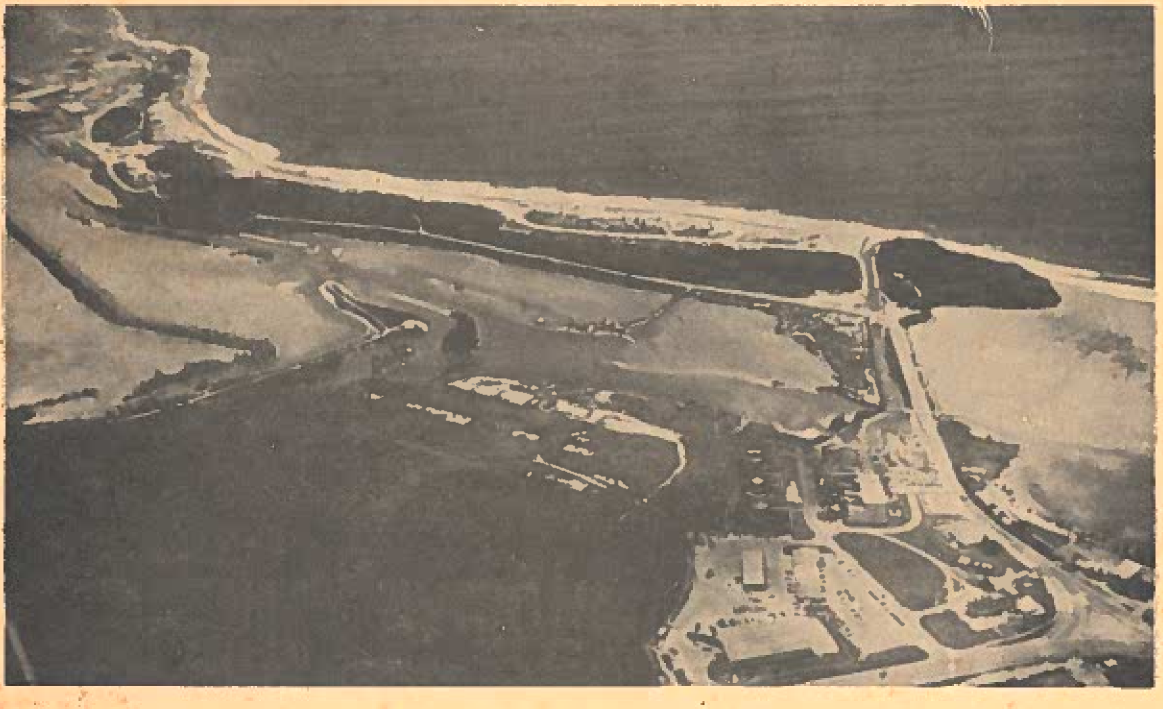
MARINE ENVIRONMENTAL EFFECTS OF DREDGING AND POWER-PLANT CONSTRUCTION IN PITI BAY AND PITI CHANNEL, GUAM

by JAMES A. MARSH, JR. and GREGORY D. GORDON



UNIVERSITY OF GUAM MARINE LABORATORY

Technical Report No. 8

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[Cover photo: Aerial view of the study area in July 1972 before construction began.]

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INTRODUCTION[1]

Guam Power Authority is presently constructing the new steam-generating Cabras Island Power Plant on a site just north of the existing Piti Power Plant at Cabras Island, Guam (Figure 1). Construction began in December 1972. Unit 1 is expected to be completed in September 1974, with completion of Unit 2 coming approximately one year later. There are plans for the future construction of additional generating units.

We have been conducting environmental studies in areas affected by construction activities, areas affected by heated effluent from the existing Piti Power Plant, and areas expected to be affected by heated effluent from the Cabras Island Plant. The construction site itself is former submerged land which was filled during the early phases of the present construction. At the same time Tepungan Channel, which lies at the western end of Piti Bay (Figs. 1,2), was enlarged to provide a source of cooling water for the condensers of the new plant. Dredge spoil removed from Tepungan Channel was used as fill material on the construction site. The receiving area for heated effluent from the Piti Plant and the Cabras Island Plant is the upper (eastern end of Piti Channel). From this point water flows westward down Piti Channel and eventually enters the Commercial Port area of Apra Harbor, although there is some spreading of water onto adjacent tidal flats. Our studies have included all these areas.

The purpose of this report is primarily to present information about the observed effects of construction activities in Tepungan Channel and the adjacent reef flats of West Piti Bay. Our studies began in January 1972 and will continue at least through the end of 1974. Our first report (Marsh and Gordon, 1972) was prepared in June 1972 and presented a general environmental survey of West Piti Bay, the construction site, Piti Channel, and adjacent tidal flats. The report was prepared before construction activities began and was considered by the U. S. Army Corps of Engineers before they issued a dredging and filling permit to Guam Power Authority. Our second report was concerned primarily with the effects of the Piti Power Plant on the environment of Piti Channel, adjacent tidal flats, and Commercial Port. Particular attention was given to the thermal regime in the area and how this was affected by heated effluent from the plant. The present report is thus the third one that we have prepared and deals primarily with observations during 1973.

The Piti Power Plant has a generating capacity of 74 megawatts. It pumps approximately 4.85 cubic meters per second (64,000 gallons per minute) of cooling water through its condensers and is designed to raise the temperature of this water by 5.6°C (10° F). The two units of the Cabras Island Plant presently under construction will have a generating capacity of 66 MW each and will pump a total of approximately 9.01 m^3 sec^{-1} (120,000 gpm) through the condensers, raising the temperature 5.6-8.3°C (10-15° F). Construction of future units at the Cabras Island Plant will add at least two additional units of at least 66 MW each. The total volume of cooling water pumped through the condensers of all units and being emptied into

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[1] The views expressed by the authors are their own and do not necessarily reflect those of the Marine Laboratory, the University of Guam, or the Government of Guam.

Piti Channel may eventually reach as much as 25.2 m^3 sec^{-1} (400,000 gpm), including the 4.85 m^3 sec^{-1} presently being pumped through the Piti units. The newly enlarged Tepungan Channel was dredged to allow a movement of 25.2 m^3 sec^{-1} to the plant intakes with a flow velocity not to exceed .61 m sec^{-1} (2 ft sec^{-1}) anywhere in the channel. Tepungan Channel presently communicates with the Piti Plant intakes via a passageway through the Cabras Island Causeway (Fig. 2). The newly dredged arm of the channel will communicate with the Cabras Island Plant intakes via a new passageway (presently under construction) through the causeway. In addition to Tepungan Channel, the man-made Piti Canal (Fig. 2) serves as an auxiliary source of cooling water for the power plant condensers. It is most effective at low tides or during very light surf conditions, when there is a low surf-generated flow of water across the outer reef flat of West Piti Bay and into Tepungan Channel.

METHODS

Information on water turbidity was obtained from visual observations in the field and by collecting samples in plastic bottles for later analysis in the laboratory. The samples were analyzed in a Hach turbidimeter, Model 1860, applying the nephelometer principle for determination of the light scattered by suspended particles.

The velocity of water currents was determined by timing the movement of patches of fluorescein dye over a known distance, and the direction of movement was sighted with a hand-held compass. The use of Scuba gear enabled us to make such measurements in the bottom of Tepungan Channel. Volume transport was calculated as the product of velocity and cross-sectional area, where the cross-sectional area is oriented perpendicular to the direction of water flow. The cross-sectional area was determined as the product of depth (which changes with tidal state) and width of the particular channel or reef transect of interest.

Our judgement of biological conditions continues to be based on visual field observations. These observations are primarily qualitative to enable us to continuously monitor extensive areas.

Field temperature measurements were made in the outfall area from a small boat or by wading on the tidal flats; a battery-powered telethermometer with thermistor probes was used for this purpose. Continuously recording Dickson "Minicorders," each with a vapor-filled, temperature-sensitive bulb connected to a spiral Bourdon tube, were used to get 7-day temperature records at selected locations. As noted in our last report (Marsh and Gordon, 1973), operating difficulties with these instruments have limited the amount of data we have been able to accumulate. However, we have previously established the major temperature patterns in the outfall area; and data gathered during the second year of our study serve primarily to give added confirmation of these observed patterns.

Determinations of reactive phosphorous, nitrite, and nitrate followed the procedures of Strickland and Parsons (1968). Dissolved oxygen determinations were made according to the azide modification of the Winkler Technique (A.P.H.A., 1971).

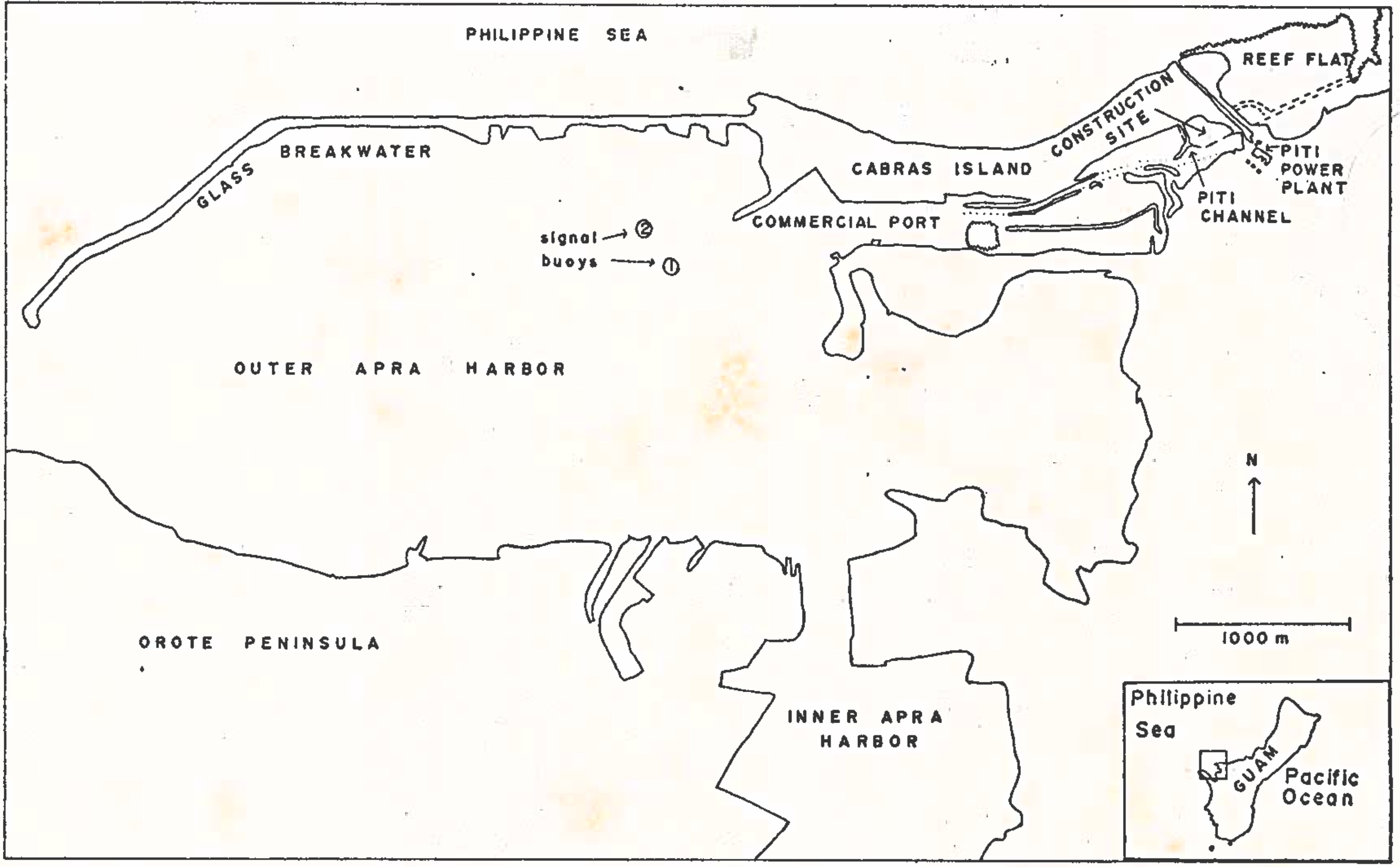


Figure 1. Geographic setting of the study area,

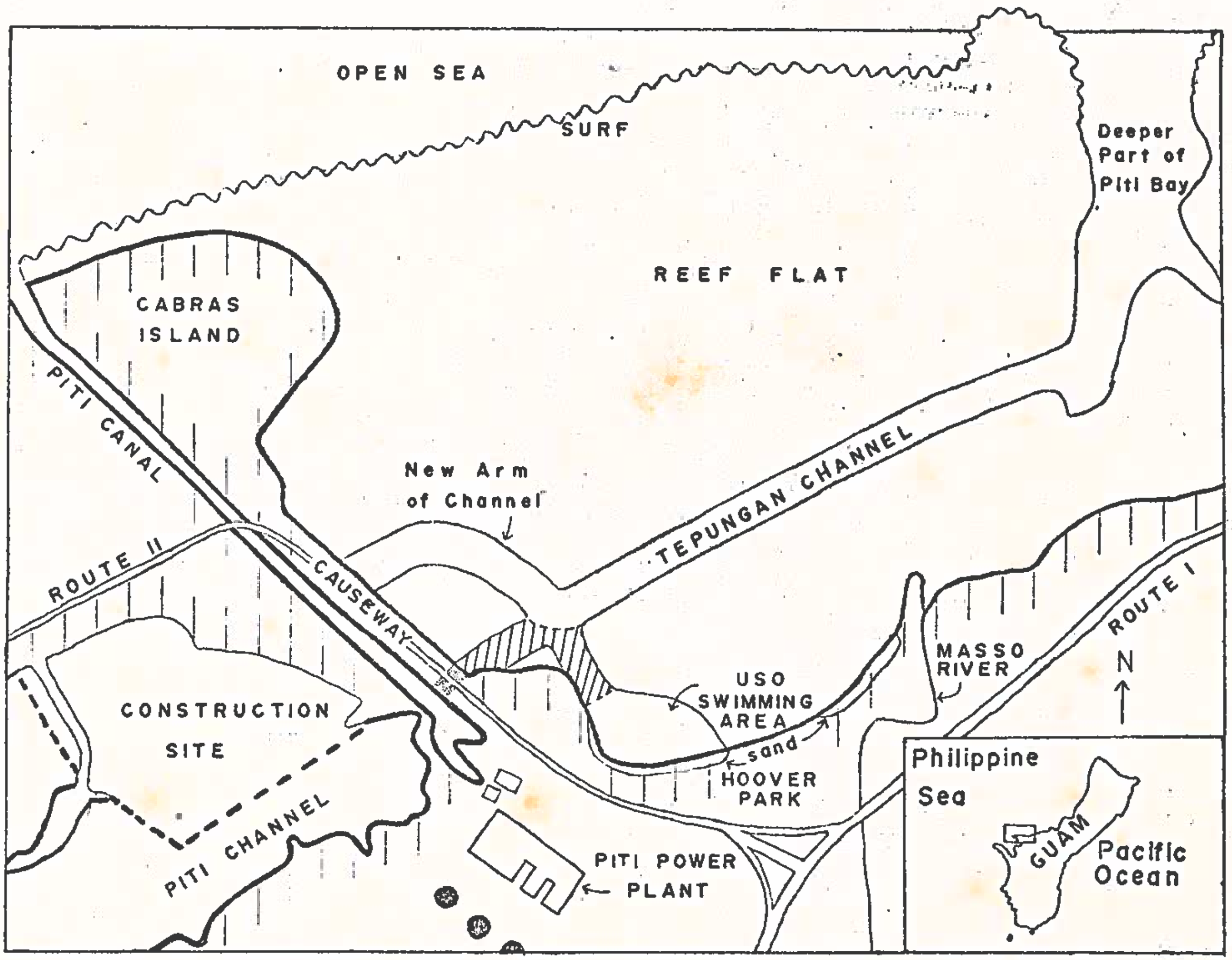


Figure 2. Map of West Piti Bay and the study area, showing major features discussed in the text. The diagonal lines mark the only undredged portion of the channel area. The stippling on the causeway represents the point where the older part of Tepungan Channel passes under the causeway to connect with Piti Canal and the intake lagoon for the Piti Power Plant.

PITI BAY

General Observations

A general description of the study area in West Piti Bay was given by Marsh and Gordon (1972). The area consists of extensive reef flats, cut by Tepungan Channel running east-west across the southern portion, and a diverse coral community in the western portion. The western end of Tepungan Channel communicates with Piti Canal and the intakes of the Piti Power Plant through a passageway which runs under the Cabras Island Causeway. The USO swimming area is located at the southwestern corner of the reef flats, and a small channel connects it with Tepungan Channel. Refer to Fig. 2 for a map of the area.

Table 1 gives a log of activities and observations during and after dredging operations in Tepungan Channel. The work began in December 1972 with the start of construction of a temporary access dike (built of dredged material) across the reef flat parallel to and just north of the channel. This access dike served as a platform for a drag-line dredge and provided a roadway for the hauling of dredged material to the fill site on the western side of the Cabras Island causeway. A new arm of Tepungan Channel was first dredged to connect up with the older portion of the channel (Fig. 2). This older portion was then enlarged to its new dimensions of approximately 48 m (157 ft) wide by 5 m (16.4 ft) deep. The older portion of the channel west of the new arm was not enlarged (Fig. 2). The new arm was completed in January 1973, and enlargement of the older part of the channel was then begun. By the end of January the access dike extended east on the reef flat for approximately half the length of the older part of the channel (Fig. 5). The dike reached its easternmost extension by the middle of February (Fig. 10). The dredge spoil from the eastern end of the channel consisted of fine silt which was piled on the dike and required a longer drying time than the rest of the dredged material. Dredging operations were completed in early April and the access dike was removed.

