AN ABSTRACT OF THE THESIS OF Teina Rongo for the Master of Science in Biology presented November 22, 2004.

Title: Coral community change along a sediment gradient in Fouha Bay, Guam.

Approved: ______________________________

Robert H. Richmond, Chairman, Thesis Committee

Fouha Bay is a small, semi-elliptical bay about 400 m long, located on the southwest shore of Guam. The bay drains the La Sa Fua watershed, which is a small catchment with an area of 5 km^2 and composed of steeply sloping and highly erodible lateritic soils. Terrigenous sediments associated with runoff from heavy rain events correlated with coral community change within the bay, with the majority of sediments being deposited on the southern side of the bay channel. Moving Window Analysis (MWA) was used to examine shifts in coral community structure. The shift for the north into a more diverse community occurred at 70 m, which also represented the shift into the normal reef composition for southern Guam. A shift for the south into a more diverse community occurred at a distance of 100 m, while the shift into the normal reef of southern Guam occurred at 280 m. The sediment input into Fouha Bay was approximately 2515 tonnes/year, yielding 503 tonnes/km^2/year of sediment from the La Sa Fua catchment. Sedimentation rates ranged from 235 mg/cm^2/day at the river mouth to 10 mg/cm^2/day at the channel mouth. A model was derived from sedimentation data to estimate the quantity of sediments that are carried offshore by using three parameters: rain, wind, and waves. The model also indicated that 31% of sediments collected in traps placed in the inner part of the bay and 15% in the outer part were attributable to resuspension of previously deposited material. Based on daily sedimentation rates, the model calculated the distance over which sediment deposition (50 mg/cm^2/d) can adversely affect corals extends to 86 m offshore. This finding was consistent with the MWA results, which indicated a transition (100m) into a more diverse coral community. This study can be used as a reference for assessing the effectiveness of the proposed reforestation project for reducing soil erosion within the La Sa Fua watershed. Furthermore, managers can use the model as a tool on reefs within bays of similar characteristics for providing information about the status of a watershed so that better land-use practices can be implemented. Studying small bays such as Fouha Bay is practical and provides a basis for developing management plans to improve situations on small scales that can be implemented on larger scales as well.

Keywords: Sedimentation; Moving Window Analysis; Coral community change; Sediment load model; Guam.

TO THE OFFICE OF GRADUATE SCHOOL AND RESEARCH

The members of the Committee approve the thesis of Teina Rongo presented on November 22, 2004.

Robert Richmond, Chairman

Laurie Raymundo, Member

Mohammad Golabi, Member

Peter Schupp, Member

ACCEPTED:

Lee Yudin
Coordinator, Graduate Studies

May 6, 2005
Date

CORAL COMMUNITY CHANGE ALONG A SEDIMENT GRADIENT IN FOUHA BAY, GUAM

BY

TEINA RONGO

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

IN

BIOLOGY

UNIVERSITY OF GUAM

November 2004

ACKNOWLEDGEMENTS

This study was funded by the EPA Star Program and NOAA COP/CRES. I thank my committee members for all their assistance: Dr. Robert Richmond, Dr. Laurie Raymundo, Dr. Mohammad Golabi, and Dr. Peter Schupp. Special thanks to the following people for assisting me in various aspects of my study: Jackie Holbrook, Peter Houk, Dr. Eric Wolanski, Dr. Terry Donaldson, Barry Smith, Aja Reyes, Constantine Apimwyar, Wendy Mendiola, Jack Idechong, Elaine Pinder, and Dr. Veikila Vuki. Appreciation also goes out to the boat technicians Chris Bassler, Frankie Cushing, Jason Miller, Butch Irish and the secretaries Marie Peredo and Angela Duenas for their help. Lastly, thanks to John Jocson (WERI), Sonia Shjegstad, and Chie Takase for the photographs.

I thank my mother Tera-iti-rere-ki-avaiki Rongo and especially my father Ngatoko Rongo for unknowingly guiding me to an interest in Biology.

Special thanks to the following people: to Dr. Gustav Paulay who inspired me to pursue an education in Marine Biology, to Dr. Richmond for all the help and support that he has provided me, and to Dr. Rebecca Stephenson and Dr. Hiro Kurashina for being my parents here on Guam.

This thesis is dedicated to my three children O'Neal Isaia, Myria Moana, and Konini Rongo, who have been the inspiration and drive behind everything I do.

TABLE OF CONTENTS

TABLE OF CONTENTS (*Continued*)

PAGE

LIST OF TABLES

PAGE

LIST OF FIGURES

PAGE

LIST OF FIGURES (*Continued*)

PAGE

INTRODUCTION

Coral reefs are important structures for the protection of low-lying coastal areas from strong wave action and coastal erosion. Reefs also provide food, recreational opportunities, medicinal products, and are a major attraction for tourism industries (Richmond, 1993). With the increase of human activities over the years, coral reefs and coastal ecosystems around the world have been degraded (Wilkinson, 2000). Sedimentation and accompanying eutrophication are among the main threats affecting coastal coral reefs. It is clear that there has been an increase in terrigenous sediment from runoff into the marine environment over the past several decades in many areas (Birkeland, 1997). Depending on the type of human disturbance, rates of sediment loads entering the ocean from land-based erosion can increase by as much as 100-fold (Doolette and Magrath, 1990).

Sediments on coral reefs can be divided into two broad categories based on their sources: biogenic and terrigenous (Hallock, 1997). Biogenic sediments are composed predominantly of carbonates derived from the calcareous skeletons of a variety of marine animals and plants, and to a lesser extent, from siliceous skeletons of other taxa. Reef binders, such as microalgae and bacteria, can establish themselves on sediments, stabilizing them and thus contributing to reef growth (Hallock, 1997). Terrigenous sediments are mainly composed of materials derived from the physical, chemical and biological decomposition of rocks from land. Human activities are a major factor contributing to the increase in sediment in the marine environment. These activities include land clearing, road construction, development projects, dredging, and beach reclamation.

Without the impact of human activities, natural levels of suspended sediments on reefs are usually less than 5 mg/l, rarely exceeding 40 mg/l (Larcombe *et al.*, 1995); during tidal movements and storms (both of which re-suspend sediments) or terrestrial runoff due to heavy rains, suspended sediment levels can range from ≈ 20 - 200 mg/l (Gilmour, 1999). Biogenic sediments can also affect reef organisms. However, these organisms are generally adapted to continuous long–term patterns of production and distribution. With human activities such as dredging, biogenic sediments can have adverse effects on reef organisms. For example, dredging and filling destroyed a reef area of 440 ha at Johnston Atoll and resuspension of fine sediment particles affected an area six times greater (Brock *et al.*, 1996).

Terrigenous sediments, on the other hand, are damaging to reef organisms (especially reefs close to rivers) because the distribution of sediments is not uniform and entry of sediments into the marine environment occurs in pulses. Terrigenous sediments may also serve as carriers of pollutants from land-based sources (Fabricus, 2005). This is most often associated with periods of heavy rain. Terrigenous sedimentation levels that are anthropogenic can exceed 200 mg/l. For example, the vegetation burning and land clearing of La Sa Fua watershed, Guam, resulted in levels of suspended sediment exceeding 1000 mg/l during heavy rains (Wolanski *et al.*, 2003a).

An additional confounding factor results from other types of suspended materials, which include calcareous, fecal, and detrital particles. There is also a transparent exopolymer particle (mucus) produced by plankton, algae, and bacteria. The particles are sticky and are rapidly aggregated via flocculation forming what is called "marine snow". Marine snow flocs can exceed several centimeters in diameter, depending on wave activities. In comparison to wave-exposed areas, sheltered areas tend to have larger flocs (Wolanski *et al.*, 2003b). Increased prevalence of marine snow is enhanced by increased nutrients. On Guam, marine snow is common on the southwestern exposure of coastal areas. It can remain suspended for several hours. However, suspended fine clay from runoff can attach to marine snow forming "muddy marine snow," which sinks to the bottom at a faster rate. Muddy marine snow is detrimental to young corals; a study by Fabricus and Wolanski (2000) on the effect of muddy marine snow on corals indicated that the mortality rate is 10 times greater for young corals than for adult colonies.

High levels of sediments are deleterious to corals and other marine organisms. Sedimentation can significantly reduce larval survival and settlement (Gilmour, 1999). Since many corals have external fertilization and pelagic larval development, sedimentation is likely to affect larval recruitment on adjacent reefs as they pass through a sediment-impacted reef (Gilmour, 1999). Rogers (1990) predicted the following consequences for increased sedimentation rates over reefs: 1) lower species diversity; 2) reduced coral cover; 3) relative increases in corals that are highly tolerant to reduced light levels and sediment smothering; 4) smaller colonies favored because of their ability to better reject sediments; 5) slower coral growth rates; 6) higher survival of corals in shallower waters; 7) higher survival of branching corals than other growth forms; and 8) abundance of old colonies due to sediment limiting recruitment. West and Van Woesik (2001) indicated a shift in coral community structure with increasing distance from river mouths using Moving Window Analysis (MWA).

Wave action causes sediments to be re-suspended. Waves can be categorized into two broad groups: swells (generated by tropical storms and are generally large) and wind-generated waves (generally smaller). Understanding the wind conditions on certain coasts can provide information on how waves are generated and how they might affect sediment resuspension. Larcombe *et al.*, (1995) studied the effects of waves on suspended sediment concentrations (SSCs). In their study, swells exhibited long wavelengths with periods of > 7s, and wind-waves exhibited shorter wavelengths with periods of < 7s. Both wave types had an effect on SSCs at different depths. Waves with longer wavelengths suspended sediments both shallow and deep, while those with shorter wavelengths suspended sediments at shallow depths, with minimal effect on sediments in deeper water.

The major contributor to sediment load in coastal marine environments is runoff. Runoff from land depends on 1) watershed size and slope, 2) volume and intensity of rainfall, 3) soil condition, and 4) land use (Hubbard 1987). Embayments that have high sedimentation rates and reefs within, or in close proximity to, these areas can be badly degraded as a result. Thus, embayments can be used as natural laboratories for studying the effect of terrestrial runoff on reef systems.

The impact of sedimentation on coral reefs has been the subject of intensive research (see reviews in McManus *et al.*, 2000; Fortes, 2001; McCook *et al.*, 2001). To date, much of the research has focused on community changes on sediment-impacted reefs, but very little has been documented correlating the quantity of sediment found on reefs and its effect on coral community change. Sediment quantity is important because the ability of corals to shed sediments depends on the quantity and the duration of burial (see review in Rogers, 1990).

The reefs of southern Guam are impacted by high erosion and associated sediment deposition rates. The La Sa Fua watershed of the Umatac area deposits sediment into the adjoining bay (Fouha Bay; 13°18'N 144°39'E). Scheman *et al.* (2002) examined the erosion rate from badlands (large areas of exposed soil) within the La Sa Fua watershed, finding that the average erosion rates ranged from 480 to 1200 tons km^{-2} $year^{-1}$. Erosion falls into two categories: geological and accelerated erosion; the latter is due to land clearing, crop cultivation and burning of vegetation. Burning is one of the most common causes of erosion on Guam, used by southern villagers to clear areas for easier deer and pig hunting, as these animals are attracted to new vegetation growth falling burn-off. Burning leaves soil uncovered and subject to severe erosion during heavy rain events. On average, the annual rainfall of Umatac is 2.5 m. The dry season extends from December to June, while the wet season usually lasts from July through November. August to October are the wettest months, with a mean rainfall of 35 cm $month^{-1}$ (Wolanski *et al.*, 2003a).

The La Sa Fua watershed has a catchment area of 5 km^2, and is steep and composed of geologically volcanic and highly erodible lateritic soils (Wolanski *et al.*, 2003a). Fouha Bay (see Figure 1), on the southwest shore of Guam, is a small semi-elliptical bay about 400 m long. A funnel-shaped channel runs from the river mouth to the ocean in the middle of the bay. The river mouth enters the ocean on the south side of the channel. Depth within the bay varies from < 1 m on the reef flat to 3 - 11 m in the channel.

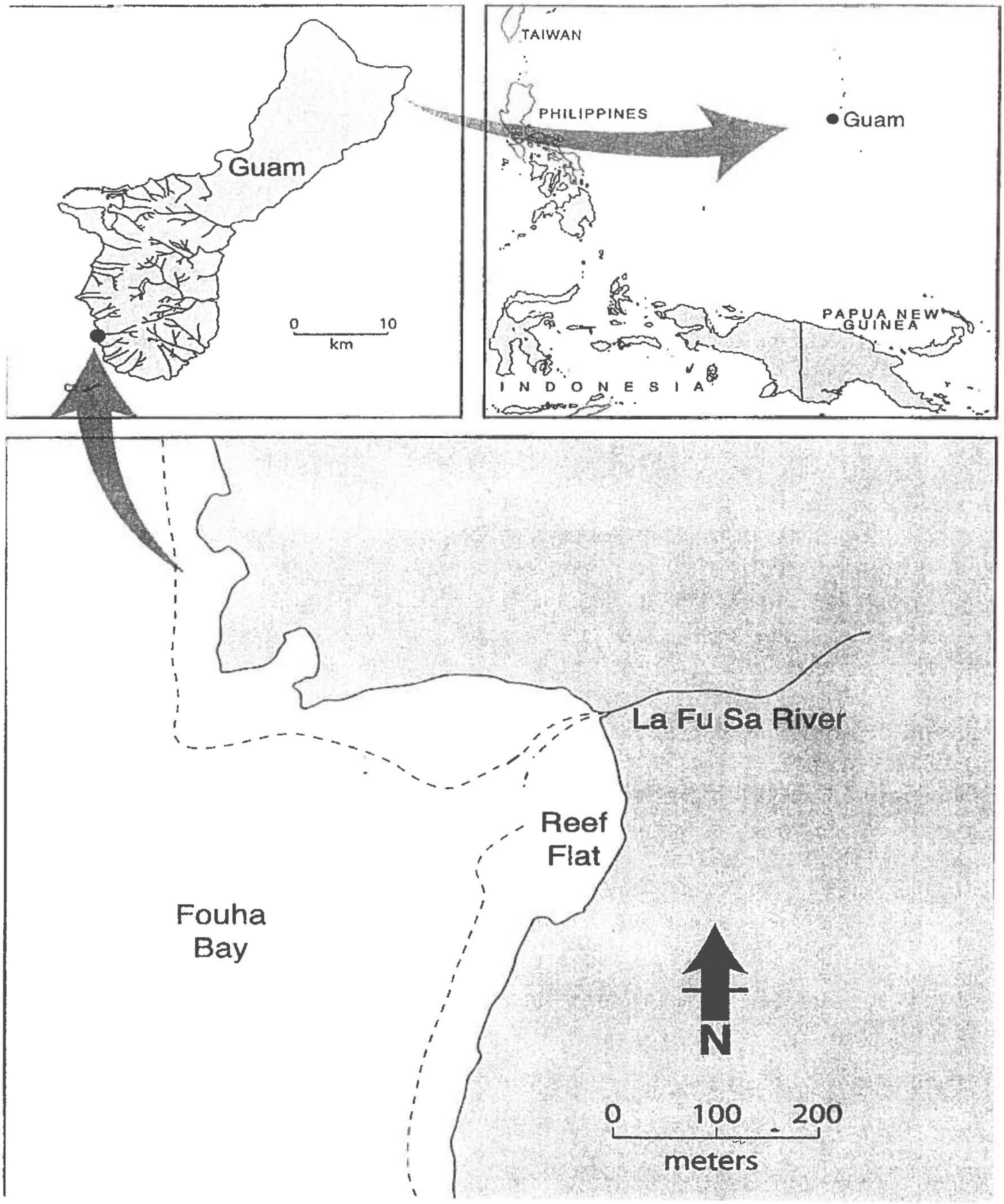

Figure 1. Fouha Bay, southwest side of Guam (13°18'N 144°39'E). Figure taken from Wolanski *et al.*, 2003a.

During 1988 a road was constructed within the watershed to access Fouha Bay. This resulted in a high sediment load into the bay, which buried and killed many corals from 1988–1990 (Richmond, 1993). Prior to this event, Birkeland and Randall (1978) examined the natural gradient of suspended sediment load and coral community structure from the mouth to the head of the bay. They found that sediment from soil erosion discharges in pulses associated with periods of heavy rainfall. The sedimentation rate ranged from 237 $mg/cm^2/day$ near the river mouth to 21 $mg/cm^2/day$ near the bay mouth. They also indicated that along with the fresh water discharge, terrigenous sediment was a major contributing factor to the near absence of corals at the inner part of the bay.

Wolanski *et al.* (2003a) examined the suspended sediment concentration (SSC) in Fouha Bay and reported that it exceeded 1,000 mg l^{-1} in 2001, especially during periods with strong wave action or during pulses of heavy rain. Furthermore, 75% of the terrigenous sediment was trapped within the bay, though quantities flushed out during periods of wave swell from the south. Their study estimated the annual sedimentation rate for Fouha Bay to be 1.8×10^6 kg $year^{-1}$. On average, there are 10 floods per year that contribute large sediment loads that are retained within the bay, while flushing occurs only about 2-5 times per year by storm- driven swells.

This study quantified the deposition of sediment from the La Sa Fua watershed into Fouha Bay, and the distribution pattern along a gradient from the river mouth. This study also examined how coral community structure changed along the sediment gradient. A model was then derived based on the sediment data to predict sediment load and effects on this reef. Basic objectives included:

1. To examine the relationship between rainfall and sediment load.
2. To compare sediment load between the north and south side of the channel.
3. To compare sediment load and distribution among stations along the gradient from the river mouth.
4. To compare sediment load near the bottom and near the surface in the water column within the bay channel.
5. To characterize coral community structure with increasing distance from the river mouth.
6. To derive a model predicting sedimentation rate and load with increasing distance from the river mouth within Fouha Bay.

