# Final Project Report (3/31/14)

# "Effects of Watershed Erosion Control on Land-Based Sources of Pollution to Coral Reefs in RCP Priority Sites"

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## Executive Summary

This project extended our previous ARRA and NOAA CRC funded sediment monitoring work in St. John, USVI over another field season (7/11-3/12) and included assessments of trace metal transport from "ridge to reef" and water quality. Our aim was to make spatial comparisons of sedimentation, geochemistry, and water quality between sites drained by undeveloped ("control") watersheds and mitigated sites to determine the source of variation in sedimentation. In addition, we compared our 2011-12 post-mitigation data to data collected prior to the ARRA mitigation (2008-11). We also analyzed the geology and geochemistry of watershed bedrock, soil and streambed sediments as well as representative marine sediments to determine: 1) what metals or metal compounds traced terrigenous sediment input; 2) how the mineralogy/lithology and concentration of metals and metal compounds varied from ridge to reef and differed between developed vs. undeveloped areas.

For this grant we conducted sediment and water-quality (TSS) monitoring at 14 stations (below developed and undeveloped watersheds) in 4 bays in eastern St. John, US Virgin Islands 10 times from July 2011-March 2012.

We found that the mean proportion of terrigenous sediment (% terrigenous) and the total and terrigenous sediment accumulation rates (mg/cm$^2$/day) decreased significantly from mangrove to shore to reef. Terrigenous sediment accumulation below developed watersheds were 5-40 times, 6-55 times, and up to 60 times higher in the shore, reef and mangrove environments, respectively below developed watersheds than at equivalent environments below undeveloped watersheds. Though relatively low sediment accumulation rates (< 10 mg/cm$^2$/day) persisted for most of the time series, major storm events resulted in total sediment accumulation rates greater than 50 mg/cm$^2$/day on the coral reefs. However, these integrated (26-day) mean accumulation rates may underestimate the acute sedimentation rates that occur during the few days that a storm passes over.

The pre- and post-mitigation comparisons at the shore stations showed either significant decreases or decreasing trends in the total and terrigenous sediment accumulation for some of the traps that were below major mitigation areas in Coral Bay. But these patterns were also observed below undeveloped/unmitigated areas. In many cases the statistical comparisons had low power (chance of type II error) because of the high natural variability in sediment accumulation rates. Due to the short duration (one season) and relatively low number of storms during the 2011-12 post-mitigation period, it was not possible to evaluate whether the ARRA mitigation had significantly reduced sedimentation. A longer time series is needed to make meaningful pre-vs. post-comparisons.

The mineralogy and general geochemical composition of bedrock soils and eroded terrestrial sediments was similar for terrestrial samples collected in both developed and undeveloped study watersheds. The concentrations of tracer "terrestrial" elements were generally less in marine sediment samples than in samples collected in the watershed, likely due to dilution of terrigenous sedimentat by marine carbonates. Marine near-shore sediments collected below developed watersheds were more similar geochemically to the terrestrial watershed sediments than were those collected below the undeveloped watersheds. Comparison of the average concentrations of "terrestrial" metals in marine near-shore and reef sediments show concentrations that were typically between 5 and 10 times higher at developed compared to the undeveloped near-shore sites and between 2 to 52 times higher at developed compared to undeveloped reef sites. Marine metal flux rates were typically between 2 to 7 times higher at developed shore sites and 33 to 430 times higher at developed reef sites than at corresponding sites in the undeveloped areas. These differences were generally consistent with modeled sediment yields, which were 12.6 times higher for the developed compared to the undeveloped watershed (Ramos-Scharron, personal communication).

TSS measurements made during regular 26-day monitoring trips (usually fair weather) were highly variable but generally low (<10 mg/L), suggesting generally good water quality most of the time. "Fair-weather" TSS over the 5-year study was significantly higher in shore environments below developed compared to undeveloped watersheds, suggesting that watershed development and dirt roads may impact water quality. But these differences were not significant at reef environments. TSS measured opportunistically during a storm in 2010 indicated acute turbidity levels 10's to 100's of times above fair-weather background values. If these conditions persist more than a few days or occur frequently, they may cause harm to corals and other reef organisms. A program of systematic water-quality measurement during acute storm events is needed to evaluate the true impact of watershed development on TSS and other water quality parameters.

Our outreach objectives were to: a) establish scientific and educational collaborative partnerships with scientists and environmental managers; b) inform scientists, students and the public about the impacts of watershed development on coral reefs, and c) provide tangible data for scientists and environmental managers. From 7/23/11-6/13/13, we conducted 35 outreach events, which consisted of meetings, presentations, or article/abstract submissions. Through these activities we reached at least 1832 people, including USVI locals, students at all levels, the general public, and scientific and management communities. Products from this grant include one journal article, one report, 13 professional meeting abstracts & presentations, two Master of Science theses, three undergraduate research projects, and one awarded proposal for $75,000 (with $78,379 in matching funds).

## Introduction & Project Objectives

In the coastal areas of US Virgin Islands, land-based sources of pollution (LBSP) including sediment and storm-water runoff are one of the primary causes of coral reef degradation. In July 2009, The V.I. RC&D and its partners were awarded funding from the American Recovery and Reinvestment Act (ARRA) to implement erosion & sediment control practices to reduce sediment-loading rates into the coastal waters and coral reefs of Coral Bay and Fish Bay St. John. From 2007-2010, our research team and our community partners have conducted marine and terrestrial sediment and water quality monitoring directly below the sites of ARRA watershed erosion control projects and in adjacent unmitigated and “control” sites for comparison. This 3-4 year record of regular 25-28-day sampling and more recent targeted “storm event” sampling provides a valuable pre-mitigation “baseline” data set over multiple seasons and environmental conditions. The ARRA erosion control projects in Coral Bay were be completed in August of 2011.

This project extends our previously funded ARRA and NOAA CRC funded work over another field season (7/11-3/12) including assessments of metal transport from “ridge to reef” and water quality. Our aim was to make temporal comparisons among data collected prior to mitigation (2008-11) and after the mitigation is complete (post mitigation) (2011-12). In addition, spatial comparisons of data among sites drained by a) undeveloped (“control”) watersheds, b) developed unmitigated, and c) mitigated sites will help us to determine the source of variation in sedimentation.

Our study examined three types of sediments in three marine bays: suspended sediments (water samples), settling sediments (sediment traps) and accumulated sediments (bay-floor benthic surface samples). In addition we have measured some parameters of marine and terrestrial water quality (TSS).

We also analyzed the geology and geochemistry of watershed bedrock, soil and streambed sediments as well as representative marine sediments. The objectives of our geological/geochemical assessment was to determine: 1) what metals or metal compounds traced terrigenous sediment input in St. John, USVI; 2) how the mineralogy/lithology and concentration of metals and metal compounds changed from ridge to reef; and 3) whether there were differences in these concentrations between developed vs. undeveloped areas.

Our specific educational and public outreach objectives were to: a) establish scientific and educational collaborative partnerships with scientists working in the USVI and interested citizens; b) inform students and the public about the impacts of watershed development on corals reefs, and c) provide tangible data for territorial and local environmental managers.

## Summary of Research Activities

### A. Field work: USVI/VIERS
### (Virgin Islands Environmental Resource Station)
### (7/17/11-6/30/12)

On July 17th, 2011, a research team from USD traveled to VIERS (Virgin Islands Environmental Resource Station) on St. John, USVI to conduct field research from 7/17/11-8/3/11. The team included Dr. Sarah Gray (P.I.), Dr. Beth O'Shea (Faculty and hydrogeochemist at USD), Robert Harrington (USD graduate student) and Amanda Greenstein (USD undergraduate student). The USD team joined Zoe Hastings, the USD/VIERS field research technician who was already on site at VIERS. During the 19-day field season, we checked, repaired and installed sediment traps and current meters at our sampling locations in Great Lameshur Bay, Little Lameshur Bay, Coral Bay, and Hurricane Hole in St. John (Figs. 1, 2, 3; Table 1). We also hired and trained community field assistants. Dr. Beth O'Shea and MS student Robert Harrington conducted a watershed survey and collected soil and rock samples at representative locations (Fig. 4) in order to compare the geochemical/mineralogical composition of the rocks and soils to the suspended and dissolved load in the runoff (Fig. 5). Dr. Carlos Ramos-Scharron has given us representative sediment samples from his terrestrial sediment traps so that we can compare the geological composition of sediments in the marine and terrestrial environments.

From July 1 2011-March 14 2012, Zoe Hastings, our research assistant in residence at the Virgin Islands Environmental Resource Station (VIERS) regularly monitored sedimentation and water quality at 14 stations in 4 bays (Great Lameshur, Little Lameshur, Coral Bay, and Hurricane Hole) (Figs. 1, 2; Table 1). She collected water and sediment samples at regular intervals (approximately every 26-28 days) with the help of five local field assistants, Roy Proctor, Phil Strenger, Bruce Swanson, Sarah Groves, and Hew Schlereth. Between July 2011 and March of 2012, there were ten sampling periods of 25-28 days each. Dates of Coral Bay sampling during this reporting period were: 7/25/11, 8/20/11, 9/15/11, 10/11/11, 11/5/11, 12/1/11, 12/29/11, 1/21/12, 2/15/12, and 3/14/12. Samples were collected in Lameshur Bay two days after the Coral Bay sampling. For each of the collection periods, sediments (suspended, trapped, and bottom) and water samples were processed at the VIERS (Virgin Islands Environmental Resource Station) laboratory. Dried and frozen sediments and water samples were sent to the University of San Diego for further chemical and geological analyses (see methods below).

Tropical Storm Irene passed near St. John on August 21st and generated ghut flow that continued for about three days in Coral and Lameshur Bays. Later, on September 10th, 2011, tropical storm Maria brought flash flooding and terrigenous runoff to St. John Bays. Tropical storm Ophelia passed near St. John in late September (9/27) but did not bring much rain. Local field assistant Matt Knoblock and Zoe Hastings took pictures and collected samples of the ghut water and suspended sediments during the first two of these three storm events (TS Irene and TS Maria).

***Figure 1**. Map of St. John showing the boundary of the VI National Park (blue line) and the study areas in Coral Bay and Lameshur Bay, eastern St. John.*

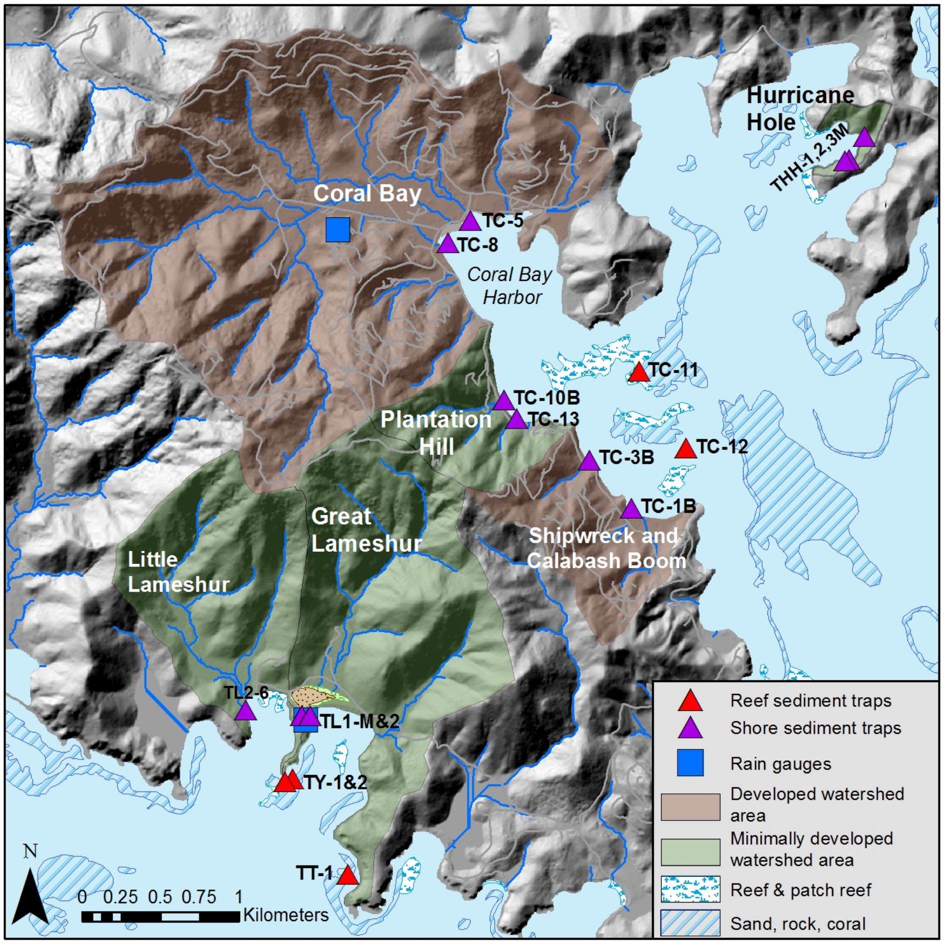


***Figure 2.** Eastern St. John showing Lameshur and Coral Bays. Red and purple triangles mark reef and shore study sites, respectively. The developed watershed areas are shaded in brown and the minimally (undeveloped) watershed areas are shaded in green. Rain gauge deployment locations are marked with blue squares. D. Coral Bay E. Lameshur Bay.*

**Table 1. Sampling locations, sediment trap height and sampling interval for sediment traps.**

| Bay | Station | Environment | Trap | Trap Height (cm) | Collection interval | Lat. 18' N. (min.) | Long. 64' W. (min.) |
|---|---|---|---|---|---|---|---|
| **Coral** | Calabash Shore | Shore | TC-1 | 30 | 26-day | 19.810 | 42.278 |
| | | | TC-1B | 60 | 26-day | 19.815 | 42.272 |
| | | | TC-1S | 30 | storm | 19.815 | 42.271 |
| | Shipwreck Shore | Shore | TC-3 | 30 | 26-day | 19.976 | 42.429 |
| | | | TC-3S | 30 | storm | 19.980 | 42.424 |
| | | | TC-3B | 60 | 26-day | 19.977 | 42.423 |
| | Plantation Hill Shore | Shore | TC-10B | 60 | 26-day | 20.187 | 42.733 |
| | | Shore | TC-13 | 60 | 26-day | 20.122 | 42.687 |
| | South Mangrove | Mangrove/bay | TC-8 | 60 | 26-day | 20.720 | 42.931 |
| | North Mangrove | Mangrove/bay | TC-5 | 60 | 26-day | 20.795 | 42.849 |
| | | | TC-5S | 60 | storm | 20.793 | 42.849 |
| | North Reef | Reef | TC-11 | 60 | 26-day | 20.278 | 42.241 |
| | South Reef | Reef | TC-12 | 60 | 26-day | 20.018 | 42.072 |
| **Hurricane Hole** | Hurricane Hole Shore | Mangrove | THH-1B | 60 | 26-day | 20.988 | 41.471 |
| | | | THH-2 | 60 | 26-day | 21.065 | 41.414 |
| | | | THH-3M | 30 | 26-day | 20.982 | 41.485 |
| **G. Lameshur** | G. Lameshur Mangrove | Mangrove | TL1-M | 60 | 26-day | 19.125 | 43.477 |
| | | | TL1-MS | 60 | storm | 19.125 | 43.477 |
| | G. Lameshur Shore | Shore | TL1-2 | 30 | 26-day | 19.123 | 43.448 |
| | | | TL1-2S | 30 | storm | 19.123 | 43.448 |
| | Tectite Reef | Reef | TT-1 | 60 | 26-day | 18.585 | 43.315 |
| | Yawzi Reef | Reef | TY-1 | 60 | 26-day | 18.910 | 43.512 |
| | | | TY-2 | 60 | 26-day | 18.901 | 43.540 |
| **L. Lameshur** | Little Lameshur Shore | Shore | TL2-6 | 60 | 26-day | 19.146 | 43.681 |
| | | | TL2-6S | 60 | storm | 19.145 | 43.682 |

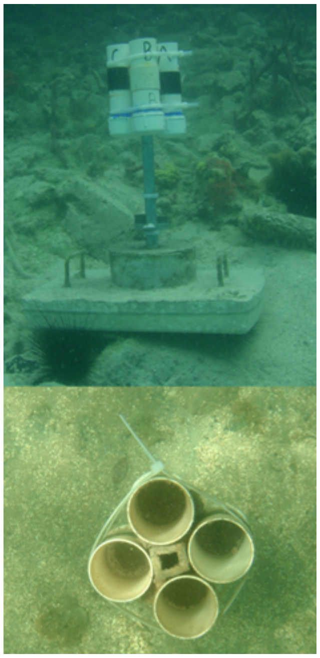


***Figure 3.*** *Marine sediment trap posted 60 cm off the sea-floor. Tubes were made of PVC with a 4:1 height-to-diameter ratio.*

