A FRESH-WATER "KILL" ON THE CORAL REEFS OF HAWAII

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INTRODUCTION

It is known that reef corals in general have a low tolerance to freshwater and that the flooding of reefs by streams of the high islands is one of the major factors in keeping open the passes through the reefs (see Davis [1928] on general reef structure and Edmondson [1928] on tolerance of Hawaiian corals to freshwater). Yet seldom in the literature have cases of extensive coral "kills" been recorded from flooding after violent storms, and never have there been data on the actual extent of the lowering of salinity. The most recent reports of kills were those of Slack-Smith (1960) on an inshore reef near Brisbane, Australia, after a period of heavy rains and flooding; of Goreau (1964) on the effects of a hurricane on the reefs of Jamaica; and of Cooper (1966) on the flooding of the Mbau Waters of Fiji after the near-miss of a hurricane in the same year.

The killing of the corals on a reef is of considerable importance to the knowledge of coral reef growth and form. It may also be of importance to the development of knowledge of the distribution of toxic fish which cause the disease known as ciguatera. These fish, of species which are normally safe to eat, are discontinuous in distribution both in space and time. The origin of the toxin is not known, but it has been hypothesized that the toxin originates with a fine benthic alga, at the base of the food chain, and is passed through fish to man. Randall (1958) further suggested that the discontinuous distribution may be the result of "new surfaces" on which the postulated alga would grow early in the ecological succession. Thus, if many of the corals growing on a reef were to be killed, their skeletons would present such a new surface for algal growth; and if the algae were toxic, toxicity might occur or increase in the fish.

An opportunity to study the effects of a freshwater kill presented itself in Kaneohe Bay, Oahu, Hawaii, during the week of 2 to 8 May, 1965. Unfortunately the possibility of the extremely heavy rainfall and resultant kill was not planned for, so the observations were made in an impromptu fashion without a coherent over-all plan; emergency work to save both homes and boats diminished the effectiveness of observations during the storm, and the normal University routine, as well as repair demanded by the storm, interfered with the observations following the storm.

The author wishes to thank the following individuals at the Hawaii Institute of Marine Biology for their aid in gathering the data: Dr. Philip Helfrich, Dr. Ernst S. Reese, Dr. Twesukdi Piyakarnchana, Miss Kanitha Silthornivisudh, Mr. William F. Van Heukelem, Mr. Lester Zukeran, and Mr. Charles Barry. The author also wishes to express his appreciation to Mr. Saul Price of the U. S. Weather Bureau for making the Bureau's official records, including photostats of station records, available; to the U. S. Marine Corps Air Station in Kaneohe and the U. S. Corps of Engineers for making their records available; and to Dr. Lucius Eldredge, University of Guam, and Dr. E. Alison Kay, University of Hawaii, for the proper scientific names of some of the specimens referred to.

KANEOHE BAY

Kaneohe Bay lies on the northeastern side of the island of Oahu (21°28' N, 147°48' W) (Figure 1). It is about 6.9 nautical miles long and 2.3 nautical miles broad. It fronts on the open Pacific for 5.5 nautical miles of its length, but this ocean frontage is mostly obstructed by shoal reefs, with only two deeper passages from the ocean to the interior of the bay: a "Sampan Channel" to the southeast, about 0.5 miles broad and with a

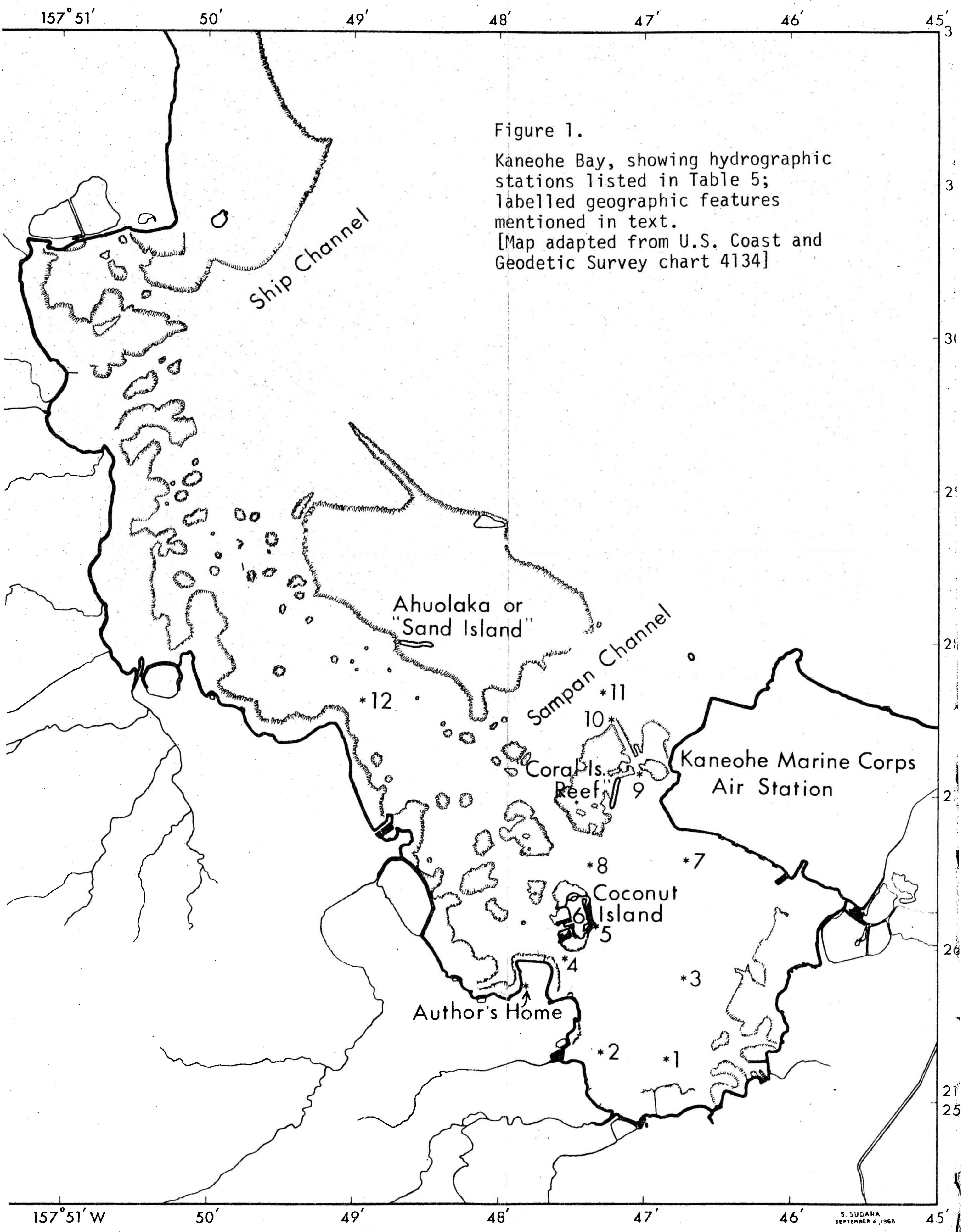

Figure 1.