A number of dynamite blasts were set off in Tepungan Channel, mostly during February 1973, to help dislodge limestone material which could not be removed by the dredge alone. The first blast was observed on 31 January and the last on 26 February. The specific area of the blasting is indicated in Fig. 6. On 31 January we examined the area immediately after the blasting to see if any damage had been done to the biota. A particular search was made for dead fish, since these organisms were the most likely to be affected. It was impossible for the search to be thorough because the high turbidity limited underwater visibility to a meter or so. No dead fish or other dead organisms were found by us or reported by other people. We consider any possible effects on the biota to be minimal.

After completion of the work in Tepungan Channel, the dredge was moved onto the reef flat adjacent to the USO and was used to remove accumulated sediments in the swimming area. This was done as a service to the USO because of the turbidity and siltation problems that had been caused during the channel dredging. (Use of the swimming area had fallen off markedly during that time.) Two large piles of dredge spoil were left on the reef flat for approximately a month (Fig. 11). Water turbidity in the area remained high during this time.

Table 1. Log of major activities and observations in the study area.

PITI BAY

1972	
Oct. - Nov.	Aerial exposure of extensive portions of reef flat by extremely low tides and falling sea level.
Dec. 1	Beginning of construction of temporary access dike.
5	First small <u>Sargassum</u> thalli observed colonizing reef margin.
12	Beginning of dredging for new arm of Tepungan Channel; first extensive silt plume observed in west end of bay.
1973	
Jan. 16	First turbidity samples taken; turbidity in USO swimming area greater than 10 JTU.
18	Beginning of dredging to enlarge older part of Tepungan Channel; portion of dike adjacent to new arm of channel complete; no culverts through dike.
25	First culvert and primary pass through curved portion of dike complete; some decrease in turbidity of waters in western reef flats behind this portion of dike.
31	Construction dike extending approximately halfway along length of Tepungan Channel; dynamiting in the channel.
Feb. 5	Dynamiting in Tepungan Channel; second culvert in place in straight portion of dike.
8	Turbid water moving out deeper portion of Piti Bay into open ocean.
14	Construction dike along Tepungan Channel reaching its furthest extension; reverse water flow observed in swimming area.
20	Blockage of second culvert through dike; portion of straight part of dike removed to low-tide level; pile of fine silt left at east end of Tepungan Channel.
22	Renewed movement of water through second culvert; secondary pass through dike immediately adjacent to second culvert, but little water movement through this; clearer water in swimming area, but dredge inoperative for preceding several days.
26	Dike again continuous; dynamiting in Tepungan Channel.
Mar. 6	Clear water on southern inner reef flat enclosed by dike; filamentous form of brown alga <u>Padina</u> growing here.
12	Large gap in curved portion of dike adjacent to new arm of channel, with large volume of water moving through this gap; obvious silt plume passing out deeper portion of bay into ocean and moving west outside surf.
20	Dike again complete except for small missing portion at eastern end of Tepungan Channel; no opening through curved portion of dike adjacent to new arm of channel.
Apr. 2-7	Final removal of temporary dike; operation of bulldozer across live coral community; dredging in swimming area; piles of sediment left on reef flat adjacent to this area.
7-8	Large boulders left in middle of live coral community.

Apr. 9	Removal of boulders from live coral community; additional operation of bulldozer in this area; protest made to GPA.
10	Blue-green algal mats growing in newly enlarged Tepungan Channel.
12	First school of fish (small apogonids) seen among rocks on northern edge of channel.
24	Blue-green algae growing extensively in bulldozed area.
28	Clean-up of reef flat by Hawaii Dredging and Construction Corporation; growth of green alga *Enteromorpha* covering former dike locality; nudibranch mollusks swarming along edge of new arm of Tepungan Channel.
May 2	Dense stand of blue-green alga *Hormothamnion* on bulldozed reef flat; water with deep yellow-brown color at low tide.
26	Inspection of bulldozed reef flat by representative of Corps of Engineers, Environmental Division.
Jul. 6	Blue-green algae much less abundant than before in bulldozed area; some blue-green algae appearing on portions of reef flat formerly buried by construction dike and formerly occupied by turbid water.
10	Filaments of brown algae more abundant than blue-green algae in bulldozed area; small fish living among coral rubble; grazing fish ranging across damaged area; people fishing newly created holes in sand flat near causeway shoreline.
25	Regeneration noted in *Acropora* thickets at bases of standing dead corals.
31	Dive on reef face reveals silt settlement on substrate near gap in reef margin.
Aug. 14	Beginning of construction of new passageway through Cabras Island causeway to cooling water intake of new power plant.
23	River-derived turbid water covering most of reef flat at low tide.
Sept. 19	Brown algae common in bulldozed area.
1974	
Mar. 15	Washout of large amounts of terrigenous sediments into Piti Bay after heavy rainfall; movement of silt plume from East Piti Bay into swimming area at low tide.

OUTFALL AREA

1973	
Jan. 30	Discovery of fish kill which had occurred one or two days previously.
Mar. 26	Normal-temperature water entering outfall lagoon rather than heated water.
Jun. 18	Two outfalls from construction site dumping turbid water into outfall area.
20	Dredging in outfall lagoon immediately adjacent to outfalls from Piti Power Plant.
Jul. 6	Outfall lagoon clearer, with turbid water no longer coming through Piti Power Plant; turbid water still entering outfall area from construction site.
Oct. 16	Waters of outfall lagoon with intense brownish-reddish-yellowish color.
Nov. 14	Large amounts of *Sargassum* blocking Piti Power Plant intake passageway under road.

Several large boulders were left on the reef flat adjacent to the eastern part of the channel until after the dike had been removed. These were then moved by bulldozer across the live coral community toward the Cabras Island Causeway. A significant portion of that community was thereby destroyed. This is the worst and longest-lasting environmental problem associated with dredging of the channel, and it will be discussed in more detail later in this report.

There is one additional environmental stress, although a rather minor one in comparison with the major turbidity and siltation problems that previously occurred. Construction of a large passageway through the Cabras Island Causeway is presently underway. This passageway will conduct cooling water from the new arm of Tepungan Channel to the new plant intakes. The construction is creating a plume of turbid water extending down-current along the causeway shoreline (Fig. 12). The plume extends to the point where water from the old arm of Tepungan Channel enters the passageway leading to the cooling water intakes for the Piti Power Plant. The areal extent of the silt plume is rather small, and the effects are mostly localized. With the completion of the new passageway, this last short-term environmental stress in Piti Bay will be cleared up.

Water Circulation

Fig. 3 shows general patterns of water circulation in West Piti Bay before and after the temporary construction dike was in place. The dominant pattern is the movement of surf-generated currents across the reef flat, extending as far as the USO swimming area, with a subsequent flow eastward toward the deeper portion of the bay. Much of the eastward flow is in Tepungan Channel. The original pattern was restored after removal of the dike, as we had expected. Figs. 4 and 5 show circulation patterns at different phases of dike extension and indicate that these patterns were considerably altered in the area south of the dike.

Of particular interest were circulation patterns and water exchange in the swimming area while the dike was in place. In the normal pattern, water enters the swimming area from the north, through the small channel that connects with Tepungan Channel, and exits across the reef flat east of the swimming area. As discussed in our original report before dredging began (Marsh and Gordon, 1972), we expected that the dike would block this circulation and lead to the possibility that polluted Masso River water would move westward into the swimming area. Hence, we recommended that a series of culverts be placed through the western portion of the dike to allow the continued movement of water through the swimming area, although on a reduced scale. Figs. 4 and 5 show that, to the extent there was any movement in the area at all, it did not follow the normal patterns. When water did enter the swimming area, it did so by moving across the reef flat from the east, especially the portion of the reef flat adjacent to Tepungan Channel. Water exit was sometimes through the connecting channel and sometimes across the southern portion of the reef flat. On one occasion when the dike was in place (18 January 1974), the total volume of water leaving the swimming area across the reef flat was calculated to be 0.46 m^3 sec^{-1}, compared with a calculated value of 3.5 m^3 sec^{-1} on one occasion before the dike was in place. The maximum observed velocities were 0.28 and 1.3 m sec^{-1} respectively.

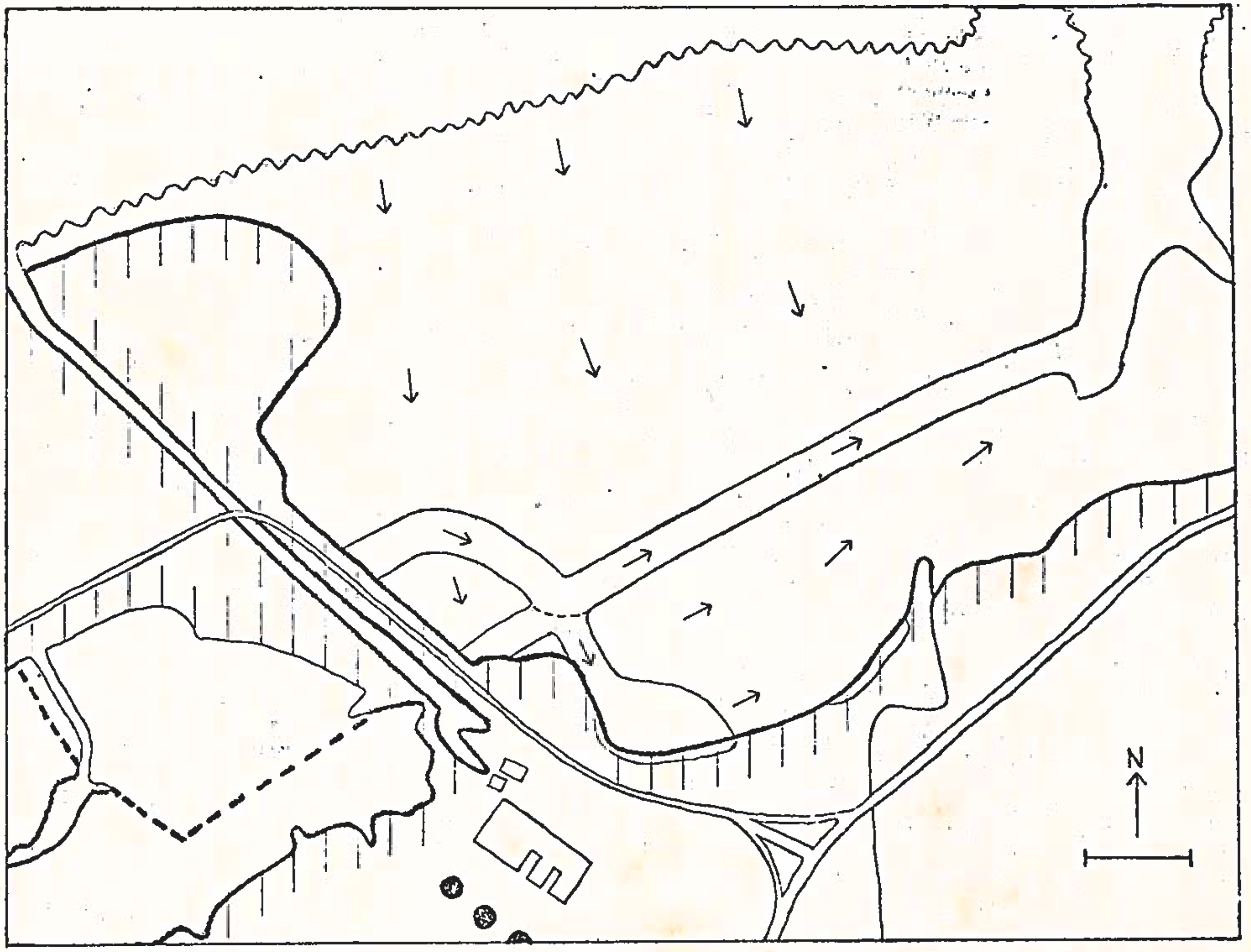


Figure 3. General current patterns in West Piti Bay with no construction dike in place.

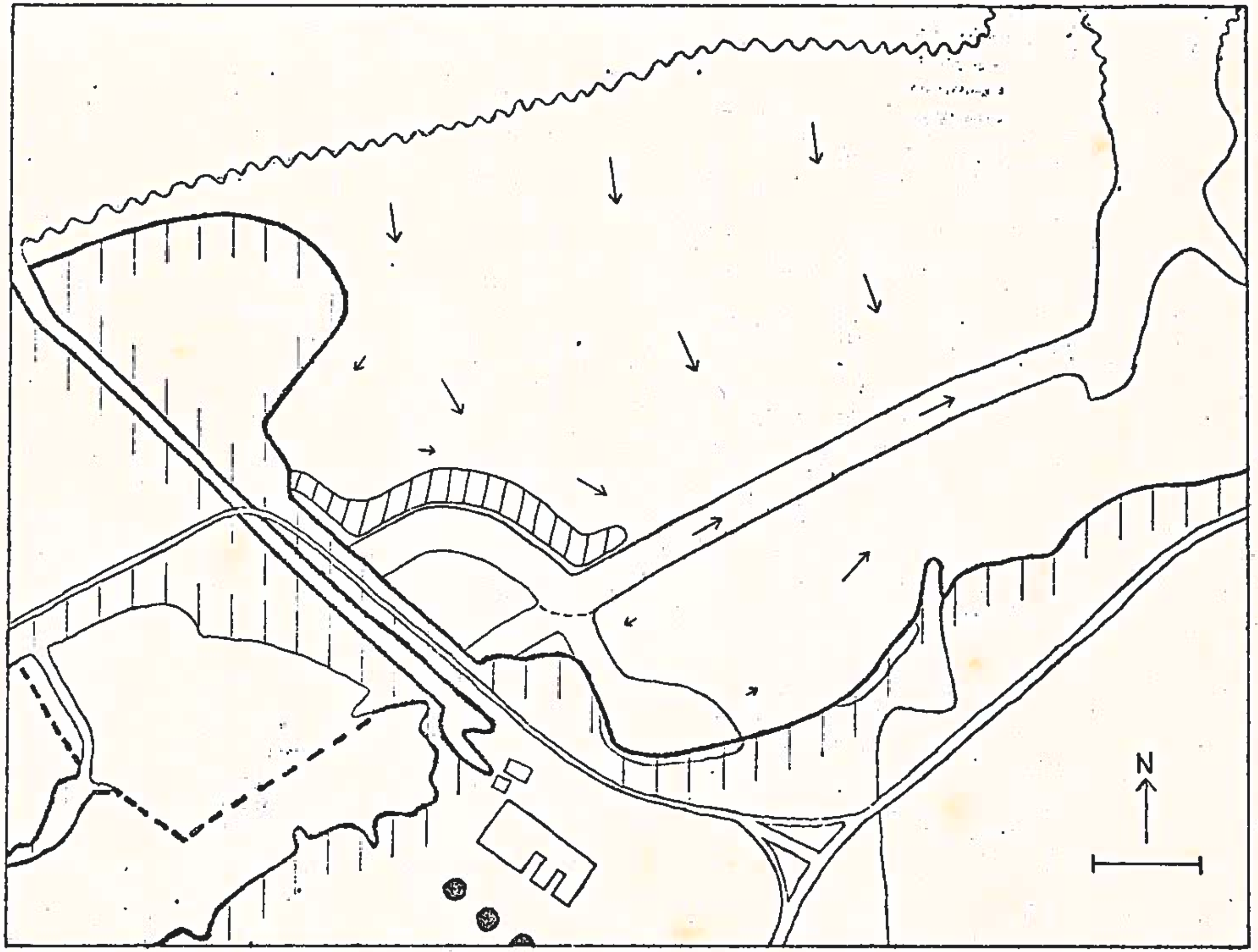


Figure 4. General current patterns in West Piti Bay with the curved portion of the construction dike in place. Note the lack of culverts through the dike. The length of the arrows is roughly proportional to the flow velocity.

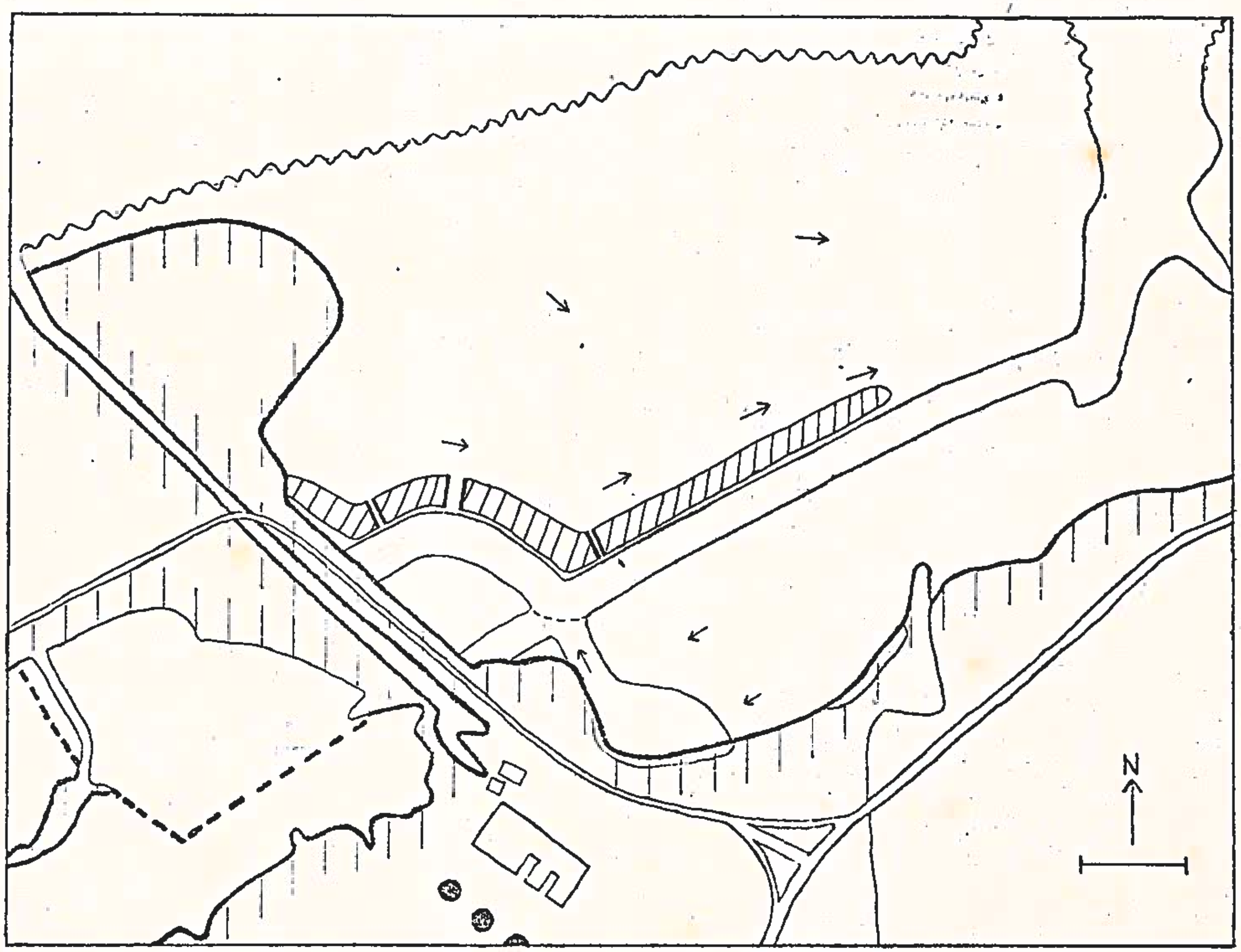


Figure 5. General current patterns in West Piti Bay with the construction dike extending approximately halfway along Tepungan Channel. The length of the arrows is roughly proportional to the flow velocity. Note the placement of culverts and passes in the dike.

