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An assessment of nutrients and sedimentation in the St. Thomas East End Reserves, US Virgin Islands

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Abstract Nutrients and sedimentation were monitored for approximately 2 years at six sites in the St. Thomas East End Reserves (STEER), St. Thomas, USVI, as part of a NOAA project to develop an integrated environmental assessment. Concentrations of ammonium (NH_4^+) and dissolved inorganic nitrogen (DIN) were higher in Mangrove Lagoon and Benner Bay in the western portion of STEER than in the other sites further east (i.e., Cowpet Bay, Rotto Cay, St. James, and Little St. James). There was no correlation between rainfall and nutrient concentrations. Using a set of suggested nutrient thresholds that have been developed to indicate the potential for the overgrowth of algae on reefs, approximately 60% of the samples collected in STEER were above the threshold for orthophosphate ($HPO_4^=$), while 55% of samples were above the DIN threshold. Benner Bay had the highest sedimentation rate of any site monitored in STEER, including Mangrove Lagoon. There was also an east to west and a north to south gradient in sedimentation, indicative of higher sedimentation rates in the western, more populated areas surrounding STEER, and sites closer to the shore of the main island of St. Thomas. Although none of the sites had a mean or average sedimentation rate above a suggested sedimentation threshold, the mean sedimentation rate in Benner Bay was just below the threshold.

Introduction

Located on the southeastern end of the island of St. Thomas, US Virgin Islands, the St. Thomas East End Reserves or STEER (Fig. 1), is a collection of Marine Reserves and Wildlife Sanctuaries (MRWS) containing extensive mangroves and seagrass beds, along with coral reefs, lagoons, and cays. STEER comprises an area of 9.6 km^2, with approximately 34 km of coastline, and is thought to be one of the most valuable fisheries nursery areas remaining around St. Thomas (STEER 2011). There is a large active landfill along with numerous marinas and boatyards, various commercial and industrial activities, an EPA Superfund Site, a horse racetrack, and residential areas served primarily by individual septic systems (IRF 1993) in the western portion of STEER, and towards the east a number of resorts, all of which can contribute a variety of pollutants including nutrients, to STEER.

As part of a project by NOAA's National Centers for Coastal Ocean Science (NCCOS) to characterize chemical contaminants, bioeffects, and the biological communities within STEER, nutrients were monitored for

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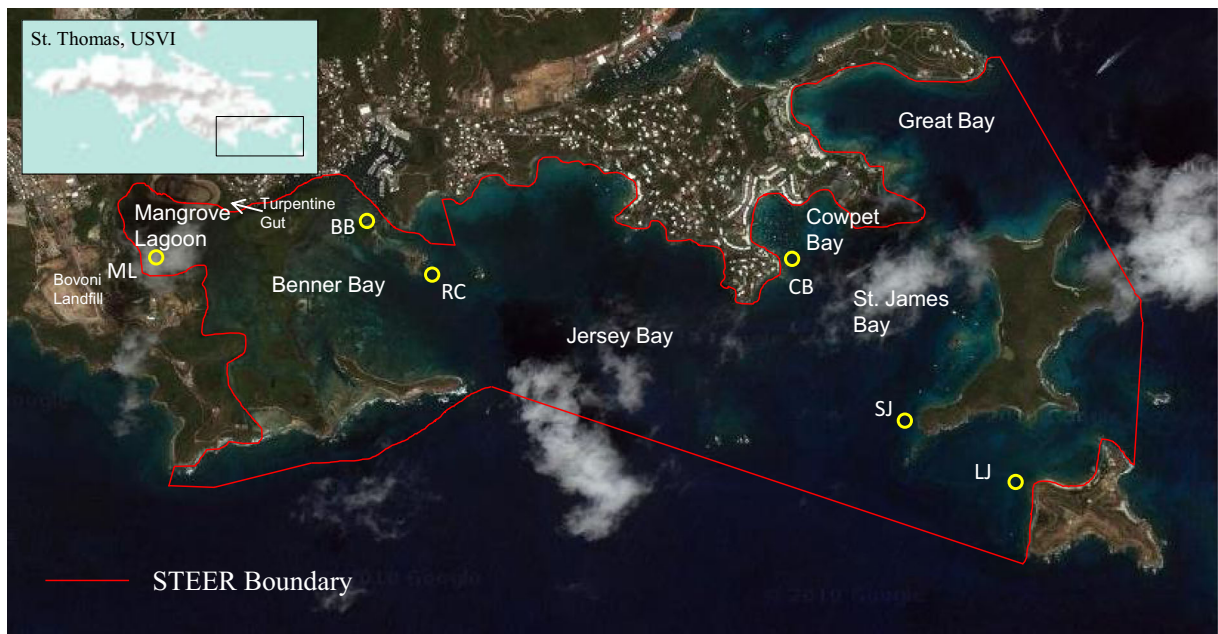
Fig. 1 Sampling sites for nutrients and sedimentation along with the STEER boundaries

