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MONITORING THE EFFECTS OF LAND DEVELOPMENT ON THE NEAR-SHORE REEF ENVIRONMENT OF ST. THOMAS, USVI

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ABSTRACT

This study evaluated the impacts of shoreline development on the coral reef at Caret Bay, St. Thomas USVI. Studies in rates of sedimentation, changes in water quality and changes in the abundance and diversity of corals and other reef organisms were conducted along five permanent transects from July 1997 and March 1999. Results from monthly monitoring before, during and after construction indicated that sedimentation and total suspended solids increased during large rainfall events, and that sediment load onto Caret Bay reef was greatest directly below ravine outlets and in locations where shoreline was sheltered. After buildings, landscaping and road paving were completed peak sedimentation rates decreased relative to average monthly rainfall. Visual assessment of coral condition documented that coral pigment loss was associated with both influx of terrigenous sediments and with natural seasonal phenomena. Bleaching of coral colonies during the 1998 bleaching event showed a strong positive relationship with sedimentation ($r^2 = 0.92$). Reef sites exposed to sedimentation rates between 10 to 14 mg cm^{-2} d^{-1} showed a 38% increase in the number of coral colonies experiencing pigment loss than reef sites exposed to sedimentation rates between 4 to 8 mg cm^{-2} d^{-1}. Coral cover along the entire reef tract declined about 14% (range: −3.92% to −31.34%). This decline in coral cover from pre- to post-construction surveys showed weak negative associations with sedimentation ($r^2 = 0.52$) and bleaching ($r^2 = 0.48$). Patterns of abundance of macro algae, sponges and encrusting gorgonians were primarily related to natural seasonal changes rather than to rates of sedimentation. This study provides evidence that stress from sedimentation may lead to decline in living coral through secondary effects such as bleaching. Monthly monitoring was able to detect changes in the reef environment associated with human activity and was able to segregate these changes from natural causes. The results of this study provide coastal managers quantitative measures of allowable sedimentation rates to better evaluate and mitigate future development in sensitive coastal areas.

Recent reports of coral reef deterioration and coral death throughout the Caribbean and other parts of the world focused attention on the potential contribution of man-made activities over this resource. Human activities resulting in over-fishing, sedimentation and nutrient enrichment are the primary sources of ecological stress for coral reefs (Roberts, 1993). Although the synergistic effect of these three human-related stresses can be severe, Sebens (1994) considered excess sedimentation to be the single greatest threat to coral reefs. Suspended sediments decrease light penetration and reduce photosynthesis and coral growth (Dodge et al., 1974; Rogers, 1979). Deposition of fine sediments onto the reef directly contributes to tissue loss or mortality due to smothering of coral colonies and reduces coral larvae settlement success (Rogers, 1979, 1983, 1990; Sebens, 1994; Sladek Nowlis et al., 1997). At the same time, sedimentation increases coral energy costs by increasing respiration while decreasing photosynthesis of symbiotic zooxanthellae (Lasker, 1980; Abdel-Salam and Porter, 1988). Chronic sedimentation may reduce the abundance and diversity of corals and other reef organisms, increase coral stress and susceptibility to diseases, bleaching and predation, and reduce the ability of corals and other reef organisms to recover and regenerate after natural disturbances such as hurricanes (Acevedo and Morelock, 1988; Rogers, 1990; Rice and Hunter, 1992).

Over the past several decades the Virgin Islands have experienced rapid development from the shoreline to the mountain tops. The removal of the natural vegetation and construction of unpaved roads has greatly increased erosion rates relative to natural conditions (MacDonald et al., 1997; Anderson and MacDonald, 1998). This load of silt and clay poses a direct threat to the health of the corals and other reef organisms (Rogers, 1990; Sladek Nowlis et al. 1997). The Virgin Islands Coastal Zone Management (CZM) has recognized this threat and has begun to implement a strict code for developers proposing to build projects in sensitive shoreline areas. In a recent case in St. Thomas, CZM required the developer of the Caret Bay Villas project to install and maintain strict sediment control measures as recommended by the University of the Virgin Islands Cooperative Extension Service (Wright, 1997). These measures included minimal disturbance of natural vegetation, properly built and maintained sediment fences and sediment basins, and placement of straw matting on bare soils until vegetative ground cover was established. The developer was also required to fund a 4 yr monitoring program intended to record the condition of the reef complex along the coast of the development and to determine if there were any adverse effects on the reef environment due to development.

One of the major challenges of reef assessment is to quantify the impact of development on the coral reef environment, while accounting for natural variation in the measured parameters. For management purposes, it is also important to determine the distribution of these sediments across the near-shore reef environment and to know when thresholds in the allowable amounts of sediment originating from a development are exceeded. The primary objectives of this study were to: (1) measure rates of sedimentation onto the coral reef, (2) monitor water quality, (3) quantify changes in the abundance and diversity of sessile reef organisms, (4) document the acute and chronic effects of sedimentation on coral condition, and (5) develop management guidelines for evaluating the effectiveness of sediment control measures. Within the scope of this project, we anticipated the strict sediment control measures to greatly reduce erosion and sedimentation. If sediment control measures were inadequate or were not properly maintained we expected the reef community to show signs of stress and mortality associated with excess sedimentation. We report on the results of the first two years of marine surveys conducted before, during and after construction of the Caret Bay Villas.

Materials and Methods

Study Site.—Caret Bay, located on the northwest side of St. Thomas, US Virgin Islands (N18°22′23, W 64°58′51), is exposed to the waters of the Atlantic Ocean (Fig. 1). The Caret Bay Villa development was positioned along a steep rocky hillside less than 50 m from the shoreline. The Caret Bay Villas construction site was initially hand cleared to expose general topography and reduce erosion (W. F. McComb, pers. comm.). Major land development (i.e., cutting roads, digging foundations) was initiated in late August 1997 and was largely completed by December 1998. Final landscaping was completed in April 1999. Two ravines or guts pass through the construction site. The large eastern ravine drains the Caret Bay watershed as well as receives runoff from the eastern half of the development. The smaller western ravine receives runoff from only the western half of the construction site.

