EFFECTS OF RUNOFF FROM UNDERDEVELOPED VERSUS LIGHTLY DEVELOPED WATERSHEDS ON TROPICAL PLANKTONIC ECOSYSTEM

by

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ABSTRACT

Two bays in St. John, U.S. Virgin Islands have been sampled during the past year. One of the bays, Great Cruz Bay, is lightly developed with single and dual family residences, (average density of 1.5 residences per acre) paved and unpaved roads, and has been dredged for use by private boats. The other bay is undeveloped and protected within the V.I. National Park. Rainfall has been measured and runoff estimated in both watersheds. Measurements of salinity, temperature, turbidity and nutrients have been done and plankton have been collected and evaluated. A comparision is made of the effects of the runoff on the two bays. Water quality is good in Great Cruz Bay because natural ecosystems modifying runoff have not been seriously altered during development. The major difference between the bays seems to be the occasionally high sediment load in Great Cruz Bay due to earlier dredging. The increased turbidity may affect productivity. There are two findings of significance. The first is that as long as the natural saltpond-mangove ecosystems are left undisturbed only relatively heavy rains (over 2 inches per 24 hours) show any effect, regardless of development in the watershed. The second is that some link apparently exists between rainfall and successional increase of phytoplankton and finally of fish populations.

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EXECUTIVE SUMMARY

The island of St. John is a small tropical island of 19 square miles extend and with a population of about 3,000 persons. About two-thirds (2/3) of the island is a National Park, now designated as a Biosphere Reserve. At one time about 95% of the island was cleared and planted in sugar cane, indigo, hemp, and bay rum. Most of the island is now in secondary to tertiary successional tropical forests.

The two watersheds and bays studied were Great Cruz Bay, lightly developed with homes, guest houses, and small businesses, and Greater Lameshur Bay an undeveloped area except the geomorphic profiles for both water-sheds are similar; a small flat alluvial plain with fossil beach berms and mangroves at the shore. The soils of both are shallow Cramer series over volcanic rock. The beaches are Juacas sand and worn cobbles. Behind the beach and beach berm in both cases lie mangrove forests and small salt ponds of 4-5 acres. Both watersheds have 30"-40" rainfall per year.

Major differences between the bays are in population, vegetation removal, and drainage patterns. Great Cruz Bay has about 300 people in the watershed, Lameshur Bay has 6 people. The leaf area index (cover at an "average" point) is 1.2, whereas at Lameshur Bay it is 3.4. Cruz Bay has developed about 80% of the natural area, Lameshur Bay has 6% developed.

Cruz Bay was 2^{o}-3^{o} centigrade cooler than Lameshur Bay all year. The range as well as the absolute levels of turbidity was 2 to 3 times higher in Cruz Bay. The salinity in Cruz Bay averaged 5%-8% higher than in Lameshur and the range of levels were more variable. The phosphate levels and phytoplankton blooms were higher in Lameshur Bay after rains of more than 1 inch per 24 hours.

Nutrients and phytoplankton levels were similar in both bays. About 3-4 weeks after a series of rains and algae and turtle grass (Thalassia) on the inner bay bottoms doubled in biomass (grams) per square meter. This bottom growth increased during December and January but as rain ceased temperature and salinity increased the bottom flora began to die back with more and more plants appearing in the water column during March and April.

Most of the die-off was followed by a large increase in Phosphate in late May and in June. This nutrient increased was followed by growth of phytoplankton.

There are three significant findings of this study:

1. Up to a point it is less significant for the nearshore marine systems whether the watershed is developed or not than whether the salt pond/shoreline vegetation and the beach berms are left intact.
2. There is a connection between the watershed runoff and the primary production of the bays but except

for very large rains, the connection is probably subsurface drainage, is delayed, and is not disruptive.

3. The occurance of rain triggers a definable ecological succession of phytoplankton, zooplankton, and algal growth which in turn may be instumental in keying fish spawning and/or survival of the fish larvae. Presumably the type and range of succession would depend on how extensive development was done and whether the coastal berms and vegetation were preserved.

INTRODUCTION

The Caribbean region is being developed for residential, commercial and industrial purposes. Tourism and vacation potential are being exploited at the same time as the island populations are increasing, and with them a need for broader based economies. The trend is especially true in the U.S. Virgin Islands, and appears to be accelerating. The growth has increased land values and resulted in a spiralling pressure for development of available land. Effects of construction and land-form changes in tropical environments are not well documented. This paper and the related study done in Lameshur and Watermelon Bays (Purcell, 1980) may serve as a step in understanding the effect that changes in a watershed may have on rainfall runoff and the resultant alteration of the physical and biological state of the bay associated with the watershed.

The project measured the rainfall in two watersheds on St. John, USVI: Little Lamshur Bay has an undeveloped watershed and Great Cruz Bay has a lightly developed residential watershed subject to growth (Figure 1). Concurrent measurements were made in the associated bays for salinity, temperature, turbidity, nutrients levels and plankton numbers, and these were associated to the amount of rainfall and runoff. The differences in measured data which manifested themselves between the two bays might be assumed to be caused in part by differences in development.

Examination of these variances may in turn reveal a means of utilizing a watershed in the most efficient and elast destructive manner.

METHODS AND MATERIALS

Rainfall was measured in each watershed by a "Weathermeasure" tipping-bucket rainfall guage connected to a Weathermeasure automatic event recorder. A passive guage was placed nearby to serve as a backup. One instrument was set up in an open area near the ranger residence in Lameshur Bay; the other near a private house in Great Cruz Bay (Figures 2 and 3). Recording graphs were changed weekly.

Streams in St. John are intermitant and do not flow during much of the year. Sites were established for streamflow guages in each of the two watersheds (FIgure 2, 3) and the guages were to be emplaced when flow was adequate for measurement. The cross section of the streambed at these sites was measured and plotted to use as an estimate of runoff volume. The area of the Lameshur and Great Cruz Bay drainage areas were adapted from the Virgin Islands Sdiment Reduction Plan (1979).

Two marine sampling stations were established in each the bays (Figure 2, 3) one near the outfall of the major portion of the runoff and the other in the mouth of the bay. Samples were taken once a month from each of these stations. Additional samples were obtained following rains of 1.27 cm (0.5 in) or more. Temperature and salinity were measured *in situ* at each

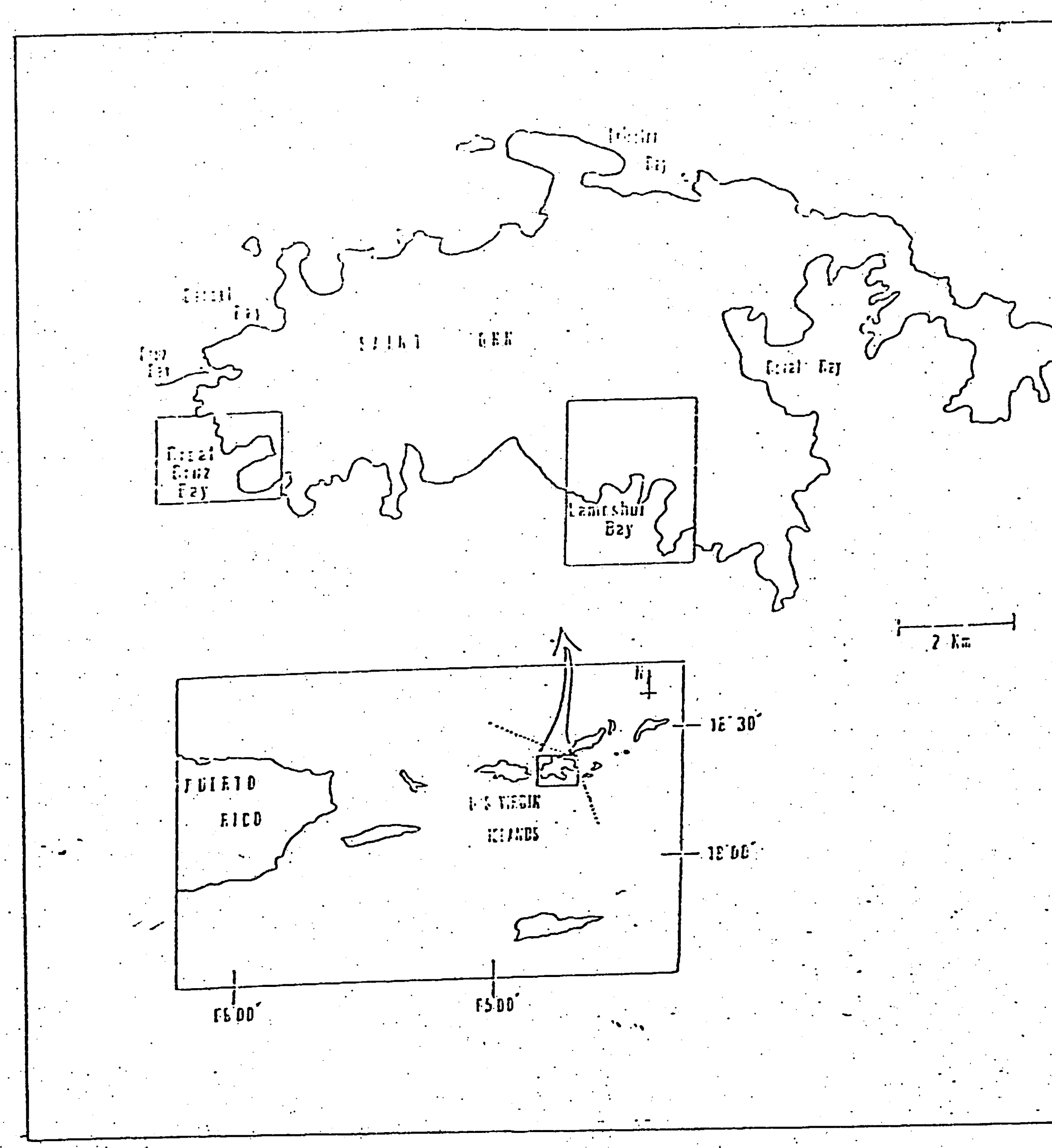


Figure 1. Puerto Rico and the Virgin Islands with St. John enlarged to show sampling areas.

station using a calibrated mercury thermometer and an A.O. Refractometer with salinity scale. Water samples were taken at each station with a 5 L. Van Dorn bottle and transported back to the lab for analysis. A 500 ml water sample was preserved with H_2SO_4, frozen as quickly as possible and held until analysis for nitrates and phosphates could be accomplished. Nitrate/nitrogen was measured by the brucine-sulfanilic acid method, and phosphates by the ammonium molybdate method as outlined in E.P.A. Methods for Analysis of Water and Wastes (1976). A Coleman 6/30 Junior II spectrophotometer (23 mm wavepath) was used for colorimetric determination.

A second water sample from each site was used for measurement of turbidity in Nephelometric Turbidity Units (NTU) utilizing a Fisher DRT - 1000 Turbidimeter.

A final 5-10 ml water sample was preserved at the site with buffered formalin and transported to the laboratory for settling and analysis of phytoplankton populations using modifed Ultermohl techniques outlined in the Phytoplankton Manual (1978) Counts were made with an Olympus IM inverted plankton counting microscope at 200x. Photographs were taken of a typical field of each sample at 40 x to help in analysis of sediment.

SITES

Little Lameshur and Great Cruz Bays were chosen as study areas because of physical similarities and development differences as well as practical concerns such as access. The bays are similar in drainage area, general shape of the bay and direction of opening and both have a single main outfall into the bay. Lameshur watershed is undeveloped, with one dirt road and one dwelling. Great Cruz Bay watershed, on the other hand is lightly developed with 1.5 residences per acre, several paved or dirt roads and the Department of Public Works sanitary landfill and incinerator site near the top of the watershed. It is important to note that neither watershed has development within the low lying area behind the beach through which the watershed drains, and that the beach area has been little changed. When the study began plans had been made to develop this area of Great Cruz Bay with condominium construction. The project has been delayed or cancelled by legal action.

Lameshur Bay is located on the Soth shore of St. John, U.S. Virgin Islands Figure 1), and is separated into two parts, Greater and Lesser, each with its own drainage area (Figure 2). The watershed for Lesser Lameshure is fairly steep, rising to 1,100 feet at the Bordeaux mountain ridge. The mean altitude of the ridge is closer to 700 feet. The hills are fairly steep, well forested and drain into several channels or "guts" which coverge in a broad thorn/mangrove area less than 3 meters (10 ft) above mean sea level with the seaward exit of the drainage channel being at sea level.

The surface soils are composed primarily of Cramer gravelly clay loam with slopes of 12 to 60 percent. The U.S. Department of Agriculture Soil Survey (1970) characterize drainage as good,

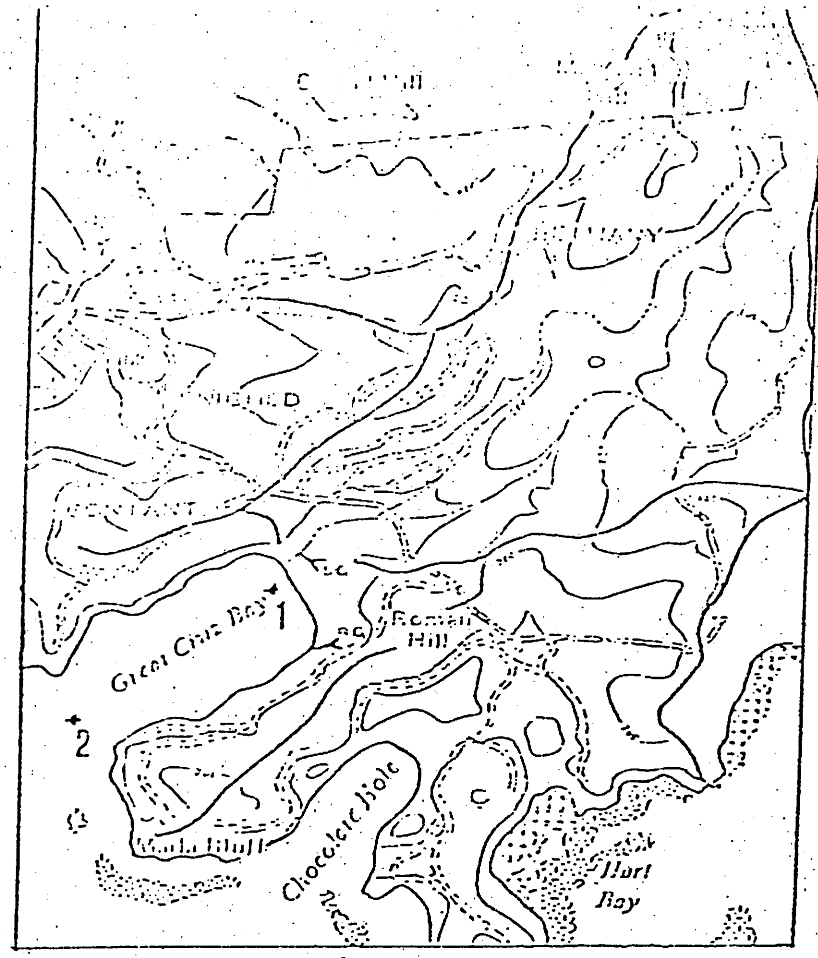


Figure 2. Watershed of Great Cruz Bay, showing sampling stations and gage sites.

