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WATER CIRCULATION ON TWO GUAM REEF FLATS

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ABSTRACT

Flourescein dye was used to trace water movements and to determine flow velocities and volume transports on two Guam fringing reef flats. Wave-driven water crossed most portions of the reef margin in a direction roughly perpendicular to the shoreline. As it moved across the reef flat it gradually changed direction until it was flowing as a longshore current in a deepened moat zone adjacent to the shoreline. After flowing in this longshore current for distances up to 1500 m, the water gradually moved seaward in a more dispersed pattern and exited the reef flat through major cuts in the reef margin. Smaller, more restricted portions of both reef flats had very sluggish water movements with less distinct patterns.

Of the total water volume crossing transects which extended perpendicularly from the shoreline, 10-100% flowed in the moat zone within 80 m of the shore. Flow velocities ranged up to 0.6 m sec^{-1}. Mean volume transport across entire transects was up to 61.6 m^3 sec^{-1}, and in the moat zone alone was up to 23.5 m^3 sec^{-1}. There was a significant correlation between surf and flow velocity, as well as between surf and volume transport in the moat, at all transects and tidal states tested in one bay; but the correlations were less conclusive in the other bay. Velocity was more strongly correlated with surf than was volume transport in the moat for most of the correlation analyses.

INTRODUCTION

Understanding water circulation patterns and water budgets on fringing reef flats is often a prerequisite to understanding other natural processes and human impacts. Such knowledge is also important if reef ecosystems are to be managed wisely. The development of water budgets allows for the development of nutrient budgets and an understanding of the processing of terrestrially derived sediments, dissolved pollutants, and freshwater runoff. It may also contribute to an understanding of the dynamics of plankton communities, notably the larval components of these communities, and the processing of detritus.

The reef flats of Guam are shallow and often have extensive areas subaerially exposed at low spring tides. Windward reef flats, as exemplified by Pago Bay, have somewhat higher elevations and larger areas subject to such exposure than do leeward reef flats, as exemplified by Tumon Bay. Both types of reef flats may be subdivided into outer reef flats, with low-tide exposure, and inner reef flats, which retain water at low tide. The deepest areas of both types are adjacent to the shoreline in a zone designated as the moat; the water depth here often approximates 0.5 m at low tide and 1.5m at high tide. Such reef physiography probably both influences and is influenced by water circulation patterns.

METHODS

The basic study method was to measure the velocity and flow direction of replicate patches of fluorescein dye released at intervals along transect lines. Two types of transects were set up: (1) those extending seaward from the shoreline in a direction roughly perpendicular to the shoreline (this was also roughly perpendicular to the reef margin in most cases), and (2) those extending along the reef margin generally parallel to the surf line. In both cases the volume of water transported perpendicularly across the transect was determined. For the first type of transect this was the volume of water moving from place to place on the reef flat in a generally longshore direction; for the second transect this was the volume of water moving unto the reef flat across the seaward margin or the volume of water moving seaward off the reef flat. The transects covered only portions of the total reef flat areas on any given day and hence did not result in a complete synoptic picture at a given time. However, during the course of the study, transects were laid out to cover all major areas at one time or another, many of these transects were repeated a number of times.

Along the study transects, dye-release points were generally spaced at 50-m intervals. They were closer together in the deeper moat area near the shoreline or near cuts in the reef margin where there

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were localized flow patterns. Each transect point was taken as representative of a wider transect segment centered on the point; most dye-release points represented 50-m segments of the transect. Volume transport across the entire transect was then taken as the sum of values for individual segments. All observations on a given transect were generally completed within 0.5 h, during which it was assumed that there was no significant tidal change.

Water flow on the reef margin was generally, perpendicular to the direction of the transects laid out there. Following the methodology discussed by Maragos (1978), volume transport across the transect) parallel to the direction of dye movement) was calculated as the product of velocity × cross-sectional area. The cross-sectional area was determined as height (water depth) × width, where the width was arbitrarily taken as a 1-m segment of the transect. Volume transport across a longer segment of the transect could then be obtained by multiplying the value for the 1-m segment by the appropriate length of the transect segment under consideration.

