VIRGIN ISLANDS RESOURCE MANAGEMENT COOPERATIVE

BIOSPHERE RESERVE RESEARCH REPORT NO.20

A GENERAL REVIEW OF SEDIMENTATION AS IT RELATES TO ENVIRONMENTAL STRESS IN THE VIRGIN ISLANDS BIOSPHERE RESERVE AND THE EASTERN CARIBBEAN IN GENERAL

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U.S. MAN AND THE BIOSPHERE PROGRAM

Virgin Islands National Park

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ABSTRACT

This report discusses the impacts of sedimentation on tropical marine environments. Because of the greater susceptibility of reefs, the majority of the discussion is aimed at this specific environment. Included are:

1. A review of the general types of sediment stress that occur in marine systems.

2. A discussion of the critical parameters that should be measured in any study of sediment stress.

3. A discussion of sources of sediment stress in the Caribbean, including examples from within the V.I.. Biosphere Reserve, the U. S. Virgin Islands and the eastern Caribbean.

4. A more specific treatment of area-wide problems, along with strategies that exist or should exist to cope with them.

This document is not meant to be an exhaustive review of the subject. Rather, it is intended to highlight the problems, provide some reasonable management guidelines, and serve as a starting point for developing future VIRMC projects dealing with this important topic. A synthesis such as this will never totally satisfy the needs of all individuals. Hopefully it can be a useful reference tool for those interested in pursuing the problem further.

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INTRODUCTION

Background

This is a final report to the Virgin Islands Resource Management Cooperative (VIRMC) outlining a number of topics related to the impacts of sedimentation within the V. I. Biosphere Reserve (VIBR). Specifically, the tasks initially outlined include:

1) A review of the literature on the impacts of sedimentation on tropical marine ecosystems ;

2) A review and evaluation of USVI and Federal legislation, policy and programs to control sedimentation in the USVI ;

3) A discussion of the general causes of sedimentation and its impacts within the V.I. Biosphere Reserve, the U. S. Virgin Islands and the eastern Caribbean ;

4) Recommendations on specific watershed management tools that might be useful within and around the V.I. Biosphere Reserve ;

5) A prioritized list of future research projects that would address site-specific problems within the VIBR.

This report is divided into two main sections. The first deals directly with sedimentation as it impacts marine systems (i.e. items 1 and 3). The primary focus will be on the coral reef system for two reasons. First, it is probably the most sensitive and least understood of the nearshore tropical marine ecosystems (mangroves, seagrass beds and reefs). Second, the focus of the management strategy within the VIBR with respect to sedimentation is likely to center primarily around reefs.

The second section specifically discusses the state of present protection measures with respect to sedimentation. The focus is on present strategies to stem sedimentation (item 2), as well as potential management approaches that might be useful to provide additional protection (item 4). Consistent with the embryonic state of our knowledge, the final recommendations must be somewhat general and cannot be imposed on every site-specific problem with equal vigor. Nevertheless, it is hoped that they will provide a useful framework from which to build a rational management plan within the VIBR.

The following discussions are not intended to exhaust the subject of sedimentation in the nearshore tropical system. Nor do they purport to reference all the critical papers on the subject. The complexity of the process and the poor level of understanding largely preclude this possibility. Furthermore, the background of the author, and thus the interpretations of the available literature; must reflect a physical bias toward the subject. The primary goal of this report is to help the reader appreciate the state of our knowledge and the problems upon which we must focus if we are to understand these complex processes.

Statement of the Problem

The literature dealing with sedimentation in the marine environment is certainly extensive. However, despite the great number of papers dealing with the subject, our understanding of its impacts is still in its infancy. Central to the problem are two things: 1) the lack of baseline data before sedimentation events, and 2) the lack of long-term field measurements relating increasing levels of sedimentation to metabolic processes within individual organisms.

As an example of the latter problem, several short-term or laboratory studies (e.g. Thompson, undated; Rogers, 1983) have demonstrated a surprising tolerance on the part of certain corals to short-term high doses of sediment. Yet, the literature is replete with what amounts to post-mortem autopsies of reefs destroyed by sedimentation during and after dredging in nearby environments. At the crux of this problem are the differences between high doses of sediment over a short period (acute stress) vs. much lower doses on a continuous basis (chronic stress). This is compounded by the general lack of baseline data on the condition of various marine areas prior to stress and subsequent degradation.

This problem surrounds our ignorance of the specific metabolic processes that occur within potentially affected organisms as levels of stress progressively increase. For example, a storm will have a greater impact on a marine environment that is already stressed by background sedimentation than one which occurs in pristine conditions. Before we can understand these cumulative effects, however, we must come to grips with the organism-level response to individual stresses.

Our attempts to model nearshore marine systems tell an unfortunate tale of confusion. Aller and Dodge (1974) and Dodge, et al. (1974) studied sedimentation in Discovery Bay, Jamaica. They concluded that the small size of the coral heads was an adaptation to sediment stress whereby smaller colonies would have a shorter distance to move sediment and clear the colony. Thus larger heads would eventually die, leaving the size distribution they observed. In contrast, Maragos (1974 a, b) interpreted the presence of all larger heads as a reflection of the same sediment stress. His logic centered around the inability of coral larvae to successfully recruit under conditions of high sediment load. Thus, the only corals that remain are those that recruited successfully prior to the existing conditions of high turbidity.

The above example typifies the problems in dealing quantitatively with the topic of sediment stress. Either one set of researchers is wrong about the controls of sedimentation, or else the controls in the two areas of study are somehow different from one another. In either case, extreme confidence in our quantitative understanding of the problem is probably not warranted. Attempts to model the interactions of tropical marine systems (e.g. Berwick and Chamberlin, 1985) have raised some "interesting" possibilities, but unfortunately will do little to understand the complex nature of the problem until realistic input data for such models are available.

In this respect, we are really back at the beginning. We certainly understand that sedimentation is (generally) detrimental to marine systems at some level. The problem centers around determining at what level that will occur, and how that might be incorporated into a rational management scheme that allows human entry into such fragile areas. Certainly mangroves are less susceptible to siltation than reefs; in fact, mangrove systems thrive under some conditions of high sedimentation in the absence of associated pollutants (e.g. heavy metals). Seagrasses, while more susceptible to sedimentation than mangrove complexes, can still tolerate a wide range of turbidity and sedimentation compared to coral reefs. As coral reefs are probably the best-represented of the major nearshore systems in the VIBR, and are profoundly affected by sediments at all levels, they become the most problematic in terms of management.

This report will first look at the types of impacts typically occurring during sedimentation events. While seagrasses and mangroves are considered (although briefly), the main focus is on coral reefs. The impacts on mangrove and seagrass systems are more related to direct removal (i.e. dredging, deforestation) than to indirect sedimentation. Thus, the management strategy becomes less dependant on understanding a complex cause-and-effect relationship and more one of strict preservation. Coral reefs, in contrast, are potentially affected by any marine or upland activity. They therefore become the most problematic from a management standpoint, and are the primary focus of this report.

The following section attempts to generally summarize the impacts of sedimentation on reefs. The discussion concentrates on scleractinean corals for three main reasons. First, they appear to be the most intolerant species present on the reef, and therefore represent the most critical problem in developing a management strategy. Second, the experience of the author is more broadly based with respect to scleractinean corals. And, finally, the available literature relating sedimentation to distributions of other organisms is limited and inconclusive.

With respect to the latter point, it probably is safe to say that octocorals, sponges, crinoids and a host of other organisms are more tolerant of (and in some instances thrive on) sedimentation. While it is not intended to ignore the importance of these organisms on modern reefs, their usefulness in the context of this discussion is more related to identifying conditions less favorable to stony coral growth. Thus, their occurrence is more useful in establishing ambient conditions. With respect to management, they become less problematic (although not wholly unimportant) from the standpoint of preserving water quality.

TYPES OF SEDIMENT IMPACTS

Increased sedimentation can adversely impact coral reefs in a variety of ways. These include:

1) smothering of the coral by settling;
2) reducing incident light by turbidity;
3) scouring of the coral by bedload transport of primarily sand;
4) inhibiting recruitment by juvenile corals.

Smothering

Of all the potential impacts, smothering is probably the easiest for a layperson to visualize. Dredging next to a reef suspends sediment and that material is moved in the prevailing currents until it settles on the nearby reefs. Certainly much of the damage documented from past dredging projects (Nichols, *et al.*, 1972; Johannes, 1975; Dodge and Vaisnys, 1977; Bak, 1978; Taylor and Saloman, 1978) is related to the direct impact of sediments smothering reef organisms. Loya (1976) cited similar references to sediment damage in Australia (Fairbridge and Teichert, 1948), Johnston Island (Brock, *et al*, 1966), Hawaii (Johannes, 1975; Maragos, 1972), Puerto Rico (Kaye, 1959) and the Virgin Islands (van Eepoel and Grigg, 1970). Impacts due to increased runoff from the land have been discussed along the west coast of Puerto Rico by Morelock, *et al*. (1983). On Algarrobo Reef off Mayaguez, coral cover is presently below 2%, and is dominated by *Porites asteroides* and *Montastrea cavernosa*. At nearby Escollo Rodriguez Reef, increased runoff over recent decades has deposited up to 1 m of fine silt on the backreef and eliminated all coral cover.