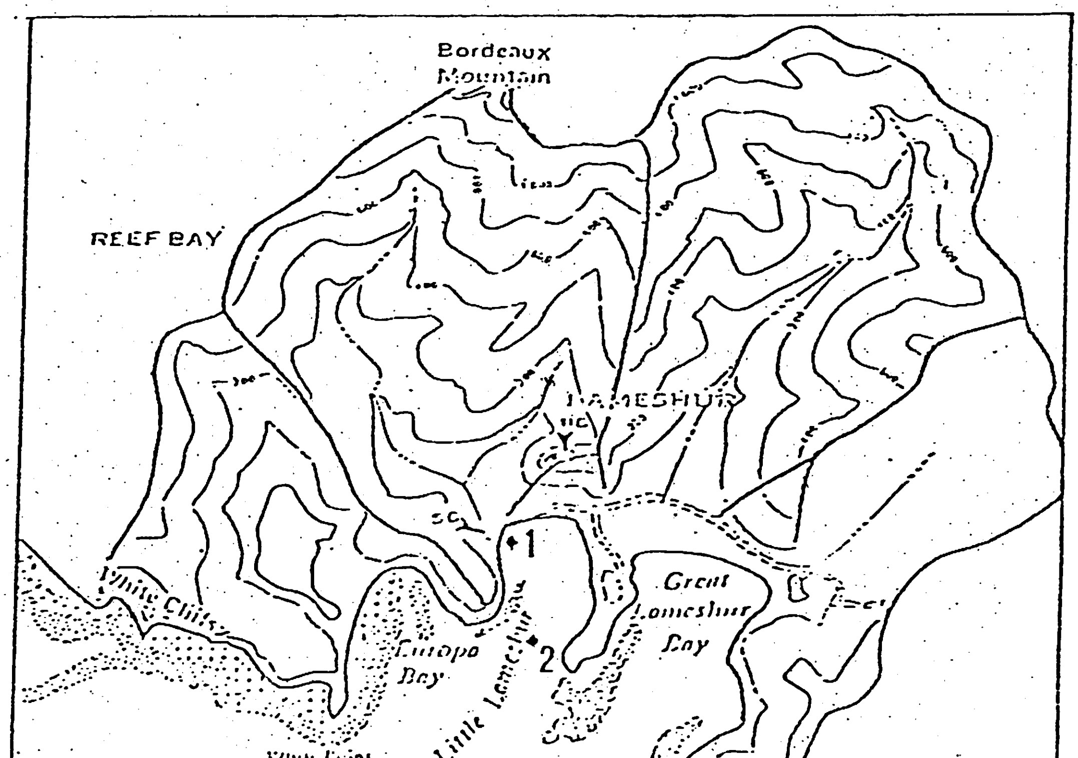


Figure 3. Watershed of Little Lameshur Bay showing sampling stations and gage sites. RG = rain gage ; SG = stream gage; ◆ 1 = station.

runoff as medium to rapid and permeability as moderate. The Cramer series soils here are generally shallow (25-50 cm) over partly weathered basic volcanic rock. The southern slope is cobbly alluvial land, and stony with resultant rapid permeability and low water holding capacity.

Drainage area for the watershed is 536 acres (2.17 km^2) (Sediment Reduction Program, 1979). A natural berm which rises between the flats and a cobble beach generally serves to retain the runoff. There is one inhabited dwelling in the watershed, the N.P.S. ranger residence (Figure 2). A septic field is used for waste disposal. There are also two pit/chemical toilets for use of park visitors. A beach occupies the Northern shore of the bay. The Juacas sand beach to the east is separated from the cobble beach by a rock outcropping which extends into the bay about 30 meters, with several rocks emergent. The outfall occurs on the western end of the cobble beach. Use of the beach by visitors is not high as access must be over the single dirt road or by foot.

The bay bottom near the cobble beach is rocky with scattered corals. The slope is gradual, and 20 to 30 meters offshore in a depth of 2 meters the bottom changes to sand. Maximum depth near the mouth of the bay is 15 meters. Most of the central part of the bay is covered with a grass bed composed mainly of *Thalassia*. The remainder of the eastern and western shore are steeper and rocky with good coral and gorgonian development.

Easterly winds dominate, and the resultant swells enter the bay at a broad angle but during weather they may be refracted enough to break on the cobble beach. Wave action and storm runoff, had, at the beginning of the study in mid-May breached the beach berm at the outfall, creating a situation where the low lying area behind the berm was infiltrated with salt water and the runoff from the watershed would, after mixing with standing water have direct access to the bay through a narraw (2-3 meters) gap. The last two thirds of the study was done with the breach filled in by natural action and no direct access between runoff and the bay. Bay water could pass through the berm slowly however, and surface water close to the berm tended to be saline. This, after prolonged periods of ligh rain, tended to be over 30 parts per thousand of salinity. Circulation in the bay appears good, and the flushing time seems low.

Great Cruz Bay is located in the Soth-western corner of St. John (Figure 1). The watershed is not as steep as that of Lamshur Bay with the highest points being slightly more than 800 feet (Figure 3) and an average height of approximately 500 feet. The water shed is narrow and long and empties into two principal water channels which join to form a single outfall at the bottom of the slope. The larger of these two "guts" is Guinea Gut, which drains the watershed from the area of the saitary land fill. The two channels become one just below the south road and continue toward the bay. The beach creates a a berm which contains the water flow, and forces it over its banks into the low lying area behind the beach during high rainfall periods.

Like the rest of St. John the slopes are primarily Cramer soils with Isaac soils on the foot slopes. The majority of the low land south of the road is characterized by the Soil Survey of the Virgin Islands (1970) as an alluvial fan of San Anton clay loam, with a tidal flat area close to a Juacas sand beach. Permeability of the entire watershed is moderate, and topsoil on the slopes is quite shallow. The majority of the slope area is well forested, and roadways tend to run cross slope or along ridgelines.

The drainage area for Guinea Gut and the associated gut is 447 acres ($1.81KM^2$), with some additional drainage from the Roman Hill area, making it 84% of the size of the Little Lameshur watershed. More than 50 residences (1978 data) are located in the watershed. Several are near the beach, but the largest number are in Bethany and in an area East of Enighed. There are also some houses along the road leading past Gift Hill to the sanitary landfill site. Most of the houses would use septic fields. There is a main road, primarily of asphalt, located along much of the perimeter and several dirt roads running cross-slope on the Western side of the watershed.

The beach is Juacas sand and subject to very little wave action, protected by the depth of the bay. A number of private craft use Great Cruz Bay as an anchorage, and it has been dredged in the past to allow access of these boats. The bay bottom is primarily sand which appears to have a very fine silt-like quality. There are no significant grass beds within the bay, but there is sparce growth here and there. The bottom is very gradual slope, approaching 20 feet (6 meters) at the mouth. Some coral and gorgonian growth exists near the mouth.

The runoff from Great Cruz Bay watershed was never observed during the study to run over the beach and directly into the bay, although witnesses have reported this as happening in the past. There was infiltration of salt water behind the berm, and like Lameshur, during periods of low rainfall the standing water became quite salty.

RESULTS

Data resulting from the study are sumarized in Figures 4 through 11. The daily, monthly and yearly rainfall are shown in Figures 4 and 5 for Lameshur and Great Cruz Bay respectively. The data are presented in inches for ease of comparison with the total body of past rainfall data. Mechanical problems with the meter in Great Cruz Bay caused the loss of the first 48 days data. Yearly rainfall in Lameshur was 43.53 inches (110.5 cm) or 0.45 (1.1 cm) less than the mean of 43.98 inches (111.7 cm) (Figure 12). Yearly rainfall in Great Cruz Bay was considerably less, being only 29.31 inches (74.4 cm) or 14.7 inches (37.3 cm) less than the mean. Rainfall was highest at both stations in April, May and October, and lowest in February, March and June.

Temperature of the surface water in degrees centigrade at the bay sites (0.5 M water depth) is presented in Figure 6, and the salinity given in parts per thousand (ppt) is shown in Figure 7. The temperatures in Lameshur Bay ranged from 30.8°C

DAY	'80 MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	'81 JAN	FEB	MAR	APR
1	0	.05	.06	0	.04	0	2.00	0	0	0	0	0
2	.04	.02	0	.48	0	.16	0	.04	0	.06	0	.11
3	0	0	.06	.69	.48	.01	.16	.06	.08	.03	0	5.46
4	0	0	0	.34	.09	.21	.12	.14	0	0	0	.73
5	0	0	.35	0	0	.10	.05	.03	0	0	.20	.17
6	0	0	0	0	0	.91	.02	.15	0	.03	.01	.10
7	0	0	.03	.49	0	.36	0	.97	0	0	0	.02
8	0	0	.10	.06	0	.53	0	0	.20	.29	0	.07
9	0	.14	0	.22	.07	0	0	0	0	.15	0	.47
10	0	.09	.56	.11	.01	0	.02	0	.02	.18	0	0
11	0	.28	0	0	.01	0	0	0	0	.12	0	0
12	0	.10	0	0	.57	0	0	.03	0	.04	0	.02
13	0	.15	.31	.04	.17	0	0	.05	.01	.03	0	.01
14	1.62	0	0	.28	.10	0	0	.41	0	.06	0	.04
15	.08	0	.32	.16	.06	.73	.15	.06	.02	.03	0	0
16	.01	0	0	0	0	.01	.12	.03	.14	0	0	0
17	0	.12	0	0	.05	.27	0	.11	0	.16	0	.06
18	.32	0	.72	0	.02	0	.01	0	0	.06	0	0
19	0	0	0	.02	.32	0	.06	.07	0	.06	0	0
20	.05	.15	.05	0	.02	1.80	.14	.05	0	0	0	0
21	.03	.05	0	0	.04	.52	.47	.08	0	.22	0	0
22	0	0	0	.04	.07	.69	.03	0	.01	0	.10	.02
23	0	0	0	0	0	.21	.01	.04	0	0	0	.03
24	.06	0	.17	0	.07	.16	.12	.20	0	0	0	.08
25	0	0	0	.06	0	.24	0	.30	.06	0	0	.07
26	.29	.02	.33	0	.26	.03	.01	0	0	0	0	.48
27	.12	.03	0	0	0	0	.10	0	0	0	0	0
28	.56	.04	0	.05	1.58	0	0	.15	2.02	0	.01	.07
29	.77	0	0	.08	0	.02	0	0	.11		0	.01
30	0	0	0	.03	0	.23	.15	0	.10		0	.14
31	0		0			.63		0	.50		0	
TOTAL	3.95	1.24	3.06	3.15	4.03	7.82	3.75	2.97	3.27	1.52	0.32	8.45
RAIN-DAYS	12	13	12	16	19	20	18	19	12	15	4	20

Total Year 43.53 inches

Figure 4. Daily rainfall recorded in Lameshur Bay watershed from 1 May, 1980 through 30 April, 1981.

DAY	MAY *	JUN *	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
1			.02	0	0	0	.33	0	0	0	0	.05
2	.05		.18	0	.01	.03	.67	.02	0	.04	0	.09
3			.12	.34	.14	0	.09	0	.02	.06	0	.09
4			0	.33	.81	.40	.04	.06	0	0	0	1.31
5			0	.13	0	.24	.02	0	0	0	.01	.72
6		.10	0	0	0	.88	.01	.01	0	0	0	0
7			0	.69	0	.38	0	1.23	0	.04	0	.04
8			0	.03	0	.65	0	0	0	.02	0	.13
9	0		0	.03	.10	.17	0	0	0	.09	0	.24
10			0	.09	.20	0	0	0	0	.12	0	.03
11			0	0	.04	0	0	.04	0	0	0	0
12			0	.07	.74	0	0	0	0	.04	0	.01
13		.55	0	.11	.09	0	0	.07	0	.03	0	.01
14			.13	.25	.01	0	0	.06	0	.05	0	0
15			.08	.01	.13	.12	0	.13	.07	.03	0	0
16	2.27		0	0	0	.25	0	.02	0	.11	0	.06
17		.44*	.05	0	0	.06	0	.04	0	.07	.03	.01
18		.01	0	0	.01	0	.08	0	0	.01	0	0
19		.02	.19	.01	.30	.82	.01	.10	0	0	0	0
20		.08	.14	0	.03	.26	.11	.01	0	.41	0	0
21		0	.31	0	0	.03	.29	0	0	0	0	0
22		0	0	0	.07	.92	.39	.02	0	0	0	.05
23	.41	0	0	0	.16	.33	.10	.21	0	0	.02	0
24		0	.23	0	.34	.36	.04	.29	.02	0	0	.03
25		.01	0	.08	0	0	.11	0	0	0	0	0
26		0	0	0	.03	.11	0	0	0	0	0	.57
27		.33	.10	0	.31	.03	0	0	0	0	.03	0
28		.06	0	.14	.12	.04	.05	0	.03	0	.01	0
29		.03	0	0	0	.13	0	0	.01	0	.03	0
30	1.44	.14	0	0	0	0	0	0	.03		0	.35
31			0	0		.31	.03	0	0		0	
TOTAL	*3.17	*1.77	1.55	2.31	3.64	5.60	2.37	2.31	3.36	1.14	0.13	3.79
RAIN-DAYS			11	14	19	21	16	15	6	14	6	17

Total Year 29.73 inches

* - Estimated from Cruz Bay rainfall

Figure 5. Daily rainfall recorded in Great Cruz Bay watershed from 1 May, 1980 through 30 April, 1981.

at station I in October down to 26.4^{o}C in February at the mouth of the bay. Great Cruz tended to be a bit cooler throughout the year with a high reading of 30.0^{o}C in October down to 26.~~4~~ 2^{o}C at both stations in February. Salinities for Lameshur ranged from 34.0 ppt (Oct.; Station 1) to 36.2 ppt. (Dec.; Station 2) and for Great Cruz Bay from 34.0 (Oct. both Stations) to 38 ppt. (Feb., Station 1). The stations at the mouth of the bays tended to be cooler and more saline. Preliminary perculation studies show hyposaline cooler water to be perculating up through the sand bottoms at several points during the months of November - February.

The levels of the nutrients phosphate (PO_4) and nitrate-nitrogen (NO_3-N) are presented in mg per liter in Figures 8 and 9 respectively. Due to equipment problems early samples had to remain frozen for several months before analysis. There were peaks noted in May for both nitrate and phosphate, and peaks during the late summer as well. The remainder of the year showed readings low enough to fall below the confidence levels for the instrument used.

Turbidity, in Nepolometic Turbidity Units (NTU) is presented in Figure 10. Turbidity ranged from 0.~~4~~ 2 (Sta 2, ~~16 Oct.~~ June-July.) to 6.0 (Sta 1, 29 May) in Lameshur and from 0.~~8~~ 2 (Sta ~~1~~ 2, ~~29 Sept.~~ 30 July) to 13.0 (Sta 1, 24 Feb.) in Great Cruz Bay.

