Factors affecting land-based sedimentation in coastal bays, US Virgin Islands

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Abstract. In the US Virgin Islands, land-based sources of pollution including sediment and storm-water runoff are one of the primary causes of coral reef degradation. Watershed development, especially the building of dirt roads, has increased the land-based (terrigenous) sediment accumulation in coastal bays with coral reefs. From 2008-2011, our research team and community partners have monitored marine sedimentation (using sediment traps) directly below developed watersheds (Coral Bay) and below undeveloped watersheds (Lameshur Bay) for comparison. These data suggest that total and terrigenous sediment trap accumulation rates below the developed watersheds were significantly higher than below undeveloped watersheds. The highest rates of terrigenous sediment accumulation occurred when there were periods of significant terrigenous runoff linked to major storm events, such as Hurricane Otto in October of 2010. Episodically high sediment accumulation rates on some reefs during storm events were consistent with rates shown elsewhere to cause stress to corals (>50 $mg/cm^2/day$). Outside of storm events, total and terrigenous sediment accumulation rates on the coral reefs were generally low (<10$mg/cm^2/day$). Recently, (July, 2011) watershed sediment erosion control projects were constructed above our study sites in the developed watersheds. In the future, temporal comparisons of our pre-mitigation (baseline) (2008-2011) and post- mitigation (2011-13) data, complemented by spatial comparisons between areas below developed, undeveloped and mitigated watersheds may provide data to inform the development of Best Management Practices (BMP) applicable to other tropical islands.

Key words: Sedimentation, St. John, US Virgin Islands, Land-based pollution, sediment traps

Introduction

Land-based pollution is harmful to coral reefs because it delivers dissolved nutrients, chemicals, and suspended particulate matter (sediment) to the water column. Sedimentation and high turbidity can negatively affect coral health, growth, coverage, diversity, and reproduction (Fabricius 2005; Rogers and Miller 2006). Corals on fringing reefs and in semi-enclosed bays adjacent to steep watersheds may be especially vulnerable to high turbidity during periods of high watershed runoff. Declines in live coral reef cover in the USVI have been linked to sedimentation from coastal development (Rogers 1998).

Here we present the results of an ongoing multi-year study of the impact of watershed development on terrigenous (land-based) sedimentation on reefs in St. John, US Virgin Islands. St. John is an ideal location to study the impact of watershed development on sediment delivery to coral reefs for several reasons: 1) there are no sources of carbonate sediment on the island, making it possible to compositionally distinguish land-based (terrigenous) sediment from marine (carbonate) sediment sources; 2) terrestrial erosion has been quantified, modelled and linked to development on St. John (Ramos-Scharrón and MacDonald 2005); 3) the fringing coral reefs that surround St. John are regularly observed and ecologically monitored (Jeffrey et al. 2005; Rogers 1998; Rogers and Miller 2006; Edmunds 2005; Smith et al. 2008) providing the opportunity to link physical sedimentation data with reef health matrices; 4) the watersheds are small and some are undeveloped due to their protection within the Virgin Islands National Park; and 5) there is strong community interest and concern about reducing the impact of land-based sources of pollution to the local St. John coral reefs.

Our study focuses on characterizing sedimentation patterns in two bay areas on St. John, USVI (Coral Bay and Great and Little Lameshur Bays), which