Even those corals that successfully cope with elevated levels of sedimentation must pay a price in the removal of that material. Energy must be expended in mucus production, polyp expansion, or whatever sediment-clearing strategy an individual organism might employ. Different corals deal with sediment in different ways. Some depend almost solely upon external physical energy (e.g. waves and currents) to remove sediment and, therefore, are severely limited in the environments they can occupy. Some (e.g. Madracis mirabilis) move sediment by ciliary action, while others rely on polyp expansion or mucus generation. Madracis mirabilis appears to remove sand by tentacular action while muddy sediments are moved by active cilia (Bak and Elgershuizen, 1976). Thus, the state of this particular coral affects its ability to remove sediments of varying sizes. When the tentacles are extended, the colony will be more effective at removing larger particles. During retraction, increased ciliary action will facilitate mud removal, but will impede sand rejection.

The ability of the reef to clear sediment has been difficult to quantify. Rogers (1977; 1983) demonstrated the ability of Diploria strigosa and D. clivosa to tolerate single, coarse sediment doses of 800 mg/sq cm and daily doses of 200 mg/sq cm for a period of 45 days. Acropora cervicornis also showed remarkable tolerance to short-term sediment loading. Thompson (undated) demonstrated a high tolerance of Porites to both carbonate sand and certain types of drilling mud. In contrast, Acropora palmata colonies died after single doses of 200 mg/sq cm (Rogers, 1983), and are likely susceptible to damage at much lower levels of stress. Bak (1978) felt that the platy form of Porites asteroides often found at depth on many Caribbean reefs was almost totally incapable of clearing sediment settling on its surface.

Montastrea annularis, probably the most important frame-builder in Caribbean scleractinian reefs has exhibited a wide range of tolerance in different studies. Lasker (1980) reported an ability to remove up to 16 mg/sq cm-day of deposited sediment. In contrast, Dodge, et al. (1974) inferred a reduction in coral growth related to sedimentation (their "resuspension") rates as small as 1.1 mg/sq cm-day. In this latter study, however, it was not demonstrated that the sedimentation levels measured during the 8 days of their investigation were those necessarily responsible for the long-term growth rates measured in their coral samples.

The impact of sedimentation on colony size is not well understood, and cannot be considered as much beyond speculation at this time. Dodge and Vaisnys (1977) felt that older colonies are more susceptible to sedimentation than younger colonies as they have to move sediment a greater distance to effect removal. Hubbard, et al. (1985) documented a gradual decrease over time of the growth rate of 100+ year-old Montastrea annularis colonies in Reef and Fish Bays on St. John. While they attributed the trend to subtle changes in runoff as the hillsides reforested, this decrease in growth rate may reflect a response similar to that described by Dodge and Vaisnys (1977). Maragos (1974a, b), however, described an opposite effect, whereby coral recruitment is inhibited by sedimentation. Therefore, older and larger corals formed prior to sedimentation will dominate on stressed reefs. There is probably at least some merit to both hypotheses which together point out the complexity of the problem.

Corals have evolved a complex set of strategies to deal with increasing sediment stress. These can be important at the level of the individual organism or the whole colony. At the organism level, Hubbard and Pocock (1972) related the sediment tolerance of individual corals to overall colony morphology, calyx structure and age of the coral. They felt that the more effective corals would have a greater number of more complex septa (related to the structural integrity of the skeleton/organism pair), higher calical relief (i.e. the polyps are elevated above the surrounding skeleton), V- or U-shaped calical floors and a lighter skeleton. Bak and Elgershuizen (1976) felt that long meandroid colonies (e.g. Diploria strigosa, Manicina aureolata, Colpophyllia natans) would be better at clearing sediment than those with short, reticulate valleys (e.g. Agaricia agaricites).

Colony shape and orientation are also important in determining the ability to shed sediment. Using Agaricia agaricites, Bak and Elgershuizen (1976) found that the ability of the colony to clear sediment could be progressively increased by tilting the coral away from the horizontal. This in fact appears to be the strategy by which otherwise sensitive species deal with sedimentation at depth. In Montastrea annularis, they showed that hemispherical colonies could remove sediment in a fraction of the time required by flatter morphs of the same coral. Also, hemispherical colonies were more effective at removing sand, while flatter colonies had an easier time with mud-sized sediment. Whether this is a long-term adaptation to the smaller sediment sizes introduced onto deeper-water corals (i.e. quieter energy) cannot be said with certainty, but is a tempting hypothesis.

Shading

In addition to settling on benthic organisms, sediment can reduce the amount of light reaching the bottom at any given depth. Inasmuch as a substantial portion of the carbohydrates required by corals are produced by photosynthetic algae (zooxanthellae), this raises another potentially limiting problem for the coral reef. Similar impacts are likely important in seagrass beds.

Rogers (1977; 1979) clearly demonstrated the impacts of extreme shading on the corals of San Cristobal Reef in southwestern Puerto Rico. After 5 weeks of shading by black plastic, colonies of Acropora cervicornis showed significant bleaching of coral tissue and reductions in colony-extention rate. She proposed a relationship between polyp size and resistance to shading where corals with larger polyps would likely have a greater dependence on zooplankton and other in-water food sources. Corals with smaller polyps (A. cervicornis) were the first to show bleaching, followed by M. annularis (medium-size polyps) and two species of Diploria (largest polyps).

There are several excellent discussions of this problem in the literature. However, none of them establish quantitative limits above which reefs or other marine systems can be expected to suffer specific levels of damage. Cortes and Risk (1985) described a reef system at Cahuita, Costa Rica along which coral growth (and probably cover) has been gradually reduced due to increasing development pressure. They cite an increase in the amount of terrigenous sediment trapped within the coral skeletons over time as a response to growing agriculture and logging since the late 50's. Their data on coral growth, however, do not make a convincing correlation between runoff, reduced water quality and actual coral-growth rate.

Morelock, et al. (1979) described an environmental shift in the positions of reef zones within Guayanilla Canyon off the south coast of Puerto Rico. In the canyon, 18 m is the lower limit of coral growth, compared to 37 m along unstressed shelves. Furthermore, the corals within this zone were those typical of deeper-water environs in other areas, demonstrating an upward shift in depth zonation under conditions of higher turbidity (i.e. lower light). Dodge and Lang (1983) related a sudden drop in coral-growth rate in the Flower Gardens reef in the Gulf of Mexico with increased turbidity (and light reduction) during flooding of the Atchafalaya River. Rezak and Bright (1981) related it to submarine collapse of the underlying carbonate terrain , dropping the corals to a depth at which light level was significantly lower. In either case, the effect of lowered light levels remains a central control of the rate of coral growth.

Roy and Smith (1971) described an area on Fanning Island (Pacific Ocean) where reefs are surviving (31% cover) under conditions of high natural turbidity. In turbid areas (3.5 mg/l Total Suspended Solids - TSS) coral cover was reduced to 31% compared to 62% in less turbid areas (1.0 mg/l TSS). This was accompanied by a shift in the importance of ramose corals in turbid water (50%) compared to clear water (10%). Based on their observations, they placed light attenuation at the top of the list of impacts, followed by smothering and larval inhibition by burial. Once again, however, there is some question as to whether the conditions measured during the brief study period were in fact those responsible for the differences observed in the coral population. Nevertheless, changes in turbidity at some level emerge as important controls of reef development.

The critical question in this regard relates to the effects of specific levels of turbidity on various reefal organisms. Table 1 summarizes turbidity and sedimentation rates drawn from several literature sources. It appears that levels of TSS in the range of 1-2 mg/l can be considered as "normal" on most reef systems. Instances of reduced coral cover appear in areas where total suspended solids reach 3-5 mg/l over extended periods of time. Rogers (1982) did report storm-related turbidity levels of 10-30 mg/l on St. Thomas, however, with little environmental damage. Once again, these data together point to an ability for marine systems to tolerate significant short-term perturbations in water quality, while being relatively intolerant of much lower but chronic stresses.

Rogers (1979) reported reductions of light levels in 2 m of water to less than 65 microeinsteins/ sq m - sec. These conditions corresponded to TSS values of 9-16 mg/l. Decreasing of the TSS levels to 1.4 mg/l resulted in an order-of-magnitude increase in light level to 700 microeinsteins at the same depth. If these levels of TSS are reasonable indicators of reef responses to sediment stress, then minor shifts in the water quality of a reef system **over a long period of time** would appear to have a very profound impact on reef structure. Certainly this is not good news to those interested in protection of reefs from impending stress. What is yet to be established, however, is whether these levels of suspended solids are those responsible for the observed patterns of reef development. At a minimum, long-term measurements of water quality in these areas are needed. These would provide a more reasonable estimate of the present conditions associated with these environments. Even more useful would be historical data on water quality and reef character, but these kinds of information are essentially nonexistent.

Scouring and Inhibition of Recruitment

The impact of scouring on corals is more likely related to the occurrence of bedload (i.e. sandy) transport. Therefore, this is probably more important as a natural control in areas adjacent to sand-dominated systems. For example, reefs close to the beach are often characterized by corals sitting on pedestals that elevate the main colony from the prevailing traction carpet of shifting sediments. Likewise, the dominance of *A. palmata* on many reef crests is likely a response to the energetic sand transport over the reef surface. By growing rapidly upward, this branching coral can quickly attain a position above the zone of periodic scour by shifting sands. There are other competitive strategies

Table 1. Sedimentation data from several marine environments.