During the dredging a large steel plate was placed across the entrance to the passageway that leads from Tepungan Channel under the Cabras Island causeway to the intake lagoon of the Piti Plant. Hence, intake water for the plant came only from Piti Canal during that time. If the Tepungan Channel intake had not been blocked the plant's intake pumps would probably have caused a greater westward flow in the channel and increased water circulation in the area enclosed by the construction dike. However, this would not necessarily have been beneficial since it would have increased the likelihood of Masso River water being drawn toward the swimming area.

The Corps of Engineers dredging permit issued to Guam Power Authority in October 1972 specified that enough culverts should be placed through the western half of the dike to pass 50 cubic feet per second ($1.41\ m^3\ sec^{-1}$) at high tide. As indicated in Table 1, no culverts were placed when the curved portion of the dike was constructed and the new arm of the channel dredged. After protests from the authors, a single 68-cm diameter culvert and a 4-m wide open pass were placed through the dike at the locations shown in Fig. 6. Water was flowing through these at the time of high tide on 25 January 1973. The culvert was located partially below the low-tide level; the open pass was shallow enough to pass no water at low tide and had a water depth of less than 0.5 m at high tide. By 5 February a second culvert, consisting of a double set of 68-cm pipes, was in place at the location shown in Fig. 6. The elevation of this set was above low-tide level. This culvert was subsequently blocked part of the time during dredging operations (Table 1), although a secondary pass through the dike immediately adjacent to the second culvert was sometimes open.

On several occasions we measured the volume of water flowing through all culverts and passes at or near the time of high tide. These measurements are shown in Table 2. The maximum flow observed was $0.87\ m^3\ sec^{-1}$ (31 cfs), or only slightly more than half the flow specified in the Corps of Engineers permit.

Since the completion of dredging we have made measurements of current velocity and volume transport at three stations in Tepungan Channel (station locations shown in Fig. 6). We originally released dye patches at surface, mid-depth, and bottom. However, preliminary results indicated that there were no significant differences between these depths, and we have subsequently released patches only at the bottom. This was done at five locations spaced across the width of the channel at each station. The swiftest velocities at all three stations occur on the side of the channel away from the surf zone. Flows on the side of the channel nearest the surf zone are slower and more likely to be characterized by eddies and complex mixing patterns. Velocities and volume transports are shown in Table 3. Velocities at Station C have been so great that we could work there only at low tides. In all cases for which we have actual measurements the flow has been eastward in the channel. However, we know that the flow can be westward during a rising tide when the tidal amplitude is great (probably greater than approximately 0.6 m). The values presented in Table 3 have all been obtained under conditions of at least moderate surf and mostly under conditions of heavy surf, so they tend to be higher than "average" values might be. Velocities and volume transports generally increase downstream (eastward). The highest velocity observed was $0.42\ m\ sec^{-1}$ at Station B. However, we suspect that velocities at Station C can exceed $0.61\ m\ sec^{-1}$ ($2\ ft\ sec^{-1}$) when there is a heavy surf and high tide.

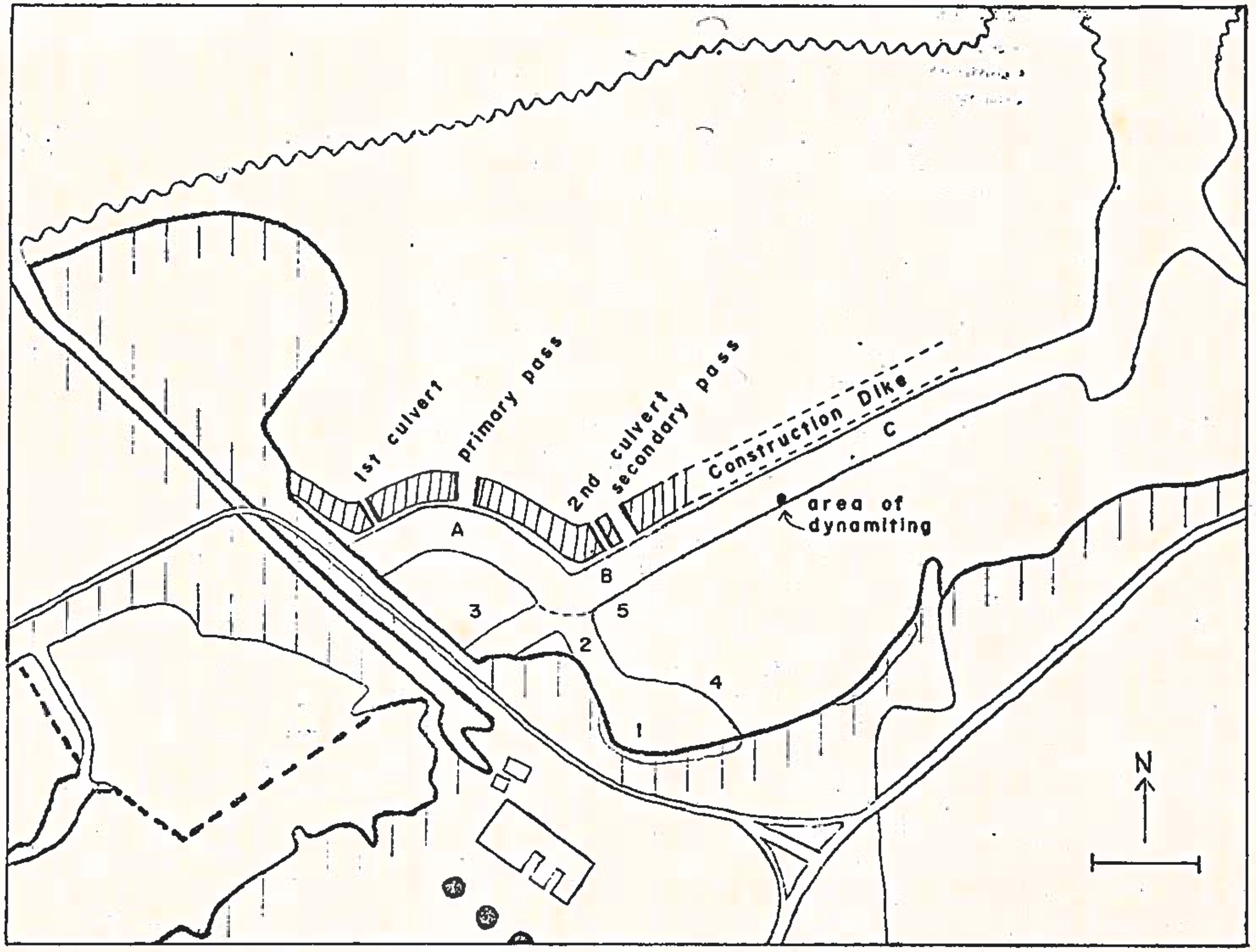


Figure 6. Location of features and sampling stations referred to in the text and in Tables 3 and 4. The letters indicate stations for flow velocities and volume transports in Tepungan Channel after dredging was completed. The numbers indicate turbidity sampling stations.

Table 2. Volume transport (m^3 sec^{-1}) of water through breaks in the construction dike. See the text for a description of the culverts and passageways.

Date	Culvert 1	Primary Pass	Culvert 2	Secondary Pass	Total
25 Jan. 73	.22	.16	-	-	.48
8 Feb. 73	.24	.08	.18	-	.50
22 Feb. 73	.22	.30	.16	.19	.87
6 Mar. 73	.26	.43	.16	-	.85

Table 3. Current velocities (m sec^{-1}) and volume transports (m^3 sec^{-1}) for 3 stations in Tepungan Channel. See Fig. 6 for station locations. The range of velocities is given for 5 stations spaced across the width of the channel. Total volume transports are given for the entire cross-sectional area of the channel.

	Station A		Station B		Stations C	
Date	Velocity	Volume Transport	Velocity	Volume Transport	Velocity	Volume Transport
1974						
Mar. 1	.19-.26	27				
Mar. 6	.16-.20	23				
Mar. 8	.12-.18	20	.08-.21	36	.11-.25	40
Mar. 13	.18-.23	31	.15-.29	37		
Mar. 15	.24-.37	44	.19-.42	63		

The effect of pumping cooling water through the new Cabras Island Plant will be to decrease the eastward current velocity in the channel. When Cabras Island Units 1 and 2 go into operation, approximately 9.0 m^3 sec^{-1} (120,000 gpm) will be withdrawn from the channel. This will not be enough to reverse the current flow in Tepungan Channel under surf and tidal conditions where it is not already reversed. Indeed, it should take no more than half the toal volume transport presently moving eastward in Tepungan Channel at low neap tides when the surf is heavy. If future cooling water demands reach a total of 25.2 m^3 sec^{-1} (400,000 gpm), or 20.4 m^3 sec^{-1} (324,000 gpm) greater than the demands presently exerted by the Piti Plant, then this should still not create a current reversal in the eastern portion of the channel during high tides and heavy surf conditions, but it will probably do so during low tides and light surf conditions. Such a current reversal will increase the likelihood of bacteria-laden Masso River water being drawn toward the swimming area. It is unlikely that future plant demands will create a westward-flowing current in Tepungan Channel greater than the maximum value of 0.61 m sec^{-1} (2 ft sec^{-1}) specified by the Guam Environmental Protection Agency.

Turbidity

The major environmental problem caused by dredging was high water turbidity. This affected the whole southwest portion of the bay closed off by the construction dike, the deeper portion of the bay at the eastern end of Tepungan Channel, and sometimes oceanic waters lying outside the reef. The latter communicate with Tepungan Channel through the deeper portion of the bay. The swimming area was particularly affected. Some representative observations will be reported here.

The first silt plume was observed as soon as construction of the dike began. By 12 December 1972 approximately half of the curved portion of the dike adjacent to the new arm of the channel was in place and had blocked water circulation to its southwest. There was a silt plume in the water behind the dike, and the bottom was covered by a layer of fine silt at least 10 cm deep over what had formerly been sand flat.

By 18 January 1973 the curved portion of the construction dike had been completed (Fig. 7). Water samples were taken that day and analyzed later in the laboratory turbidimeter. The resulting water turbidity values, expressed as Jackson Turbidity Units, are shown in Table 4 and Fig. 7. It can be seen that all stations in the swimming area and the southwest portion of the reef flat affected by the dredging had water turbidities at least an order of magnitude higher than water flowing across the reef flat and not affected by the dredging. Water flowing across the outer reef flat had turbidities less than 1 JTU at all stations. Turbidity in the swimming area measured 33 JTU, and recorded values registered as high as 42 JTU in the enclosed western portion of the reef flat. The highest turbidity, 86 JTU, was found immediately adjacent to the site where the dredge was working. A silty plume extended eastward along the southern shoreline away from the swimming area. Values in the eastern end of Tepungan Channel were less than 1 JTU. The recommended culverts had not been placed through the dike at this time.

By 25 January 1973 the construction dike had been extended slightly and the first culvert and the primary passageway were open through the dike (Fig. 8). Water collected from stations upstream of the construction dike again had turbidity values of less than 1 JTU. The swimming area registered a reading of 36 JTU

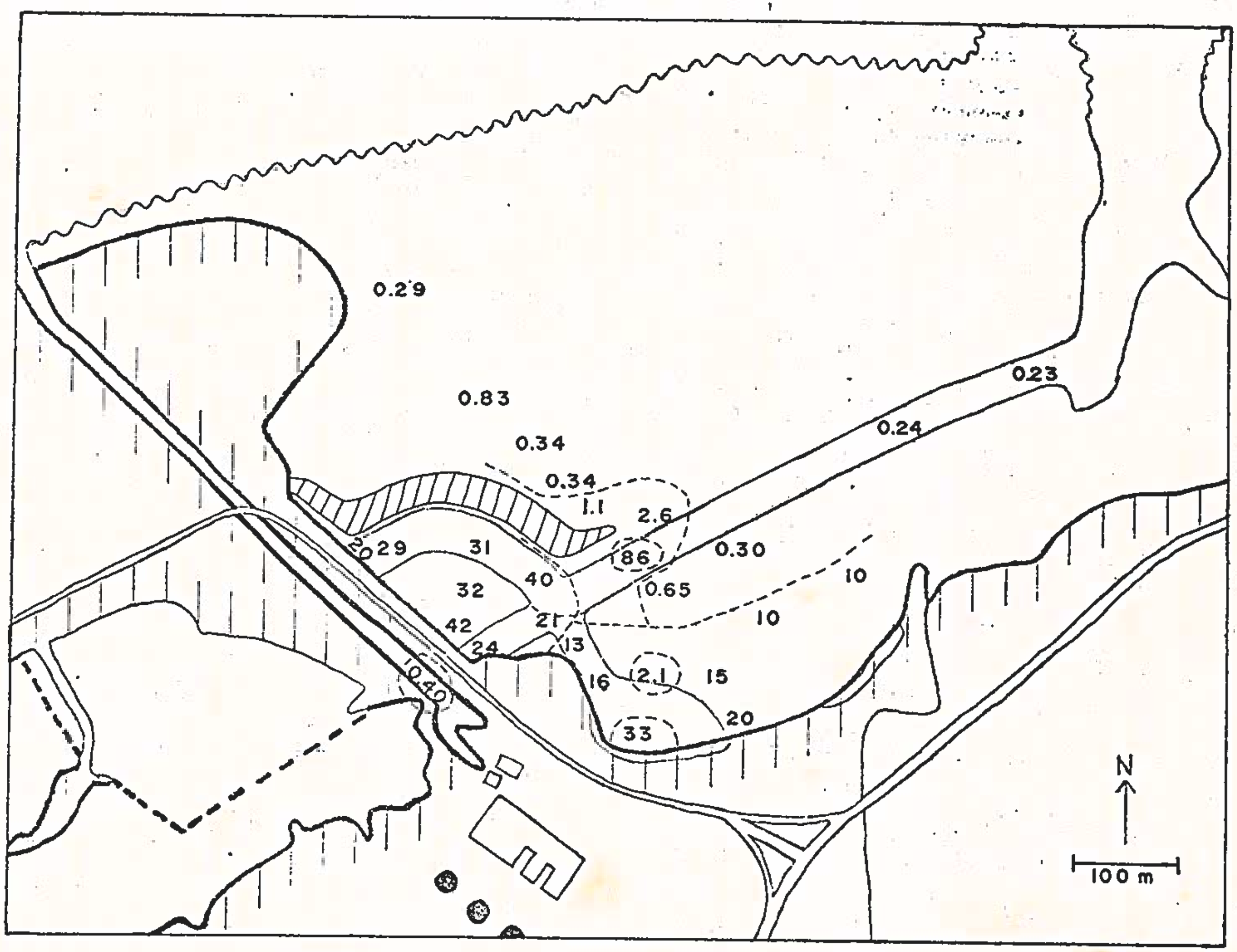


Figure 7. Turbidity values (Jackson Turbidity Units) in West Piti Bay on 18 January 1973. The dashed lines separate areas of widely different turbidities. Note the lack of culverts through the construction dike.

Table 4. Turbidity values (Jackson Turbidity Units) at selected stations in West Piti Bay during the dredging of Tepungan Channel. See Fig. 6 for station locations.

	STATIONS					
	1	2	3	4	5	Comments
1973						
Jan. 16	13	22	35	1.4		
18	33	21	32	15		
25	36	40	25	21	64	1st culvert & primary pass in place.
31	17	126			120	
Feb. 5	20	16	16	26	21	
8	4.0	4.8	11	36	22	
14	6.8	6.9	5.6	5.2	6.7	Dredge at E end of channel culverts blocked.
20	14	16	22			
22	8.6	16	14	8.2		
26	14					
Mar. 6	10	10	22	22	14	
12	7.9	7.6	2.9	6.5	8.4	Dike partially gone.
20	14	16	22	130	39	Dike replaced; no culvert.
Apr. 10	8.9	2.1		4.4		Sediment piles on reef flat; no dike.
12	9.2	5.4	0.61	18		Same
24	2.6	0.86	0.57	1.4	0.53	Same

and values in the enclosed western portion of the reef flat ranged from 20 to 40 JTU. Highest values were again adjacent to the specific dredging site and ranged from 150 to 162 JTU. It may be seen from Fig. 8 that the extent of turbid water on the reef flat south of the channel had increased further to the east but that the eastern end of Tepungan Channel still registered a value of less than 1 JTU. Since samples on this day were taken on a rising tide, we assume that the extent of silty water was less than would have been the case on a falling tide.