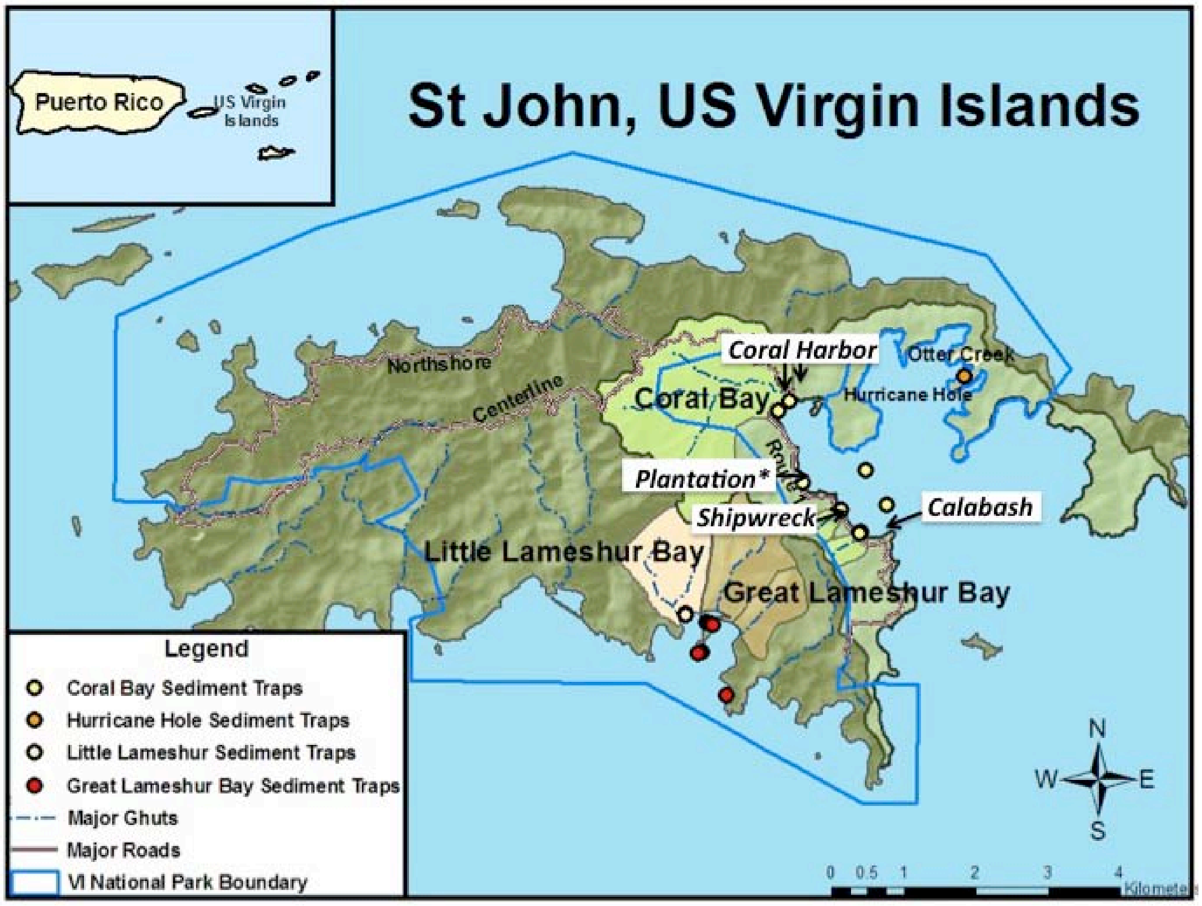

Figure 1: Map of St. John showing the boundary of the VI National Park (blue line) and the watersheds and sediment trap/sampling locations below developed (Coral Bay) and undeveloped (Great & Little Lameshur Bays and Hurricane Hole) watersheds.

drain six watersheds or sub-watersheds (Fig. 1). Coral Bay (CB) is a 13.3km^2 bay with mangroves, sea-grass beds, reefs, *Acropora* corals and turtle nesting areas. The watersheds that drain into CB have steep slopes (averaging 18% with large areas over 35%), erodible soils, and high runoff volumes associated with average rain events (Center for Watershed Protection, 2008). Rapid development of the hill slopes has resulted in many steep dirt roads, which provide a source and conduit to terrigenous sediment runoff (Ramos-Scharrón and MacDonald 2005). Geological studies of historical sedimentation rates in CB have shown a dramatic increase in bay sedimentation rates since the 1950s with development and building in the CB community (Brooks et al. 2007).

This study compares sedimentation in watersheds in developed watersheds in CB to undeveloped sites, which serve as "reference" sites for comparison. These "reference" sites include: locations in Great and Little Lameshur Bays within the VI National Park, sites below watersheds with limited or no development in Coral Bay (Plantation), and Hurricane Hole within the US Virgin Islands Coral Reef National Monument (Fig. 1).

In order to characterize sedimentation at the shore and reef sites, we determined the composition (% terrigenous, organic and carbonate) and quantity (accumulation rate) of sediments and examined how these parameters varied: a) between areas with different types and degrees of development, b) temporally during the 4-5 year study period, c) with environmental parameters (storms, runoff, wind and currents), and d) with watershed changes (such as new development or sediment mitigation).