23 months by partners at the University of the Virgin Islands (UVI). Nutrients were identified as a major environmental concern in the STEER Management Plan (STEER 2011). While dissolved nutrients are essential to productivity in aquatic systems, an overabundance of nutrients in coral reef systems can result in blooms of algae with the potential to outcompete and smother juvenile and adult corals, ultimately resulting in the loss of those corals (Box and Mumby 2007; D'Angelo and Wiedenmann 2014).

Sediments deposited on coral reefs from surface water transporting eroded soils as might occur during a storm, or through the resuspension of bottom sediments, can also have serious impacts (Burke and Maidens 2004; Fabricius 2005; Waddell and Clarke 2008). The deposition of sediments in reef areas can act to smother corals and physically abrade coral tissues. At the very least, sediments "raining" down upon corals would likely cause them to expend more energy to remove sediment particles; meaning less energy would be available for other functions including growth and reproduction. Elevated sedimentation has been linked to less coral cover, lower diversity, and recruitment, along with lower growth and calcification rates (ISRS 2004; Rogers 1990; Burke and Maidens 2004). Like nutrients, the input of sediment was identified as a major threat in the STEER Management Plan (STEER 2011).

Materials and methods

The locations for the monitoring sites (Fig. 1) were selected non-randomly by project partners at UVI and the Virgin Islands Department of Planning and Natural Resources (DPNR), in order to target potential sources of land-based pollution. The sites were used to assess terrestrial inputs from the surrounding watershed including residential areas surrounding Benner Bay, along with the Bovoni Landfill, adjacent to Mangrove Lagoon. Samples for nutrient analysis and sedimentation were collected monthly from five targeted sites from January 2012 to November 2013. A sixth site, at Little St. James (LJ. Fig. 1), was added in March 2012 at the request of DPNR. The methods used for the collection and analysis of each of these parameters are described below.

Nutrients

At each site, duplicate subsurface samples were collected for the analysis of dissolved nutrients. Personnel wore nitrile gloves, in order to prevent contamination of the water samples. Samples were then filtered at the time of collection into acid-washed 125 ml high-density polyethylene (HDPE) bottles, using 60 ml syringes equipped with disposable Millipore Sterivex 0.22 μm filter units. The syringe was first rinsed with several full

volumes of site water. Next, the syringe was refilled, the Sterivex filter was attached, and a full volume of site water was pushed through the filter. The sample bottles were rinsed three times with filtered site water. The filter was removed and the syringe refilled with site water. After replacing the filter, the syringe/filter process was repeated until the bottles were filled, leaving adequate headspace to allow for expansion during freezing. Samples were immediately packed on ice for transport to the laboratory at the UVI Center for Marine and Environmental Studies. Upon return to the laboratory, the water samples were frozen until shipped.

Water samples were analyzed by the Geochemical and Environmental Research Group (GERG) at the Texas A&M University, through a subcontract with TDI-Brooks, Inc., a NOAA contract laboratory. The following is a brief summary of methods used for the analysis of nutrients in the water samples. Nitrate and nitrite analyses were based on the methodology of Armstrong et al. (1967) which uses a ground cadmium column for reduction of nitrate to nitrite. Orthophosphate was measured using the methodology of Bernhardt and Wilhelms (1967), with the modification of hydrazine as a reductant. Ammonium analysis was based on the method of Harwood (Harwood and Kuhn 1970) using dichloroisocyanurate as an oxidizer. Urea was measured using diacetyl-monoximine and themicarbozide. Total nitrogen and total phosphorus concentrations were determined after an initial decomposition step. This method involves persulfate oxidation while heating the sample in an autoclave (Hansen and Koroleff 1999). After oxidation of the samples, nutrient determinations were conducted on a Technicon® II analyzer.