The first blasing occurred in Tepungan Channel on 31 January 1973. Immediately after the dynamite charges were set off, water samples for turbidity analyses were taken in the vicinity of the blast. Values ranged up to 352 JTU. This was the highest turbidity value we recorded during the entire dredging operation. Lower values were found at successively greater distances from the blast site.

By 5 February the construction dike had been extended more than halfway down the length of Tepungan Channel, and the second culvert had been placed through the western portion of the straight stretch of dike (Fig. 9). Samples were taken at low tide when turbidity values might be expected to be at their highest. Probably because the working site for the dredge was now further east than before, turbidity values in the swimming area were somewhat lower (20 JTU). A value of 16 JTU was found on the enclosed reef flat west of the curved portion of the dike. It is possible that water moving through the culverts and open passageway of the dike had resulted in somewhat clearer readings in the enclosed area, in addition to the fact that the dredge was working further away. Values on the eastern end of the reef flat south of the channel were somewhat higher than before, ranging up to 70 JTU. The higher values in this area are not surprising, since it was nearer to the actual dredging site on this day. As indicated in Fig. 9, a distinct visual boundary between turbid and clear water extended eastward from the end of the dike.

Fig. 10 shows turbidity conditions over all the closed-off area on 14 February 1974, when the construction dike was at its maximum extent. The dredge was working at the eastern end of the dike and, as usual, was creating a distinct silt plume in the immediate vicinity, as indicated in the figure. A turbidity value of 6.8 JTU was found for the swimming area and a value of 8.3 JTU for the reef flat west of the curved arm of the dike. Values on the reef flat south of Tepungan Channel ranged from 2.9 to 6.7 JTU. As usual, a sample outside the dike had a turbidity value less than 1 JTU for inflowing water. Overall, there was obvious clearing in areas far removed from the site of actual dredging operations.

Turbidity values in the swimming area were not observed to exceed 15 JTU during the rest of the time the dike was in place (Table 4). This was also the case for the adjacent reef flats. As the dredge continued to work up and down the channel and there was occasional dynamiting of limestone materials in the channel, localized turbidity plumes were created and renewed. However, values over wide areas did not exceed those reported above.

During the middle of March there was a large gap in the curved portion of the construction dike adjacent to the new arm of the channel. This gap was apparently caused by heavy surf and strong currents sweeping the dike away, as it had not been stabilized with temporary rip-rap or boulders. At

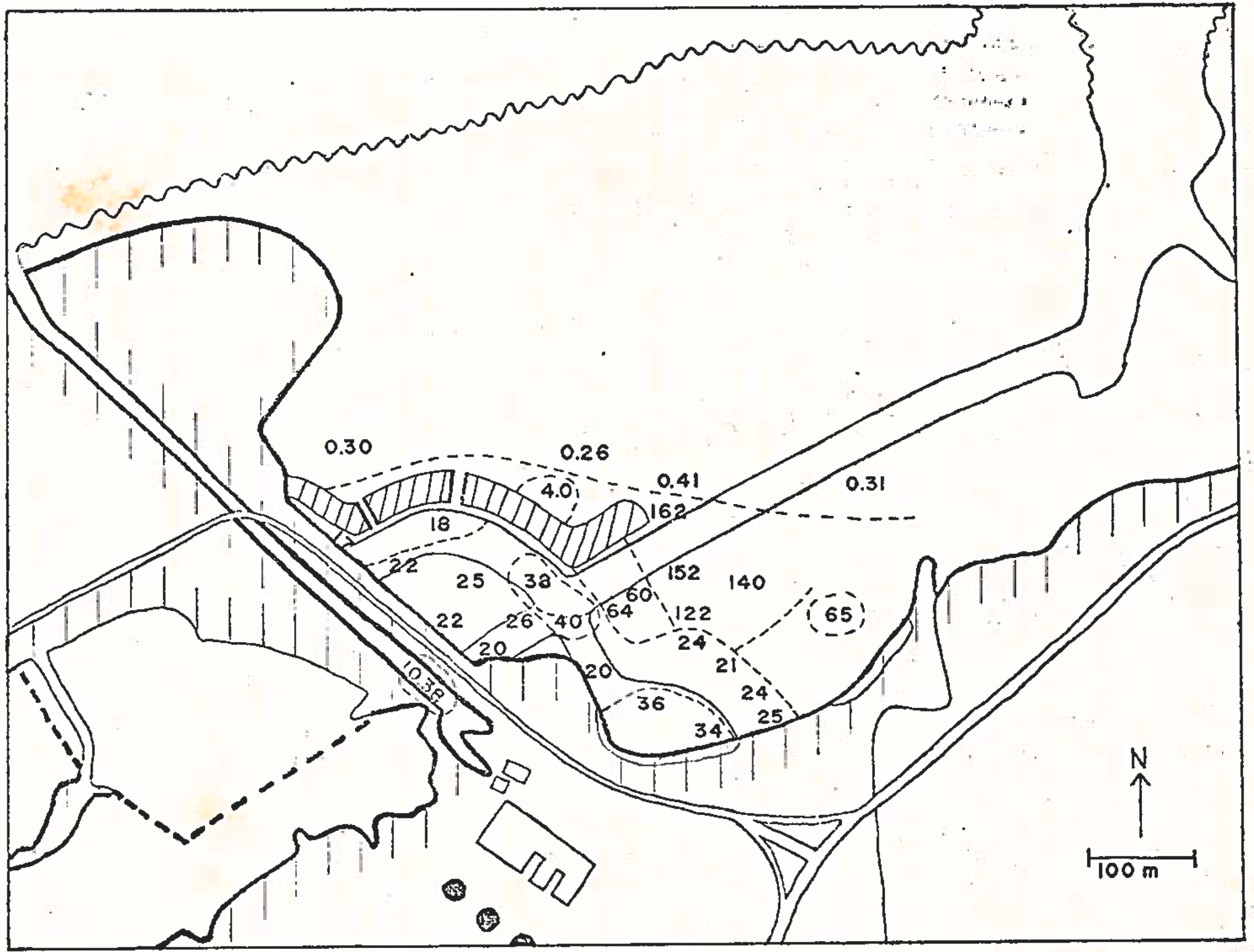


Figure 8. Turbidity values (Jackson Turbidity Units) in West Piti Bay on 25 January 1973.

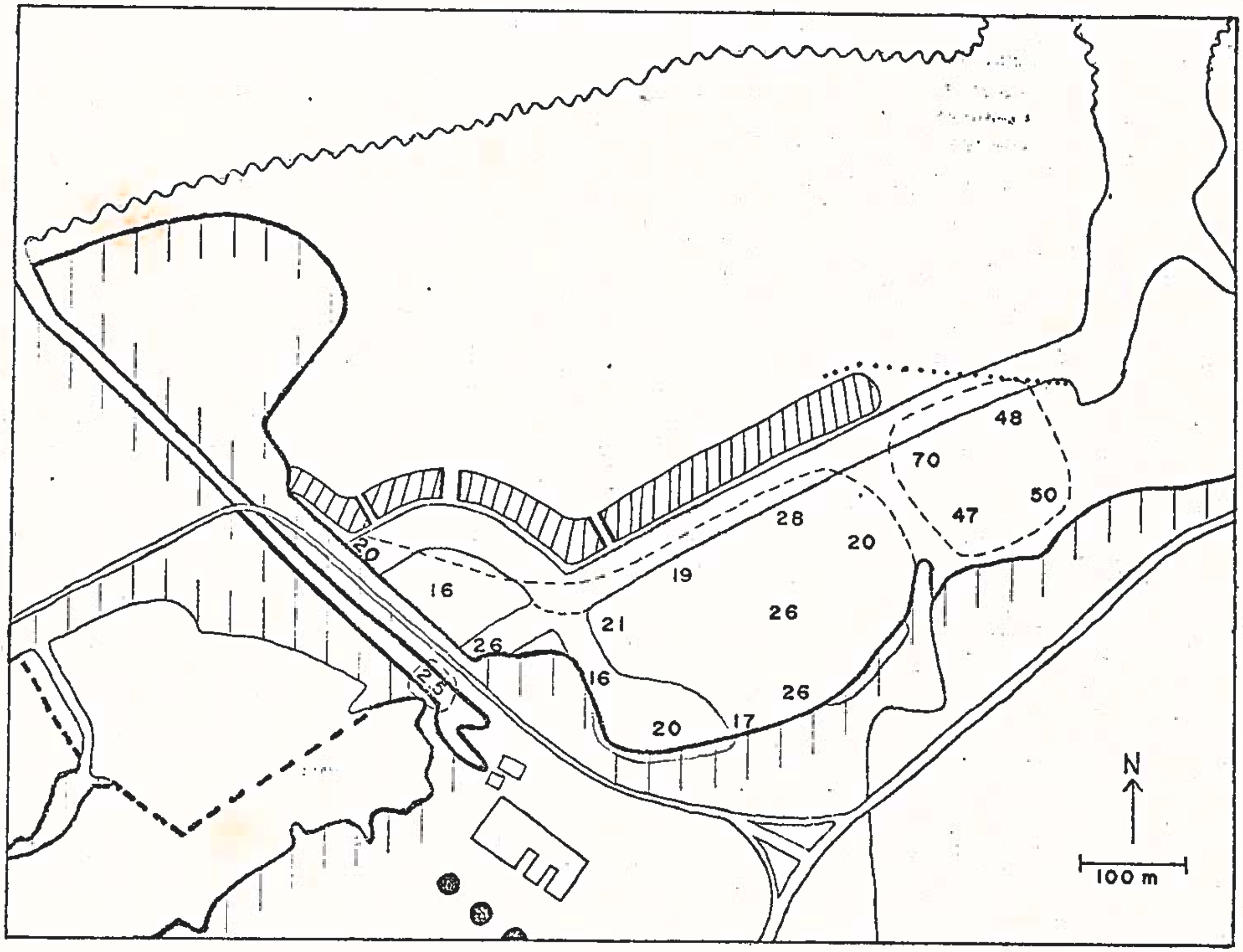


Figure 9. Turbidity values (Jackson Turbidity Units) in West Piti Bay on 5 February 1973. The dotted line extending eastward from the end of the construction dike represents the boundary between visually turbid and clear water.

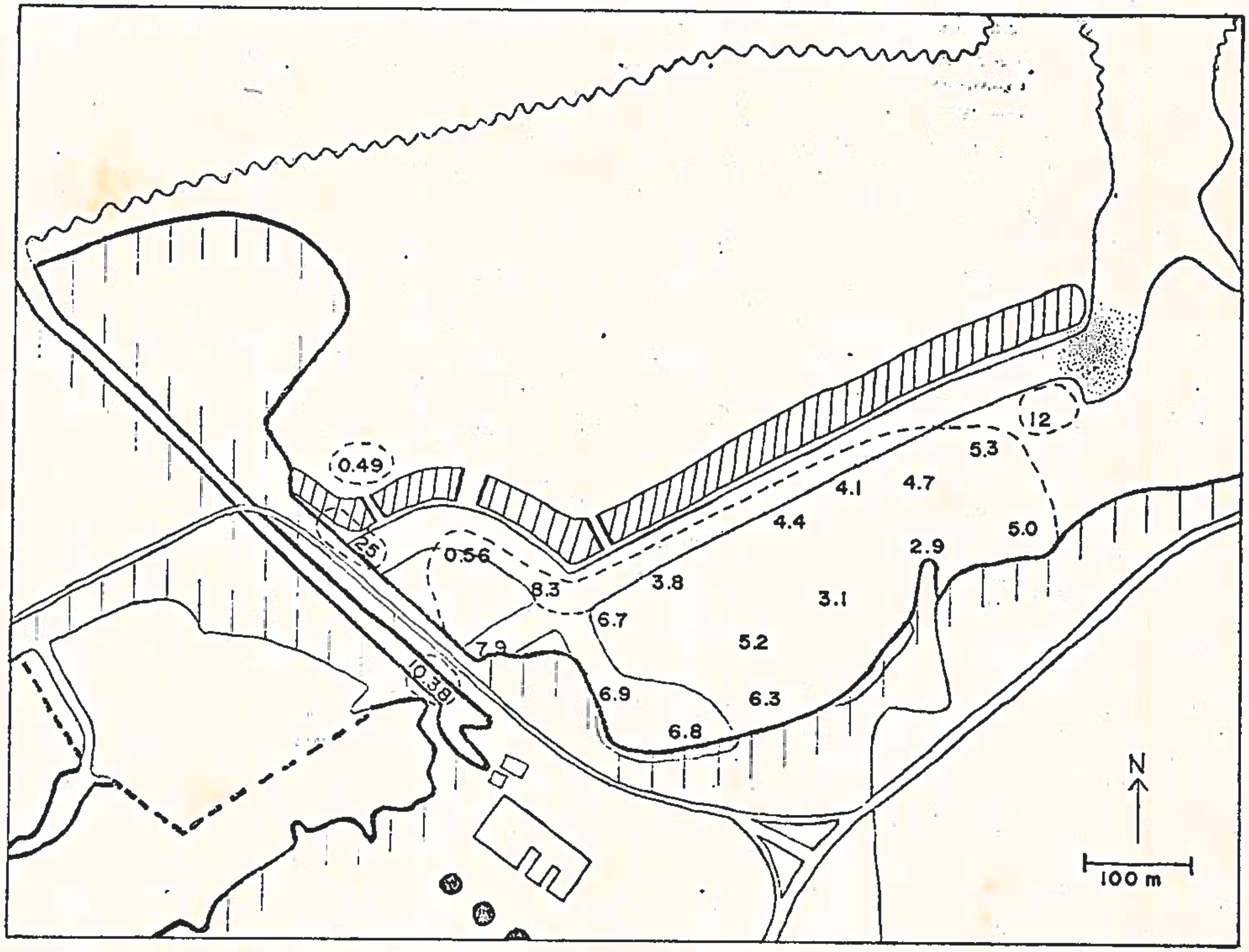


Figure 10. Turbidity values (Jackson Turbidity Units) in West Piti Bay on 14 February 1973 with the construction dike at its maximum extent. The stippling in the deeper part of the bay represents a visually obvious region of highly turbid water.

the same time a distinct silt plume could be seen outside the reef margin. This resulted from material being swept out the deeper part of the bay and moving westward outside the surf. The gap in the dike was repaired, and it remained in place until the beginning of April.

The results of turbidity sampling done after the removal of the dike are shown in Fig. 11. Two sediment piles were still present on the reef flat adjacent to the swimming area at this time. Turbidity values over most of the area had dropped to less than 1 JTU, but samples down-current from the sediment piles exceeded 3 JTU.

Some general comments emerge from our turbidity sampling program. We must point out the great variability of actual turbidity measurements. Thus, although we have presented absolute values here, for lack of a better way of discussing our observations, replicate samples often differed from each other by as much as 25%. Hence, it is more valid to consider the range of observed values than to dwell on individual absolute values. In particular, it is doubtful that absolute differences between specific values of less than 1 JTU actually mean very much with the laboratory instrument we used. In any case, dredging created silty waters which were always at least an order of magnitude more turbid than natural conditions, often two orders of magnitude more turbid, and sometimes three orders of magnitude more turbid.

In watching the dredge in operation, we observed that it continually created visually obvious plumes of water murkier than the surrounding water, even though the surrounding waters might already appear quite turbid. Samples taken under such conditions showed a great deal of variability from minute to minute. Dynamite blasting also greatly increased turbidity in the immediate locality. Measurements with the laboratory turbidimeter usually reinforced visual observations, so that water visually judged more turbid one day than the previous day was usually found to register a higher turbidity on the laboratory instrument.

A narrow silt plume was always present outside (north of) the construction dike, with a distinct boundary line between this and clear reef flat waters driven inward by the breaking surf. This outside silt plume was confined to within about 10 m of the dike almost all the time.

Associated with turbid waters was the deposition of large volumes of silt onto bottom communities. This inevitably killed all organisms present on the pre-existing reef flats and sand flats. As expected, those areas of reef flat enclosed by the construction dike were practically devoid of macroscopic life while dredging was taking place. Obviously, the side effects of dredging destroyed much larger areas than were destroyed by physical removal of the substrate.

The question naturally arises as to the effectiveness of the culverts and passes which were placed through the construction dike. As implied above, they were not very effective. Table 1 indicates that the culverts were not placed while the curved portion of the dike was being constructed. A large deposit of silt built up in the western corner of the reef flat between the dike and the older arm of Tepungan Channel. This provided a reservoir of material for continuous resuspension during the rest of dredging operations.