The following hypotheses were tested:

H_0 sediment load is not correlated with rainfall.
H_1 sediment load is correlated with rainfall.

H_0 sediment load does not vary between north and south sides of the channel.
H_1 sediment load varies between north and south sides of the channel.

H_0 sediment load does not vary among stations.
H_1 sediment load varies among stations.

H_0 sediment load does not vary with depth.
H_1 sediment load varies with depth.

H_0 coral community structure does not change with increasing distance from the river mouth.
H_1 coral community structure changes with increasing distance from the river mouth.

The study was divided into three areas covering sediment load, coral community changes, and the sediment load model. This study can be used for assessing the effectiveness of the proposed reforestation project (for reducing soil erosion) within the La Sa Fua watershed. Furthermore, managers can use the model as a tool for determining the impact of land-based activities on coastal areas so that better land-use practices can be implemented.

MATERIALS AND METHODS

SEDIMENTS

Sediment trap deployment

Twelve sediment trap stations were established within Fouha Bay, along the main channel traversing the reef (see Figure 2). Five were located along the north side of the channel margin (F1N, F2N, F3N, F4N, & F5N; yellow crosses), and five along the south side (F1S, F2S, F3S, F4S, & F5S; red crosses). These were spread roughly equidistant from each other from the river mouth seaward following the reef crest. Two were located at deeper sites (F3SD & F4ND; white crosses), at the bottom of the channel, directly below their respective shallow stations (F3S & F4N). GPS coordinates were taken for all stations (see Appendix A).

Sediment traps were constructed from Schedule-40 PVC tubes (2.4-cm diameter) cut to 40-cm lengths. Four tubes cable-tied together were deployed at each trapping station. A rubber stopper sealed the bottom of each tube, and the tubes were then fastened to a steel rebar hammered into the reef (see Figure 3). Traps were deployed at 1 to 2.5 m at low tide with the exception of the following stations: F3SD (~5 m) and F4ND (~7 m). Unlike Randall and Birkeland's (1978) study where traps were deployed near the channel bottom, this study used shallow depths because corals were abundant in shallower areas. Furthermore, Wolanski *et al.* (2003a) noted that the plume during floods of calm days at Fouha Bay floats near the surface in a band of a meter or less thick.

The majority of the sediment traps were deployed on January 17, 2003. Traps at stations F3SD, F4ND, & F5S were deployed on February 7. Most sediment samples were collected weekly. Sampling ended in December 27, 2003.

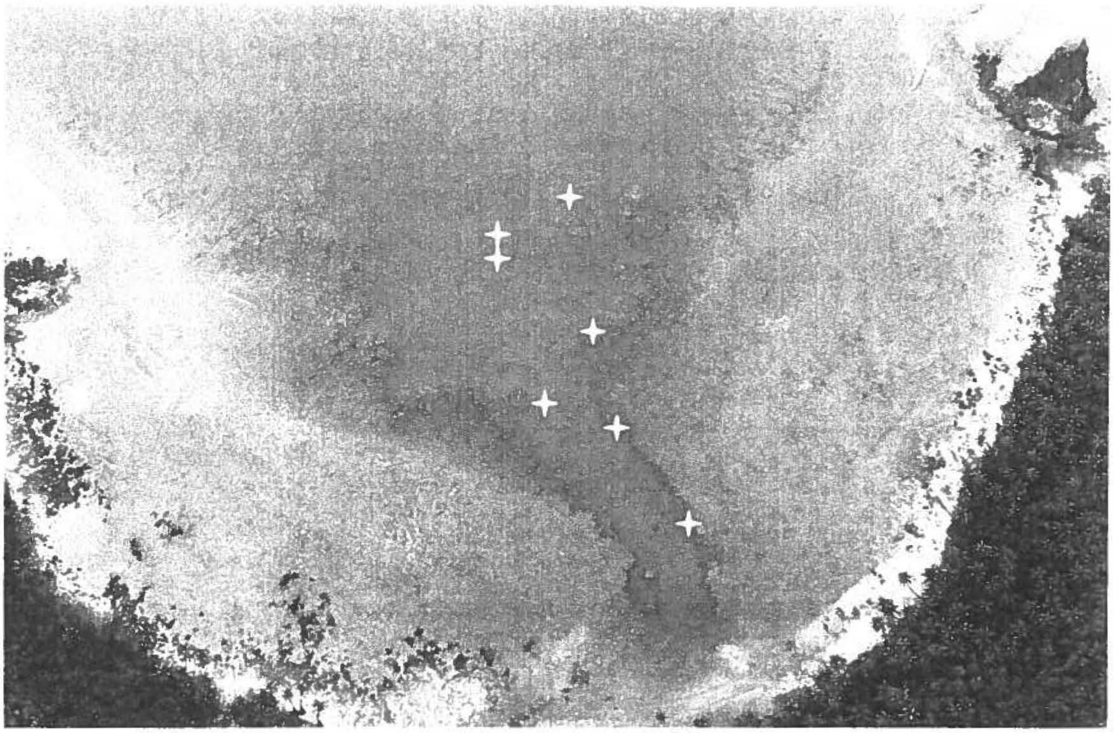

Figure 2. Sediment trap stations in Fouha Bay. Yellow indicates the northern stations, red indicates the southern stations, and white the deep stations.

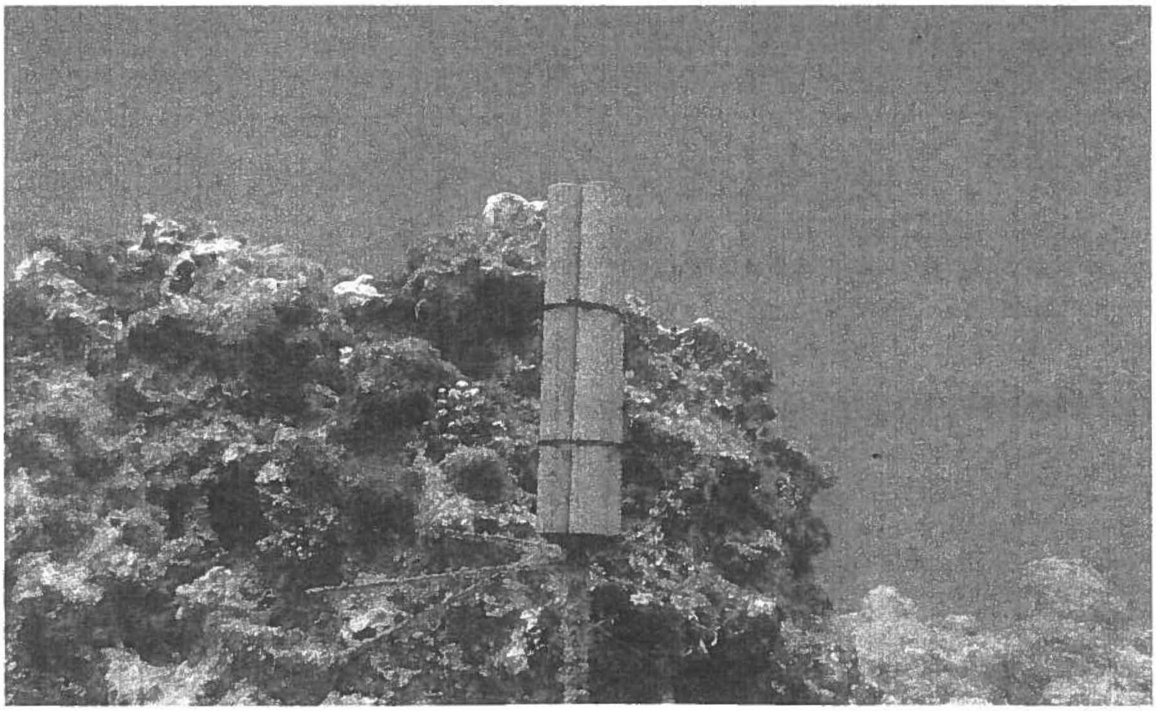

Figure 3. Sediment trap station containing four PVC pipes fastened to a rebar stake.

The distance from the river mouth to each station was measured using a meter-transect tape. The following are the distances between each station from the source station (F1S) near the river mouth: 20 m (F1N), 31 m (F2S), 39 m (F2N), 45 m (F3S), 74 m (F3N), 105 m (F4S), 117 m (F4N), 135 m (F5S), and 137 m (F5N). F1S was used as the source station because of its close proximity to the river mouth, and data suggested that this station has the highest sediment load.

Processing of sediment

Generally, sediments from all four tubes per station were used unless tubes contained animals (gastropods, fish, etc.) during the collecting period. Sediment samples were washed with fresh water in plastic cups, and then allowed to sit for 24 hours for fine sediments to settle. The water was decanted, and similar washing cycles continued for 2-4 days to remove salts. During decanting the water removed was poured through a 0.02 mm sieve and any sediment collected was rinsed back into the sample. After these washes, the samples were oven dried at 60 °C. After four days the samples were weighed to the nearest microgram using an electronic balance (UHAUS, TS120). A correction factor was applied for data from weeks where the scheduled collection dates were missed. A correction factor $7/x$ was multiplied to the dry weight of samples (7 being the number of days of the week and x the number of days before collection). The average of the replicates from each trapping station was used for all analyses.

Rainfall data

Daily rainfall data were provided by the United States Geological Survey (USGS) from their established rain gauge within the La Sa Fua Watershed, located approximately

1 km upstream from the bay. The measurements were given in inches, and these were converted to millimeters for the analysis (see Appendix B).

Data analysis

Sediment load from all stations

Annual observed sediment load (raw data) from all stations was plotted against the distance of each station from F1S. Analysis of Variance (ANOVA) was used to test for differences between desired comparisons. All analyses required data to be transformed to in order to meet the assumptions of ANOVA. Two transformations used in analyses were log-transformation and square-root transformation. Analyses only used data from collection periods with traps recovered from all stations.

Correlation between rainfall and sediment load

Linear-regression analysis was carried out to test for a correlation between rainfall and sediment load for each station. Only the sediment data from periods with rainfall greater than 20 mm were included in this analysis. A preliminary correlation performed at F1S using 20 mm as the minimum limit provided the strongest correlation ($r^2 = 0.6355$, $p < 0.01$). Rainfall less than 20 mm was not sufficient to deliver sediments into the bay. Sediment data from collection periods with recorded typhoon or swell events were included because heavy rain events occurred during these times.

Comparison of North and South

The inner stations of the north (F1N and F2N) and south (F1S and F2S) were pooled for their respective sides to increase sample size, because an initial ANOVA indicated no significant difference between stations on each side (see Appendix C and D). The outer stations of the north (F3N, F4N and F5N) and south (F3S, F4S and F5S) were also pooled on their respective sides to increase sample size, because an initial ANOVA indicated no significant difference between stations on each side as well (see Appendix E and F). A One-Way ANOVA was then used to examine the difference between North and South for both groups.

Sediment load among stations

A One-Way ANOVA Pairwise comparisons and Box-and-Whisker plots were used to examine differences between stations for each side of the channel. The analysis only included collection periods where all traps from F1 – F5 were retrieved; data from periods with missing traps were not included.

Differences between shallow and deep stations

Analyses between shallow and deep stations compared the following pairs of sediment traps: F3S & F3SD and F4N & F4ND. A further test was included to examine differences between the two shallow stations (F3S & F4N) as well as the two deep stations (F3SD & F4SD). One-Way ANOVA was carried out for all comparisons, and Box-and-Whisker plots were used to graphically compare data sets.

CORAL COMMUNITY CHANGE

Coral survey

One 50-m transect was placed following the reef contour along the reef edge starting from the first station (F1S or F1N) near the river mouth at depths ranging from one to two meters. The transect was laid 6 times, covering a total of 300 m on each side of the bay. A 1- m^2 quadrat frame was tossed haphazardly every 5 m along the transect for a total of 60 quadrats for the entire length of the surveyed reef. The analysis of coral communities was carried out along the 300-m transects of both sides.

A reference site was selected to represent the reef community outside the bay area. The site was located about 555 m away from the end of the northern transect, and 250 m away from the end of the southern transect. A 100-m transect line was deployed at the reference site, recording a total of 20 quadrats at 5-m intervals. Also, due to observations of coral community structure to the north lacking similar characteristics to that of the reference site, another 100 m was added for additional testing.

Corals were identified to the species level when possible and surface area within a quadrat was obtained by measuring the maximum length and width (perpendicular to length) along the general contour of each colony. A coral was only included in the quadrat if at least half of the colony fell within the edges of the quadrat frame. This method examines the reef as a three-dimensional structure, therefore corals in cracks and crevices were recorded and total surface area occupied by colonies could, therefore occupy an area greater than 1 m^2. From this survey, data on coral cover (m^2), species richness (species per quadrat), and population density (colonies per quadrat) were obtained.

Moving Window Analysis

Moving window analysis (MWA), a scaling technique adapted from landscape ecology to reef systems by West and Van Woesik (2001), was utilized to determine over what distance the effects of river discharge influenced reef communities. MWA uses a community dissimilarity measure (Bray-Curtis dissimilarity) between adjacent analysis windows to locate the distance over which benthic community change occurs. The Bray-Curtis distance between two samples *j* and *k* is calculated using Eq. 1:

$$D_{jk} = \sum_{i=1}^{p} \frac{|(Y_{ij} - Y_{ik})|}{(Y_{ij} + Y_{ik})} \qquad (1)$$

p represents a coral group (genus or species); Y_{ij} represents the entry in the *i*th group in the *j*th quadrat; and Y_{ik} represents the entry of the *i*th group in the *k*th quadrat. The Bray-Curtis dissimilarity between two quadrats is the absolute summation of the difference between two quadrats along the group axis divided by the summation of all groups within the two quadrats.

Data analysis

After testing to see which groupings would best demonstrate community change, corals were grouped at the genus level. However, genera with one species were grouped at the species level (i.e. *Acanthastrea echinata, Leptastrea purpurea, Leptoria phrygia, Montastrea curta, Stylocoeniella armata, Stylophora mordax*). The genus *Porites* was separated into three groups based on its observed distribution from the river mouth: 1) *P.*

lutea, *P. lobata*, and *P. australiensis* (common to the inner part of the bay), 2) *P. annae* and *P. rus* (common to middle part of the bay), and 3) *P. vaughani* (common to the outer part of the bay).

Data were log-transformed and converted to percentages for analysis. A similarity matrix was created to compare adjacent windows based upon percentages of coral cover. A 100% dissimilarity measure indicates two very different communities adjacent to each other, thus delineating a boundary between dissimilar coral communities. Quadrats were assigned to a "zone" based upon a large spike in dissimilarity. These zones were then subjected to an analysis of similarity (ANOSIM) based upon community composition (Clarke and Warwick, 1994), to test whether these boundaries represent significant community changes. Zone 1 for both North and South was devoid of coral, thus were excluded from analyses. Five quadrats were randomly selected from each zone for ANOSIM. To avoid an edge effect (Fernández *et al.*, 2002), quadrats near transition areas were not included in the random selection. ANOSIM was also carried out to determine how the zone furthest from shore on each side compared to the reference site.

The results of ANOSIM generated R values that provided a confidence limit on the degree of community similarity: 0 (similar) to 1 (different). Communities are well-separated if the R values are greater than 0.75; communities overlap but are clearly different at R values less than 0.75 but greater than 0.5; communities overlap if R values are greater than 0.25 but less than 0.5; and communities are similar if R values are less than 0.25 (Clarke and Warwick, 1994).

Similarity Percentages-Species Contributions (SIMPER) were carried out for zones on both sides of the bay to see which coral groups contribute to differences between adjacent zones. Fifty percent was the cut-off value implemented for the cumulative percentage of corals contributing to the differences.

MODEL

Based on sediment data collected in this study, a model was derived to predict sediment load for Fouha Bay. Though there may be several parameters influencing load inputs into the bay, only three were used for the model: rainfall, wind direction, and waves (swells). Parameters are discussed below.

Rainfall data

The total rainfall for each collection period was calculated for the model. For the source of these data, see *Sediments* section.

Wind data

Wind direction is important because an onshore wind generates waves, which can cause sediment resuspension (Larcombe *et al.*, 1995), while an offshore wind has minimal effect on resuspension. Two data sets were used for the wind: strength in km/hr and direction in decimal degrees. These data sets were provided by the National Weather Service Forecast Office, Tiyan, Guam: www.prh.noaa.gov/guam/climate.html.

For the purpose of this model, the wind directions were put into two groups: onshore and offshore winds. Based on the exposure of Fouha Bay, onshore winds included those with directions >161° and <339°. Winds that fall outside this sector were considered offshore (see Figure 4). To calculate wind direction, the following equation was applied (Eq. 2):

(2) Wind direction = WS· cos [2π (WD – 250)/360]

WD = observed wind direction; WS = observed wind strength

Eq. 2 generated positive and negative values. Positive values were identified as onshore winds and negative values as offshore (Figure 4). The value entered into the model equation was wind strength (WS). The WS for onshore winds were entered unchanged into the model equations. The WS of offshore winds were entered as zero, as it was assumed that they had no effect on sediments.