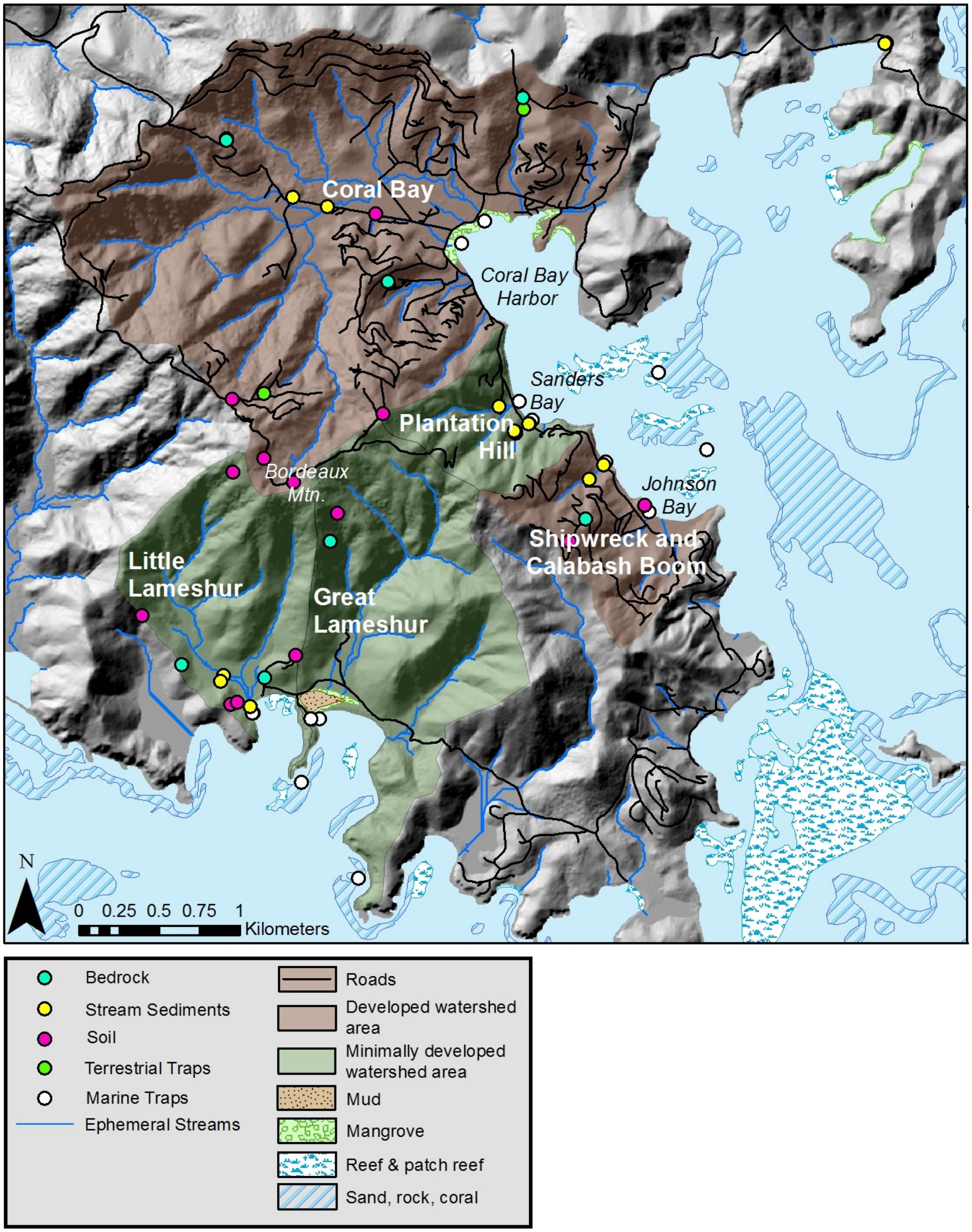


***Figure 4.*** *Eastern St. John, USVI showing geochemistry sample collection locations and sample types (in different colored circles). Minimally developed watersheds (Little Lameshur, Great Lameshur, and Plantation Hill) are indicated by green shading. Developed watersheds (Coral Harbor and Shipwreck/Calabash Boom) are indicated by brown shading. Blue lines mark ephemeral stream drainages (ghuts) and black lines mark roads.*

***Figure 5A.*** *MS student Robert Harrington, collects paired bedrock and soil horizon samples in St. John to make a geological and geochemical comparison between bedrock, soil and marine terrigenous sediments.*

***Figure 5B.*** *Dr. Beth O'Shea and her students collected soil and rock samples at representative locations in order to compare the geochemical/mineralogical composition of the rocks and soils to the suspeneded and dissolved load in the runoff. The photo above shows Dr. Beth O'Shea collecting a sample of muddy storm-water runoff, which is overflowing over one of Dr. Ramos-Sharrons' terrestrial sediment traps.*

## B. University of San Diego (USD) laboratory research

Laboratory research focused on analyzing rocks, sediments and water samples were conducted by graduate students Whitney Sears and Robert Harrington and undergraduate students Ruby Teague and Jake Holley. These analyses included: 1) compositional (LOI) and textural (laser particle sorter) analysis of marine sediment samples, 2) whole rock geochemical analysis of rocks and sediments by XRF (X-ray fluorescence), XRD (X-ray diffraction) and petrography, 3) analysis of water samples for total suspended sediments (TSS). Detailed methodologies are described in each for the "Research Findings" sections below.

## C. University of San Diego (USD)/ University of the Virgin Islands data synthesis

The P.I. collaborated with ARRA monitoring partners Drs. Tyler Smith and Marcia Taylor of the University of Virgin Islands (who conducted marine monitoring at other locations in the USVI) and Dr. Carlos Ramos Scharron of UT Austin (who conducted terrestrial monitoring in Coral Bay) to integrate data sets and synthesize results. We conducted several conference calls and presented our integrated findings as a final marine monitoring report to NOAA/ARRA and as a presentation to the US Coral Reef Task Force meeting on Feb. 24th, 2012 and a Marine Monitoring Report for the NOAA/ARRA program.

## D. Research findings

### A. Marine sedimentation

#### Methods

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 (Fig. 3). 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 (< 3mm), 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 550ºC for % organic and 950º 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

#### Results & Discussion

Only the data for the last 10 sampling periods were collected as part of this grant (7/11/11-5/10/12) but we present the 2011-12 funded on this grant in the context of data from previous years (collected since 2007 or 2008 at some sites in and 2009 for all sites).

### *i. Sediment composition*

As one would expect, the mean proportion of terrigenous sediment decreased significantly from mangrove to shore to reef (Kruskal-Wallis: Coral Bay, $n = 159$; $p \leq 0.001$; Lameshur Bay, $n = 137$, $p \leq 0.001$) (Fig.6). 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. 6).

### *ii. Terrigenous sedimentation (spatial variability)*

Terrigenous sediment accumulation rates were spatially variable (Fig. 7). 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. 7). The highest mean terrigenous accumulation rates were recorded at two sites below areas of extensive watershed development: Coral Harbor, and Shipwreck (Fig. 2). 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. 7). 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. 2). 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. 7). 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. 7).

### *iii. Time series of total and terrigenous sediment accumulation at sampling sites*

Site by site time series of sediment trap accumulation and compositional sediment accumulation (7/2009-5/2012) results are plotted in Figures 8-10. Only the data for the last 10 sampling periods were collected as part of this grant (7/11/11-5/10/12) but it is appropriate to view the 2011-12 data in the context of pervious years. Total and terrigenous sediment accumulation was generally higher below the steepest and most developed watersheds (such as Shipwreck [TC-3B] and Coral Harbor [TC-5, TC-8]) than below the undeveloped watersheds (such as Plantation Hill) for equivalent environments (Figs. 8 and 9). Total sediment trap accumulation rates were highest at the Shipwreck shore site, which is below a developed steep watershed. This site was one of the sites for ARRA sediment mitigation projects. The sediment trap accumulation rates were lowest at

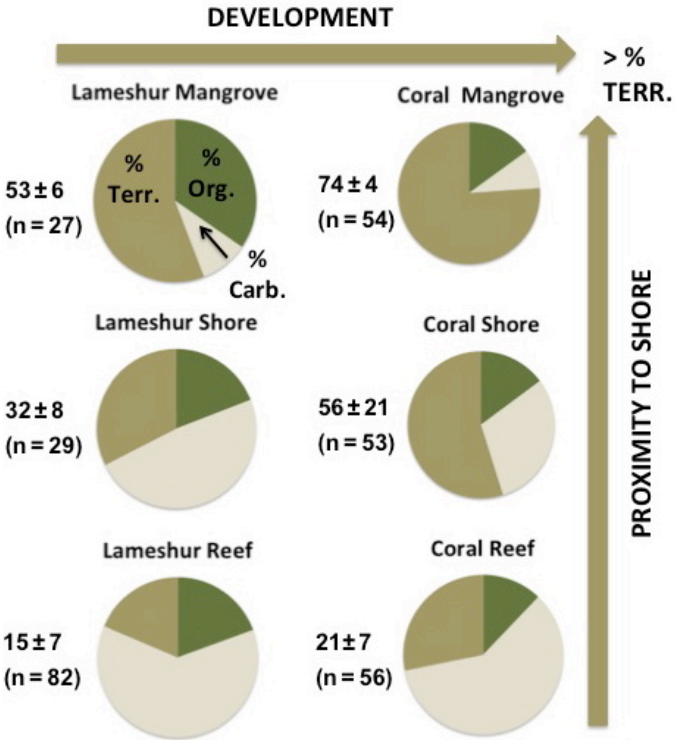


***Figure 6.*** *Comparison of mean sediment composition (% terrigenous, % organic, and % carbonate) at mangrove, shore and reef environments in bays below a developed (Coral) and an undeveloped (Lameshur*) watershed within the Virgin Islands National Park for the period 8/09-12/11.*

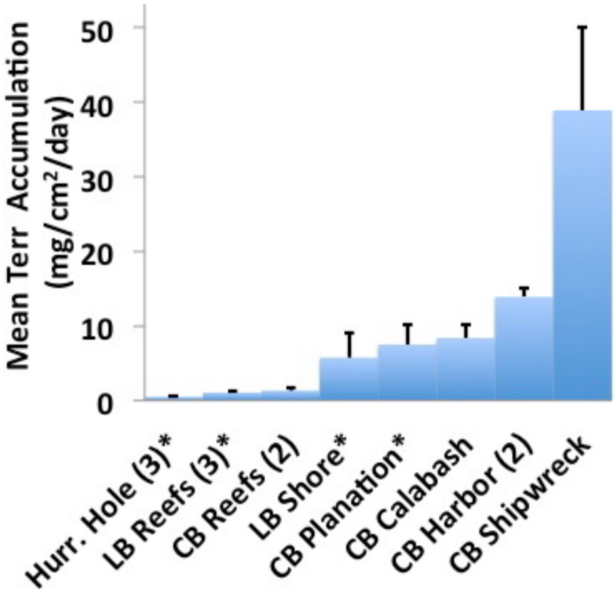


***Figure 7.*** *Variation in mean (+/- SE) terrigenous sediment accumulation (mg/cm$^2$/day) in Coral Bay (CB), Lameshur Bay (LB) and Hurricane Hole (Fig. 1) for the time series (2.5-5 years). The sites below undeveloped reference watersheds are marked by asterisks.*

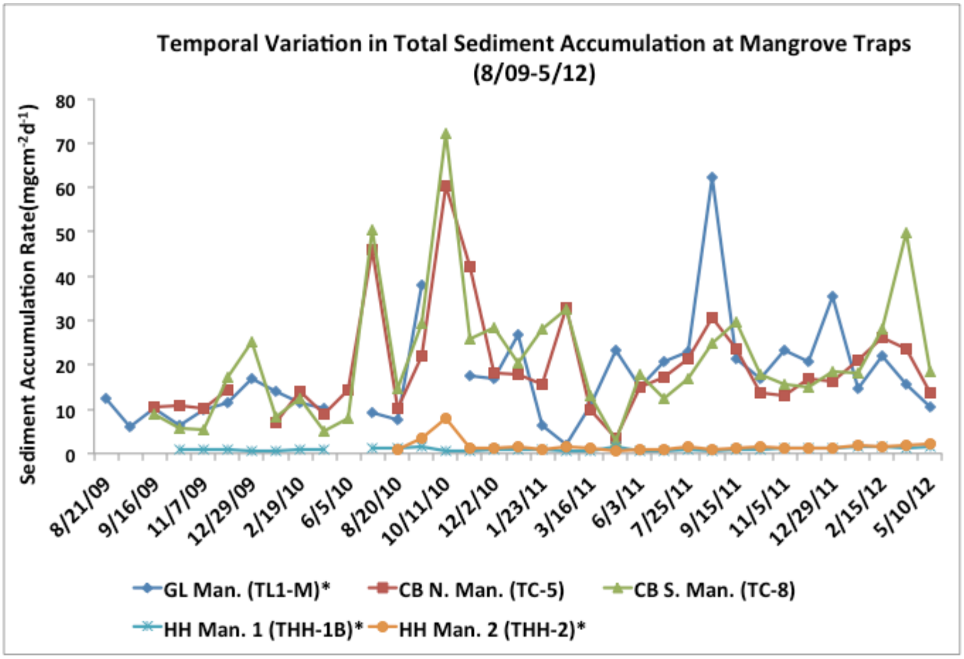


***Figure 8A***. *Total sediment accumulation in mg/cm$^2$/day at mangrove sites for every sampling period from 8/21/09-5/10/12. Highest sediment accumulation was recorded in the Coral Bay Harbor for all but one sampling period and during October of 2010 when there were record rains and sediment runoff.*

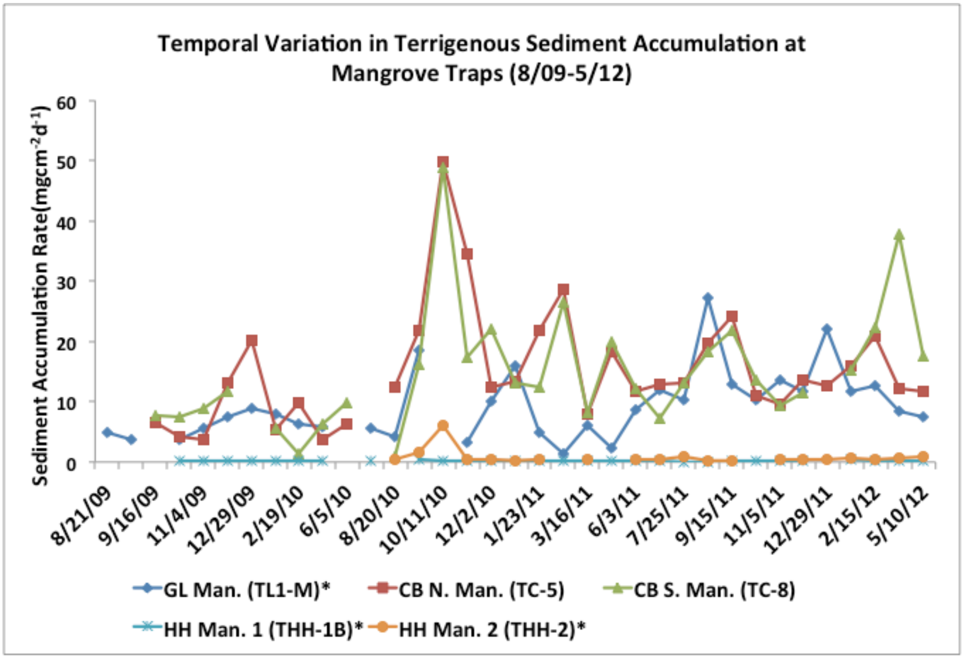


***Figure 8B***. *Terrigenous sediment accumulation in mg/cm$^2$/day at the mangrove sites for every sampling period from 8/21/09-5/10/12. Highest terrigenous sediment accumulation was at the CB Harbor for all but one sampling period and during October of 2010 when there were record rains and sediment runoff associated with Hurricane Omar.*

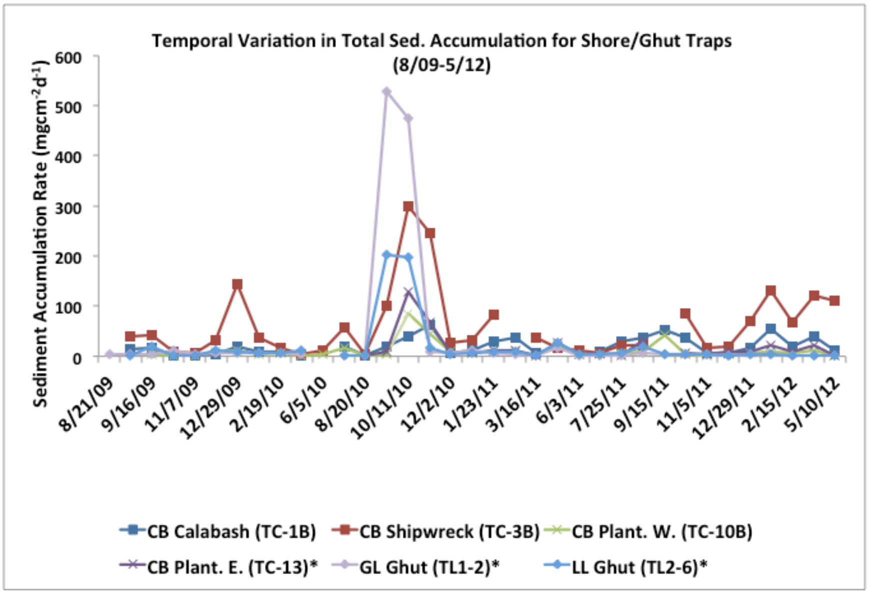


***Figure 9A**. Total sediment accumulation in mg/cm$^2$/day at shore sites for every sampling period from 8/21/09-5/10/12. Highest total sediment accumulation was recorded at the Shipwreck site (TC-3B) for most sampling periods and during October of 2010 when there were record rains and sediment runoff. Total accumulation at Plantation Hill sites (TC-10B and TC-13), which are undeveloped "control site" are almost always lower than at the Shipwreck site.*

