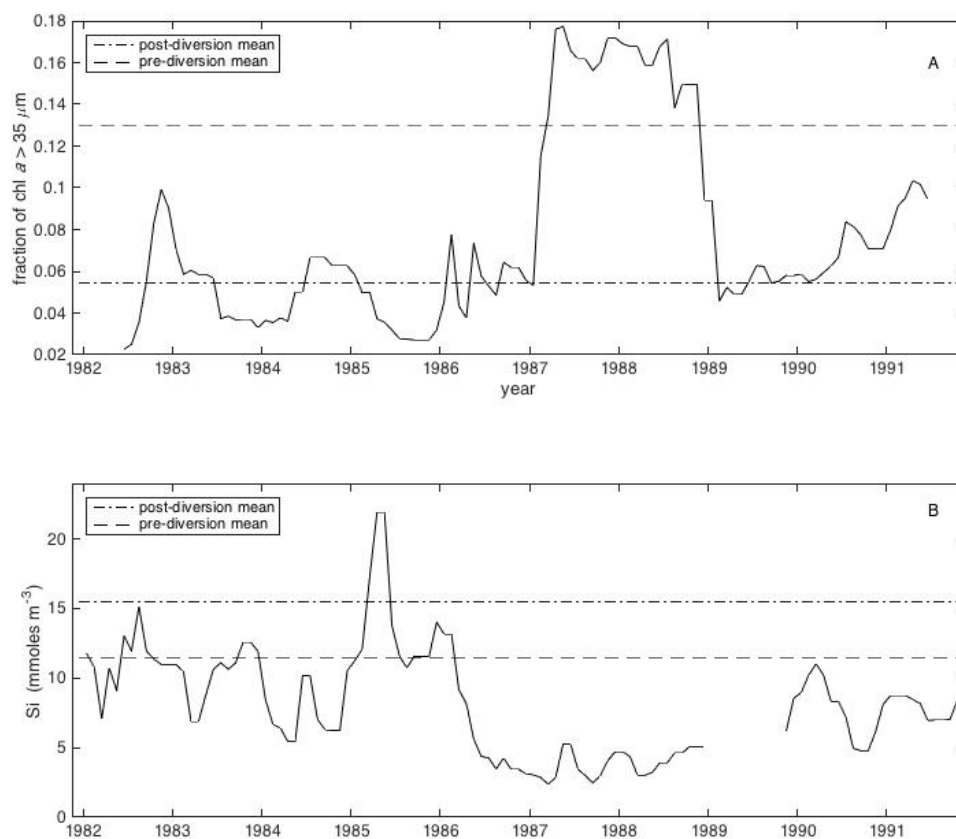
Figure 3. (**A**) The six-month running means of the fraction of chlorophyll *a* retained on a 35-micron filter from late 1982 through late 1991 in the southeast sector of Kaneohe Bay and (**B**) three-month running means of silicate concentrations in the southeast sector of Kaneohe Bay. Tick marks as in Figure 2.
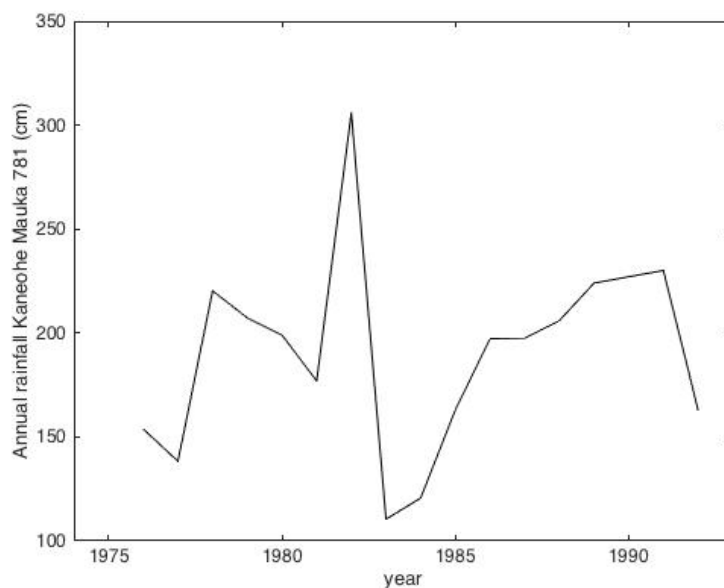
Figure 4. The annual rainfall at Kaneohe Mauka station 781 from 1977 through 1992.

Nitrate concentrations during 1987–1989 were far above concentrations that would be expected to limit phytoplankton growth [24], but based on the work of Ringuet and Mackenzie [18], we might expect phosphate to be limiting if the source of nutrients was land runoff. However, phosphate concentrations during 1987–1989 were in the range 0.4–0.5 μM (Figure 4B), roughly an order of magnitude higher than growth-rate-limiting concentrations [25–28].