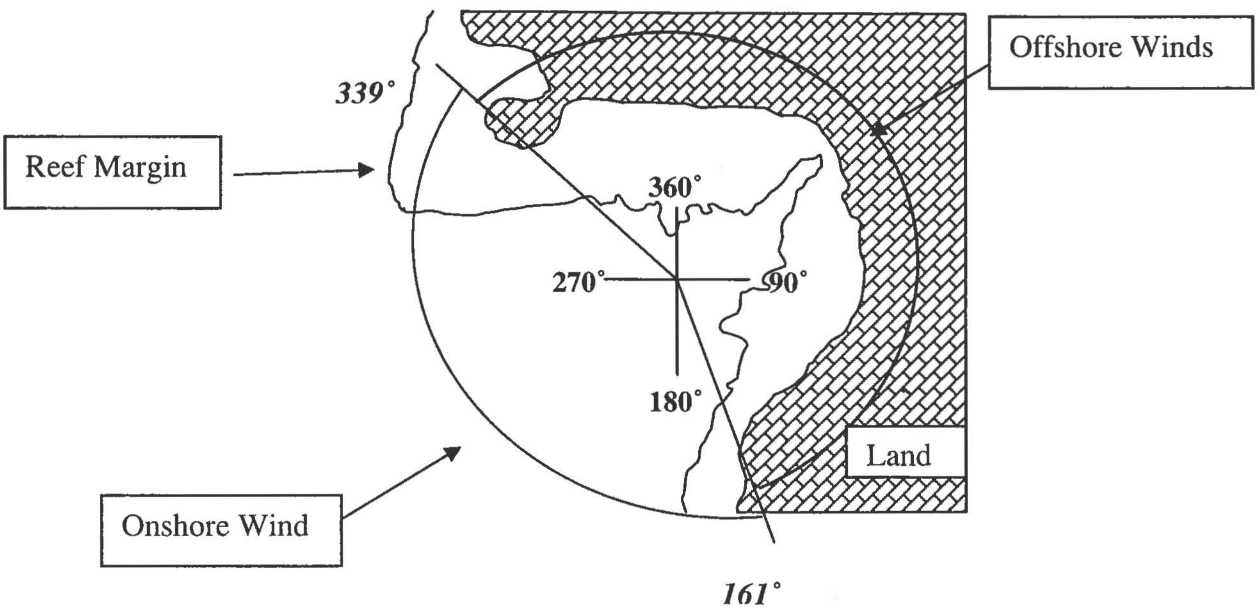

Figure 4. Diagram of wind selection.

Wave data

Wave height data in the model were used to indicate the condition of the sea (rough or calm). Daily wave data for 2003 were provided by National Weather Service Forecast Office, Tiyan, Guam, taken from the only two observation sites for southern Guam: Apra Harbor and Merizo Pier (these are observed data as no wave gauges are deployed on the west side of Guam). Apra Harbor is located about 16 km north of Fouha Bay, and Merizo Pier is about 5 km south of the bay. Compared to Apra Harbor, Merizo Pier provided a better estimation of water conditions at Fouha Bay due to their close proximity and similar exposure. On days where there were no data taken at Merizo Pier, data from Apra Harbor were used.

Waves were put into two categories based on the water condition (rough or calm) for the week of each collection period. Rough conditions are periods with days having big swells (>1.5 m). This distinction was made because data suggest that sediment load due to resuspension increases during rough conditions (Kruskal-Wallis Multiple-Comparison Z-Value Test, $Z = 3.5565$; see Appendix G). Sediment data for this analysis were taken from deep stations F3SD and F4ND, which were combined and separated with regard to their respective water conditions. Data from the two stations were combined because they were not significantly different (see Sediment results section: *Sediment load between shallow and deep station*). Therefore, for the purpose of the model, "1" was assigned to rough and "0" to calm conditions.

Model

The model is based on the assumption that the sediment collected in the traps (whether from runoff or resuspension) is the result of one of two types of events: stationary or non-stationary. The stationary model (SM) assumes that sediment load of a particular week depends on events occurring that same week. In contrast, the non-stationary model (NSM) is dependent on events from the week prior. For example, if in two consecutive weeks heavy rain was reported, the first week would have higher sediment load than the following week because of the assumption that most loose sediments will be washed off by the rain of the first week. Similarly, if in a particular week big swells are observed (in which case sediments are re-suspended and washed out), one can predict a low sediment load in the week to follow because there will be less sediment to re-suspend. These two models are discussed separately below.

Stationary model

The SM consists of three equations: Eq. 3, 4, and 5. The equations are as follows:

(3) $\text{IF } (R_{obs} > R_{lim}, k_{r1} (R_{obs}) + k_w (W_{obs})), \text{ IF } (R_{obs} < R_{lim}, k_{r2} (R_{obs}) + k_w (W_{obs}))$

(4) $\text{IF } (SI = 0, \text{Eq. } 3), \text{ IF } (SI > 0, k (\text{Eq. } 3))$

(5) $\text{IF } [W_{obs} > W_{lim}, k (\text{Eq. } 4), \text{ IF } (W_{obs} < W_{lim}, \text{Eq. } 4)$

Key: R_{obs} (observed rainfall), R_{lim} (rainfall with some limit), k_{r1} (first rain constant), k_w (wind constant), W_{obs} (observed wind), k_{r2} (second rain constant), SI (swell index), k (constant), W_s (strong wind), W_{lim} (wind with some limit).

Eq. 3 predicts that a certain amount of rainfall is required to deliver sediments to the reef via runoff. This equation incorporates a limit to the observed rainfall data (R_{lim}). For this model, the minimum limit of 80 mm was implemented because the model aims to detect sediments from heavy rain events, predicting how far offshore they are delivered. These heavy rain events are important to the model because they deliver a large amount of sediment into the bay in a short time period, potentially threatening the reef community. The wind constant k_w was the same for both parts of the equation, but changed at each station as distance offshore increased.

Based on the findings of Wolanski *et al.* (2003a), where most runoff sediments in Fouha Bay deposit at the channel bottom, the model makes two assumptions: 1) sediments are uniformly distributed within the channel, and 2) the effect of wind on sediment resuspension decreases as depth increases away from shore. Therefore, increasing distance from shore decreases k_w values at each station.

Eq. 4 is a continuation of Eq. 3, except rough conditions due to swells are added. This equation states that when swells are equal to zero, the sediment load due to resuspension will remain as predicted by Eq. 3. However, when swells are greater than zero, the sediment load predicted should be higher. Thus, the sediment load predicted by Eq. 3 will be multiplied by a constant (k) greater than one.

Eq. 5 continues from Eq. 4, with the addition of strong winds. Studies have indicated that wind-generated waves re-suspend sediment (Larcombe *et al.*, 1995). Winds greater than 37 km/h generate surface chop (Stafford-Smith, 1993; Delaney, 2004; Bassler, personal communication.). Eq. 5 predicts that onshore winds greater than 37 km/h can cause an increase in sediment load predicted by Eq. 4. Thus, if onshore winds were greater than 37 km/h, the predicted load from Eq. 4 will be multiplied by a constant greater than one. However if winds were less than 37 km/h, then the predicted load remains the same as in Eq. 4.

Non-stationary model

The NSM consists of three equations: Eq. 6, 7, and 8. These equations are as follows:

(6) IF ($R_{i-1} > R_{lim}$, k_{r1} (R_i) + k_w (W_i)), IF ($R_{i-1} < R_{lim}$, k_{r2} (R_i) + k_w (W_i))

(7) IF ($SI_{i-1} = 0$, (Eq. 6), IF ($SI_{i-1} > 0$, k (Eq. 6)

(8) IF [$W_{i-1} > W_{lim}$, (Eq. 7), IF ($W_{i-1} < W_{lim}$, k (Eq. 7)]

Key: R_{i-1} (previous observed rainfall data), R_{lim} (rainfall with some limit), k_{r1} (first rain constant), R_i (current observed rain data), k_w (wind constant), W_i (current observed wind data), k_{r2} (second rain constant), SI_{i-1} (previous observed swell index), k (constant), W_{i-1} (previous observed wind data), W_{lim} (wind with some limit).

Eq. 6 has two parts: the first part states that if the rainfall data of the previous week was greater than the minimum limit of rainfall (80 mm) then the predicted sediment load for the current week will be the product of k_{r1} (first rain constant) and R_i (current observed rain data) added to the product of k_w (wind constant) and W_i (current observed wind data).

The second part of the equation states that if rainfall of the previous week was less than the limit of 80 mm, then the predicted sediment load for the current week will be the product of the second rain constant k_{r2} (which will be greater than k_{r1}) and R_i

(current observed rain data) added to the product of k_w (wind constant) and W_i (current observed wind data).

Eq. 7 is a continuation of Eq. 6, except the swell effect from the previous week is added (SI_{i-1}). The equation consists of two parts: the first part states that if SI_{i-1} is zero, then sediments from the previous week will be available for resuspension during the current week. Thus, the sediment load from Eq. 6 will be increased by some factor (k) greater than one. The second part states that if SI_{i-1} is greater than zero, then sediment load due to resuspension will remain as predicted by Eq. 6.

Eq. 8 continues from Eq. 7 with the addition of strong winds. This equation states that if onshore winds from the previous week (W_{i-1}) were greater than 37 km/h then the sediment load of the current week will remain as in Eq. 7. However, if W_{i-1} was less than 37 km/h, then the result of Eq. 7 will be multiplied by a constant (k) greater than one.

Data analysis

Determining the preferred model

The selection for the best-fit model (SM or NSM) was performed by examining correlations between the observed and model sediment loads for both models. Because data indicated that sediment load deposits more towards the south of Fouha Bay (see *Sediments* results: Figure 6), correlations between model and observed sediment loads from stations F1S and F2S were used for better model estimates. These stations were used in analyses because of their close proximity to the river mouth, thus yielding better load estimates from runoff sediment.

Using the preferred model, correlation matrices were performed for all southern stations. Collection periods with missing data were excluded from analyses.

Sediment load decay model

After determining the preferred model (SM or NSM), the results of that model were then incorporated into a sediment load decay model (see Eq. 9) as constant *A*.

$$(9) \qquad \text{Sediment load decay} = (A)e^{r(d)}$$

Key: *A* (sediment load constant; calculated from SM or NSM), *e* (base of the natural logarithm), *r* (rate of decay; negative value), *d* (distance in meters).

Sediment load decays exponentially at a rate with increasing distance from shore (refer to *Sediments* results, Figure 6). To obtain the rate of decay (*r*), the best-fit equation to the plot between the annual sediment loads for each southern station versus their relative distance to F1S was computed.

Eq. 9 has distance in meters as a variable. Distance is an important variable because it allows the model to predict how far offshore sediments are delivered from the source station, especially during heavy rain events.

Estimating annual sediment load

Annual sediment load (tonnes/year) was calculated in two steps based on observed sedimentation rates (g/cm^2/year converted to tonnes/km^2/year) of southern stations by: 1) multiplying the rate for each station to its respective area in the bay (see Figure 5), and 2) adding together the loads obtained in Step 1. Each respective area was obtained using an IKONOS photograph of Fouha Bay in ArcView GIS.

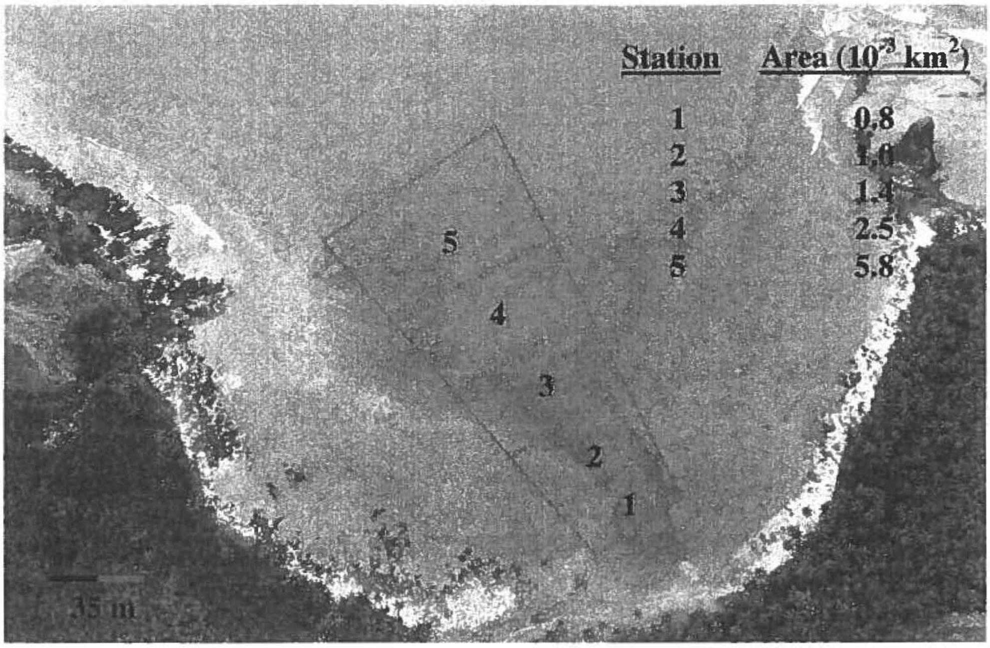

Figure 5. Area of Fouha Bay affected by sedimentation. Photo taken by John Jocson (University of Guam Water and Energy Research Institute).

Estimating resuspension using the model

The model was able to estimate the ratio of runoff to resuspension. Data were taken from collection periods with rain (greater than 20 mm), onshore winds, and big swells. Since wind and waves cause resuspension, these parameters were factored out of the equation by setting their values to zero. Thus, the resulting load would be from runoff sediment only. The ratio can then be obtained by looking at the difference between loads before and after setting the parameters to zero.

RESULTS

SEDIMENTS

Sediment load from all stations

Figure 6 suggests that sediments were deposited more to the southern side of Fouha Bay channel. Furthermore, the observed sediment load to the south suggests an exponential decay of load as distance offshore increases.

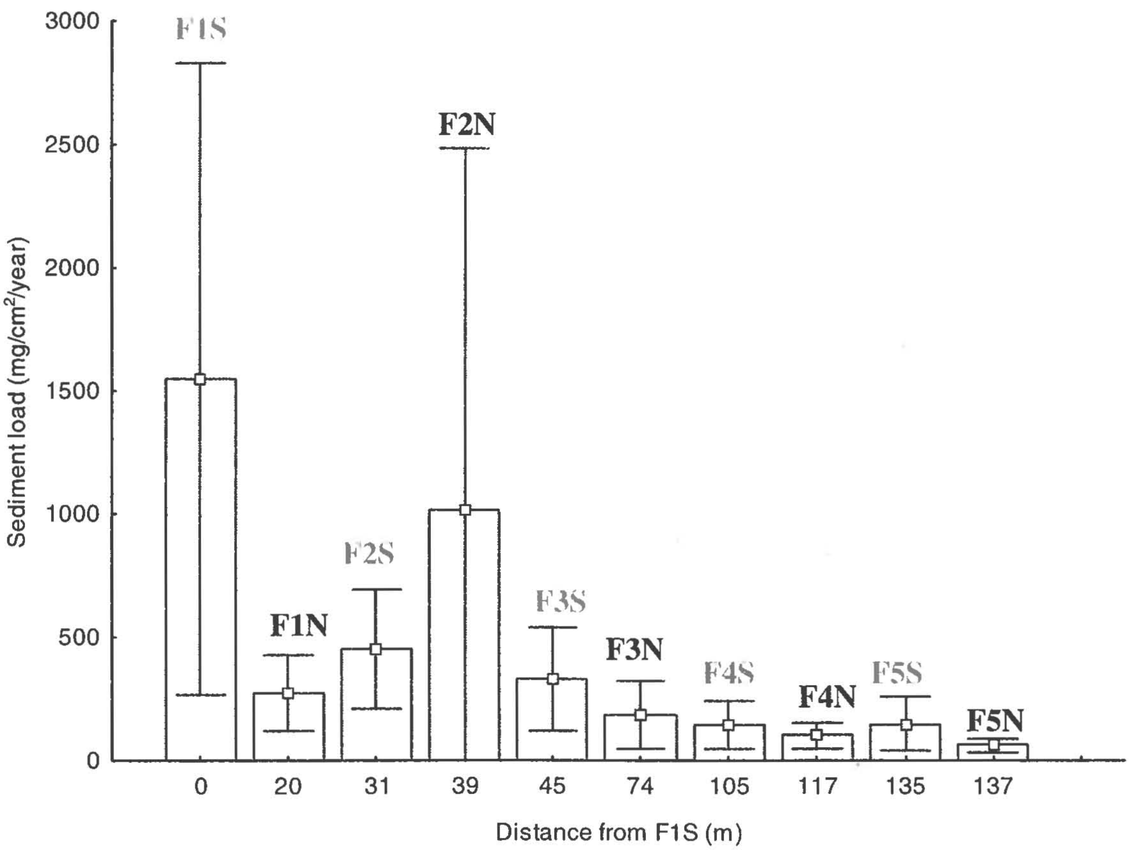

Figure 6. Annual observed sediment load from all stations. Sample size was 34 for each station to the north and 33 for each station to the south.

Correlation between sediment load and rainfall

The correlations between sediment load and rainfall indicated that all were significant for all stations. The correlation to the south was stronger, with r-squared values ranging from 0.5490 – 0.7341 (see Table 1). At the northern stations, the correlations were poor for sediment stations F2N ($r^2 = 0.2088$) and F4N ($r^2 = 0.2169$).

Table 1. Correlations between rainfall (> 20 mm) and sediment load for all stations.

Station	r-squared value	Sample size
F1N	0.69	21
F2N	0.21	20
F3N	0.69	25
F4N	0.22	26
F5N	0.52	22
F1S	0.64	24
F2S	0.72	25
F3S	0.73	25
F4S	0.57	25
F5S	0.55	23

Comparison of North and South

A comparison of the inner stations between North and South indicated no significant difference (One-Way ANOVA, $F_{1,138} = 1.3528$, $p = 0.2468$; see Appendix H). However, the trend suggests that much of the sediment is deposited to the south (see Figure 7).

A comparison of the outer stations between North and South indicated no significant difference (One-Way ANOVA, $F_{1,184} = 0.9796$, $p = 0.3236$; see Appendix I). Figure 8 shows a similar trend for the inner stations, where sediments deposit more to the south.