LOCATION	ZONE	TSS(mg/l)	SETTLING(mg/cm-da)
Costa Rica	outer crest	0.3-4.6	
	inner crest	1.4-18.8	
	lagoon	0.2-36.6	12.8-1180
	bay	2.8-54.0	
	rivers	1.4-6200	
Grand Cayman	general reef	0.1-2.4	
San Cristobal, PR	general reef	0.8	10.0 (1-21)
Guayanilla, PR	canyon	4.5-6.1	1.1-9.8
Punta Ventana, PR	canyon	3.5	2.3
Round Reef, Cstd, STX	backreef	1.3-1.5	
	forereef	2.1-3.4	
	east tip	2.0-3.4	
Long Reef, Cstd, STX	w. forereef	1.4-1.6	
	e. forereef	1.9-2.5	
	backreef	1.5-2.3	
Christiansted, STX	general		3-247
Limetree Bay, STX	general		
Florida Keys	general	3-5	
Discovery Bay, Jam.	general		0.5-1.1
Negro Bank, PR	e reef (steep)	11-17	3-5
	w reef (flat)	20	15
Fanning Is.	turbid lagoon	3.5	<1mm/yr
	clear lagoon	1.0	
	open ocean	0.3	
Discovery Bay, Jam.	backreef		0.5-1.1
Virgin Gorda, BVI	general	0.9-2.2	0.1-1.4
Brewers Bay, STT	grassbed		1.2

in this rapidly growing, branching morphology (e.g. shading), but growing out of the zone of sediment scour is probably an important factor in shallow reef areas.

Likewise, inhibition of larval recruitment can be important. The effects of this factor are very difficult to quantify, however. Morelock, et al. (1979) discussed the importance of substrate type in limiting larval recruitment. The gradual cover of the substrate by fine-grained sediment or algae limits the space available for settling. Roy and Smith (1971) cited the importance of sedimentation to larval recruitment on Fanning Island, but related it more to the decreased tolerance of the younger corals to sedimentation. Also, sedimentation increases (especially from terrestrial sources) are often accompanied by elevated levels of nutrient input. This favors colonization by fleshy algae, which further inhibit coral development.

WHAT ARE THE CRITICAL PARAMETERS?

Given that sedimentation can impact corals in many ways, the problem is reduced to determining how important each of these is in controlling reef development, and what the critical parameters that should be measured are. The following section will address two topics. First, the relative importance of the above limiting factors in a few example corals will be discussed to illustrate controls of sedimentation on coral type and zonation. Specific examples will be used to demonstrate the controls of bedload and suspended sediments on reef development in natural systems. Second, an attempt will be made to address the parameters related to sedimentation that can and should be quantified to eventually understand sedimentation as a control of reef development. Some guidelines concerning ways to measure these parameters and their general usefulness are offered .

Sedimentation Effects on Corals - a General Discussion

Of the four effects of sedimentation discussed above, siltation and light reduction are felt to be the most important. It is likely that the zonation seen on natural reefs, and therefore stressed reefs as well, is a response to both of these factors. Reduced light levels can vertically suppress zone boundaries (Morelock, et al., 1979; Adey and Burke, 1977). Hubbard, et al. (1985; in press) hypothesized that a gradual reduction in water clarity beginning 3-5,000 years ago has resulted in a progressive decrease in coral cover, diversity and reef accretion in Salt River submarine canyon on St. Croix. Likewise, sedimentation can reduce coral cover (Roy and Smith, 1971; Cortes and Risk, 1985) and slow the rate of coral growth (Dodge, et al., 1974; Rogers, 1982; Hubbard, in press; Hubbard, et al., 1985).

The success of Acropora palmata in the shallow reef zone is likely related to all the parameters discussed above (reduced shading, lower sedimentation levels and reduced scour), but sediment removed by wave action probably sits at the top of the list. Even low levels of sedimentation have a detrimental impact on this coral (Rogers, 1977). Changes in Acropora morphology appear to be some adjustment of the colony to offset the buoyant lifting forces generated by waves in the different reef zones (Shinn, 1966).

M. annularis appears to adapt morphologically to levels of sedimentation, while its growth rate is more a function of light level (Dustan, 1977; Hubbard and Scaturo, 1985). Bak and Elgershuizen (1976) showed that hemispherical colonies were more adept at removing sand found in shallower reef environments, while platier colonies occurring in deeper water were better adapted to removing finer particles. Hubbard, et al. (1985) cited the occurrence of knobbier forms of this coral in higher-stressed areas of Fish and Reef Bays on St. John as a possible adaptation to sediment loading.

Agaricia agaricites demonstrates a poor ability to clear sediment of any kind, and relies on a high angle with the substrate to clear sediment (Bak and Elgershuizen, 1976). This implies that smothering rather than light attenuation is more of a control in the distribution of this coral.

While excellent examples of sedimentary controls on reefs can be found in site-specific studies, stress on a given reef is generally the result of a combination of effects, and the relative role of each is difficult to quantify. Hubbard (in press) describes variations in reef development along the north coast of St. Croix where increases in the amount of sediment delivered from upwind shelves result in a progressive degradation of the reef cover. While bedload sedimentation is invoked as the primary control, accompanying changes in water quality are undoubtedly important as well. Adey, et al. (1977) cited increased sedimentation along the south shore of St. Croix 9,000 years ago as the cause of a a cessation of reef accretion, but is was not obvious how much of this was related to sedimentation as opposed to reduced light levels. A similar situation has recently been discovered along the shelf-edge reefs of La Parguera in southwestern Puerto Rico (Hubbard and Morelock, unpubl. data), where a present-day head-coral community veneers an A. palmata reef that stopped accreting, probably 4-5,000 years ago.

The complexity of the problem should not discourage future attempts to model sedimentary controls on modern reefs. In fact, isolation and manipulation of individual controls likely lies at the heart of solving the problem. It is important, however, that the researcher addressing sedimentation recognize the degree of complexity involved and not place too much emphasis on any one factor measured in a field situation. Given that word of caution, the next section attempts to list primary controls of sedimentation, and to suggest reasonable ways to measure them.

Important Parameters to Consider

The above sections have dealt with the general stresses induced by sediment loading and their impacts on reefs and reef organisms (primarily corals). This section addresses the parameters felt to be most important in understanding these impacts on reefs and other marine systems. At the outset, it should be stated that the factors listed below reflect the biases of the author, and may not be in agreement with the priorities of all researchers in the field.

Concentration of suspended solids - Certainly one of the the most important factors in dealing with sedimentation is the amount of sediment introduced into the water column. This parameter is important in determining both the attenuation of light in the water column and the potential for sedimentation as material settles over time. Total suspended solids (TSS) are typically determined by filtering large quantities of water through pre-washed and pre-weighed membranes (0.45 micron pore openings are the most common). Requirements for this procedure include a suitable filtering apparatus, an analytical balance, a clean drying oven and a controlled (i.e. temperature and humidity) room in which to weigh and manipulate samples. Controlled laboratory conditions and extremely careful procedures are required for this method; unless the minimal conditions listed above can be met, the data are nearly meaningless.

Recently, several optical methods have become available for **approximating** total suspended solids. These instruments measure some character of the suspended solids (i.e. reflectance, scatter, absorption) and report it in digital units. This methodology has several advantages, including precision and speed of data aquisition. Profiles of water character can be taken and used to map changes in the distribution of these parameters temporally and spatially. While of great value when used properly, all these methods share one serious disadvantage: they measure optical parameters affected by suspended particles, but do not actually measure the concentration of the particles themselves. Depending on the size, shape and composition of the suspended particles, optical measures can vary dramatically among samples of the same concentration of suspended solids.

Nevertheless, these methods can be valuable if two conditions are met. First, the researcher must establish the optical parameters that most likely affect the marine organisms of interest. Unfortunately there is little agreement as to which of the three parameters listed above is the most critical. Even then, the optical data are likely to relate only to impacts of shading and not of smothering. Second, the researcher must "calibrate" the instrumentation with the local sediments. Only by understanding the "signature" of the various components of the suspended particle spectrum can optical data be quantitatively related to values of total suspended solids. It must be further understood that these calibrations are site specific (i.e. optical calibrations from a reef/lagoon area in the open ocean cannot be used to translate optical data into TSS figures off of a river mouth where sediments have a different character).

Having said this, the author still feels that these optical methods may show the greatest promise for the future. But, they will be useful only after the above calibration procedures have been applied and only if the researcher remembers what he or she is measuring. Otherwise spatial and seasonal variations in the composition of suspended solids will likely lead to gross errors in subsequent interpretations.

At this point, a careful program of successive filtering for TSS concentration and composition as described below is the most reliable methodology. This coupled with calibrated optical methods, however, will greatly increase our ability to monitor spatial and temporal variations in suspended solids not logistically feasible using filtering alone.

<u>Settling rate</u> - Along with shading, direct sedimentation on benthic organisms plays the major role in limiting reef cover. At the simplest level, the absolute quantity of the material landing on the substrate is probably the most important parameter in determining the likelihood of damage due to smothering.

The most common method involves placing some sort of open container on or near the bottom and collecting material falling from the water column. While simple in concept, obtaining reliable measurements is in fact quite difficult. At the heart of the problem is designing a trap that will duplicate the amount of sediment that settles, is resuspended, and again settles on the adjacent bottom. A trap that is too wide at the mouth will allow scour within the trap to remove previously settled sediment more easily than it is resuspended from the adjacent substrate (undertrapping). Conversely, traps too narrow at their mouth relative to their vertical dimension artificially hold material within them while sediments on the adjacent bottom are resuspended and carried elsewhere (overtrapping). Gardner (1980a and b) evaluated a variety of trap designs, and concluded that a simple vertical-walled trap with a height-to-width ratio of 2.3 would most closely approximate settling conditions on the adjacent substrate. This value is based on both field and laboratory experiments. Baffles were recommended for areas where highly turbulent conditions might be expected (e.g. upper forereef).