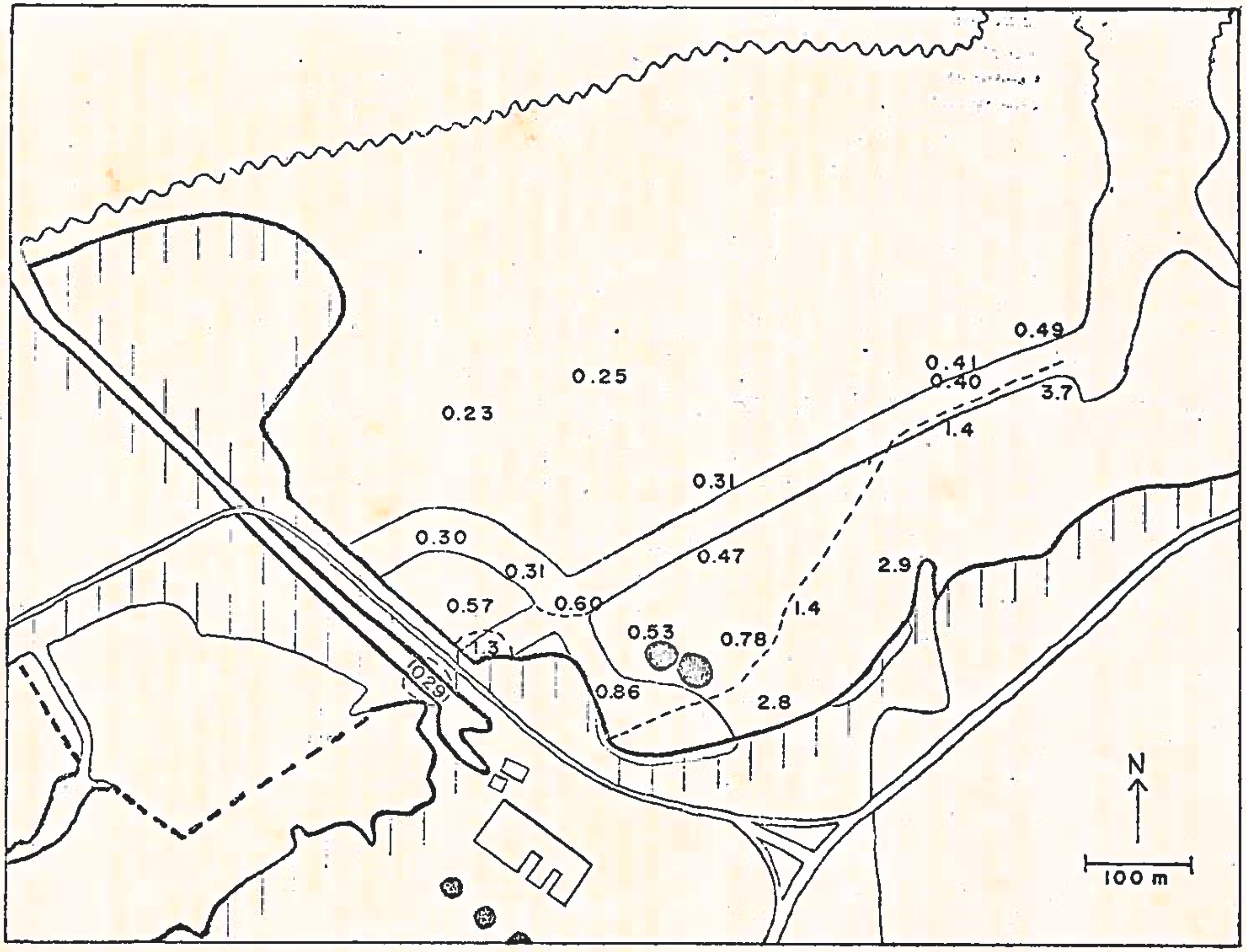


Figure 11. Turbidity values (Jackson Turbidity Units) in West Piti Bay on 24 April 1974 after removal of the construction dike. The blackened areas on the reef flat represent two large silt piles left after dredging of the adjacent swimming area.

In the swimming area, as dredging of the channel and construction of the dike progressed, conditions at first got worse as long as the actual dredge site was upstream. As the dike was extended further and dredging moved toward the east end of Tepungan Channel, there was some clearing of water in the area.

Bulldozer Damage

The most destructive occurrence on the Piti Reef flat took place in the final stages of work after the access dike had been removed. Several large boulders which had previously been left on the reef flat adjacent to the eastern end of the channel were removed to the shoreline of the Cabras Island causeway. These boulders were "herded" across the reef flat by a bulldozer operating well outside (north of) prescribed construction limits. They were pushed across the live coral community rather than being moved across the reef flat immediately next to the channel where the access dike had recently been removed (Fig. 12). Thus, the total area of reef flat affected by construction activities was more than doubled in only a few days in an action which was unnecessary for successful completion of the dredging project. This was contrary to the recommendations which we had made in our original environmental survey report to the Guam Power Authority (Marsh and Gordon, 1972) and which had been incorporated into the Corps of Engineers dredging permit. No justification for this action has been given by the contractor.

As explained in a letter to the Guam Power Authority on 12 April 1973 and in numerous conversations with Authority and contractor officials, ecological damage in the area was extensive. A number of large, spherical *Porites* coral heads were broken up, overturned, or crushed. Staghorn *Acropora* corals were crushed and pulverized. (Although much of the taller staghorn coral had been killed by low tides in October and November 1972, it was still standing in place and provided extensive habitat for fishes and other organisms. Living coral was still present at the bases of the taller dead forms.) Many invertebrate organisms were killed, with crushed sea urchins and sea cucumbers being particularly obvious and likely numbering in the hundreds. There were almost no fishes in the area in the month after the incident, and it was practically devoid of other living organisms as well. The underlying substrate was compacted by the passage of heavy equipment but was left covered by a layer of loose sediment resulting from the breaking up of the corals and larger rubble. The three-dimensional structure of the living community was reduced to a two-dimensional sediment and rubble deposit. In short, the live coral community was generally destroyed everywhere it was subjected to the passage of the bulldozer.

The area of live coral affected was approximately 3,000 square meters, or at least 25% of the total area of the previously intact biological community. Adjacent reef flat communities with dominant organisms other than corals were also decimated.

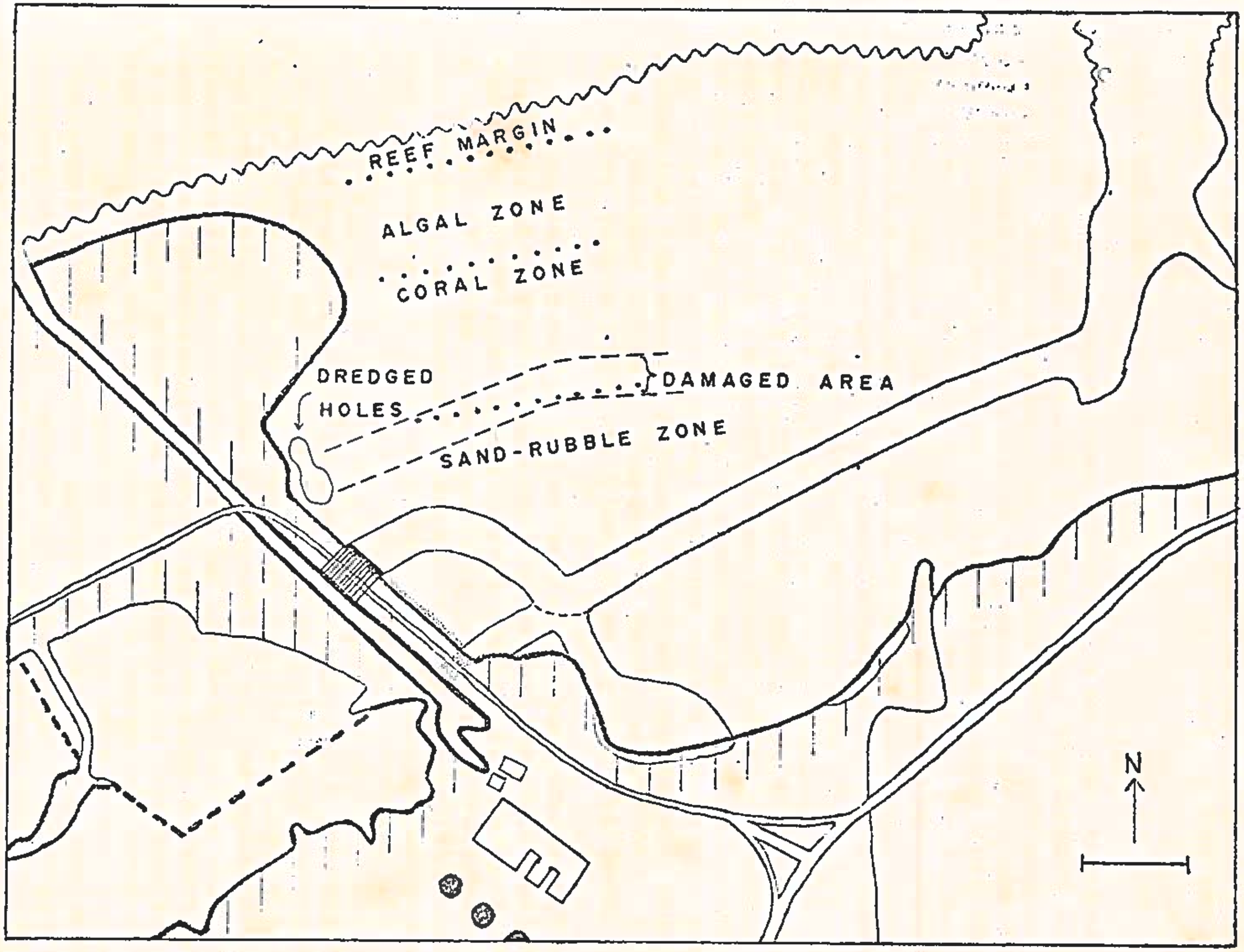


Figure 12. Reef zones, bulldozer-damaged area, and other features referred to in the text. The parallel lines across the causeway at the end of the curved part of the channel represent the construction area for a new submerged passage through the causeway. The stippling next to the causeway shoreline represents a silt plume caused by this construction.

Large amounts of litter were left on the reef flat. A length of large-diameter steel cable was discarded in the destroyed area, and twisted steel reinforcing bar and other debris was left scattered about on the bottom. Discarded debris was also left in the newly enlarged Tepungan Channel.

After strenuous protests from the authors, the Guam Environmental Protection Agency, and others, Guam Power Authority's contractor organized a clean-up party composed of hand labor to work on the reef flat. The work took place on 25 April 1973 under the supervision of the authors, a representative from the Guam Environmental Protection Agency, and a representative from the Guam Division of Fish and Wildlife. Since irrevocable damage to the biological communities had already been done, there was little that the work party could do other than to clean up the debris. Hence, most of the day was spent in searching out and removing such debris by hand in order to avoid further damage to the reef flat. Scrap cable, wire, and reinforcing bar were taken from the reef flat to be hauled away. Because of the high turbidity, snorkelers and a Scuba diver were unable to find and remove most of the pieces of reinforcing bar (formerly used as dredging markers) which had been discarded in the newly enlarged channel. We attempted to do what was possible to encourage re-introduction of corals into the area under favorable growth conditions. Damaged and piled-up heads of Porites coral were turned upright and rolled apart so as to allow their partial recovery. Pieces of broken heads were placed so that their living surfaces were exposed to good water circulation and not covered by sediment or exposed to air at low tides. It was the consensus of the biological advisors that this would have a rather minimal effect in encouraging overall recovery of the total destroyed area, but it seemed to be the only thing that could be done. More than 75% of the total damaged area was left barren of corals because there were not enough live coral pieces available to distribute widely.

Subsequent inspection trips revealed no concentrations of man-made debris and no living pieces of <u>Porites</u> still piled up. However, there were occasional pieces of discarded wire and scrap metal in widely scattered locations along Tepungan Channel. Some piles of broken and dead coral and pushed-up sediment were left on the reef flat; these have gradually become more dispersed over the past year, and most of the piled-up sediments have now been swept away by currents.

Immediately after the bulldozing, the area was almost completely barren of any macroscopic organisms. However, adjacent undamaged coral communities harbored a number of fishes (primarily pomacentrids) displaying abnormal behavior and apparently in higher-than-average densities. These were apparently fishes from the denuded area that had been driven to seek shelter elsewhere after their original habitat had been destroyed, and their invasion was resisted by the resident fishes in the undamaged areas. Within two to three weeks, we no longer observed this situation, and we are not sure about the fate of the apparently displaced fishes. However, we doubt that their chances for survival and reproduction were very good.

Within about two months the destroyed area had developed a dense growth of blue-green algae, particularly of the genera *Hormothamnion* and *Microcoleus*; their density later declined. Much of the bottom, however, still consisted of loose sediment which did not provide a stable substrate for benthic organisms. Many fishes, particularly acanthurids, scarids, and siganids, could be seen at the boundary between the bulldozed area and the coral community; but fish were not very abundant in the bulldozed area itself. The sea cucumber *Synapta* became much more noticeable in the damaged area than it had been previously. We are not sure if it was actually more common than in the live coral areas or was simply more obvious because of fewer hiding places. Individual cucumbers were up to a meter long and had probably moved into the destroyed area from adjacent areas, since they were too large to represent a new generation that could have appeared since the bulldozer damage. Many of the scattered pieces of broken up *Porites* heads were still alive and appeared to be healthy.

Biologically, the bulldozed area now resembles the nearby reef flats rather than the coral community which was previously there. The fragments of *Porites* coral are still alive, but any possible growth has been too slight for us to note. No fragments smaller than about 10-15 cm are still alive. Widely scattered larger pieces of live staghorn *Acropora* and *Porites* provide shelter for damselfish and sea urchins, especially urchins of the genus *Diadema*. Herbivorous fishes range commonly through the area. The same green, blue-green, and brown algae which are found on adjacent reef flats (see discussion below) are common in the damaged area, but the brown *Padina tenuis* is by far the most dominant.

Of primary interest is the question of whether or not the destroyed area will ever recover completely. Certainly we did not expect it to retain for long the barren state it exhibited immediately after the bulldozing. This indeed was the case. However, the question is not so much one of whether some form of life will recolonize the area as whether or not the original condition of the coral community will eventually be re-established. With our present level of understanding we cannot answer this question in a very satisfactory way. However, a reasonable estimate of the time for new *Porites* heads to grow to the size of the old ones and for the three-dimensional structure of a coral community to replace the existing sand flat would be on the order of 25 years at a minimum. It might be possible to make longer-term projections for the area within ten years or so.

Biological Recovery

We have also made observations of biological succession on the altered portions of the reef flat and channel since the completion of dredging activities. In our original report (Marsh and Gordon, 1972) we noted that most of the area to be affected was a non-coral reef flat characterized by algae and echinoderms and adjusted to minor silt stress. We expected that heavy sedimentation would smother living organisms in areas not directly removed by dredging or buried under the construction dike, and this was indeed the case. The issue thus became one of the recolonization of organisms on the reef flat and in the channel after dredging was completed.

By the second week in April 1973, approximately a week after removal of the construction dike, a dense mat of the green alga Enteromorpha sp. appeared in a band adjacent to the newly enlarged channel. This alga occupied only the portion of the substrate which had formerly been buried under the dike. The substrate at that time still consisted primarily of loose sediment and was rather unstable. The bloom of Enteromorpha lasted only a few weeks. There was a light surf most of the time and only weak currents were driven across the reef flat, so the loose substrate material was not immediately swept away. Later there was a period of heavy surf on the reef margin and strong currents across the reef flat, thus exposing rubble and pavement limestone which provided more suitable substrate for colonization by other algae.

An interesting occurrence was observed on 28 April 1973 and several successive days at the western end of Tepungan Channel, primarily the new arm of that channel. There was a massive aggregation of small (less than 2 cm) nudibranch molluscs, probably the species Stylocheilus longicauda, swarming along the seaward edge of the channel. This was apparently a breeding aggregation and likely numbered several million individuals. We do not know whether the aggregation was associated with some particular condition caused by the recent removal of the construction dike and the bloom of Enteromorpha. Such aggregations are natural occurrences, but it is unclear why this should have taken place on the altered substrate rather than elsewhere on the reef flat.

As of this writing we can say that the reef flats which were formerly buried under the construction dike or affected by sedimentation have qualitatively returned to their original condition. Algae and echinoderms are again common and appear to be as abundant as before. The range of natural variation and conditions is great enough that we think the altered areas fall within this range. Among the algae, the browns are the most common, with the visually dominant ones being Padina tenuis, Hydroclathrus clathratus, and Dictyota bartayresii. The blue-greens Hormothamnion enteromorphoides and Schizothrix calcicola are also particularly abundant. Common echinoderms which are again appearing on the reef flats are sea cucumbers Holothuria argus and at least two other species of the genus Holothuria; echinoids Echinothrix diadema, Echimometra mathaei, and Diadema spp.; and the blue starfish Linckia laviegata. There are scatterd corals of the genera Acropora and Pocillopora, and territorial pomacentrids (damselfish) are usually associated with these. There are common free-ranging schools of acanthurids (surgeonfish), scarids (parrotfish), mullids (goatfish), and lutjanids (snappers). Schools of siganids (rabbitfish) are common but appear to be less abundant than schools of other fish.

Colonization in the channel itself has been much slower. The bottom was covered with a thick layer of fine silt after dredging, but some of this silt has since been swept away, especially in the western half of the channel. The instability of the substrate has hampered the colonization of benthic organisms. The only such organisms present in abundance are snapping shrimps and gobies of undetermined species. These maintain individual burrows in which a single shrimp and a single fish live together. We previously noted such a symbiotic shrimp-goby association in Piti Channel and in Tepungan Channel before its dredging (Marsh and Gordon, 1972), but we are uncertain if the species present now are the same ones that were there before. The rather steep sides of the channel are freer of silt than the bottom and therefore have been more colonized by the same species of algae and echinoderms that are present on the reef flats. The same families of fishes as mentioned above for the reef flats are also present along the edges of the channel, but in addition there are schools of small carangids (jacks) and sometimes apogonids (cardinalfish).

One of the recommendations (incorporated into the Corps of Engineers dredging permit) of the Bureau of Sports Fisheries was that the enlarged channel be left with protruding boulders and patches of hard substrate to provide physical habitat for fish and benthic organisms. No boulders or patches of coral rubble were left in the bottom of the channel, but the sides of the channel do consist partially of stable substrate. More extensive areas of such substrate would have enhanced the habitat value of the channel and led to greater biological colonization.

Several holes were left on the reef flat adjacent to the point where the construction dike previously joined the causeway shoreline (Fig. 12). Boulders and pieces of broken-up culvert were left in these holes, and this has provided a physical habitat not previously available at this locality. Goatfish and jacks have been particularly abundant in these holes, and octopuses can commonly be found as well. People commonly fish for young jacks here. In July 1973 five or six fishermen were there all day for at least two weeks and were catching up to twenty fish each per day.