Kaneohe Bay, showing hydrographic stations listed in Table 5; labelled geographic features mentioned in text. [Map adapted from U.S. Coast and Geodetic Survey chart 4134] minimal depth of about 10 feet, and a "Ship Channel" to the northwest, with a dredged passage of 90 yards breadth and a depth slightly less than 30 feet. The northern and central sections of the bay communicate by these passages and are characterized by fringing reefs along the shore, the large reef fronting on the ocean, and numerous patch reefs between the two. The waters of the southern section of the bay are largely cut off from the waters of the central portion of the bay and the ocean by Coconut Island (Moku-o-loe) and extensive shallow water reefs; biologically, this section appears to be distinct from the central section, at least in its plankton (Piyakarnchana, 1965). In the southern section there were once fringing reefs around the shores (in 1965 these reefs were deteriorating), the complex of reefs near Coconut Island, and a patch reef that once existed south of the island but that was dredged to about 12 feet during the second World War.

The shoal areas in the bay are extensive; Bathen (1968) estimates that 50 percent of the area within his "inner boundary" as less than 3.3 meters deep. Inshore, these shoal areas are largely sand or mud flats; in the middle and outer reefs, the surface is of sand and coral rubble and normally have increasing amounts of living coral as the margins are approached. The margins of almost all outer reefs and of inshore reefs away from the mouths of streams are steep and composed largely of living coral down to depths of 10 to 30 feet, the depth of the living coral being controlled by the clarity of the water and the silt of the substrate.

The tides of the bay are of narrow range, with the maximum range of 4.1 feet (U. S. Coast and Geodetic Survey, based on eight years of records of a tidal gauge at Coconut Island [report unpublished]). Bathen (1968) provided figures for calculation of the amount of water exchange in the bay during tidal cycles. For his work he demarked the "bay" from ocean by two arbitrary lines; the inner boundary is "the approximate line where the entrance reefs begin"; however, as it is a straight line, some of the bay reefs lie outside of it. Correspondingly, the outer boundary, drawn straight between headlands, includes oceanic waters beyond the reefs. By his definitions, the "inner bay" exchanges 19 percent of its water on maximal tides and 7.7 percent on minimal tides; at the outer boundary the figures are 17 percent and 7 percent respectively.

The currents of the bay have been extensively studied (Bathen, 1968). In general, the water of a rising tide enters the bay across its entire front, and the maximal outflow under trade wind conditions is on the northwestern side, near the Ship Channel; however, there is definite outflow through the area of the Sampan Channel, especially during periods of calm, such as the week of the storm.

Most of the area draining into Kaneohe Bay from the land is shown in Figure 2; it is roughly 18 square miles in extent, and normally drains by a series of small streams. During periods of torrential rainfall the streams overflow their banks and water from every surface surrounding the bay, with or without streams, pours into the bay. Because the land in general is steep and the streams short, there is no great time lag between the period of maximal rainfall and the stream crest. Bathen (1968), considering only the greatest reported stream runoff and ignoring both general land runoff and precipitation directly on the bay, estimates that a maximum of $10,650 \times 10^6$ gallons per day would be discharged into the bay, amounting to 16 percent of the total volume of the bay to his inner boundary and 10 percent to his outer limit.

During periods of normal wind and rainfall the salinity in all parts of the bay is close to that of the open ocean. Two studies, made about 10 years apart in the waters of the southern portion of the bay, report a normal chlorinity ranging between 19.0 and 19.5 parts per mille with an

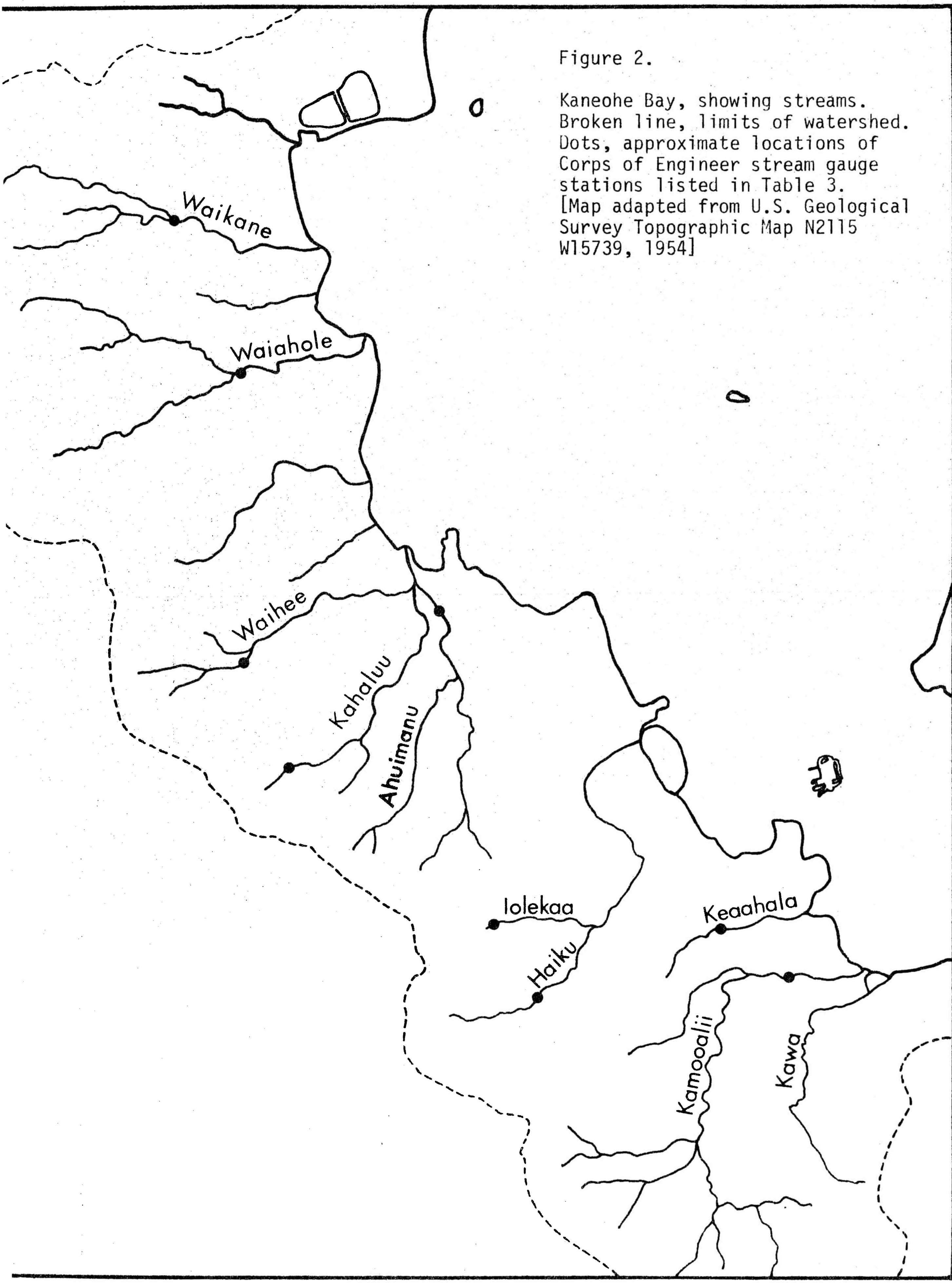

Figure 2.