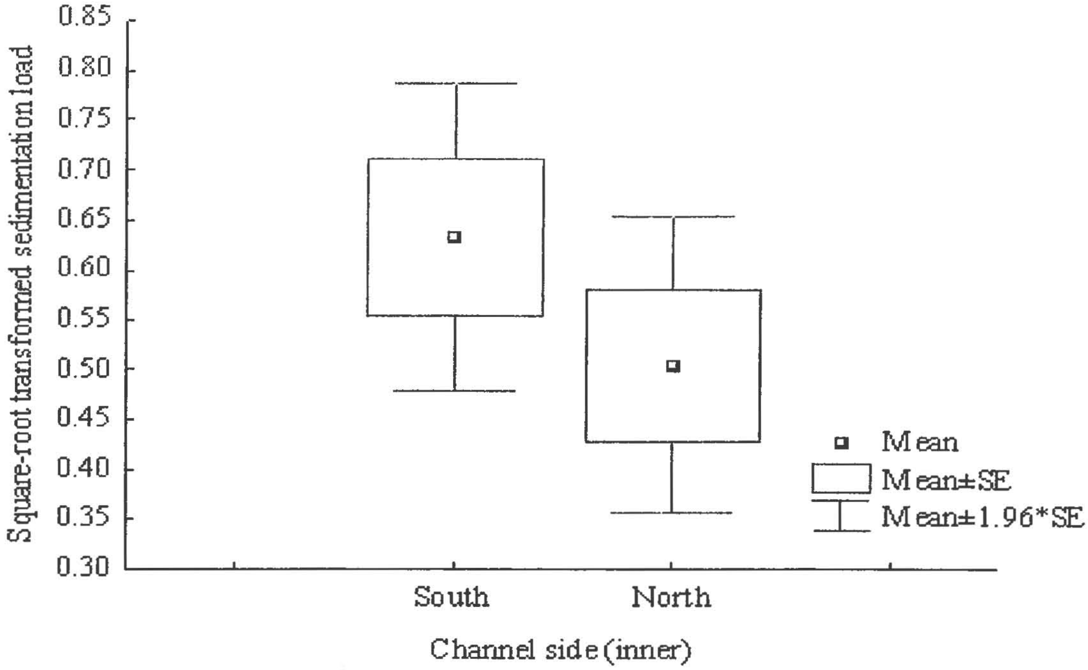

Figure 7. Inner stations (F1 and F2) pooled for their respective side of the channel.

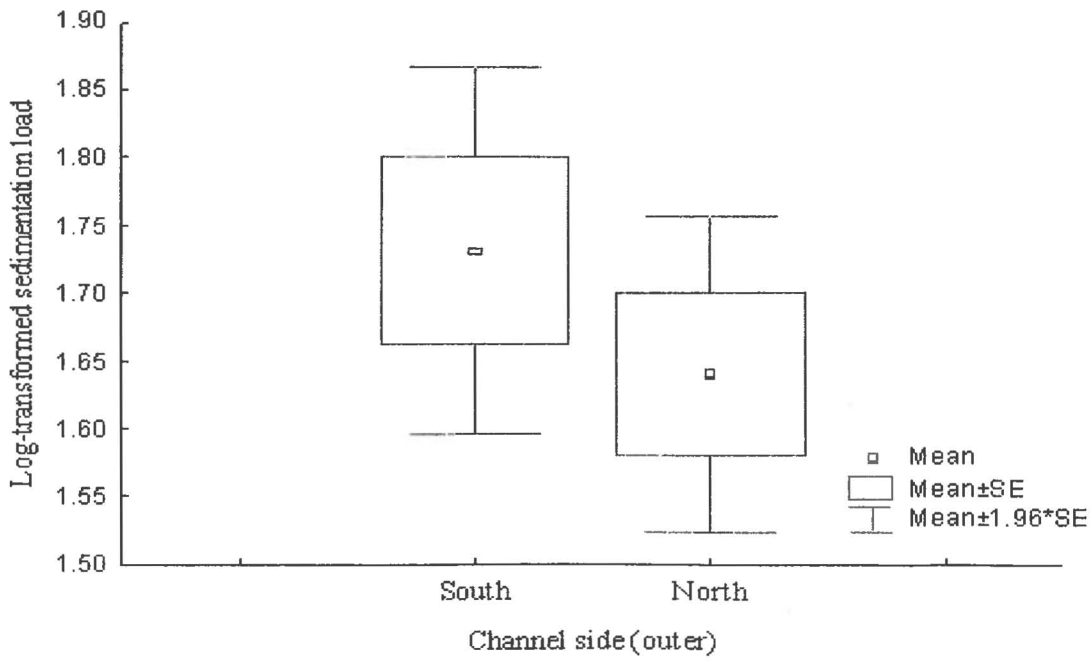

Figure 8. Outer stations (F3, F4, & F5) pooled for their respective side of the channel.

Sediment load among stations

Analysis for sediment load among stations of the north indicated a significant difference (One-Way ANOVA, $F_{1,160}$ = 0.7.7180, $p < 0.01$; see Figure 9 and Appendix J). Analysis for sediment load among stations of the south indicated a significant difference (One-Way ANOVA, $F_{4,164}$ = 5.6379, p = 0.0003; see Figure 10 and Appendix K).

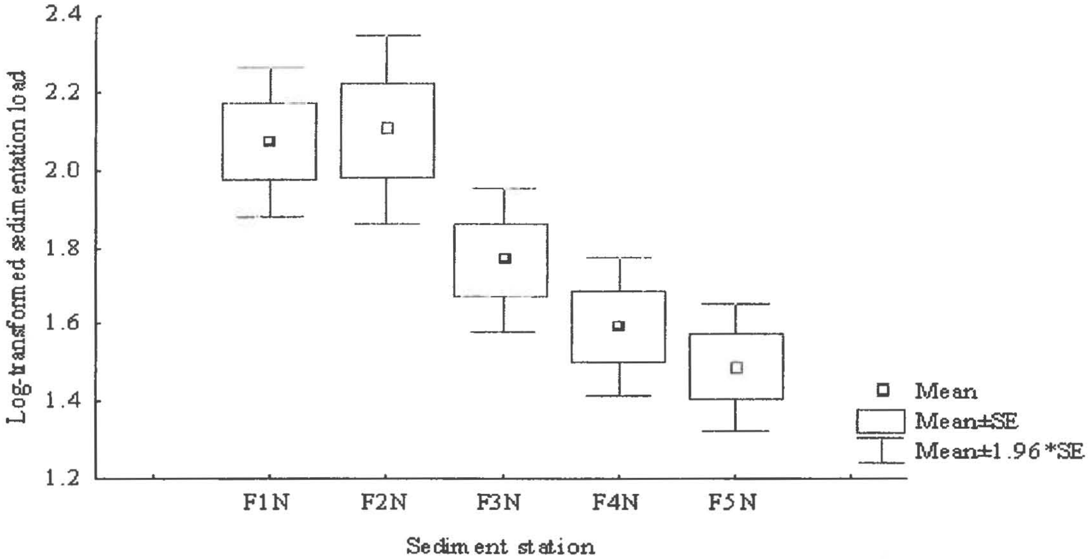

Figure 9. Sediment load along the northern stations (n = 33 for each station).

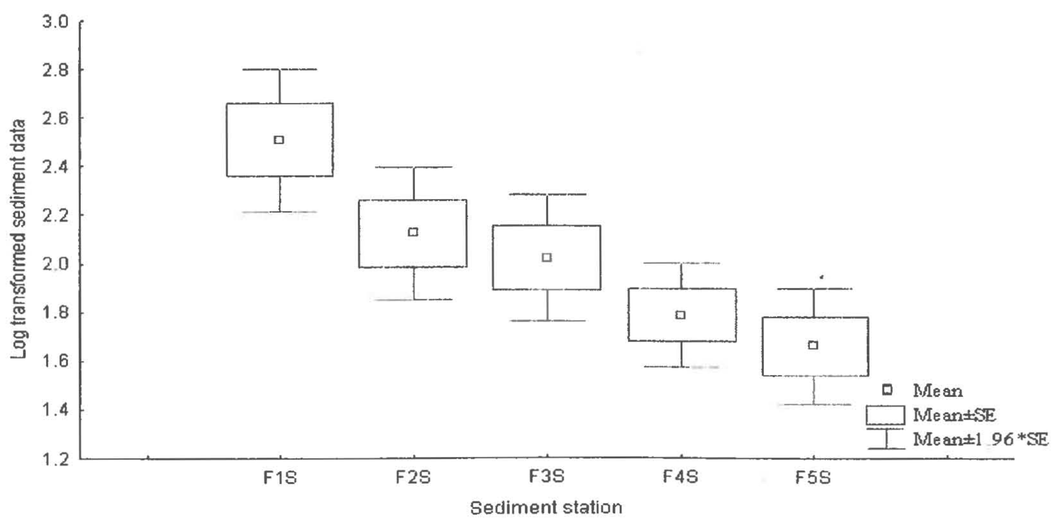

Figure 10. Sediment load along the southern stations (n = 28 per station).

Sediment load between shallow and deep station

Analysis indicated that shallow and deep stations were not significantly different (F3S and F3SD: One-Way ANOVA, $F_{1,74}$ = 0.1996, p = 0.6564; see Figure 11 and Appendix L; F4N and F4ND: One-Way ANOVA, $F_{1,74}$ = 0.2900, p = 0.5919; see Appendix M). However, shallow stations F3S and F4N were significantly different (One-Way ANOVA, $F_{1,74}$ = 4.0614, p = 0.0475; see Appendix N) while the two deep stations (F3SD and F4ND) were not significantly different (One-Way ANOVA, $F_{1,74}$ = 3.1455, p = 0.0803; see Appendix O). Interestingly, shallow station F3S was significantly greater than shallow station F4N, suggesting heavier sediments entering the bay during floods do not travel far offshore, but settle out before reaching F4N (~121 m away).

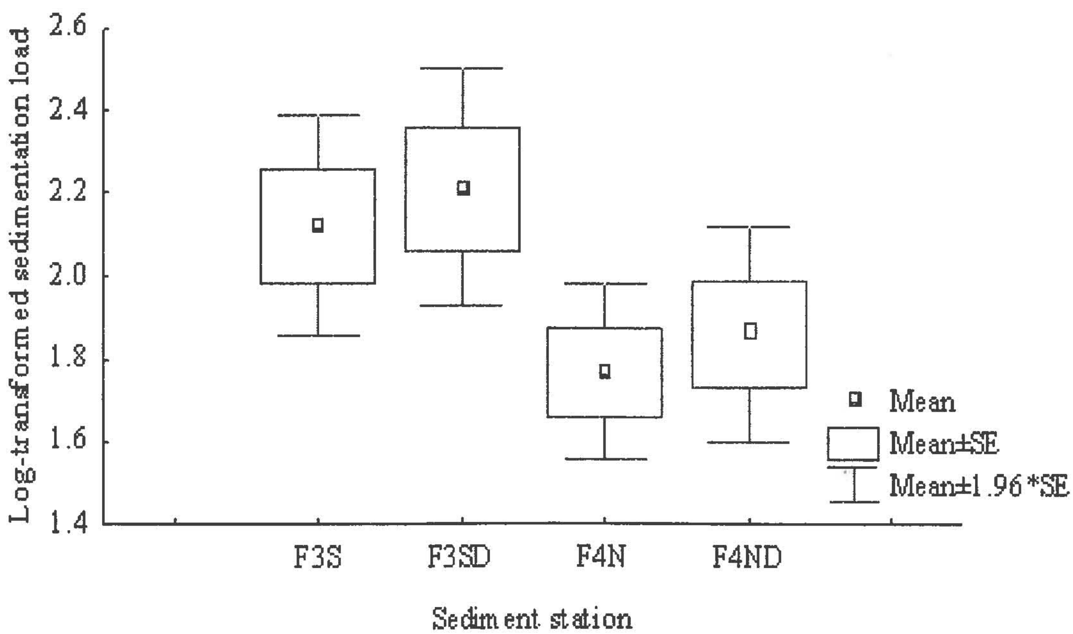

Figure 11. Comparison of sediment load between shallow and deep stations.

CORAL COMMUNITY CHANGE

Moving Window Analysis

The MWA for the north indicated one major spike of 100% dissimilarity (see Figure 12a) at 50 m within the first 300 m of the transect beginning at F1N (70 m from F1S). Although the transect extension indicated another 100% spike at 385 m, only the first 300 m were used in analysis to maintain consistency with the southern transect. Zoning was tested on the northern side to investigate how communities change. Therefore, a limit of >80% dissimilarity was assigned. As a result, one additional spike of 87% dissimilarity was identified at 255 m. A total of three zones were identified for the north separated by spikes: Zone 1N (0-40 m, no corals), Zone 2N (45-255 m), and Zone 3N (260-300 m).

The MWA for the south indicated two major spikes at 100 m and 280 m from F1S (see Figure 12b). Four major zones were identified for the south: Zone 1S (0-40 m, no corals), Zone 2S (45-95 m), Zone 3S (100-275 m, which is the largest community), and Zone 4S (280-300 m). See below for zoning results.

North and South coral communities

<u>Northern Zone</u>

ANOSIM showed no significant change in coral community between two pair-wise comparisons: Zone 2N and 3N (R-Statistic= 0.348, p >0.01) and Zone 3N and the reference site (R-Statistic= 0.292, p >0.01). This suggests that zones are very similar, thus SIMPER was not carried out. See Table 2 for summary of results.

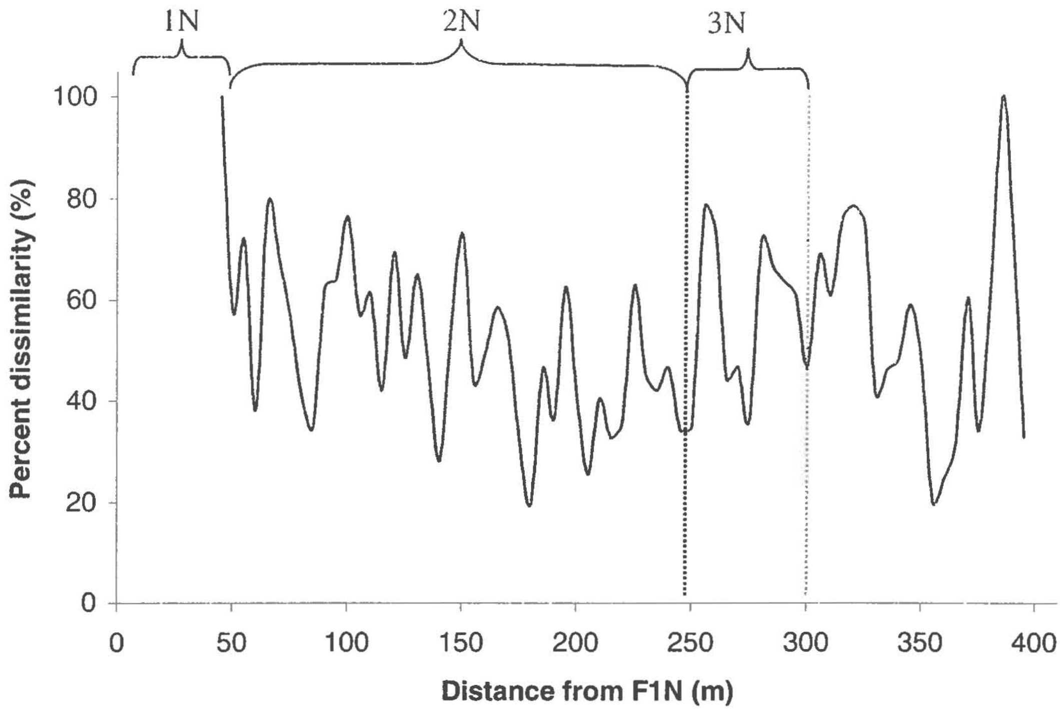

Figure 12a. Moving Window Analysis results for the north.

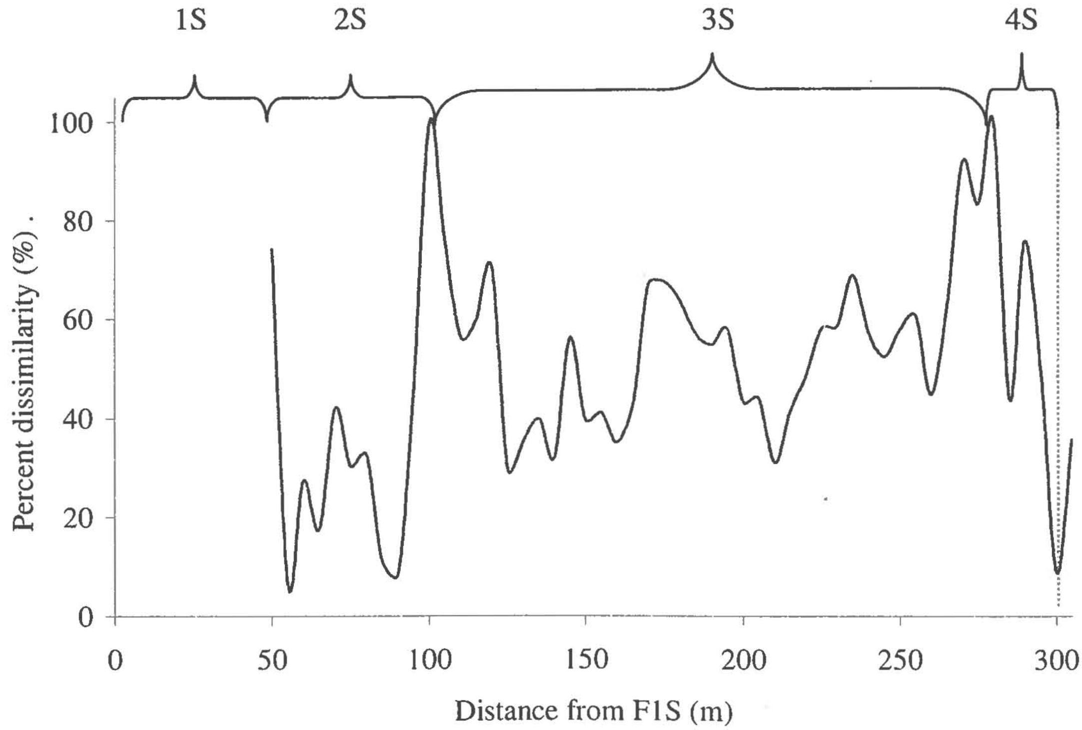

Figure 12b. Moving Window Analysis results for the south.