The marine environment below the development consists of a fringing reef that slopes gently to 10 m depth then drops abruptly to a sand channel at 15 m depth. The reef edge is composed of large

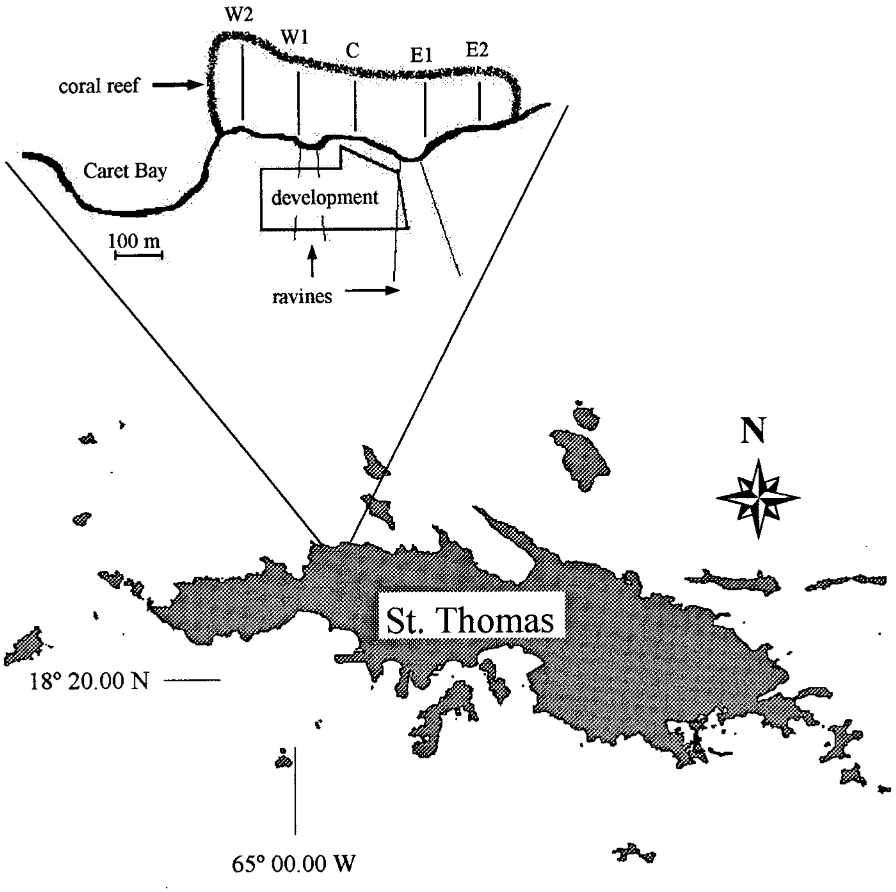

Figure 1. Caret Bay study site on north shore of St. Thomas showing location of five permanent transects (West 1, West 2, Central, East 1 and East 2), construction site and ravines (guts) draining hillside. Note that West 1 and East 1 transects were positioned directly below ravines. Also note the location of the small offshore islands northeast of the Caret Bay study site.

scleractinian coral colonies whereas the gently sloping platform is coral pavement with dense gorgonian growth and small, isolated corals and sponges. The distance from shoreline to reef edge varies in width from 75 m on the eastern boundary of the study site to 140 m on the western boundary (Table 1). Overall, the reef is fairly uniform with a marginal increase in coral cover and decrease in gorgonian density from west to east. Monitoring was conducted along five permanent transects established perpendicular to shore and about 100 m apart (Fig. 1). Selection of transect location was based on similarity in topography and reef habitat and represented a range of potential impacts. The Central transect was centered on the reef between the two ravine discharge points. Transects East 1 and West 1 were positioned at the discharge points of the east and west ravines, respectively. Transects East 2 and West 2 were positioned 100 m east and west of transects East 1 and West 1, respectively. Based on general surface current patterns (Dammann, 1969), it was assumed that transect East 2 was furthest upstream of the ravine discharge and would be least impacted by sedimentation whereas the western transects would receive most of the sediment entering the sea.

A pre-construction base-line survey of the coral reef below the Caret Bay Villa development was completed in July and August 1997. Surveys continued monthly through the first year and bimonthly

Table 1. Mean differences (± SE) in physical parameters among transects from July 1997 to March 1999. Grain size categories include coarse sand (<4.75–2.0 mm), medium and fine sand (<2.0–0.075 mm), and silt and clay (<0.075 mm).

Transect	West 2	West 1	Central	East 1	East 2
Transect length (m)	144	120	100	101	75
Avg. depth (m)	8.4	8.7	7.7	7.3	5.8
No. lost sediment traps	6	7	9	3	4
Sediment Load (mg cm^{-2} d^{-1})					
Shallow traps (5 m)					
Coarse sand	0.56 (0.25)	0.48 (0.21)	12.59 (8.26)	3.49 (1.15)	3.12 (1.30)
Med./fine sand	148 (46.37)	96.3 (31.14)	91.8 (28.79)	118 (29.44)	174 (51.92)
Silt/clay	7.2 (1.86)	13.1 (3.72)	8.1 (1.59)	11.0 (2.09)	11.0 (2.85)
Deep traps (12 m)					
Coarse sand	9.7 (5.39)	0.36 (0.14)	1.0 (0.91)	1.05 (0.48)	1.05 (0.59)
Med./fine sand	132 (56.95)	64.8 (16.22)	35.3 (10.52)	132 (33.94)	82.6 (23.47)
Silt/Clay	4.5 (0.85)	9.1 (1.83)	7.4 (1.56)	10.3 (2.18)	10.1 (2.27)
Water Quality					
TSS — mg L^{-1}	7.96 (0.51)	8.83 (1.76)	8.17 (0.73)	7.45 (0.32)	7.04 (0.53)
Turbidity — ntu	0.49 (0.09)	0.43 (0.08)	0.41 (0.01)	0.48 (0.33)	0.43 (0.04)

thereafter. Four months were missed due to extended periods of inclement weather (January and March 1998, February 1999) and to Hurricane Georges (September 1998), all of which generated large ground swells on the north shore of St. Thomas. Thus, data were collected for 2 mo pre-construction (July and August 1997), 16 mo during construction (September 1997 to December 1998) and 3 mo post-construction (January to March 1999).