Photographic representation of settled materials from each sample are presented in Appendix A.

Phytoplankton total number are presented in Figure 11a as cells per liter x 10^2, and as composition of the population in Appendix B. A list of identified species is also to be found in Appendix B. Zooplankton numbers are presented in organisms per cubic meter in Figure 11b.

DATE	LAMESHUR STA. 1	LAMESHUR STA. 2	GREAT CRUZ STA. 1	GREAT CRUZ STA. 2
8 May, 1980	30.0	29.8	29.2	28.0
16 May	28.0	28.5	28.4	27.9
29 May	28.5	28.2	28.5	28.0
26 Jun	30.1	29.5	29.1	29.0
30 Jul	30.0	29.5	29.1	29.0
22 Aug	30.2	29.8	29.2	29.5
5 Sep	30.0	29.5	29.5	29.5
29 Sep	30.5	29.8	29.5	29.8
8 Oct	30.5	30.2	30.0	29.5
16 Oct	30.8	30.1	29.9	29.5
23 Oct	30.0	29.9	29.9	29.5
8 Dec	27.4	27.5	27.0	27.0
28 Jan, 1981	27.9	27.5	27.0	27.0
24 Feb	26.5	26.4	26.2	26.2
17 Mar	27.9	27.8	27.5	27.0
10 Apr	27.5	26.5	-	-

Figure 6 . Temperature of water at the 1 M depth in Lameshur and Great Cruz Bays in C^{o}.

DATE	LAMESHUR STA. 1	LAMESHUR STA. 2	GREAT CRUZ STA. 1	GREAT CRUZ STA. 2
8 May, 1980	36.0	36.0	36.0	37.0
16 May	35.0	36.0	36.0	36.5
29 May	35.0	35.5	35.5	36.0
26 Jun	35.0	35.5	36.0	36.5
30 Jul	35.5	35.0	35.0	36.0
22 Aug	35.0	35.5	35.0	35.0
5 Sep	35.0	35.0	34.5	-
29 Sep	34.0	35.0	35.0	35.0
8 Oct	34.5	34.5	34.0	35.5
16 Oct	34.0	34.5	34.0	34.0
23 Oct	34.5	35.5	34.5	35.0
8 Dec	35.9	36.2	34.5	35.5
28 Jan, 1981	34.5	35.5	36.0	35.5
24 Feb	36.0	36.0	38.0	37.0
17 Mar	36.0	35.0	35.0	35.0
10 Apr	34.5	35.0	-	-

Figure 7 . Salinity of the water at the 1 M depth in Lameshur and Great Cruz Bays in ppt ($^{o}/oo$).

DATE	LAMESHUR STA. 1	LAMESHUR STA. 2	GREAT CRUZ STA. 1	GREAT CRUZ STA. 2
8 May,1980	0.11	0.38	0.03	.017
16 May	0.32	0.24	0.12	0.13
29 May	0.0	0.0t	0.02	0.0
26 Jun	0.01	0.0t	0.03	0.0t
30 Jul	0.01	0.0t	0.0t	0.0
22 Aug	0.05	0.07	0.03	*
5 Sep	0.0t	0.0	0.01	0.01
29 Sep	0.0t	*	0.01	0.01
8 Oct	*	0.01	0.0t	0.0
16 Oct	0.01	*	*	0.01
23 Oct	0.0t	*	0.01	0.01
8 Dec	*	*	*	*
28 Jan,1981	0.0t	0.01	0.01	0.0t
24 Feb	0.01	0.01	0.01	0.0t
17 Mar	0.01	0.01	0.01	0.0t
10 Apr	*	*	*	*

Figure 8. Phosphate levels in the water from 0.5 m depth from Lameshur and Great Cruz Bays in mg per liter (ppm). t = trace; * = no data, breakage or equipment failure.

DATE	LAMESHUR STA. 1	LAMESHUR STA. 2	GREAT CRUZ STA. 1	GREAT CRUZ STA. 2
8 May,1980	1.1	2.7	0.9	0.8
16 May	0.4	1.2	0.9	0.8
29 May	0.1	0.0	0.0	0.2
26 Jun	0.0	0.1	0.0	0.0
30 Jul	1.4	1.1	1.3	1.6
22 Aug	0.5	0.5	0.2	*
5 Sep	3.1	3.4	0.0	0.0
29 Sep	0.0	0.1	0.0	0.1
8 Oct	*	0.0	0.0	0.0
16 Oct	0.1	0.2	0.4	0.2
23 Oct	0.2	0.1	*	0.0
8 Dec	0.2	0.0	0.0	0.0
29 Jan,1981	0.0	0.2	0.0	0.0
24 Feb	0.1	0.1	0.2	0.1
17 Mar	0.3	0.1	0.2	0.2
10 Apr	0.3	0.2	*	*

Figure 9. Nitrate-Nitrogen levels from 0.5m depth from Lameshur and Great Cruz Bays in mg per liter (ppm). * = no data, breakage or equipment failure.

DATE	LAMESHUR STA. 1	LAMESHUR STA. 2	GREAT CRUZ STA. 1	GREAT CRUZ STA. 2
8 May,1980				
16 May				
29 May	6.0	3.2	9.6	4.8
26 Jun	1.9	0.2	4.0	1.0
30 Jul	2.0	0.2	0.3	0.2
22 Aug	2.3	0.7	2.5	0.7
5 Sep	1.6	0.8	3.5	1.8
29 Sep	2.3	1.1	0.7	2.5
8 Oct				
16 Oct	0.5	0.4	0.9	2.1
23 Oct	1.5	1.4	3.2	0.9
8 Dec	2.3	1.0	2.8	1.1
28 Jan,1981	3.0	1.3	7.4	3.6
24 Feb	1.1	1.5	13.0	2.3
17 Mar	1.4	1.8	4.6	3.0
10 Apr	1.1	0.9	-	-

Figure 10. Turbidity of water from 0.5M in Lameshur and Great Cruz Bays in N.T.U.

DATE	LAMESHUR STA. 1	LAMESHUR STA. 2	GREAT CRUZ STA. 1	GREAT CRUZ STA. 2
8 May,1980	11,608	94	41	61
16 May	8,457	92	400	68
29 May	1,092	514	632	210
26 Jun	458	79	206	59
30 Jul	105	278	144	53
22 Aug	187	117	117	83
5 Sep	169	75	102	123
29 Sep	243	129	154	58
8 Oct	201	258	60	34
16 Oct	209	60	18	17
23 Oct	238	108	219	65
8 Dec	250	203	118	161
28 Jan,1981	172	176	179	287
24 Feb	66	46	128	60
17 Mar	85	70	47	48
10 Apr	27	50	-	-

Figure 11a. Total numbers of phytoplankton from stations in Lameshur and Great Cruz Bays in Cells per liter X 10^2.

DATE	LAMESHUR TOW 1	LAMESHUR TOW 2	GREAT CRUZ TOW 1	GREAT CRUZ TOW 2
8 May, 1980	3576	8111	13576	14508
16 May	12248	14875	11635	5677
29 May	13192	13870	9720	8437
26 Jun	6765	36411	23605	34948
30 Jul	50332	17768	36155	18242
22 Aug	38541	166199	14868	6005
5 Sep	65959	210575	115615	80822
29 Sep	518782	198449	636529	323626
8 Oct	117182	71593	145572	33617
16 Oct	119220	102184	304875	67493
23 Oct	73959	91968	44200	66098
8 Dec	140348	43177	125351	35495
28 Jan, 1981	46585	21283	35043	15208
24 Feb	78868	189499	66124	33163
17 Mar	2186	2232	9262	11753
10 Apr	110926	139246	-	-

Figure 11b. Zooplankton numbers in organisms per M^3 at tows taken at each station in Little Lameshur and Great Cruz Bays.

DISCUSSION

Rainfall in the Caribbean is highly variable, both in time and location, but differences are not so pronounces spacially that comparisons between two watersheds on the same island an not be made. Rainfall for the sampling year May 1980 through April 1981, was below normal in total accumulation at both study sites. When compared to the average for Cruz Bay of 111.71 cm (43.98 inches) shown in Figure 12, Little Lameshur Bay was only 1.15 cm (0.45 inches) less with 110.53. Rainfall in Great Cruz Bay was only 67% of that in Little Lameshur having had only 74.45 cm (29.31 inches) accumulation for the year, 37.26 cm (14.67 inches) less than the mean for the island. References to rainfall in St. John indicate that this is not unexpected. Bowden (1969) in particular says that the Lameshur watershed when "...Compared to the three eastern stations of St. John... has a higher rainfall and a greater reliability."

Most of the rainfall accumulation on St. John and the other islands tend to be in short showers of less than 1 inch. Evapotransportation is practically always higher than rainfall in this region (Sediment Reductin Plan) and the effects of the light rains are lost to the island almost immediately. Rainfalls of greater than an inch are needed to recharge the aquifer. If the rain comes after a dry period, however, the effects may still be lost due to runoff. The water will start to soak into the surface soils somewhat, but the dampening of the clayey Cramer-Isaac soils will make them less permeable (Soil Survey, 1970), and most of the water from such a downpour situation will run off. The question of the effect of this runoff on the bay is examined in this study.

The accumulated rainfall during the study was a little below average, as has been mentioned above. The total number of raindays were, however, normal. Calculations on data adapted from Cosner (1972) show that rainfalls in amouts greater than 0.025 cm (0.01 inch) can be expected on 49% of the days during a year. Lameshur had rain on 182 days or 50% of the time, while Great Crux Bay had measureable rain on 46% of the days. Runoff potential was not great, as only 6 of those raindays, or 3%, in Lameshur and 3 days, or 1%, in Great Crux Bay were greater than an inch. The hillside runoff in Great Cruz Bay watershed was never adequate to pass over the beach berm and flow into the bay directly. The berm in Lameshur Bay however was breached after the first sampling trip in May, by rough weather and stream flow, and the runoff was allowed to pass directly into the bay. This breached area was less than two inches deep which did not permit the use of the stream flow guage. No runoff measurements were obtained directly. This was followed by an immediate change in turbidity, nutrients, and plankton (Figure 8, 9, 10, 11a,11b).

Rainfall did not necessarily fall in Lameshur Bay on the same days that it fell in Great Cruz Bay. This is another part of the variability of rainfall in the Virgin Islands. There was precipitation in one bay but not the other during 87 days, or 27% of the comparable time. Still, the periods of heavy rainfall which were most likely to promote runoff matched fairly well. The general rainfall pattern for the year was quite similar (Figure 14) with low accumulations in March and June and the greatest rainfall in April and October. This seems fairly typical for the island, although the 30 year mean rainfall (Figure 14) showed months with the highest rainfall to be May and September/October.

The calculated data (Figure 13) shows that the measured difference in rainfall becomes a greater difference in potential runoff because the Great Cruz Bay watershed is smaller; Little Lameshur had a runoff potential 1.8 times greater. The smaller 'Great Cruz Bay potential is also entering a bay which is 1.6 times larger than Little Lameshur. The effects of an equivalent then, would be expected to be significantly less than in Lameshur Bay.

The force and effect of runoff in both bays was affected by the presence of beach berms and low lying alluvial deposits behind the berms (Purcell, 1980) mentioned in the earlier paper. Water flowing down the runoff channel meets the resistance of the berm, but can rise only a few inches before overtopping the banks of the channel. The runoff water spreads over the fairly extensive area of the alluvial bottom land both allowing suspended material to drop out and reducing the downward force of the water. The water thus trapped leaches through the berm, which is composed primarily of Juacas sands and organic debris (Soil Survey, 1970). The water table behind the beach rises

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
Caneel Bay Plantation - Mean Rainfall 19[illegible];19[illegible]-1976, in inches	2.73	2.14	2.12	2.72	4.79	3.33	3.93	4.92	5.21	[illegible]	[illegible]	4.57	46.57
National Park Service;Cruz Bay - Mean Rainfall 1970-1975.	2.99	1.87	1.79	2.78	2.50	2.74	3.29	4.74	5.82	7.96	5.17	4.49	46.14
NOAA, Environmental Data Service; Cruz Bay- Mean Rainfall 1941-1970	2.60	1.82	1.70	2.25	4.52	3.45	3.93	3.93	5.60	4.97	4.10	2.96	41.83
Mean rainfall													43.98

Figure 12. Mean monthly rainfall records adapted from various sources.

	WATERSHED: LAMESHUR	WATERSHED: GREAT CRUZ
AREA		
ACRES	536	447
SQUARE METERS	2.169×10^6	1.809×10^6
RAINFALL		
INCHES	43.53	29.31
METERS	1.11	0.74
GALLONS	636.22×10^6	353.78×10^6
CUBIC METERS	2.41×10^6	1.34×10^6
ACRE-FEET	1944.3	1091.8
CALCULATED DATA		
EVAPOTRANSPORTATION LOSS (87-91% OF TOTAL)	$2.10\text{-}2.19 \times 10^6$ M^3 ($553.5\text{-}579.0 \times 10^6$ GAL)	$1.17\text{-}1.22 \times 10^6$ M^3 ($307.8\text{-}321.9 \times 10^6$ GAL)
POTENTIAL RUNOFF (4.5 % OF TOTAL)	1.08×10^5 M^3 (28.6×10^6 GAL)	0.60×10^5 M^3 (15.9×10^6 GAL)
RECHARGE OF AQUIFER (4.5-8.5% OF TOTAL)	$1.08\text{-}2.05 \times 10^5$ M^3 ($28.6\text{-}54.8 \times 10^6$ GAL)	$0.60\text{-}1.14 \times 10^5$ M^3 ($15.9\text{-}30.1 \times 10^6$ GAL)

Figure 13. Summary of total annual rainfall in each of the watersheds. Calculated data derived from figures given by Cosner(1972).