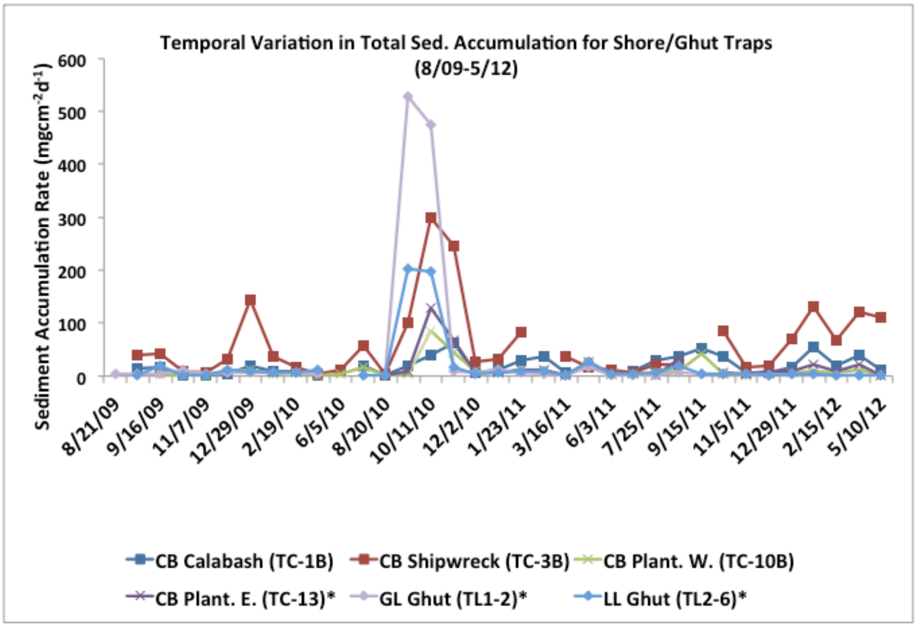


***Figure 9B**. Terrigenous sediment accumulation in mg/cm$^2$/day at shore sites (60 cm traps only) for every sampling period from 8/21/09-5/10/12. Terrigenous sediment accumulation was highest at the Shipwreck site (TC- 3B) for most sampling periods. Highest terrigenous sediment accumulation was recorded during the fall months (Sept.-Nov.) of 2010 when there were record rains and runoff at all locations.*

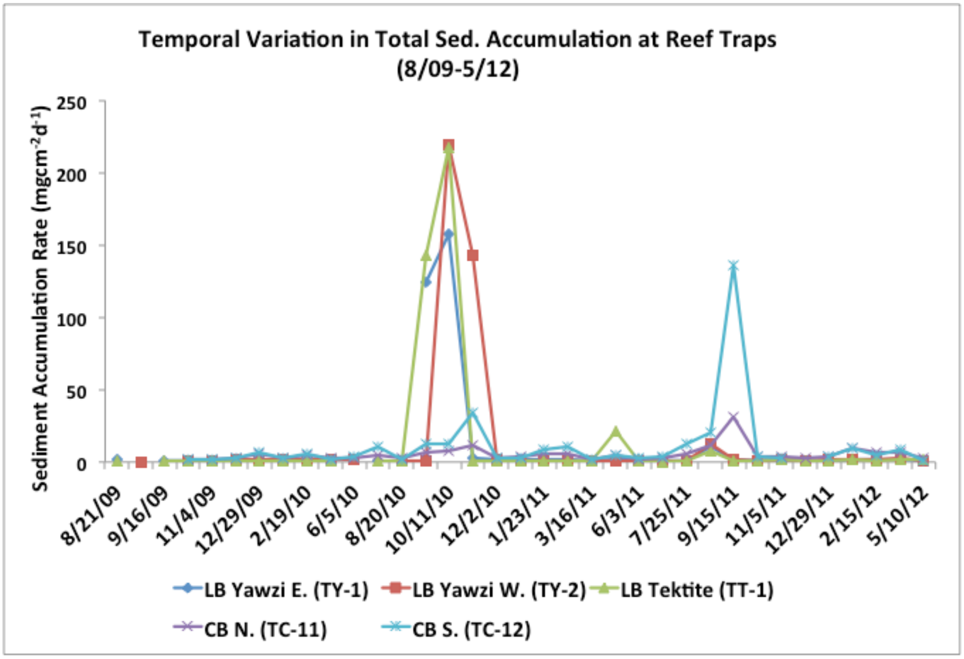


***Figure 10A**. Total sediment accumulation in mg/cm$^2$/day at the Coral Bay and Lameshur Bay reef sites for every sampling period from 8/21/09-5/10/12. Highest sediment accumulation occurred during the fall months (Sept.-Nov.) of 2010 and Aug. of 2011. The high sediment accumulation in August of 2011 was likely due to re-suspension of carbonate sediment rather than input of excess terrrigenous sedument from watershed runoff. There was not a large peak in terrigenous accumulation (Fig. 9B) during that time.*

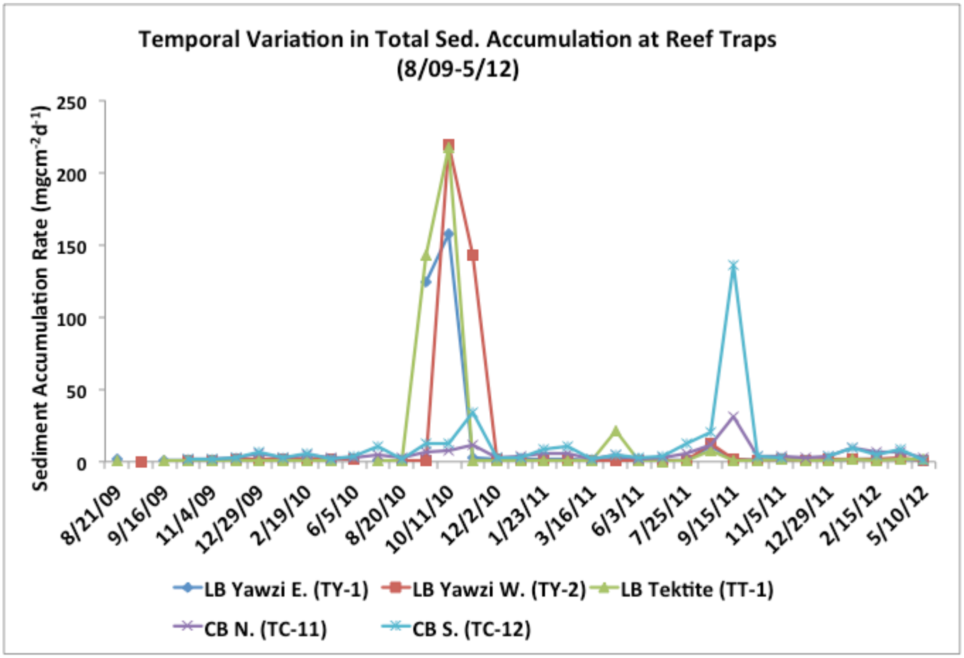


***Figure 10B**. Terrigenous sediment accumulation in mg/cm$^2$/day at reef sites for every sampling period from 8/21/09-5/10/12. For most of the time series, sediment accumulation was higher at the Coral Bay reefs than at the Lameshur Bay Reefs (Yawzi & Tektite). Highest sediment accumulation was recorded at the Coral Bay reefs during the fall month (Sept.-Nov.) of 2010 when there were record rains and runoff.*

two locations in Coral Bay below less or undeveloped watersheds (Plantation Hill TC-10 & TC-13) (Figs. 8 and 9). For most of the 2+ year time series, total and terrigenous sediment accumulation was higher at the Coral Bay reefs than at the Lameshur Bay Reefs (Yawzi & Tektite) (Fig. 10). For all environments, the highest total and terrigenous sediment accumulation and proportion were recorded during the fall months (Sept.-Nov.) of 2010 when there were record rains and sediment runoff (Figs. 8-10).

iv. *Synthesis of spatial and temporal variability between sites (including historical data and data collected in Fish Bay and East End Bay by UVI).*

Mean and median terrigenous sediment accumulation was highly variable between stations (Fig. 11) and over time. In Figure 8, the ARRA measurements are combined with historical data collected since 2007 for all of the sites and data collected at Fish Bay St. John, and East End St. Croix by Tyler Smith and Marcia Taylor at the Univ. of the Virgin Islands (492 site means and 1000's of measurements). Median terrigenous accumulation rates were higher at shore sites than at reef sites in both the developed and reference locations (Fig. 11). The highest median terrigenous accumulation rates were recorded at two sites below areas of extensive watershed development: Fish Bay Main Ghut (TFB-1) and Coral Bay S. Shipwreck (TC-3) (Fig. 11). These two sites are also the target of ARRA mitigation. Terrigenous accumulation below the Fish Bay main gut (where the watershed is developed) were much higher than below the Fish Bay Second Gut (TFB-2), which drains a less developed area of the Fish Bay watershed, which is partially within the VI National Park. In the reef environments, median terrigenous accumulation was much higher at the Fish Bay reefs than at the Coral Bay or East End.

These data clearly show that the lowest terrigenous sediment accumulation occurred below undeveloped watersheds. Developed to reference (or "control") site comparisons show that on average, terrigenous accumulation rates below developed watersheds were 5-40 times, 6-55 times, and up to 60 times higher in the shore, reef and mangrove environments, respectively than at equivalent environments at reference sites (Table 2).

Examination of temporal variability in mean terrigenous sedimentation since 2007 or 2008 at the shore sites for all locations (Fig. 12) shows again that for most sampling periods, the highest rates of terrigenous accumulation were recorded below at developed watersheds. Terrigenous accumulation rates at the Fish Bay show were consistently higher than other shore locations. The highest rates of terrigenous sediment accumulation occurred when there were periods of significant terrigenous runoff (indicated by the red storm symbol in the figure). The highest terrigenous sediment accumulation during the 4-5 year time series was recorded following T.S. Otto (which passed St. John on 10/9/10-10/11/10) (Fig. 12). The ARRA erosion mitigation projects were completed by August of 2011 so the fall 2011 rainy season represents the first "post-mitigation" rainy season.

At the reef sites the highest mean total (dashed lines) and terrigenous (solid lines) sediment accumulation was recorded during storm events (Fig. 13). Outside of storm events total and terrigenous sediment accumulation was typically low. The exceptions were the swell susceptible western Fish Bay reef stations in the spring of 2011.

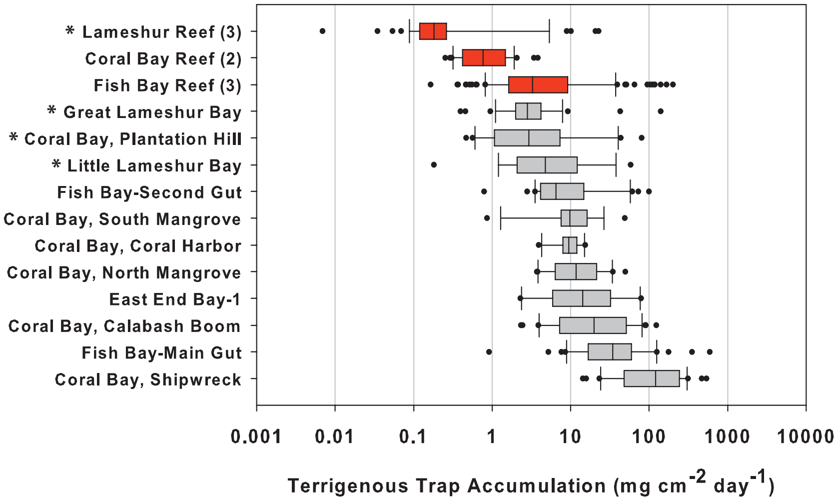


***Figure 11.*** *Median terrigenous sediment accumulation for all sites over the ARRA and historical sampling periods (8/2007-12/2011). The graph is arranged in order of increasing terrigenous accumulation with the reef sites in red and the gut/shore sites in white. The data comprise 492 site means and 1000's of measurements. The box represents the 25th and 75th percentile and the whiskers representing the 10th and 90th percentiles. The median is the center line in the box. The dots show outliers, which usually were measured during storm events. The highest mean terrigenous sedimentation occurred at the Shipwreck site along the south shore of Coral Bay and the Fish Bay main gut. The data are plotted on a log scale. Undeveloped/control sites are marked with an asterisk.*

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

| **Environ-ment** | **Terrigenous Sed. Accumulation developed/control* site** | **mean ratio** | **N** |
|---|---|---|---|
| Reef | Coral Bay/Lameshur* | 6 | 26 |
| | Fish Bay/Lameshur* | 55 | 25 |
| Shore | Coral S./Lameshur* | 24 | 28 |
| | Fish Bay/Lamehsur* | 40 | 25 |
| | Coral S./Plantation Hill* | 5 | 27 |
| Mangrove | Coral Harbor/Hurr. Hole* | 60 | 25 |

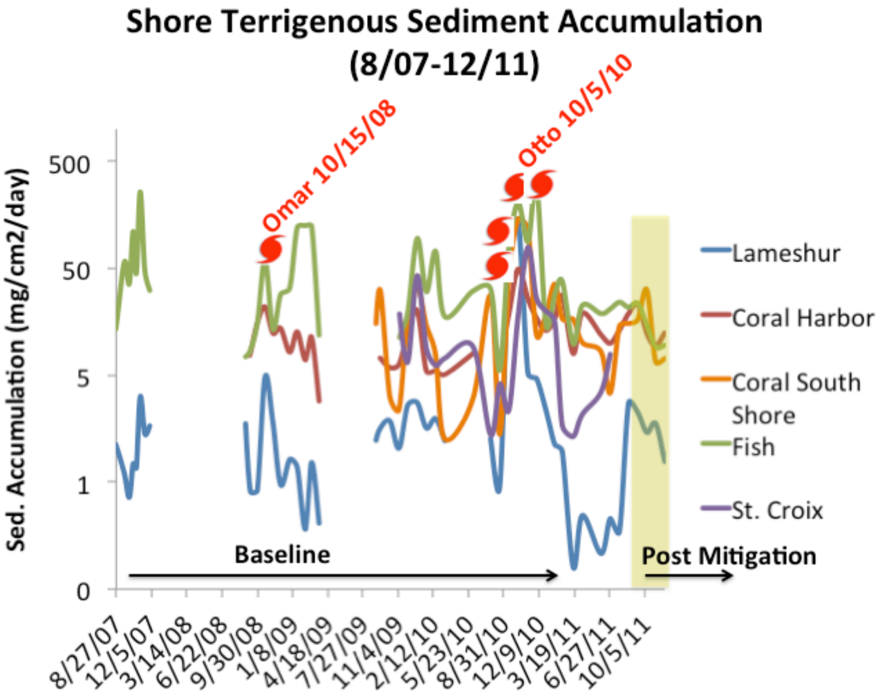


***Figure 12.*** *Temporal variability (8/07-12/11) in mean terrigenous sediment accumulation in shore and mangrove environments. Highest terrigenous accumulation occurs during periods when there were major runoff events brought on by low-pressure systems or tropical storms/hurricanes. Major runoff events are indicated by the storm symbols. Watershed erosion mitigation structures were completed in August of 2011, which marks the beginning of our post-mitigation period.*

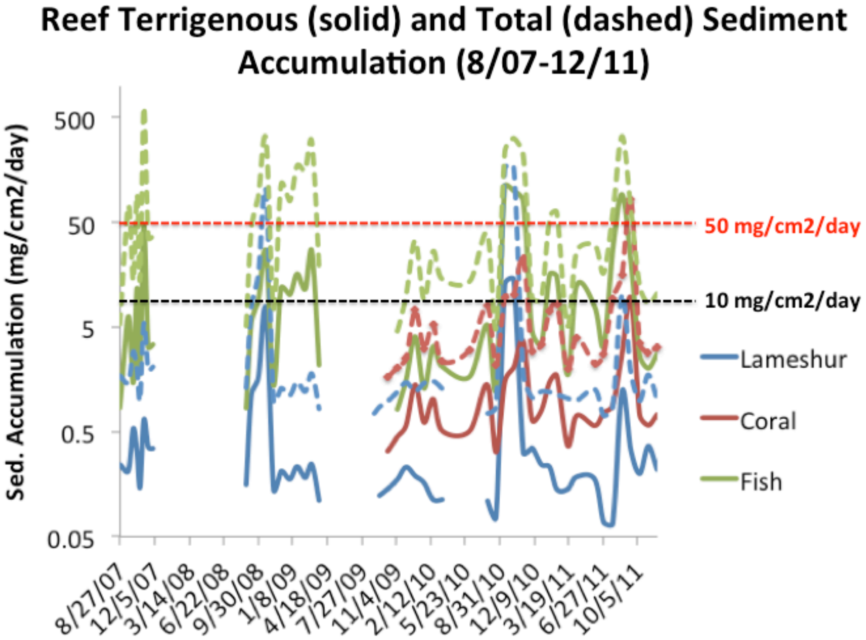


***Figure 13.*** *Temporal variability (8/07-12/11) in mean total (dashed) and terrigenous sediment accumulation (solid) at reef sites in Coral and Fish Bays (developed watershed) and Lameshur Bay (reference watershed). Highest total and terrigenous accumulation occurred during major storms. Sediment accumulation rates during these storm periods surpass 10 and reach up to 100 mg/cm$^2$/day, a sedimentation rate that has been suggested to cause coral stress.*

In addition, both total and terrigenous accumulation were higher at the reefs below Fish Bay than below Coral Bay. The lowest total and terrigenous accumulation rates were measured on the Lameshur Bay reefs 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 (Fig. 13). Mean total sediment accumulation at the Lameshur Bay reefs were higher than at the Coral Bay reefs but still lower than at the Fish Bay reefs (Fig. 13). 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 reefs, which were 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.