SEDIMENT AND SEAWATER ANALYSIS.—Sedimentation was measured using sediment traps (5.2 × 20.8 cm) secured with cable ties and hose clamps to steel bars pounded into the coral pavement. Trap height above the sea floor ranged from 25 to 40 cm. Traps were set at the deep (~12 m depth) and shallow (~5 m depth) ends of each transect and were capped under water and replaced with empty traps during monthly visits. Sediment load was calculated as milligrams of sediment per area of trap opening per number of days traps were collecting. This value (mg cm^{-2} d^{-1}) gave a measure of chronic sedimentation or the flux of terrigenous sediments entering the sea and settling to the reef each month. Sediment that accumulated in the traps was rinsed with fresh water and oven dried. During winter months when large swells resuspended coarse sand and gravel, the sediment sample was sifted through a series of stainless steel US Standard Testing sieves for particle size analysis. Sediment that passed through the sieve with the smallest mesh (<0.075 mm) consisted of silt and clay particles that were considered terrigenous in origin (Gee and Bauder 1986). When accumulated sediment was minimal and consisted of only fine particles, as in summer months, trap contents were filtered with suction through pre-weighed glass fiber filters and rinsed with distilled water. The filter and sediment were dried at 100°C before weighing. Two-way ANOVA was used to test for differences in the amount of fine sediments (particles <0.075 mm) being deposited on the reef at each depth for each transect.

Seawater samples were collected monthly and following rain events that exceeded 1.27 cm [0.5 in] of rain in 24-h period. Two replicate samples were collected from the top 1 m along the near-shore end of each transect. These were analyzed for total suspended solids (TSS mg L^{-1}) and turbidity (nephelometric turbidity units – ntu). To measure TSS, 1 L of seawater was filtered through a pre-weighed glass fiber filter, rinsed with distilled water to remove salts, oven dried at 100°C and cooled in a desiccator before weighing. Turbidity was measured with a Hach 2100P turbidimeter. Replicate water samples were averaged and analyzed with a single factor analysis of variance test using either TSS or turbidity as dependent variable and transect as the independent variable. For this and all subsequent analyses the significance level for the F statistic was set at alpha = 5% ($P < 0.05$).

Precipitation.—Daily rainfall was recorded from a manual rain gauge at the Caret Bay construction site from July 1997 through December 1998. Due to incomplete rain data records after that date, subsequent rain data were obtained from rain gauges located in Estate Dorothea, 2 km east of Caret Bay, and in Estate Pearl, 3 km to the south. Overlapping rainfall data from the three locations were compared graphically and were found have a similar number and intensity of peak rainfall events.

Coral Reef Monitoring.—Percent cover of scleractinian corals, sponges and encrusting gorgonians was estimated monthly using 1 m^2 quadrats divided into 10×10 grid (100 10 cm^2 squares). Percent cover of macro algae was also recorded since an increase in terriginous sediments and associated nutrients may facilitate the growth of macro algae, which could compete directly with other reef organisms. Within the quadrat boundaries the number of up-right gorgonians were counted and identified to genus and coral colonies showing signs of bleaching, disease or damage were recorded. Quadrats were randomly placed along each transect line using numbers generated from a random number table. We usually completed 24 quadrats per transects, but occasionally could only complete as few as 10 due to rough sea conditions. Typically, each diver could complete between 6 and 12 quadrats per dive. Analysis of variance was used to compare the difference in percent cover and abundance of sessile organisms among transects. Paired T-tests were used to test the null hypothesis that no significant decrease in the density of scleractinian corals and up-right gorgonians occurred within transects from the beginning to the end of the study. This analysis compared the first three reef monitoring surveys (July, August and September 1997) with the last three surveys (November 1998, January and March 1999). Even though construction had already begun by late August 1997, the first three reef surveys were used for this analysis because this time period preceded any major rainfall events.

Focused monitoring was done on individual coral heads of *Porites astreoides* and *Montastrea annularis* located along each transect line at approximately 6, 9 and 12 m depths. These species were selected due to their sensitivity to sedimentation (Bak and Elgershuizen, 1976; Bak, 1978; Rogers 1983, 1990; Gleason, 1998). All but two of the *P. astreoides* were the green color morph, which is more sensitive to sedimentation than the brown color morph (Gleason, 1998). These small colonies (~15 cm diameter) were photographed monthly and the incidence of coral bleaching, disease, damage and death were recorded. In February 1998 large swells dislodged two *M. annularis* coral heads at 6 and 12 m on the West 1 transect. The 6 m coral head disappeared completely whereas the 12 m coral was broken from its narrow pedestal base. Two additional *M. annularis* colonies were selected as replacements. Large swells were also responsible for the loss of several shallow sediment traps during the study (Table 1).

Results

Sediment and Seawater Analysis.—Statistical analysis of terrigenous sediments deposited in traps (e.g., silt and clay particles <0.075 mm) indicated a significant difference among transects and depths (Transect: $F_{4,10} = 33.49$, $P < 0.0001$, Depth: $F_{1,10} = 22.57$, $P < 0.001$, Transect × Depth: $F_{4,10} = 7.342$, $P < 0.005$). More fine sediments were deposited in shallow (5 m) traps and on transects below ravines (East 1 and West 1) at both 5 and 12 m depths (Table 1, Fig. 2). East 2, the most easterly transect, received similar amounts of sediment as transects below ravines (East 1 and West 1), whereas West 2, the most westerly transect, received the least. The Central transect received the most amount of coarse sediments whereas medium and fine sediments were more common at opposite ends of the study site (Table 1). Coarse sediments were only deposited in sediment traps during months when large ground swells occurred.

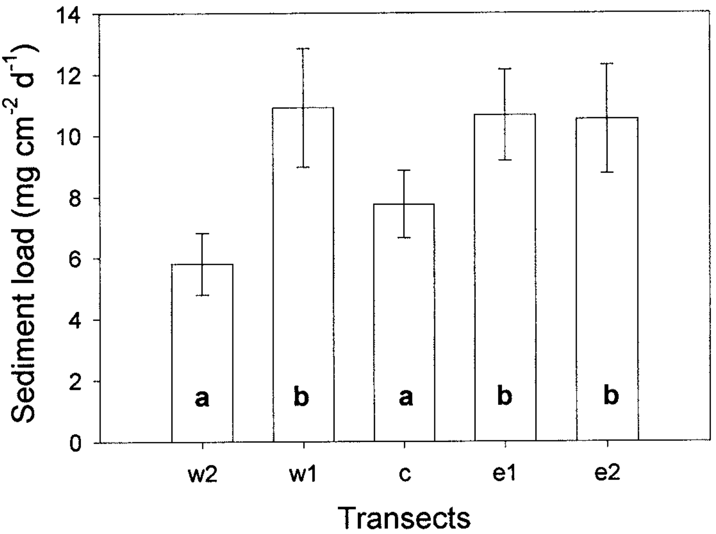

Figure 2. Average sediment load (± SE) from August 1997 to March 1999 among the five permanent transects: west 2 (w2), west 1 (w1), central (c), east 1 (e1) and east 2 (e2). Bars with the same internal letter were not significantly different (ANOVA, a = 0.05).