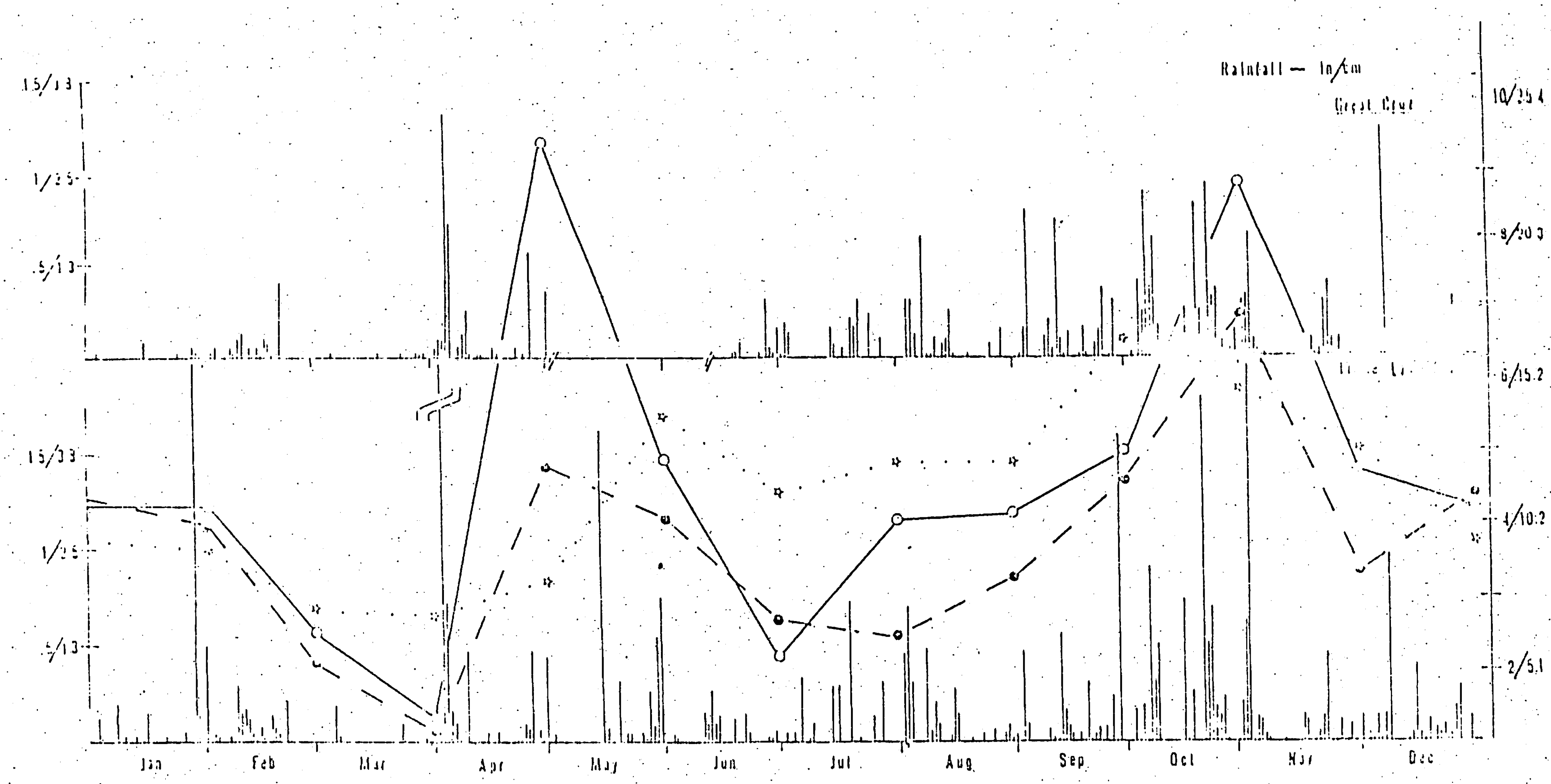


Figure 14. Daily rainfall in Lameshur (lower graph) and Great Cruz (upper graph) Bays with monthly totals and 30 year mean for Cruz Bay, from 1 May, 1980 through 30 April, 1981.
● = Lameshur ○= Great Cruz ✱ = 30 Year Mean.

during this time as water is absorbed into the permeable San Anton soils, then drops fairly quickly according to measurements made on water levels in a well in Cinnamon Bay (Bowden, 1972). Nevertheless, the slowing of the water's course means that it is probable that far less water directly reaches the bay then the amount calculated (Figure 13). Some of the difference in observed direct runoff into the bay and calculated runoff would go toward recharging the aquifer in the lower sections of the slope, and the rest would either evaporate from the broad expance of the tidal flat aread or perculate through the berm and bay bottom. If this were the case, and spot perculation studies (p. 12) showed cool, hyposaline water coming from the bottom, then turbidity would be nil and nutrients would go primarily to benthie production. The expectation in general, then, was to find little effect on either of the bays, due directly to runoff, but to note more change in the waters of Great Cruz Bay because of higher development and population within the watershed.

The measured data for nutrients and turbidity appear to bear the first part of this hypothesis out. Only slight correlation can be found between rainfall, runoff and nutrient level in either of the bays. It is convenient at this point to quickly review the sampling periods, observations and results throughout the year before further discussion.

6 May. Nutrients levels were high in both bays. Quantities of macroalgae and grasses which were cropping at the time were present throughout Little Lameshur, especially in the sur zone. The water was quite green probably as a result of phytoplankton in number exceeding 1×10^6 cells per liter. The phenomenon was not present in Great Cruz Bay which has a very limited benthic community. There had been no significant rainfall for some time before sampling took place.

16 May. Heavy rains prior to sampling and wave action broke through the berm in Little Lameshur and allowed water to run directly to the bay and to flush the tidal flat area with each tide. A sill remained at the opening however with a water depth of only 5-6 cm. Water near the outfall was brown and quite turbid indicating suspended materials carried from the shore into the bay. The berm in Great Cruz Bay held and runoff was retained behind it. The water could still filter through, as has been discussed above. Nitrates may thus have passed through. Plankton numbers at the head of Great Cruz Bay increased from 5000 cells per liter to 40,000 while those in Little Lameshur decreased slightly and changed composition.

29 May. Continued rainfall and runoff did not break down the berm in Great Cruz Bay. The breach in the berm in Lameshur remained open to tidal flushing, but flow rate to the bay was not great across the sill. The amount of nitrates and phosphates in both bays dropped to trace levels. The numbers of phytoplankton at both inshore stations was high:

Populations in Lameshur decreased slightly from the bloom conditions several weeks before, while the numbers in Great Cruz Bay increased to more than 60,000 cells per liter, the high for the year. The water remained turbid, especially inshore.

27 June. Rainfall was low during June, the second lowest month in total rainfall. Rain showers were short duration with low accumulation and no runoff was noted. Nutrients in the bays remained at levels below those at which measurements were felt to be accurate. Plankton numbers at all stations decreased, as did turbidity. Temperature of the bay waters increased, and salinity remained much the same. The input of nutrients during this month, from whatever source, was less and the phytoplankton populations could not be sustained.

July. The rainfall accumulation was slightly highly than in June but rainfall days were the same (12). There were no significant falls or runoff into either bay. There was an increase in nitrate/nitrogen at all stations, but little change in phosphate. Turbidity was low at all stations but slightly higher inshore in Lameshur. Temperature and salinity remained the same. Phytoplankton number generally decreased with the exception of station LLB-2 where numbers tripled. The input of materials via runoff was non-existant this period, with the exception of ground water exfiltration from the land. Nitrate might have been increased by this water movement or by an increase in zooplankton population. The latter case seems likely but there is no data to support the though.

August. Total rainfall did not increase much in August, but numbers of days of rain did, from 40% to 58% - Great Cruz Bay increased more than did Lameshur. There was no evidence of runoff entering directly into either bay. Lameshur berm was in the process of building slowly back and water was restrained from flushing in and out. Temperature increased slightly, and salinity decreased. Phosphates increased very slightly in Lameshur while nitrates decreased at all stations. Turbidity increased in Great Cruz Bay and decreased slightly in Lameshur. Plankton populations remained generally the same. This was a static period with the runoff having no effect on the bay, and control was probably benthically and oceanically derived.

September. Total number of raindays per month increased again to 63% at both stations with the beginning of the fall rainy period. Accumulated rainfall also increased (28% in LLB and 56% in GCB). When sampling took place early in the month and again at the end, no runoff was entering either of the bays directly. Phosphates declined, but nitrates in Lameshur increased to the highest point of the year in early September. Levels of both nutrients dropped in Great Cruz Bay. Turbidity was lower in Little Lameshur than in Great Cruz Bay, giving suspicion that the nitrates were not part and parcel with the sediment particles, while phosphates might well be. Temperature continued a slow increase, while salinity continued slightly downward. Plankton/productivity did not change. The water runoff might have overtopped the berm, although there was no indication of this at the time of sampling. More likely the water rose high enough to quickly filter through the sandy berm, thus introducing the nitrate into the bay.

Nutrients fell off to practically nothing at the end of the month, while plankton numbers increased at all stations but GCB-2. The water was clear and temperature and salinity continued their trends upward and downward respectively. There was a good deal more rain in Lameshur than in Great Cruz Bay due to a single 4 cm. (1.58 inch) rainfall in that watershed. There seemed little difference between the effects on the two bays, so one must assume that whatever indirect runoff there was had no significant effect.

October. Rainfall accumulations in October were quite high (19.9 cm 7.82 inches in Lameshur; 14.22 cm 5.60 inches Great Cruz Bay), and the percentage of rainfall days was high as well at 65%-68% (The differences in total amount were the result of larger showers in Lameshur). There seemed to be little effect on nutrients during this month. There may have been a slight increase, but it occurred in the ranges less than 0.5 ppm and is therefore suspect to experimental error. Temperature showed an upward bulge during the month, while salinity was depressed slightly. Turbidity was low, and phytoplankton seemed to decrease slightly, on the average, during the month. Except for slight changes, the extensive rainfall had little effect on either of the bays. The berm in Lameshur had completely repaired itself, and no water flowed into either bay as direct runoff. It is interesting that October was a month typified by large numbers of fry in Lameshur while Great Cruz Bay had no such increase in juvenile fish numbers.

November, December, January. Rainfall was about average, although the number of raindays was low in January. Salinity rose slightly, during these three months, and the temperature dropped shrply. Nutrient levels were quite low throughout both bays, and plankton numbers were average. There was an increase in turbidity at GCB-1 This continued into February and probably had to do with weather and water conditions. There was virtually no rainfall in the Great Cruz watershed, so the increase could not be due to runoff.

Frbruary. Rainfall was low (3.5 -3.6 cm), although it rained half of the days of the month. No increase in nutrients was noted, but there was an increase in salinity and a decrease in temperature. Turbidity was low except inshore at GCB-1. Plankton numbers were low at all stations. The turbidity was probably due to rough water conditions, which existed during and prior to sampling.

March. March had the lowest rainfall of the year and no runoff. Although measurements of nutrients in the water column were quite low, there seems to be a slight upward trend in nitrate; there was no change in phosphate levels. Turbidity decreased radically at GCB-1 in spite of a swell entering the bay. Temperature rose and salinity dropped. Phytoplankton numbers dropped.

April. There was high rainfall in April, due primarily to the largest single rainfalls of the year. Rainfall days were high as well (56%-GCB; 67%-LLB), but there was no change in nutrient

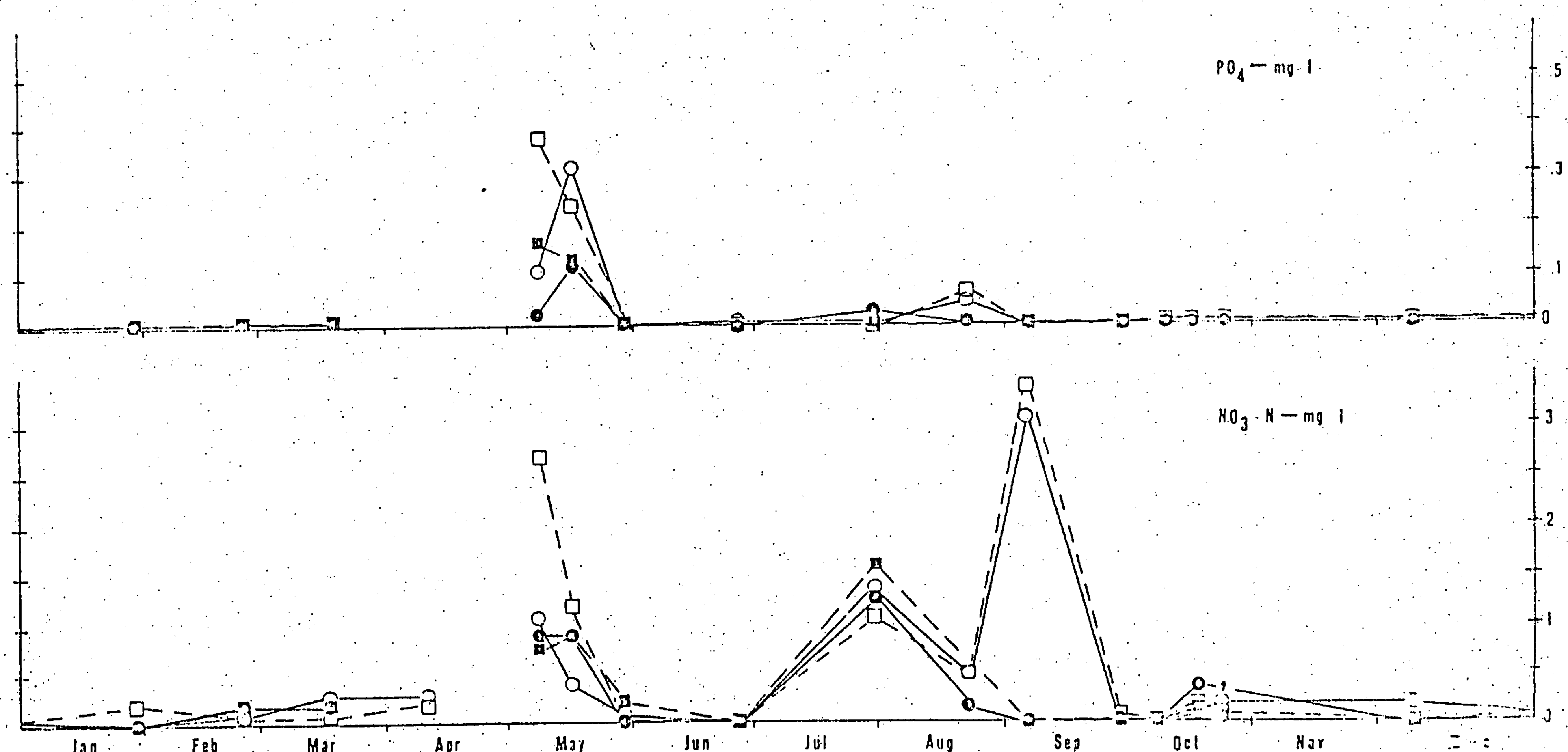


Figure 15. Phosphate (upper graph) and nitrate (lower graph) levels measured in Little Lameshur and Great Cruz Bays from 1 May,1980 through 30 April,1981, in mg per liter.
= Station LLB-1 = Station LLB-2 = Station GCB-1 = Station GCB-2