Water flow on the transects extending seaward from the shoreline was usually perpendicular to the transect in the areas near shore (the longshore current), but it progressively approached a shoreward flow parallel to the transect as the observers moved toward the reef margin. Hence, it was necessary to apply a vector analysis to calculate the volume transport perpendicular to the transect; this was, of course, lower than the total volume transport in the direction of the dye-patch movement. The first step in the vector analysis was to plot a baseline which was perpendicular to the sampling transect. This baseline formed an angle with the dye patch which was between 0 and 90°. The cosine of this angle thus varied from 1 to 0; when it was multiplied by the total volume transport in the direction of the dye patch, the resulting product was the volume transport perpendicular to the transect or parallel to the baseline.

At the times the transects were run, observations were made of wind velocity and direction and surf condition. Most observations were made under surf conditions ranging from non-existent to moderate; strong surf conditions are underrepresented in the data. The tidal state as predicted from tables for Apra Harbor, on the leeward side of Guam, was also recorded. Preliminary observations showed that the times of high and low tides in Tumon Bay, as well as the tidal range, approximately coincided with the predicted tides for Apra Harbor. In Pago Bay, on the eastern (windward) side of the island, the observed tidal range was similar to that predicted for Apra Harbor, but the times of high and low tides lagged behind the predicted by varying intervals up to 40 min.

RESULTS AND DISCUSSION

Figures 1 and 2 show generalized current patterns in the two bays. Surf-driven water moves across most portions of the reef margins and flows shoreward, gradually changing direction until it flows as a longshore current in the deepened moat area adjacent to the shorelines. The longshore current is usually northeastward in the central portion of Tumon Bay and southwestward in the central portion of Pago Bay, although reverse flows may occur on strongly rising tides. The longshore curent flows for up to 1500 m in Tumon Bay and up to 1200 m in Pago Bay before giving way to a more seaward flow that eventually leads to the excurrent channels. In Pago Bay the major excurrent flow is in the Pago River channel, along with entrained river water. In Tumon Bay the major excurrent flow is through San Vitores channel and across the adjacent reef margin. Less pronounced or intermittent excurrent flows also occur in smaller channels through the reef margins, these flows are strongest during periods of heavy surf and may be non-existent during periods of light surf. The northeast regions of both bays have more restricted water circulation cells. This is more pronounced in Tumon Bay, whose northeast end has essentially no surf-generated through-flow and where slow tidal exchange is the dominant factor.

Current speeds in Pago Bay ranged from 0 to 0.6 m sec^{-1}, both in the moat and on the reef margin. Most observations fell in the lower half of this range. Speeds in the Tumon Bay moat ranged up to 0.6 m sec^{-1} but were mostly less than 0.2 m sec^{-1}. Landward flows on the outer reef flats ranged up to 0.3 m sec^{-1} and seaward flows up to 0.5 m sec^{-1} in this bay. In the San Vitores channel, current speeds ranged up to 1 m sec^{-1} for flows either into or out of the bay. We could not work during periods of maximum surf but suspect that velocities may exceed 1 m sec^{-1} during such times. Maragos (1978) reported that a review of past studies showed current velocities commonly varying between 0 and 0.50 m sec^{-1} or more on reefs, values comparable to ours. He used a ducted current meter placed approximately 100 m behind the breaker zone at Enewetak Atoll to get continuous records of current velocity for 18 h and found that maximum velocities often exceeded 1.20 m sec^{-1}. This was comparable to Munk and Sargent's (1948) values of 1.10 m sec^{-1} at Bikini Atoll and higher than our maximum observed velocities on Guam's fringing reef flats. Our values are consistent with the general observations of Emery (1962) in Agana Bay, Guam. (See Maragos for additional references).