Sedimentation

Sediment traps are commonly used in conjunction with laboratory techniques to provide insight into sedimentation rates, composition, sources, and distributions in marine environments. Beginning in December 2011, sediment trap arrays were deployed at five sites located throughout STEER (Fig. 1). In March 2012, at the request of DPNR, an additional station was added near Little St. James (LJ) to address concerns related to major ongoing construction activities on the island. GPS coordinates were recorded for each station and are shown in Table 1.

Each sediment trap deployed by UVI consisted of a 2-in.-diameter PVC cylinder, sealed at one end, with a height-to-diameter ratio of 4:1, the same as those in use by the University of the Virgin Islands (Smith et al. 2008). This height to diameter ratio has been shown to minimize resuspension and escape of trapped sediments under normal flow conditions (Smith et al. 2008). The cylinders were deployed vertically, affixed to metal posts at a height of approximately 60 cm above the seafloor, and approximately 30 cm for very shallow sites (Benner Bay and Mangrove Lagoon). Three replicate cylinders were spaced approximately 1 m apart, in order to minimize the effects of water flow disturbances between replicates, thus helping to ensure independence of replicate samples (Butman 1984).

At four sites (Little St. James, St. James, Cowpet Bay, and Rotto Cay), traps were exchanged by SCUBA divers. For trap arrays located in the shallowest sites (Mangrove Lagoon and Benner Bay), the exchange was generally accomplished by wading, taking care to minimize disturbance to bottom sediments. During sediment trap exchanges, each trap was carefully removed from its post and was sealed with a tight-fitting cap. Because a variety of small fish and invertebrates were attracted to the refuge provided by the sediment traps, cylinders were checked for the presence of marine organisms prior to being capped. Replacement traps were cleaned thoroughly between deployments and were rinsed just prior to deployment at each site. Newly deployed traps were visually inspected just before divers departed a site, in order to ensure that no sediment entered during the exchange process. If sediment was observed in a newly deployed trap, the cylinder was removed from the post, cleaned, and replaced. Beginning in April 2012, Pettit (Kop-Coat, Inc.) inflatable boat anti-fouling paint was applied to the upper 5 cm of the traps due to concerns that biofouling of trap apertures at several sites could significantly affect trap performance.

Upon retrieval, the sealed sediment traps were stored upright until decanted and filtered. In the laboratory at UVI, sediment samples were decanted, filtered, rinsed to remove salts, and then dried completely at 70 °C. Samples were then cooled to room temperature in a desiccator and were weighed to the nearest 0.001 g to obtain total dry weight of accumulated sediments for each trap. An analysis of sediment composition (organic/carbonate/terrigenous fractions) was carried out using loss on ignition (LOI) at 550 °C and 950 °C following the

Table 1 Location of sites and mean water quality values from STEER sites

Site name	Site Code	Latitude (DD)	Longitude (DD)	Salinity (ppt)	Turbidity (NTU)	pH	Depth (m)	Chlorophyll a (μg/l)	DO (mg/l)	Temperature (°C)
Mangrove Lagoon	ML	18.31385	− 64.87988	35.6 ± 0.3	4.07 ± 0.71	8.09 ± 0.03	1.3 ± 0.1	1.86 ± 0.17	6.79 ± 0.13	29.3 ± 0.3
Benner Bay	BB	18.3167	− 64.8674	36.0 ± 0.1	10.7 ± 1.4	8.13 ± 0.03	1.2 ± 0.1	1.12 ± 0.08	6.18 ± 0.12	29.3 ± 0.2
Rotto Cay	RC	18.31331	− 64.86423	35.8 ± 0.1	1.41 ± 0.20	8.13 ± 0.02	2.1 ± 0.1	0.37 ± 0.03	6.37 ± 0.16	28.6 ± 0.2
Cowpet Bay	CB	18.31487	− 64.84267	35.9 ± 0.1	0.91 ± 0.13	8.17 ± 0.02	1.7 ± 0.1	0.32 ± 0.02	6.54 ± 0.03	28.3 ± 0.2
St. James	SJ	18.30302	− 64.83671	35.9 ± 0.1	1.03 ± 0.16	8.16 ± 0.02	1.8 ± 0.1	0.28 ± 0.03	6.42 ± 0.02	28.0 ± 0.1
Little St. James Island	LJ	18.30069	− 64.83003	35.8 ± 0.1	1.52 ± 0.13	8.15 ± 0.02	1.6 ± 0.1	0.28 ± 0.03	6.51 ± 0.02	28.4 ± 0.1