Material and Methods

Marine sedimentation was monitored regularly (every 26 days for 9 months a year for 3-5 years) and during storm events at 15 sites below 6 sub-watersheds on St. John (Fig. 1). The variation in total and terrigenous sediment accumulation was determined by deploying sediment trap arrays consisting of four 2" diameter X 8" long PVC pipes placed 60 cm above the sediment-water interface on metal stakes. The water depth of trap deployment varied between environments (1.3 m in shore & mangrove environments and 8-10 m on the reefs). In the laboratory, sediments accumulated in the sediment-trap tubes were filtered (< 3μm), rinsed, dried and weighed to determine the mass of sediment accumulated per unit area over the time deployed. The % organic matter and % carbonate sediment in each sample were measured by loss on ignition (LOI) (combusting 3 hours at 550^{o}C for % organic and 950^o C for 3 hours for % carbonate) (Heiri et al. 2001). The proportion (%) of terrigenous sediment was then determined by subtraction from the % organic and % carbonate and multiplied by the sediment accumulation rate to get the rate of terrigenous sediment accumulation in the trap tubes.

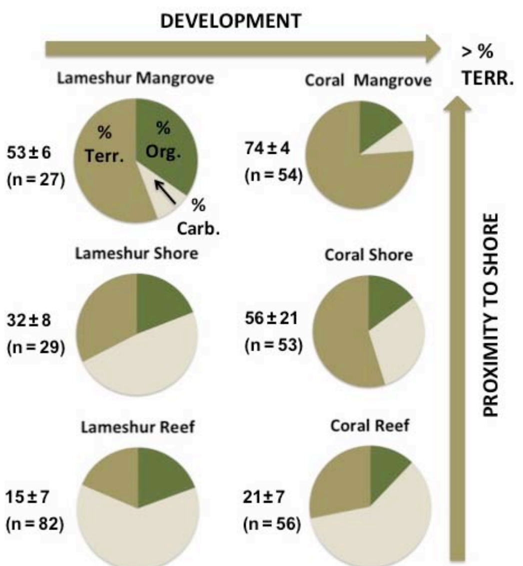

Figure 2: Comparison of mean sediment composition (% terrigenous, % organic, and % carbonate) at mangrove, shore and reef environments in bays below a developed (Coral) and an undeveloped (Lameshur*) watershed within the Virgin Islands National Park for the period 8/09-12/11.

Results

One would expect the proportion of terrigenous sediment to decrease with distance from the shore. We found that the mean proportion of terrigenous sediment (% terrigenous) decreased significantly from mangrove to shore to reef (Kruskal-Wallis: Coral Bay, $n = 159$; $p \leq 0.001$; Lameshur Bay, $n = 137$, $p \leq 0.001$). But when sediments in each of three environments (mangrove, shore, reef) were compared between the developed and reference areas, the proportion (%) of terrigenous sediment was always significantly higher at the developed sites (Mann-Whitney U: mangrove, $n = 81$, $p \leq 0.001$; shore, $n = 82$, $p \leq 0.001$; reef, $n = 133$, $p \leq 0.001$) (Fig. 2).

Terrigenous sediment accumulation rates were spatially variable (Fig. 3). Mean terrigenous accumulation rates for the 2.5-5 year monitoring period differed significantly among eight locations (Kruskal-Wallis: $n = 8$, $p \leq 0.001$) (Fig. 3). The highest mean terrigenous accumulation rates were recorded at two sites below areas of extensive watershed development: Coral Harbor, and Shipwreck (Figs. 1 & 3). The watershed above Coral Harbor is the largest watershed on St. John and contains many dirt roads. Mangroves lining the shoreline at the Coral Harbor may effectively be reducing terrigenous sediment delivery. Though Calabash is a steep and developed watershed adjacent to and geographically similar to the Shipwreck watershed, terrigenous sedimentation rates at the Calabash site were significantly lower than at Shipwreck (Mann-Whitney U: $n = 51$, $p \leq 0.001$) (Fig. 3). Construction of a leaky sediment retention pond in 2008 at Calabash may have reduced terrigenous sediment runoff during all but the major storm events (when it overflows). Similar in size, steepness, and geographic orientation to Shipwreck and Calabash along the south shore of Coral Bay, Plantation consists of two sub-watersheds with minimal or no development (Fig. 1). Mean terrigenous sediment accumulation rates below this reference sub-watershed of Plantation were significantly less than below developed & unmitigated Shipwreck (Mann-Whitney U: $n = 83$, $p \leq 0.001$) and Coral Harbor watersheds (Mann-Whitney U: $n = 120$, $p \leq 0.001$) (Fig. 3). Mean terrigenous sediment accumulation rates were significantly higher at the developed (CB) compared to the reference (LB) reef and mangrove sites (Mann-Whitney U: reef, $n = 166$, $p \leq 0.001$; mangrove, $n = 131$, $p \leq 0.001$) (Fig. 3).