Southern Zone

ANOSIM accurately detected a significant change in coral community between two pair-wise comparisons: Zone 2S and 3S (R-Statistic= 0.716, p <0.01) and Zone 3S and 4S (R-Statistic= 0.892, p <0.01). SIMPER suggested that differences between Zone 2S and 3S were due to percent contributions from the following corals: genus *Goniastrea* (29.9%), *Psammocora* (13.8%), and *Porites* (11.7%). The following corals contributed to differences between Zone 3S and 4S: *Porites* (21.1%), *Pocillopora* (14.7%), *Leptastrea* (10.2%), and *Psammocora* (9.1%). No community change was detected between Zone 4S and the reference site (R-Statistic= 0.038, p >0.01). See Table 2 and 3 for summary of results.

Table 2. ANOSIM Pairwise Test results for the northern and southern zones.

Zones	R-Statistic value	Significance level (significant at p <0.01)
Northern Zones		
2N and 3N	0.348	0.040
3N and Reference	0.292	0.056
Southern zones		
2S and 3S	0.716	0.008
3S and 4S	0.892	0.008
4S and Reference	0.038	0.373

Table 3. SIMPER results for the southern zones.

Genus	Contribution Percentage (%)	Percent Cumulative (%)
Zone 2S and 3S		
Goniastrea	29.9	29.9
Psammocora	13.8	43.7
Porites	11.7	55.4
Zone 3S and 4S		
Porites	21.1	21.1
Pocillopora	14.7	35.8
Leptastrea	10.2	46.0
Psammocora	9.1	55.1
Zone 4S and Reference		
Pocillopora	18.7	18.7
Goniastrea	15.9	34.6
Acropora	12.8	47.4
Porites (P. vaughani)	10.6	58.0

Coral cover, species richness, and population density

Data for coral cover, species richness, and population density per quadrat were plotted against distance from F1S. Figure 13a indicates that coral cover and species richness are higher at the northern transects than at the reference site. However, the population density suggests that there are more colonies per quadrat at the reference site. A total of 49 species of corals were recorded in 60 quadrats compared to the 21 species found at the reference site. Unlike the southern transects (see Figure 13b), the northern transects do not indicate any clustering of high values between 100 and 250 m as seen in Zone 3 of the south.

The plot for coral cover and species richness to the south (Figure 13b) suggests that Zone 3 has the highest, and Zone 2, 4 and the reference site are similarly low. Although the population density in Zone 2 is higher than Zone 3, Zone 2 is comprised of only a few species and dominated by *L. purpurea*.

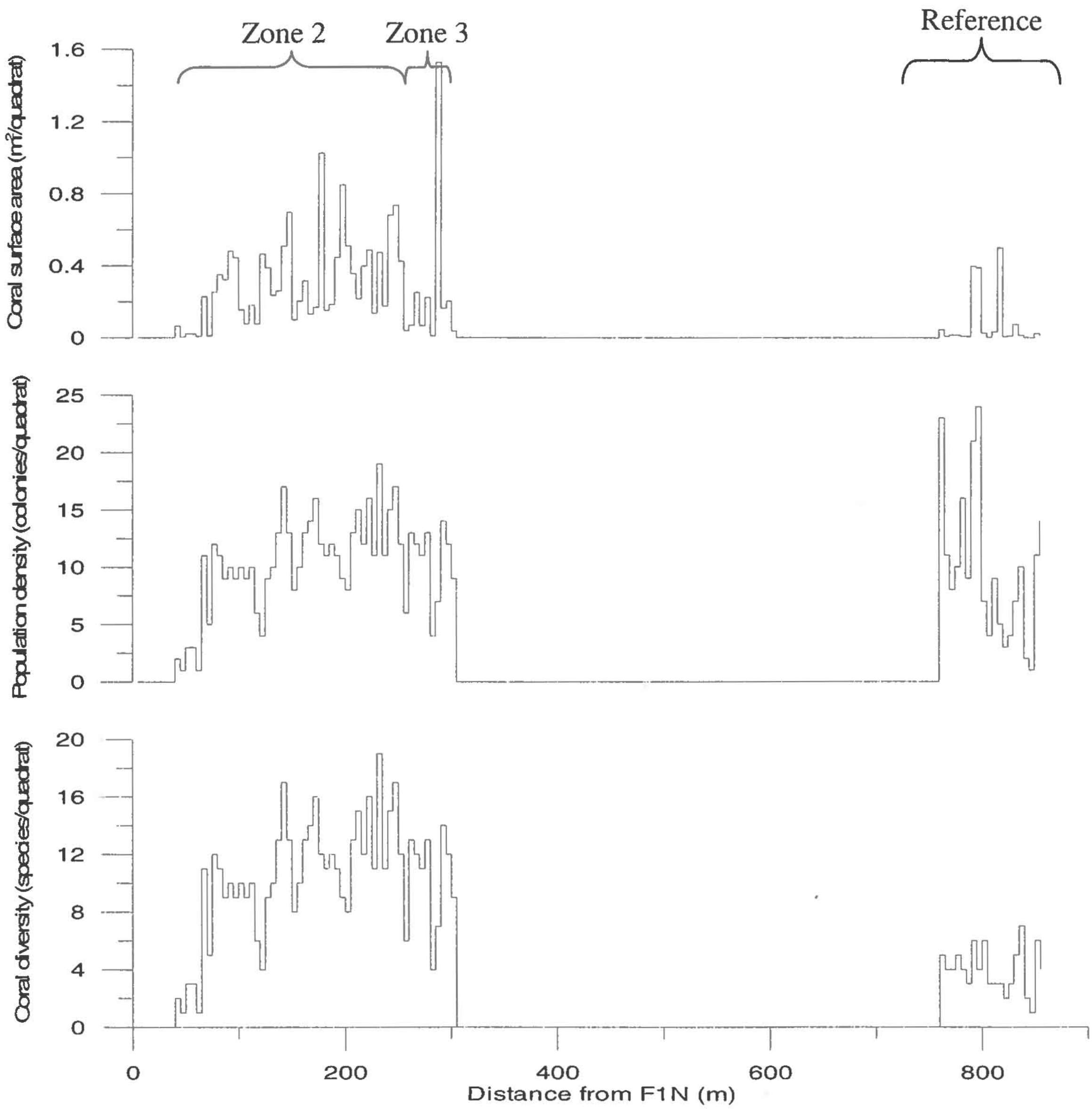

Figure 13a. Coral cover, population density, and species richness for the northern transects and the reference site.

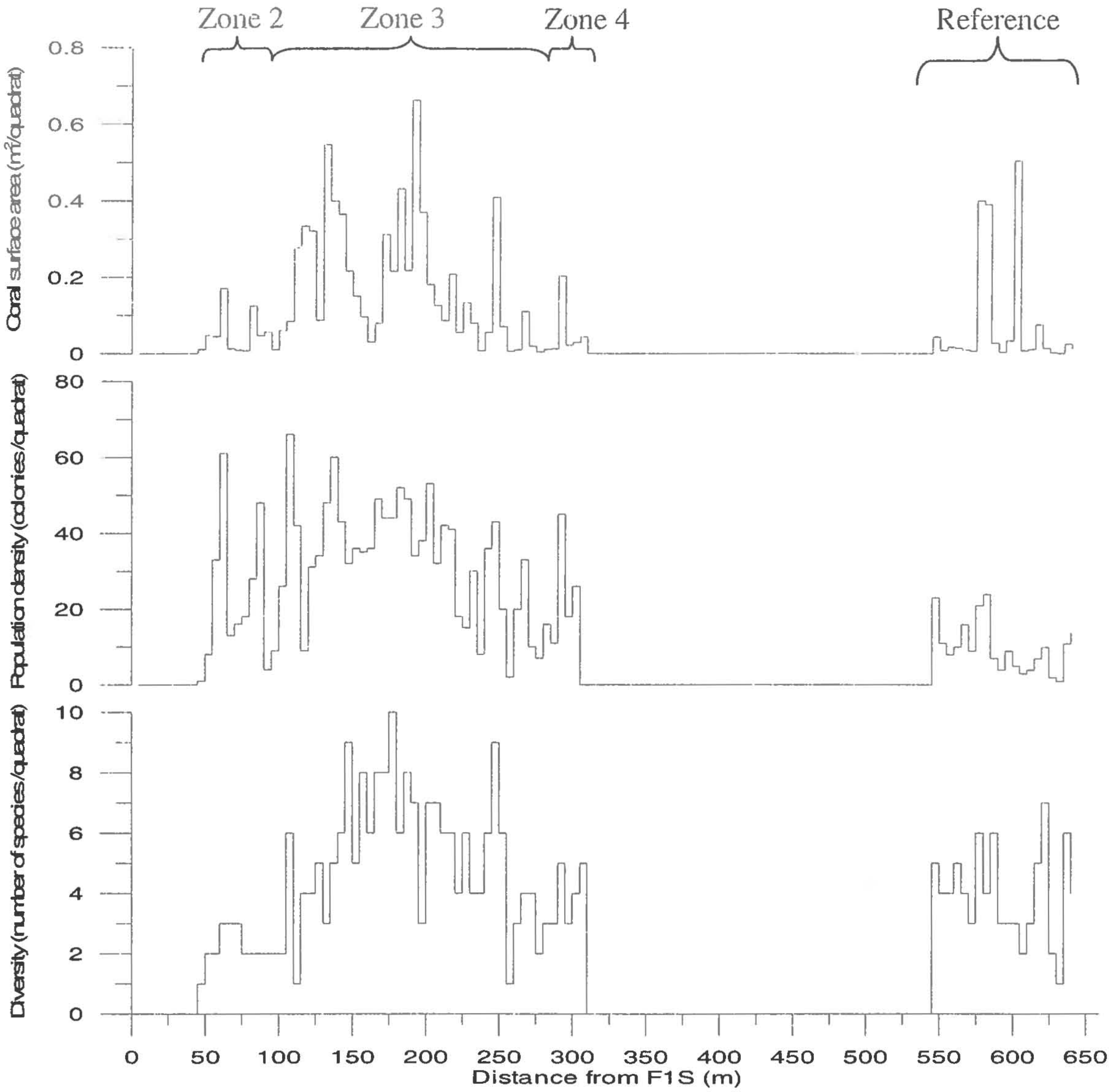

Figure 13b. Coral cover, population density, and species richness for the southern transects and the reference site.

Table 4 shows a summary of coral cover with the highest density within each zone indicated for the northern and southern zones as well as the reference site. Some corals indicated a high density even with low coverage; low coverage was due to the abundance of small colonies.

Table 4. Coral cover for northern and southern zones as well as the reference site. Percent coverage of taxa were recorded for each zone along transects. Values are given for each zone in percent cover, where (-) indicates that no data for the taxa were recorded and red values indicate taxa with the highest density.

Taxa	Northern Zones		Southern Zones			Reference site
	2	3	2	3	4	
Acanthastrea echinata	-	1.4	-	3.4	-	-
Acropora spp.	2.1	2.6	-	1.0	5.1	1.0
Coscinarea spp.	-	-	-	2.4	-	-
Cyphastrea spp.	0.6	0.6	-	0.7	-	-
Favia spp.	0.9	0.3	-	0.4	-	2.4
Favites spp.	2.0	-	-	-	-	0.1
Galaxea spp.	2.3	-	-	1.2	-	-
Goniastrea spp.	39.0	58.8	2.3	33.1	18.0	53.5
Goniopora spp.	1.0	-	-	-	-	-
Hydnophora spp.	0.6	-	-	-	-	-
Leptastrea purpurea	1.0	0.9	6.4	1.0	2.0	0.4
Leptoria Phrygia	7.6	0.1	-	4.3	-	-
Lobophilia spp.	0.1	-	-	-	-	-
Millepora spp.	4.9	24.2	-	8.3	51.5	34.8
Montastrea spp.	0.2	0.2	-	0.5	1.6	0.6
Montipora spp.	1.6	1.7	-	1.2	-	1.3
Pavona spp.	1.0	1.2	0.9	7.5	2.6	0.3
Platygyra spp.	0.3	-	-	0.5	-	0.1
Pocillopora spp.	6.0	2.3	-	2.1	18.8	2.1
Porites rus & annae	3.6	-	-	1.3	-	-
Porites vaughani	0.8	0.7	-	0.2	0.5	1.6
Porites (all other species)	15.7	3.3	90.4	27.5	-	1.4
Psammocora spp.	8.2	0.6	-	2.7	-	0.3
Stylocoeniella spp.	0.7	1.0	-	0.1	-	0.1
Stylophora spp.	0.2	-	-	0.8	-	-

MODEL

Determining the preferred model

The SM was selected because this model provided a better fit between the prediction and the observed sediment load for F1S and F2S (see Figure 14). Overall peaks in model load corresponded well with peaks in observed load. Furthermore, correlations were higher with the SM (see Table 5 for r^2-values).

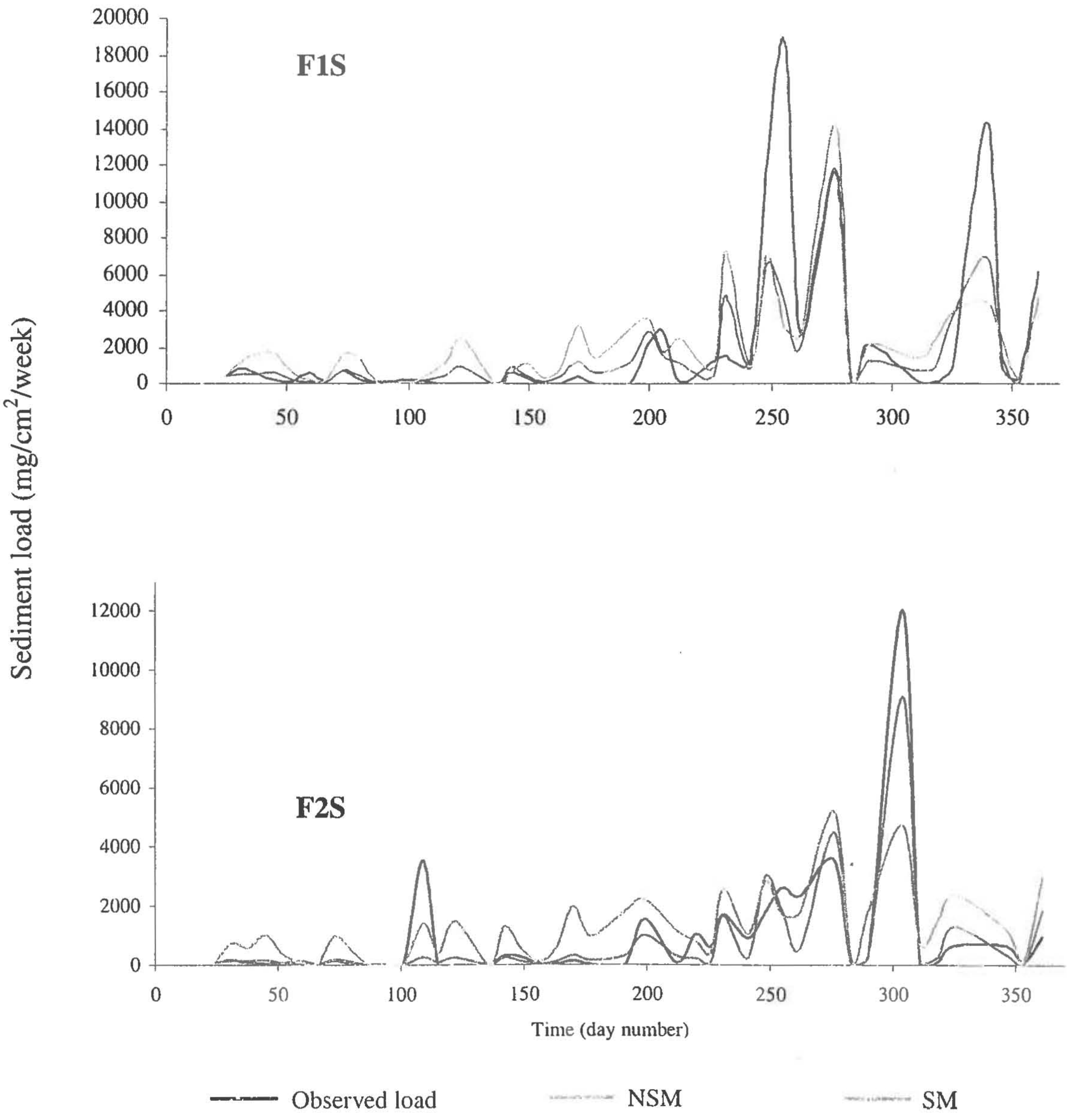

Figure 14. Observed and model sediment loads from F1S and F2S.

Table 5. Correlation between observed and model sediment loads for F1S and F2S.

Sediment station	Model	r^2	P-value	N
F1S	SM	0.6343	<0.001	41
	NSM	0.3599	<0.001	41
F2S	SM	0.8455	<0.001	39
	NSM	0.4828	<0.001	39

Correlations performed after model selection indicated significance between observed and model sediment load for southern stations (see Table 6). Correlations were improved by fine-tuning the model to fit major peaks associated with heavy rain and swell events in observed data. A graphical representation of that fit is illustrated using F1S and F5S (see Figure 15). Adjustments made to constants of each variable in the model led to the improvement of correlations, as seen in F1S and F2S.

Table 6. Correlation between the observed and model sediment load for southern stations.