Kaneohe Bay, showing streams. Broken line, limits of watershed. Dots, approximate locations of Corps of Engineer stream gauge stations listed in Table 3. [Map adapted from U.S. Geological Survey Topographic Map N2115 W15739, 1954] extreme low of a three-year study of 14.94 (Tseu, 1953, Piyakarnchana, 1965).

The normal fauna of the bay is not as varied as would be found in islands south and west of Hawaii. While no comprehensive reports on the fauna or ecology of the bay have ever been issued, some knowledge of the normal fauna has been derived from the years of work of the personnel of the Hawaii Institute of Marine Biology. Various elements of the fauna will be discussed in the section on the effects of the storm.

The Storm of 2 to 8 May

The storm was described by Glenn P. Ingwersen, Lt. Col., Corps of Engineers, in a typewritten report submitted to the Chief of Engineers, Department of the Army (typewritten letter, dated 11 Augut 1965):

"There was a sharp low pressure trough over the islands with cool air less stable than usual. There was a strong jet stream at a very high level and a weak low pressure area on the surface moving east to west. The storm hovered over the islands (Kauai, Oahu, Maui, and Hawaii) mainly because the upper level trough was not moving . . . . On Oahu the greatest concentration [of rain] was on the Windward side beginning at the south shore of Kaneohe Bay and extending to Kahana Bay. The gauge at Kahana recorded 28.5 inches of rain in this area [for the 1 - 3 May storm] . . . ."

The rainfall over the general area is shown on the map (Figure 3) with the isohyetals taken from Col. Ingwersen's report; the rainfall figures are the totals for 2 - 3 May. From the U. S. Weather Bureau "Climatological Data for Hawaii" for May, 1965, a few selected stations give greater details in Table 1.

Figure 3.

Storm on Island of Oahu, adapted from sketch map in report of Col. Glenn P. Ingwersen, U. S. Corps of Engineers. Isohyetal lines in inches giving total rainfall for the two-day period.

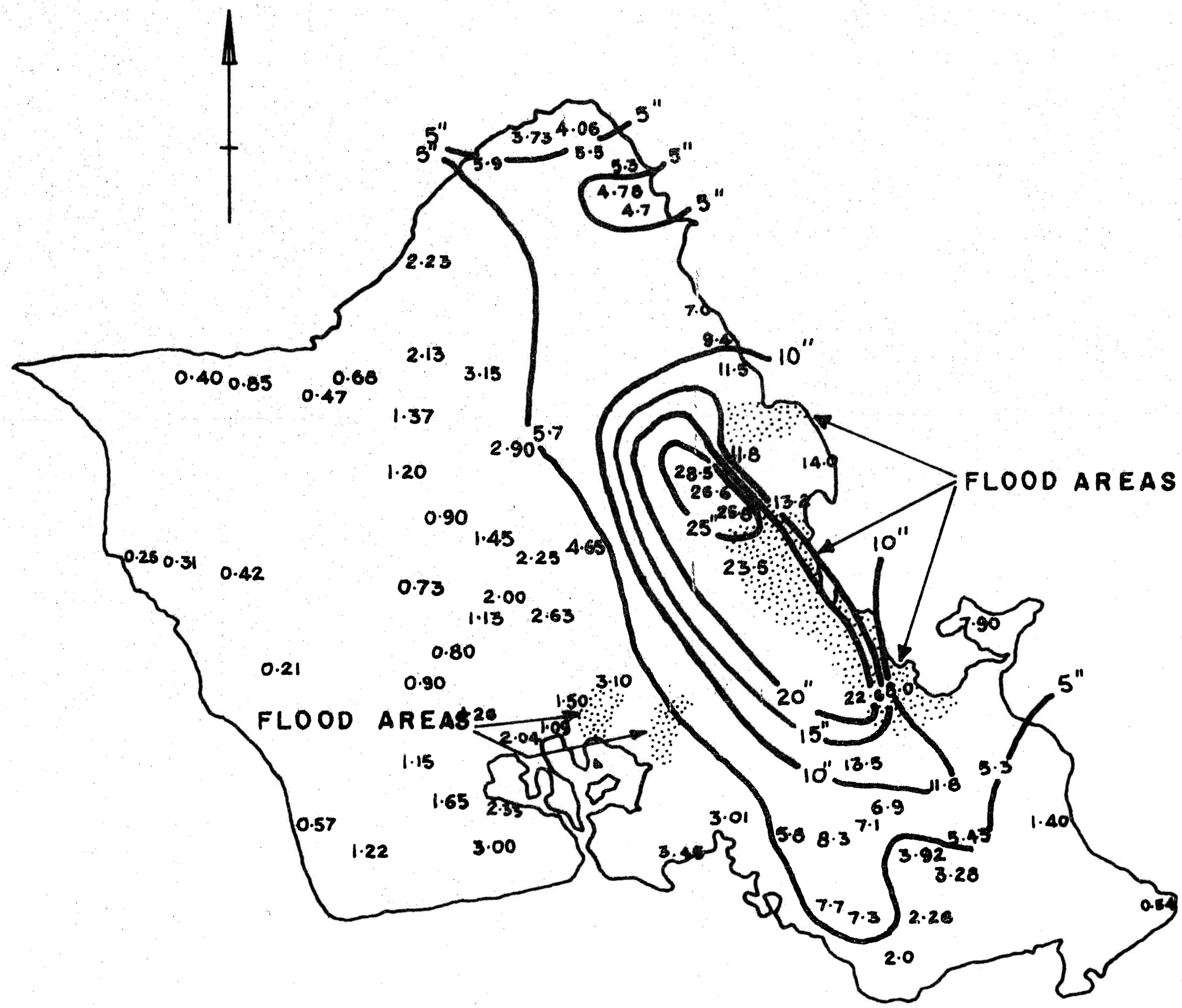

Table 1

Rainfall about Kaneohe Bay, 1 - 9 May 1965

Readings taken about 8 A.M., representing rainfall in inches for previous 24 hours, unless otherwise noted

Station	May 1	2	3	4	5	6	7	8	9	Nine day total
Kaneohe Mauka	0.33	0.67	21.61	1.90	2.15	0.05	0.12	0.13	4.10	31.06
Coconut Island	0.21	10.52[1]	0.63	3.65	0.63	0.38	0.11	0.0	1.85	17.98
Personal Gauge[2]	0.21	17.16	1.37	0.88	--	0.46[3]	0.13	3.92	0.0	24.13
Waiahole	--	--	23.50[4]	4.00	2.54	0.50	0.59	--	(1.45)[5]	(32.58)[6]

[1] Reading at 6 P.M.