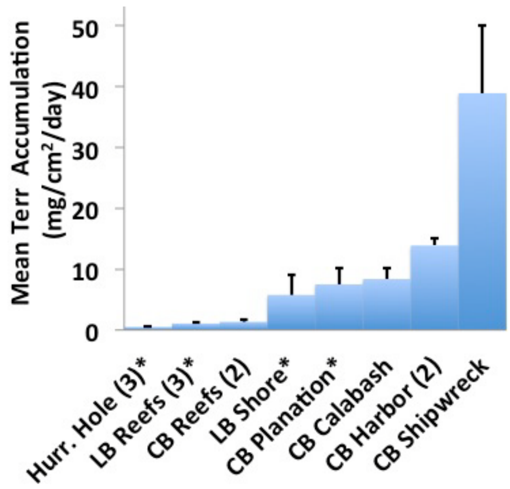

Figure 3: Variation in mean (+/- SE) terrigenous sediment accumulation (mg/cm^2/day) in Coral Bay (CB), Lameshur Bay (LB) and Hurricane Hole (Fig. 1) for the time series (2.5-5 years). The sites below undeveloped reference watersheds are marked by asterisks.

Examination of temporal variability in sedimentation at the shore sites (Fig. 4) shows that for most sampling periods, the highest rates of terrigenous accumulation were recorded at sites below

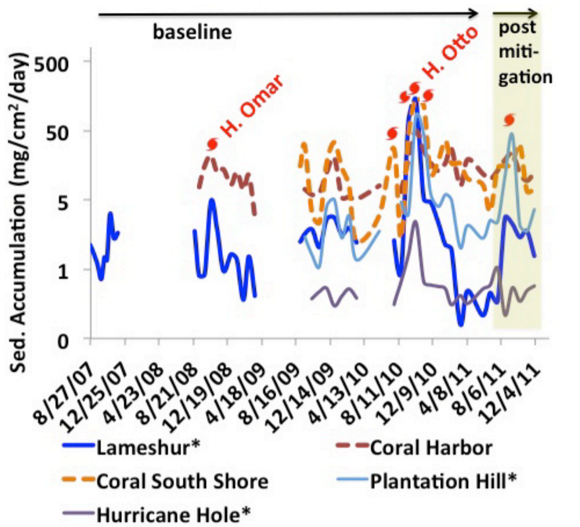

Figure 4: Temporal variability (8/07-12/11) in mean terrigenous sediment accumulation in shore and mangrove environments below developed (dashed) and reference (solid, asterisk) locations. Highest terrigenous accumulation occurs during periods of major runoff brought on by low-pressure systems or tropical storms/hurricanes. Major runoff events are indicated by the storm symbols. Watershed erosion mitigation structures were completed in Coral Bay in July of 2011, which marks the beginning of our post-mitigation period.

the developed watersheds (dashed lines in Fig. 4) compared to the reference sites (solid lines). The highest rates of terrigenous sediment accumulation occurred when there were periods of significant terrigenous runoff linked to major storm events. The fall rainy season of 2010 brought at least two tropical storms/hurricanes and 2 low-pressure systems, which resulted in record rains, landslides and terrigenous runoff that turned the bays brown. The highest terrigenous sediment accumulation during the five-year time series was recorded following Hurricane Otto (which passed St. John on 10/9/10-10/11/10) (Fig. 4). At the reef sites (Fig. 5), the highest total (dashed lines) and terrigenous (solid lines) sediment accumulation were recorded during storm events indicating that delivery of terrestrial sediment is closely linked to prevailing weather conditions.

In addition, both total and terrigenous accumulation were higher at the reefs below the developed watershed (CB) than below the reference watershed (LB) for most sampling periods. An exception was observed during the sampling period when Hurricane Earl (8/30/10-8/31/10) passed over St. John. Total sediment accumulation at the Lameshur Bay reefs was the highest measured at reefs during the time series (Fig. 5). This storm did not bring much terrigenous runoff but brought high swells and waves from the south, which re-suspended carbonate bottom sediment in Lameshur Bay, turning the bay a whitish color. By comparison, H. Earl had less impact on sedimentation at the CB reef sites, which were