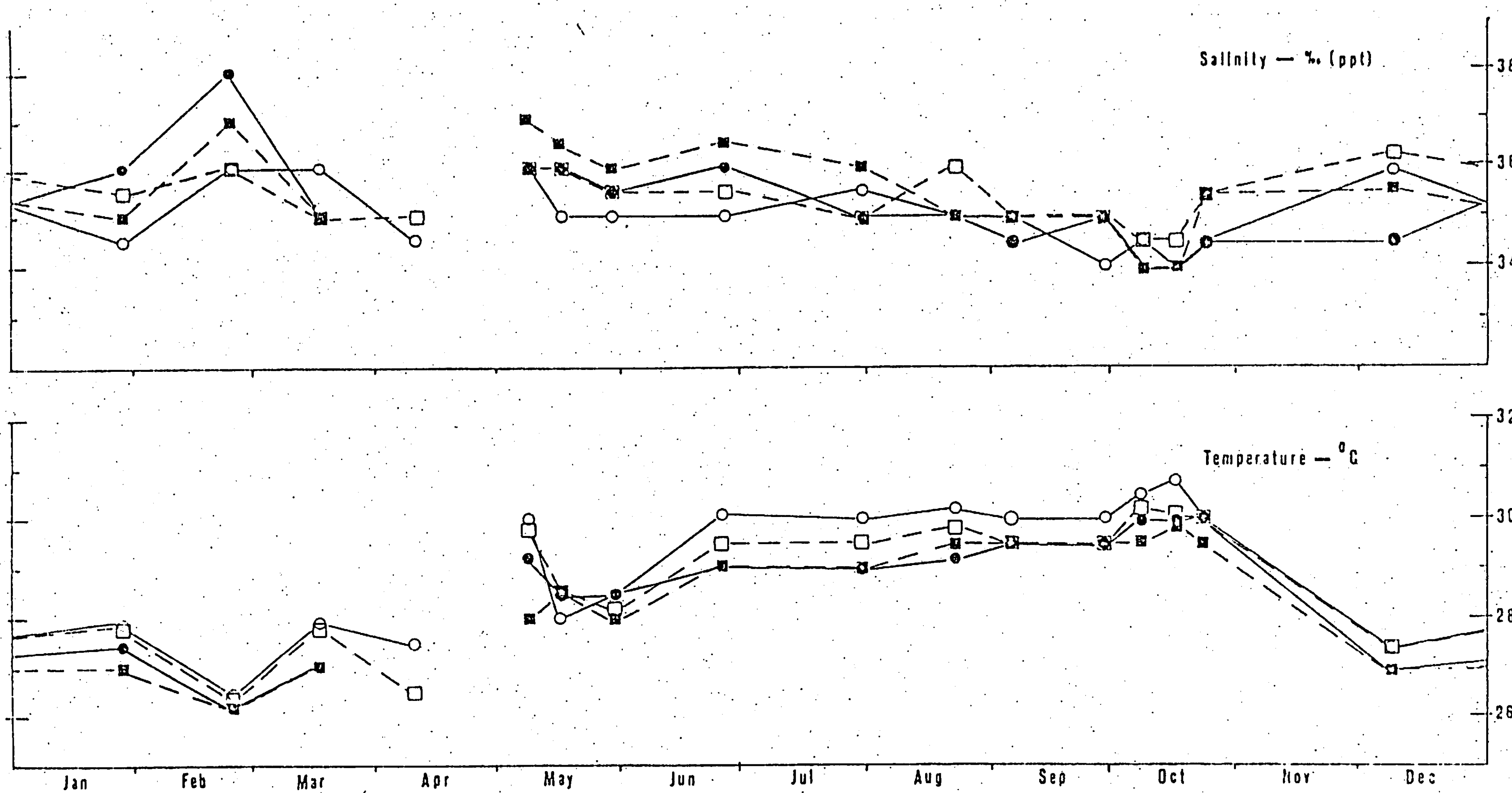


Figure 16. Salinity (upper graph) in parts per thousand and temperature (lower graph) in degrees centigrade measured in Little Lameshur and Great Cruz Bays from 1 May1980 through 30 April, 1981.
= Station LLB-1 = Station LLB-2 = Station GCB-1 = Station GCB-2

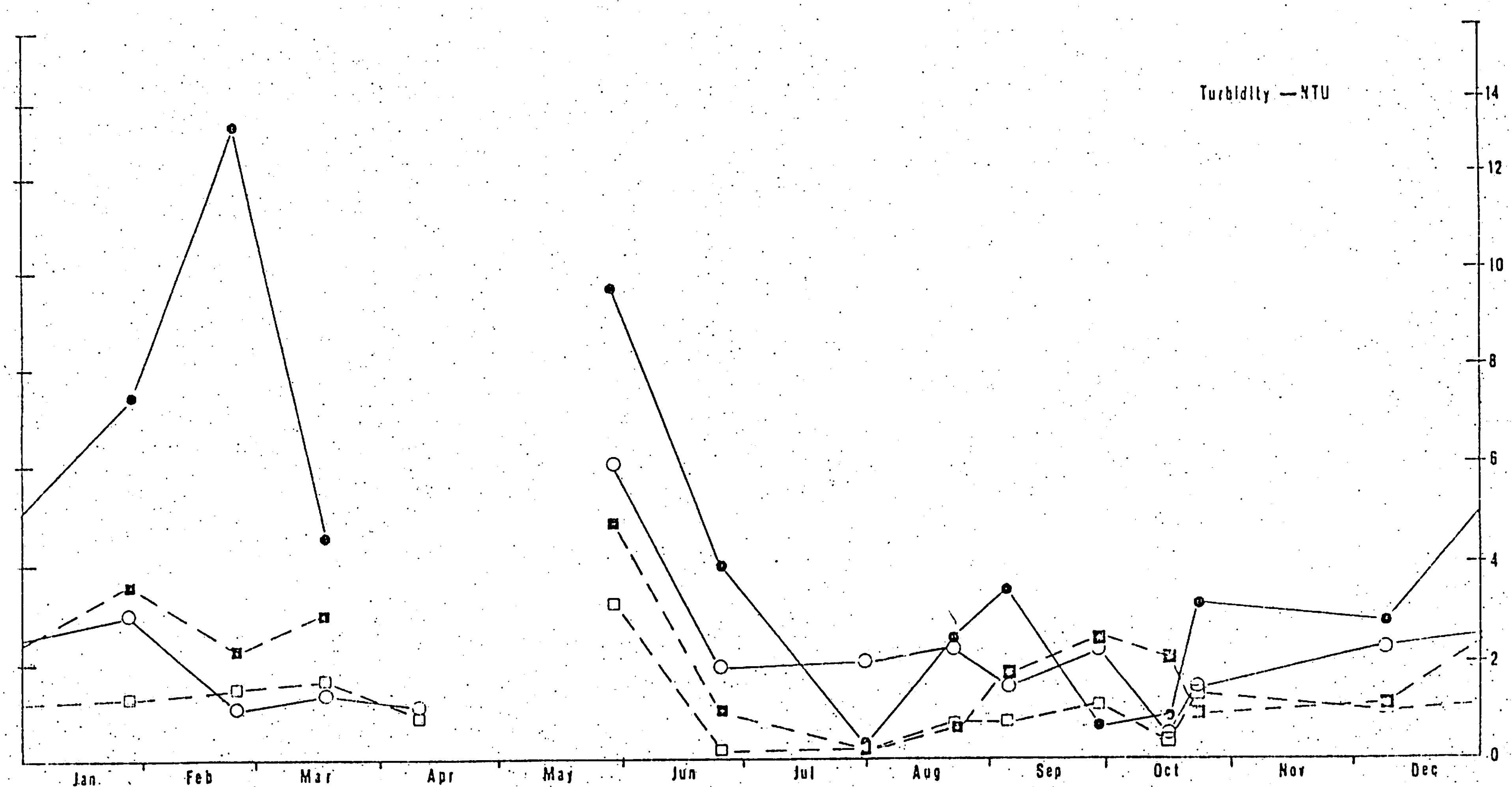


Figure 17. Turbidity in nephelometric turbidity units measured in Little Lameshur and Great Cruz Bays from 1 May, 1980 through 30 July, 1981.
= Station LLB-1 = Station LLB-2 = Station GCB-1 = Station GCB-2

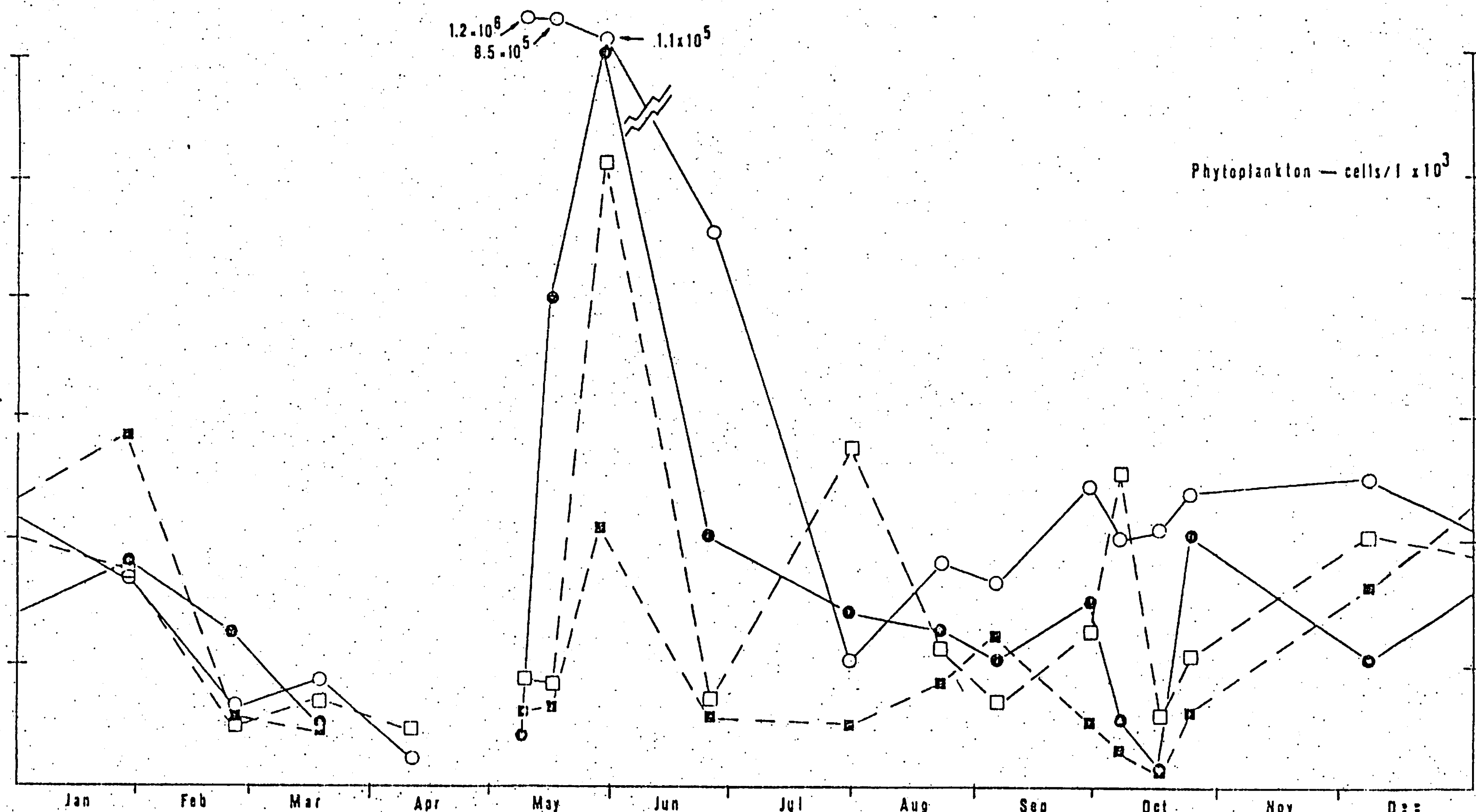


Figure 18. Total numbers of phytoplankton in Little Lameshur and Great Cruz Bays in cells per liter x 10^3. from 1 May,1980 through 30 April, 1981.
=Station LLB-1 = Station LLB-2 = Station GCB-1 = Station GCB-2

levels. Measured turbidity was lower, although the extraneous material in the plankton samples was the highest seen at any time during the year. The material looked like a precipitate of some sort, and was assumed to be sampling artifact. No samples were obtained in Great Cruz Bay due to mechanical failure.

There is no direct correlation to be found between rainfall, runoff, and events occurring in the bays. There were, however, two occasions when there seemed to be a reaction in the bay as a result of runoff. The principal case occurred in May of 1980, just as sampling began. The high nutrient levels noted at the beginning of the month were not associated with runoff, as there had been no rain since the beginning of the month. It is interesting that levels of nitrate were quite high at the beginning of the month, especially in Little Lamsehur Bay, and dropped rapidly toward the end of the month. One should also note that levels of phosphate were high offshore at both stations at the beginning of the month and declined significantly in the middle of the month following a heavy rainfall. Nutrients at all stations then dropped to very low levels at the end of the month. These changes are a result of several interacting factors. The nutrient levels at the beginning of the month could be ascribed to the breakdown of cropped macroalgae and grasses in the bays. Lameshur had much higher amounts of available nitrate-nitrogen because the benthic flora is much richer. The nitrates are generally considered limiting factor in tropical waters, and the increase of this nutrient in Little Lameshur caused a massive increase in the phytoplankton numbers. The inshore bloom, in turn, depressed the amount of nutrient. The off-shore stations did not have the phytoplankton populations and were higher in both nitrates and phosphates.

The heavy rainfall preceeding the second sampling may have introduced some nutrients in the runoff water into the bay. Both bays showed depression of salinity and temperature in the samples, and Little Lameshur had an increase in phosphates. There was also an increase in plankton numbers at the three stations not already undergoing a bloom. One may surmise that the increase in free phosphates and nitrates in Great Cruz Bay were a result of runoff.

The large increase in phosphates in Little Lameshur is attributed to the breakdown of the berm, which allowed particulate phosphate or phosphate absorbed on particles (Lake and MacIntire, 1976) to flow directly into the bay. The final sampling period in May also followed heavy rainfalls, but no particular effects could be attributed to that runoff event. It is possible that the first even carried the majority of the available materials to the bay with the result that in the second rainfall/runoff period the levels of transported materials were not high. The nutrients which were introduced might have allowed the phytoplankton populations to remain at high levels for a slightly longer period, but the uptake would have reduced the nutrients to the lower detection level.

The other instance which appeared to have a connection between rainfall and runoff occurred in early September. The rainfall was not great, but it followed a period of two weeks which were relatively dry, the bay temperature was up, and an algal die-off was in progress. There was an increase in nitrates in Little Lameshur concurrent with the rainfall, and increase in plankton in the following sampling period. Phosphate was still below our measurement limit. This may have been related to the water and the particulate material suspended in it being stopped by reformed berm.

The effects of runoff events in October are more difficult to assess. There was considerable rainfall during the period, which appeared to affect both salinity and temperature (Figure 16). Nutrients remained low however, so we must conclude the runoff came in but some mechanism removed most of the nutrients. There was considerable fluctuation in phytoplankton numbers, but they seemed to show little overall change. The microzooplankton/larval plankton and the numbers of small juvenile fish did increase during this month in Little Lameshur Bay, but not in Great Cruz Bay. It appears that the changes taking place in the bay are primarily related to indirect factors. This may be taken to be combination of runoff percolated drainage wind and offshore water movement, and possibly day length or temperature.

Heavy rainfalls in February and in April did not seem to immediately or directly affect either of the bays insofar as the paramenters measured.