[2] Personal rain gauge--for details see next paragraph; readings at 6 P.M.

[3] Two day total

[4] Three day total, rain gauge overflowed (data taken from original data sheet)

[5] Three day total, reading on 10 May

[6] Ten day total

During Sunday, 2 May, I was able to read my personal rain gauge at irregular intervals while trying to protect my home from flooding. The gauge is located in the open on the waterfront about 0.5 miles southwest of Coconut Island (see Figure 1). The collecting funnel is about 4 feet above the ground; the gauge (a non-professional model) consists of a funnel with a plastic tube holding 6 inches of precipitation. The calibrations of the gauge read to 0.1 inches, with interpolation values to an accuracy of ± 0.02 inches or less. The intermittent readings given in Table 2 reflect the varying intensity of the storm.

Table 2

Rainfall at 46-099 Lilipuna Road, Kaneohe, 2 May 1965

Time of Reading	Period since last reading (hours:minutes)	Reading in inches	Average for measured period in inches per hour
9:15 am	15:15	1.70[1]	0.11[1]
9:40	0:25	1.52	3.65
10:20	0:40	1.93	2.90
11:15	0:55	3.00	3.27
11:35	0:20	2.00	6.00
11:50	0:15	1.20	4.80
12:10 pm	0:20	1.80	5.40
12:23	0.13	0.47	2.17
1:15	0.52	2.70	3.11
3:20	2:05	0.42	0.20
7:25	4:05	0.48	0.12
Totals	25:25	17.22	0.68

[1]No rain noted until daylight (about 6 am), and presumably most of the precipitation occurring in 2 to 3 hours.

Another indication of the intensity of the storm are the records reported by Lt. Col. Ingwersen from the U. S. Geological Survey on the stream flow in the Kaneohe drainage (Table 3). The locations of the stream gauges are shown in Figure 2.

During the week of the heavy rains and the week that followed, there were only slight winds; the daily averages, shown in Table 4, were obtained from the U. S. Marine Corps Air Station on the eastern side of Kaneohe Bay (see Figure 1). The average wind for the two-week period was only 4.6 knots.

Hydrographic Conditions

During the initial period of the storm the tides were near maximal springs with a range on 3 June of 3.8 feet according to the actual recordings made by the U. S. Coast and Geodetic automatic tidal gauge located on Coconut Island (see Figure 4). This extreme range of tide had three effects: it exposed more reef to direct rainfall, it lowered the floating layer of fresh-water to contact more fixed reef animals, and it probably hastened the loss of freshwater to the surrounding ocean and its mixture with the underlying waters through the stronger tidal currents. By the following week the tides were in the neap range.

During the day of maximal precipitation, 2 May, no observations were made upon the water condition in the bay, but a brief tour on the morning of 3 May showed that all of the southern section and the central section, at least as far as the inner portion of the Sampan Channel, were covered by a thick layer of extremely muddy water; apparently the surface waters were almost or entirely fresh. On 3 May diving within the lagoon at Coconut Island showed a very turbid and cold layer about 1.5 m deep floating on a much clearer and warmer bottom layer. A week later on 11 May diving in

Table 3

Estimated Stream Flow at Selected Gauges

		Maximum Flood Previously Known			Flood of 1-5 May 1965	
Station No.	Name of Station Windward Oahu	Gauge Ht. (feet)	Discharge (c.f.s.)	Date	Gauge Ht. (feet)	Discharge (c.f.s.)
2739	Kamooalii Stream at Kaneohe	8.3	6,610	10/23/58	7.47	5,400
2744.99	Keaahala Stream at Kam Highway at Kaneohe	8.18	1,789	10/23/58	11.5	2,750
2750	Haiku Stream near Heeia	5.39	3,160	3/26/51	7.94	5,740
2780	Iolekaa Stream near Heeia	2.92	172	4/15/63	5.6	797
2834.8	Ahuimanu Stream near Kahaluu	11.44	6,000	2/ 4/65	11.64	6,610
2838	Waihee Stream near Heeia [Kahaluu] at altitude 260'	6.12	1,700	2/ 4/65	5.68	1,050
2910	Waiahole Stream at altitude 250' near Waiahole	4.80	2,230	4/15/63	4.8	2,230
2949	Waikane Stream at Waikane	10.76	8,800	2/ 4/65	8.39	3,300

Table 4

Winds at Kaneohe Marine Air Station
2 to 16 May 1967

Date	Prevailing Direction[1]	Hours of Duration[2]	Average Velocity[3]
2 May	NE	6	8.5
3	ENE	8	6.8
4	E / NE	5 / 5	4.9
5	Calm	6	2.8
6	NE	18	4.8
7	NE	9	3.9
8	Calm	11	2.5
9	NW	7	1.7
10	Calm	9	3.0
11	NE	7	5.7
12	E	7	5.7
13	S	10	7.5
14	SE	17	5.25
15	E	6	3.25
16	ENE	7	4.6

[1]The direction most frequently recorded.

[2]The number of hours the wind was blowing from the "prevailing direction."

[3]The average for 24 hours, in knots, unvectored.