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 Lameshur Bay and Coral Bay 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.

### *v. Preliminary comparison of pre- and post-mitigation sediment accumulation in Coral Bay*

Pre- and post-mitigation total and terrigenous sediment accumulation were compared with two-way ANOVA for Coral Bay, with station and pre- and post-mitigation as factors (Fig. 14). Traps of 30 cm height at Calabash Boom (TC-1) and Shipwreck (TC-3) were excluded due to variability associated with sediment accumulation due to shallow water re-suspension. In addition, the control site, Plantation (TC-10) was excluded, as mitigation was not expected to have any effect on sediment accumulation. Data were only taken from the wet season, defined as between July 15 and December 15. The wet season tended to produce more run-off associated sedimentation, as opposed to the dry season, which was associated primarily with sediment accumulation generated by swell induced re-suspension. In addition to the tests directly with total and terrigenous sedimentation, data were normalized by the cumulative rainfall over the trap deployment period (sediment accumulation * interval rainfall$^{-1}$).

Statistical comparison of total and terrigenous sediment accumulation and total and terrigenous sediment accumulation normalized to interval rain for Coral Bay showed that all significant differences were among trap stations. In general, the mangrove sites (TC-5 and TC-8), Calabash Boom (TC-1), and Shipwreck (TC-3) had the highest total sediment accumulation, and, with the exception of Calabash Boom, these same sites had the highest terrigenous sediment accumulation (Fig. 14). A similar pattern was evident with the total and terrigenous sediment accumulation normalized to interval rain (data not shown). Individual one-tailed t-test comparisons among sites were also not significant ($\alpha = 0.05$), and this was likely an effect of high variability sediment accumulation amounts among sampling intervals. However, there was an apparent strong trend for Shipwreck, where total and terrigenous sediment accumulation rates were 2.3 and 3 times greater in the pre- versus post-mitigation periods, respectively.

In summary, the pre- and post-mitigation comparisons showed either significant decreases or trends of decreases in the total and terrigenous sediment accumulation for many of the traps that were below major mitigation areas in Coral Bay. In many cases the statistical comparisons had low power (chance of Type II error) because of the high natural variability in sediment accumulation in traps. Sources of this variation are rainfall and swell. When rainfall was accounted for with normalization some comparisons were shown to be significant. These results may suggest that watershed restoration resulted in lower sediment delivery and, hence, trap accumulation rates in Coral Bay but further study and monitoring is needed.

## B. Geochemistry from ridge to reef

### Objectives

The objectives of MS student Robert Harrington's thesis research to better understand the linkages between terrigenous erosion and marine deposition of metals were focused on determining: 1) what metals or metal compounds traced terrigenous sediment input; 2) how the mineralogy/lithology and concentration of metals and metal compounds changed from ridge to reef; 3) any differences between developed and undeveloped watershed-bay pairings in terms of a) major and trace elemental concentrations and b) metal flux; and 4) whether developed vs. undeveloped differences in major and trace element concentrations and flux in the marine environment were consistent with watershed-scale modeled sediment yield rates.

### Methods

Samples for the "ridge to reef" geochemistry study were collected from: a) bedrock, b) soil [A, B, and C-horizons] (Fig. 4, 5A), c) stream beds, d) marine sediment trap, and f) marine benthic sediments by hand using a rock hammer (a, b, c) or were collected in sediment traps and from the sea floor as described below (d and e) (Figs. 4 & 5). In order to identify the lithologic textures and mineralogy, 10 rock and 34 sediments were thin-sectioned at National Petrographic and visually inspected under a petrographic microscope. X-ray diffraction (XRD) scans of 25 samples were produced on a Philips X'Pert Pro XRD at San Diego State University (SDSU) Department of Geologic Sciences. Metal concentrations in rock and sediment samples (119) were analyzed by X-ray fluorescence (XRF) at Washington State University Geoanalytical Laboratory (WSU) following standard methods (Johnson et al. 1999 and an additional 56 rock and sediment samples were analyzed on the Innov-X systems X-5000 XRF analyzer at The University of San Diego (USD). Principle component analysis (PCA) (Abdi and Williams 2010) was employed to determine the geochemical correlations and differences between bedrock or environment

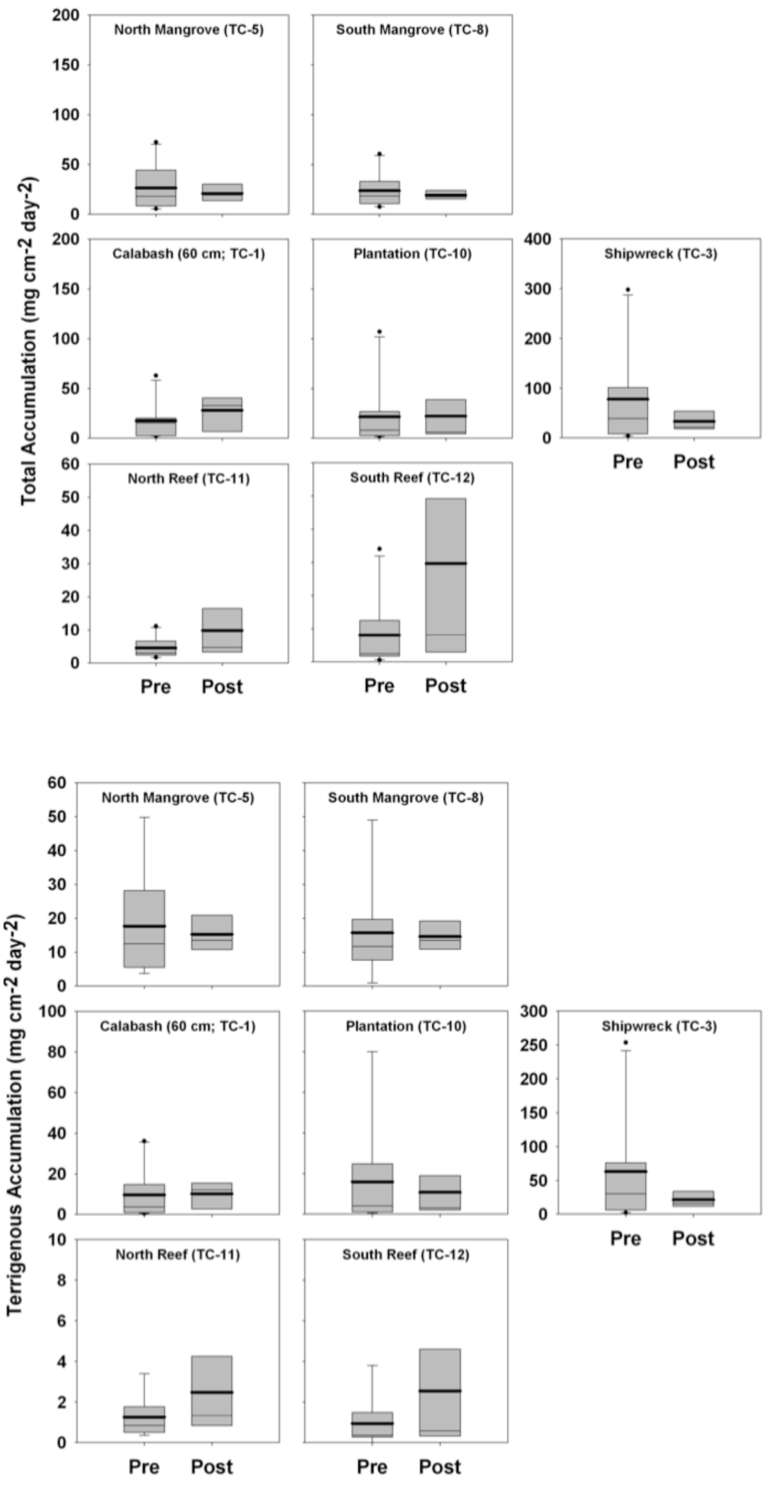


***Figure 14**. Box diagrams of pre- (2008-2010) and post-mitigation (2011) total (above) and terrigenous (below) sediment accumulation rates for Coral Bay monitoring sites. Data were compiled from the wet season, defined as trap intervals ending between July 15th and December 15th. The box represents the 25th and 75th percentile and the whiskers representing the 10th and 90th percentiles. The median is the light line and the mean is the heavy line in the box. The dots show max/min values.*

types (O'Shea and Jankowski 2006). The PCA (n=63) was performed on 10 major elements and 12 trace elements separately using Statistical Product and Service Solutions (SPSS) software. For this study we graphed PC1 against PC2 to identify samples with similar geochemical signatures.

## Results

### *i. Petrography and mineralogy*

Petrographic and mineralogic analyses revealed that the plagiorhyolite and basalt of the bedrock units (Water Island Fm.) and eroded sediment were similar in composition and composed of mostly albite, quartz, chlorite (plagiorhyolite) and plagioclase, clinopyroxene, epidote, chlorite, and opaque minerals including iron oxide coatings which suggest weathering of iron from minerals (Fig. 15).

### *ii. Major and trace element concentrations*

The average major element concentrations of terrestrial sediment (Table 3) generally reflected the average elemental concentrations of all bedrock samples (Table 4). Compared to reef sediment, terrestrial sediment contained 6 times more $SiO_2$, 15 times more $Al_2O_3$, 7 times more FeO, 18 times more Ba, and 4 times more Cu. Compared to terrestrial sediments, reef trap sediments contained 22 times more CaO, 2 times more MgO and 34 times more Sr. Compared to its concentration in other sample types, Barium was particularly concentrated in the soils (3, 9 and 27 times more Ba than stream sediments, near-shore sediments and reef sediments, respectively) (average: 1097 ppm, Table 4), and the hydrothermally altered bedrock (average: 2046 ppm, Table 3).

### *iii. Elemental indicators of terrigenous sediment*

In order to determine which elements in the marine sediment were likely derived from the watershed (and thus trace terrestrial input from the watershed to the bays), a linear regression analysis was conducted to identify elements whose concentrations were strongly correlated with the proportion (%) of terrigenous sediment (determined by LOI) in the marine sediment. Major element (Fig. 16 I & II) and trace element (Fig. 16 III) concentrations of 22 elements were significantly correlated ($p < 0.001$) to the proportion (%) of terrigenous sediment in marine samples, but the 8 elements with the greatest $R^2$ values are plotted in Figure 16. Concentrations of $SiO_2$, $Al_2O_3$, FeO, $TiO_2$, MnO, Sc, Cu, and Zr were significantly [$p < 0.001$, Appendix VIII] correlated to % terrigenous material with $R^2$ values greater than 0.80 (Fig. 16).

### *iv. Spatial variability of metal concentrations*

As one would expect, the concentrations of three of the "terrestrial" elements (MnO, FeO, and Cu) were generally greater in samples collected in the terrestrial environment than the marine environment. However, in most cases concentrations were highly variable and did not differ significantly between bedrock, soil and stream (Figs. 17-

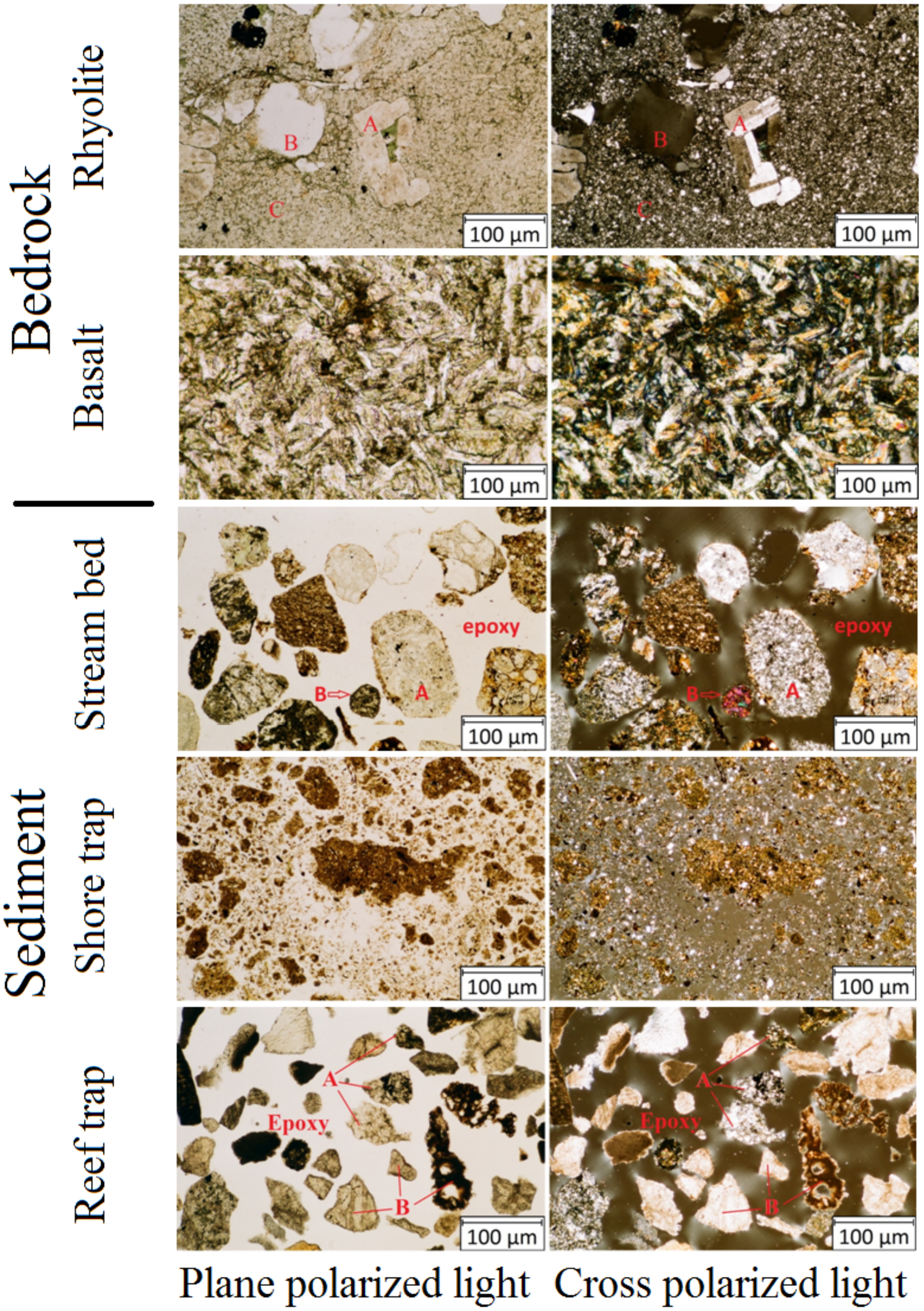


***Figure 15.*** *Photomicrographs of rock and sediment thin sections are shown in order from ridge (top) to reef (bottom). Rhyolite thin sections show albite (A) quartz (B), and ground mass (C). Stream bed sediments consist of rhyolite (A) and basalt (B) grains. Reef trap sediments consist of rhyolite (A) and carbonate (B) grains. Basalt and rhyolite grains originate from the Water Island Fm. (top two rows). Weathering rinds can be observed on some grains in the plane polarized stream sediments photomicrographs as an orange coating.*

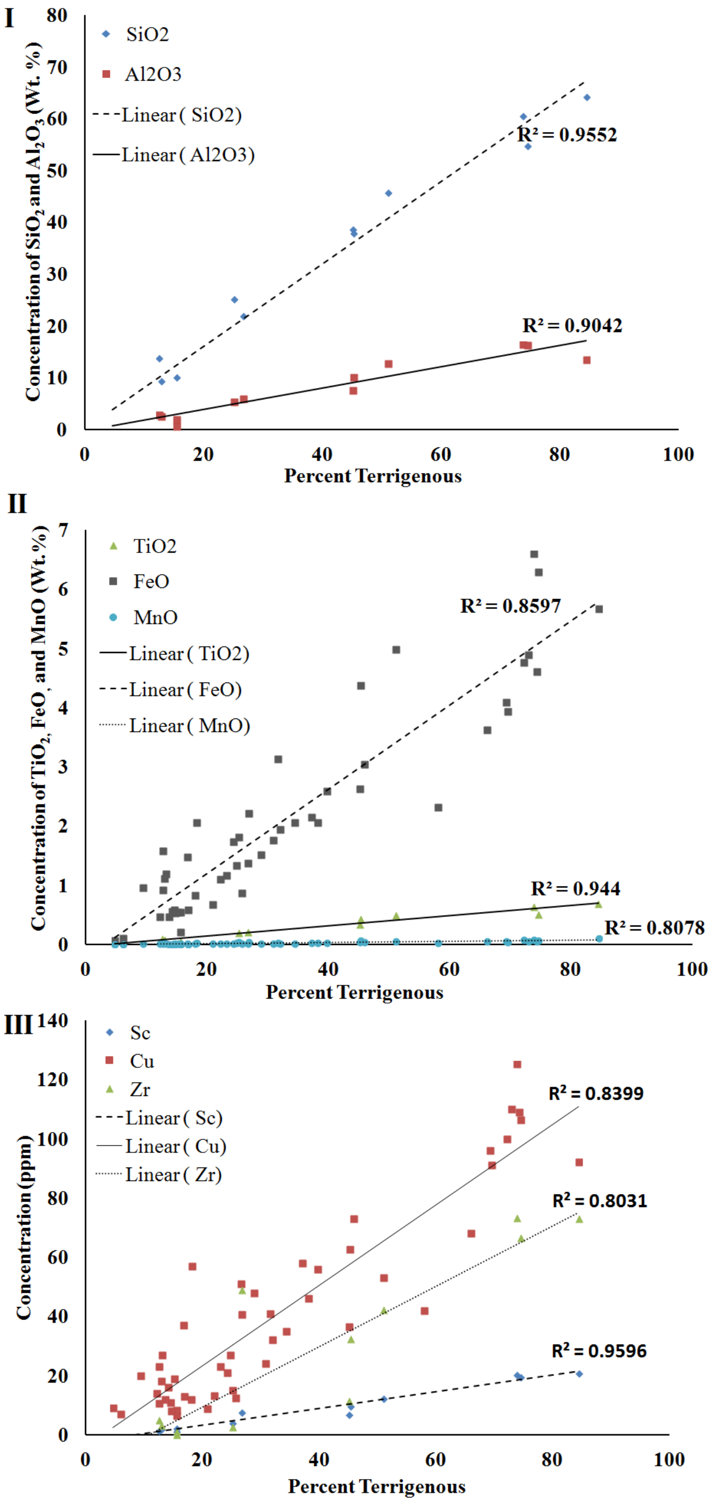


**Figure 16.** *Linear regression models evaluating how major and trace element concentrations in marine sediment collected on St. John USVI vary with the % of terrigenous sediment (as determined by LOI [loss on ignition]). All models (I-III) show a significant correlation ($P < 0.001$) between each element and the percent terrigenous fraction of sediment. The high $R^2$ (.80-.96) indicates that terrigenous material explains the majority of variability in the data [$SiO_2$ and $Al_2O_3$] (I), [$TiO_2$, FeO and MnO] (II), [Sc, Cu, Zr] (III), and the percent terrigenous material in the sediment.*