Once a suitable trap design is chosen, the traps are placed in the field and allowed to collect sediments for some suitable period of time. Personal experience has shown that some interval less than a week is desirable unless conditions are highly uniform temporally. Traps are sealed in situ and returned to the lab. Filtering of the trap contents through pre-washed, pre-weighed filters provides a total weight of trapped material. Alternately the water can be evaporated from the container, but correcting for the salt content of the sediments and evaporated water becomes problematic unless very large quantities of sediment are trapped.

Origin of suspended and settled solids - Matter suspended in the water column can consist of inert sedimentary debris or more reactive organic material (e.g. plant and animal fragments, plankton). Each of these has a different impact on reef organisms, and the relative importance of each component must be identified. Organic matter is often beneficial to the marine system, whereas sediment almost always produces stress. There are several ways to differentiate between sediment and organic matter in the water column. The most common is dissociation of the organics by some method (chemical additives such as hydrogen peroxide; ashing of the organics at high temperatures) followed by filtration and reweighing. Equipment is identical to that listed above, with the addition of a muffle furnace for high-temperature ashing.

Character of the sediments - There are two critical parameters related to the suspended sediments. These are **size** and **composition**. Of the two, size is the most difficult to measure. In high concentrations, pipette analysis can be used to determine size distribution. The methodology is described in Folk (1974). This method is very time-consuming, however, and precision is achieved only under **very** carefully controlled conditions.

In lower concentrations, size distribution is extremely difficult and costly to determine. Coulter counters, originally designed for blood analyses, have been used effectively, but are expensive, and preparation is tedious. More recently, particle counters using a laser beam have become available, but like any optical instrument, must be "calibrated" against pipetting to give a reliable size distribution. Nevertheless, at a cost of around $18,000 they probably represent the easiest and least expensive means of determining size characteristics of suspended sediments in concentrations typically found on reefs.

This is obviously not an inexpensive venture. Unfortunately it probably lies at the heart of understanding the impacts of sedimentation on coral reefs and other marine systems. Our laboratory studies to date have used primarily coarse material (fine sand) to stress corals. Yet, much (if not most) of the material reaching reefs from distant sources is comprised of silt and clay.In terms of predicting the dispersion of muddy sediments introduced into the marine environment, sediment size is critical as it determines the rate at which material will settle to the bottom. Thus, trends in water turbidity and settling are determined by this parameter along with local current patterns.

It is the author's opinion that understanding the control of sediment size **within the mud range** will prove to be the most critical step in ultimately unraveling the sediment-stress equations. Sediment size determines the nature of the stress (i.e. light attenuation vs. smothering), the likely mechanism by which the coral will expel sediment, and the likelihood that the sediment will carry adsorbed materials detrimental to the well-being of the reef (e.g. heavy metals).

The other element of sediment character is composition. At the most basic level, one must consider whether the sediment is carbonate (i.e. biological) or siliciclastic (i.e. likely from a terrestrial source). Within siliciclastic materials, the specific origin of the sediment, especially in the clay range, may have important implications to the adsorption of pollutants, heavy metals and nutrients. Observations by the author infer that corals can expel carbonate mud with greater ease than siliciclastic mud. While no concrete data can be provided to support this contention, the author feels that composition of the muddy sediment in the water column plays a role only slightly below that of size in determining stress levels.

Carbonate vs siliciclastic content can be determined by several methods. The most popular is digestion of the carbonate fraction in dilute (ca. 10%) hydrochloric acid. As in the case of organic digestion, the filter must be washed, redried and reweighed. The procedures for organic and carbonate contents must be done separately.

Composition of the siliciclastic fraction is typically done by X-ray diffraction. The equipment is available in most mainland geology departments, but is sufficiently specialized that it would not be readily available in the Virgin Islands. The U. S. Geological Survey likely operates an XRD unit in San Juan, Puerto Rico.

Light levels - One of the easiest measurements to make is that of light intensity. Numerous instruments are available to manually or remotely collect light data. Standard methods have been established to determine light intensity using a reasonably accurate, photographic light meter. More sophisticated units (e.g. Licor light probes) are commercially available within the price range of most local laboratories.

Light measurements taken through the water column can give a valuable picture of the effect of suspended materials. It is important that these data be taken on at least some sort of seasonal basis, as spot measurements taken at haphazardly chosen intervals can give a misleading picture. If a regular program of light measurements cannot be undertaken, certainly a careful collection of light data after extreme events (e.g. heavy seas, rains) can provide valuable information on the range of light conditions expected in the marine environment of interest.

Within the shallower water depths, data on light spectra may be useful. At greater depths, however, filtering of the red end of the spectrum results in somewhat uniform conditions. Spectral data may eventually prove to be more important than is implied here, but is is felt to carry a secondary importance to the more basic parameters discussed above.

Other factors - The above factors represent the primary parameters that can be measured or manipulated in an effort to understand the effects of sediment on marine organisms. In addition, there are several factors that, while still important, are not easily manipulated. They are nevertheless still important in affecting to what degree the above parameters might have an effect, and are worth mentioning.

Water depth plays an important role in determining the character of a marine system whether under natural or stressed conditions. Physical energy levels are progressively buffered with depth. On the positive side, short-term events such as hurricanes are less destructive in deeper water. On the negative side, however, lower energy levels limit the occurrence of organisms that rely heavily on water motion to clear sediment.

The primary importance of depth is related to light. With increasing water depth, both the intensity and the character of the light are modified. Absorption and scattering of light decreases the intensity and narrows the spectrum of the light reaching the bottom. In a natural system, the pattern of light intensity with depth in part controls the distribution of many reef organisms. Sediment introduced into the water column effectively reduces the amount of light reaching the bottom at any depth. On a large scale, the vertical compression and shallowing of faunal zones on the reef can result (Morelock, et al., 1979; Hubbard, et al., in press). On a local scale, the depths at which many marine organisms occur can predetermine the potential for impact due to sedimentation. In shallow marine systems ($d<2m$) moderate levels of sedimentation are somewhat benign from a standpoint of light limitation. Thus, impacts are limited to smothering and abrasion. In deeper water, however, many of the organisms are already at or near their lower threshold with respect to light. Thus, environmental damage can be done by reduced light even when sediment never directly contacts the substrate.

Current patterns are also important in determining the pathways over which sediment will travel. Whether related to dredging or runoff, sediment will typically have a direct effect (i.e. at the point of introduction) and an indirect impact at some "downstream" site. Critical parameters in predicting the patterns of sediment dispersal include:

1 - settling velocity of the suspended sediments
2 - current speed and direction
3 - diffusive and turbulent spreading of the sediment
4 - water depth over which the sediments are being spread
5 - the character of the bottom over which the plume is spreading and settling

Antecedent conditions play an important role in determining the potential impact of marine sedimentation. Certainly an already impacted area will be more susceptible to damage than one that is untouched by prior stresses. Thus, a critical management decision centers around whether an already stressed environment requires more protection because of its increased sensitivity or less protection because it is already in a degraded state. Often this must be a subjective decision.

Upland character is important in predicting the amount and type of sediment a marine system might presently be receiving. While not in the same general category as the parameters above, understanding the character of the watersheds and coastal areas adjacent to the marine environment is a key component of any rational management plan. This will be discussed in more detail in the following section.

PRIMARY SOURCES OF SEDIMENT STRESS

There are numerous ways in which reefs can be stressed by sediment. These include resuspension by boat traffic, hazardous spills, inadvertent dumping of sediment into the marine environment (e.g. open-ocean dumping), landfill and a host of others. The most common problems, however, are related to two general activities: marine dredging and upland development. While the importance of the other potential sources of stress should not be ignored, these latter two represent the most common assault on the marine environment, certainly in the Caribbean and likely on a worldwide basis. As they undoubtedly represent the primary problems from a standpoint of local resource management, the following discussions will focus on these two activities.

Dredging

Probably the most direct and easy to visualize impacts on the marine environment are related to dredging. Direct impacts are related to disruption (i.e. removal) of the marine habitat in the area of excavation. In addition, numerous downstream effects related principally to shading and smothering by suspended sediment take on equal importance.

The adverse effects of dredging on coral reefs and seagrass beds is well documented (Nichols, et al., 1972; Johannes, 1975; Dodge and Vaisnys, 1977; Bak, 1978; Taylor and Saloman, 1978; Penn, 1981). The immediate impact on the environment is obvious. A significant portion of the sea bed is disrupted. Downstream effects are more subtle and difficult to predict.

Although the area being disrupted is occasionally a reef (e.g. channel excavation), more typically it is open sediment or seagrass beds. Although seagrasses are more tolerant of sedimentation than reefs, they can be smothered given sufficient quantities of suspended sediments. The general importance of seagrass beds has been discussed extensively (for review, see Taylor and Saloman, 1968; Thayer, et al., 1985; Burrell and Schubel, 1977; McRoy and Helfferich, 1977, 1980). Removal of seagrass beds can impact stability of the substrate. Furthermore, the potential for seagrasses to act as sinks for heavy metals (Faraday and Churchill, 1979; Lyngby, et al., 1982) raises the likelihood of long-term toxic effects.

Once totally uprooted, seagrass beds will take over 5 years to recover even under ideal conditions. (Patriquin, 1975; Zieman, 1976; Thorhaug, 1981). While recovery can be accelerated by transplantation (Phillips, 1976; 1980), direct loss of seagrasses must be thought of as a long-term disturbance.