Sediment station	r-squared	P values	N (sample size)
F1S	0.7666	<0.01	40
F2S	0.7431	<0.01	41
F3S	0.8055	<0.01	39
F4S	0.7259	<0.01	37
F5S	0.6732	<0.01	36

NOTE: Correlations are significant at p <0.01

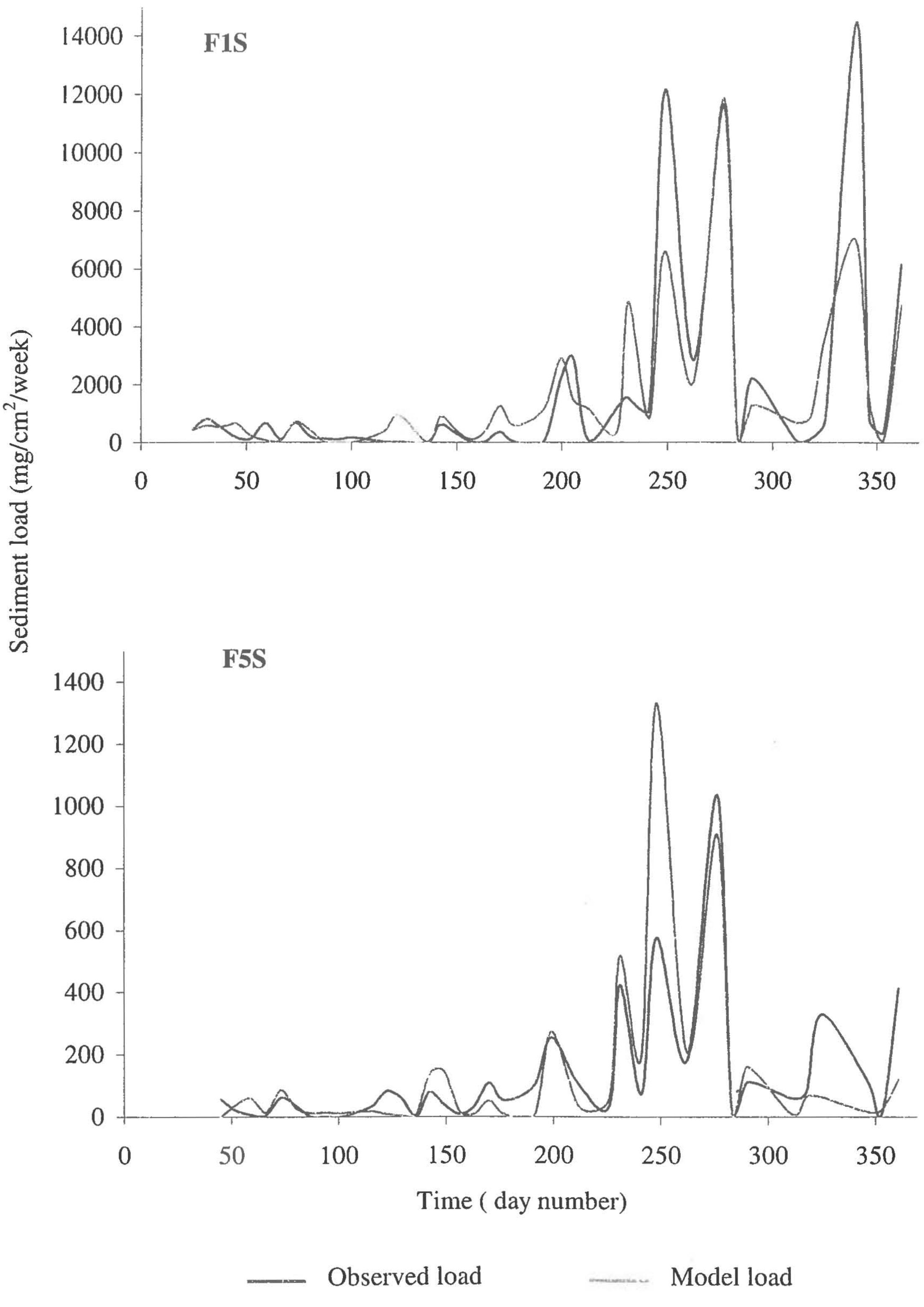

Figure 15. Observed and SM sediment load from stations F1S and F5S.

Sediment load decay model

The rate of decay (r = -0.0145, see Figure 16) obtained from this plot was improved by adjusting the rate to individual events, especially to major storm events. The improved rate used in Eq. 9 is -0.018. Using the improved rate in the model, sediment load can be estimated at any distance d offshore from F1S. Figure 17 gives an example of model use based on hypothetical rainfall data (keeping wind and swell variables at zero).

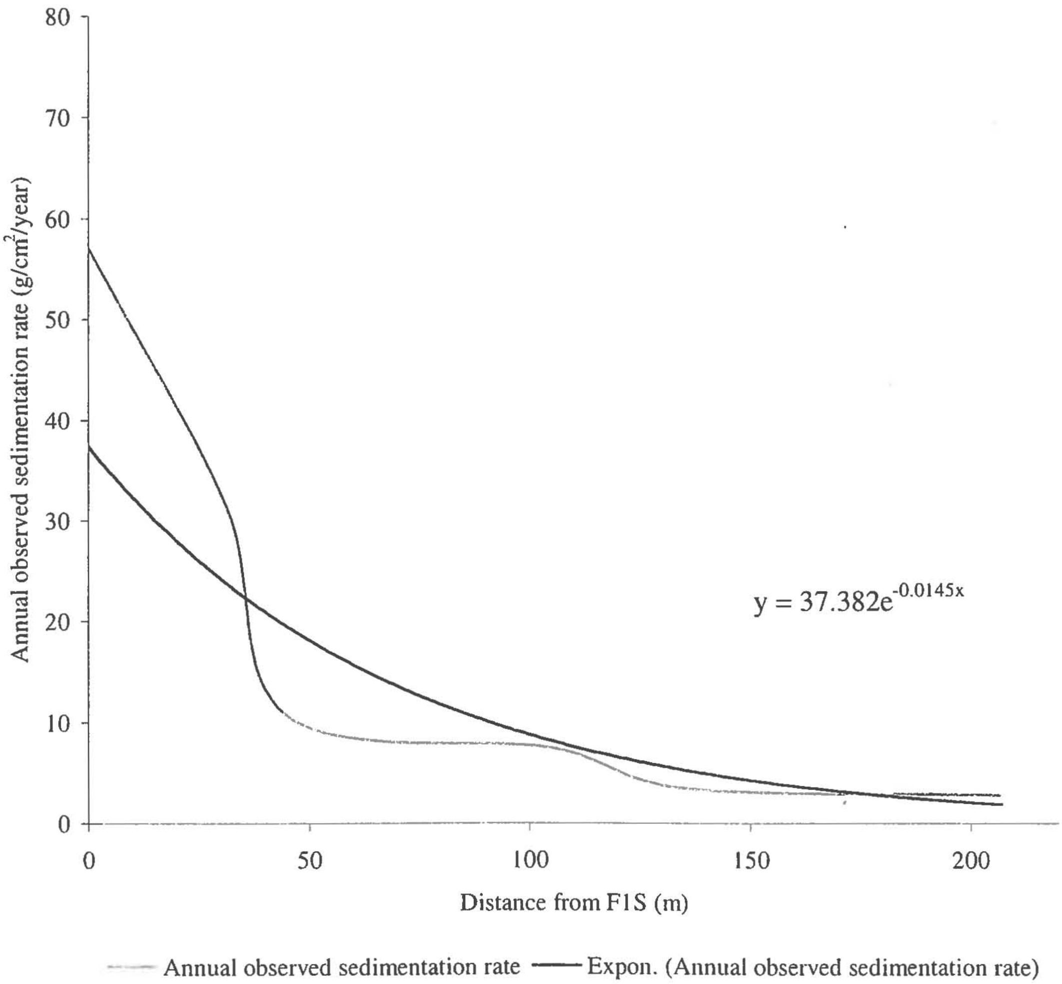

Figure 16. Best-fit exponential decay curve to annual observed sediment load. Note: x = distance d.

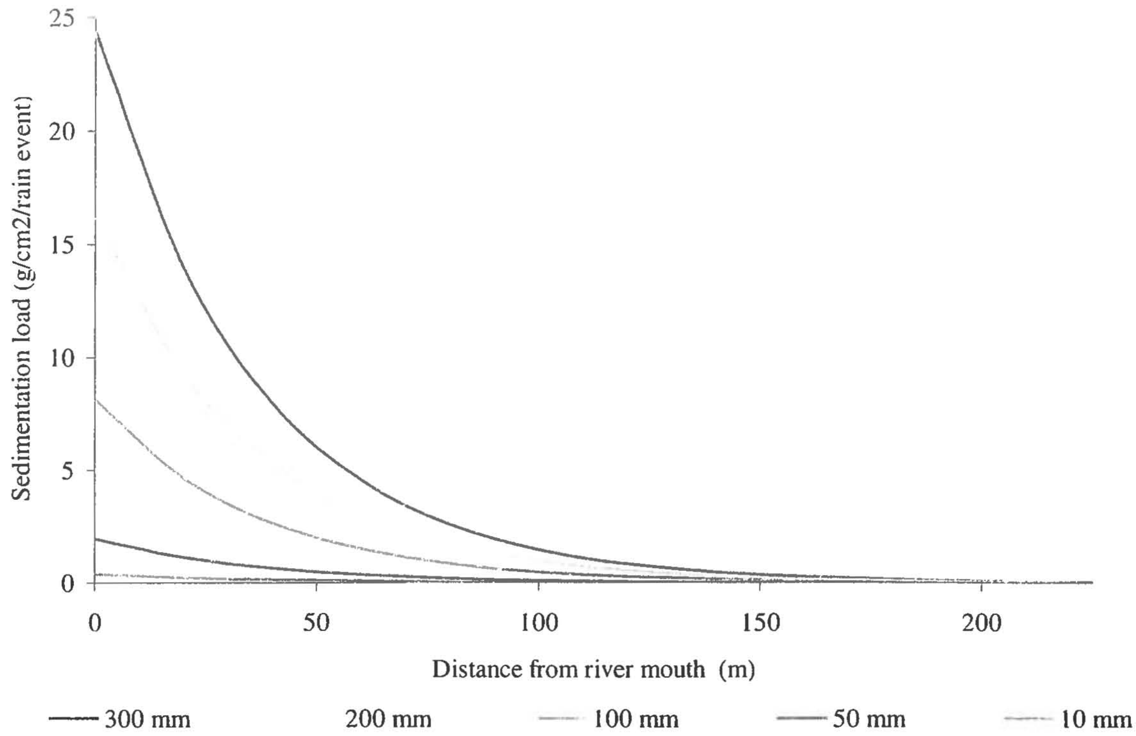

Figure 17. Predicted sediment load with increasing distance from river mouth at different rainfall measurements.

Estimated annual sediment load

The annual observed sedimentation rate (g/cm^2/year) for each station include: 84.7 (F1S), 51.7 (F2S), 46.8 (F3S), 12.3 (F4S), and 5.6 (F5S). Multiplying the rates to their respective areas (Figure 5) gave an estimated load of 2,515 tonnes/year. In order to obtain the yield (eroded sediments from the watershed), the annual load was divided by 5.0 km^2 (area of the watershed; Wolanski, 2003c) obtaining a yield of 503 tonnes/km^2/year. Table 7 compared sediment load and yield for Scheman (2003), Randall and Birkeland (1978), and this study.

Table 7. Comparison of sediment load and yield from studies within La Sa Fua Watershed and Fouha Bay.

Study	Bay area (km^2)	Watershed area (km^2)	Load (tonnes/year)	Yield (tonnes/km^2/year)
*Randall & Birkeland (1978)	1.2×10^{-2}	5.00	2,533	506
Scheman (2002)		5.00	2,400	480
Current study (2003)	1.2×10^{-2}	5.00	2,515	503

*NOTE: The calculations of load and yield for Randall and Birkeland's study were performed by applying their annual rate at their first southern station to the sediment load decay model (Eq. 9). Bay area calculations were taken from this study.

Estimated resuspension using the model

Though correlations between rainfall and sediment load were significant for all stations, noise within the correlation was due to swell events causing resuspension. Using the model, the percent contribution of runoff sediment and resuspension for the respective inner and outer stations was calculated (see Figure 18a and 18b). Data indicated that for the inner part (Figure 18a) average sediment load due to resuspension is 31%. For the outer part (Figure 18b), the average load is 15%. This suggests a two-fold increase of re-suspended sediments of the inner part to the outer part of the bay. Traps collected on Day 142 (note in both plots), gave a high percentage of resuspension because this period experienced little rain and high swell events.

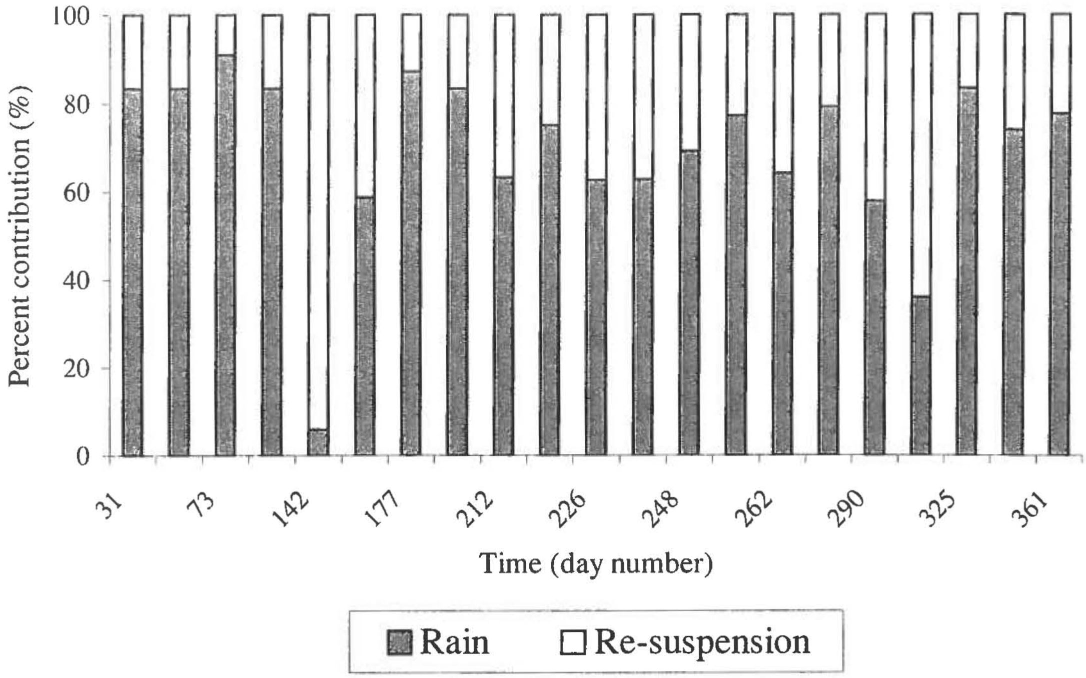

Figure 18a. Model ratio of runoff sediment to resuspension at F1S.

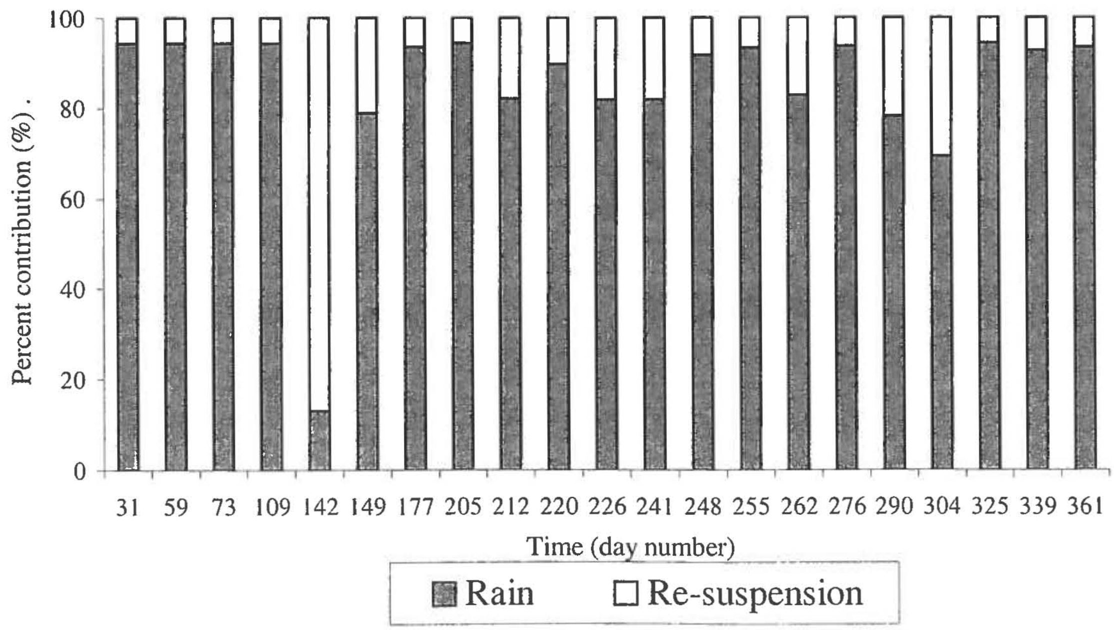

Figure 18b. Model ratio of runoff sediment to resuspension at F5N.

DISCUSSION

SEDIMENTS

Several factors may contribute to the amount of runoff sediments delivered into Fouha Bay. Hubbard (1987) indicated the following factors: watershed size and slope, soil condition, land use and volume and intensity of rainfall. Analyses for this study clearly demonstrated that runoff sediments are dependent on rainfall. Correlations between sediment load and rainfall were significant for all stations (F1 – F5). Analyses also indicated that correlations were higher at southern stations, suggesting that southern stations are more in the path of runoff sediments. Sediment data from this study have also indicated that one rain event can deliver a large amount of sediment into the bay. For example, the first big rain in eight months (82 mm for the week of 7/11/03 - 7/18/03), occurring over a two-day period (two high intensity, short-lived rains) delivered a load of 61 tonnes into the bay.