19). For both the developed and undeveloped areas the MnO concentrations of bedrock, soil, and stream samples were significantly greater than of marine samples and MnO concentrations of samples collected in near-shore environments were significantly greater than the concentrations of their corresponding reef environment samples (ANOVA and SNK test, $p = 0.007$ and $p < 0.001$) (Fig.17). The concentration of FeO in Coral Bay (Fig. 18 I) exhibited a similar trend as MnO (Fig. 17). FeO concentrations were also significantly different between near-shore and reef environments and terrestrial environments in Lameshur Bay (undeveloped) (Fig. 18, $p = .004$). Concentrations of Cu in in all areas did not vary significantly between environments (Fig. 19). Other terrestrial elements such as $SiO_2$, $TiO_2$, $Al_2O_3$ $K_2O$, Zr, and Ba followed the same concentration trends. Concentrations of FeO, MnO, and Cu in bedrock, soil, and stream sediment environments were not statistically different between developed and undeveloped watershed or reef sediments but were significantly greater in the near-shore sediments below developed compared to undeveloped watersheds (Fig. 17-19; KS test: $p < .001$).

To evaluate how the geochemistry (considering all 10 major and 12 trace elements measured) varied spatially between environments and watershed types, we employed Principle Component Analysis (PCA) to reduce the data to 2 variables (PC1 and PC2) each for major (10) and trace (12) element data sets (Fig. 20 I & II). Principal components, PC1 and PC2, accounted for 67% and 61% of the variance in the major and trace element concentrations, respectively. The PCA analysis indicated marine near-shore sediments collected below developed watersheds were more similar geochemically to the terrestrial sediments than were those collected below the undeveloped watershed (Fig. 20 I). For the trace elements (Fig. 20 II), strongly negative PC2 was correlated to a greater concentration of Sr, which may have been affected by the typically high Sr found in marine biogenic carbonate clasts.

### *v. Developed vs. undeveloped comparisons marine metal concentrations and flux rates*

Comparison of the average concentrations of five "terrestrial" metals ($TiO_2$, $Al_2O_3$, FeO, Zr, and Ba) in marine near-shore and reef sediments show concentrations that were typically between 5 and 10 times higher at developed compared to the undeveloped shore sites and between 2 to 52 times higher at developed compared to undeveloped reef sites (Table 5; Fig. 21). Marine metal flux rates were typically between 2 to 7 times higher at developed shore sites and 33 to 430 times higher at developed reef sites than at corresponding sites in the undeveloped areas (Fig. 21). These differences were generally consistent with modeled sediment yields, which were 12.6 times higher for the developed compared to the undeveloped watershed (Ramos-Scharron, personal communication).

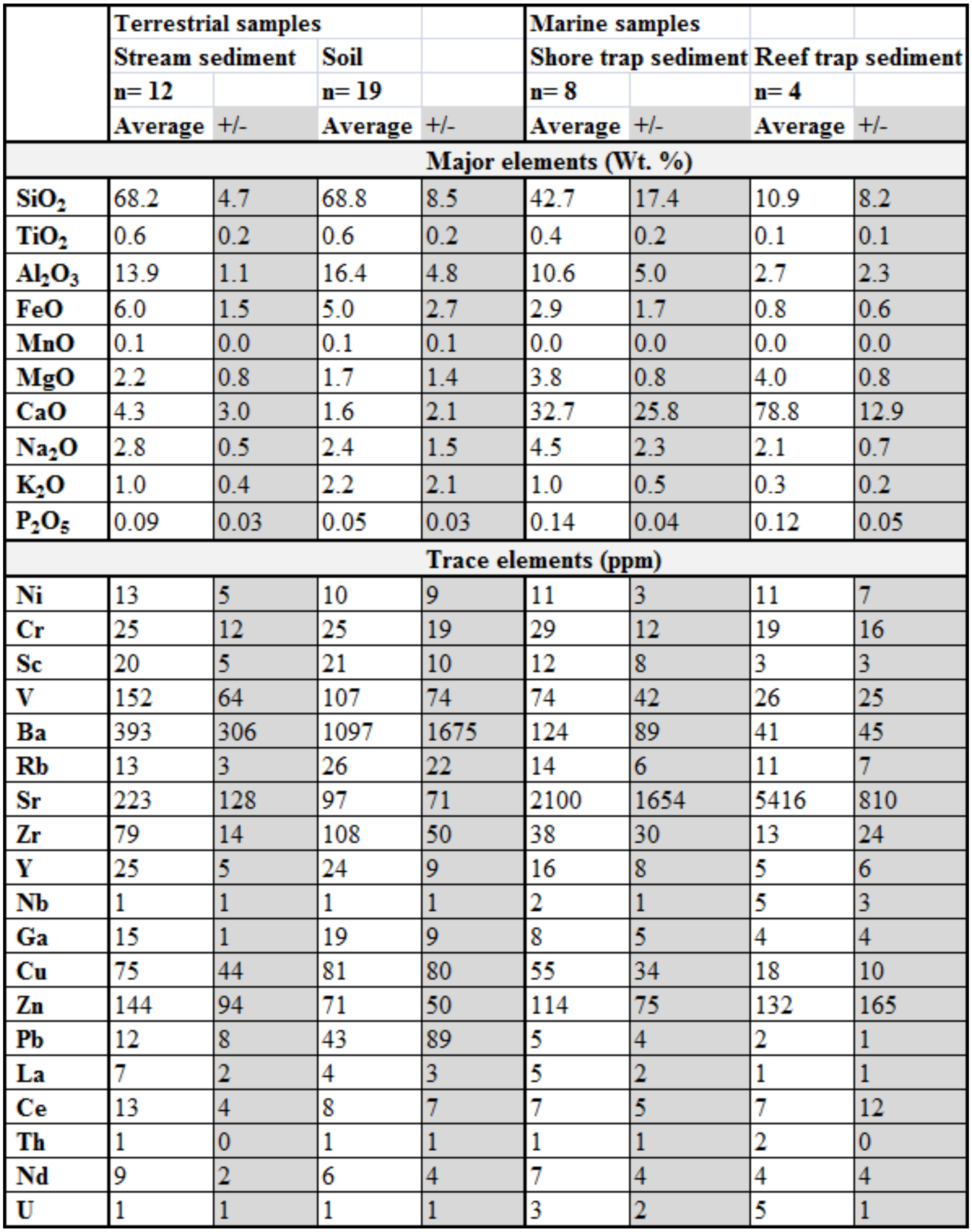
### *vi. Variation in terrestrial metals in marine sediments between storm and fair weather periods*

Concentrations of FeO, MnO, and Cu of near-shore sediments were compared between sampling periods where there were storms and minimal rainfall in near-shore (Fig. 22) and reef (Fig. 23) environments. Concentrations of MnO, FeO, and Cu in near-shore and reef sediments were significantly greater (and more variable) in the developed areas

**Table 3.** *Average metal concentrations (± SD) each of the three different bedrock lithologies.*

| | **Plagiorhyolite** | | **Basalt** | | **Hydrothermally altered** | |
|---|---|---|---|---|---|---|
| | **n=9** | | **n=4** | | **n=4** | |
| | **Average** | +/- | **Average** | +/- | **Average** | +/- |
| **Major elements (Wt %)** | | | | | | |
| **$SiO_2$** | 76.9 | 2.3 | 51.7 | 2.8 | 79.4 | 8.4 |
| **$TiO_2$** | 0.2 | 0.1 | 0.7 | 0.4 | 0.4 | 0.2 |
| **$Al_2O_3$** | 12.5 | 1.4 | 17.7 | 1.0 | 12.8 | 6.3 |
| **FeO** | 2.6 | 0.5 | 10.3 | 1.2 | 2.9 | 2.0 |
| **MnO** | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 |
| **MgO** | 1.2 | 0.5 | 7.0 | 1.8 | 0.4 | 0.3 |
| **CaO** | 0.5 | 0.2 | 7.9 | 1.1 | 0.0 | 0.0 |
| **$Na_2O$** | 4.8 | 1.6 | 3.4 | 1.4 | 0.2 | 0.1 |
| **$K_2O$** | 1.1 | 1.5 | 0.2 | 0.1 | 3.8 | 2.1 |
| **$P_2O_5$** | 0.03 | 0.01 | 0.10 | 0.12 | 0.01 | 0.00 |
| **Trace elements (ppm)** | | | | | | |
| **Ni** | 1 | 1 | 30 | 7 | 1 | 1 |
| **Cr** | 5 | 3 | 54 | 28 | 4 | 2 |
| **Sc** | 12 | 2 | 43 | 8 | 12 | 6 |
| **V** | 17 | 16 | 291 | 35 | 32 | 11 |
| **Ba** | 117 | 121 | 54 | 42 | 1703 | 275 |
| **Rb** | 8 | 10 | 4 | 2 | 42 | 23 |
| **Sr** | 64 | 14 | 185 | 102 | 14 | 3 |
| **Zr** | 95 | 14 | 39 | 34 | 110 | 46 |
| **Y** | 26 | 5 | 15 | 8 | 19 | 13 |
| **Nb** | 1 | 1 | 1 | 1 | 1 | 0 |
| **Ga** | 12 | 2 | 18 | 1 | 17 | 3 |
| **Cu** | 6 | 5 | 82 | 29 | 113 | 105 |
| **Zn** | 50 | 25 | 76 | 15 | 11 | 11 |
| **Pb** | 3 | 2 | 2 | 2 | 42 | 35 |
| **La** | 4 | 2 | 3 | 5 | 2 | 2 |
| **Ce** | 8 | 3 | 10 | 10 | 4 | 1 |
| **Th** | 0 | 0 | 0 | 0 | 1 | 1 |
| **Nd** | 9 | 3 | 7 | 7 | 3 | 1 |
| **U** | 0 | 0 | 1 | 1 | 1 | 1 |

**Table 4.** *Average metal concentrations (± SD) measured in terrestrial and marine sediments collected in four different environments on St. John.*



| | **Terrestrial samples** | | | | **Marine samples** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Stream sediment** | | **Soil** | | **Shore trap sediment** | | **Reef trap sediment** | |
| | **n= 12** | | **n= 19** | | **n= 8** | | **n= 4** | |
| | **Average** | +/- | **Average** | +/- | **Average** | +/- | **Average** | +/- |
| **Major elements (Wt. %)** | | | | | | | | |
| **$SiO_2$** | 68.2 | 4.7 | 68.8 | 8.5 | 42.7 | 17.4 | 10.9 | 8.2 |
| **$TiO_2$** | 0.6 | 0.2 | 0.6 | 0.2 | 0.4 | 0.2 | 0.1 | 0.1 |
| **$Al_2O_3$** | 13.9 | 1.1 | 16.4 | 4.8 | 10.6 | 5.0 | 2.7 | 2.3 |
| **FeO** | 6.0 | 1.5 | 5.0 | 2.7 | 2.9 | 1.7 | 0.8 | 0.6 |
| **MnO** | 0.1 | 0.0 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| **MgO** | 2.2 | 0.8 | 1.7 | 1.4 | 3.8 | 0.8 | 4.0 | 0.8 |
| **CaO** | 4.3 | 3.0 | 1.6 | 2.1 | 32.7 | 25.8 | 78.8 | 12.9 |
| **$Na_2O$** | 2.8 | 0.5 | 2.4 | 1.5 | 4.5 | 2.3 | 2.1 | 0.7 |
| **$K_2O$** | 1.0 | 0.4 | 2.2 | 2.1 | 1.0 | 0.5 | 0.3 | 0.2 |
| **$P_2O_5$** | 0.09 | 0.03 | 0.05 | 0.03 | 0.14 | 0.04 | 0.12 | 0.05 |
| **Trace elements (ppm)** | | | | | | | | |
| **Ni** | 13 | 5 | 10 | 9 | 11 | 3 | 11 | 7 |
| **Cr** | 25 | 12 | 25 | 19 | 29 | 12 | 19 | 16 |
| **Sc** | 20 | 5 | 21 | 10 | 12 | 8 | 3 | 3 |
| **V** | 152 | 64 | 107 | 74 | 74 | 42 | 26 | 25 |
| **Ba** | 393 | 306 | 1097 | 1675 | 124 | 89 | 41 | 45 |
| **Rb** | 13 | 3 | 26 | 22 | 14 | 6 | 11 | 7 |
| **Sr** | 223 | 128 | 97 | 71 | 2100 | 1654 | 5416 | 810 |
| **Zr** | 79 | 14 | 108 | 50 | 38 | 30 | 13 | 24 |
| **Y** | 25 | 5 | 24 | 9 | 16 | 8 | 5 | 6 |
| **Nb** | 1 | 1 | 1 | 1 | 2 | 1 | 5 | 3 |
| **Ga** | 15 | 1 | 19 | 9 | 8 | 5 | 4 | 4 |
| **Cu** | 75 | 44 | 81 | 80 | 55 | 34 | 18 | 10 |
| **Zn** | 144 | 94 | 71 | 50 | 114 | 75 | 132 | 165 |
| **Pb** | 12 | 8 | 43 | 89 | 5 | 4 | 2 | 1 |
| **La** | 7 | 2 | 4 | 3 | 5 | 2 | 1 | 1 |
| **Ce** | 13 | 4 | 8 | 7 | 7 | 5 | 7 | 12 |
| **Th** | 1 | 0 | 1 | 1 | 1 | 1 | 2 | 0 |
| **Nd** | 9 | 2 | 6 | 4 | 7 | 4 | 4 | 4 |
| **U** | 1 | 1 | 1 | 1 | 3 | 2 | 5 | 1 |