Table 1 shows mean volume transports across various transects extending from the shoreline to the outer reef flat, volume transports across the moat zones of those transects (i.e. volume

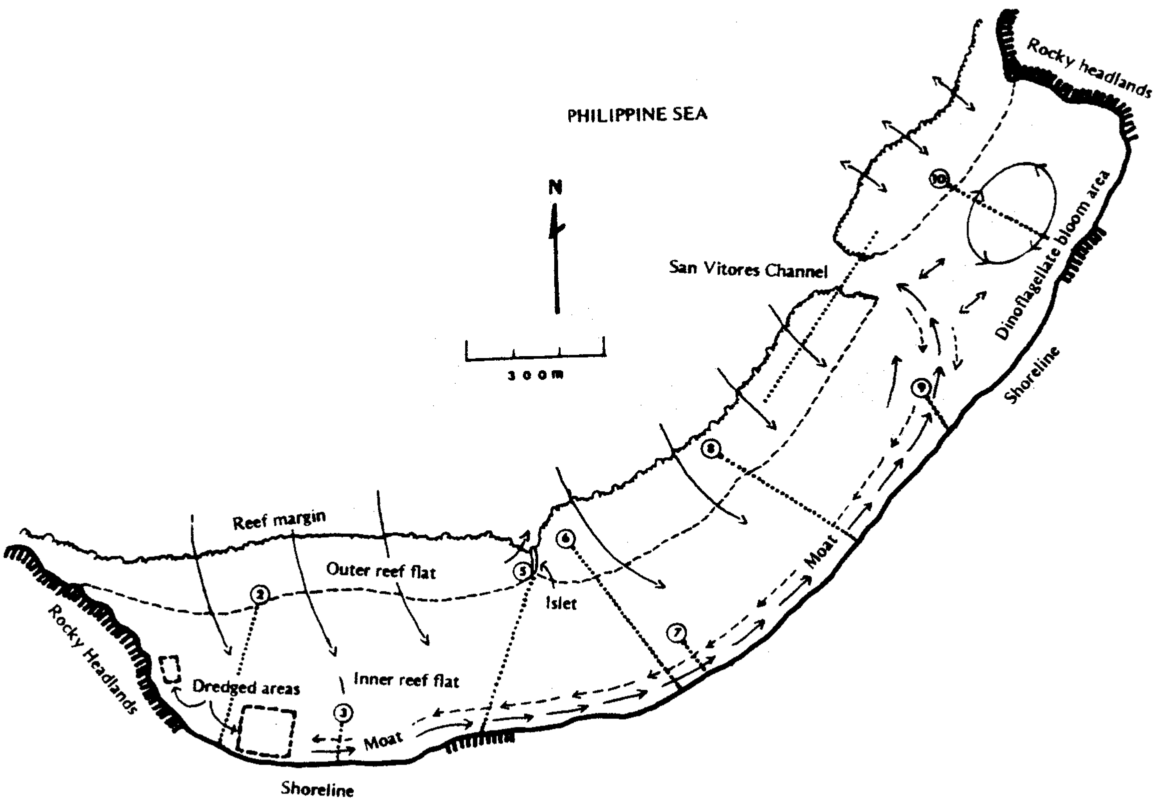

Figure 1. Tumon Bay, Guam. Solid arrows indicate water movement under usual flow conditions; dashed arrows indicate reverse flow on strongly rising tides. Circled numbers show study transects.

transports across the first 80 m of the transects adjacent to the shoreline), and the percentage of total flows accounted for by the longshore flows in the moats. The downstream (more southwestward) transects in Pago Bay were longer and had generally higher mean volume transports, but this was not the case in Tumon Bay. Besides volume transport values determined in the moats as part of longer transects, a number of additional observations were made in the moats alone; Table 2 presents the combined values of all moat observations.

Of the total volume transport crossing various transects extending out from the shoreline, 10-100% flowed in the moat zones within the first 80 m adjacent to shore. However, for repetitive observations on individual transects, the percentage was much less variable (Table 1). Volume transport in the moat zones of 3 central transects in Pago Bay was significantly correlated with that across the entire transects (r values exceeding 0.78), and there was a decrease in the percentage of total volume transport occurring in the moat for the wider downstream transects than across the narrower upstream transects. No such pattern was evident in Tumon Bay, where the length of the transects was more nearly constant.