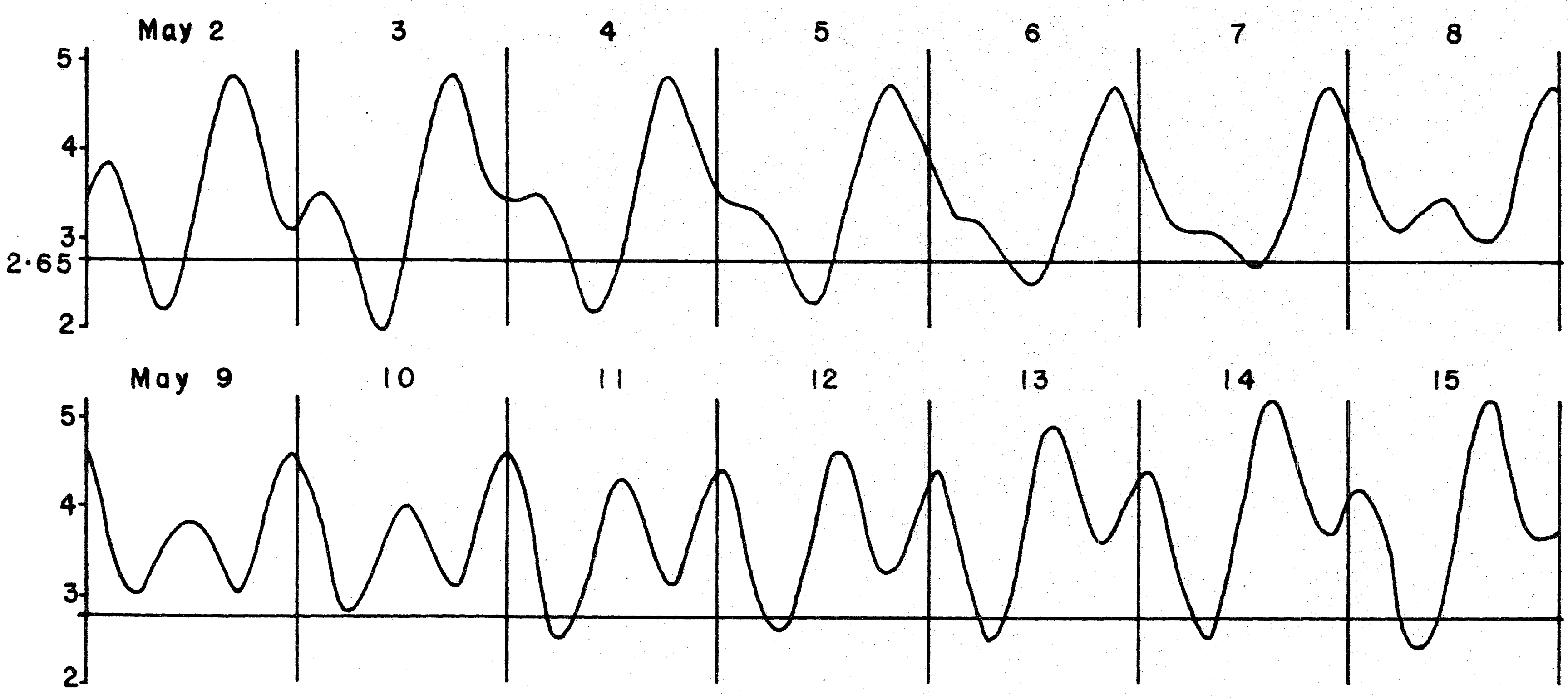

Figure 4.

Tidal record for May 2-15, 1965, from U. S. Coast and Geodetic Survey automatic tide gauge located on Coconut Island; heights in feet, with datum line at 2.65 feet (equals 0.0 feet on charts and in tide tables).

the same locality revealed the persistence of the layer. However, a diver at each of the hydrographic stations taken on the open bay on 12 May (see Table 5 and Figure 5 for locations) could not find a sharp demarcation between upper and lower layers, and temperature studies on that day showed that the upper waters were warmer, without any trace of thermal inversion.

Unfortunately it was not possible to obtain any salinities until five days after the major storm, on 7 May, and no samples other than surface could be taken until 10 May. Salinity was measured by the Knudsen method, with Copenhagen water as a standard. All salinity, oxygen, and Secchi disk measurements were taken by Twesukdi Piyakarnchana. The results of the salinity measurements are presented in Table 5, the stations at which they were taken are shown in Figure 1; and a distribution of oxygen with depth at Station 3 on 12 May in Table 6.

According to Piyakarnchana's year long study of the southern sectors of the bay, the average salinity of his stations ranged from 33.10 o/oo to 35.72 o/oo; in Bathen's similar study (1968) his lowest salinities were down to 31 o/oo but only near the mouths of streams, 32 o/oo for some open bay stations. For the entire period up to 18 May no surface waters of the southern or central portions of the bay exceeded the salinity of 32 o/oo and on 7 May, off the mouth of Keaahala Stream, the salinity was as low as 7.84 o/oo. In all samples taken at or deeper than 5 meters the water was found to be above 34 o/oo, within the normal range of surface waters. Obviously neither the light winds nor the ebb and flood of the tide caused sufficient turbulence to mix the water masses of highly different specific gravities.

Secchi disk readings, started on 10 May, showed the extreme turbidity of the water with the minimal depth reading of 4.7 feet on the first day of measurement; however, in the previous week the readings would have been much

Table 5

Salinities and Transparencies at Certain Stations,
South and Central Kaneohe Bay, 7 - 18 May 1965

DATE	HOUR	STATION	DEPTH (M.)	SALINITY	TRANS. BY SECCHI DISC	DATE	HOUR	STATION	DEPTH (M.)	SALINITY	TRANS. BY SECCHI DISC
7 May	1230-	2	0	7.84		12 May	0930-	2	0	32.50	8 ft.
	1400	3	0	31.57			1040		1	32.51	
		4	0	18.23					2	32.86	
		5	0	30.37					3	33.37	
		6	0	22.19					5	34.09	
		8	0	26.50				3	0	31.53	6 ft.
		9	0	32.76					1	33.11	
									2	33.64	
8 May	0830-	2	0	30.41					3	33.94	
	0950	3	0	23.32					5	34.17	
		4	0	21.69					10	34.62	
		5	0	21.57					13	34.70	
		6	0	22.96				5	0	31.51	
		8	0	23.13				8	0	31.61	
		9	0	19.70				11	0	33.92	
									1	34.21	
10 May	1430-	2	0	16.11	4.7 ft.				2	34.43	
	1600		1	32.40					3	34.54	
			2	33.74				12	0	30.75	
			3	33.78					1	30.93	
			5	34.10					2	33.76	
		3	0	29.94	5 ft.				3	34.01	
			1	29.89					5	34.25	
			3	33.63					10	34.63	
			5	34.16					14	34.68	
			10	34.23							
			15	34.66		18 May	1010-	2	0	30.14	6 ft.
		4	0	23.55	5.7 ft.		1204		1	31.03	
			1	31.43					2	33.78	
			2	32.75					3	33.95	
			3	33.67				3	0	32.56	9 ft.
			5	34.14					1	33.61	
			10	34.56					2	34.05	
			12	34.57					3	34.08	
		5	0	25.31				4	0	31.89	
		8	0	24.82					1	32.68	
		10	0	32.63	9.8 ft.				2	33.31	
			2	34.50					3	34.06	
		11	0	33.77	13 ft. (?)			5	0	32.72	
			1	34.01				8	0	32.89	
			2	34.40				11	0		4 M.
			3	34.49					1	34.01	
		12	0	29.88					2	34.14	
			2	33.87					3	34.17	
			3	33.99				12	0		9 ft.
			5	34.19					1	33.32	
			10	34.56					2	33.35	
			13	34.72					3	33.75	