CONCLUSIONS

Rainfall runoff does appear to affect the tropical bays examined. The most obvious is that nutrients seem to be introduced into the system as dissolved nitrogenous material or particulate and absorbed phosphates after heavy rains or when the berm is breached. These materials, especially phosphate complexes, are both most easily carried into the bays if the natural system of low lying alluvial area and beach berm are altered to allow direct flow. The increase in nutrients causes an increase in productivity within the bay waters. When the free nutrients reach a maximum threshold (1.mg NO_3 or 0.1 mg PO_4) there is a 2 week lag followed by a plankton bloom.

While there is an effect of the runoff, there are many other factors which enter into the complex situation. The cycles in productivity in the bay are integral and depend not only on runoff to transport nutrients into the system but on bacterial action on cyclia die-off algae and grasses cropped algae, water currents and wind driven movement, zooplanktonic excretion and reaction across the air-water interface. All of these are important in the balance of the natural system.

One can see, within this study, some of the effects of change related to development. Great Cruz Bay has been lightly developed, and has not, apparently, been changed enough to alter runoff characteristics. The beach and back-beach structures are intact, and that physical and ecological buffering system still functions. The hillsides in the watershed have been left intact for the most part and the cover not cleared off. This slows the rate of runoff and increased the time the water spends on the slope, which should improve recharge of the aquifer. Thus the level of light development seen in Great Cruz Bay seems to do no harm to the bay.

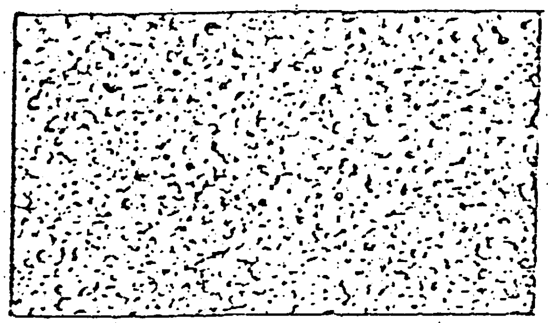
The differences in productivities between the two bays studied are felt to lie in rainfall pattern and alterations to Great Cruz Bay itself. The dredging which was done in 1971 removed most of the benthic plants from the bay. This in turn removed one of teh subsystems important to the production of organic material and the cycling and retention of nutrients.

The important lesson to learn in a study of this type is that changes in a system can be made, and the overall balance of that system not be radically altered. The trick is in understanding which portions of the watershed can be changed, and by how much, to avoid upsetting the balance. In Great Cruz Bay the building of houses and roads was compensated by leaving the beach berm and alluvial fan area intact. It appears that runoff at least during the period studied, did not affect conditions in the bay any more that it would have in a natural system. The bay itself was altered by the earlier dredging, which apparently altered its productive capability. This an example of change exceeding the absorbtive capability of the system.

The question remains as to the effects of extensive development: How rainfall runoff is changed and whether the bay can absorb or adapt to those changes. Studies of urban runoff have been done, but seldom on a tropical island. Graham (1977) noted rainfall runoff had the effect in Kingston Harbor of increasing productivity compared to surrounding waters. The extent of cause and effect, nevertheless, remains an open one. Another serious question is, "where does the major runoff, with its nutrients and organic load, go?" Clearly it reaches the shore ecosystems. Some may be used in these systems, but can it possibly use all of the load? The run-off and load comes in "slugs", but there is no evidence of a slug in the bays. This leaves an open question, "Can a natural ecosystem be "eco-engineered to absorb and use effluent loads?" If so the implication for the tropical islands are great. Finally, "Does the lost nutrients and water relate to our cyclic growth of benthic producers and fish?"

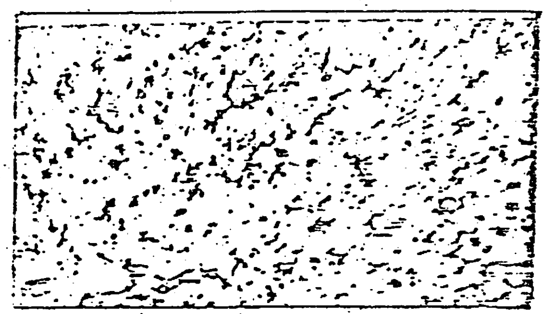
APPENDIX A

Photographic representation of the settled material from each of the samples taken at two stations in Little Lameshur Bay (LLB-1, LLB-2) and Great Cruz Bay (GCB-1, GCB-2). The Photographs were taken at 50X. Three mm equals approximately 50 microns. The vast majority of the material in the micrographs is non-living, and represents material suspended in the water column, causing turbidity.