Monthly sediment load peaked in October and December 1997, and during April and October 1998 (Fig. 3). The October 1998 sampling period included rainfall associated with Hurricane Georges that passed over the Virgin Islands on 21 September 1998. Regression analysis indicated no significant relationship between daily rainfall and sediment load ($r^2 = 0.18$, $F_{1,23} = 2.44$, $P = 0.147$). Lack of a relationship occurred because the magnitude of sedimentation changed relative to rainfall during the course of construc-

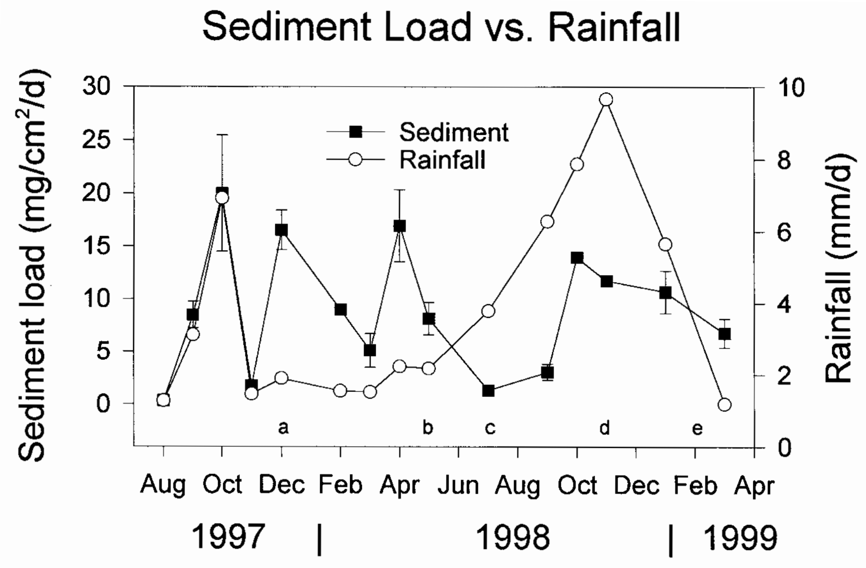

Figure 3. Sediment load (± SE) in relation to average daily rainfall and progress of development: a) building foundations complete, b) 60% of roads paved, c) 90% of roads paved, d) all roads paved, e) 80% landscaped.

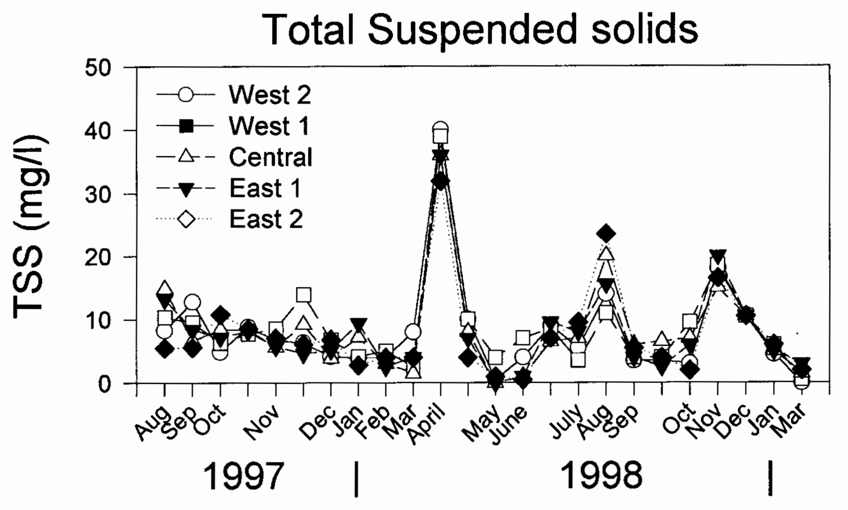

Figure 4. Total suspended solids (TSS) from sea water samples collected monthly and after rainfall events that exceeded 1.25 cm in 24 h.

tion. Sedimentation rate closely tracked rainfall during the first 4 mo of construction (August to November 1997), was high relative to rainfall during the next five sampling periods (December 1997 to May 1998) then low relative to rainfall in the five subsequent sample periods (July 1998 to January 1999). Progress that reduced exposed soils at the construction site included pouring the building foundations, paving the three roads accessing the site and landscaping. Foundations were completed by December 1997, scheduled paving had completed 60% of the road surface area by February 1998, 90% by July 1998, and 100% by November 1998 and 80% of landscaping was complete by February 1999 and 100% by April 1999. Evidence of sediment on the Caret Bay reef was only observed during calm summer months (June to August) when fine sediments accumulated in depressions on the coral pavement between coral heads. At other times of the year, storm surge cleared fine sediments from the reef surface.

No significant differences in total suspended solids ($F_{4,5} = 1.11$, $P = 0.446$) or turbidity ($F_{4,5} = 0.72$, $P = 0.616$) were found among transects. Peaks in TSS were detected in April, August and November 1998 (Fig. 4). No clear patterns emerged from turbidity data. Regression analysis was used to examine if there was a relationship between the amount of rainfall 1 d prior to water collection and TSS and turbidity. No relationship for either TSS ($r^2 = 0.01$, $f_{1,28} = 0.174$, $P = 0.68$) or turbidity ($r^2 = 0.11$, $f_{1,23} = 2.94$, $P = 0.10$) was found.