Values are ± standard error. Abbreviations: *DD* decimal degrees, *ppt* parts per thousand, *NTU* nephelometric turbidity units, *m* meters, *DO* dissolved oxygen, *mg/l* milligrams/l, *°C* degrees Celsius.

Note that depth is the water depth at which the water quality measurements were made and not the depth of the site

techniques described by Heiri et al. (2001). Additional information on the analysis of sediment composition can be found in Pait et al. (2015).

Statistical analysis

The data collected from the project were analyzed using JMP® statistical software. Because the data were not normally distributed, non-parametric tests (e.g., Wilcoxon rank sum and Spearman's multivariate correlation) were used.

Results and discussion

Water parameters

In addition to the site location information, Table 1 also contains a summary of the water parameters measured. Note that depth refers to the depth made for the water quality measurements and not the depth of the water at the site. Mean turbidity was highest at the Benner Bay site (10.7 NTU). A non-parametric (Wilcoxon rank sum) pairwise comparison indicated that the turbidity varied by site (chi-square = 54.8750; $p < 0.0001$), and that the Benner Bay site was significantly higher than all the other sites sampled monthly in STEER, including Mangrove Lagoon (Table 2). Salinity did not vary by site (chi-square = 8.1348; $p = 0.1490$), but dissolved oxygen did (chi-square = 41.8334; $p < 0.0001$), and Benner Bay was significantly different (lower) than all other sites.

Nutrients

A summary of the results from the nutrient monitoring can be seen in Table 3. In general, higher nutrient concentrations were found in the western portion of the study area, specifically in Mangrove Lagoon and Benner Bay.

Non-parametric analyses (Wilcoxon) indicated that ammonium (NH_4^+) (chi-square = 27.1308, $p < 0.0001$), nitrite (NO_2^-) (chi-square = 24.9447, $p = 0.0001$) and dissolved inorganic nitrogen (DIN) (chi-square = 20.6362, $p = 0.0009$) varied significantly by site. The variation of the combined nitrate/nitrite ($NO_3 + {}^- NO_2^-$), however, was not significant (chi-square = 6.7878, $p = 0.2369$) across sites. Mangrove Lagoon and Benner Bay had significantly higher mean levels of NH_4^+ and DIN than all other sites (Table 2). For nitrite, Benner Bay had significantly higher mean values than all other sites, except for Mangrove Lagoon. Finally, Mangrove Lagoon and Benner Bay did not differ significantly from each other for any of the nutrient species analyzed, indicating elevated levels of nutrients (e.g., NH_4^+ and DIN, and nitrite) at both locations. The watershed surrounding the western portion of the study area includes the higher density residential areas of Estate Bovoni and Anna's Retreat, along with the active Bovoni Landfill, all of which are likely contributing nutrients to STEER. In addition, there appear to be a number of live-aboard boats in Benner Bay, which are potential sources of nutrients as well. The east to west gradients seen with nitrogen compounds were not seen for orthophosphate and total phosphate, which indicates a different matrix of sources and/or forcing functions that drive distributions of these nutrients. Nutrients in freshwater are highly soluble, whereas phosphates are

Table 2 Significant differences in parameters by site in the STEER

| Parameter | Chi-square | p | Sites | | | | | |
			Mangrove Lagoon	Benner Bay	Rotto Cay	Cowpet Bay	St. James	Little St. James
Turbidity	54.8750	< 0.0001	B	A	BC	C	C	C
Dissolved oxygen	41.8334	< 0.0001	B	A	B	B	C	B
Ammonium	27.1308	< 0.0001	A	A	B	B	B	B
Nitrite	24.9447	0.0001	AB	A	BC	BC	BC	C
DIN	20.6362	0.0009	A	A	B	B	B	B
Percent terrigenous sediment in traps	38.9661	< 0.0001	B	A	C	C	C	C
Mean sediment accumulation rate	71.0320	< 0.0001	B	A	B	C	C	C
Mean terrigenous accumulation rate	70.2037	< 0.0001	B	A	B	C	C	C

Sites with the same letter were not significantly different from each other for the parameter measured *DIN* dissolved inorganic nitrogen, *p* probability

usually associated with sediment under aerobic conditions. The delivery of nitrates and phosphates to coastal waters from rainfall runoff and groundwater seepage will follow different paths.