4. Discussion

A logical explanation for the elevated chl *a* concentrations, the increased relative abundance of large phytoplankton, and the drawdown of silicate concentrations during 1987–1989 is a leak in the sanitary sewer line. The samples were collected directly over the site of the old KMWTP outfall. A compelling argument against land runoff or groundwater seepage as being the cause of the bloom is that silicate concentrations decreased during the bloom (Figure 3B) whereas nitrate concentrations increased (Figure 4A). The ratio of silicate to inorganic nitrogen in streams that discharge into the SE sector of Kaneohe Bay is roughly 10 on a molar basis, whereas the corresponding ratio in the sanitary sewage is roughly 0.5 [4]. Diatoms require Si and N in roughly equimolar amounts [29]. A diatom bloom stimulated by stream runoff would, therefore, be expected to leave the water depleted in inorganic nitrogen, whereas a diatom bloom stimulated by sanitary sewage would be expected to leave the water depleted in silicate. The 1987–1989 bloom clearly produced the latter effect.

Because the flushing time of Kaneohe Bay is no more than a few weeks [4], it seems unlikely that the roughly two-year period of elevated nutrient and chl *a* concentrations after the New Year's Eve storm can be attributed to that event, and the fact that the increase preceded the flood clearly cannot. The bloom does not appear to have been the result of meteorological phenomena. Temperatures were virtually identical during the bloom and during the five years preceding the bloom; average annual rainfall during 1987–1989 was only about 10% above the long-term average; and PAR was actually about 19% lower during the bloom than during the two preceding years. The 1987–1989 bloom was clearly not the result of unusually heavy rainfall and land runoff. There was, in fact, a very large phytoplankton bloom immediately following the 1987/1988 New Year's Eve flood, but the bloom we have documented began in the last few months of 1986 and persisted until the end of 1989. The location, duration, and intensity of the bloom suggest that it was caused by an undetected leak in the sanitary sewer line that was previously used to discharge treated sewage into the bay.

The elevated concentrations of nitrate and phosphate and reduced concentrations of silicate during the bloom are very consistent with expectations if the bloom was caused by inputs of sanitary sewage. The extent of the leak can be roughly estimated by comparing the mean chl *a* concentration during the bloom (2.1 mg m^{-3}) with the mean pre-diversion (1976–1977) and post-diversion (May 1978 to May 1979) concentrations of 4.40 and 1.38 mg m^{-3}, respectively. If the elevation above the post-diversion mean is assumed to be proportional to the sewage input, then the leak amounted to (2.1 − 1.38)/(4.40 − 1.38) = 24% of the flow in the sewer line. As a check on these calculations, we can compare the pre-diversion and post-diversion chl *a* concentrations with the corresponding deliveries of dissolved inorganic nitrogen (DIN). According to Table 7 in Smith, Kimmerer [4], the pre-diversion and post-diversion deliveries of DIN to the OF area were 12.45 and 3.10 kmoles d^{-1}. The ratio of post-diversion to pre-diversion DIN delivery was, therefore, 3.10/12.45 = 0.25, which is comparable to the ratio of post-diversion to pre-diversion chl *a* concentrations, 1.38/4.40 = 0.31. The small difference likely reflects a net efflux of nutrients stored in the sediments in the year following the sewage diversions [8]. Thus, chl *a* concentrations at the OF site appear to be roughly proportional to rates of nutrient delivery.