Analyses of sediment load among stations indicated a significant difference for both north and south, suggesting a trend where load decreases with increasing distance offshore (consistent with Randall and Birkeland, 1978). Southern stations showed this trend clearly. For the most part, the same trend was also seen at northern stations. However, F2N exhibited a higher sediment load than F1N. The location of F2N (within a pocket in the reef margin) may be the cause of the higher load, with contributions from both runoff and resuspension. Generally, the path of the river flows over F1S and across the channel to F1N before heading towards open-ocean. However, during flood events (when flow rate is extremely high and large amounts of sediment are delivered into the bay), the plume flows over F2N instead of F1N.

Analyses indicated no significant difference between the north and south stations (pooled data). However, this may be due to variability in the data. An obvious trend was noted in sediment data, showing more sediments depositing to the south. Also, while analyses between the two deep stations (F3SD and F4ND) indicated no significant difference, the two shallow stations (F3S and F4N) showed a significant difference. This suggests that sediments drop out before reaching F4N (117 m from the source station), supporting the hypothesis that most sediments deposit to the inner part of the bay. The analyses is consistent with Randall and Birkeland (1978), who indicated a six-fold decrease in sediment load to the south and a 34-fold decrease to the north between the first and the fourth station. They noted a major drop in sediment load from inner to outer stations, suggesting that most sediment deposited to the inner part of bay to the south.

Analyses of data collected at shallow and deep stations indicated no significant difference between them (F3S& F3SD and F4N & F4ND). Sediment data for both shallow and deep indicated that rough periods deposited the most sediment into traps (with similar amounts) for both shallow and deep. Notably, sediment deposition during calm periods deposited more sediment at deep stations. Due to the amount of sediments collected on rough periods outweighing those collected on calm periods, analyses (pooled data from both periods) indicated no significant difference between shallow and deep stations. This may be due to well-mixing of Fouha Bay during swell events, which is consistent with Wolanski *et al.* (2003a). Their salinity data indicated a well-mixing of the bay during periods with heavy rain and swells.

In summary, data clearly indicated that sediment load is dependent on rainfall events. Data also indicated that most sediments deposit to the inner part of the bay, with trends indicating a higher load to the south.

CORAL COMMUNITY CHANGE

The MWA in this study showed two major shifts in community composition to the south of Fouha Bay channel. ANOSIM accurately detect these changes in this depauperate community. The two shifts reflect coral dominance; the first shift at 100 m is a community supporting mainly *Leptastrea purpurea* and *Porites spp.* corals (Zone 2) to a diverse community of 15 genera dominated mainly by *Goniastrea retiformis, Porites spp.,* and *Pocillopora* corals (Zone 3). The last shift at 280 m into Zone 4 is mainly dominated by *Pocillopora spp.* corals. ANOSIM clearly indicated that Zone 4 was not significantly different to the reference site. Therefore, the last shift indicated a transition into the normal reef of southern Guam. The shift at 280 m is consistent with results from a study by West and Van Woesik (2001) who found this shift at 400 m with a much larger bay in Okinawa, Japan.

The north had one major shift at 50 m from F1N (70 m from the source station). Though, corals were recorded within Zone 1, lack of sample size prevented its inclusion in the ANOSIM. Notably, the shift abruptly changed from a community supporting mainly scarce colonies of *Leptastrea purpurea* (Zone 1) to a diverse community of 21 genera mainly dominated by *Goniastrea retiformis*, *Porites spp.*, and *Psammacora spp.* corals (Zone 2 and 3). The shift seen at 255 m after setting a limit of 78% for percent dissimilarity was not significant because according to ANOSIM, Zone 2 and 3 were not distinct communities but were similar. ANOSIM also indicated that Zone 3 and the reference site are similar. This suggests that the first shift in coral community composition (70 m) is the shift into the normal reef of southern Guam. The last shift at 385 m (405 m from source station) was not included in the analyses. Observation around this area indicated that corals became extremely scarce in comparison to Zone 3 to the north and the reference site. Therefore, this shift may suggest a transition into a more depauperate community. The cause for this last shift may be explained by the natural freshwater seepage (which can contribute to coral mortality through bleaching; Anderson *et al.*, 2001) located towards the outer part of the northern side of the bay next to Fouha Rock.

Trends suggest that coral cover, population density, and species richness are higher within the bay (especially Zone 2 to the north and Zone 3 to the south) than in the outer zones (Zone 3 to the north and Zone 4 to the south) and the reference site. This is consistent with the results from a study by West and Van Woesik (2001; Hija, Japan), who indicated that the zone before a shift into the 'normal' reef is slightly more diverse. This may be due to a complex combination of factors providing favorable conditions for corals at certain distances from shore. Such factors may include water movements, nutrient levels (especially particulate organic matters from runoff), and reef morphology. Studies have shown healthy corals to exist in chronically turbid waters, especially with strong prevailing currents (Marshall and Orr, 1931; Roy and Smith, 1971; Fabricius, 2005). Furthermore, a study by Anthony (2000) on the Great Barrier Reef indicated that corals in inshore turbid environments can flourish as they become more heterotrophic than their conspecifics on less turbid reefs.

Observations indicated that corals were abundant at the edge of the reef margin and rarely on the reef flat. Roberts *et al.* (1992) indicated the importance of reef morphology (i.e. spur-and-groove formations) contributing to maintain healthy coral communities within turbid environments by allowing for better water movement and thus preventing sediment accumulation. Transects were laid on the reef margin where spur-and-groove formations exist. The sudden drop (to the inner part) and the steep slope (to the outer part) into the bay channel may also contribute to better water movement at the reef margin. These formations are much reduced to the outer part of the bay (Zone 4 to the south) and the reference. This may explain why coral communities in these outer zones were more depauperate than the inner zones.

Trends indicated coral cover and species richness to be higher to the north. However, the south indicated a higher population density. One explanation for differences in density may be explained by 'die-back' corals. Die-back corals are small patches of the same species which used to be one continuous colony. These were common in the bay among a few species. The most common was *Goniastrea retiformis*; others include *Cyphastrea spp.*, *Psammacora spp.* and *Galaxea spp.* corals. Corals go through a period of slow death after being subjected to high levels of sedimentations (Dodge and Vaisnys, 1977). Thus, die-backs may be indicators of a dramatic increase in sedimentation within the bay.

Another explanation for density differences in corals to the north and south of the bay may be due to small colony size. Smaller colonies found to the south side of the channel supported one of Rogers (1990) predictions that colonies tend to be small in sediment-impacted areas. Furthermore, studies have indicated a reduction in growth rate in corals of sediment-impacted areas (Bak, 1978; Van Woesik and Done, 1997). Small sizes colonies were noted among several corals but were common among *Porites.* spp, especially with the stunted growth forms of *Porite lutea.* This is consistent with Stafford-Smith's (1993) findings that smaller colonies are better at rejecting sediments. This may explain the high coral density to the south (coral recruits were not considered because none were detected during the survey). Therefore, this suggests that the southern side of Fouha Bay is indeed more impacted by sedimentation.

Randall and Birkeland (1978) have indicated that suspended sediment load ranging from 200 to 160 mg/cm^2/d (upper range) would expect less than 10 coral species covering less than 2% of the hard substrate; load ranging from 30 to 5 mg/cm^2/d (lower range) expects a diverse community of more than 100 species. Based on the model data, the calculated distance for the upper range was from 9 to 21 m from the source station. The calculated distance for the lower range was from 114 to 212 m. Also, Pastorok and Bilyard (1985) estimated the degree of impact of various sedimentation rates on coral communities (see Table 8). Their degrees ranged from slight to moderate (1 - 10 mg/cm^2/day), moderate to severe (10 – 50 mg/cm^2/day), and severe (> 50 mg/cm^2/day). The model calculated these rates to be at the following distances from the source station: greater than 175 m (slight to moderate), 175 to 86 m (moderate to severe), and less than 86 m (severe). Figure 19 is a summary of the ranges indicated by Randall and Birkeland (1978) and Pastorok and Bilyard (1985), including the coral community shifts from MWA for the southern side of Fouha Bay and their corresponding sedimentation rates calculated by Eq. 9. Coral community shifts occurred at 45 m, 100 m, and 280 m.

Table 8. Estimated degree of impact of various sedimentation rates on coral communities (from Pastorok and Bilyard, 1985).

SEDIMENTATION RATE (mg/cm²/day)	DEGREE OF IMPACT
1 – 10	Slight to moderate • Decreased abundance • Altered growth forms • Decreased growth rates • Possible reductions in recruitment • Possible reductions in number of species
10 – 50	Moderate to severe • Greatly decreased abundance • Greatly decreased growth rates • Predominance of altered growth forms • Reduced recruitment • Decreased number of species • Possible invasions of opportunistic species
> 50	Severe to catastrophic • Severely decreased abundance • Severe degradation of communities • Most species excluded • Many colonies die • Recruitment severely reduced • Regeneration slowed or stopped • Invasion by opportunistic species

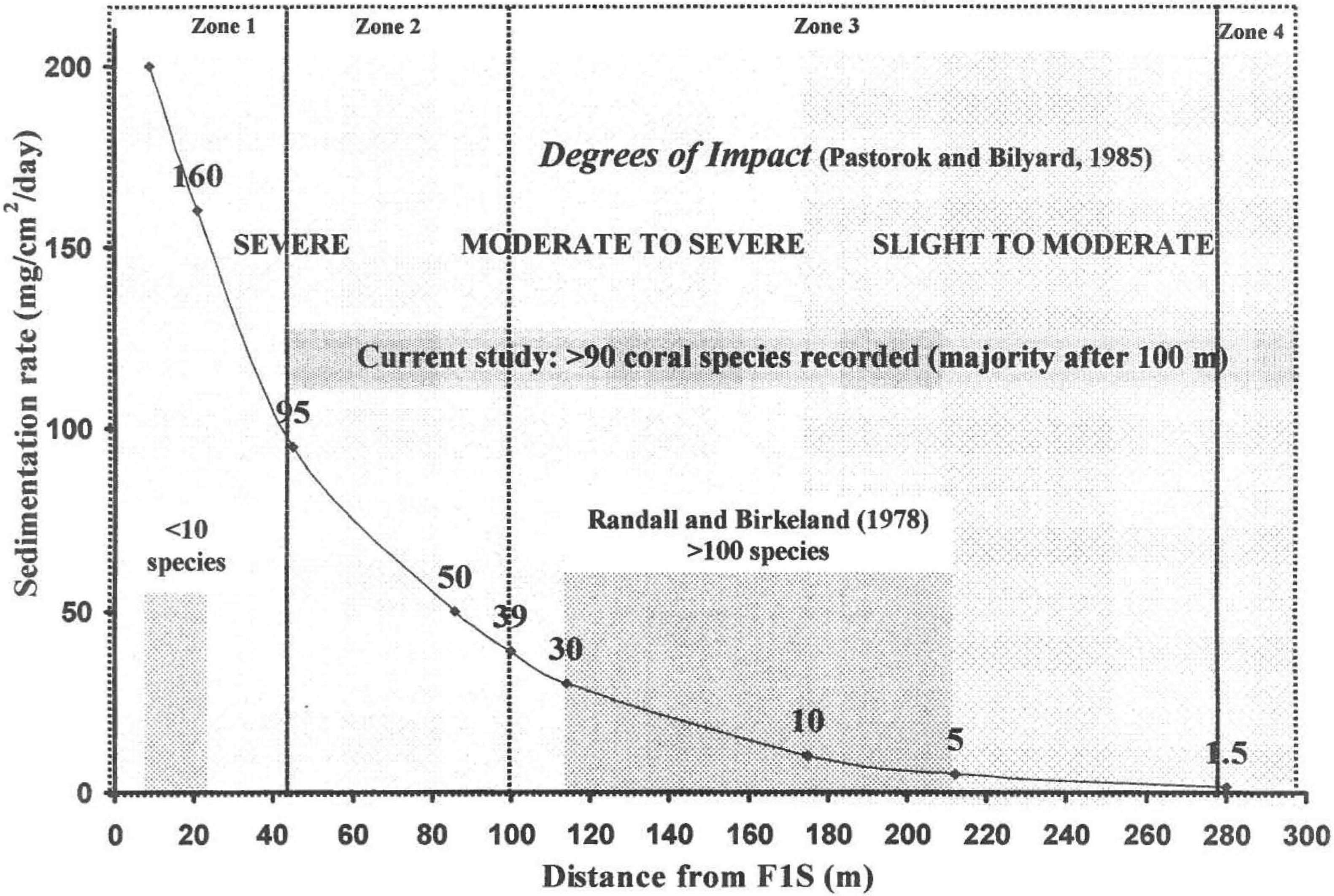

Figure 19. A summary of sedimentation rate ranges indicated by Randall and Birkeland (1978) and Pastorok and Bilyard (1985) impacting corals, including the coral community shifts from MWA for the southern side of Fouha Bay.

Randall and Birkeland's (1978) findings were consistent with this study's coral data because within their upper range, one coral species was recorded (three species were recorded outside the quadrats within these ranges). Furthermore, this study recorded over 90 species of corals after 45 m from the source station (see Appendix P), with the majority of coral records occurring after 100 m (sedimentation rate of <39 mg/cm^2/day); this was also consistent with Randall and Birkeland's lower range (Figure 19).

The effects of sediments along a gradient were consistent to data from the MWA for the southern side of the bay. The MWA for the south showed the shift into a more diverse community at 100 m from the source station, with sedimentation rates of 39 mg/cm2/day (indicated by Pastorok and Bilyard (1985) as having a moderate to severe impact on corals). Model calculations of sedimentation rate greater than 50 mg/cm^2/day (indicated by Pastorok and Bilyard (1985) as having a severe impact on corals; Table 8) occurred within 86 m from the source station, suggesting that coral within this distance are experiencing lethal levels of sedimentation. These levels may explain low diversity to the inner part of the bay on the southern side, as well as die-back corals which are common to this part. Based on these findings, sedimentation does indeed influence coral community structure. Furthermore, these communities have not changed at least within the last 25 years.

In summary, coral community shifts into the normal reef of southern Guam occurred closer (70m) for the northern communities and further (280m) for the southern communities from the source station. Coral data indicated a much healthier community existing to the northern side of the bay.

MODEL

Correlations between sediment load for both models (SM and NSM) and the observed sediment load were significant, suggesting that the model can indeed give good estimates of sediment load for Fouha Bay. The r^2-values ranged from 0.67 to 0.81, suggesting that the model can explain over 70% of sediments collected in traps.

To date, no study has examined the ratio of runoff to resuspended sediments. This model was able to give an estimate of that ratio. According to the model, about 31% of sediment load was from resuspension at the inner part of the bay. This may be a result of the location of inner traps at shallower parts of the channel where resuspension was greater. On the other hand, load due to resuspension was two folds lower (15%) at the outer part of the bay. This may be a result of the location of outer traps at deeper parts of the channel, as traps are too shallow for heavier resuspended particles to reach.

Wolanski *et al.* (2003a) indicated that 75% of runoff sediments are retained within the inner part of Fouha Bay channel. Therefore, the channel bottom may be a source for resuspended sediments. Other sources contributing to resuspension may include algal communities, especially on the reef flat. From a brief benthic survey carried out on the reef flat within the bay (not included in the results), over 70% of the substrate were recorded as algae (mainly branching and filamentous types). Purcell (2000) indicated that branching types of algae hold sediments better than other types, which may add to the availability of sediments for resuspension during swell events.

The estimated annual sediment load for Fouha Bay during this study was 2,515 tonnes/year. This value may be an underestimate because calculations assumed that most sediment was within the area indicated (Figure 5). Randall and Birkeland's (1978) annual load was 2,533 tonnes/year (based on this study's model calculations), and Scheman (2002) reported 2,400 tonnes/year. In comparison to this study, the load did not change substantially since 1978. This may suggest that land use practices within this watershed had not changed much since Randall and Birkeland's 1978 study. The introduction of slash-and-burn techniques for agriculture on Guam came with the arrival of the Spanish and became a common practice in southern Guam possibly after World War II (Minton, personal communication). Although burning can cause erosion, it may not be a major contributor to runoff sediments because ashes from burning can seal pores in the ground forming a crust on the soil surface which reduces soil permeability (Golabi, personal communication). Thus, during heavy rain events water can run off the surface without carrying sediments. Although several contributors may indirectly lead to sedimentation, the main cause of sediment runoff is possibly due to large areas with minimal or no vegetation covers within the watershed. This may explain why sediment load has not varied substantially over the years. However, variations in sediment load between years may be due to the length of dry periods (which allow eroded sediments to accumulate) interrupted by occasional rain events of high intensity at large volumes.

CONCLUSIONS AND RECOMMENDATIONS

The annual sediment load for Fouha Bay during this study was 2,515 tonnes/ year. This load did not change substantially since 1978. The reefs in southern Guam have been subjected to sedimentation for many years and have not changed at least for last 25 years. Provided that conditions remain the same on land, the reefs adjacent to watersheds of southern Guam will remain devoid of corals as chances of recovery through recruitment are slim to none. Thus, these reefs can only get better provided that activities within the watershed are improved upon (i.e. increase vegetation cover). The ongoing attempt to replant trees within the watershed brings value to this study, as it can be used as a reference for assessing the effectiveness of improvements on land.

Further studies in the bay should include examining the holding capacity of different algal communities. Algae are seasonal; different communities appear at different times of the year. Algal assemblages have different holding capacities based on their growth form (Purcell, 2000). A study can be designed to examine what wave strength dislodges these sediments for resuspension. This value can be incorporated as another parameter into the model, which may assist in accounting for sediment load due to resuspension within the bay.