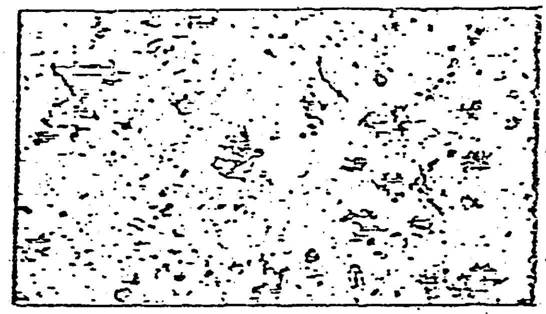


LLB-1

LLB-2

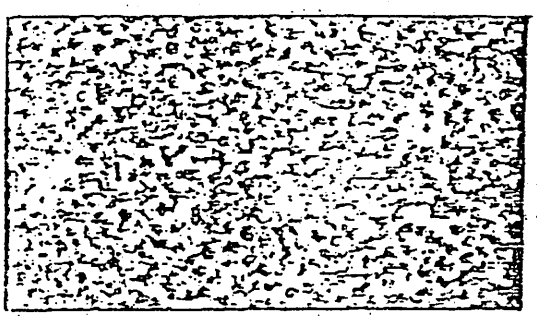


GCB-1

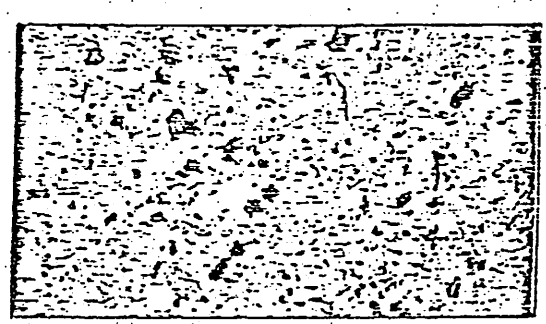


GCB-2

8 May,1980

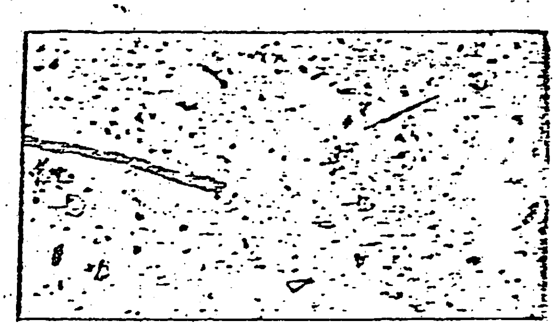


LLB-1



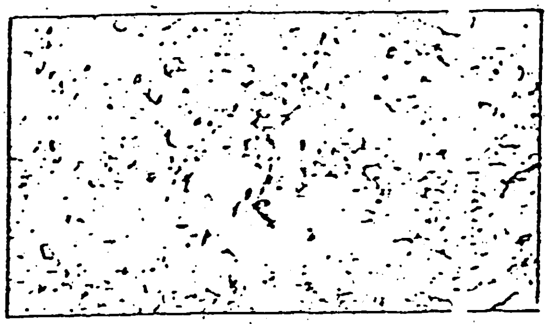
LLB-2

GCB-1



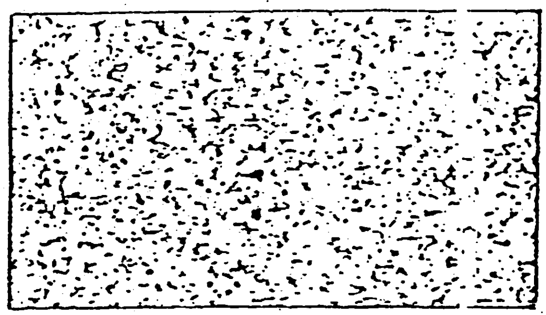
GCB-2

16 May,1980

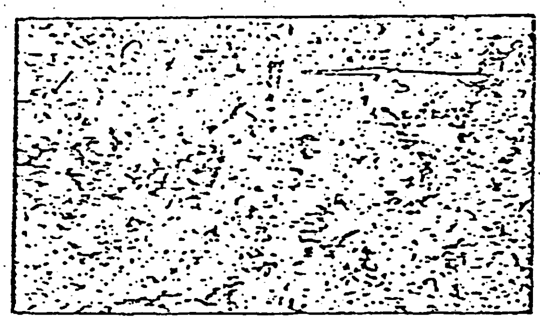


LLB-1

LLB-2

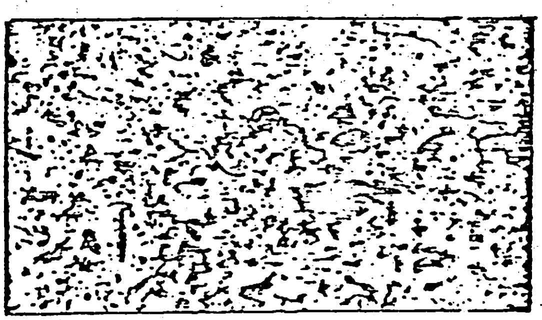


GCB-1

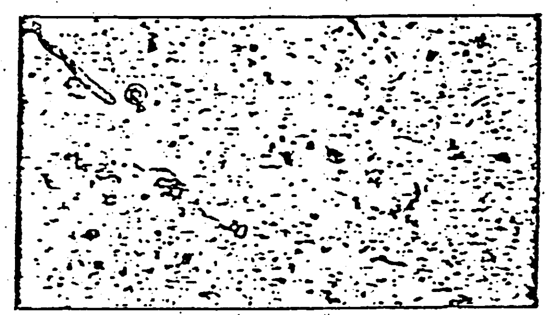


GCB-2

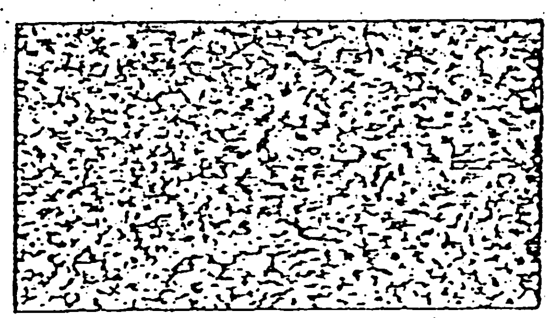
29 May, 1980



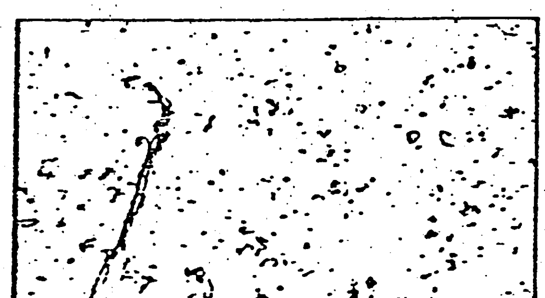
LLB-1



LLB-2

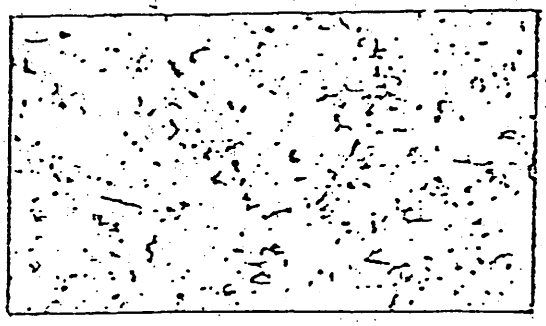


GCB-1

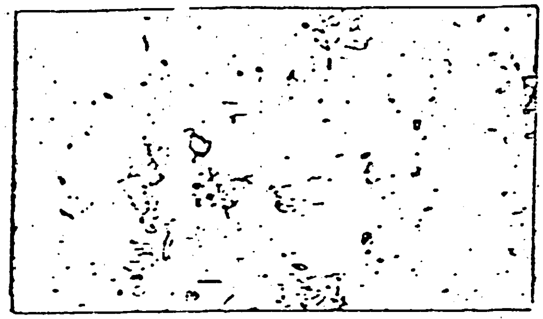


GCB-2

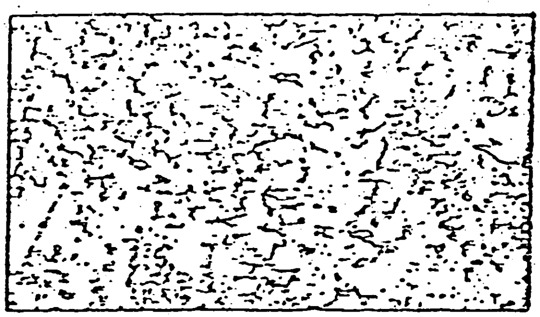
25 Jun, 1980



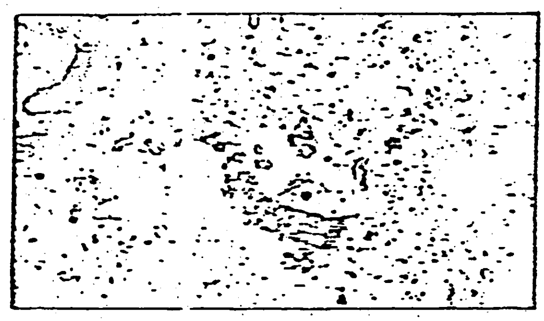
LLB-1



LLB-2

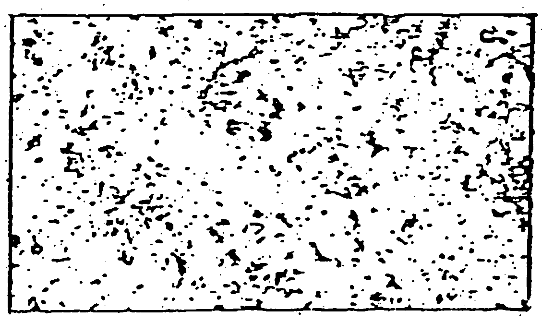


GCB-1

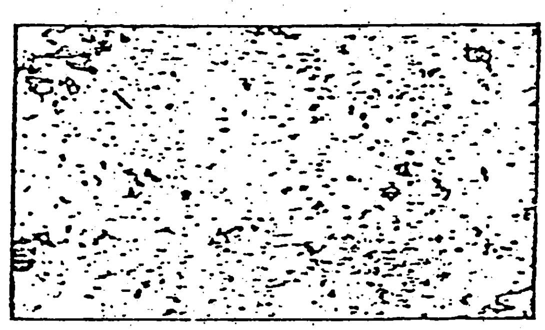


GCB-2

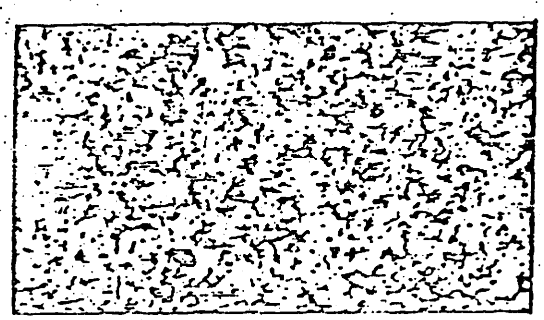
30 Jul, 1980



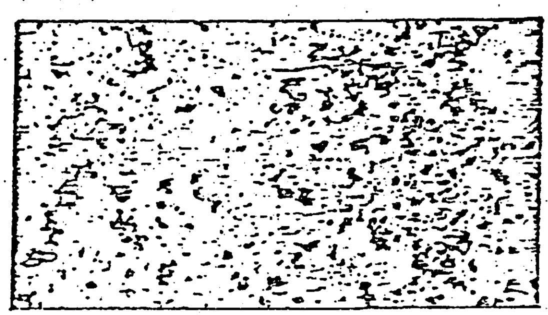
LLB-1



LLB-2

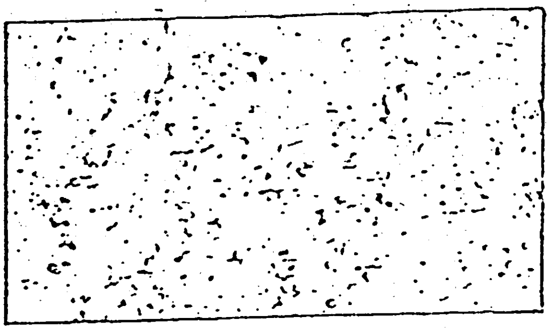


GCB-1



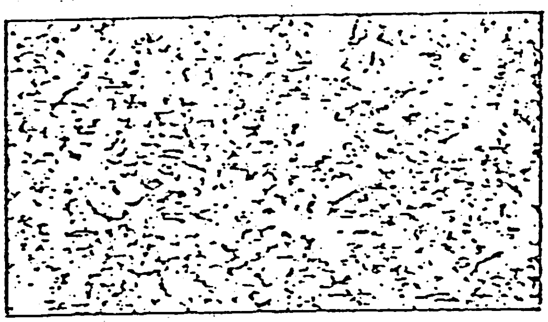
GCB-2

22 Aug, 1980

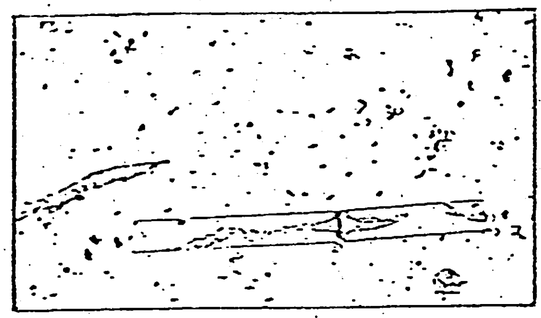


LLB-1

LLB-2

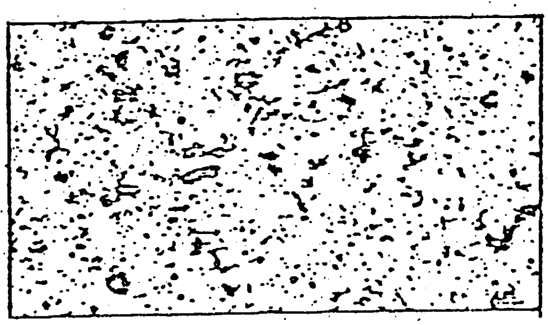


GCB-1

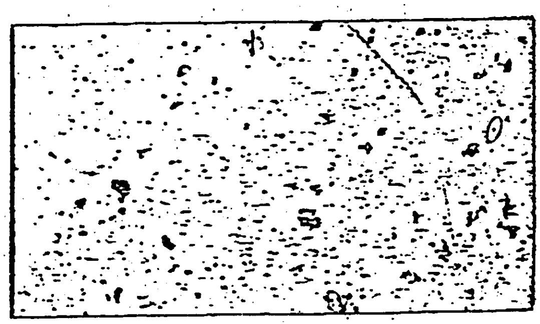


GCB-2

5 Sep, 1980

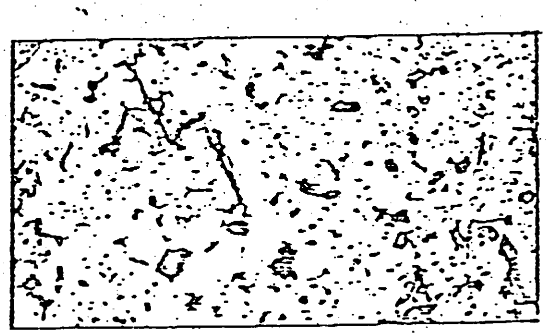


LLB-1



LLB-2

GCB-1

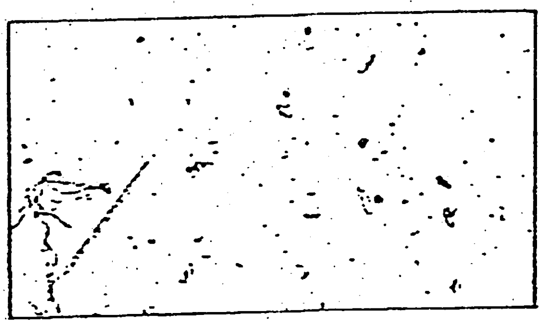


GCB-2

29 Sep, 1980

LLB-1

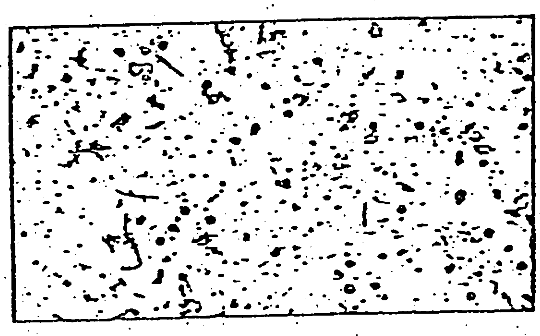
LLB-2



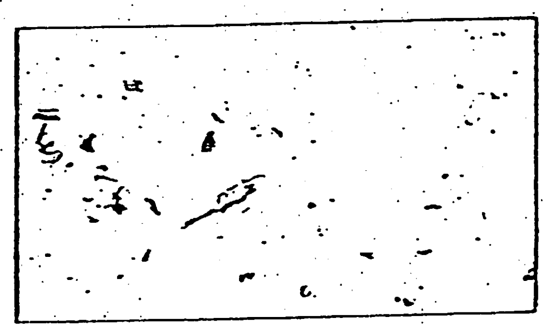
GCB-1

GCB-2

7 Oct, 1980

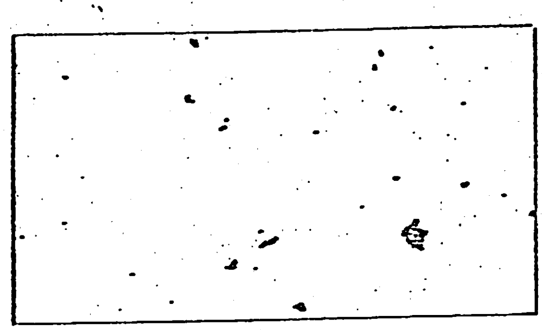


LLB-1



LLB-2

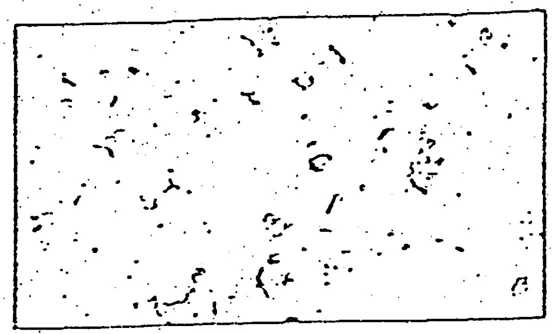
GCB-1



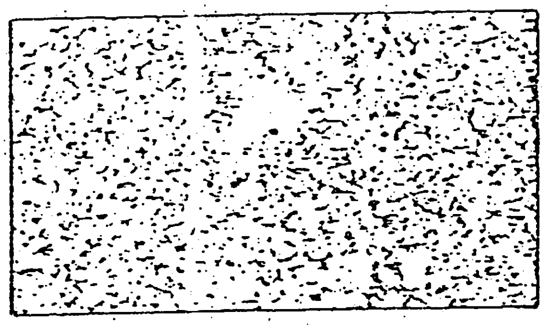
GCB-2

16 Oct, 1980

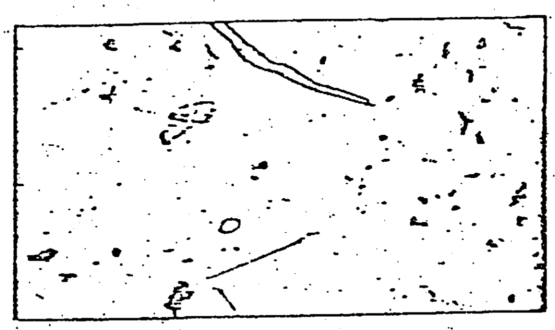
LLB-1



LLB-2



GCB-1

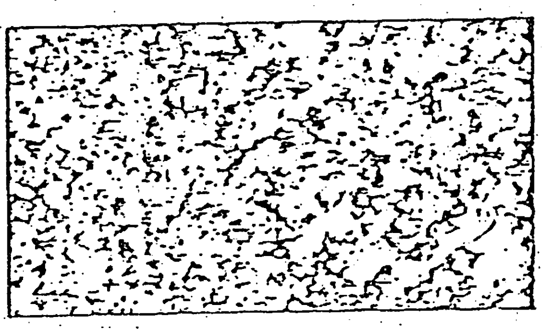


GCB-2

23 Oct, 1980

LLB-1

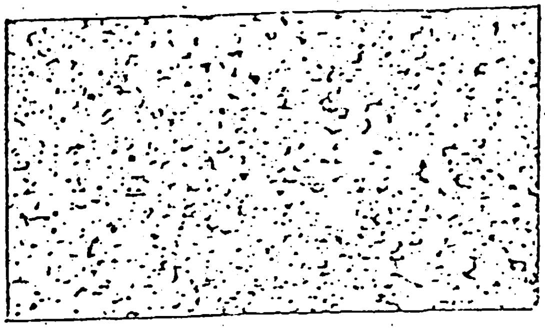
LLB-2



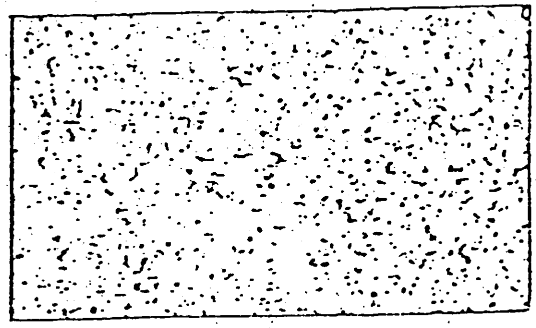
GCB-1

GCB-2

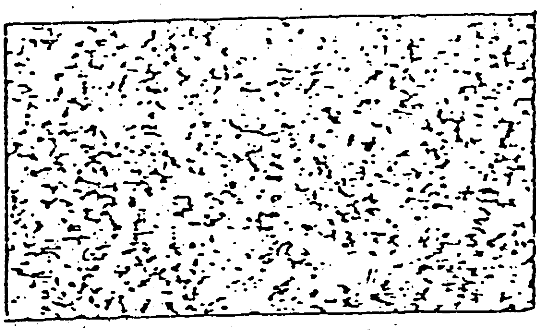
8 Dec, 1980



LLB-1



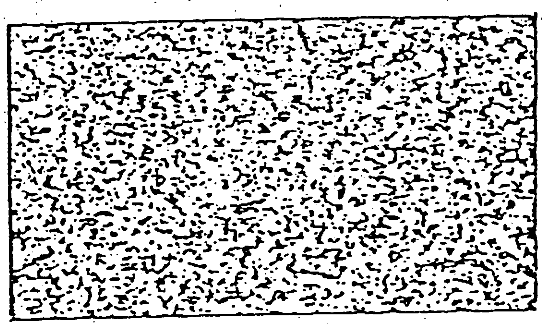
LLB-2



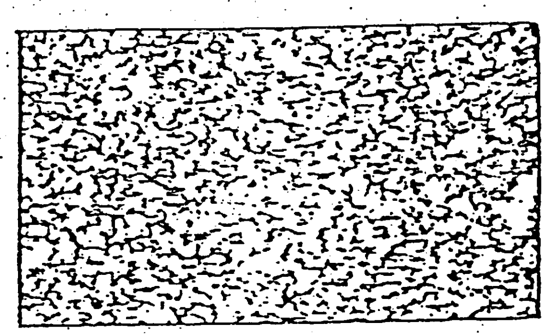
GCB-1

GCB-2

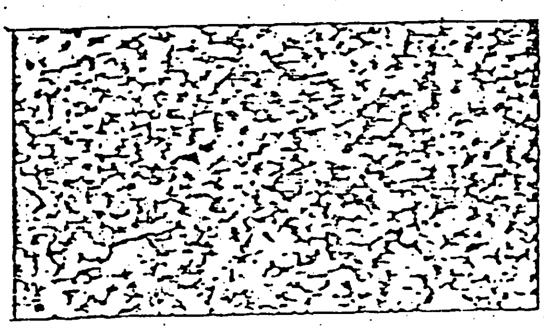
29 Jan, 1981



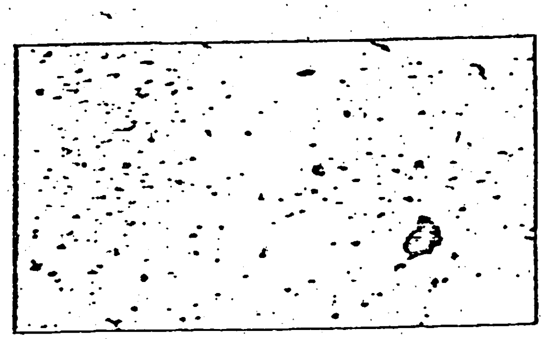
LLB-1



LLB-2

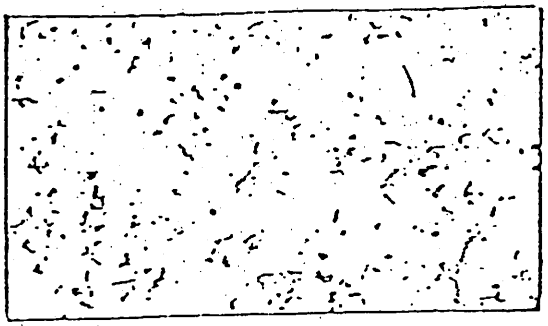


GCB-1

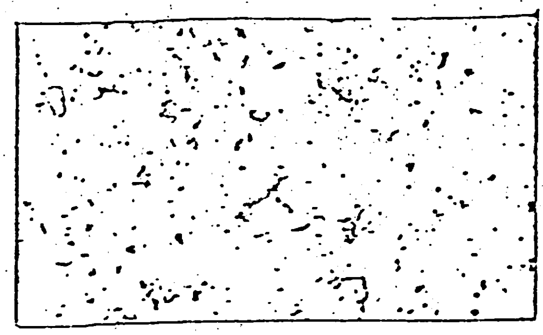


GCB-2

24 Feb, 1981

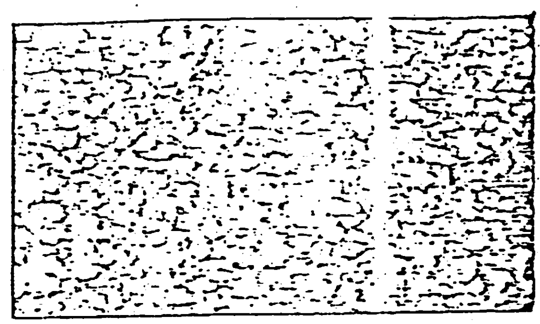


LLB-1



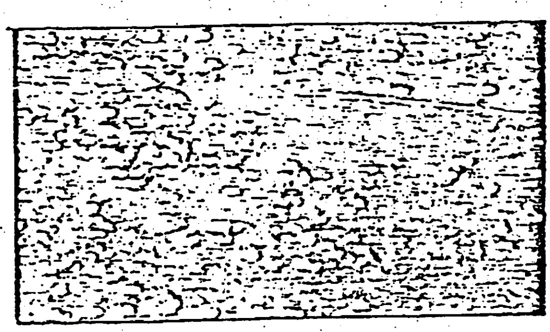
LLB-2

GCB-1

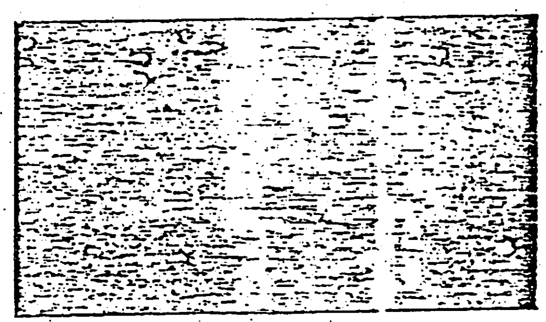


GCB-2

17 Mar, 1981



LLB-1



LLB-2

NO DATA

GCB-1

NO DATA

GCB-2

10 Apr, 1981

APPENDIX B

Part 1: Breakdown of phytoplankton populations in numbers of cells per liter of major groups. The groups are pennate diatoms, centric diatoms, dinoflagellates, monads(single cell flagellates),coccolithophores, blue-green algae and other forms. The breakdown is by number (#) and by percent of the entire population(%).

Part 2: list of phytoplankton species identified in samples during the study.

DATE/ STATION		PENNATE DIATOM.	CENTRIC DIATOM.	DINOFL.	MONAD	COCCO.	BLUE-GREEN	OTHER	TOTAL
08 May,80									
LLB-1	#	2200	400	1102200	56000	0	0	0	1160800
	%	-	-	95	5	-	-	-	
LLB-2	#	2096	304	6032	1680	16	16	880	9376
	%	22	-	64	10	1	2	4	
GCB-1	#	1936	144	1376	416	32	64	144	4122
	%	47	4	23	10	1	2	4	
GCB-2	#	3760	520	580	660	320	80	200	6120
	%	62	8	9	11	5	1	3	
16 May									
LLB-1	#	2963	0	813689	28304	0	480	280	845716
	%	-		95	4		-	-	
LLB-2	#	2048	368	4880	1488	0	112	320	9216
	%	22	4	53	16		1	2	
GCB-1	#	24100	1300	8700	5000	0	200	700	40000
	%	60	3	22	13		-	2	
GCB-2	#	2880	2860	620	180	0	60	180	6780
	%	42	42	9	3		1	3	
29 May									
LLB-1	#	29760	71040	4880	2080	0	1040	240	109200
	%	27	65	4	2		1	-	
LLB-2	#	10920	36080	3120	1360	0	160	360	51400
	%	21	70	6	3		-	-	
GCB-1	#	44900	1500	9900	4800	100	100	1900	63200
	%	70	2	16	8	-	-	3	
GCB-2	#	13320	3640	1560	1280	40	560	560	21000
	%	63	17	7	6	-	3	3	
25 JUN									
LLB-1	#	7480	240	12640	23640	0	840	1000	45840
	%	16	-	28	52		2	2	
LLB-2	#	2120	240	3440	1600	40	200	240	7880
	%	27	3	44	20	-	3	3	
GCB-1	#	15200	240	2480	1920	0	0	640	20640
	%	74	1	12	9			3	
GCB-2	#	3480	160	1320	600	0	220	120	5920
	%	58	3	23	10		4	2	
30 JUL									
LLB-1	#	4540	60	3860	1260	0	200	540	10460
	%	43	1	37	12		3	4	
LLB-2	#	10640	1120	11732	3000	0	480	800	27772
	%	38	4	42	11		2	3	
GCB-1	#	8860	1440	2140	1200	120	0	[illegible]	
	%	62	10	15	9	1		2	
GCB-1	#	3020	1660	220	220	0	60	[illegible]	5280
	%	57	32	4	4		1	2	

DATE/ STATION		PENNATE DIATOM.	CENTRIC DIATOM.	DINOFL.	MONAD	COCCO.	BLUE-GREEN	OTHER	TOTAL
22 Aug,80									
LLB-1	#	4340	60	8820	3600	0	1460	420	18700
	%	23	-	47	19		8	2	
LLB-2	#	2160	40	6500	2280	280	80	360	11700
	%	18	-	56	19	2	1	3	
GCB-1	#	6660	380	2640	1340	60	40	600	11720
	%	57	3	23	11	1	-	5	
GCB-2	#	2920	140	1380	2040	1420	100	280	8280
	%	35	2	17	25	17	1	3	
05 Sep									
LLB-1	#	2340	0	8920	4980	0	220	440	16900
	%	14		53	29		1	3	
LLB-2	#	2420	1040	2900	700	0	140	320	7520
	%	32	14	39	9		2	4	
GCB-1	#	4680	350	2900	1580	80	120	450	10160
	%	46	3	29	16	1	1	4	