Downstream impacts on seagrass beds are harder to quantify and predict. Likewise, the major impact on adjacent mangrove systems are related to removal, and stands remaining after development (both natural and replanted) often appear to be coping with existing conditions. Since the 60's, the south coast of St. Croix has come under heavy pressure from industrial construction and operations. Despite high suspended-sediment levels over a protracted period of time, expansive seagrass beds still remain in the area between two major industrial complexes (VI Marine Advisors, 1984). No estimates of the primary productivity of that system have been made, nor have there been any studies of the indirect impacts on other marine organisms using those grassbeds. Nevertheless, they are existing at surprisingly high levels of stress from ambient sedimentation levels.

Generally the hardest hit, and therefore the areas of greatest potential concern, are the reefs. Sediment suspended by the dredge or poorly managed sediment-receiving areas on shore can move considerable distances from the initial point of introduction. How far the sediment will travel depends on a number of factors. These include:

1 - sediment size (settling velocity)
2 - current speed
3 - water depth
4 - importance of resuspension downstream

Once the dredging has ceased, the potential often remains for resuspension as the newly dredged area becomes a center for commercial navigation. The impacts due to this phenomenon are not trivial, and must be considered in terms of long-term environmental degradation.

Upland Development

Probably more important in the Caribbean are the impacts of upland development. Poor land management can result in a substantial increase in the sediment load delivered to the shore's edge. One factor that is often ignored and thus makes terrestrial impacts all the more dangerous is the cumulative impact of small projects that would be somewhat benign by themselves. As will be discussed below, a major problem in our present management and protective schemes is a system that is set up to evaluate primarily larger projects, while ignoring smaller ones that can collectively have a great impact.

To better understand the nature of the problem, it is instructive to first examine examples from Caribbean areas, and to then discuss some of the factors responsible for damage document in the literature. Morelock, et al. (1983) related dramatic increases in sedimentation off Mayaguez over recent years to urbanization, industrialization and cane agriculture in western Puerto Rico. Loya, (1976) described the effects of increased turbidity on the reefs south of Mayaguez, again a likely response to upland activities. Degraded reefs off Guayanilla on the south coast of Puerto Rico have had similar impacts due to nearshore development, dredging and ship traffic (Morelock, et al., 1979). On St. Croix, industrialization on the south shore has resulted in substantial loss of habitat (primarily seagrass and mangrove), and undoubtedly contributes in part to the poor water clarity along the southwest corner of the island. All three islands in the U.S. Virgin Islands have come under increasing pressure from upland development, and this problem is becoming progressively more acute on St. John, the least developed of the three.

The importance of this problem has been recognized at least to some extent by the National Park Service on St. John and the VIBR in that terrestrial sedimentation has been one focus of VIRMC studies over the past two years. The Park (and the VIBR) must coexist with adjacent development, and the impacts of these surrounding activities therefore take on paramount importance in the formulation of a workable management plan.

Central to minimizing the impacts of upland development on adjacent marine systems is understanding the factors that control runoff. An excellent review of the subject at a general level can be found in Gottfried (1985). Excellent references are made to worldwide importance of upland erosion (Crosson, 1983; Eckholm, 1976; Brown and Wolf, 1984), the importance of short intense rains typical of the Caribbean in affecting high rates of runoff (Suarez de Castro, 1950; Wolman and Miller, 1960; Hudson, 1971; Roose, 1977) and the effects of land use on runoff (Smith and Abruna, 1955; Wilson, 1972; Dunne, 1979; Veloz, et al., 1985).

Jordan (1972) described decreases in overland runoff in the U.S.V.I. over the past century, and related them to gradual reforestation of the island watersheds after the decline of the sugar cane industry on those islands. On St. John, excellent tax records compiled by Tyson (report in prep for VIRMC) show patterns of land use similar to those described on St. Croix by Jordon (1972). A likely conclusion would be that runoff in subsequent years showed a similar decline, thereby reducing stress levels on nearby reef systems. However, Hubbard, et al. (1985) were not able to relate this supposed decrease in sedimentation to any measurable change in the growth rates of Montastrea annularis sampled in Reef or Fish Bays on the south shore of the island. Short-term impacts on the growth rates of nearshore corals in Hawksnest Bay were found to correlate well with construction activity in the watershed, but no long-term effects could be found.

Crucial to the problem of managing upland development is understanding the effects of various land-use practices on sediment runoff, and to be able then to relate elevated sedimentation levels to specific levels of damage. Gottfried (1985) agreed with the contention of Dunne (1979) that land use is probably **the** primary control of runoff in tropical systems. Therefore, management of upland development takes on paramount importance in any management scheme. In this light, potential land-use problems and management solutions are discussed at the end of this report. At this point, however, some discussion of general controls of runoff are in order.

Controls of runoff - General guidelines for predicting the amount of fresh-water runoff (and therefore, sediment runoff) are provided in the Engineering Field Manual for Conservation Purposes (Kautz, 1975). The principal controls are:

1 - watershed area
2 - rainfall (volume and intensity)
3 - watershed slope
4 - soil conditions (i.e. is the soil wet or dry?)
5 - land use

Deitrich, *et al.* (1982) summarized the pathways through which water from precipitation might be cycled:

P = I + OF + AET + SM + GWS + GWR, where:

P = precipitation
I = water intercepted by vegetation
OF = water flowing over the ground surface
AET = evapotranspiration
SM = soil moisture
GWS = potential for groundwater storage
GWR = underground runoff

A discussion of the importance of each of these parameters is beyond the scope of this discussion. However, some general comments on some of these factors is instructive. In the Virgin Islands, evapotranspiration is high, resulting in a significant loss of water back into the atmosphere during periods between rains. Thus, much of the water retained in the upland system is lost before it can be converted to potable water. This lies at the heart of our local water problem which often takes on crisis proportions. Typically, the potential for groundwater storage is moderate to small on all but the largest islands (e.g. the size of Puerto Rico). This is compounded even further during periods when antecedent soil moisture is high and most of the rainfall runs overland to the sea. As a result of these factors, modest olumes delivered in short but intense bursts on many small Caribbean islands do little to ameliorate the potable water problem while causing above-normal sedimentation damage.

GENERAL SEDIMENTATION PROBLEMS IN THE CARIBBEAN

The Caribbean islands (especially in the eastern Caribbean) share many common problems with respect to land use, water management and stress of nearshore and coastel areas. For a number of obvious reasons, development has and will continue to be concentrated along island shorelines. This development includes home construction, hotels, condominiums, port development and industrialization, to name a few. Each of these types of development carries with it a peculiar set of stresses, but they all share the common impact of increased sedimentation. In the case of land-based development, initial sedimentation is generally related to increased runoff as sites are cleared for construction. Later on, lower levels of chronic sedimentation related to permanent modifications of upland drainage pathways become more important. In the marine environment, stress is generally related to habitat disruption during dredging and filling operations, spreading of suspended solids away from the project site, disruption of previously existing flow patterns in the area and resuspension of sediments by continual operation of the new facility. This section focuses on problems occurring within the U.S. Virgin Islands and the VIBR, but it should be understood that most of the problems discussed below occur throughout the region.

Land-Based Development

There are numerous and recent examples of problems with upland development in the Virgin Islands. As recently as the spring of 1986, 30 acres of land were cleared for development of a resort hotel in Davis Bay on the island of St. Croix. Despite efforts to maintain construction-related runoff, sediment plumes have been seen after even moderate (ca. 1 inch) rains. Much of the upland drainage from the adjacent 400 acres has been diverted into a single watercourse, and the effect of this modification will have to await the passage of time. It is certain, however, that if sedimentation becomes a chronic problem in this area that the Acropora palmata formations to the west (i.e. downcurrent) of the project will suffer, as they are very intolerant of sedimentation (Rogers, 1983).

Hotel construction is on the rise on both St. Thomas and St. John. At the Virgin Grand Hotel on St. Thomas, major modifications to the upland watershed could have adverse impacts on nearshore coastal waters in the future. On St. John, hotel construction in Great Cruz Bay has opened a substantial hillside to erosion with few apparent erosion-control measures. The area was already modified in the past by dredging, but increased runoff will undoubtedy have an effect nonetheless.

During October, 1980, ground was broken for the construction of a hospital at the head of Hawksnest Bay on St. John. Studies of the corals in the bay fronting the watershed showed a significant decrease in the coral-growth rates after post-construction rains in 1981 and 1983 (Hubbard, et al., 1985). Prior to construction, more severe rainstorms had produced no such effects. Fortunately, the impact of construction was short-lived, and the significant amount of vegetative cover separating the construction from the ocean somewhat buffered sedimentation impacts. A gradual increase in water quality and coral-growth rate followed cessation of construction and gradual restabilization of at least part of the upland watershed. Were the construction closer to the beach, however, or were it part of a longer-term project, it is likely that the damage would have been considerably more severe.

In the British Virgin Islands, development appears to be progressing not out of any need for employment, but rather in response to a growing government need to financially support its infrastructure. Thus, management is driven by other criteria and is somewhat more complicated. Development around Roadtown Harbor has progressed with no apparent plan, and little evidence of traditional West Indian architecture is readily discerned in new construction. The proliferation of small homesites, roads to serve them, dredging in the harbor and hotel construction are all proceeding at a very rapid pace. On Peter Island, a proposed 18-hole golf course could profoundly alter present runoff patterns and have far-reaching impacts on the nearshore reefs.