A good indication that the nutrients came from a leak in the sewer line rather than the routine discharge of sanitary sewage is the high concentration of nitrate during the bloom. The principal form of DIN in sanitary sewage is ammonium [4], and if the DIN were coming directly from a sewer outfall, the concentrations of nitrate would be relatively low, as was the case during pre-diversion conditions (Figure 5A). The high nitrate concentrations during the bloom, therefore, suggest that some of the ammonium was oxidized to nitrate by nitrifying bacteria as the sewage leaked out underground and moved toward the bay. Leaky sewer lines are a common cause of high nitrate levels in drinking water wells [30].
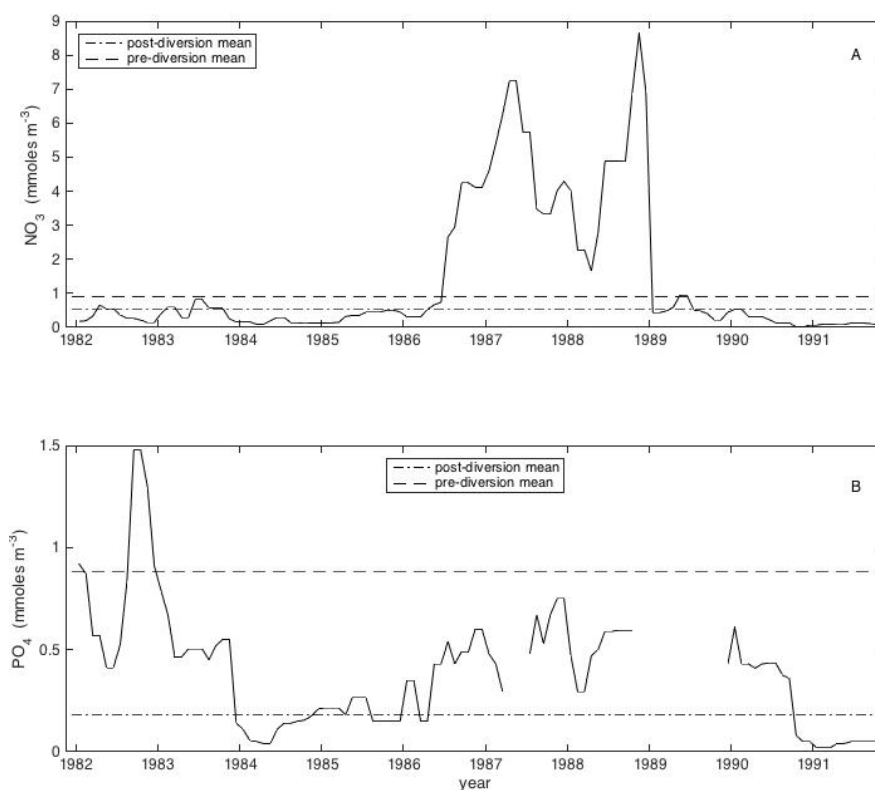
Figure 5. (**A**) The six-month running means of nitrate concentrations in the SE sector of Kaneohe Bay and (**B**) the three-month running means of phosphate concentrations in the SE sector of Kaneohe Bay. Tick marks as in Figure 2.

A possible explanation for the failure of the phytoplankton to fully exploit the DIN and phosphate is that the nutrient input was coming from a point source, and physical processes were dispersing the enriched patch before the phytoplankton could fully exploit the nutrients. Caperon [31] has estimated the growth rates of phytoplankton in the SE sector to be 0.36 d^{-1} prior to sewage diversion. At that growth rate, the critical patch size required to overcome losses to turbulent diffusion is roughly 4–7 km [32], and herbivore grazing would increase that critical patch size further [33]. The SE sector of Kaneohe Bay has an area of about 8.4 km^2 [4] and, hence, linear dimensions of roughly 3 km.

The system of underground pipes used to route sanitary sewage to treatment plants on Oahu has had a long history of developing leaks [34,35] and, on 15 May 1995, the United States district court for the district of Honolulu entered a consent decree that required the City and County of Honolulu (CCH) to undertake specific actions to improve conditions in its wastewater collection system. Much of the concern with the leaks in the collection system has been focused on enteric pathogens for example (e.g., [35]), and among the weaknesses in the collection system specifically cited by the Environmental Protection Agency have been the Kaneohe/Kailua force mains, which are pressurized pipes that carry sewage from residences and commercial/industrial sources to wastewater treatment plants [34]. Because force mains are pressurized, even a small break can lead to a large discharge and, hence, may explain how 24% of the flow in the sewer line was discharged into Kaneohe Bay for a period of roughly 40 months. The fact that (1) the 1987–1989 phytoplankton bloom began and ended abruptly, (2) that the bloom occurred in the immediate vicinity of the former KMWTP outfall, and (3) that the nitrate and phosphate concentrations were elevated while silicate concentrations were lowered during the bloom all suggest that the 1987–1989 phytoplankton bloom in Kaneohe Bay was caused by a leak in the wastewater collection system that went undetected for three years. The poor record of the City and County of Honolulu in maintaining its wastewater collection system [34] may well account for the lack of detection.

The coral reefs in Kaneohe Bay and, particularly those in the SE sector, were seriously impacted by the plankton blooms caused by the discharges of treated sewage into the bay prior to 1977. Maragos [14] estimated that 99.9% of the corals in the SE sector had died, the principal mechanisms being competition with benthic filter feeders that benefitted from the increased concentrations of plankton in the water and reductions in the amount of light reaching the bottom, again, due to the dense concentrations of plankton. Although the corals in the bay made a remarkable recovery after the sewage discharges were diverted from the bay [4,36], they are now threatened by a combination of ocean acidification and global warming [37]. Any additional stress could be devastating. A routine water-quality-monitoring program should be sufficient to detect the kind of phytoplankton bloom that occurred in 1987–1989.

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