Coral Reef Monitoring.—Coral condition was evaluated both from monthly photographs of individual *P. astreoides* and *M. annularis* corals and from monthly quadrat data. Besides the two *M. annularis* colonies that were dislodged in February 1998, no mortality of individual coral heads occurred at the 6, 9 or 12 m stations up to April 1998. Examination of the photographic slides of each coral head revealed a large number of *M. annularis* with white spots. Incidence of white spots increased dramatically from August to October 1997 (Fig. 5). Closer inspection of these white spots revealed that they resulted from a variety of conditions including spotty pigment loss (Rogers, 1983), predation by parrot fish (Bruckner and Bruckner, 1998) and *Coralliophila abreviata* (Bruckner et al., 1997), and the natural pigmentation pattern of *M. franksi* (Weil and Knowlton, 1994). There was

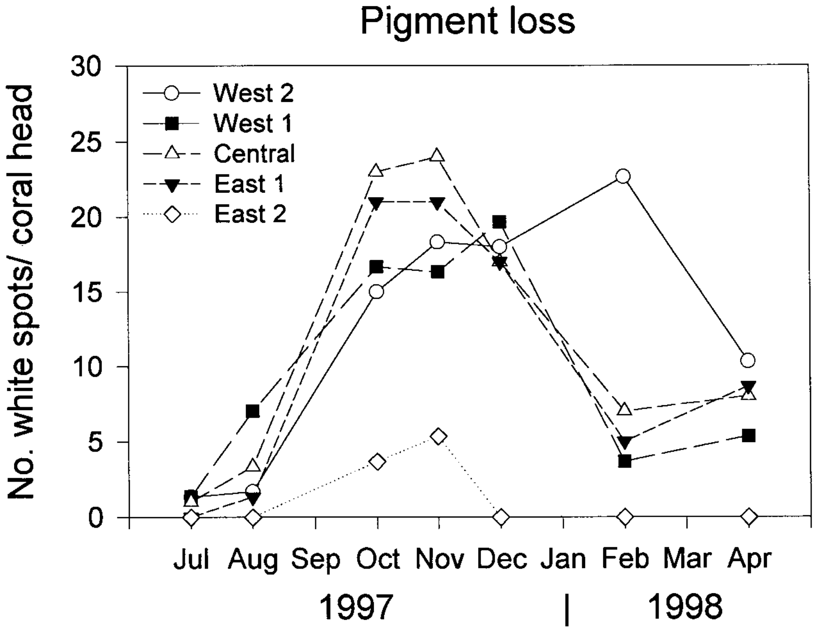

Figure 5. Development of white spots counted on *Montastrea annularis* coral heads (n = 3 per transect) using monthly photographs.

a general trend of white spot reduction into the spring of 1998. Why all these factors coincided is unknown but may have been related to stress associated with peak sedimentation in October 1997. *P. astreoides* showed no incidence of stress, disease or predation.

Data recorded by divers on coral condition within quadrats revealed seasonal low-level bleaching during July and August (Fig. 6). The Caribbean-wide bleaching event that occurred in the fall of 1998 was also detected at Caret Bay. We documented that bleaching of corals along all transects peaked in October 1998 (Fig. 6). Average percent bleaching (% ± SE) in October 1998 for each transect was: W2 (23.93% ± 6.081), W1 (39.65% ± 5.437), C (22.64% ± 4.877), E1 (37.55% ± 5.823) and E2 (37.22% ± 5.886). Although most corals had regained pigment by March 1999 some mortality was observed throughout the study site.

The extent of mortality due to bleaching and other factors was 14% along the reef tract (Fig. 7). The decline in coral cover from the first three surveys to the last three surveys ranged from 3.92 to 31.34% (Table 2), but this change was significant for only transect East 1 (Fig. 7). No significant changes occurred in the number of gorgonians or other organisms between the beginning and end of the study, although encrusting gorgonians and sponges showed seasonal peaks in November and the macro algae *Dictyota* sp. was most abundant during early spring. Simple linear regression was used to calculate the relationship between decline in coral cover, percent bleaching and sedimentation. Bleaching data were obtained from the October 1998 survey and represented peak bleaching recorded on Caret Bay reef (Fig. 6). The results indicate a weak negative correlation between percent change in live coral cover with both sedimentation rate ($r^2 = 0.523$) and percent bleaching ($r^2 = 0.481$, Fig. 8). Regression analysis indicated a strong positive relationship existed between sedimentation and percent bleaching ($r^2 = 0.918$, Fig. 8).

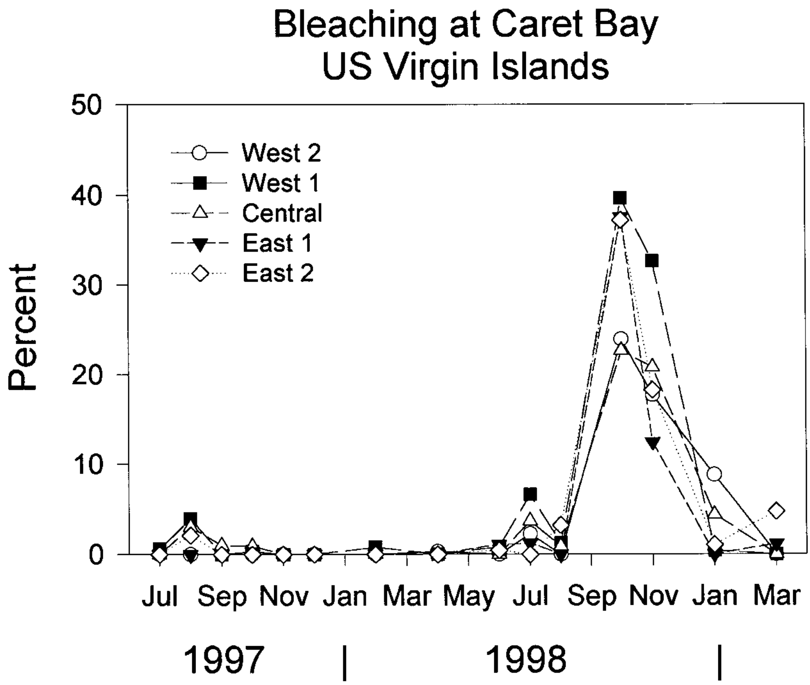

Figure 6. Percent bleaching in corals at Caret Bay study site. Data were obtained during quadrat survey of coral abundance along the five transects.

Reef sites exposed to average sedimentation rates between 10 to 14 mg cm^{-2} d^{-1} showed a 38% increase in the number of coral colonies experiencing pigment loss than reef sites exposed to sedimentation rates between 4 to 8 mg cm^{-2} d^{-1}.