Another significant component of shore-based development is industrialization. Morelock, et al. (1979) cited this as part of the reason for increased sedimentation on the west coast of Puerto Rico. On the south shore of St. Croix, the South Shore Industrial Complex was developed starting in the 60s, and continues today. Contained in the complex are two refineries (Hess and VIRCO) and a major alumina processing plant (formerly Harvey Aluminum and now Martin Marietta). Over a 10 year period, many acres of mangrove were either dredged, filled or indirectly disrupted as part of the project. A declining economy and a need for local jobs were cited as a rationale for sacrificing the largest mangrove complex in the Virgin Islands. Ironically, Martin Marietta is now closed, Hess Oil has drastically cut back its work force and the recognition that tourist dollars and not heavy industry are now needed to solve all our financial woes represents the basis for the latest onslaught on the marine system - hotel and condominium construction.

The negative impacts of industrialization are shared by many members of the Caribbean community. Refineries and oil-handling facilities are located on St. Croix, Puerto Rico, Trinidad, St. Lucia and Barbados (ECNAMP, 1980). Tourism is on the rise throughout the Caribbean, and will likely accelerate in light of a strengthening U.S. economy and a rise in world-wide terrorism. Accelerated development raises the liklihood of poor planning in the face of a rapid influx of tourists and dollars.

Another Caribbean-wide sedimentation problem is agriculture. Traditionally sugar cane has been a major crop throughout the Caribbean, and presumably nearshore marine environments have suffered in the past. The fact that Hubbard, et al. (1985) were unable to relate land-use practices on St. John to long-term changes in the growth rates of *Montastrea annularis* raises some concern over our ability to detect sediment stress in the absence of adequate baseline data. This method has been very useful in other areas, but either adaptation of local colonies to stress or some other factor (perhaps an absence of stress) have resulted in a relatively stable population of this one coral species on St. John over time.

On some Caribbean islands, sugar cane cultivation continues today (e.g. St. Kitts, Barbados, Antigua; ECNAMP, 1980). Elsewhere (St. Lucia, Guadalupe), large-scale agriculture is based on other crops (mostly bananas and coconuts). On Dominique agriculture exists at a subsistence level, but the cumulative impact of individual farmers can still be substantial.

A major problem on St. Croix and many Caribbean islands centers around clearing large hillsides of brush and forest to encourage grass. The plots are cleared just prior to the rainy season to ensure an adequate water supply for the new vegetation. Unfortunately the flashy rains typically result in wholesale slope erosion, loss of valuable topsoil and the introduction of large volumes of sediment into the marine environment. In 1977, a large rainstorm deposited a soil delta 60 ft out into Teague Bay on the north shore of St. Croix. Direct smothering and subsequent degradation of water quality due to resuspension likely caused significant damage to the bay ecology. At Salt River, to the west, a similar event flushed large quantities of suspended sediments into the bay and onto steep reef environments beyond. Visibility was reduced to less than 2 m for a period of several months, resulting in an estimated 20% reduction in live coral cover. Little was apparently learned from this episode as recent agricultural clearing near the base of the watershed and plans for marina development threaten further damage. Further evidence of indifference to this problem lies in the exemption granted to agriculture under the Coastal Zone Management Act of 1978. Under this mandate, all activity within the coastal zone, **except agriculture**, must come under the scrutiny of the organization created by the Act.

Port Development

Other than general upland construction, the most widely shared environmental pressures in the Caribbean probably come from port development. In an island community that has traditionally depended upon the water for transportation, commerce and communication, opening of further marine-based connections continues to dominate our thinking. Except now, instead of small-scale down-island commerce, we are facing tanker traffic and cruise liners of ever-increasing size.

Port development shares all the impacts of upland construction. Unique to port development, however, are:

1 - habitat loss due to dredging and filling
2 - long-term degradation of water quality due to resuspension

3 - potential pollution from spills and discharges

Between 1966 and 1972 over 0.5 million cubic yards of sediment were removed from Christiansted Harbor (V.I. Marine Advisors, 1983). Justifications included creation and maintenance of navigable channels, creation of new fastland, beach nourishment and excavation of construction aggregate. Many of the present harbor-erosion problems are related to construction of condominiums on land created during that time. In the western harbor, one complex presently sits 25 m seaward of the natural shoreline that existed prior to shoreline filling. The occupants are committed to a long-term program of beach nourishment to protect their investment. Next door, a costly seawall was built to stem runaway erosion related to the same problem.

It is difficult to assess the impact of all this activity on the marine environment as little or no baseline data exist. Eastern Long Reef and Round Reef certainly support a sparser cover than do other areas to the east and west. Relating this to specific events or to sedimentation in general is difficult in the face of nonexistent data prior to development. Similarly, on the south coast of the island, water quality is typically poor near and downcurrent of the South Shore Industrial Complex (SSIC). While turbidity levels are demonstrably higher than those upcurrent, there are several lines of evidence that construction is only in part responsible for the dirty water in the area. First, turbidity levels are typically elevated in the same area on aerial photographs prior to construction. Second, the southwest corners of tradewind islands typically exhibit a similar pattern in the absence of a readily identifiable development source. And finally, the presence of Sandy Point downstream of the development infers a persistent flow of sediment into this area over a very long span of time. The SSIC has likely protracted the turbidity problem along St. Croix's south shore, but the problem is in determining to what degree that has occurred and how the benthic population has changed as a result.

On St. Thomas, Charlotte Amalie harbor is coming under increasing development pressure. Expansion of port facilities in the western harbor continue as vessel traffic becomes progressively heavier. Recent dredging to accommodate the S.S. Norway increased the maximum harbor depth. Port development on this scale has a host of other problems including pollution, navigation conflicts, cross uses of the harbor and increasing density of moored and transient vessels. Sediment damage due to port creation and maintenance is difficult to assess as little or no data exist upon which to make an evaluation.

On St. John, Cruz Bay is falling under increased pressure to accommodate more vessel traffic. Present users include the National Park Service, small charter operators, local boaters, various ferries and commercial freight carriers, small cruise ships and the V.I. Seaplane Shuttle. Congestion in the harbor has necessitated plans to move part of the port operation to other sites, primary among them a small pond to the south. In addition to the lost sediment-retention function of the pond, the potential of sediment damage during dredging looms as a major possibility.

In the British Virgin Islands, increased boating traffic and construction is raising the need for larger harbors and the location of suitable sources of construction material. A large dredging project is presently underway in Roadtown harbor. Plans are being evaluated to select dredging sites on the eastern end of the island for extraction of construction aggregate.

Similar activities are occurring throughout the eastern Caribbean. Port operations in Guadalupe, St. Lucia and Trinidad all rely on dredging to maintain navigable ports. These activities undoubtedly continue on a smaller scale throughout the islands, largely without any real regard for damage to the marine environment. More examples could be given, but the basic story would remain the same. Expansion of ports and shore-based facilities continues throughout the eastern Caribbean to meet the demands of a spreading technological and tourism base. These projects are done largely without adequate baseline data upon which to predict effect or measure impact. These problems are not limited, however, to poor third-world countries who lack the technology or the money to properly address the problem. Many of the best available examples available of unecessary environmental damage occur within the U. S. Virgin Islands, and the local government has apparently learned little from past lessons.

The remainder of this report will focus on identifying elements of the problem that can be addressed at the local level. Primary development problems are listed, and possible solutions are suggested. Hopefully, some of these strategies will prove viable at least within the VIBR, and eventually in the Virgin Islands and the eastern Caribbean.

SPECIFIC PROBLEMS AND STRATEGIES

Problems

Examples of the general kinds of problems that occur in the Caribbean region have been discussed above. Also, the types of concerns that need to be addressed in studying the impacts of sedimentation in the marine environment have been elucidated. This section provides a more specific list of the main problems that exist specifically within the VIBR, but also within the greater Caribbean as well. A discussion of management strategies follows. Finally, a brief list of possible projects that might advance our knowledge of sedimentation effects is proposed.

Slope clearing - This represents one of the most significant problems facing the U.S. Virgin Islands today. Upland contruction sites are typically cleared with little or no regard for impacts of runoff. In the rare instances where sedimentation control measures are required by government agencies, they consist of a short-term sediment fence, temporary berms or similar structures. These measures are generally ineffective, poorly monitored, and do nothing to stem the longer-term erosion problems once the temporary structures have been removed and the development goes into operation. The clinic on St. John stands as our best documented example of this problem. Short-term degradation was documented (Hubbard, et al., 1985) and was minimized only by the short duration of the project and the remaining heavy vegetation in the lower watershed. Larger construction projects can often clear entire watersheds, and the potential for impact is much greater.

Agricultural clearing - Similar in impact to construction-related clearing is agricultural development. Two additional problems typically make this an even greater problem. First, clearing is often done just prior to the rainy season, thus maximizing the potential for sediment runoff. Second, this activity falls outside the control of Coastal Zone Management (CZM) and many other agencies created to stem erosion.

Building in watercourses - With the shortage of available building sites and the steep slopes that dominate most eastern Caribbean islands, many homesites and commercial developments are placed in the central valleys to watersheds. Structures placed along the sides of the valley add to the water and sediment load within the central gut. Those directly within the gut reduce the ability of the streambed to retain water and sediment. This can have significant impacts both within the watershed (increasing runoff to lower properties) and in the marine environment beyond (increased sediment load).

Road construction - Generally associated with any sort of development is the creation of roads and accessways. On steep slopes typical of Caribbean islands, these scars along hillsides not only serve as sites of erosion but can also provide channels to facilitate the carrying of eroded sediment to the ocean.