A natural occurrence on the reef margin and adjacent portion of the outer reef flat during 1973 was the unusually heavy growth of the brown seaweed Sargassum cristaefolium. This growth began in December 1972, after the occurrence of abnormally low sea level and reached its peak in the third quarter of 1973. At about this time there was also an unusually heavy settlement of juvenile sea urchins of the genus Diadema on the Piti reef flats, as well as other Guam reef flats.

Natural Stresses

In addition to the stresses caused by Guam Power Authority contractors working in Tepungan Channel, there are other stresses to which the Piti reef flat has been subjected. One of these is caused by fresh-water runoff from the Masso River (Fig. 2) whenever there is a heavy rainfall. This brings in not only fresh water but also large amounts of terrestrial silt. Under most circumstances this runoff moves directly into the deeper part of the bay mixing with water flowing from Tepungan Channel, and eventually flows out into the ocean. The west Piti reef flat is not ordinarily affected by land-derived runoff if there is a moderate to heavy surf or a water level more than a foot or so above Mean Low Low Water, because under such conditions the southward current flow across the reef flats away from the surf and into Tepungan Channel tends to be maintained. However, on one occasion (23 August 1973) river runoff with a heavy silt load covered most of the reef flat during an early morning low tide when there was only a light surf. There had been heavy rainfall for the preceding 24 hours, and the volume of river runoff was high. The reef margin was covered by oceanic water with very little movement. Just behind this was a sharp boundary between oceanic and river water, marked by temperature and turbidity differences. As the tide rose this distinct boundary was maintained and gradually pushed southward across the reef flat to Tepungan Channel. Detectable amounts of silt did not settle onto the substrate from the river water.

Another incursion of silt-laden, land-derived water occurred during the second week of March 1974, when large amounts of soil washed into the eastern half of Piti Bay (the area known as the "bomb holes") from a construction site on Nimitz Hill. This had been a major problem in East Piti Bay for the preceding six months, and silt settlement had led to the smothering of extensive live coral communities. The problem had not extended to our study area in West Piti Bay before the heavy rains during the week noted above. At that time there were strong easterly winds which eventually drove a silt plume across the deeper portion of the bay and westward in Tepungan Channel at low tides. This plume moved into the swimming area during the afternoon low tide of 13 March. A large amount of silt also moved out the deeper portion of the bay into the ocean and then westward outside the surf line of our study area. There was an obvious brown coloration in the breaking waves and some silt was undoubtedly transported back across the reef flat by the surf-generated currents. There was not a heavy settlement of terrigenous silt onto the reef flat in the study area, if indeed there was any settlement at all. Hence, West Piti Bay remains in a much healthier state, biologically, than East Piti Bay, which has largely had its biological communites killed by silt settlement. The fact that West Piti Bay was not similarly affected is due in part to the heavy surf and resulting strong currents across the reef flat during the period of heavy rainfall. However, it is possible that the remainder of the live coral community on the west Piti reef flats could be affected by runoff from the Nimitz Hill construction project under unfavorable weather and oceanic conditions. There is also an aesthetic problem for the USO swimming area, one of the few such recreational areas on Guam.

Another natural stress on the reef flats in the study area was caused by extremely low tides and falling sea level, which reached the maximum extent in October and November 1972. This resulted in the complete drying out of large areas of the higher-lying portions of the Piti reef flat and killed all or most of the benthic organisms in these areas. The lower-lying portion of the reef flat at the western end retained a non-circulating mass of water less than a meter deep. This was sufficient to allow most of the organisms in the coral community to remain alive, even though they were undoubtedly stressed by high temperatures. Large areas of staghorn (_Acropora_ sp.) coral thickets were killed by exposure to the air, however, since they occupied higher level portions of the substrate. Subsequent to the return of higher tides and raised mean sea level, there was extensive recolonization of the higher portions of the reef flat by the same species of algae (especially brown algae) and echinoderms that had previously occupied these areas. The extensive cover of _Sargassum_ which developed on the reef margin has already been described. The live coral continued to thrive, and in the dead staghorn coral thickets there was new growth in the open spaces. The cause of the temporary drop in mean sea level is not known for sure, but it appears to be related to Pacific-wide meteorological and oceanographic conditions. Prediction of possible future occurrences of this phenomenon cannot be made with our present level of knowledge and understanding.

PITI CHANNEL AND APRA HARBOR

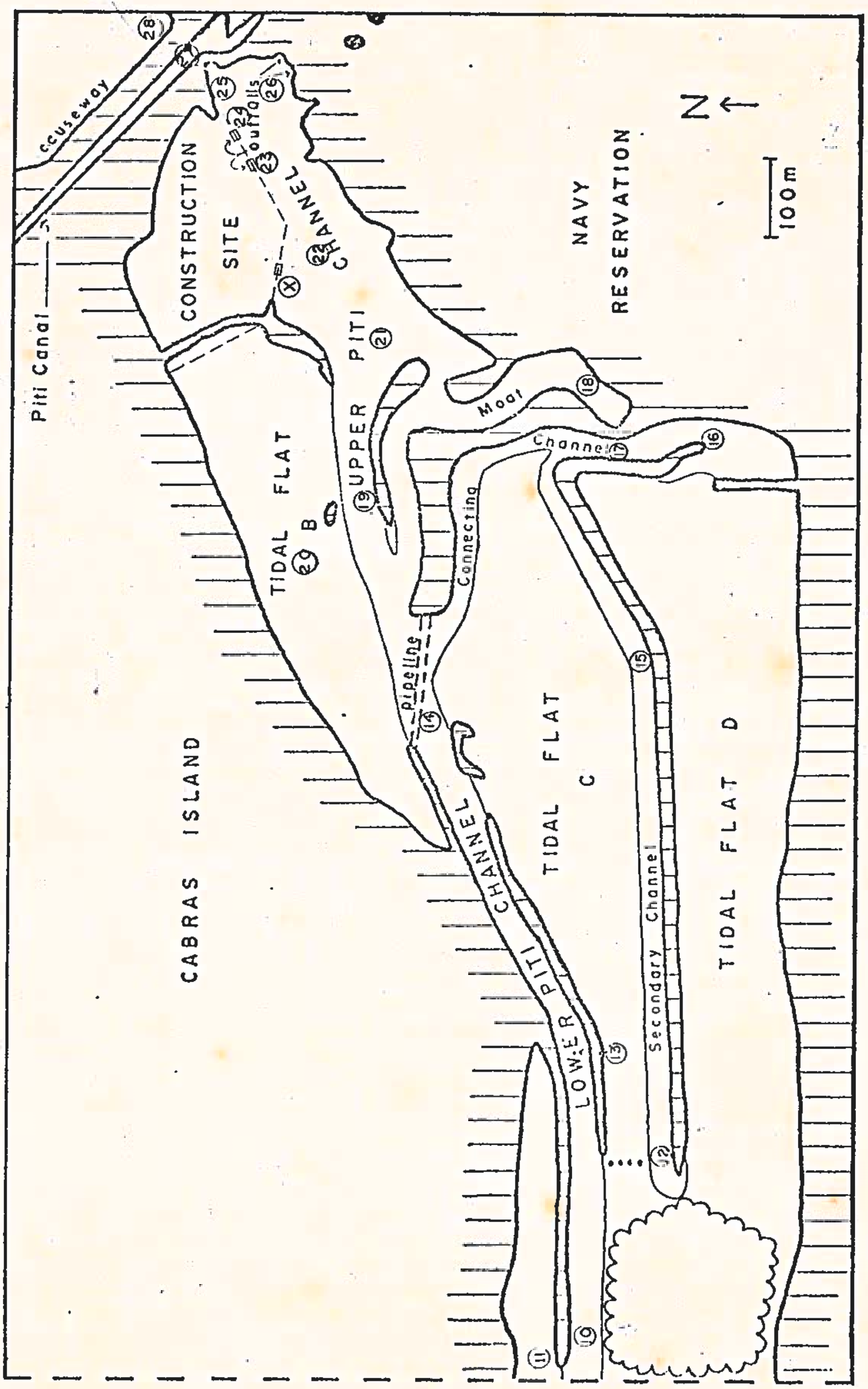
Construction Effects

Filling of the submerged land on the construction site began in December 1972, and construction itself began shortly thereafter. The fill and construction site was stabilized with a concrete-and-rock seawall. The brown alga Padina tenuis has been the only organism we have observed colonizing this seawall so far. As soon as excavations began for the plant foundations it became necessary to pump seepage water out of the excavated area, and this has continued to the present time. This silt-laden water is pumped into the outfall lagoon of the Piti Power Plant and enters it at two points approximately 20 m apart along the new seawall (Fig. 13). The silty water enters the eddy system of heated effluent water from the Piti Plant and is rapidly dispersed throughout most of the outfall lagoon. Recently a new effluent point for silty water has been created at the point where cooling water outfalls for the Cabras Island Plant are now being constructed.

The most obvious thing that has happened in the outfall area since filling and construction operations began has been the marked increase in turbidity. The turbid conditions have existed almost continuously, but there was a period of clearer water in early July 1973. The water has sometimes had a reddish-brownish-yellowish tinge to it, but we are not sure what causes this. The seawall at the site of the construction outfalls is stained reddish-brown, as if some dissolved material were being precipitated out of the water. We have also observed a similar stain track on the soil adjacent to the cooling water outfalls of the Piti Plant where rain water sometimes drains off the storage lot.

An apparently different kind of reddish color observed more recently is probably caused by the suspension of terrestrial sediments in the water. We described above the movement of terrigenous sediments into the west end of Piti Bay from the Nimitz Hill construction project during the heavy rains of March 1974. If a significant volume of silt-laden water moved through the passageway under the Cabras Island causeway and into the cooling water intakes of the Piti Plant, then this would be pumped through the plant condensers and appear in the outfall lagoon. Indeed, during the third week of March we observed obvious deposits of such reddish sediments on some bottom areas of Piti Channel. It is doubtful that this washed in from adjacent land areas. We had not observed such sediments in the study area during the previous two years, despite having looked specifically for this when the reddish-brownish-yellowish coloration first appeared in the outfall lagoon after construction began. Moreover, the sediments which led to obvious water turbidity in the dead-end moat (Fig. 13) are more brownish than elsewhere in the outfall area and have no reddish tinge. With heavy rainfall these sediments are washed directly into the moat from adjacent land, as has been noted on numerous occasions.

Field estimates of visibility have often been made while we were doing other things in the outfall lagoon and Piti Channel. There was an obvious decline in visibility after construction began, with estimates seldom exceeding 1 m, as compared with estimates of 3 m before construction began. In addition, occasional samples were taken for later turbidity analysis in the laboratory. Sampling locations are shown in Fig. 13, and results are shown in Table 5. It may be seen from the table that, with only two exceptions, turbidities at all stations exceeded 1 JTU. One of the exceptions was a sample taken in the Piti Canal on 30 January 1973 before there was any construction-caused disturbance to


Piti Canal
causeway
CONSTRUCTION SITE
outfalls
UPPER PITI CHANNEL
NAVY RESERVATION
N
100 m
TIDAL FLAT B
Connecting Channel
Moat
Pipeline
CABRAS ISLAND
LOWER PITI CHANNEL
TIDAL FLAT C
Secondary Channel
TIDAL FLAT D
X
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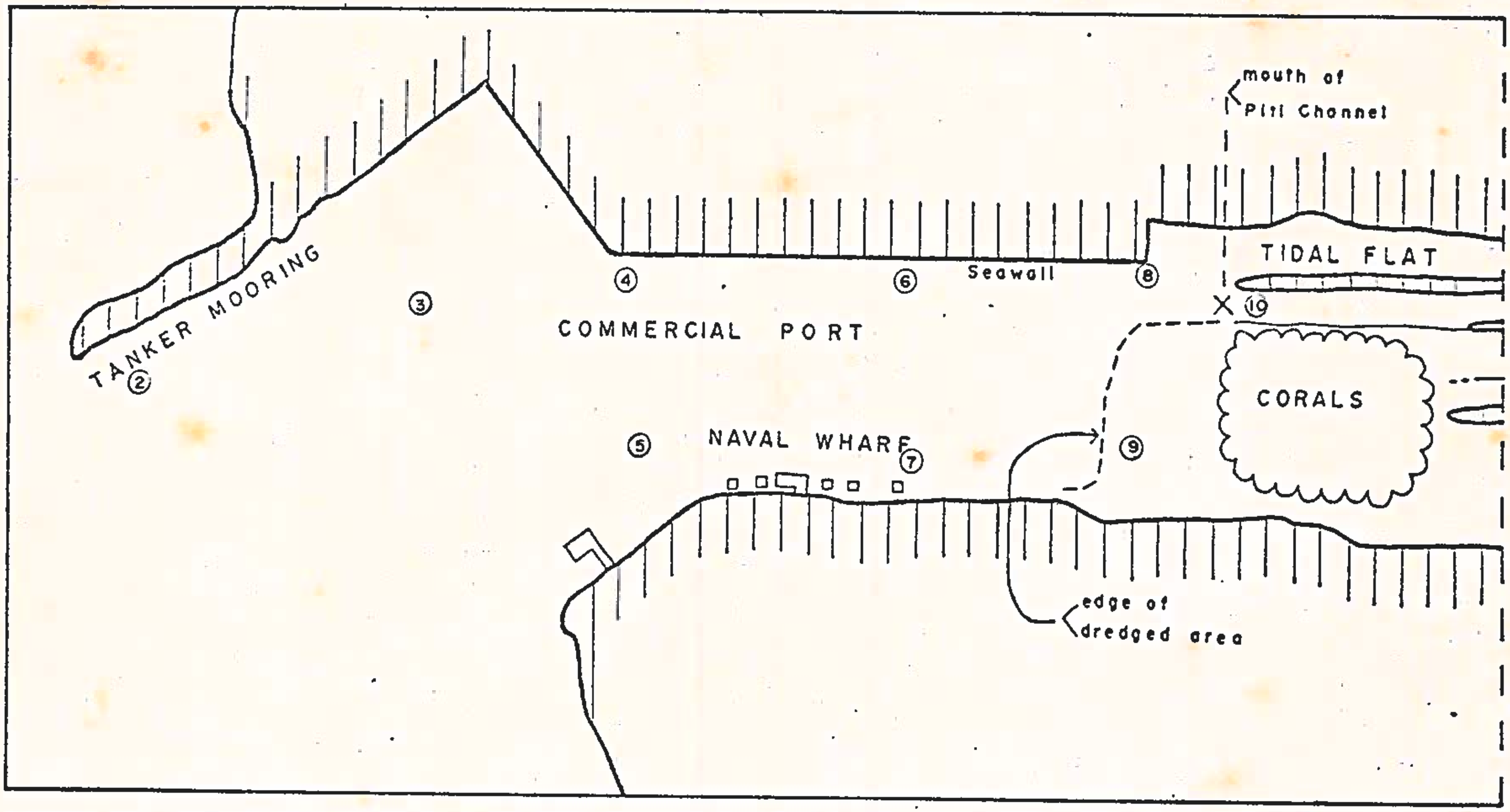

Figure 13. Map of the study area in Piti Channel and the harbor, showing major features and numbered sampling stations referred to in the text. A. (top) Eastern half of the study area. The circled "X" in Upper Piti Channel marks the site of the future cooling water outfall for the Cabras Island Plant. The labeled "outfalls" indicate cooling-water outfalls for the Piti Power plant and outflows of silty water from the construction site. The dotted line at the western end of Tidal Flat C indicates the transect for volume transports (discussed in the text). B. (bottom) Western half of the study area. This connects with Outer Apra Harbor on the west. (Station 1 is located in the outer harbor at Signal Buoy 1 shown in Fig. 1).

the waters there. The other exception was for a sample taken in the outer part of the harbor on 19 March 1974. Other samples taken from that part of the harbor have always exceeded 1 JTU. Almost all samples in the outfall lagoon and Piti Channel have ranged between 1 and 4 JTU (Table 5), a range which is much lower than the worst conditions reported for the Piti reef flats and Tepungan Channel in the earlier part of this report. However, although these values for Piti Channel and the outfall lagoon may not seem very high, visual observations usually indicate that the water is murky; and there is an obvious turbidity problem in the outfall lagoon.

Water Movement

Determinations of volume transport were made in the channels during falling tides in August 1973 to augment previous observations (Marsh and Gordon, 1973). The station locations for Piti Channel, the connecting channel, and the secondary channel are shown in Fig. 13, and the data are shown in Table 6. It may be seen from the table that the greatest flow was in Piti Channel and was westward away from the plant outfalls until approximately 1.5 hours after low tide, when a reverse flow began. The volume transport in the secondary channel was less than in Piti Channel and was also westward away from the plant outfalls until approximately 1.5 hours after low tide, when a reverse flow began. The volume transport in the secondary channel was less than in Piti Channel and was also westward most of the time during the falling tide. However, there was a slight eastward flow at one time shortly after high tide (1100) on 16 August. Water movement in this channel is mostly due to water draining off the adjacent tidal flats during falling tides. No flow reversal was observed on 14 August, but there was a reversal on 16 August approximately 1.75 hours after low tide, with water moving eastward at that time. In the connecting channel water movement was always southeastward if there was any movement at all, but the volume transport was very small. It is possible that some heated effluent water from the Piti Plant moves into this small channel after crossing the pipeline (Fig. 13), but the volume is obviously small and most of the effluent water moves directly westward in Piti Channel. It is likely that little of the effluent water moves onto the adjacent tidal flat.

The volume transports reported in Table 6 for Piti Channel are lower than the maximum value of 22 m^3 sec^{-1} (350,000 gpm) given in our last report (Marsh and Gordon, 1973). We used this value as a basis for projecting maximum future velocities and volume transports in Piti Channel if total cooling water outflow from the power plants increased to 12.6 m^3 sec^{-1} (200,000 gpm) and 25.2 m^3 sec^{-1} (400,000 gpm). Our maximum calculated velocities were .85 m sec^{-1} (2.8 ft sec^{-1} and 1.2 m sec^{-1} (3.9 ft sec^{-1}), respectively. Our additional data presented in Table 6 do not lead to an increase in the projected maximum velocities.