The 12 most common coral species composed over 95% of the coral cover on the Caret Bay reef. Six of these 12 coral species showed declines in abundance between the first three and the last three reef surveys, albeit only *Millepora* spp. was statistically significant (Fig. 9). Actual observed mortality due to bleaching included several species of corals, most notably small colonies of *Acropora cervicornis*, *Diploria strigosa, D. clivosa*, *Millepora* spp., *P. astreoides* and *Agaricia agaricites*. Moreover, two *M. annularis* colonies were dislodged from the reef by large ground swell. Other scleractinian corals recorded, in order of relative abundance, were *Dichocoenia stokesii*, *Colpophyllia natans*, *Favia fragum*, *Meandrina meandrites*, *A. cervicornis*, *Dendrogyra cylindrus*, *Mycetophyllia* spp., and *Cladocora arbuscula*. The most common gorgonians included *Briarium asbestinum, Plexaura* spp., *Pseudopterogorgia* spp., *Pseudoplexaura* spp. and *Gorgonia* spp., respectively.

Discussion

Four major findings emerged from this monitoring study. First, the distribution of fine sediments along the reef generally followed patterns found in other studies (Sladek Nowlis et al., 1997). Eroded sediments discharged into the sea by storm-water runoff were generally deposited with increased proximity to ravine outlets. Based on the general current

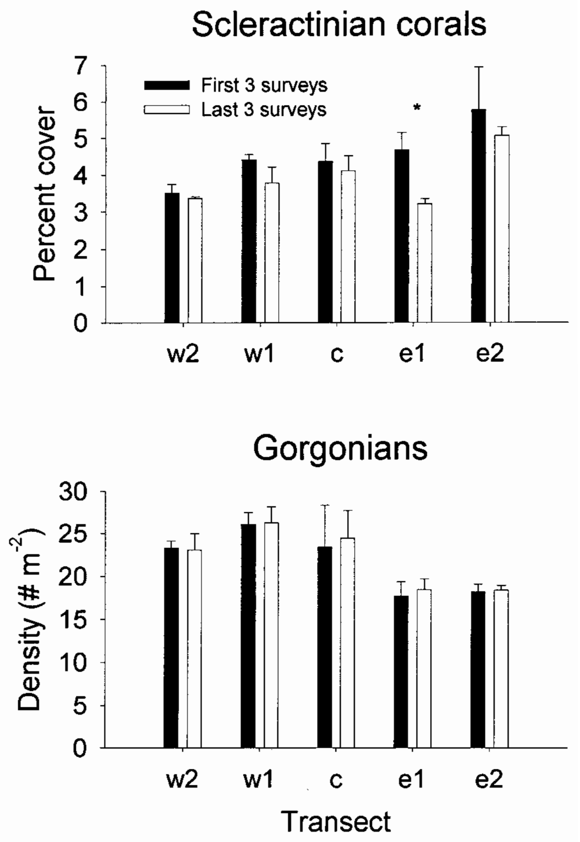

Figure 7. Percent cover of scleractinian corals and density of upright gorgonians at Caret Bay study site during the first three (pre-construction) and last three (post-construction) reef surveys. One-factor ANOVA revealed significant differences among transects for corals ($F_{4,70} = 11.42$, $P < 0.0001$, Tukey post-hoc test: e2 > e1, c, w1, w2; c > w2) and for gorgonians ($F_{4,70} = 26.69$, $P < 0.0001$, Tukey post-hoc test: e2, e1 < c, w1, w2). Paired T-tests of coral and gorgonian abundance between pre- and post-construction surveys indicated a significant decline in coral cover on transect e1 ($t = 3.67$, df = 2, $P = 0.03$).

Table 2. Mean differences (± SE) among transects in biological parameters from July 1997 to March 1999. Parameters include abundance (percent cover), diversity of reef organisms and the change in percent cover of scleractinian corals between July 1997 and March 1999.

Transect Species abundance and diversity	West 2	West 1	Central	East 1	East 2
% hard coral	3.6 (0.56)	4.2 (0.65)	4.5 (0.87)	3.9 (0.60)	5.2 (1.01)
% change in coral cover	–3.92	–14.06	–5.75	–31.34	–12.29
% encrusting gorgonian	1.7 (0.38)	1.9 (0.38)	2.2 (0.39)	2.0 (0.42)	1.6 (0.48)
% sponge	2.7 (0.47)	2.2 (0.32)	2.5 (0.38)	2.2 (0.31)	2.3 (0.48)
% macro algae	1.2 (0.46)	1.1 (0.25)	1.3 (0.39)	1.8 (0.33)	1.9 (0.49)
# gorgonians	24.3 (1.65)	27.4 (1.88)	26.1 (1.87)	18.6 (1.32)	18.9 (1.38)
# gorgonian genera	10	10	10	9	9
# coral species	17	17	17	17	18