GCB-2	#	4100	1440	3500	1960	320	520	480	12320
	%	33	12	28	16	3	4	4	
29 Sep									
LLB-1	#	2680	1080	11800	6760	0	280	1960	24280
	%	11	4	49	28		1	8	
LLB-2	#	1820	80	5900	4180	160	260	480	12880
	%	14	1	46	32	1	2	4	
GCB-1	#	3880	1640	5760	2880	320	160	720	15360
	%	25	11	38	19	2	1	4	
GCB-2	#	2620	180	1360	840	160	340	320	5820
	%	45	3	23	14	3	6	6	
08 Oct									
LLB-1	#	2880	200	15080	1560	0	80	920	20120
	%	11	1	75	8		-	5	
LLB-2	#	1920	160	16480	6080	0	720	480	25840
	%	7	1	64	23	-	3	2	
GCB-1	#	1120	160	2560	1000	240	600	280	5960
	%	19	3	43	17	4	10	4	
GCB-2	#	780	60	1040	660	480	160	240	3420
	%	23	2	30	19	14	5	7	
16 Oct									
LLB-1	#	2800	280	13040	3960	40	120	680	20920
	%	13	1	62	19	-	1	3	
LLB-2	#	920	80	3040	1160	240	40	520	6000
	%	15	1	51	19	4	1	9	
GCB-1	#	300	80	800	200	100	120	200	1800
	%	17	4	44	11	6	7	11	
GCB-2	#	420	180	284	240	360	180	80	1744
	%	24	10	16	14	21	10	5	

DATE/ STATION		PENNATE DIATOM.	CENTRIC DIATOM.	DINOFL.	MONAD	COCCO.	BLUE-GREEN	OTHER	TOTAL
23 Oct.80									
LLB-1	#	9360	560	9240	3600	0	440	640	23840
	%	39	2	39	15		2	3	
LLB-2	#	4200	760	3960	1320	80	40	400	10760
	%	39	7	37	12	1	-	4	
GCB-1	#	12200	800	4360	2920	120	280	1240	21290
	%	56	4	20	13	1	1	5	
GCB-2	#	2460	900	1340	700	200	80	800	6480
	%	38	14	21	11	3	1	12	
08 Dec									
LLB-1	#	3360	1403	16967	2440	0	40	800	25110
	%	13	6	68	10		-	3	
LLB-2	#	3640	12760	1760	1120	80	40	880	20280
	%	18	63	9	6	-	-	4	
GCB-1	#	5320	1720	2160	1520	400	120	520	11760
	%	45	15	18	13	3	1	4	
GCB-2	#	4960	6400	1880	1680	520	80	600	16120
	%	31	40	12	10	3	-	4	
29 Jan,81									
LLB-1	#	8360	320	6160	1760	80	120	400	17200
	%	49	2	36	10	-	1	2	
LLB-2	#	3280	7560	3920	1880	280	80	600	17600
	%	19	43	22	11	2	-	3	
GCB-1	#	6560	8720	1000	800	320	40	480	17920
	%	37	49	5	4	2	-	3	
GCB-2	#	2360	23600	400	1280	760	80	200	28680
	%	8	82	1	4	3	-	1	
24 Feb									
LLB-1	#	1880	40	2760	1600	0	40	320	6640
	%	28	1	41	24		1	5	
LLB-2	#	1960	0	1040	1200	40	40	320	4600
	%	42		23	26	1	1	7	
GCB-1	#	10760	80	840	640	0	160	280	12760
	%	84	1	7	5		1	2	
GCB-2	#	2960	920	760	840	240	40	240	6000
	%	49	15	13	14	4	1	4	
17 Mar									
LLB-1	#	2280	120	3120	2240	0	120	640	8520
	%	27	1	37	26		1	8	
LLB-2	#	3120	280	2360	880	80	40	280	7040
	%	44	4	34	13	1	-	4	
GCB-1	#	2560	290	540	670	0	0	600	4660
	%	55	6	12	14			13	
GCB-2	#	2920	600	280	760	0	0	280	4840
	%	60	12	6	16			6	

DATE/ STATION		PENNATE DIATOM	CENTRIC DIATOM	DINOFL.	MONAD	COCCO.	BLUE-GREEN	OTHER	TOTAL
10 Apr,81									
LLB-1	#	1440	400	1240	1040	0	200	640	4960
	%	29	8	25	21		4	13	
LLB-2	#	880	360	400	680	0	0	280	2600
	%	34	14	15	26			11	

DIATOMS******************************

AMPHIPRORA SPP.

ASTERIONELLA [illegible]

A. JAPONICA

A. NOTATA

BACILLARIA PAXILLIFER

BACTERIASTRUM COMOSUM

B. ELONGATUM (?)

BACTERIASTRUM SPP.

BIDDULPHIA SPP.

CERATAULINA BERGONII

CHAETOCEROS AFFINIS

C. ATLANTICUS

C. COMPRESSUS (?)

C. COSTATUS

C. CURVISETUS

C. DIDYMUS

C. GRACILIS

C. LAEVIS

C. PERPUSILLUS

C. PERUVIANUS

CHAETOCEROS SPP.

CLIMACOSPHENIA SPP.

COCCONEIS SPP

COSCINODISCUS MARGINATUS

COSCINODISCUS SPP.

GRAMMATOPHORA MARINA

GUINARDIA FLACCIDA

HEMIAULUS HAUCKII

H. MEMBRANACEUS

ISTHMIA ENERVIS

LEPTOCYLINDRUS DANICUS

LICMOPHORA SPP.

LITHODESMIUM SPP.

MASTEGLOIA SPP.

MELOSIRA SPP.

NITZSCHIA CLOSTERIUM

N. DELICATISSIMA

N. LONGISSIMA

N. PUNGENS

PLAGIOGRAMMA VANHEURCKII

PLEUROSIGMA SPP.

RHIZOSOLENIA ALATA

R. CALCAR AVIS

R. CASTRACANEI

R. DELICATULA

R. FRAGILISSIMA

R. HEBETATA

R. IMBRICATA

R. STOLTERFOTHII

R. STYLIFORMES

SKELETONEMA COSTATUM

STRIATELLA UNIPUNCTATA

STRIATELLA SPP.

THALASSIONEMA NITZSCHOIDES

DINOFLAGELLATES************************

AMPHIDINIUM ACUTISSIMUM

A. GLAUCUM

A. GLOBOSUM

A. KLEBSI

A. SCHROEDERI

A. SPHENOIDES

A. TURBO

AMPHIDINIUM SPP.

AMPHIDOMA (?) STEINI

AMPHILOTHUS QUINCUNCIALIS

CERATIUM FURCA

C. FUSUS

C. LINEATUM

C. [illegible]ILIENSE

C. [illegible]LLERI

C. PENTAGONIUM

C. SETACEUM

C. TERES

C. TRICHOCEROS

C. TRIPOS

CERATOCORYS HORRIDA

DINOPHYSIS CAUDATA

DINOPHYSIS SPP.

EXUVIAELLA APORA

E. BALTICA

E. COMPRESSA

E. MARINA

E. OBLONGA

EXUVIAELLA SPP.

GONIAULAX BIROSTRIS

G. DICANTHA

G. MINIMA (?)

G. MINUTA

G. MONOCANTHA

G. POLYGRAMMA

G. SCRIPPSAE

G. SPINIFERA

G. TRICANTHA

G. TURBYNEI

GONIAULAX SPP.

GYMNODINIUM GIBBERUM (?)

G. MIRABILE

G. OCHRACEUM

G. SIMPLEX

G. SPLENDENS

GYMNODINIUM SPP.

GYRODINIUM SPP.

HETERODINIUM OBESUM (?)

OXYTOXUM GRACILE

O. LATICEPS

O. PARVUM

O. VARIABILE

OXYTOXUM SPP.

PERIDINIUM AVELLANA

P. BREVIPES (?)

P. CERASUS

P. CONICUM

P. DIVERGENS

P. GLOBULUS

P. GRANDE

P. GRANI

P. HIROBIS

P. ROSEUM

P. STEINI

P. TROCHOIDEUM

P. UMBONATUM (?)

P. WEISNERI

PERIDINIUM SPP.

PROROCENTRUM MICANS

P. MINIMUM

PROROCENTRUM SPP.

WARNOWIA SPP.

CYANOPHYCEAE************************

MERISMOPEDIA SPP.

OSCILLATORIA SPP.

SPIRULINA SPP.

COCCOLITHOPHORIDAE********************

CALCIOSOLENIA MURRAYI

COCCOLITHUS SPP.

DISCOSPHAERA TUBIFERA

PONTOSPHAERA SPP.

SYRACOSPHAERA SPP.

OTHER*****************************

EUTREPTIA MARINA

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