On 12 occasions in each bay, time-series observations were conducted at moat stations to determine how current velocities or volume transports, or both, changed with the tidal cycle. No consistent picture emerged with respect to current velocities. Volume transports in the moats showed a much clearer response to tidal change in both bays. This can be seen in Table 3, which also shows different changes in volume transport with different surf conditions. With light surf or none at all, the furthest downstream station in each bay showed no consistent change with tide; this probably reflects the fact that these stations were subject to tidal flooding from inward flow in the channels that ordinarily served as excurrent areas.

Simultaneous volume transport observations in the moat were made for paired stations at tr, 1, 3, 4, or 6 in Pago Bay and 1, 3, 5, 7, 8, and 9 in Tumon Bay. Such simultaneous pairs were always highly significantly correlated for tr 3, 4, and 6 in Pago and tr 7, 8, and 9 in Tumon; other simultaneous pairs were not significantly correlated. Hence, strong

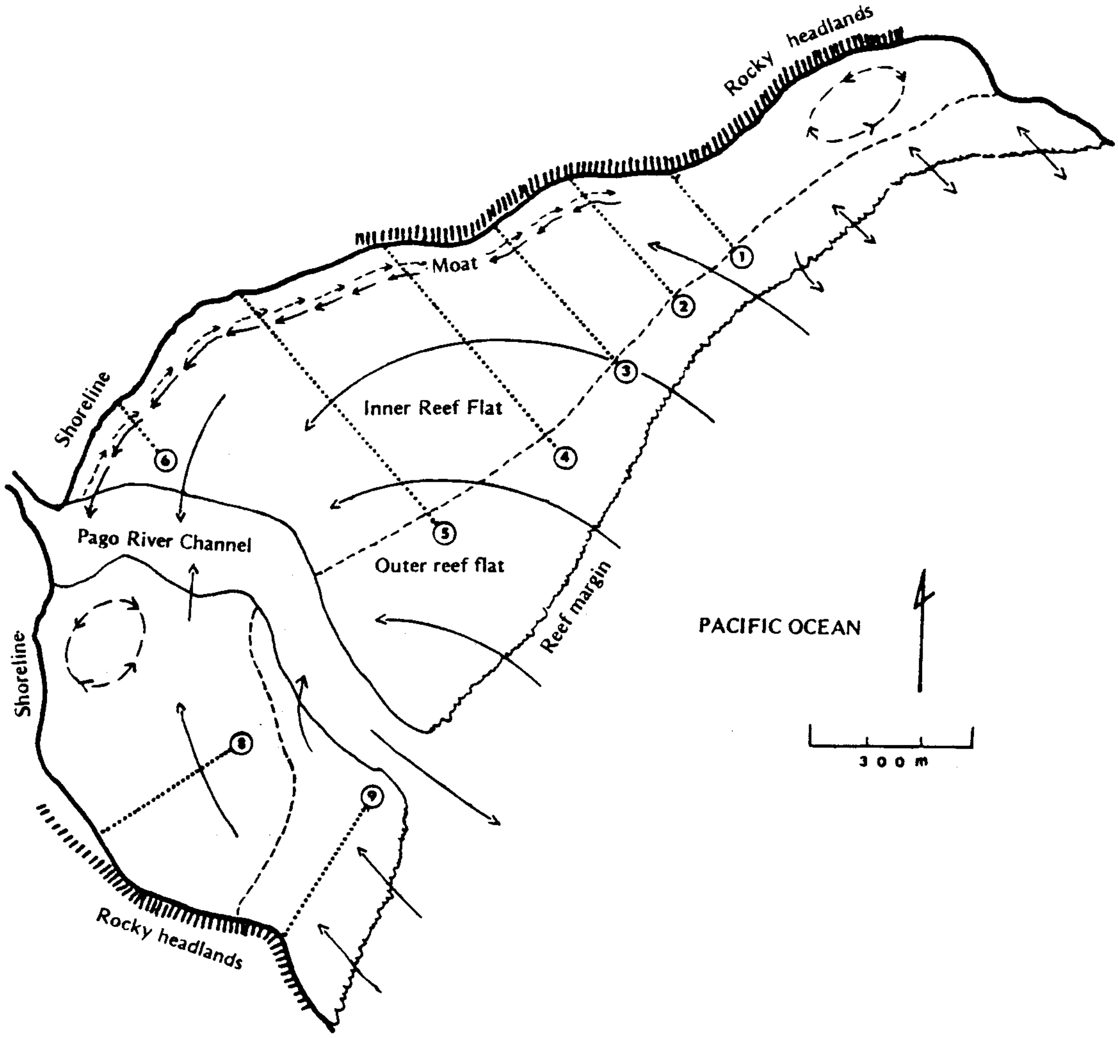

Figure 2. Pago Bay, Guam. Solid arrows indicate water movement under usual flow conditions; dashed arrows indicate reverse flow on strongly rising tides. Circled numbers show study transects.

upstream-downstream correlations were found only in the central regions of both bays. Furthermore, the downstream flow in the moat was less than the upstream flow for all but 6 of the 77 pairs tested (reverse flows not considered).

Reverse flows were observed in the moat zones of both bays on strongly rising tides, particularly with light surf. These extended as far southwestward as tr 5 in Tumon Bay and northeastward to tr 3 in Pago Bay. Reverse flows in the moats generally had much lower volume transports than the "normal" flows at the same locations (Table 2).