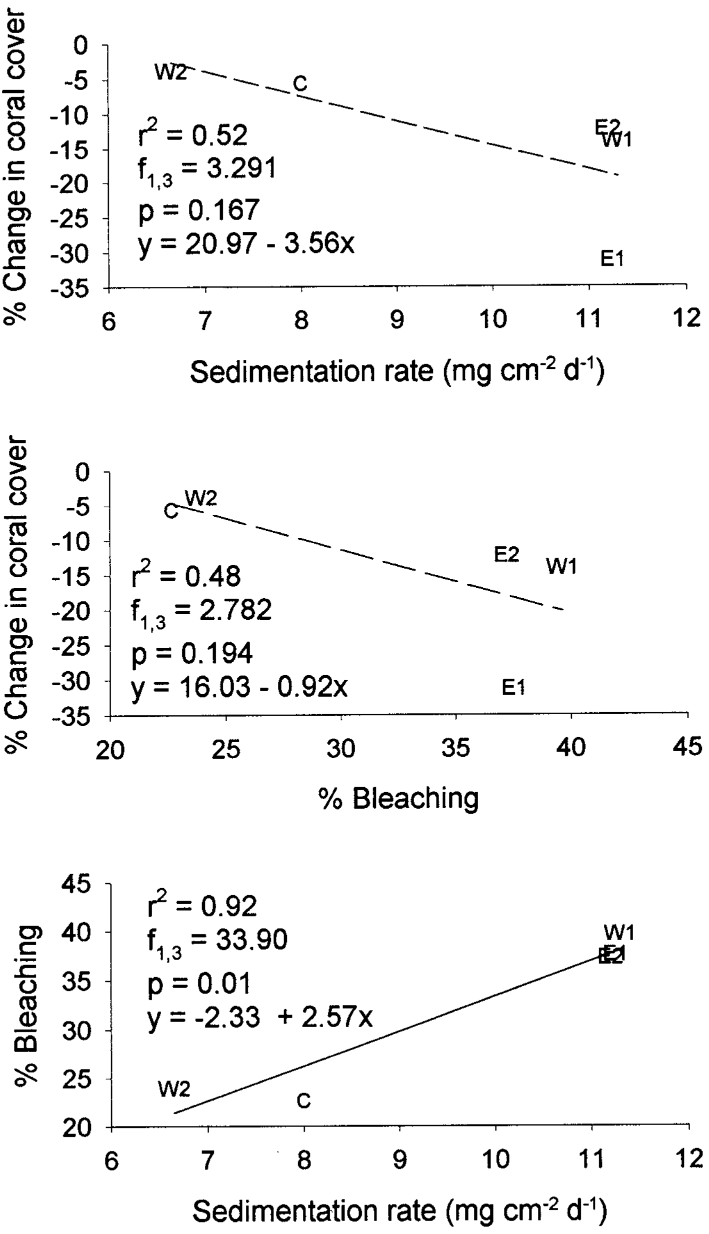

Figure 8. Relationships between, a) average sedimentation rate and percent change in coral cover, b) % bleaching and % change in coral cover, and c) average sedimentation rate and % bleaching during the first three and last three reef surveys of the five transects: west 2 (W2), west 1 (W1), central (C), east 1 (E1) and east 2 (E2).

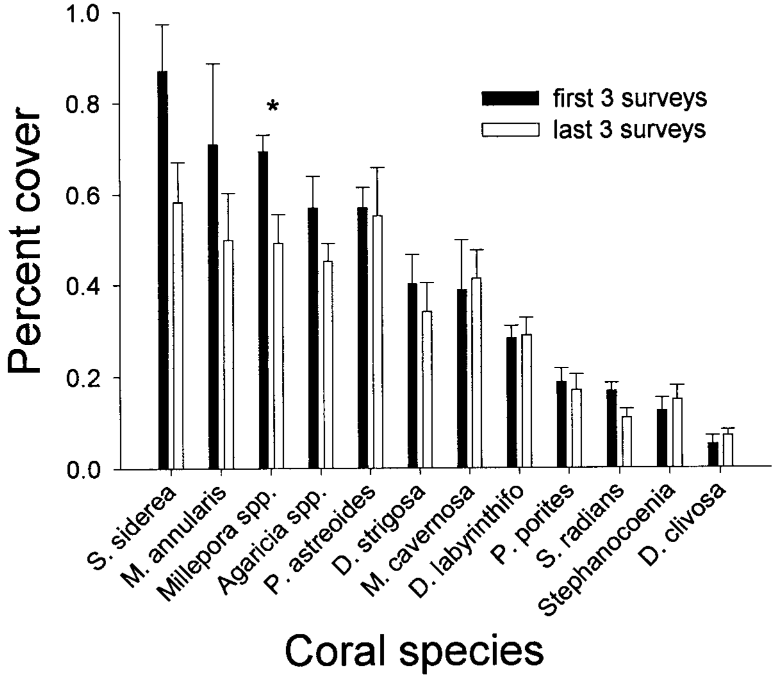

Figure 9. Percent cover of the 12 most common coral species along the Caret Bay reef during the first three and last three reef surveys. * $F_{1,28} = 5.326$, $P = 0.028$.

pattern along the north shore of St. Thomas (Dammann, 1969), the predicted sediment distribution path was westward. On the contrary, the most easterly transect (East 2) received a greater amount of sediment than predicted while transects West 2 and Central received the least (Table 1, Fig. 2). Two hydrodynamic features of the Caret Bay site may have contributed to this result. When seas were large the typical east-to-west current reversed (R.S.N. pers. observ.). Moreover, the eastern end of the study site was sheltered from large swells by Inner and Outer Brass Islands located less than 2 km northeast (Fig. 1). Since large swells were typically associated with heavy rainfall, any sediment entering the sea would be carried eastward with the reversed current and, as the sediment-laden water moved into the lee of the Brass Islands, the suspended sediments would have a greater chance of settling onto the reef. Thus, transect E2, which was expected to be a low-impact site, actually received some of the highest amounts of sediment. Placing transects too close to the source of sedimentation was one of the primary limitations of this monitoring study. More distant control sites would have minimized the effect of localized currents and eddies and would have provided greater resolving power to the experimental design.

The second major finding of this study was that patterns of sedimentation, relative to monthly rainfall, were related to the progress of construction. Sedimentation rates tracked monthly rainfall during the first four months (August to November 1997), exceeded rainfall during the next 6 mo (December 1997 to May 1998), and then were lower relative to rainfall during the last 8 mo (June to January 1999). The magnitude of sediment runoff during these periods corresponded roughly with the construction schedule in that the largest area of exposed soil occurred between October 1997 and April 1998. During the same time period of the following year rainfall greatly exceeded 1997 levels but sedimentation rates were considerably lower relative to rainfall (Fig. 3). Reduced sedimentation rates could be attributed to the progress of construction where 90% of the dirt roads accessing the site were paved by July 1998 and a majority of the site was landscaped by February 1999. The intensity of tropical rain showers on bare soils promotes suspension and movement of soil particles, and road cuts concentrate and accelerate storm water runoff further increasing erosion. Unpaved roads and lack of vegetative cover are the primary sources of sedimentation in the Virgin Islands (MacDonald et al., 1997; Sladek Nowlis et al., 1997; Anderson and MacDonald, 1998), therefore changes in these parameters (i.e., area of exposed soil) will greatly influence erosion rates.

The third major finding of this study was that the percent cover of living coral decreased from 4.55 to 3.91% across Caret Bay reef, representing a 14% decline over 18 mo. Mortality of coral colonies on Caret Bay reef could have resulted from dislodgment by large waves during winter months, smothering due to excess sedimentation or death due to pigment loss. Direct mortality due to dislodgment by large swells was documented. It is well known that large waves associated with hurricanes can have a devastating effect on shallow water coral communities (Woodley et al., 1981; Rogers et al., 1982; Edmunds and Witman, 1991; Hubbard et al., 1991; Rogers et al., 1991; Bythell et al., 1993). However, it is unlikely that excessive wave energy produced the patterns of coral mortality observed at Caret Bay (Table 2). If the amount of coarse sand collected in the sediment traps and the number of lost sediment traps are used as a measure of wave energy at each transect, then Central transect should have received the greatest wave energy and shown the greatest decline in coral cover (Table 1). Moreover, the sheltering effects of the Brass Islands would have provided greater protection to the eastern end of the study site, an area that actually showed the greatest decline in coral cover.