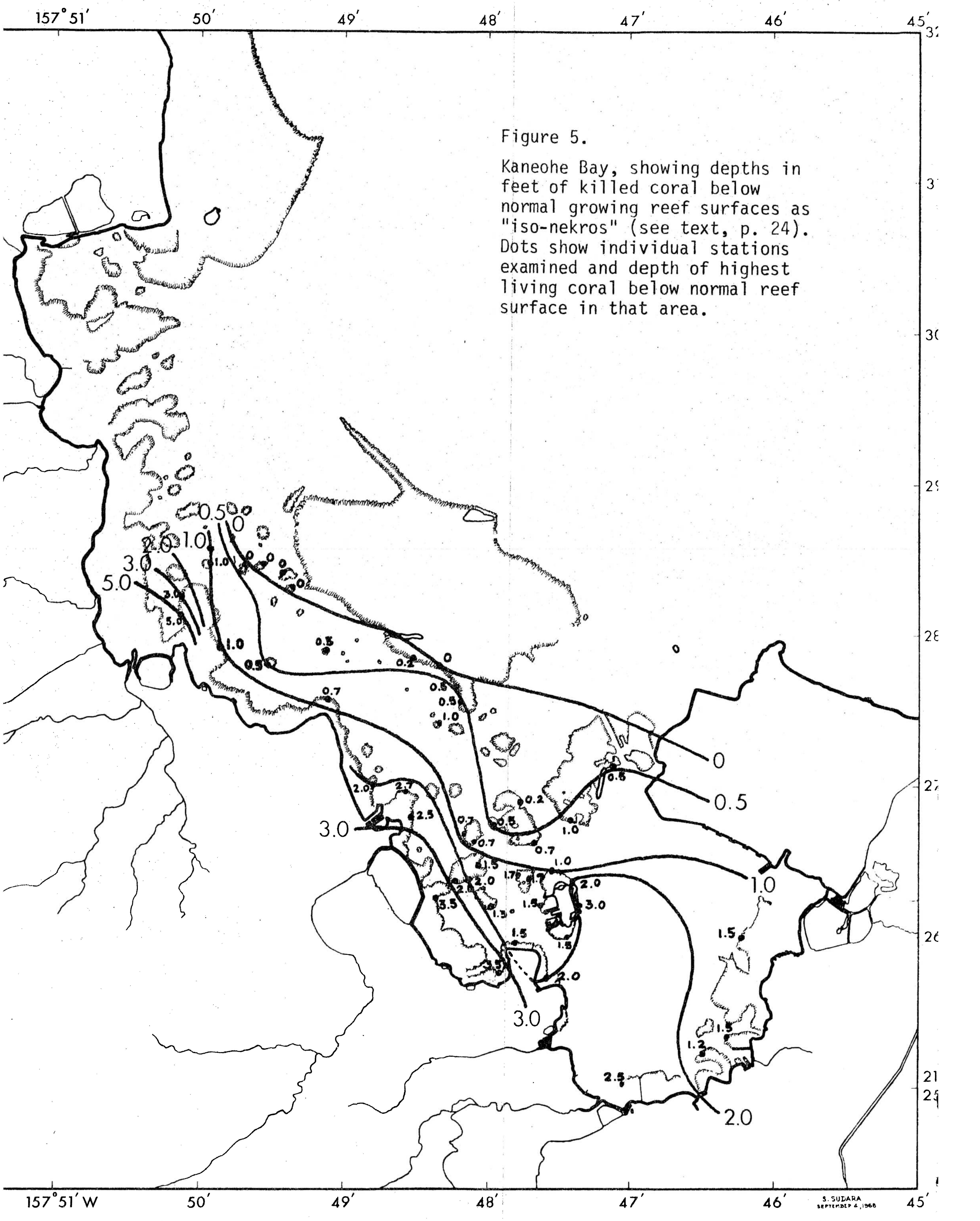

Figure 5.

Kaneohe Bay, showing depths in feet of killed coral below normal growing reef surfaces as "iso-nekros" (see text, p. 24). Dots show individual stations examined and depth of highest living coral below normal reef surface in that area.

lower. During the period of two weeks the color of the water changed from a brown from suspended silt to a green-brown as silt slowly settled and as the bloom of phytoplankton (see below) increased.

A few days after the major rainfall of 2 May the southern section of the bay developed a smell of decomposition, with the odor of hydrogen sulfide not only permeating the air immediately above the bay, but also being carried inland by the slight breezes. On 11 May a diver, Van Heukelem, described the water as "muddy, rotten, and dirty" and found some water to be "slimy." Oxygen was not measured until 12 May, and then only at Station 3, normally one of the less contaminated portions of the southern bay (Table 6).

Table 6

Oxygen concentrations at Station 3, 12 May, 0930-1040 hours
Depth in meters, Salinity in parts per thousand, Oxygen in ml/L

Depth	Salinity	Oxygen
0	31.53	4.08
1	33.11	3.40
2	33.64	3.01
3	33.94	2.89

Piyakarnchana reports that the average surface oxygen level in this portion of the bay (Line 2) of his year's study ranged between 5.0 and 6.0 ml/L. Tseu in her 13 month study reports no oxygen concentrations in her deep water station (Station 1) below 4.0 ml/L, and only slight differences between the surface and the deeper waters. Bathen reports an annual mean for all of his stations (at 1200 hours, 0-3 m deep) as 4.5 ml/L, but that the average was depressed by stations near stream mouths and sewer outfalls; he also reported that the 3-8 m deep average was 4.3 ml/L, and that his lowest oxygen concentration of 2.5 ml/L was at the sewer outfalls.

The figures in Table 6 represent a definite depression of the normal oxygen content, and it could be surmised that when hydrogen sulfide was evolving earlier in the week the oxygen was yet lower.

Biological Observations

Like the hydrographic observations, the biological observations were made intermittently and without a coherent plan; a number of these observations were made by other biologists working at the Hawaii Institute of Marine Biology who largely confined their observations to the groups in which they were interested. Several general but superficial surveys were made, one on 3 May, the day after the maximal rainfall, and several more intermittently during the next several weeks. Van Heukelem did some diving around Coconut Island and took underwater pictures; unfortunately with the turbidity of the water, the pictures were not clear. Various areas were revisited a number of times during the three years after the flood.

General Plankton:

When the bay was turbid, no observations on the plankton could be made; it is presumed that those plankters which could not avoid the fresh-water layer were killed. The effect of the lowered oxygen levels and the evolution of H_2S must be presumed to have as bad an effect upon the plankters as did the lowered salinity, and probably extended to even greater depth. However, the nutrient salts in the water from the land run-off and the decompositional products of animals in the bay caused an enrichment of the environment. An unknown green plankter occurred, a visible bloom that was first noticed in the Sampan Channel on 9 May, one week after the major rain. The conspicuous green bloom was observed reaching further and further into the bay as the water cleared. On 20 May chlorophyll A was measured by Piyakarnchana by the method of Strickland and Parsons (1960) at three stations in the southern bay and compared to the average for the area for the year he found in his study (Table 7).