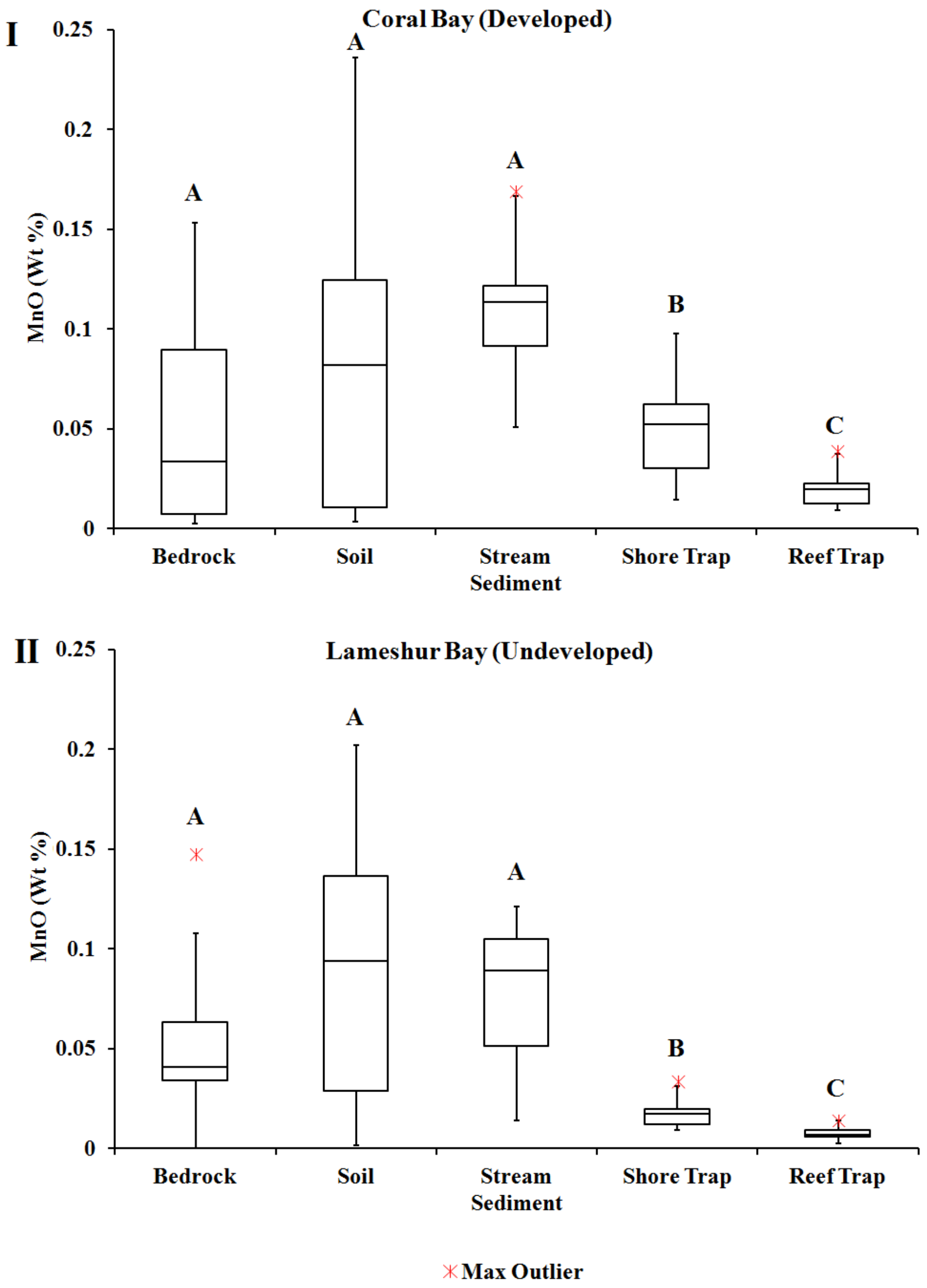


**Figure 17.** *Box and whisker plots showing variation MnO concentrations between bedrock and sediment types from ridge to reef in Coral Bay and its watershed (I, developed) and Lameshur Bay and its watershed (II, undeveloped). The box represents the inter quartile range (IQR) between the 25th and 75th percentile, and the whiskers represent a value 1.5 times the IQR above and below the 75th and the 25th percentile. The median is the center line in the box. The dots show outliers. Letters (A-C) indicate significantly different groups derived from ANOVA and SNK test.*

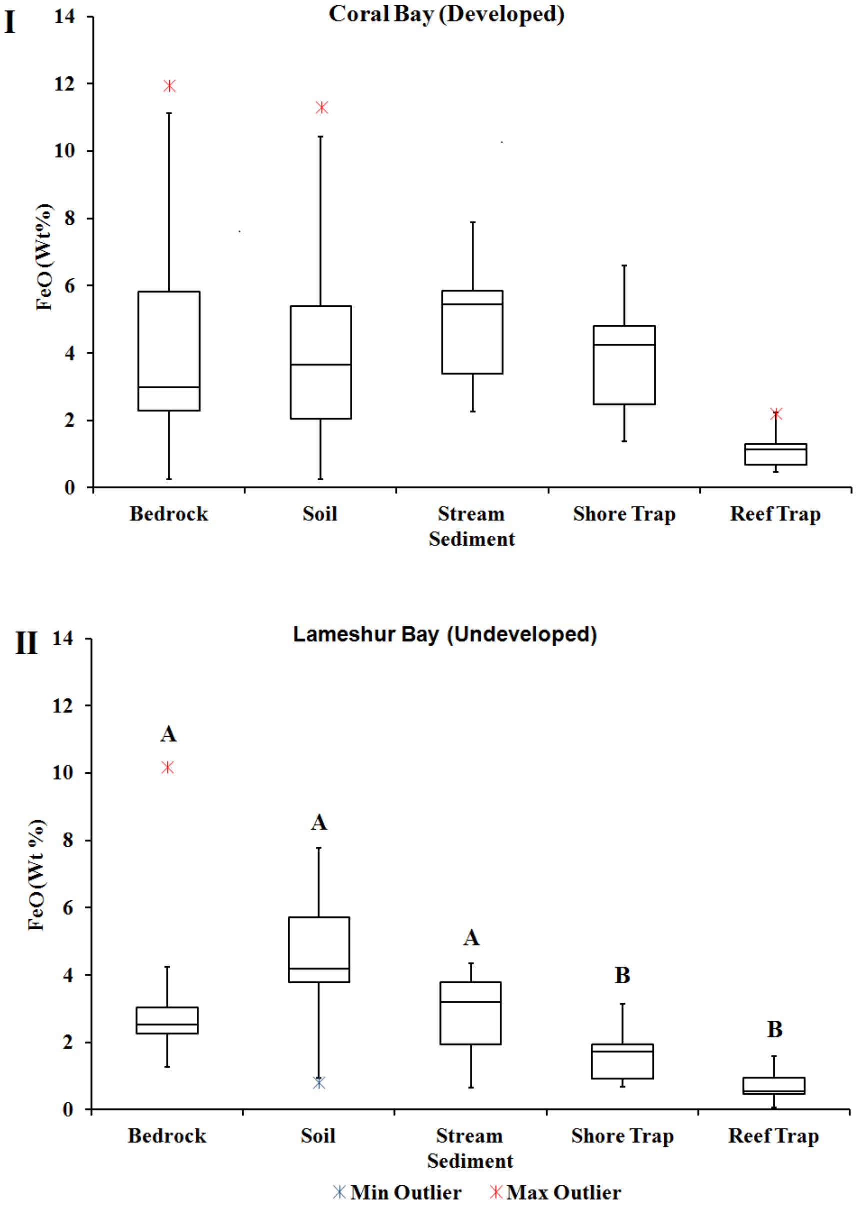


**Figure 18.** *Box and whisker plots showing variation in median FeO concentrations from ridge to reef in Coral Bay and its watershed (I, developed) and Lameshur Bay and its watershed (II, undeveloped) and their watersheds. The box represents the inter quartile range (IQR) between the 25th and 75th percentile, and the whiskers represent a value 1.5 times the IQR above and below the 75th and the 25th percentile. The median is the center line in the box. The dots show outliers. Letters (A and B) indicate significantly different groups derived from ANOVA and SNK test. There were no significant differences in FeO concentrations between groups for Coral Bay and its watershed.*

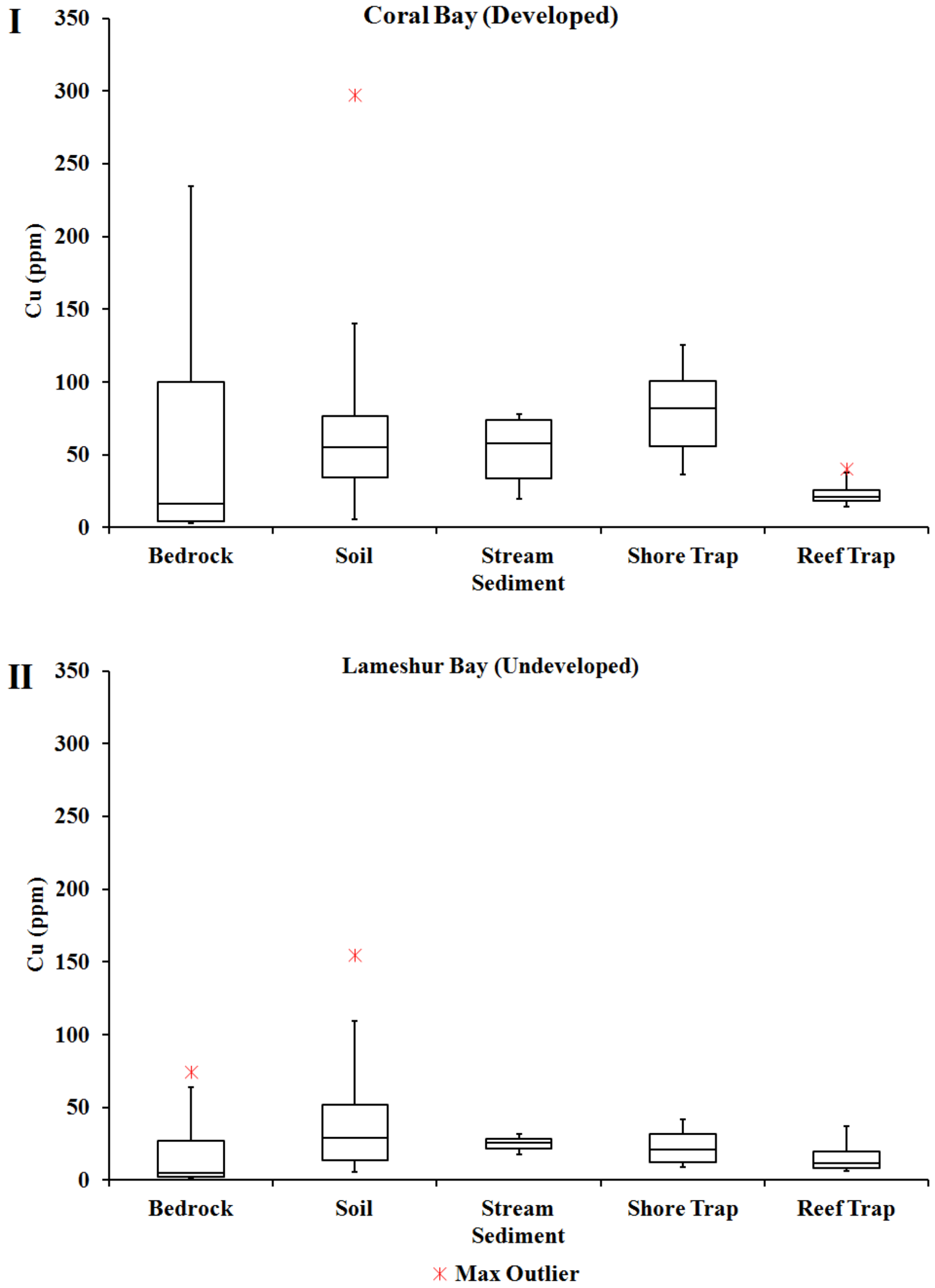


**Figure 19.** *Box and whisker plots showing variation in median Cu concentrations from ridge to reef in Coral Bay and its watershed (I, developed) and Lameshur Bay and its watershed (II, undeveloped) and their watersheds. The box represents the inter quartile range (IQR) between the 25th and 75th percentile, and the whiskers represent a value 1.5 times the IQR above and below the 75th and the 25th percentile. The median is the center line in the box. The dots show outliers. There were no significant differences in Cu between groups for Coral Bay and Lameshur Bay and their watersheds.*

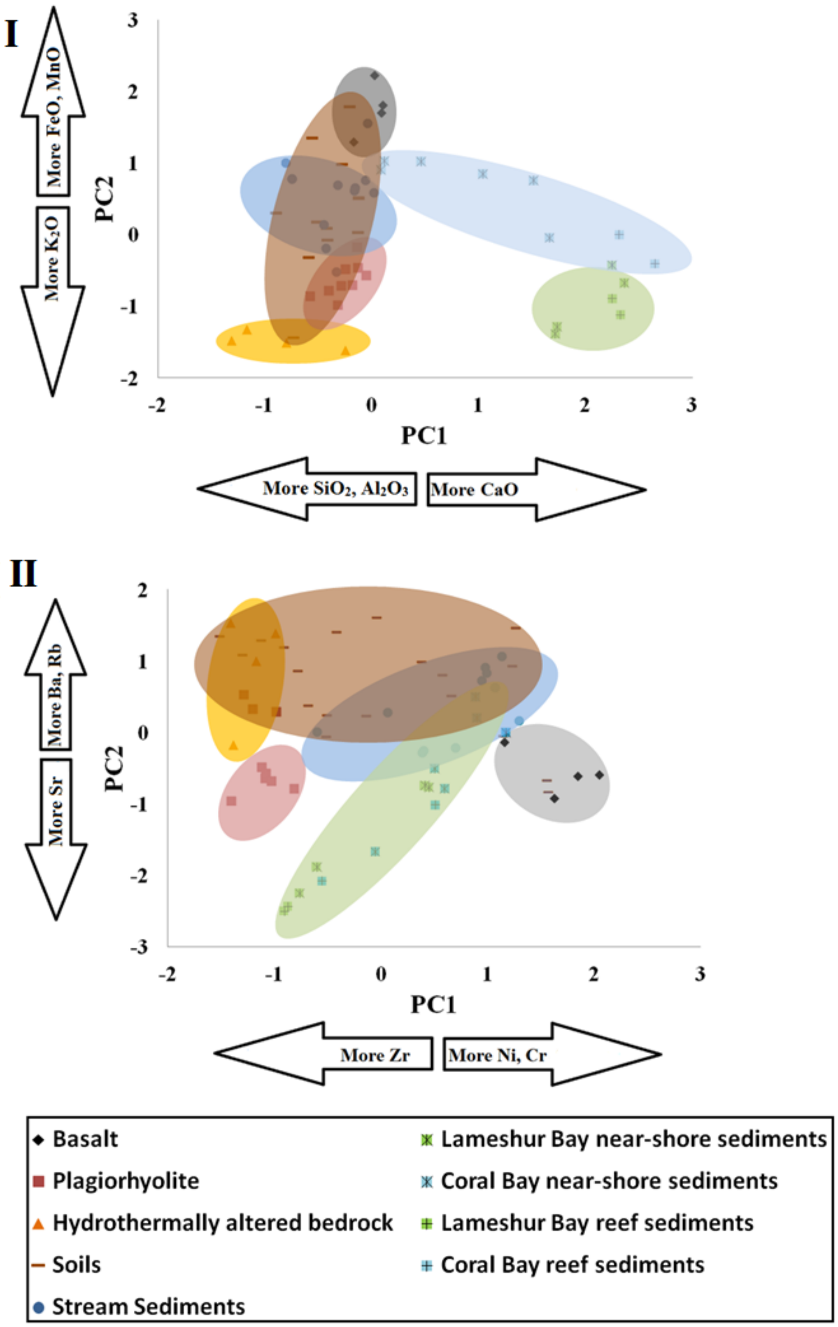


***Figure 20.*** *Graphical results of the principle component analyses (PCA) of major (I) and trace (II) element concentrations. The PCA clustered the geochemical concentrations for different types of samples into five groups indicated by the shaded areas: plagiorhyolite (red), basalt (dark gray), hydrothermally altered (orange), Soils (brown), stream sediments (dark blue), marine sediments from bays under developed watersheds (light blue), and marine sediments from bays under undeveloped watersheds (green). (I) A large positive PC1 loading score indicates greater FeO, MnO, and CaO and less* $SiO_2$ *and* $K_2O$ *and a large positive PC2 indicates greater* $Na_2O$ *and less* $K_2O$*. (II) A large positive PC1 indicates greater Ni, Cr and less Rb and Zr and a large positive PC2 indicates greater Ba and Zr and less Sr. Six separate groups are displayed: basalt (shaded gray), plagiorhyolite (shaded red), hydrothermally altered bedrock (shaded orange), soils (shaded brown), stream sediments (shaded blue) and marine (reef and near-shore) sediments (shaded green).*

**Table 5.** *Marine sediment major and trace element concentrations (top) and flux rates (bottom) plotted by developed sites in Coral Bay and undeveloped sites in Lameshur Bay.*

| **STATIONS** | **ENVIRONMENT** | **DEV. or UNDEV.** | | **Metal Concentrations** | | | | |
|---|---|---|---|---|---|---|---|---|
| **(CB= Coral Bay)** | | | **N** | **Major elements (Wt.%)** | | | **Trace element (ppm)** | |
| **(LB= Lameshur Bay)** | | | | **$TiO_2$** | **$Al_2O_3$** | **FeO** | **Zr** | **Ba** |
| CB shore | Shore | Dev. | 3 | 0.50 | 13.41 | 5.18 | 50.37 | 169.71 |
| LB Shore | Shore | Undev. | 1 | 0.10 | 2.81 | 0.93 | 5.0 | 21.2 |
| CB Reef | Reef | Dev. | 2 | 0.16 | 4.25 | 1.67 | 26.0 | 66.9 |
| LB Reef | Reef | Undev. | 2 | 0.04 | 1.25 | 0.38 | 0.5 | 16.1 |
| | | | | | | | | |
| | | | | | | | | |
| **Stations** | **ENVIRONMENT** | **DEV. or UNDEV.** | | **METAL FLUX (in $mg/cm^2/day$)** | | | | |
| **(CB= Coral Bay)** | | | | **Major elements (Wt.%)** | | | **Trace element (ppm)** | |
| **(LB= Lameshur Bay)** | | | **N** | **$TiO_2$** | **$Al_2O_3$** | **FeO** | **Zr** | **Ba** |
| CB shore | Shore | Dev. | 3 | 0.90 | 19.28 | 7.99 | 2.8E-04 | 1.3E-04 |
| LB Shore | Shore | Undev. | 1 | 0.28 | 7.96 | 2.63 | 6.0E-05 | 3.0E-05 |
| CB Reef | Reef | Dev. | 2 | 0.01 | 0.30 | 0.12 | 4.2E-06 | 2.1E-06 |
| LB Reef | Reef | Undev. | 2 | 0.00 | 0.01 | 0.00 | 1.2E-07 | 5.6E-08 |