Nutrient concentrations were also assessed to determine if they varied by longitude and latitude. A non-parametric analysis revealed a significant and negative correlation between longitude and ammonium

Table 3 Summary statistics for nutrients measured in the STEER. All units are expressed as mg/L N or mg/L P

| Nutrient | Mangrove Lagoon | | | Benner Bay | | | Rotto Cay | | |
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
$NO_3^- + NO_2^-$	0.04 ± 0.023	0	0.422	0.013 ± 0.004	0	0.075	0.007 ± 0.002	0	0.022
NH_4^+	0.020 ± 0.003	0	0.055	0.016 ± 0.003	0.004	0.042	0.007 ± 0.002	0	0.039
Urea	0.004 ± 0.001	0	0.017	0.007 ± 0.003	0	0.056	0.004 ± 0.001	0	0.023
DIN	0.061 ± 0.024	0	0.442	0.029 ± 0.005	0.005	0.08	0.014 ± 0.003	0	0.059
DON	0.305 ± 0.048	0	0.652	0.280 ± 0.040	0.047	0.62	0.258 ± 0.037	0.037	0.467
Total N	0.366 ± 0.060	0.033	1.094	0.309 ± 0.040	0.062	0.701	0.272 ± 0.037	0.056	0.526
$HPO_4^=$	0.004 ± 0.001	0	0.012	0.006 ± 0.001	0	0.012	0.005 ± 0.001	0	0.011
Total P	0.012 ± 0.001	0.006	0.027	0.012 ± 0.001	0.006	0.022	0.017 ± 0.006	0.006	0.116
Nutrient	Cowpet Bay			St. James			Little St. James		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
$NO_3^- + NO_2^-$	0.007 ± 0.002	0	0.021	0.009 ± 0.002	0	0.024	0.007 ± 0.002	0	0.024
NH_4^+	0.006 ± 0.002	0	0.022	0.006 ± 0.001	0	0.017	0.006 ± 0.001	0	0.015
Urea	0.003 ± 0.001	0	0.01	0.003 ± 0.001	0	0.007	0.003 ± 0.001	0	0.008
DIN	0.014 ± 0.003	0	0.034	0.015 ± 0.003	0	0.036	0.013 ± 0.003	0.001	0.036
DON	0.251 ± 0.032	0.034	0.502	0.255 ± 0.037	0.067	0.438	0.297 ± 0.036	0.052	0.45
Total N	0.265 ± 0.031	0.046	0.504	0.270 ± 0.036	0.074	0.469	0.310 ± 0.036	0.056	0.463
$HPO_4^=$	0.005 ± 0.001	0	0.011	0.005 ± 0.001	0	0.013	0.005 ± 0.002	0	0.018
Total P	0.013 ± 0.003	0.005	0.047	0.011 ± 0.002	0.004	0.05	0.009 ± 0.001	0.006	0.022

Abbreviations: *Min.* minimum, *Max* maximum, NO_3^- nitrate, NO_2^- nitrite, NH_4^+ ammonium, *DIN* dissolved inorganic nitrogen, *DON* dissolved organic nitrogen, $HPO_4^=$ orthophosphate

(Spearman's Rho = -0.4030, $p < 0.0001$), nitrite (Spearman's Rho = -0.3866, $p < 0.0001$) and DIN (Spearman's Rho = -0.3510, $p = 0.0002$), indicating that moving east to west, concentrations of these nutrients tended to increase. For latitude, there was a significant positive correlation also for ammonium (Spearman's Rho = 0.2661, $p = 0.0058$), nitrite (Spearman's Rho = 0.3824, $p < 0.0001$), and DIN (Spearman's Rho = 0.2315, $p = 0.0170$), indicating that as latitude increased (i.e., moving towards the shore of the island of St. Thomas), nutrient concentrations also tended to increase.