Correlation analyses were run to test for the relationship between surf height and flow velocity in the moats of both bays. This was done for high, intermediate, and low tides in Pago Bay but only for all water heights combined in Tumon Bay, where there were fewer observations. In Tumon Bay there was a significant correlation between surf and moat velocity at all three transects tested ($r = 0.849$ at tr 7, 0.931 at tr 8 and 0.856 at tr 9). In Pago Bay there were significant correlations at tr 3 ($r = 0.723$ at highest tidal levels, 0.855 at intermediate levels and 0.999 at lower levels) but not at tr 4 or tr 5 for any tidal states.

Partial correlation analyses were run to test for the relation between moat volume transport on one hand and either surf state or tidal height on the other hand. Volume transport was significantly correlated with both surf state and tidal height at all 3 transects in Pago Bay (r values of 0.630-0.876). In Tumon Bay volume transport was significantly cor-

Table 1. Volume transports across various transects extending from the shoreline to the outer reef flat, volume transports across only the moat sectors of those transects, and the percentage of total flow accounted for by longshore flow in the moats. Values given are means and standard deviations (in parentheses).

Transect	Length (m)	Volume Transport Entire tr.	Volume Transport Moat Only	% Transport in Moat	No. of Observ.
		Pago Bay			
2	310	22.5 (2.1)	9.6 (1.2)	42 (1.3)	2
3	310	53.1 (26.9)	23.5 (11.1)	45 (5.2)	6
4	520	52.7 (30.3)	9.3 (5.5)	19 (7.0)	9
5	660	61.6 (34.0)	7.3 (3.9)	12 (2.2)	4
8	300	30.0 (10.1)	9.2 (4.3)	30 (4.1)	5
9	200	33.3 (14.9)	19.8 (10.4)	58 (14.9)	5
		Tumon Bay			
2	320	18.1 (12.9)	7.2 (2.7)	47 (15)	3
5	360	25.1 (16.2)	9.1 (4.4)	42 (13)	5
5 (Reverse Flow)	120	-11.2 (9.4)	-7.6 (5.2)	74 (15)	2
6	370	20.8 (21.6)	7.7 (7.2)	37 (22)	4
6 (Reverse Flow)	320	-18.8 (1.7)	-11.2(0.4)	60 (8)	2
8	370	18.2 (18.6)	5.7 (5.2)	46 (29)	7
8 (Reverse Flow)	370	-25.5 (21.3)	-6.0 (4.8)	24 (1)	2

Table 2. Longshore volume transports across various transects in the moat sectors of Pago and Tumon Bays. All transects extended perpendicularly out from the shoreline for a distance of 80 m.