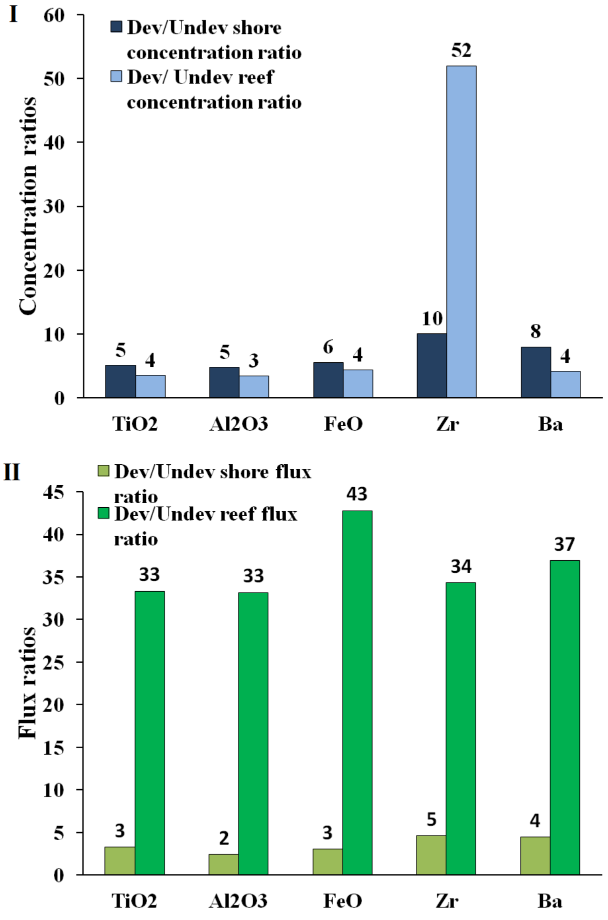


***Figure 21.*** *(I) Average developed/undeveloped metal flux ratios for different elements for the near-shore (olive green) and reef (medium green) environments. (II) Average developed/undeveloped ratios of metal concentrations for different elements for the near-shore (navy blue) and reef (light blue) environments.*

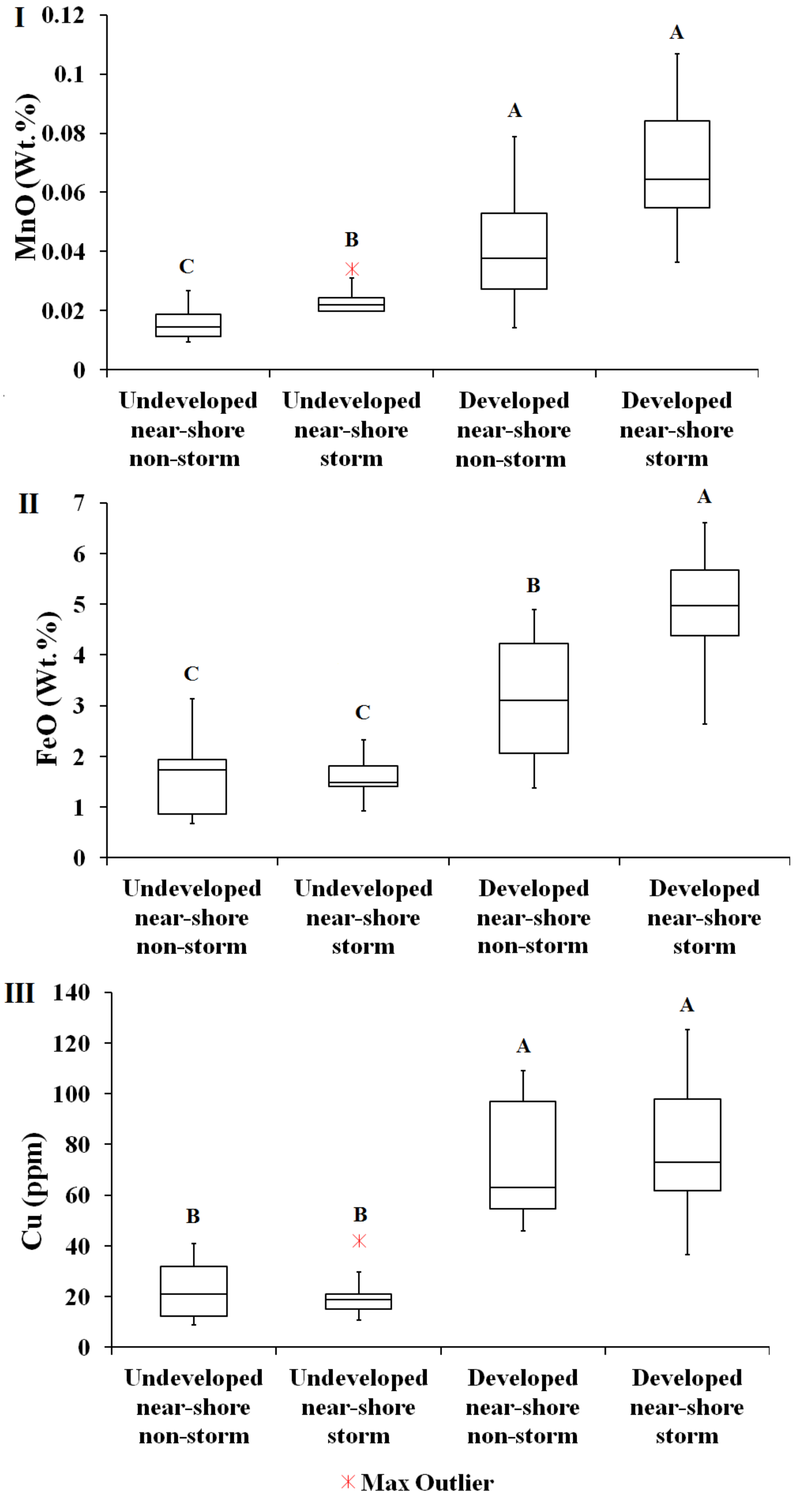


***Figure 22.*** *Box and whisker plots showing near-shore sediment MnO (I, [Wt. %]), FeO (II, [Wt. %]) and Cu (III, [ppm]) concentrations separated by developed and undeveloped bays during storm and non-storm periods. The box represents the inter quartile range (IQR) between the 25th and 75th percentile, and the whiskers represent a value 1.5 times the IQR above and below the 75th and the 25th percentile. The median is the center line in the box. Letters (A-C) indicate significantly different groups derived from ANOVA and SNK test.*

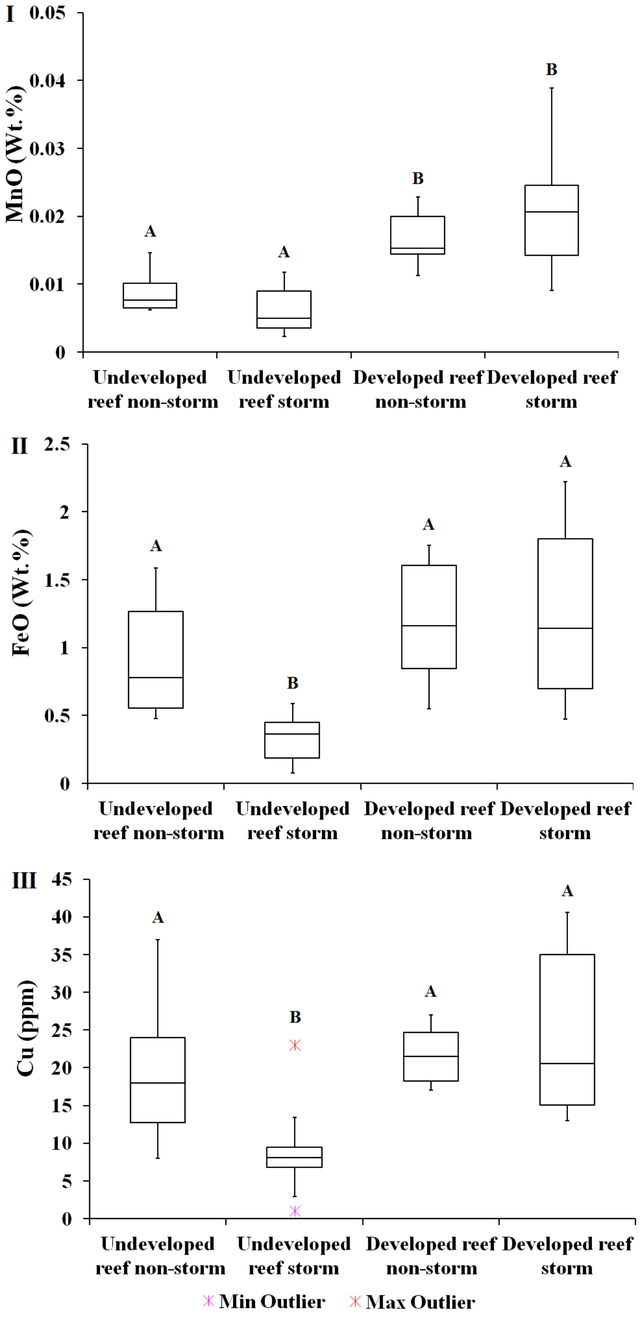


***Figure 23.*** *Box and whisker plots showing reef sediment MnO (I [Wt. %]), FeO (II [Wt. %]) and Cu (III [ppm]) concentrations (Appendix V) separated by developed and undeveloped bays during storm and non-storm periods. The box represents the inter quartile range (IQR) between the 25th and 75th percentile, and the whiskers represent a value 1.5 times the IQR above and below the 75th and the 25th percentile. The median is the center line in the box. Letters (A and B) indicate significantly different groups derived from ANOVA and SNK test.*

during both storm and non-storm periods compared to undeveloped areas during those same periods ($p < 0.001$) (Fig. 22 and 23). But there were no significant concentration differences between concentrations between storm and non-storm periods.

## C. Water Quality (TSS)

### Objectives

In order to examine how watershed development and major storms have affected total suspended solids (TSS), we compared TSS measurements a) between sites and over time and b) between fair weather periods and a major storm event.

### Methods

We monitored TSS at our study sites every 26 days from 2009-2012. Almost all of these samplings were conducted during periods of fair weather. In addition, we sampled TSS opportunistically, during a storm in St. John from 7/20/10-7/23/10. TSS was determined by filtering 1 L bottles of seawater onto pre-weighed filters (Whatman GFF, 1.5 $\mu$m pore size) that were dried and weighed to calculate TSS (mg/L).

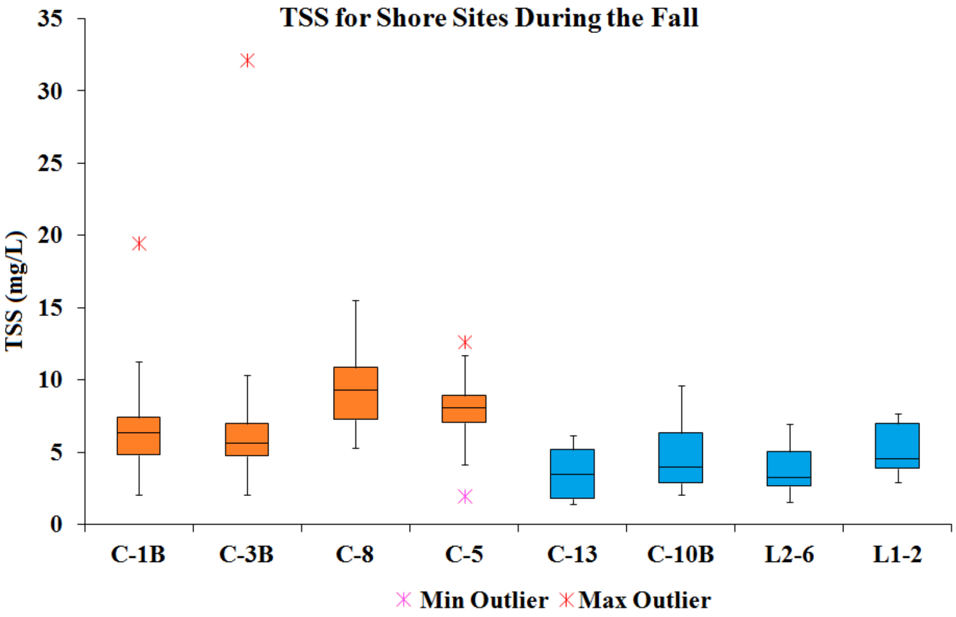
### Results

#### *i. Regular 26-day TSS (usually fair weather)*

The "fair-weather" TSS measurements at the developed shore stations were significantly higher than at the undeveloped shore stations (Student-Newman-Keuls test, P=0.002) but there were no significant differences in TSS between developed and undeveloped reef stations (Fig. 24) suggesting that watershed development and dirt roads may impact water quality. The maximum TSS for all 5 years was higher at the developed compared to the undeveloped shore stations (Fig. 25). The maximum TSS at 7 of the 8 sites occurred during the unusually stormy 2010 season. Most of the measurements at the undeveloped reefs (>95%) were below what has been classified as classified as "background" turbidity thresholds (<5 mg/L) for coral reefs (Thomas et al., 2003). However, TSS measurements as high as "severe" (>30 mg/L) were measured at the developed reef sites several times. TSS measurements at regular 26-day intervals during fair-weather periods were highly variable but generally low (<10 mg/L), suggesting generally good water quality most of the time.

#### *ii. Storm event TSS (usually fair weather)*

We measured TSS opportunistically following a record-breaking rainfall event from 7/20/10-7/23/10. The TSS ranged from 45 mg/L to 730 mg/L during the storm. By contrast, the TSS of non-storm event samples range from 1.5 to 33 mg/L, an increase in turbidity between 20 to 32 times compared to background conditions. Though the waters clear out after a few days-weeks, on the short term, these high turbidity levels could be detrimental to corals. Turbidity following this major was high below both developed and undeveloped watersheds. If these conditions persist more than a few days or occur frequently they may cause harm to corals and other reef organisms.



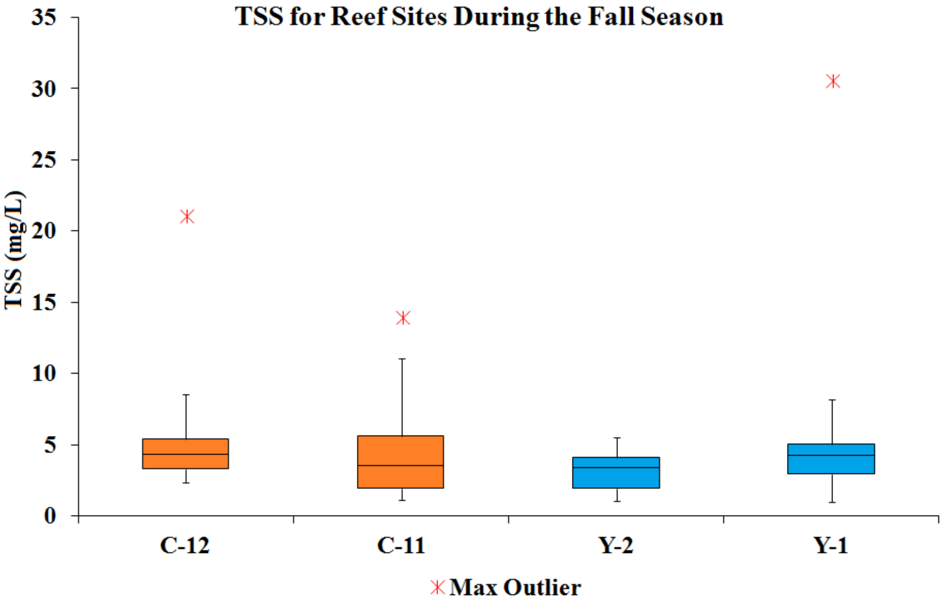


***Figure 24***. *Box and whisker plots of median TSS over 5 fall rainy seasons (2008-12) for the shore (top) and reef (bottom) sampling stations [median = middle bar; with 75 (box) & 95 (whisker) percentiles and outlier values as red stars]. Stations below developed sites are colored orange. Background (<5 mg/L) and severe (>30 mg/L) impact turbidity thresholds determined by Thomas et al., 2003 are marked. Though TSS did not differ significantly between any reef sites it was significantly higher at all developed compared to undeveloped shore stations (Student-Newman-Keuls test; P=0.002)*