Table 7

Chlorophyll A in mg/m^3 in Kaneohe Bay

Station	Average Aug. 1963 - July 1964	20 May 1965
Station 8 Line I	1.084	1.888
Station 3 Line II	1.167	1.683
Station 1 Line III	2.401	4.787

Porifera:

Previous to the storm three sponges were common and conspicuous on the western side of Coconut Island, some exposed at the lowest tide levels, some high in the subtidal. These were *Zygomycale parishii* (Bowerbank) *Toxadocia violacea* de Laubenfels, and *Tedania ignis* (Duchassing and Michelotti). During the week of the storm those on the reef flat and upper reef front were found to be rotting and slimy, while those a few feet deep appeared to be intact. However, in October 1965 a University class made a field trip to this reef to observe the sponges and found almost none remaining except those lower than 5 to 6 feet below the reef edge.

Coelenterata:

Hydrozoa

All *Pennaria tiarella* McCrady, normally abundant on floats at the laboratory docks, on stakes and posts on the reef, and on floating objects such as swimming floats and boat buoy in the southern section of the bay, were killed. By late summer the colonies were re-established.

Scyphozoa

Two scyphomedusae, *Cassiopea mertensi* Brandt and *Mastigas papua* (Lesson), both recently introduced into Kaneohe Bay and normally quite abundant during summer and fall months, were seemingly less common, but the judgment of their relative abundance was subjective.

Anthozoa

Three conspicuous members of the anthozoan fauna were spectacularly affected by the lower salinity and other changes in their environment: the sea anemone, *Radianthus cookei* (Verrill), the zoanthids or soft corals, and the corals of the reefs themselves.

Radianthus grows with its body buried in the sand of the reef flats, with its oral disk and tentacles expanded flush with the surface of the sand; its range normally extends from perhaps six to nine inches above low low tide level to a foot or so below that level. After a period of neap tides all are shades of brown, but when maximal spring tides occur, those highest in the intertidal may bleach to an off-white. On 9 May on an extension of the Sand Island reef the anemones high in the intertidal zone were blanched to a dead white and would not react when touched, while those about a foot below low low tide level retained much of their natural color and would react. In the following days similar white anemones were seen in various parts of the southern bay and about Coconut Island. Some, apparently dead, had come out of the sand and were lying with their bodies exposed. As late as August some of the anemones in the intertidal zone were still white. Experiments made during the summer of 1964 by Silthornivisudh on this species showed that an immersion in 40 percent seawater for 24 hours could cause the rupture of the gastrodermal cells and the expulsion of the zooxanthellae (unpublished).

As part of a research study, the areas on the Coconut Island reef with growing zoanthids were mapped. There were two species known, *Zoanthus* sp. nov.[1] growing densely on the surfaces of dead coral and extending from low in the intertidal zone to several feet below, and *Palythoa* sp. nov.[1] growing imbedded in the sand of the intertidal flats with only the disk appearing. On 11 May these beds were inspected. Most specimens of *Zoanthus* appeared intact, yet dead, and would collapse or disintegrate when touched. A few were observed in cracks in the coral that retained the green color of the disc and would normally contract when touched. *Palythoa* was not apparent on the reef flat, either being dead or withdrawn below the sand. By the following fall all beds were re-established, but specimens were not as numerous as before; by the spring of 1967 the colonies appeared to have regained their full numbers and by 1968 they had spread into areas of the reef flat previously occupied by living coral.

Of all the marine fauna in the southern and central sections of the bay the most spectacularly affected were the corals. In the inner portions of the bay the most common fixed corals were *Porites compressa* Dana and *Montipora verrucosa* (Lamarck); on the middle reef areas there are some specimens of *Pocillopora cespitosa* Dana and more massive heads of *Porites evermanni* Vaughan; in the wave swept areas *Pocillopora meadrina* Dana and *P. ligulata* Dana occur. Other fixed corals occur but usually do not make up much of the

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[1]Species to be described in paper in preparation by Walsh and Bowers.

reef population. *Fungia scutaria* Lamarck is especially abundant in middle reef areas, lying loosely between heads of other corals or on the sand. Before the storm the living corals extended up the reef front and for varying distances back onto the reef flat, usually with their tops dead at the level of mean lower-low water, but growing vigorously on the sides of the heads.

When the shallow water corals were seen in the inner bay on 3 May they were thickly covered by mud. Corals not exposed by the low tide could not be seen through the muddy water. By mid-week the shallow water corals which had been washed free from mud were white, similar to the sea anemones. By 9 May most of the shallow water corals were either white or had become enveloped by a thick layer of gray green mold-like substance. On 18 June, Van Heukelem, investigating the other edge of the Coconut Island reef, reported: "Heads of coral which had been covered with a brown slime are beginning to shed this cover; where the cover has been sloughed off, the coral appears white, but on close examination the individual polyps can be seen. These are transparent and without any trace of color."

Accompanying the apparent death of the heads in shallower water there appeared to be an intense grazing of the heads, probably by parrot fish (scarids). This was first noticed on 11 May and continued for several weeks. It was especially true of heads of *Porites*, where all the distal tips had been eaten off in the zone between 1 to 4 feet below low tide zone; the tips were scarred by the characteristic scratches made by the parrot fish. The white tips stood in sharp contrast to the inner branches still covered with dark mold.

The middle and southern sections of the bay were examined closely during 1966 and the depths of the living corals were noted. By this time the normal brown color of all living heads had returned and stood in contrast to the dead heads which were covered with mud and filamentous algae; later during the year numerous small oysters (*Ostrea sandvicensis* Sowerby) had attached to the dead fronds. In the various parts of the bay the line between the living and dead heads was not firm, but would vary about a foot up and down between adjacent heads. The depth of the shallowest growing head on a section of the reef was measured in reference to the previous maximal height of the adjacent reef. This was accomplished by diving, searching for the shallowest living head, and measuring its depth with a wand calibrated to quarter feet. The localities measured are shown on Figure 5 as spots, and connecting them, as contour lines, are the "iso-nekros." Above the indicated depths all *Porites* and *Montipora* and most *Fungia* were dead. Some scattered specimens of living *Fungia*, however, were found in the dead zone; these, surrounded by dead specimens of the same species, perhaps had been carried up by wave action from deeper parts of the reef.

The first reinvasion by fixed living coral into the dead zones was noted in the summer of 1968 on the Coconut Island reefs and along the small peninsula opposite it. Here were seen young round heads of *Montipora* and *Porites* up to two inches in diameter growing at 16 to 18 inches below the old growing reef top.