Infilling of coastal ponds - Over the past few decades, there has been a gradual reduction in the number of coastal ponds. Reasons include insect control, creation of fastland, and the ease with which such areas can be converted to level building sites. Underlying all these is a general disregard for the valuable functions that these ponds provide. In addition to their direct and varied ecological functions, these ponds typically serve as sediment sinks and settling basins. Typically these ponds formed at the entrances to embayments during the most recent rise of worldwide sea level. Since their formation, these ponds have been gradually filling with sediment derived from the erosion of associated upland watersheds. Because sediment is trapped in the ponds, the nearshore environments are buffered from the deleterious impacts of intense rains. With the elimination of the ponds, runoff and sediment are permitted to drain directly into the ocean.

Coastal and flood-plain clearing - Like the coastal ponds discussed above, low-lying areas serve to buffer the marine environment from upland runoff. Although the trapping function of coastal flood plains is more diffuse than that of coastal ponds, vegetative cover still serves to slow down water flow and thus retard the introduction of sediment into the ocean. Clearing of these low-lying areas minimizes or eliminates their sediment-trapping ability. In fact, drainage plans usually incorporate some means of improving the runoff potential of these areas (see discussion of channelization below).

Clearing of mangroves - Mangroves serve a number of valuable environmental functions that are sufficient reasons to justify their preservation. With respect to sedimentation, they serve two important functions. First, they stabilize the shoreline and prevent erosion. Inasmuch as they are typically associated with muddy shorelines, this translates into lower quantities of fine-grained sediment being introduced into the adjacent bay. With respect to upland runoff, they again trap sediment and thus reduce the amount of suspended load reaching seaward environs. The root structures break up flow and slow down the water coming from adjacent land areas. This results in localized sedimentation, lowering turbidity on the open shelf in the short run and creating protected areas which will further retard runoff down the line.

Building on filled submerged lands - With the shortage of flat land along the island shores, dredged material is often used to artificially extend the present shoreline. This material is often incapable of supporting the subsequent structures built in the area, causing costly engineering problems. Equally important is the greatly increased possibility of erosion and the subsequent need for coastal defense structures. The inherent instability of these areas often results in increased sedimentation offshore.

Opening of coastal ponds for marinas - If coastal ponds are tempting as future building sites, they are even more in demand as potential marinas. The already existing water body reduces the amount of dredging needed, and the cost of the project is lowered accordingly. As in the case of filling, the trapping function of the pond is compromised. Although the loss of function is not as complete as in a filled pond (i.e. the marina will still trap some sediment), the opening to the ocean still raises the potential for the movement of sediment into the ocean beyond, especially during periods of heavy rains. Fine-grained sediments trapped in the marina can necessitate maintenance dredging at a later date and can be resuspended by powerboat activity within the marina.

Channelization of water guts in lowland areas - One of the secondary problems of coastal development is the need to prevent flooding of low-lying areas. Typically sediment control plans amount to nothing more than effectively routing runoff around or through a particular area in some manner that minimizes upland flooding. While this is an understandable goal from a development standpoint, it increases the intensity of coastal sedimentation. A recent CZM permit on St. Croix included a condition wherein the developer would help to channelize runoff from adjacent properties. By eliminating periodic flooding in the surrounding neighborhood, the developer is providing an apparent service to the community. Unfortunately, the flooding of surrounding lowlands had prevented sedimentation in Christiansted harbor by ponding water long enough for some sediment to settle in the ephemeral pond created by the rains. The desire to protect personal property is understandable, but the impact on marine sedimentation occurs nonetheless.

Harbor dredging - Harbor dredging has been discussed in detail earlier in this report. Direct impacts are related primarily to habitat removal. Indirect effects include downcurrent sedimentation, habitat degradation and long-term resuspension due to vessel traffic. In areas where seagrasses are removed, sediments may become unstable even in the absence of traffic. In areas where reef is removed, the exposure to increased wave action can likewise result in increased sediment suspension and shore erosion.

Seagrass removal - The primary physical function of seagrasses is to stabilize the substrate. In experiments in Teague Bay on St. Croix, the removal of Syringodium from a small area of the lagoon allowed sediment that had been stable in currents over 1 m/ sec to be moved by currents of only 20-30 cm/sec (Hubbard, unpubl. data). Removal of seagrass on a large scale can result in a significant reduction in water quality as the fine-grained sediments are gradually winnowed from the newly exposed substrate. Eventually water clarity improves, but migration of the margins of the excavated area, especially in the presence of wave action, can cause the problem to migrate over time, greatly extending the impact of the initial removal both spatially and temporally.

Coastal defense structures - The main problem with structures placed in the marine environment is that they change the prevailing flow patterns in their vicinity. Scour around the edges of seawalls, jetties and the like can suspend sediment and cause localized erosion. This is a problem particularly at the ends of poorly planned seawalls. The most significant impact, however, is in wave reflection. Walls placed along the beach cause waves to be reflected seaward, much like a ball off a billiard cushion. Sediment suspended by the incoming wave is moved seaward by the reflected wave, and erosion results in front of the wall. This sediment is moved seaward and onto whatever might be in the immediate offshore zone. While small in comparison to problems discussed above, sedimentation related to wave suspension combined with the potential for disruption during construction do represent potential problems that will increase as shore development becomes more prevalent in the islands.

Clearing of upland vegetation - Most of the above activities in some way remove vegetation, and increased erosion typically results. In some instances, however, vegetation removal is not part of a larger construction project, but rather is done solely for the purpose of improving visual or physical access to the beach. The removal of dune grass in the mainland U.S. is a prime example. Locally it is more common for homeowners or developers to remove grass and shrubs to create more open sand, or to remove trees because they block their view. This problem is more related to ignorance, and is therefore more difficult to control. Nevertheless, the increased mobility of the underlying material results in beach erosion and the introduction of potentially large quantities of sediment into the surf zone. The future need for artificial protective structures adds to the problem.

Cumulative impacts of homesite development - Worth considering is the relative importance of single, large development projects vs. several smaller homesites. This is a hard subject with which to deal quantitatively, as homesite development can be so variable. Nevertheless, some thought needs to be given as to whether several homesites developed with virtually no sediment-retention measures can actually cause more damage than a larger project which has been forced to implement at least a poorly-conceived sedimentation control plan.

The primary potential for damage is the confidence that small projects will have small impacts. This is not always the case. A single homesite in western Reef Bay has had a substantial impact on slope stability in the immediate area. The actual impact on the adjacent marine environment has not yet been quantified, but considerable concern has been raised within the Park Service. As pressure increases on areas like St. John, homesite development could potentially play a role exceeding that of larger development.

Management Strategies

Typically there are two approaches to mananagement. One involves education, and the other regulation. Education simply consists of making people aware of the problems so they are more sensitive to them in the future. Unfortunately, due to the advanced stages of the problem and the small likelihood that developers will be in a frame of mind to be "educated" in the short term, regulation emerges as the primary tool of the manager. Past history has shown that with development, education usually emerges from regulation if only in the sense that the developers (large and small) "learn" what they can and cannot get away with. Certainly Coastal Zone Management in the Virgin Islands has brought to the forefront many of the environmental issues that concern us today. The presence of legislation and regulation at least forces the developer to listen, and hopefully to learn.

Because of the above problems with direct education, the remainder of this section will deal with legislative and regulatory approaches to management within the VIBR and the Virgin Islands in general. Inasmuch as most of the problems common in the area are related to physical and biological elements of the region, most of the strategies discussed below should be useful in the eastern Caribbean as well. What will differ from island to island is not the strategies that would be useful in a particular case, but rather the cultural elements of the situation that make one strategy or another more appropriate in each instance. The first section addresses legislative and regulatory options presently open to the territories. The final discussion suggests additional approaches that might be considered. General guidelines for the kinds of areas that should and should not be developed are suggested.

Existing regulations and laws - A number of local laws exist that can be used to affect marine protection. A paperback volume available from the Department of Conservation and Cultural Affairs (**Environmental Laws and Regulations of the Virgin Islands**) outlines these, and provides summaries of their applications. As these are already available in summary form, only the general areas of protection will be listed here.

Title 12, Chapter 3 provides protection for trees and other vegetation adjacent to watercourses. Under these regulations vegetation cannot be removed from any area within 30 ft of the center of the watercourse or 25 ft from its edge, whichever is greater. The problem with this law is likely to be inconsistent enforcement.

Title 12, Chapter 5 contains a number of regulations pertaining generally to water quality. The most applicable portion relates to the issuance of a water quality certificate prior to the granting of other related permits (e.g. Coastal Zone Management permit). Standards for water quality have been established, and any probability that a project will compromise these standards theoretically results in a denial of a certificate, and therefore, a subsequent permit. Included in these standards are minimum allowable quantities of turbidity. Degradation from upland runoff is supposedly considered in this regard. Unfortunately, color and turbidity standards are set in terms of optical measures, and these will suffer from all the problems discussed in an earlier section (i.e. the necessary calibration standards are not yet available). Nevertheless, there is a set of regulations within which the impacts of upland sedimentation can be argued. This represents one area where VIRMC could make a significant contribution.

The most locally significant piece of legislation presently in existance is the Virgin Islands Coastal Zone Management Act of 1978. This act created an organization to evaluate development within the coastal zone and a procedure to initiate that evaluation. It consists of citizen commissions on each island and a CZM Office which coordinates the activities of all the commissioners. The Office of Coastal Zone Management falls within the Department of Conservation and Cultural Affairs.