Volume transport measurements across the western end of Tidal Flat C, along the transect shown in Fig. 13, were attempted on three occasions in June, July, and August 1973. Single transects were run on a falling tide, at low water, and on a rising tide. The maximum in-flowing (easterly) velocity at any station on the rising tide was .16 m sec^{-1}, and the total volume transport of water moving eastward was calculated to be 5.8 m^3 sec^{-1} for the entire transect. This transect was run between 1230 and 1300 hours on 25 July 1973; the predicted low tide was 0.0 ft at 0922 hours, and the predicted high tide was 1.9 ft at 1701. The maximum out-flowing (westerly) velocity observed at any station on a falling tide was likewise .16 m sec^{-1}, and the total volume transport of water moving westward was 6.9 m^3 sec^{-1} for the entire transect. These observations were made between 1545 and 1600 hours on 3 August 1973; the predicted tides for that day were 2.1 ft at 1039 hours and 0.5 ft at 1645. These velocities and

Table 5. Turbidity values (Jackson Turbidity Units) at selected stations in Piti Channel and Apra Harbor. See Fig. 13 for station locations.

	SAMPLING DATE				
Station	30 Jan. 73	5 Feb. 73	1 Nov. 73	27 Nov. 73	19 Mar. 74
1		1.4			
2			1.2	1.8	0.65
8		2.5			
10	1.7	3.7	2.1	3.6	
11	1.4				
13					2.7
14			2.6	3.2	3.1
17			3.1	4.2	4.2
18			2.8	4.1	13
19			2.6	2.8	3.2
21	2.7	3.0	2.2	2.8	3.3
22			2.4	2.5	3.3
23			1.8	2.5	2.8
24			2.4	2.4	3.0
25			3.0	2.9	3.5
26	1.8	2.7	1.6	2.5	2.8
27	0.47				2.8

Table 6. Water flow in the three channels on the outfall side during falling tides. Cross-sectional areas of the channels are calculated for the major portions of the channels with significant water movement and do not include the shallow edges with little or no water movement. Station locations are shown in Fig. 13.

Station	Time	Depth (m)	X-Sectional Area (m^2)	Velocity (m sec^{-1})	Vol. Transport (m^{-3} sec^{-1})	Direction
14 August 1973 Tides: 0657, 2.3; 1352, -0.1						
Piti Channel	1333	2.0	40	.29	11	W
	1415	2.0	40	.23	9.3	W
	1455	2.1	43	.11	4.6	W
	1530	2.1	43	.089	3.9	E
	1600		No movement			
Connecting Channel	1315	1.4	22	.046	1.0	SE
	1410	1.3	20	.072	1.5	SE
	1445	1.3	20	.036	0.73	SE
	1520	1.3	20	.044	0.89	SE
	1550	1.3	20	.037	0.75	SE
Secondary Channel	1250	2.2	35	.12	4.2	W
	1400	2.2	35	.17	6.0	W
	1430		No movement			
	1515		Barely detectable movement			W
	1540		Barely detected movement			W
16 August 1973 Tides: 0822, 2.3; 1453, 0.1						
Piti Channel	1000		Barely detectable movement			
	1115	2.3	50	.32	16	W
	1235	2.2	47	.30	14	W
	1350	2.1	44	.17	7.5	W
	1450	2.0	40	.19	7.7	W
	1545	2.1	43	.088	3.8	W
	1625	2.1	43	.073	3.2	E
Correcting Channel	1030		No movement			
	1125		Barely detectable movement			SE
	1300	1.7	30	.057	1.7	SE
	1400	1.6	28	.081	2.3	SE
	1500	1.6	28	.093	2.6	SE
	1600	1.6	28	.11	3.0	SE
	1635		Barely detectable movement			SE
Secondary Channel	1100		Barely detectable movement			E
	1155	2.4	35	.042	1.5	W
	1315	2.3	33	.049	1.6	W
	1420	2.2	31	.070	2.2	W
	1515	2.2	31	.12	3.7	W
	1615		No movement			
	1640	2.2	31	.032	0.98	E

volume transports are comparable with the values reported in Table 7 for the secondary channel. However, water movement across the tidal flat was not steady and continuous, and at a given time and station it occasionally reversed itself for short intervals. We are not sure why this occurred, but it may have been correlated with the movement of ships in the Commercial Port area.

Previous extensive temperature observations in the Commercial Port area (Marsh and Gordon, 1973) led us to suspect that upwelling could be bringing bottom water to the surface at the eastern edge of the dredged area (Fig. 13). We have now looked into this question further by applying the following reasoning. If there is upwelling in a particular locale, there should be a constant temperature from surface to bottom where the cooler bottom water is rising to the surface. This water should then spread downwind on the surface and show up as a plume of cooler water which gradually becomes warmer through mixing with the adjacent water mass. Outside the upwelling region there should be a vertical temperature stratification from surface to bottom, with the warmer water forming a layer 1-2 m thick on the surface. Such a temperature stratification in the harbor was described in our last annual report (Marsh and Gordon, 1973). We reported there that the stratification existed only at low tide when warmer plant-heated water from Piti Channel and solar-heated water from the tidal flats flowed westward into the Commercial Port area. On rising and high tides,harbor water of ambient temperature enters the area and pushes the warmer water back into Piti Channel and onto the tidal flats. If there is no upwelling occurring, then the pattern of vertical stratification should be present throughout the entire area at low tides.

Extensive temperature observations at closely spaced stations in the eastern end of the dredged area for Commercial Port were made on six different days in June, July, and August 1973. No definitive evidence was found to support the hypothesis of upwelling, although the data for one day (29 June) did appear to fit the reasoning presented above. However, we did reconfirm the pattern of a layer of warmer water at the surface during falling and low tides replaced by a cooler water mass at ambient harbor temperature during rising and high tides. We have observed that the thickness of the warmer layer in the eastern end of the dredged area seems to decrease from 1-2 m to about 0.5 m when the wind blows from the east, and there is an immediate thickening of the warm water lens if the wind shifts or abates. Hence, it still seems possible that if there is a prolonged or strong enough easterly wind there could be upwelling. In any case, it appears that there is good mixing of the waters in the Commercial Port area, with no stagnant water mass occurring in the bottom depths.

Chemical Observations!

Samples for analysis of dissolved oxygen have been taken at irregular intervals at the stations shown in Fig. 13. Results are presented in Table 7. All samples were taken during the daylight hours, and temperature was measured at the same time. For the stations in Piti Channel and adjacent areas only surface samples were taken. For the stations in the harbor, including the Commercial Port area, samples were taken at the surface, midwater, and bottom. In the Commercial Port area, the bottom depths range from 10 to 15 m, while at the two sampling stations outside the Commercial Port the bottom samples were taken at 30 m. The dissolved oxygen values at all stations usually matched or exceeded saturation values except for samples taken on 11 October

Table 7. Dissolved oxygen (mg liter^{-1}) at selected stations in Piti Channel and Apra Harbor. See Fig. 13 for station locations. Depths: S, surface; M, mid-depth; B, bottom. If no depth is indicated for a given station, samples were taken at the surface.

SAMPLING DATE

Station				1973				1974	
& Depth	27 Mar.	27 Jun.	6 Jul.	18 Sept.	11 Oct.	1 Nov.	4 Dec.	16 Jan.	5 Feb.
1 S			6.62	6.58	6.26				6.54
M			6.38	6.44	6.13				6.57
B			6.28	6.61	6.20				6.66
2 S			6.50	6.16	5.96	6.02	6.27	6.06	6.59
M			6.54	6.31	6.06				6.34
B			6.40	6.06	5.95				6.62
3 S				6.41	5.90				6.48
M				6.54	6.00				6.20
B				6.06	5.69				6.55
4 S	6.76	6.77		6.57	5.95			6.32	6.23
M	6.83	6.49		6.37	5.84				6.43
B	6.69	6.79		6.40	5.89				6.54
5 S		6.86							
M		6.51							
B		6.83							
6 S	6.97	6.74		6.46	5.98			6.27	
M	6.80	6.84		6.32	6.06				
B	6.73	6.63		6.31	5.54				
7 S		6.93							
M		6.79							
B		6.91							
8 S		6.69		6.30	5.90				6.08
M		6.88		6.40	5.96				6.09
B		6.87		6.42	5.79				6.41
9 S		6.59							
M		6.69							
B		6.68							
10 S	7.22					7.02	6.09	6.26	
B	6.80								
14						6.36	6.94	6.42	
17						6.79	6.36	6.64	
18						6.14	5.87	6.30	
19						6.05	6.12	6.59	
21						6.22	6.48	6.70	

Table 7. (Continued)

	SAMPLING DATE								
	1973							1974	
Station	27 Mar.	27 Jun.	6 Jul.	18 Sept.	11 Oct.	1 Nov.	4 Dec.	16 Jan.	5 Feb.
22						6.74	6.68	6.65	
23						6.80	6.86	6.76	
24						6.32	6.78	6.81	
25						6.62	6.72	6.81	
26						6.50	6.76	6.76	
27								6.91	
28								6.82	

1973. None of the samples taken on that date exceeded oxygen saturation values. The significance and reason for this are not clear to us. However, unlike the other sampling dates, the weather on 11 October was rainy and overcast, and it is possible that the light intensity was below the compensation intensity for phytoplankton photosynthesis, thus leading to a net oxygen demand rather than a net oxygen production by the phytoplankton community. This possibility can only be checked by further data collection. The fact that dissolved oxygen levels in the study area exceed saturation during sunny days indicates a generally healthy state, provided that the nighttime values do not fall too greatly. We must get additional nighttime data before a more definitive statement can be made.

On two occasions salinities were taken at scattered locations with a handheld refractometer and rounded to be nearest 0.5 part per thousand. Results are shown in Table 8. It can be seen that salinities in the study area are rather constant, as reported by Marsh and Gordon (1973). The range is from 33.0 to 34.5 ppt, with the exception of Station 18, which had a value of 33.5 ppt on 4 December 1973. This station is affected by a small stream which drains into the moat and thus brings in fresh water after a rain (Marsh and Gordon, 1973). Salinity is not affected by operations of the Piti Power Plant.

Samples for pH determinations were also taken on two occasions. Results are shown in Table 9. Values on the two dates ranged from 8.02 to 8.20 pH units, except for a value of 7.93 on 1 November 1973 at Station 24 (Fig. 13). This station is immediately adjacent to the temporary outfall where water pumped out of the excavation for the construction site enters the outfall lagoon. Again there is no evidence that plant operations affect pH in the outfall lagoon.

Samples for reactive phosphorous have also been taken. Results for two sampling dates are presented in Table 10. Values range from 0.08 to 0.50 micro-gram-atoms per liter. The lowest value was found at the locality where the Commercial Port area joins the outer harbor. The highest value was found at Station 25 (Fig. 13) on 14 Nov 1973. This is a station which is located adjacent to the point where the raw sewer from the Piti Power Plant enters the outfall lagoon. No doubt the level of dissolved phosphorous could be higher if there is a significant outflow from this sewer.

Samples for nitrite-nitrate analyses were taken on 16 January 1974. Nitrate values are shown in Table 11. All nitrite values were below detectable limits except for Station 18 (Fig. 13), which was affected by fresh-water runoff. Here the nitrite value was 0.20 µg-at liter^{-1}, and there was no detectable nitrate. Other nitrate values ranged from 0.14 to 0.45 µg-at liter^{-} except for a high value of 4.45 µg-at liter^{-1} at Station 21. The reason for this high value is unclear to us. No spatial pattern was obvious in the result and there was no evidence that plant operations were affecting levels of dissolved nitrite or nitrate in the area.

We are aware that we need additional sampling in the study area for pH, phosphate, and nitrite-nitrate analyses before we can make more definitive statements about natural conditions or the possible effect of plant operations.

Table 8. Salinity values (parts per thousand) at selected in Piti Channel and Apra Harbor. See Fig. 13 for station locations.

Station	SAMPLING DATE 27 November 1973	 4 December 1973
1		34.5
2	34.0	34.0
4		34.5
6		34.5
10	34.0	34.5
12		33.0
14	34.0	33.5
15		34.0
16		34.0
17	34.5	33.5
18	34.0	32.5
19	34.0	33.5
20		33.5
21	34.0	33.5
22	34.0	33.5
23	34.0	33.0
24	34.0	33.0
25	34.0	33.0
26	34.5	33.0
27		34.5
28		33.0

Table 9. Observed pH values at selected stations in Piti Channel and Apra Harbor. See Fig. 13 for station locations.

	SAMPLING DATE	
Station	1 November 1973	4 December 1973
1		8.07
2		8.10
4		8.05
6		8.18
10	8.10	
12		8.20
14	8.08	8.04
15		8.12
16		8.20
18	8.02	8.09
19	8.01	8.05
20		8.11
21	8.07	
22	8.08	8.00
23	8.10	8.10
24	7.93	8.18
27		8.22

Table 10. Reactive phosphorous (ug-at P $liter^{-1}$) at selected stations in Piti Channel and Apra Harbor. See Fig. 13 for station locations.

Station	SAMPLING DATE 14 November 1973	 4 December 1973
2	0.14	0.08
4		0.11
6		0.12
10	0.13	0.10
14	0.18	0.14
17	0.17	0.16
18	0.19	
19	0.24	
21	0.21	
22	0.20	
23	0.38	0.16
24	0.40	0.20
25	0.50	
26	0.20	0.16
27		0.14

Table 11. Reactive nitrate (ug-at N liter^{-1}) at selected stations in Piti Channel and Apra Harbor, 16 January 1974. See Fig. 13 for station locations.

Station	NO_3 -N-
2	0.16
10	0.18
17	0.14
18	Below detectable limit
19	0.45
21	4.45
23	0.18
24	0.35
25	0.40
26	0.30

Temperature and Solar Insolation

Additional temperature data are available from the continuously recording Minicorders since our last report. These recorders have been placed in the outfall lagoon at Station 26, at the mouth of Piti Channel (Station 10), and at a location near the future outfall of the Cabras Island Plant (Station 21). (See Fig. 13 for station locations.) The basic patterns that we have observed reinforce those reported last year and give us added confidence in our data.

At the outfall location (Station 26) there is a daily temperature cycle with a single broad peak usually (but not always) occurring in the afternoon or early evening hours and a single broad depression usually occurring after midnight or in the morning hours. Representative temperature records for this location are shown in Figure 14. The basic pattern was different from 27 August to 3 September 1973, when two temperature peaks and two depressions per 24-hour period were observed. As noted in our last report, the basic temperature in the outfall lagoon seems to follow the daily pattern of temperature in the intake water, reinforced by the daily pattern of plant loading. Thus, temperature of the intake water and the maximum plant load usually occur in the late afternoon or early evening hours, so a similar pattern in the outfall lagoon is not surprising. The extreme temperature fluctuation at this location is from 28.9 to 35.0°C, but the more usual fluctuation is from 30.0 to 33.0°C.

The daily temperature pattern recorded at Station 21 near the site of the future Cabras Island Plant outfall is similar to that in the present outfall lagoon, with a single broad peak in the late afternoon or early evening hours and a single broad dip after midnight or in the early morning hours. This similarity is not surprising since this station is only about 300 m downstream from the station described above. Representative recordings are given in Fig. 15. The maximum temperature fluctuation is from 28.5 to 34.0°C, and the more usual fluctuation is from 30.0 to 33.0°C.

Figure 16 shows representative recordings for Station 10, located at the mouth of Piti Channel. Unlike the other two recording stations, this station shows a daily pattern which has two temperature peaks and two dips per 24-hour period. As noted in our last report, this pattern seems to follow the tidal cycle, with the dips coming at high tides, when harbor waters flood into the westernmost portion of Piti Channel, and the peaks coming at low tides, when effluent waters from the power plant affect water temperatures all the way downstream to this location. The maximum temperature fluctuation is from 28.0 to 34.5°C, and the more usual fluctuation is from 30.0 to 33.0°C. We are not sure why the maximum observed temperature here exceeded the maximum observed temperature at Station 21 described above.