Annelida:

Few observations were made on annelids, usually not a conspicuous part of the fauna. The dense covering of tube worms, probably sabellids, on floats and buoys in the inner portion of the bay was entirely killed. On 9 May some dead *Eurythoe pacifica* Kinberg were found under coral heads on sand flats, and an unidentified nereid, about 18 inches long, was found half out of the sand on a reef at the inner end of the Sampan Channel. Other dead Errantia unidentified, were found on the surface of the sand and mud flats on 3 May.

Sipunculida:

A dead sipunculid, probably of the genus *Siphunculus*, was found dead and half out of the sand on Ahuolaka or "Sand Island" on 9 May.

Arthropoda:

The first indication of the intensity of the kill was found on the morning of 3 May on the reef flats in front of the author's home (see Figure 4). Here we were able to collect in a short time a liter of dead or dying shrimp, *Alpheus rapax* Fabricius, about two liters of the burrowing crab, *Macrophthalmus telescopicus* (Owen), and not infrequent specimens of two species of mantis shrimp, *Pseudosquilla ciliata* Miers and *Gonodactylus falcatus* (Forskål). It is notable that all four species occur in burrows in these flats in the intertidal zone. On the middle reefs visited that day, other dead crustaceans noted included various species of shrimp normally found living around coral heads on the reef flat, more mantis shrimp, the box crab (*Calappa hepatica* [L]), and several portunids. It is noteworthy that none of the abundant xanthid or grapsid crabs were found dead; perhaps, if they were killed, they remained in the crevices and holes where they had been hiding. Living specimens of *Thalmita edwardsi* Borradaile were found burrowing in the tide flats on 13 May.

Within the two weeks, coincident with the death of other encrusting animals on the floats and buoys in the inner waters of the bay, the barnacles on these objects also died.

No subsequent estimates on the depletion of the crustacean fauna were made.

Mollusca:

Only a few dead gastropods were seen. Several nudibranchs and ophistobranchs were found dead on the flats of the middle reef, and a student reported dead specimens of *Hydatina amplustra* Linnaeus, *Bulla* sp. and *Mitra litterata* Lamarck, normal sand burrowing forms, on the surface of Coconut Island reef. Limpets and littorines on the sea walls did not appear to be affected. No observations were made initially on the vermetids living in coral heads, but at least in the middle reefs of the bay, including Coconut Island reef, they survived and continued to grow in spite of the death of the coral head to which they were attached.

Among the pelecypods, specimens of *Tapes phillipinarum* (Adams and Reeve) were found alive on the inner reefs of the southern sector of the bay, but some *Lioconcha hieroglyphica* (Conrad) and a specimen of *Pinctada nebulosa* were found dead on the Sand Island reef. During the two week period, the numerous oysters, *Crassostrea gigas* (Thunberg) and *Ostrea sandvicensis* (Sowby), that grow on the sea walls around Coconut Island were always closed when observed; all of the larger oysters survived, while many of the smaller ones died.

Van Heukelem had located several dozen specimens of *Octopus cyanea* Gray in their holes on the Coconut Island reef, marking the locations for studies on behavior; after the storm none could be found, either living or as decaying remains. In a subsequent but lesser storm of November 1965, he found seven octopi, similarly marked, to be dead and rotting in the burrows. Therefore it is likely that the octopi in the storm had not migrated but were killed and their bodies had disintegrated before the observations could be made.

Brachiopoda:

On 3 May no specimens of *Lingula reevi* (Davidson) could be seen where they were known to occur abundantly. However, they were in usual numbers even on the most shallow and inshore of the reefs by 13 May, so during the freshwater flooding they must have merely withdrawn below the sand.

Echinodermata:

The only conspicuous echinoderms in the bay are the sea cucumbers, especially those of the genus *Holothuria* and *Ophiodesoma spectabilis* Fisher. *Holothuria atra* Jager normally lives on the reef flat and was killed in large numbers on the middle reefs, while burrowing members of the genus were found partially or entirely out of their burrows and dead. *Ophiodesoma* normally ranged from about the low-low tide zone on the reef to waters more than 10 to 15 feet deep on the reef front. All those in the shallow water of the reef flat and on the few feet of the reef front that could be seen through the muddy water disappeared. A graduate student, studying the species for his thesis research, said he thought all of the specimens around Coconut Island had been killed. However, the species was appearing again in shallow water within a month.

No dead brittle stars or starfish were seen, but they are not a conspicuous part of the fauna.

Hemichordata:

The acorn worm, *Ptychodera flavans* Spengel, was common in the sand of "Coral Island" reef and had been used for field trip study of classes in Invertebrate Zoology for several years previous to the storm. In areas of the reef they were most abundant--often several 6-inch long worms per shovelful of sand. After the storm only a few were seen partially emerged and dead. However, on the University class field trip in November 1965, no specimens of *Ptychodera* were found, and on the trips of the fall, 1966, and spring, 1967, only a few were found; these were all of small size (up to 3 inches). To judge by the castings, the large specimens, which reach a foot or more long, on Sand Island reef were not affected.

Chordata:

Tunicata

On 10 May all the colonial tunicates of the genus *Polyclinum* which had been common on Sand Island reef were dead.

Pisces

The detailed notes on the fishes were lost, but during the first midweek, dead fishes were cast up in windrows on the shore by the onshore breezes. They included most of the common teleosts of the reef: labrids, scarids, holocentrids, pomacentrids, moray and conger eels, burrowing eels, etc. A peculiar synbranchid, an introduced species whose habitat is not well known but presumed to burrow in brackish and freshwater, was cast up in large numbers on the beach at the north end of the bay. Twice during the reef surveys on Coconut Island small healthy schools of a fish, probably Iao (*Pranesus insularum*), were seen swimming in the muddy waters of the reef flat.

Notable is the fact that the original flooding did not appear to kill the fish and that their deaths occurred when the smell of hydrogen sulfide was most conspicuous.

Summary

During the week of 2 to 8 May 1965 extraordinarily heavy rains fell in the region of Kaneohe Bay, with one rain gauge recording 32.58 inches in 10 days and with a maximum of 17.16 inches in a single day. This caused a thick layer of fresh and silt-laden water to spread over the surface of Kaneohe Bay, with perhaps the greatest amount for the longest time in the semi-enclosed southern portion of the bay. From the primary effects of freshwater and silt and from the secondary loss of oxygen and accumulation of hydrogen sulfide, almost all shallow water elements of the marine fauna were disturbed or killed. Most conspicuous was the death of the reef corals; in some areas reaching 3 to 5 feet below the previous height of growing coral. In the three years since the flooding, most animals have been able to reestablish themselves, but the corals are only beginning to recolonize the killed areas.

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