A number of projects in the US Caribbean have examined the concentration of various nutrients in nearshore waters. Summarized results from these studies, along with those from the current work in STEER, are presented in Table 4. For most of the nutrient species, the mean concentrations appeared to be somewhat higher in STEER compared to the locations monitored in St. John and St. Croix (Smith et al. 2013), although lower than that found in and around Guanica Bay, Puerto Rico (Whitall et al. 2013).

Ideally, streamflow gauge data would be used to help assess nutrient delivery to STEER. There are, however, no active streamflow gauges in the Turpentine Gut watershed, the largest watershed that drains directly to STEER at Mangrove Lagoon. Because of this, rainfall data was used as a proxy to assess possible relationships between the amount of rainfall and variations in nutrient concentrations in STEER. The rationale for using this data is that higher rainfall would be expected to result in additional runoff and nutrients entering streams that flow into STEER, and also directly into STEER through runoff from streets and hillsides, which would not be accounted for from the stream gauge data. The most

complete precipitation data available was for the Cyril E. King Airport in West Charlotte Amalie. Daily rainfall records were accessed online through NOAA's National Climatic Data Center. Daily rainfall estimates were plotted against concentrations for each nutrient species at each of the six sites in STEER.

Spearman's non-parametric tests failed to show a significant positive correlation between rainfall and nutrients across STEER or by site, although there were a number of negative correlations between rainfall and nutrients. An example of the data for nitrite + nitrate ($NO_2 + NO_3$) plotted against rainfall for Benner Bay is presented in Fig. 2. The highest concentration of nitrite + nitrate was found in the May 2013 sampling; however, rainfall for that day along with the day before was 0 mm. During the period of highest rainfall (136.4 mm) in September 2013, there were unfortunately no water samples taken for nutrient analysis. It is unclear why there was not a positive correlation between nutrient concentrations and rainfall in STEER, although there are a number of possibilities. One of these is the lack of more complete rain gauge data adjacent to STEER. Rainfall data near STEER might reveal better correlations between rainfall and nutrient concentrations. Rainfall patterns on St. Thomas can be highly localized, and more complete rainfall data near STEER might help elucidate any relationships between rainfall, the mountainous terrain, and nutrients. Another possibility is that discharges from septic systems into STEER either from streams like Turpentine Gut, or via groundwater, are providing a constant source of nutrients, independent of rainfall. Finally, resuspension of sediments through wave action could possibly stir up sediment-associated nutrients as well.

Table 4 Comparison of STEER nutrient results with those from other US Caribbean locations. All units are expressed as mg/L N or mg/L P

| | St. Thomas | | | St. John[1] | | | | | | St. Croix[1] | | | Puerto Rico[2] | | |
| | STEER | | | Lameshur Bay | | | Coral Bay | | | Teague Bay | | | Guanica | | |
Nutrient	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
$NO_3 + NO_2$	0.014	0	0.426	0.001	ND	2.664	0.001	ND	3.936	0.001	ND	0.289	0.14	0	3.68
NH4	0.01	0	0.055	0.004	ND	0.175	0.004	ND	0.233	0.010	ND	0.978	0.05	0	6.45
Orthophosphate	0.005	0	0.018	0.002	ND	0.158	0.002	ND	1.818	0.002	ND	1.234	0.05	0	1.48