It is also unlikely that the coral mortality at Caret Bay was caused from direct smothering by sediment since this condition was never observed. A more likely scenario, as suggested by the results, is that mortality was related to both the indirect effects of sedimentation ($r = 0.72$) and bleaching ($r = 0.69$). The strongest piece of evidence, and the fourth major finding, was that bleaching of corals was strongly correlated to sedimentation rates ($r = 0.96$). This suggests that excessive levels of suspended sediments increased coral susceptibility to lethal bleaching. Bleaching is often the initial response of corals to sediment stress, whether from accumulating particles or from reduced light levels from high turbidity (Rogers, 1990). Many studies have documented that sediments applied to coral tissue, either experimentally or from human or natural events, can result in bleaching, tissue loss or death of the coral colony (Goreau, 1964; Rogers, 1979, 1983; Marszalek, 1981; Acevedo and Morelock, 1988; Sladek Nowlis et al., 1997; Gleason, 1998). Studies examining species-specific responses to direct application of sediments to coral tissue in field and lab trials have produced variable results (review by Rogers, 1990). The indirect effects of reduced light intensities from suspended sediments may limit the photosynthetic capacity of the symbiotic zooxanthellae and result in their death or expulsion (Roy and Smith, 1971; Dodge et al., 1974; Loya, 1976; Bak, 1978; Dallmeyer et al., 1982; Abdel-Salam and Porter, 1988). By shading corals as a partial simulation of extreme turbidity, Rogers (1979) found that nearly all coral species in the treatment area showed some signs of bleaching and that *A. cervicornis* was the most sensitive species, followed by *M. annularis*, *Diploria labyrinthiformis* and *D. strigosa*. In Caret Bay sensitivity to high turbidity may have caused the decline in abundance of *S. siderea*, *M. annualris*, *Millepora* spp., *Agaricia* spp., *D. strigosa* and *S. radians*.

The large-scale bleaching event that occurred in the fall of 1998 provided a fortuitous opportunity to examine the synergistic effects of human-induced stresses and stress associated with natural phenomena. Reef sites exposed to average sedimentation rates between 10 to 14 mg cm^{-2} d^{-1} showed a 38% increase in the number of coral colonies experiencing pigment loss than reef sites exposed to sedimentation rates between 4 to 8 mg cm^{-2} d^{-1}. The 10 mg cm^{-2} d^{-1} threshold value coincides with the chronic sedimentation threshold suggested by Rogers (1990). Using this threshold value, average sediment load over the entire reef tract exceeded 10 mg cm^{-2} d^{-1} during six of the 13 sampling periods (Figure 3) indicating that the Caret bay reef was under chronic sediment stress nearly 50% of the time.

The 10 mg cm^{-2} d^{-1} threshold sedimentation level provides a useful benchmark for coastal zone managers to establish policy on environmental tolerance standards, to evaluate sediment control measures and to enforce environmental regulations when it is determined that a development has exceeded acceptable levels of erosion. However, this threshold must be applied carefully since it may greatly exceed tolerable levels of sedimentation at other coastal sites such as sheltered bays and lagoons. In order to enforce environmental control measures, managers need to identify the amount of sediment originating from a development. This can be difficult since erosion occurring elsewhere in a watershed could also contribute to sediment entering the sea. At the Caret Bay development, terrigenous sediments discharged from the large eastern ravine may have originated from the construction site but also from erosion higher in the watershed. Unfortunately, no information was available on other sources of erosion occurring within the Caret Bay watershed during this study. However, we can infer the level of sediment originating from the Caret Bay villas construction site based upon sediment load from the western ravine. Under natural conditions the western ravine drained very little runoff since it was located on a small ridge. During construction of the villas storm water runoff draining the western half of the construction site was diverted into the western ravine. Therefore, sediment discharged from the western ravine and measured along the shallow reef at West 1 transect (i.e., 13.3 mg cm^{-2} d^{-1}) provided a reasonable estimate of monthly sedimentation rates originating from the Caret Bay development.

The potential impact of terrigenous sediments on coral reefs will depend upon the characteristics of the watershed, site-specific conditions of the adjacent marine environment and mitigation efforts. This study provides evidence that coral reef monitoring and assessment are essential in determining the level of impact associated with sedimentation from land development. The need for well designed long-term studies will help to document and develop a database of site-specific effects of coastal development on coral reef communities. Our data indicates that monthly sampling was sufficient to detect seasonal changes in the condition and abundance of reef organisms. Longer intervals between surveys may lead to false interpretation of results when data collection happens to coincide with the seasonal decline or increase of reef organisms. This study could have been improved if more time was allowed for pre-construction monitoring and if control sites were placed greater distances from the source of sedimentation.

Best Management Practices are guidelines that stress responsible development of our coastal resources but are only effective if enforced on all major construction projects.

Although the Caret Bay Villas development represented a ‘best case’ scenario, two important factors contributed to an excess of sediment entering the marine environment: improper timing of development and lack of maintenance of sediment control devices. Development in tropical regions should be scheduled so that major excavations occur at the beginning of the dry season. The Caret Bay Villas project was started at the beginning of the rainy season, which increased the likelihood that intense rain showers would erode exposed top soil. At the Caret Bay development sediment control devices were properly installed, but maintenance of these devices was neglected. During two visits to the construction site the author (RSN) documented improperly maintained sediment basins and a damaged silt fence. The sediment basins, which are designed to receive major runoff and trap and hold sediments before they enter ravines, were filled to capacity with fine sediments from the construction site. Once filled, runoff laden with sediment flows unrestricted over the top of the basin and enters the sea. Proper maintenance requires that sediment basins are emptied regularly and accumulated sediment disposed of properly. On a second visit, the author (R.S.N.) photographed a section of sediment fence that had been undercut allowing large amounts of trapped sediments to pass under the mesh. When this occurs, fine clay and silt that have accumulated over several months are suddenly flushed onto the coral reef. This large pulse of fine sediments can be more detrimental to corals than if these sediments entered the sea gradually over longer periods of time. More frequent inspections by environmental enforcement agents could have prevented this lack of maintenance through the implementation of written warnings to the developer and subsequent fines if no action was taken. Unless managers implement appropriate mitigation plans to reduce or eliminate the impact of development on the reef community, conduct regular inspections of all major developments and strictly enforce environmental regulations, coral reefs will continue to be threatened and damaged by human activities.

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