Transect	Mean	Standard Deviation	No. of Observ.	Transect	Mean	Standard Deviation	No. of Observ.
Pago Bay				Tumon Bay			
3	13.3	11.7	19	2	3.7	2.7	5
3 (Reverse Flow	-1.1	—	1	3	4.6	2.7	3
4	8.0	6.3	20	3 (No Flow)	-0-	—	1
4 (Reverse Flow	-0.4	—	1	5	7.6	3.9	8
4 (No Flow)	0	—	1	5 (Reverse Flow)	-7.0	3.8	3
5	7.3	3.9	4	5 (No Flow)	0	—	1
6	5.2	4.4	10	7	15.1	7.3	14
6 (Reverse Flow)	-0.73	0.85	3	8	15.0	15.0	26
6 (No Flow)	0	—	1	8 (Reverse Flow)	-6.0	-4.8	2
				9	7.5	6.7	14
				9 (Reverse Flow)	-1.0	0.15	2

related with both surf state and tidal height at tr 8 and 9 ($r = 0.527$-0.802), but with neither at tr 7. Velocity was more strongly correlated with surf than was moat volume transport in most of the correlation analyses. It is evident that the transect across the narrowest portion of the Pago reef flat (tr 3) showed a greater response to changes in both surf and tidal state than was the case with the longer transects in either Pago or Tumon Bays.

A limited number of observations were made of volume transport across the reef margin of Tumon Bay for a segment including San Vitores channel. Volume transport into the bay was ca. 49 m^3 sec^{-1} for a 460-m stretch of reef margin on one rising spring tide with no surf; inflows in the channel accounted for 3 m^3 sec^{-1} of this flow, an inflow similar to that observed for the channel on several other occasions. Outflow across this transect was measured on

Table 3. Changes in volume transports (m^3 sec^{-1}) across selected transects in the moat sectors of the two bays during falling or rising tides. Each value is based on a time series with at least six intermediate observations.

Date	Surf	Transect	Tidal Change (m)	Change in Volume Transport
		Pago Bay		
7 Aug 75	Heavy	4	-0.7	15 to 1
		—	+0.6	1 to 17
16 Dec 75	Moderate	3	-0.55	24 to 0.5
		4	-0.65	22 to 0.3
		6	-0.65	10 to 0
3 Jan 76	Light	3	+0.55	0 to 9*
		4	+0.6	0 to 7*
		6	+0.6	variable (0-8)*
		Tumon Bay		
29 Dec 75	Light	7	-0.6	17 to 5
		8	-0.6	14 to 4
		9	-9.6	6 to 1
27 Jan 76	Heavy	7	-0.7	69 to 19
		8	-0.6	50 to 15
		9	-0.7	24 to 4
¹1 May 76	None	7	-0.6	11 to 5
		8	-0.6	8 to 4
		9	-0.3	little change (<1)

*There was some reverse flow within 2 h after low tide before normal flow resumed.

3 falling spring tides with light or moderate surf and ranged from 50 to 64 m^3 sec^{-1} for a 525-m segment of the reef margin. Outflow in the channel was 3-10 m^3 sec^{-1} on 5 occasions but was not always as great as that for a section of reef margin of similar width (50 m) located 150 m west of the channel.

As previously noted, both bays have restricted circulation cells in their northeast sectors. In Tumon Bay this may allow for the development of dinoflagellate blooms at the beginning of the rainy season in years when there is a heavy runoff of terrestrially derived nutrients (Marsh 1977). The area of water retention at low spring tides is estimated to be 14×10^4 m^2, with a water depth of ca. 0.5 m at low spring tides and ca. 1.5 m at high spring tides. The tidal range on neap tides is 0.3-0.4 m. Assuming that all water movement is tidally driven and that there is complete mixing of water in this region on each tidal cycle, it can be calculated that the water turnover time is 3 days during spring tides and 6 days during neap tides. The maximum outflow actually measured in this region of the bay was 10 m^3 sec^{-1} on a falling spring tide with light surf; this would allow for a complete tidal volume to flow out of the bay in slightly less than 4 h. In contrast, the major portion of the bay could experience complete turnover (through-flow rather than tidal exchange) of the water volume several times during the tidal cycle, a situation which also prevails in Pago Bay. This is probably representative of fringing reef flats in general.

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