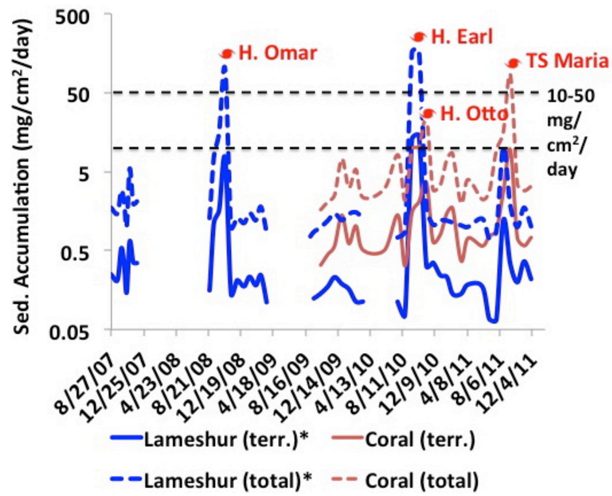

Figure 5: Temporal variability (8/07-12/11) in mean total (dashed) and terrigenous (solid) sediment accumulation at reef sites in Coral Bay (developed watershed) and Lameshur Bay (undeveloped reference watershed). Highest total and terrigenous accumulation occurred during major storms. Sediment accumulation rates during these storm periods surpass 10 and reach up to 100 mg/cm^2/day.

somewhat protected from the southerly swell. The variable impact of this storm event at different reefs illustrates the necessity of site-specific monitoring to accurately quantify the specific sedimentary response to storms.

Discussion

Pastorok and Bilyard (1985) suggested that sediment accumulation rates of 10-50 mg/cm^2/day and > 50 mg/cm^2/day cause "moderate to severe" and "severe to catastrophic" sediment stress, respectively. High sedimentation rates (>100 mg/cm^2/day) have also been shown to kill exposed coral tissue (Riegl and Branch 1995) or reduce photosynthetic yields (Philipp and Fabricius 2003). Though relatively low sediment accumulation rates (< 10 mg/cm^2/day) persisted at both the LB and CB reefs for most of the time series, three major storm events resulted in total sediment accumulation rates greater than 50 mg/cm^2/day and one event produced rates greater than 100 mg/cm^2/day. Our data therefore suggest that these reefs are not under persistent chronic sedimentation stress, in contrast to other reefs in the USVI, such as those at Fish Bay (Gray et al., 2009). However, these integrated (26-day) mean accumulation rates may underestimate the acute sedimentation that occurs during the few days that a storm passes over.

In summary, initial data from this study show consistently higher rates of terrigenous accumulation and proportions (%) of terrigenous sediment below developed watersheds with dirt roads and other sources of loose sediment compared to undeveloped forested reference sites. On average, terrigenous accumulation rates below developed watersheds are

60, 5-24 and 6 times higher in the mangrove, shore, and reef environments, respectively than in equivalent environments at reference sites (Table 1). Storm events result in increased terrigenous sediment accumulation in both the shore and reef environments. Acute total rates of sediment accumulation during these storm events are at rates high enough to be harmful to corals.

Environ-ment	developed/reference* site	mean ratio	SD	N
Reef	Coral Reef/Lam. Reef*	6	6	26
Shore	Coral S./Lam.*	24	42	28
Shore	Coral S./Plantation Hill*	5	5	27
Mangrove	Coral Harbor/Hurr. Hole*	60	46	25

Table 1: Mean ratios of terrigenous accumulation rates at developed/reference* sites for mangrove, shore and reef environments from 9/2/09-12/1/11.

However, the factors governing the quantity, duration and type of sedimentation in a particular site are complex and variable. In addition to watershed development, variability in rainfall, exposure to swells and sediment resuspension must be considered.

Terrigenous sediment erosion resulting from development activities may be managed locally through the implementation of sound watershed management best management practices (BMPs). In late 2011, a program of watershed restoration (erosion mitigation structures & BMPs) was implemented in Coral Bay to reduce sediment loading to the marine environment. The three watersheds above the sites with the highest terrigenous sediment accumulation (Shipwreck, Coral Harbor, and Calabash) were targeted for watershed mitigation efforts. Coral Bay residents have already noticed a visible reduction in bay turbidity following storms in the fall of 2011. Our ongoing sediment monitoring data has produced a comprehensive baseline database illustrating how sedimentation processes have varied seasonally and with environmental processes (wind, currents, rain, seasons) over 3-4 years. We will continue monitoring sedimentation below the mitigated watersheds (and in comparable reference sites) through 2013. Future research involving temporal comparisons of our pre-mitigation (baseline) (2008-2011) and post-mitigation data (2011-13), complemented by spatial comparisons between areas below developed, undeveloped and mitigated watersheds may provide data about the effectiveness of these mitigation measures which will inform development of BMPs applicable to other tropical islands.

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