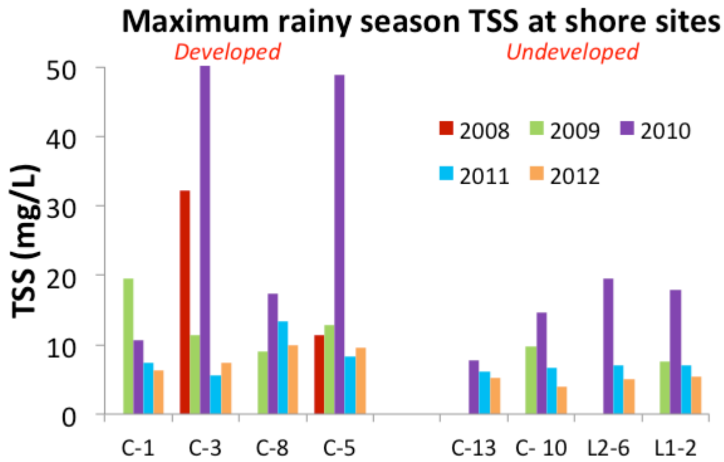


***Figure 25.*** *Variation in maximum TSS over for each of 5 fall rainy seasons (2008-12) for the shore stations.*

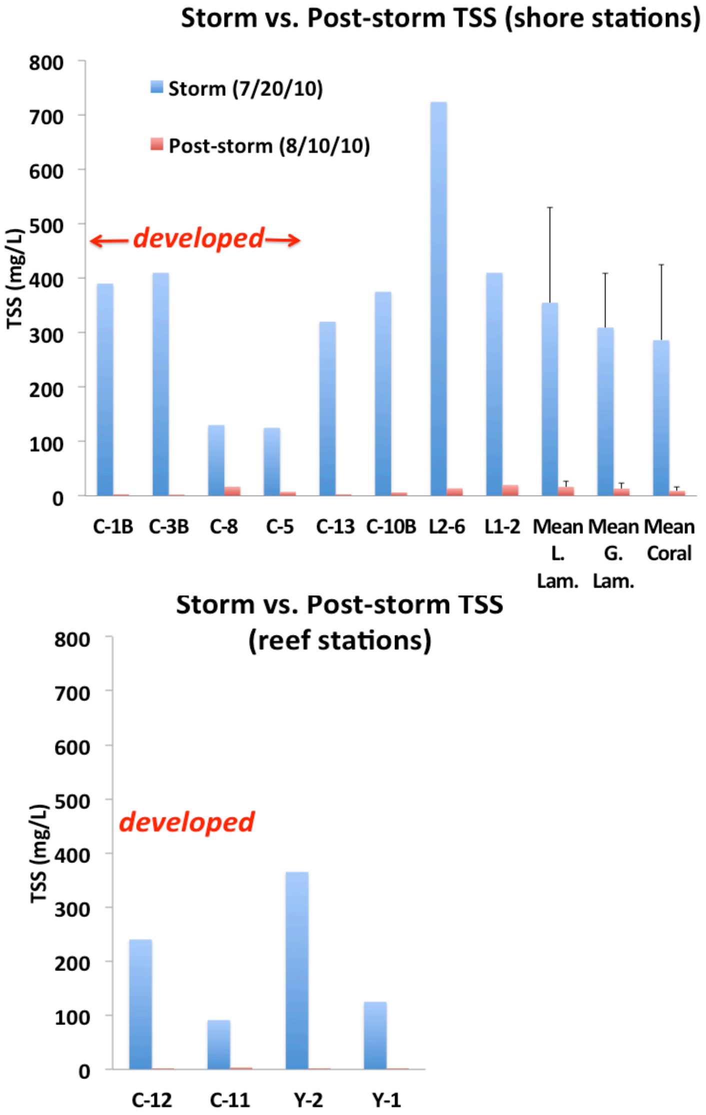


***Figure 26.*** *TSS measured on 7/20/10 during a storm and 20 days later (8/10/10) at shore (left) and reef (right) stations. Mean TSS for Little Lameshur, Great Lameshur and Coral Bays are also plotted*

## D. Outreach Summary

From 7/23/11-6/13/13, we conducted 35 outreach events, which consisted of meetings, presentations, or article/abstract submissions (Table 6). Through these activities we reached at least 1832 people, including USVI locals, students at all levels, the general public, and scientific and management communities. Products from this grant (see next section) include one journal article, one report, 13 professional meeting abstracts & presentations, two Master of Science theses, three undergraduate research projects, and one awarded proposal for $75,000 (with $78,379 in matching funds).

During the July 17-Aug. 3rd 2011 field season, Sarah Gray and her research team met with collaborators at the Coral Bay Community Council: Sharon Coldron and Chris Laude and with scientists C. Rogers and R. Boulon at the USGS/Virgin Islands National Park (Table 6). On July 27th, 2011, our research team conducted a hands-on science workshop for 16 USVI junior high and high school students attending the VIERS Science Eco camp (Fig. 27). For this workshop, we explored how watershed development can affect land-based sources of pollution and showed them the methods we're using to monitor the sedimentation (Fig. 27). We also visited the ARRA watershed projects in Coral Bay and viewed and sampled the watershed terrestrial sediment traps that Dr. Ramos-Scharron has deployed in Coral Bay to collect sediment eroded from the watershed.

Funding from this NOAA CRC grant has provided an opportunity for our research group to continue to partner with other USVI groups to examine the impact of watershed erosion mitigation and continued sediment monitoring. Through this grant we've kept in contact through meetings, emails, and regular bimonthly conference calls with our ARRA research partners at the Virgin Islands Resources Conservation & Development Council (V.I. RC&D), the Coral Bay Community Council, and researchers at the Center for Marine and Environmental Studies (CMES) at the University of the Virgin Islands (Tyler Smith and Marcia Taylor) and the University of Texas at Austin (Carlos Ramos Sharron). Several newspaper articles discussing the ARRA/NOAA grant have been published in local papers. We have worked closely with the Coral Bay Community Council (CBCC) to ensure that the data we collected for this project would be of maximum use to their community efforts for watershed management. We continue to work with members of the Coral Bay Community who volunteer as field assistants and provide discounted use of their boats. The fact that our field research is situated at VIERS (Virgin Islands Environmental Resource Station) provides an opportunity to speak to visiting K-12, university and community groups who visit VIERS from around the country/world (Table 6).

In addition, educational outreach at USD is occurring as the result of this funding. Two USD Master of Science in Marine Science students (Robert Harrington & Whitney Sears), One MS student from CICESE, and 3 USD undergraduate students (Amanda Greenstein, Jacob Holley, and Ruby Teague) in the Marine Science and Environmental Studies Department have conducted student research projects associated with this program. I also use examples from this project in my general education and majors courses at the University of San Diego.

***Figure 27**. The USD research team conducted a workshop for USVI students attending VIERS Science Eco Camp on 7/27/11.*

## E. Products

### A. <u>Products (Presentations, abstracts, publications and grants)</u>

#### i. *Grants awarded*

NOAA Coral Reef Conservation Conservation Grants* "Post-mitigation monitoring to determine the impact of watershed erosion control on LBSP to coral reefs, USVI" $75,000 with $78,379 in cost share (2012-2013).

#### ii. *Journal article*

Gray, S.C., Sears, W.T., Kolupski, M.L., DeGrood, A.M., and Fox, M.D (2012). Factors affecting land-based sedimentation in coastal bays, US Virgin Islands. *Proceedings of the 12th International Coral Reef Symposium, Cairns, Australia July 9th-13th, 2012*.

#### iii. *Reports*

Ramos-Scharrón, C. E., Gray, S.C. and Smith, T. (2012), "Executive Summary Monitoring Component USVI Watershed Stabilization, NOAA-ARRA (2009-2012)" (12/26/12).

iv. *Master of Science Thesis Completed* or in Progress*

Guidino Elizondo, N. (2012)*. "Erosion e intemperismo o las cuencas Coral Bay y Lameshur, St. John, U.S. Virgin Island" Weathering and soil erosion in Saint John US Virgin Islands. (Centro de Investigacion Cientifica de Educacion Superior de Ensenada, Baja California: CICESE).

Harrington, R.J., (2014 anticipated completion). Ridge to reef assessment of metal concentration and mineralogy in rocks and sediments on St. John, U.S. Virgin Islands. (University of San Diego MS Thesis).

*Sears, W.* (2014 anticipated completion). Factors Affecting Terrigenous Sedimentation in Coastal Bays with Coral Reefs: Implications for Monitoring the Effectiveness of Watershed Restoration. (University of San Diego MS Thesis).

i. *Professional meeting abstracts/presentations*

Smith, T., and Gray, S.C. (2012). Sedimentation and Water Quality Research in the US Virgin Islands. 2/24/12. *U.S. Coral Reef Task Force Meeting, Silver Spring, MD, 02/24/12.*

Harrington, R.J., Gray, S.C., and O'Shea, B. (2012). Ridge to reef assessment of metal concentration and mineralogy in rocks and sediments on St. John, U.S. Virgin Islands. *Southern California Academy of Sciences Annual Meeting, Occidental College, CA, 5/4/12-5/5/12.*

Harrington, R.J., Gray, S.C., and O'Shea, B. (2012). Ridge to reef assessment of metal concentration and mineralogy in rocks and sediments on St. John, U.S. Virgin Islands. *University of San Diego Graduate Research Day (5/3/12).*

Harrington, R.J., Gray, S.C., and O'Shea, B. (2012). Ridge to reef assessment of metal concentration and mineralogy in rocks and sediments on St. John, U.S. Virgin Islands. *University of San Diego Graduate Research Day (5/3/12).*

Greenstein, A. Using tropical foraminifera as indicators of water quality in coral reef environments, USVI. *Creative Collaborations Undergraduate Research Conference, University of San Diego, 4/19/12.*

Gray, S.C., Sears, W.T., Kolupski, M.L., DeGrood, A.M., and Fox, M.D (2012). Factors affecting land-based sedimentation in coastal bays, US Virgin Islands. 12th International Coral Reef Symposium, Cairns, Australia July 9th-13th, 2012.

Harrington, R.J., Gray, S.C., Ramos-Scharrón, C.E., O'Shea, B. (2012). Ridge to reef assessment of metal concentration and mineralogy in rocks and sediments on St. John, U.S. Virgin Islands. *American Geophysical Union Fall Meeting, 12/3/12-12/7/12, San Francisco, CA, Abstract #EP13D-0884.* (http://fallmeeting.agu.org/2012/eposters/eposter/ep13d-0884/).

Gudino, N., Kretzschmar, T., and Gray, S.C. (2012). A comparison of the geochemical signatures of water-rock interaction and erosion rates between developed and undeveloped watersheds, St. John, US Virgin Islands American Geophysical Union Fall Meeting, 12/3/12-12/7/12, San Francisco, CA, Abstract #EP13D-0885. (http://fallmeeting.agu.org/2012/eposters/eposter/ep13d-0885/).

Teague, R. (2012). Human Impacts on Water Quality (Turbidity) in St. John, U.S. Virgin Islands. *Summer Undergraduate Research Conference, University of California San Diego, San Diego, CA, 8/16/12.*

Holley, Jacob, (2012). Bioavailability of Heavy Metals in the Coral Bay Watershed, St. John, USVI. University of San Diego, Marine Science Undergraduate Senior Seminar, 11/16/12, San Diego, CA.

Teague, R. (2013). Human Impacts on Water Quality (Turbidity) in St. John, U.S. Virgin Islands. *Undergraduate Research Conference, University of San Diego, San Diego, CA, 4/18/13 (http://www.sandiego.edu/ugresearch/urc/).*

Holley, Jacob, (2013). Bioavailability of Heavy Metals in the Coral Bay Watershed, St. John, USVI. *Undergraduate Research Conference, University of San Diego, San Diego, CA, 4/18/13 (http://www.sandiego.edu/ugresearch/urc/).*

Teague, R., Harrington, R., Gray, S.C. and Hsieh, Y. (2013) The impact of watershed development on turbidity (TSS) in bays with coral reefs, US Virgin Islands. *22nd Biennial Conference of the Coastal and Estuarine Research Foundation, 3rd-7th November, 2013, San Diego, CA (http://www.sgmeet.com/cerf2013/default.asp)*

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Gray, S.C., Gobbi, K.L. and P.V. Narwold. 2009. Comparison of Sedimentation in Bays and Reefs below Developed versus Undeveloped Watershed on St. John, US Virgin Islands. *Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, Florida, 7-11 July 2008.*

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***Table 6.*** *Log of outreach activities.*

| **Date** | **Location** | **Person involved** | **Type of Event** | **Audience Type & (Number)** | **Comments (Link)** |
|---|---|---|---|---|---|
| Bi-monthly | Conference Call | ARRA partners | Conference Calls | ARRA Partners | Project updates |
| 7/23/11 | Cruz Bay, St. John, USVI | Caroline Rogers & Rafe Boulion | Meeting to discuss link between sedimentation research and ongoing ecological monitoring | USGS and VI National Park scientisits | |
| 7/27/11 | VIERS, St. John, USVI | Gray and field research team | Workshop for USVI high school students attending VIERS science camp (Fig. 7) | Middle and high school students (16) | |
| 7/30/11 | Coral Bay, St. John, USVI | Gray & team & Bruce Swanson | Tour of C. Ramos Scharron's terrestrial sediment trap stations in Coral Bay | USD team (5) & ARRA partner (1) | |
| 8/1/11 | Coral Bay, St. John, USVI | USD: Gray & O'Shea CBCC: Coldren & Laude | Meeting to discuss ongoing joint projects between USD and the Coral Bay Community Council (CBCC) | USD faculty (2); CBCC representatives (2) | |
| 8/1/11 | Coral Bay, St. John, USVI | Gray and field research team | Tour of ARRA mitigation sites | USD faculty & students (5); CBCC President (1) | |
| 8/5/11 | VIERS, St. John, USVI | Gray & Dr. Peter Edmonds (CSUN) | Meeting to discuss link between sedimentation research and ongoing ecological monitoring and a joint paper | CSUN ecologist & Gray | |
| 9/8/11 | Coral Bay, St. John, USVI | Zoe Hastings & Bruce Swanson | Attended a Coral Bay Community Reception where a poster of our monitoring work was presented | NOAA visitors and community members | |
| 10/1/11 | | Gray | Submittal of abstract for presentation at the International Coral Reef Symposium in Cairns, Australia in July of 2012. | Coral reef scientist | |
| 10/8/11 | VIERS, St. John, USVI | Zoe Hastings | VIERS lab tour and project presentation | K-12 students & teachers (10) | |
| 10/11/11 | VIERS, St. John, USVI | Zoe Hastings | VIERS lab tour and project presentation | NOAA Employees (4) | |
| 10/29/11 | USD | Sarah Gray | Submittal of NOAA Coral Reef Conservation Program proposal to continue marine & storm water monitoring for another season. | | |

***Table 6.*** *Log of outreach activities (cont.).*

| Date | Location | Person involved | Type of Event | Audience Type & (Number) | Comments (Link) |
|---|---|---|---|---|---|
| 12/31/11 | VIERS, St. John, USVI | Zoe Hastings | VIERS lab tour and project presentation | University students and faculty (15) | Adelphi University |
| 12/31/11 | VIERS, St. John, USVI | Zoe Hastings | VIERS lab tour and project presentation | University students and faculty (15) | St. Francis College |
| 1/2/12 | VIERS, St. John, USVI | Zoe Hastings | Project Presentation | College students (15) | |
| 1/9/12 | VIERS, St. John, USVI | Zoe Hastings | Project Presentation | Pottery group (8 adults) | |
| 2/19/12 | VIERS, St. John, USVI | Zoe Hastings | Project Presentation | High School group from MI (15 students) | |
| 3/1/12 | VIERS, St. John, USVI | Zoe Hastings | Project Presentation | Sierra Club Service Group (13 adults) | |
| 4/19/12 | University of San Diego | Amanda Greenstein | Poster presentation of research at the “Creative Collaborations” forum | Faculty, Students, general public | |
| 5/3/12 | USD, San Diego, CA | Robert Harrington | Poster presentation at “Graduate Research Day” | Faculty, students and general public (250) | |
| 5/4/12 | Occidental College, Los Angeles, CA | Robert Harrington & Sarah Gray | Presentation at the Southern California Academy of Sciences Annual Meeting | Scientists (150) | |
| 5/7/12 | USD, San Diego, CA | Robert Harrington | Feature for USD website http://www.sandiego.edu/insideusd/?p=24174 | | |
| 6/1/12 | USD | Sarah Gray | Awardal of NOAA Coral Reef Conservation Program proposal to continue marine & storm water monitoring for another season. | | |
| 6/12 | | Gray | Publication of paper in the Proceedings of the International Coral Reef Symposium | Coral reef scientist | |
| 5/14/12 | | Whitney Sears | Presentation of MS thesis proposal | Faculty (9) | |
| 6/22/12 | CICESE, Ensenada, Mexico | Napolean | Thesis Defense | CICESE faculty, students, members of the public | |
| 7/9/12 | Cairns, Australia | Gray | Presentation at the 12th International Coral Reef Symposium | International scientists and managers (40) | |

***Table 6.*** *Log of outreach activities (cont.).*

| Date | Location | Person involved | Type of Event | Audience Type & (Number) | Comments (Link) |
|---|---|---|---|---|---|
| 7/10/12 | Cairns, Australia | Gray | Met with USVI researchers Tyler Smith and Leslie Henderson to coordinate ongoing work | Faculty and researcher (2) | |
| | Conference Calls | ARRA partners C. Ramos-Scharron, T. Smith, Julia Royster, Marcia Taylor | Preparation of ARRA Monitoring Executive Summary Report. | ARRA Partners | |
| 8/15/12 | San Diego, CA | Teague | Presentation to the UCSD Undergraduate Research Conference, UC San Diego, San Diego, CA | University faculty and students (35) | |
| 9/6/12 | San Diego | Gray | Submission of NOAA invited proposal for continued integrated marine and terrestrial monitoring at our study sites | Carlos Ramos-Scharron (UT Austin), Julia Royster (NOAA) | |
| 11/16/12 | USD, San Diego | Jacob Holley (undergrad. Student) | Presentation of senior seminar | Faculty & students (~40) | |
| 12/3/12 | San Francisco, CA | Robert Harrington (grad. student) | Scientific conference (AGU) | Scientists ~60 | |
| 12/3/12 | San Francisco, CA | Napolean Gudino (grad. student) | scientific conference (AGU) | Scientists ~60 | |
| 4/18/13 | USD, San Diego | Ruby Teague (undergrad. student) | Presentation of poster at the USD undergraduate research conference | Faculty & students & members of the general public (~300) | http://www.sandiego.edu/ugresearch/urc/ |
| 4/18/13 | USD, San Diego | Jacob Holley (undergrad. student) | Presentation of poster at the USD undergraduate research conference | Faculty & students & members of the general public (~300) | http://www.sandiego.edu/ugresearch/urc/ |