As reported previously (Marsh and Gordon, 1973), we are maintaining a pyrheliograph on the roof of the USO building near the study area to record the amount of solar energy striking a horizontal surface. This gives an upper limit of the amount of solar heat that can be absorbed by the waters in the study area. An identical pyrheliograph is also maintained on the roof of the University of Guam Science building in Mangilao for comparative purposes. Results (reported as 7-day averages) are shown in Fig. 17. There may be a slight seasonal trend in the data, with lower values occurring from August

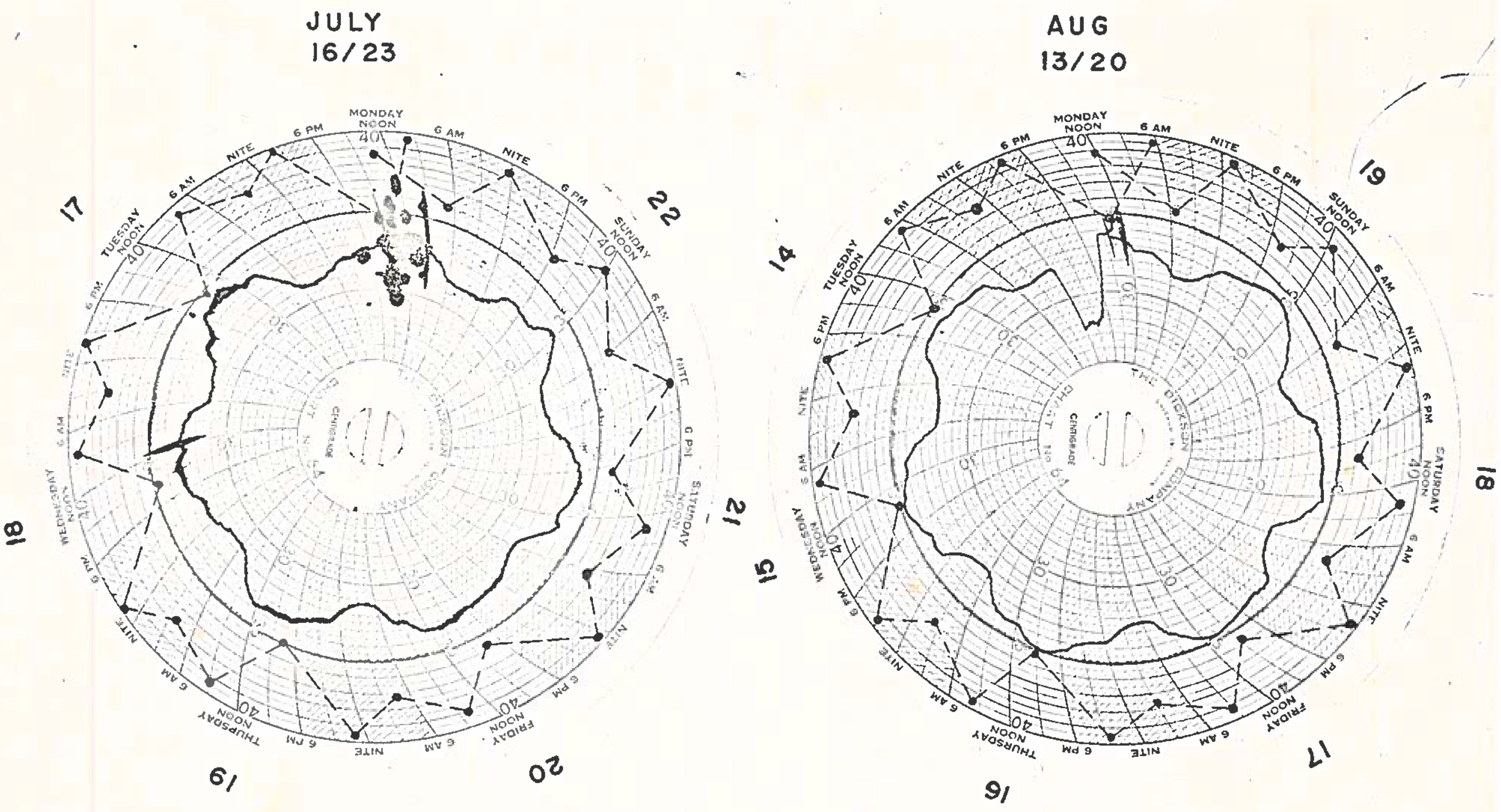

Figure 14. Sample temperature recordings for the outfall lagoon of the Piti Power Plant (Sta. 26, Fig. 13). The dashed lines indicate tidal fluctuations and were drawn by hand. The MLLW datum for the tidal records is also indicated.

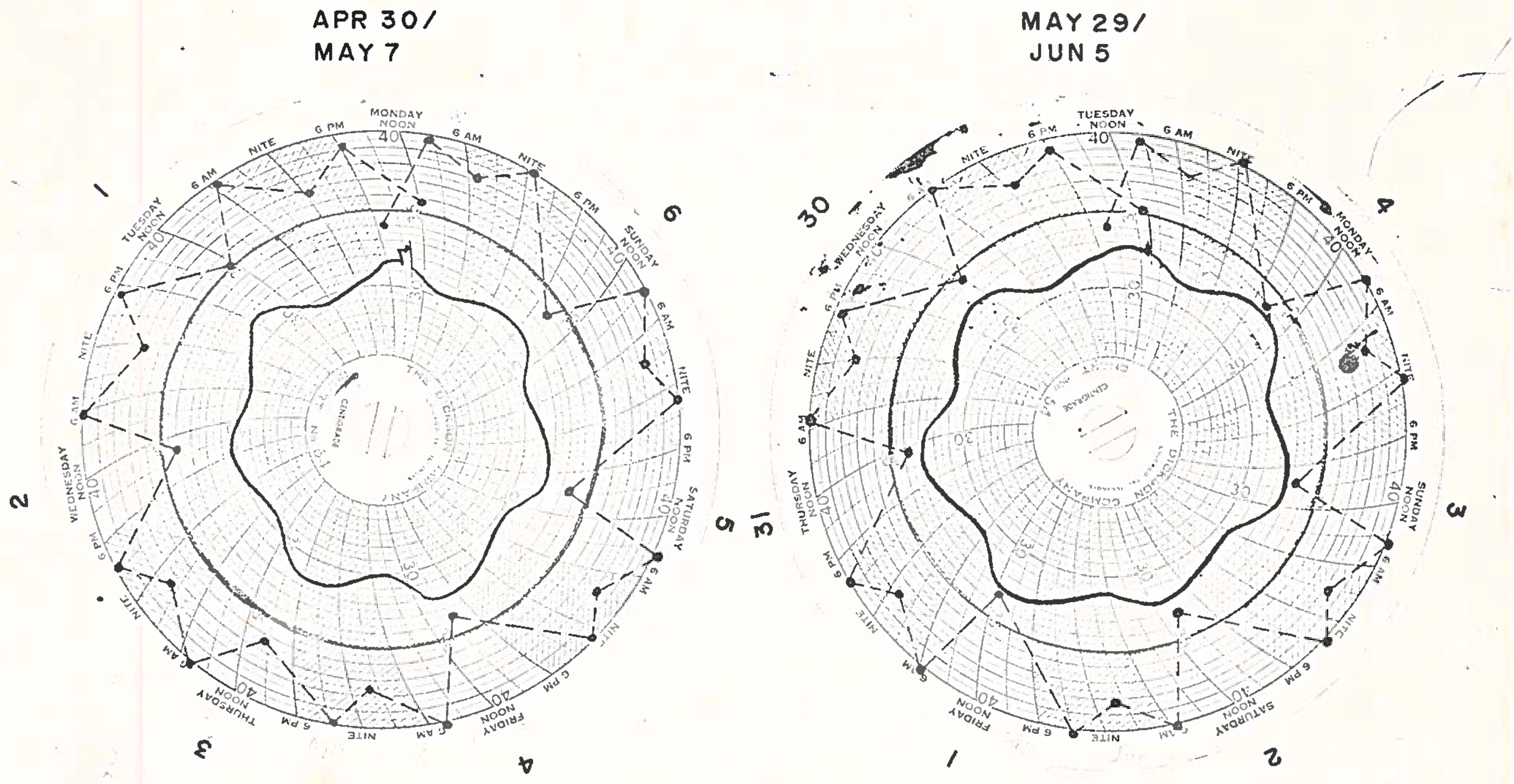

Figure 15. Sample temperature recordings for Sta. 21 (Fig. 13) near the site of the future Cabras Island Plant cooling-water outfall. The dashed lines indicate tidal fluctuations, and the MLLW datum is also indicated.

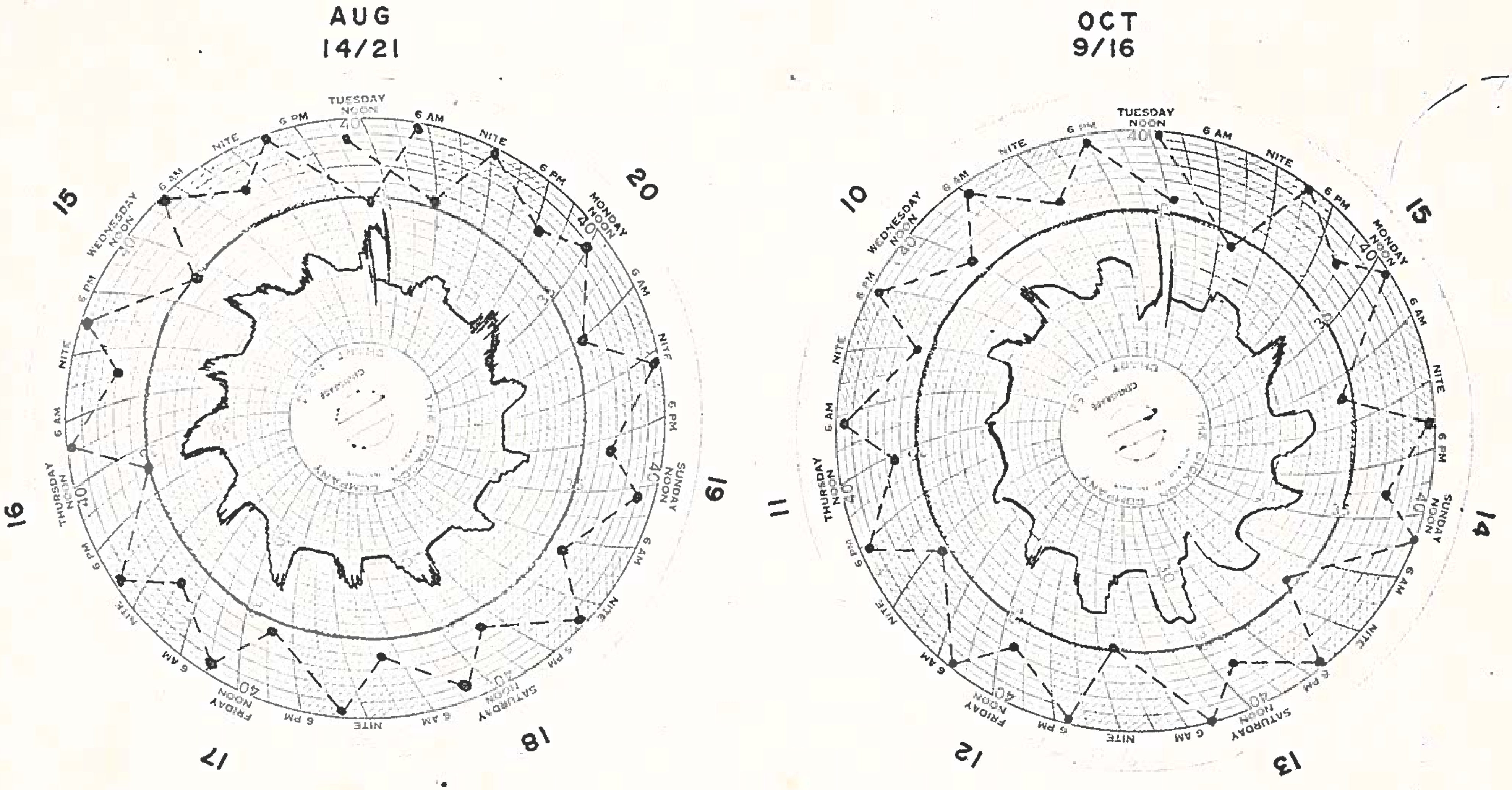

Figure 16. Sample temperature recordings for the mouth of Piti Channel (Sta. 10, Fig. 13). The dashed lines indicate tidal fluctuations, and the MLLW datum is also indicated.

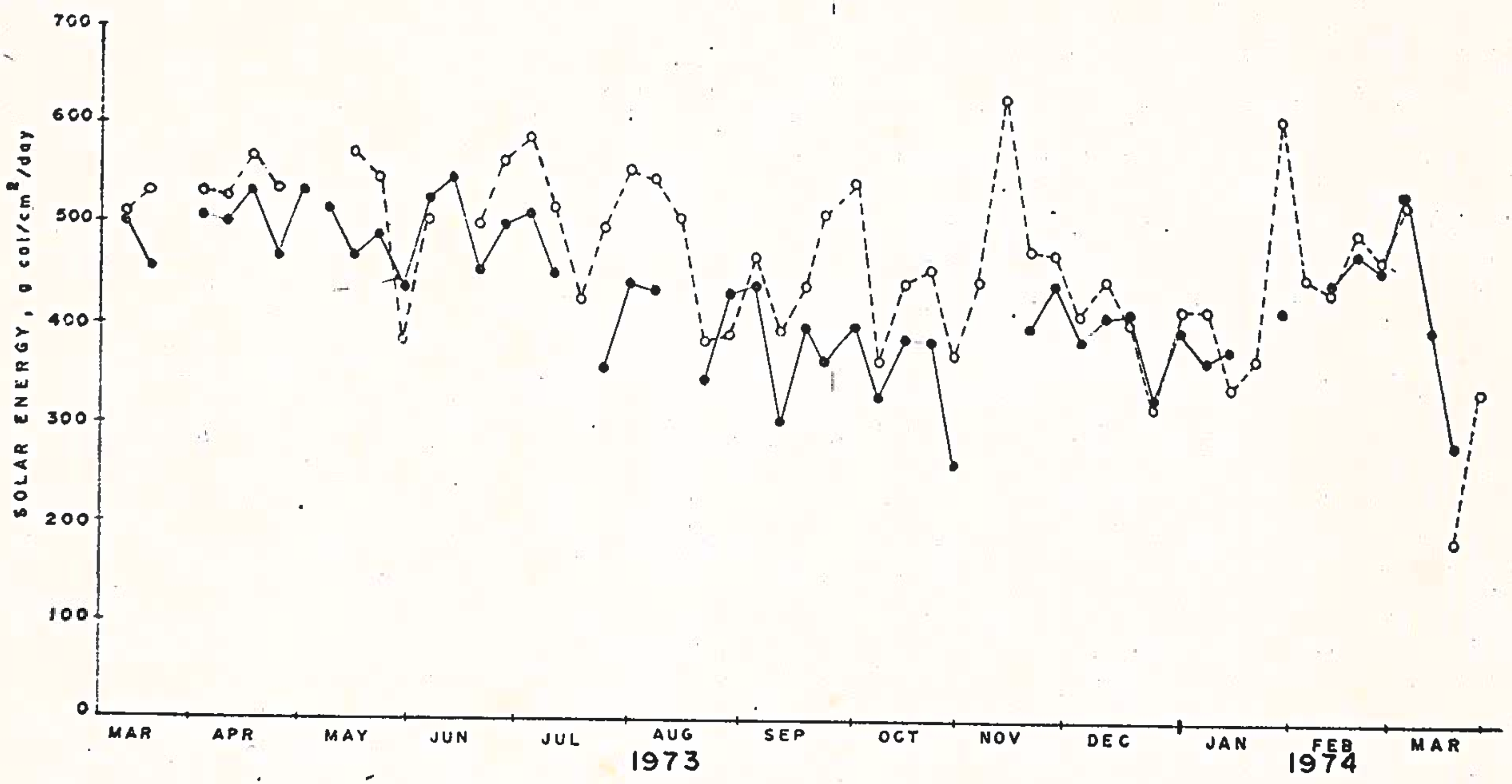

Figure 17. Pyrheliograph records for March 1973 through March 1974, The solid line and closed circles respresent a station on the roof of the USO building at Piti, Guam; and the broken line and open circles represent a station on the reof of the University of Guam Science Building at Mangilao. Most points represent the mean of seven daily observations, but a few points represent fewer than seven observations.

through January. However, variation from week to week is greater than any possible seasonal variation; and day-to-day variation (not apparent from Fig. 17) is also greater than seasonal variation. There is a tendency for values from the University of Guam Science Building to be higher than the USO values; this tendency was not apparent in last year's data.

SUMMARY

The major long-term environmental effect caused by the dredging and construction activities for the Cabras Island Power Plant has been the inadvertent damage to the coral community in the western end of Piti Bay. This was caused by a bulldozer crossing the reef flats well outside of prescribed operational limits. The damage could have been completely avoided without hampering the dredging of Tepungan Channel. About 25% of the live coral community was destroyed, and other biological communities on adjacent reef flats were also damaged. The coral community has now been replaced by an algae-echinoderm community similar to that in other reef flat areas of Piti Bay. The outlook for eventual restoration of the original coral community is uncertain.

Otherwise, the Piti reef flats which were disturbed by dredging in Tepungan Channel have returned more or less to their original state, at least in a qualitative sense, with an algae-echinoderm community being the characteristic one. Most of the fine silt deposited on the reef flats during dredging has now been swept away, and the substrate appears much as it did before. Large areas of reef flats not affected by dredging activities were subjected to a natural stress caused by a temporary lowering of mean sea level, with the resultant aerial exposure and dessication of biological communities.

The biological community in the newly enlarged channel itself is rather sparse, with a burrowing shrimp-goby association being the dominant form of macroscopic life. The bottom of the channel consists of fine silt and provides an unstable substrate not suited for the settlement of most benthic organisms. The sides of the channel partially consist of firmer rubble and have a greater variety of organisms.

Water turbidities on the Piti reef flats and in the USO swimming area increased by at least two orders of magnitude during dredging operations but have now returned more or less to normal. Waters in Tepungan Channel remain turbid and are likely to be that way for some time to come. A minor problem at the present time is the turbidity plume caused by the construction of the new culvert system through the Cabras Island causeway at the eastern end of the new arm of Tepungan Channel.

Water turbidity in Piti Channel continues to be high and is likely to remain so until construction is completed. Biological observations are difficult because of this turbidity, but we suspect that there are few macroscopic organisms there now. Daytime oxygen levels are usually at or above saturation throughout Piti Channel and the Commercial Port area. We have found no evidence that operations of the Piti Plant or construction activities for the Cabras Island Plant are affecting levels of dissolved oxygen, phosphorous, nitrite, nitrate, salinity, or pH in the outfall area.

RECOMMENDATIONS

1. Review the terms of the Corps of Engineers permit and the recommendations of our previous reports and insure that the contractor is abiding by these. Guam Power Authority should not give its contractor clearance on the final project completion or any portion thereof until it has assured itself that these terms have been met completely. If any conditions of the Corps of Engineers permit are found to be unworkable in the light of experience gained during construction of the Cabras Island Plant, then Guam Power Authority should apply for a waiver of such conditions before applying for an operational permit for the plant.

2. Guam Power Authority should take steps to insure that its contractor or subcontractors do not again cause unnecessary environmental damage such as occurred in the coral community in Piti Bay.

3. Particular attention should be given to our previous recommendation that the contractor be required to conduct a complete clean-up of all areas affected by construction activities. Clean-up of a particular area should be carried out as soon as activities are completed in that area. Marine areas adjacent to the construction site must not be regarded merely as a convenient dumping place for debris and construction wastes.

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