Herbivory on coral reefs play an important role in controlling algal communities from out-competing corals (Jompa, 2002). Thus, reducing fishing pressures on herbivorous fish within Fouha Bay may lower algal communities, therefore reducing sediments available for resuspension.

Sediments from runoff can bring nutrients and other pollutants (such as pesticides) into the ocean, causing many different problems to the early life cycles of marine organisms (Richmond, 1993). The model can be a useful tool for quantifying pollutants entering the ocean. Furthermore, shifts in coral communities may become a function of distance over time as shifts vary depending on the discharge rate of pollutants (West and Van Woesik, 2001). Thus, MWA is also a useful tool for monitoring the discharge rate of pollutants from land. Ideally, an effective land management plan implemented should reduce both the distance where sedimentation rates are lethal to corals, and the distance where community shifts into the normal reef of southern Guam.

Many studies have indicated the adverse effects of sedimentation on reefs. However, all have been performed on large rivers adjacent to large bays. This study clearly indicated how measurable these effects are even on a small scale. Studying small bays such as Fouha Bay is practical and provides a basis for developing management plans to improve situations on small scales that can be implemented on larger scales as well.

NOTE FOR MODEL USE

The key component of the model is the calculated rate of decay (*r*) of sediment load offshore. In order to accurately calculate this rate, at least three sediment traps must be deployed directly in the path of the river plume at given distances from the source station. The source station should be located near the mouth of the river discharge. The duration of the study need not be one year as long as data from one heavy rain event is recorded. Ideally, deployment should be during the wet season. One heavy rain event is sufficient to give the rate of decay for the model. Model constants (which may vary for each study area) need to be adjusted to fit the observed sediment data before estimations of runoff sediments can be obtained.

LITERATURE CITED

Anderson, S., Zepp, R., Machula, J., Santavy, D., Hansen, L., and E. Mueller. 2001. Indicators of UV exposure in corals and their revelence to global climate change and coral bleaching. Human and Ecological Risk Assessment 7 (5): 1271-1282.

Anthony, K.R.N. 2000. Enhanced particle-feeding capacity of corals on turbid reefs: Great Barrier Reef, Australia. Coral Reef 19: 59-67.

Bak, R.P.M. 1978. Lethal and sublethal effects of dredging on reef corals. Marine Pollution Bulletin 9: 14-16.

Birkeland, C. (1997). The importance of biomass accumulation in early successional stages of benthic communities to the survival of coral recruits. Proc. 3rd int. Coral Reef Congr. 1: 15-21

Bassler, C. 2004. Personal communication. University of Guam Marine Technician.

Brock, V.E., Van Heukelem, W., and P. Helfrich. (1996). An ecological reconnaissance of Johnston Islands and the effects of dredging. Hawaii Inst. Mar Biol. Tech. Rep. 11: 1-56.

Clarke, K.R. and R.M. Warwick. 1994. Similarity-based testing for community pattern: the 2-way layout with no replication. Marine Biology 118: 167-176.

Delaney, M. 2004. Wave propagation: from deep water creation to the shallow water. University of North Carolina at Wilmington: Master's Thesis submitted for Physical Oceanography:1-10.

Dodge, R.E., Vaisnys, J.R. 1977. Coral populations and growth patterns: responses to dredging and turbitity associated with dredging. Journal of Marine Research 35: 715-730.

Doolette, J.B., and W.B. Magrath (eds.). 1990. Watershed development in Asia. Strategies and technologies. World Bank Tech. Paper 127. 227 p.

Fabricus, K. 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Marine Pollution Bulletin 50: 125-146.

Fabricus, K., and E. Wolanski. 2000. Rapid smothering of coral reef organisms by muddy marine snow. Estuarine, Coastal and Shelf Science 50: 115-120.

Fernández, C., Acosta, F.J., Abellá, G., López, F., and M. Diaz. 2002. Complex edge effect fields as additive processes in patches of ecological systems. Ecological Modelling 149 (3): 273-283.

Fortes, M. 2001. The effects of siltation on tropical coastal ecosystems. In E. Wolanski (Ed.), Oceanographic processes of coral reefs. Physical and biological links in the Great Barrier Reef: 93-111. Boca Raton, FL: CRC Press (356 pp).

Gilmour. J. 1999. Experimental investigation into the effects of suspended sediment on fertilization, larval survival and settlement in a scleractinian coral. Marine Biology. 135: 451-462.

Golabi, M. 2005. Personal communication. University of Guam College of Agriculture.

Hallock.P. 1997. Reefs and reef limestone in earth history. In C. Birkeland (ed.), Life and death of coral reefs, 3:43-67. Chapman & Hall, New York., Life and death in coral reefs, 2:13-42.

Hubbard, D.K., Stump, J.D., Carter, B. 1987. Sedimentation and reef development in Hawksnest, Fish and Reef Bays, St. John, U.S. Virgin Islands. Biosphere reserve research report 21. Virgin Islands Resource Management Cooperative/National Park Service: 1-99.

Jompa, J., and L.J. McCook. 2002. Effects of competition and herbivory on interactions between a hard coral and a brown alga. Journal of Experimental Marine Biology and Ecology 271 (1): 25-39.

Larcombe, P., P.V. Ridd, A. Prytz, and B. Wilson. 1995. Factors controlling suspended sediment on inner-shelf coral reefs, Townsville, Australia. Coral Reefs 14: 163-171.

Marshall, S. M., Orr, A. P. 1931. Sedimentation on Low Isles Reef and its relation to coral growth. Scientific representative to Great Barrier Reef expedition 1: 94-133.

McCook, L.J. 2001. Competition between corals and algal turfs along a gradient on terrestrial influence in the nearshore central Great Barrier Reef. Coral Reefs 19: 419-425.

McManus, J.W., Menez, L.A.B., Reyes, K.N.K., Vegara, S.G., and Ablan, M.C. 2000. Coral reef fishing and coral-algal phase shifts: implications for global reef status. ICES Journal of Marine Science 57 (3): 572-578.

Minton, D. 2005. Personal communication. Guam National Park Service.

Pastorok, R.A., Bilyard, G.R. 1985. Effects of sewage pollution on coral-reef communities. Marine Ecology Progress Series 21: 175-189.

Purcell, S.W. 2000. Association of epilithical algae with sediment distribution on a windward reef in the northern Great Barrier Reef, Australia. Bull. Mar. Sci. 66(1): 199-214.

Randall, R.H. and C. Birkeland. 1978. Guam's reefs and beaches. Part II: Sedimentation studies at Fouha Bay an Ylig Bay. University of Guam Marine Laboratory Technical Report No. 47. 77 p.

Richmond, R.H. 1993. Coral Reefs: Present problems and future concerns resulting from anthropogenic disturbance. American Zoologist 33: 524-53.

Roberts, H. H., Wilson, P. A., and Lugo-Fernandez, A. 1992. Biological and geological responses to physical processes: examples from modern reef system of the Caribbean-Atlantic region. Continetal Shelf Research 12 (7-8): 809-834.

Rogers, CS. 1990. Response of coral reefs and reef organisms to sedimentation. Marine Ecology Progress Series 62: 185-202.

Roy, K. J., Smith, S. V. 1971. Sediment and coral reef development in turbid water: Fanning lagoon. Pacific Science 25: 234-248.

Scheman, N.D., Khosrowpanah, S., Gollabi, M., and L. Heitz. 2002. Identification of erosion process and sources of exposed patches in the La Sa Fua watershed of southern Guam. University of Guam Water and Environmental Research Institute Technical Report No. 99. 70 p.

Stafford-Smith, M.G. 1993. Sediment-rejection efficiency of 22 species of Australian scleractinian corals. Marine Biology 115: 229-243.

Warwick, R.M., Clarke, K.R. and Suharsono. 1990. A statistical analysis of coral community response to the 1982-1983 El Nino in the Thousand Islands, Indonesia. Coral Reefs 8: 171-179.

West, K. and R. Van Woesik. 2001. Spatial and temporal variance of river discharge on Okinawa (Japan): inferring the temporal impact on adjacent coral reefs. Marine Pollution Bulletin 42 (10): 864-872.

Wilkinson, C. 2000. Status of coral reefs of the world: 2000. Australian Institute of Marine Science, Townsville, Australia, 364 pp.

Wolanski, E., R. H. Richmond., G. Davis., V. Bonito. 2003a. Water and fine sediment dynamic in transient river plumes in a small, reef-fringed bay, Guam. Estuarine, Coastal and Shelf Science 56: 1029-1040.

Wolanski, E. R. H. Richmond., L. McCook., and H. Sweatman. 2003b. Mud, marine snow and coral reefs; The survival of coral reefs requires intergrated watershed-based management activities and marine conservation. American Science: 91: 44-51.

Wolanski, E. 2003c. Presentation given at the University of Guam Marine Laboratory for: Water and fine sediment dynamic in transient river plumes in a small, reef-fringed bay, Guam.

Wolanski, E., R.H. Richmond, and L. McCook. 2004. A model of the effects of land-based, human activities on the health of coral reefs in the Great Barrier Reef and in Fouha Bay, Guam, Micronesia. Journal of Marine Systems 46: 133-144.

Van Woesik, R., and Done, T.J. 1997. Coral community and reef growth in the southern Great Barrier Reef. Coral Reefs 16: 103-115.

APPENDICES

APPENDIX A. GPS coordinates of all sediment stations placed in Fouha Bay.

Station	Latitude (°N)	Longitude (°E)
North stations		
F1N	13° 18' 23.52"	144° 39' 26.58"
F2N	13° 18' 22.74"	144° 39' 25.92"
F3N	13° 18' 21.44"	144° 39' 24.59"
F4N	13° 18' 20.40"	144° 39' 23.66"
F4ND	13° 18' 20.40"	144° 39' 23.66"
F5N	13° 18' 20.53"	144° 39' 22.46"
South stations		
F1S	13° 18' 23.13"	144° 39' 27.11"
F2S	13° 18' 22.09"	144° 39' 26.32"
F3S	13° 18' 21.31"	144° 39' 35.52"
F3SD	13° 18' 21.31"	144° 39' 35.52"
F4S	13° 18' 19.62"	144° 39' 25.39"
F5S	13° 18' 18.84"	144° 39' 24.46"

APPENDIX B. Annual rainfall, wind, and wave data for 2003.

Day number	Rainfall sum (mm/week)	Swell index	Onshore wind sum (km/h)
24	18.27	0	0
31	27.41	1	0
38	30.96	0	0
45	37.82	0	0
52	13.71	0	0
59	3.55	1	0
66	3.05	0	0
73	37.06	1	0
80	24.37	0	0
87	0	0	0
94	0	0	0
101	0	0	0
109	51.78	1	0
115	21.32	0	0
122	54.82	0	0
129	39.59	0	0
136	0	0	0
142	3.05	1	38.44
149	15.23	1	7.45
156	6.09	0	0
163	21.32	0	0
170	73.10	0	0
177	30.46	0	5.25
191	67.01	0	0
199	82.23	0	0
205	73.10	1	0
212	42.64	1	15.86
220	36.55	1	4.73
226	15.23	1	5.85
231	137.06	0	0
241	30.46	1	11.68
248	128.93	1	18.94
255	101.78	1	5.85
262	77.16	1	27.08

APPENDIX B. *Continued.*

Day number	Rainfall sum (mm/week)	Swell index	Onshore wind sum (km/h)
276	264.72	1	10.25
283	9.14	0	0
290	42.64	1	22.04
304	140.10	1	94.25
311	39.59	0	0
318	54.82	0	0
325	88.32	1	0
339	146.19	1	13.35
346	79.19	0	0
353	6.09	0	0
361	103.55	1	5.45

Appendix C. ANOVA Table: comparison of the northern inner stations (F1N and F2N).

Source of variation	Df	Sums of square	Mean Square	F-value	p value
Effect	1	0.0059	0.0404	0.1455	0.7041
Error	64	2.5826	0.0059		

Appendix D. ANOVA Table: comparison of the southern inner stations (F1S and F2S).

Source of variation	Df	Sums of square	Mean Square	F-value	p value
Effect	1	0.0451	0.0451	3.5608	0.0535
Error	66	0.8366	0.0127		

Appendix E. ANOVA Table: comparison of the northern outer stations (F3N, F4N, F5N).

Source of variation	Df	Sums of square	Mean Square	F-value	p value
Effect	2	0.1738	0.0869	2.3346	0.1023
Error	96	3.5750	0.0372		

Appendix F. ANOVA Table: comparison of the southern outer stations (F3S, F4S, F5S).

Source of variation	Df	Sums of square	Mean Square	F-value	p value
Effect	2	0.0559	0.0280	2.3749	0.0983
Error	99	1.6575	0.0118		

Appendix G. Kruskal-Wallis Multiple-Comparison Z-Value Test for the rough and calm conditions. Bonferroni Test: Medians significantly different if z-value >1.9600.

Water condition	Calm	Rough
Calm	0	3.5565
Rough	3.5565	0

Appendix H. ANOVA Table: comparison of sediment load for inner part of bay (North and South).

Source of variation	Df	Sums of square	Mean Square	F-value	p value
Effect	1	0.5699	0.5699	1.3528	0.2468
Error	138	58.1363	0.4213		

Appendix I. ANOVA Table: comparison of sediment load for outer part of bay (North and South).

Source of variation	Df	Sums of square	Mean Square	F-value	p value
Effect	1	0.3796	0.3796	0.9796	0.3236
Error	184	71.3076	0.3875		

Appendix J. ANOVA Table: comparison of sediment load among stations of the north.

Source of variation	Df	Sums of square	Mean Square	F-value	p value
Effect	4	10.0677	2.5169	7.7180	<0.01
Error	164	52.1777	0.32611		

Appendix K. ANOVA Table: comparison of sediment load among stations of the south.

Source of variation	Df	Sums of square	Mean Square	F-value	p value
Effect	4	12.9776	3.2444	5.6379	0.0003
Error	164	94.3755	0.5755		

Appendix L. ANOVA Table: comparison of shallow and deep stations (F3S and F3SD).

Source of variation	Df	Sums of square	Mean Square	F-value	p value
Effect	1	0.1524	0.1524	0.1996	0.6564
Error	74	56.5074	0.7636		

Appendix M. ANOVA Table: comparison of shallow and deep stations (F4N and F4ND).

Source of variation	Df	Sums of square	Mean Square	F-value	p value
Effect	1	0.1619	0.1619	0.2900	0.5919
Error	74	41.3181	0.5584		

Appendix N. ANOVA Table: comparison of shallow stations (F3S and F4N).

Source of variation	Df	Sums of square	Mean Square	F-value	p value
Effect	1	2.3641	2.3641	4.0614	0.0475
Error	74	43.0739	0.5821		

Appendix O. ANOVA Table: comparison of deep stations (F3SD and F4ND).

Source of variation	Df	Sums of square	Mean Square	F-value	p value
Effect	1	2.3273	2.3273	3.1455	0.0803
Error	74	54.7516	0.7399		

Appendix P. Coral species for the southern transect.

FAMILY	**Coral species**
ACROPORIDAE	*Acropora humilis*
	Acropora cophodactyla
	Acropora dana
	Acropora palmerae
	Acropora tenuis
	Acropora surrculosa
	Acropora occellata
	Acropora delicatula
	Acropora vallida
	Acropora moticulosa
	Acropora digitifera
	Astreopora listeri
	Astreopora myriophthalma
	Astreopora gracilis
	Montipora verrucosa
	Montipora foveolata
	Montipora sp.1
	Montipora ehrenbergii
	Montipora danae
	Montipora hoffmeisteri
	Montipora elschneri
SIDERASTREIDAE	*Psammocora obstusangula*
	Psammocora profunducella
	Psammocora nierstraszi
	Coscinaraea columna
FAVIADAE	*Favia pallida*
	Favia stelligera
	Favia mathii
	Favia favus
	Favia rotumana
	Favites abdita
	Favites russelli
	Goniastrea retiformis
	Goniastrea edwardsi
	Goniastrea pictinata
	Platygyra pini
	Platygyra daedalea

APPENDIX P. *Continued.*

	Oulophylia levis
	Leptoria phrygia
	Montastrea curta
	Diploastrea heliopora
	Leptastrea purpurea
	Leptastrea tranversa
	Cyphastrea chalcidicum
	Echinopora lamellose
PORITIDAE	*Porites cylindrical*
	Porites danae
	Porites rus
	Porites lobata
	Porites lutea
	Porites vaughani
	Porites horizontalata
	Porites compressa
	Goniopora columna
	Goniopora tenuidens
	Goniopora minor
	Goniopora fruticosa
AGARICIIDAE	*Pavona explanulata*
	Pavona varians
	Pavona minuta
	Pavona venosa
	Pavona divericata
	Pavona cactus
	Pavona duerdeni
	Leptoseris encrustans
	Leptoseris mycetoseroides
	Gardineroseris planulata
	Pachyseris speciosa
MUSSIDAE	*Lobophylia hemprichii*
	Lobophylia costata
	Lobophylia corymbosa
	Acanthastrea hillae
	Acanthastrea echinita
OCULINIDAE	*Galaxea fascicularis*

APPENDIX P. *Continued.*

FUNGIIDAE	*Fungia fungites*
POCILLOPORIDAE	*Pocillopora damicornis* *Pocillopora eydouxi* *Pocillopora verrucosa* *Pocillopora meandrina* *Pocillopora setchelli* *Stylophora mordax*
MERULINIDAE	*Merulina ampliata* *Hydnophora microconis*
DENDROPHYLLIIDAE	*Turbinaria stellata*
ASTROCOENIIDAE	*Stylocoeniella armata* *Stylocoeneilla guentheri*
NON-SCLERACTINIAN CORALS	*Millepora platyphyla* *Millepora dichitoma* *Millepora tuberosa* *Tubipora musica* *Stylaster gracilis*
TOTAL SPECIES	**92**