Like any organization of this type, CZM has been fraught with problems ranging from understaffing to political pressure from above. Nevertheless, it remains as the strongest support for citizen input to local development yet available. The pros and cons of this organization can and have been argued on many fronts. To repeat these arguments here would be of little purpose. Two major problems with the concept of the legislation, however, bear heavily on the problem of upland runoff and are worth mentioning. First, agriculture has been specifically exempted from the process, presumably based on some perceived tradition. As wholesale clearing of upland areas undoubtedly constitutes a major problem in the V.I., removal of this activity from regulation severely compromises the ability of CZM to protect adjacent marine waters.

The second, and perhaps larger, problem is the two-tier system built into the legislation out of deference to the role of Public Works in the prior permitting process. Under this scheme, the island is divided into a first tier near the water and a second tier above. Permits in the first tier are issued by CZM. Permits in the second tier are within the realm of Public Works. In some instances, the boundary between the two is a reasonable physiographic feature (e.g. a ridgeline), but altogether too often it is simply a road or similar cultural structure. The problem with this is two-fold. First, the often arbitrary boundaries can place critical coastal areas in the second tier, where permits are much easier to obtain. Second, with the small size of the three islands and the steep slopes, there are virtually no areas that do not potentially exert great control on the coastal zones of the Virgin Islands. A proviso does exist in the Bill whereby CZM can ask to have input in upland projects that might directly impact the marine environment, even though they are in the second tier. However, if this inclusion were taken seriously, few upland projects would escape the careful scrutiny of the Office of CZM.

In the late 70s, the V. I. Sedimentation Control Plan was introduced. The most significant contribution of this program was a series of maps that provided information on watershed areas, peak discharges and other critical design factors related to upland development. While useful from a design standpoint, this data set provides little or no guidance on the volumes of sediment potentially eroded from these areas, nor are variations in land use incorporated into the runoff estimates. Given opinions by several researchers (e.g. Jordan, 1972; Dunne, 1979) that land use probably plays the primary role in controlling runoff volumes, the absence of this factor in the predictions made by the maps is reason for some skepticism. Nevertheless, these maps do provide a starting point.

Future strategies - Certainly there is tremendous room for improving the present levels of environmental protection. The problems of competition between the local needs for economic improvement and environmental preservation are numerous, and will not be discussed here. Nevertheless, there are several specific management recommendations that have merit and could be immediately integrated into the management of the Biosphere Reserve. Most of these have wider applicability to the eastern Caribben as well.

There are several practices that should be either prohibited or discouraged. These include:

1 - development in major water courses
2 - development in watersheds that empty into low-energy embayments that will have problems dissipating sediments introduced during heavy rains.
3 - any dredging within the Biosphere Reserve boundaries
4 - any removal of seagrasses or mangroves
5 - any filling of coastal ponds
6 - any large-scale clearing

In areas where development must occur, certain guidelines must be provided for the developer. These include:

1 - The establishment of a sedimentation control plan. This should include identification of marine areas sensitive to sedimentation as well as a thorough discussion of present and proposed water and sediment flow to the ocean. Reasonable measures to guard against runoff during and after construction (i.e. sediment fences, berms, settling ponds, silt curtains during dredging, etc.) should be included and described in detail. It is critical that this plan not be a water management plan whose main objective is to facilitate the passage of water over the property. In fact, the goal of such a plan should be to retard runoff until it can soak into the ground or sediment can settle out of suspension. This is typically counter to the economic interests of any developer.

2 - The encouragement of sequenced development. Recently, 30 acres of watershed were cleared for hotel development in Davis Bay on St. Croix. Unusual seasonal rains broke through sediment-retention fences and introduced sediment onto the adjacent shelf. The developer's answer to allegations was that no project that clears this kind of acreage can effectively stop this kind of runoff. This is probably true, and the lesson learned should be to develop areas in pieces, allowing revegetation of one section before another is cleared.

3 - The planning and implementation of monitoring schemes. Any project has a potential for environmental damage. If that damage is perceived to be high, then some sort of monitoring plan should be implemented. This approach serves three purposes. First, it hopefully can identify areas of stress before permanent environmental damage is done. Second, it establishes a baseline against which environmental damage can be measured. The possibility of quantifying damage (and legal responsibility) may raise the level of consciousness within the development community and finally, the observations of environmental change in response to specific levels of stress provide data upon which to base future project evaluations.

4 - The provision of economic incentives for the developer to protect the environment. A simple example of this would be to require a developer to deposit an amount of money into an escrow account equal to 10% of the anticipated project costs. This money would serve as a sort of damage deposit which would be used to offset environmental damage due to violations of the project permit conditions. If the project is nearly completed as planned without damage, then this money would be applied to the final 10% of the project costs. If the developer stays within the restrictions of his original agreement, then there is no monetary loss. If there is significant environmental damage or the developer pulls out of the project, then the money can be put toward environmental restoration. This example would probably be impossible to implement in the local V.I. climate of development panic, but it might work elsewhere in the eastern Caribbean or

certainly within park or preserve boundaries where development is more easily controlled. For this plan to work, the Park Service (or whoever operates as manager) must fall under the same restrictions and penalties.

Future Goals and Objectives

Future efforts of VIRMC should center around two elements. The first is providing baseline data in areas likely to come under stress. The second relates to establishing some level of understanding about how individual organisms and systems respond to different stress levels.

The choice of baseline areas must be based on likely future environmental pressures, and primary study sites must necessarily center around those areas that are slated for change. The importance of "control areas" (i.e. those areas that will remain natural as a frame of reference) must be recognized, but this should not be used as an excuse to concentrate on untouched, and therefore, more scientifically interesting areas.

Understanding environmental change will ultimately center around studies of the interactions of the stress components with the elements of each marine system. It is at this level that our greatest efforts should be concentrated. It is fine to understand currents, or to trace sediment transport, or to quantify patterns of runoff in some number of watersheds as has already been done on St. John. All of these are important factors but will not answer the critical questions about levels of stress and their associated impacts. If we are ever to understand stress responses of marine systems, we must first assess where impact is presently taking place or is likely to occur in the future. After that, we need to formulate a list of parameters that are most likely to affect change. Only after completing all these preliminary tasks, we must compile a plan to measure these parameters and the responses of the marine environment that result. VIRMC has passed through a necessary first stage of baseline data gathering. It has attempted on a localized basis to establish stresses and impacts. Now is the time to move on to understanding the basic elements that cause change in the ocean.

In some respects, VIRMC has approached the problem from a direction opposite to that described above. Rather than addressing the levels of change, a much greater emphasis has been placed on establishing the magnitude of "potential" stresses (e.g. historical analysis of land use; studies of watershed character) and management. Less emphasis has been placed on determining where and how much actual impact is and has been occurring. This approach has assumed (occasionally in error) that impact is everywhere and measurable.

While erring from the basic plan discussed above, these early studies were probably necessary. They represented a logical starting point considering the almost total lack of background data on the biosphere reserve. But, it is time now to move on.

With respect to sediment stress, a number of studies would be useful. Most of these center around characterizing the nature of sediments being introduced into marine systems and their impacts on individual corals. For purposes of illustration, one large-scale experiment will be described, keeping in mind that the proposed future research objectives will likely have to consist of pieces of this project conducted by a variety of individuals.

The experiment would consist of both field and laboratory studies of corals responding to varying loads of widely differing sediments. Field experiments would include subjecting marine organisms to sediment varying in amount, size and composition. These experiments would be similar to those of Rogers (1977), with the addition of a better characterization of the sediments being used. Lethal effects could be determined by simply observing the corals. Sub-lethal effects would involve respiration chambers that are now becoming commercially available. Laboratory experiments would follow a parallel line, except they would allow more carefully monitored sediment applications and perhaps a continuous level of stress more closely approximating natural conditions.

At the same time, a parallel monitoring plan should be implemented in the field. Reefs near major water guts should be quantitatively surveyed and a set of basic measurements established. A protocol should be developed for sampling that can be followed by a team of observers on short notice. The following is a partial list of tasks.

1. Baseline survey of selected study reefs near watershed centers (e.g. Hawksnest, inner Fish Bay; this has already been done on a limited basis). These surveys should identify specific quadrats or transects that can be precisely reoccupied. Permanent markers should be established such that specific areas on the reef (e.g. individual corals) can be relocated. The level of accuracy on such a survey would necessarily be much greater than what has been attempted to date.

2. Selection of the primary channel(s) out of the water course. At these sites, cross section and flow velocity should be measured on an hourly basis during rain storms. Water samples should be taken for characterization of TSS and sediment character as described in an earlier section.

3. Sampling of marine waters near water guts and in the bay during rains. Surface, mid-water and near-botton (1 m) samples should be taken hourly at each site. Sample sites should be placed on a regular grid. The size of the grid would depend on a) the size of the sediment plume and b) the extent of potentially impacted marine systems in the bay.

4. Sampling of settling sediments. Traps as described above should be retrieved on at least a daily basis. Trapped sediments should be weighed and their size distribution should be determined.

5. Permanent quadrats/transects should be examined regularly to detect sub-lethal effects of sedimentation. Field chamber experiments could be used in conjunction, especially to quantify shading effects. The logistics of this are substantial, however.

6. Once enough successful field monitoring programs have been completed, the conditions measured in the field could be duplicated in the lab. By increasing either the sediment doses or the duration of exposure, conditions beyond those measured in the field could be examined.

While the above approach has been described for upland runoff, a similar regimen could be applied to in-water projects such as dredging. For this type of approach to yield usable data, a significant long-term commitment must be made to specific field sites. Gathering of baseline data is an important first step. Unless we start to examine responses of marine organisms, however, our research efforts will never advance beyond documenting what is lost or destroyed, and our ability to predict damage will never be realized.

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