[1] Data from Smith et al. 2013

[2] Data from Whitall et al. 2013

Abbreviations: NO_3 nitrate, NO_2 nitrite, NH_4 ammonium, ND not detected

Fig. 2 Nitrate and nitrite concentrations versus rainfall in Benner Bay
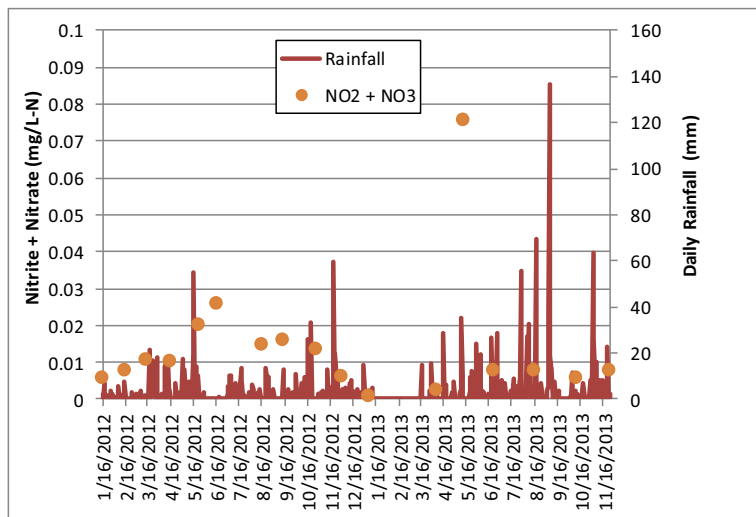
Lapointe (1997) suggested nutrient thresholds for marine waters, above which macroalgae and phytoplankton may be more likely to flourish on coral reefs, in the greater Caribbean. While the concept of nutrient thresholds for reefs have been debated in the literature, the thresholds proposed by Lapointe (1997) could be useful in identifying or targeting areas for closer scrutiny, to assess whether nutrients may be impacting corals in an area. The thresholds include orthophosphate (0.003 mg/L as P) and dissolved inorganic nitrogen (DIN, 0.014 mg/L as N). DIN is the summation of nitrate, nitrite, and ammonium.

Using the values proposed by Lapointe (1997), approximately 60% of the samples analyzed from STEER were above the threshold for orthophosphate. For DIN, the mean exceedance across STEER was 55%.

Sedimentation

For all sites, terrigenous material was the dominant fraction, accounting for 60 to 70% of total sediment in the traps, highlighting the role of terrestrial inputs to STEER. The percent terrigenous material in the sediment traps in STEER was significantly higher (chi-square = 38.9661, $p < 0.0001$) in both Mangrove Lagoon and Benner Bay compared to the other locations in STEER (Table 2). In addition to fresh inputs from the surrounding watershed, resuspended bed sediments from within STEER can enter the traps as well, from storms (wave and wind activity) or from boat traffic in shallower areas such as Benner Bay.

The mean accumulation rate varied by site (chi-square = 71.0320, $p < 0.0001$), and the rate in the Benner Bay sediment traps (9.02 mg/cm^2/day) was significantly higher than the trap accumulation rates at all other sites in STEER (Table 2). The mean terrigenous accumulation rate (6.45 mg/cm^2/day) was also higher (chi-square = 70.2037, $p < 0.0001$) in Benner Bay than the other sediment traps in STEER, including Mangrove Lagoon (Table 2). Although Mangrove Lagoon receives input from Turpentine Gut, the only perennial stream on St. Thomas, the highest rate of terrigenous sediment input into the sediment traps occurred in Benner Bay.

There were two likely sources of input to the traps placed in Benner Bay: terrestrial materials washed off the roads and hillsides from the surrounding landscape, and resuspended sediments from within Benner Bay. The hillsides in the watershed surrounding Benner Bay are fairly steep, with shallow soils, and insufficient ground cover. These factors, along with construction activities, and periodic torrential downpours, can lead to the transport of soils into STEER (HWG 2013). Pait et al. (2013) found that sediments in northern Benner Bay had some of the highest silt and clay fractions (31–56%) in STEER. Silt and clay sediments are typically derived from terrestrial sources. Sediment coring in northern Benner Bay by NCCOS in 2013 (Hartwell et al. 2016) as part of the larger project in STEER, revealed a thick layer of silt and clay over a deeper layer of shell hash, indicating that likely changes in land use over time have resulted in higher amounts of terrigenous materials being accumulated in that part of STEER.

A non-parametric analysis revealed a significant negative correlation (Spearman's Rho = − 0.6686, $p <$ 0.0001) between longitude and mean trap accumulation rate, and between the terrigenous accumulation rate and longitude (Spearman's Rho = − 0.6625, $p < 0.0001$), indicating that moving east to west, the deposition rate of terrigenous sediments tended to increase. There was also a significant (Spearman's Rho = 0.5047, $p < 0.001$) positive correlation between latitude and mean trap accumulation rate, along with the terrigenous accumulation rate, indicating that deposition tended to increase moving towards the island of St. Thomas.

The results from STEER can be compared with other recent work in the US Caribbean. The mean terrigenous accumulation fraction in sediment traps found by Sherman et al. (2013) within Guanica Bay Puerto Rico was roughly 58%, somewhat similar to what was found in STEER; however, outside of Guanica Bay, the percent terrigenous fraction was only 24%. As noted, the mean percent terrigenous sediment in the traps in STEER was higher, approximately 66% terrigenous and 20% carbonate. Within STEER, Mangrove Lagoon (73%) and Benner Bay (71%) were even higher. Working in St. John, Gray et al. (2012) found that terrigenous input into the sediment traps in Coral Bay located near the shore accounted for 56%. Out on the reefs in Coral Bay, that value fell to roughly 21%.

As with nutrients, there did not appear to be a good correlation between sediment deposition and rainfall. A plot of the terrigenous accumulation rate showed similar results. Non-parametric Spearman's analyses of the results between sedimentation and daily (Spearman's Rho = 0.0124, $p = 0.9005$) and monthly (Spearman's Rho = − 0.0747, $p = 0.4490$) rainfall (Cyril E. King Airport) failed to show any significant relationship, either across STEER or for each site. On the northwestern coast of St. Thomas, Nemeth and Nowlis (2001) found that sedimentation closely tracked rainfall during a period of early construction at a new resort near Caret Bay; however, once the earth-moving phase had been completed, that relationship disappeared, resulting in an overall lack of significance between rainfall and sedimentation during their study. In STEER, it would likely take sustained rainfall over a period of days in order to alter the amount of sediment accumulating in the traps from surface water runoff, and so correlations with daily rainfall might not be particularly useful. However, monthly rainfall amounts did not correlate with the sediment deposition rates either. It may be that other factors are also involved, including increased wave action resuspending sediments already within STEER.

Plots of sediment deposition over time, both in terms of percent deposition and by sedimentation rate for three of the sites in STEER are shown in Fig. 3. The other sites from this study can be found in Pait et al. (2015). It can be seen that the percent contributions from terrestrial, carbonate, and organic sources were fairly constant over time for both Mangrove Lagoon (Fig. 3a) and Benner Bay (Fig. 3b). In both cases, terrigenous material was the major component (~ 70%) found in the sediment traps. The lack of substantial variation in the sources (terrestrial versus carbonate) in Mangrove Lagoon and Benner Bay sediment traps, could indicate a continuous input of terrestrially derived sediments into the traps at these two sites from a combination of new inputs, resuspension of sediments from storms, tides and boats, or a combination of these phenomena. The right hand side of this figure shows the sedimentation rate ($mg/cm^2/day$). For Mangrove Lagoon (Fig. 3d) and Benner Bay (Fig. 3e), there is substantial variation in the rate of terrigenous and carbonate deposition (organic material can be derived from terrestrial or marine sources) over time. In March 2012, there was a sharp increase in the terrigenous fraction found in the sediment traps in Mangrove Lagoon (Fig. 3d). Specifically, the rate increased from 2.79 to 6.10 $mg/cm^2/day$, a factor of 2.18. However, at the same time, the carbonate deposition rate went from 0.141 to 0.456 $mg/cm^2/day$, a factor of 3.23, higher than the rate increase for the terrigenous fraction. While the increase in the terrigenous sediment deposition rate could be related to rainfall during this period, other factors such as the movement of tides and winds, leading to a resuspension of sediments cannot be ruled out. In addition, there does not appear to be a corresponding increase in the rate of sediment deposition in the adjacent Benner Bay site in March 2012, as might be expected if rainfall had resulted in higher surface water runoff from the steep hillsides, carrying terrestrially derived materials into STEER.

For Little St. James (Fig. 3c), percent deposition appeared more variable and could be related to weather and wave patterns. In Fig. 3f, it can be seen that there was a spike in terrigenous, organic and carbonate deposition into the Little St. James sediment traps sampled in September 2012. In August 2012, sediment traps in STEER were sampled around the middle of the month. In late August 2012, Hurricane Isaac (noted on Fig. 3f) passed to the south of the USVI. While there was not a substantial amount of rainfall associated with this storm,
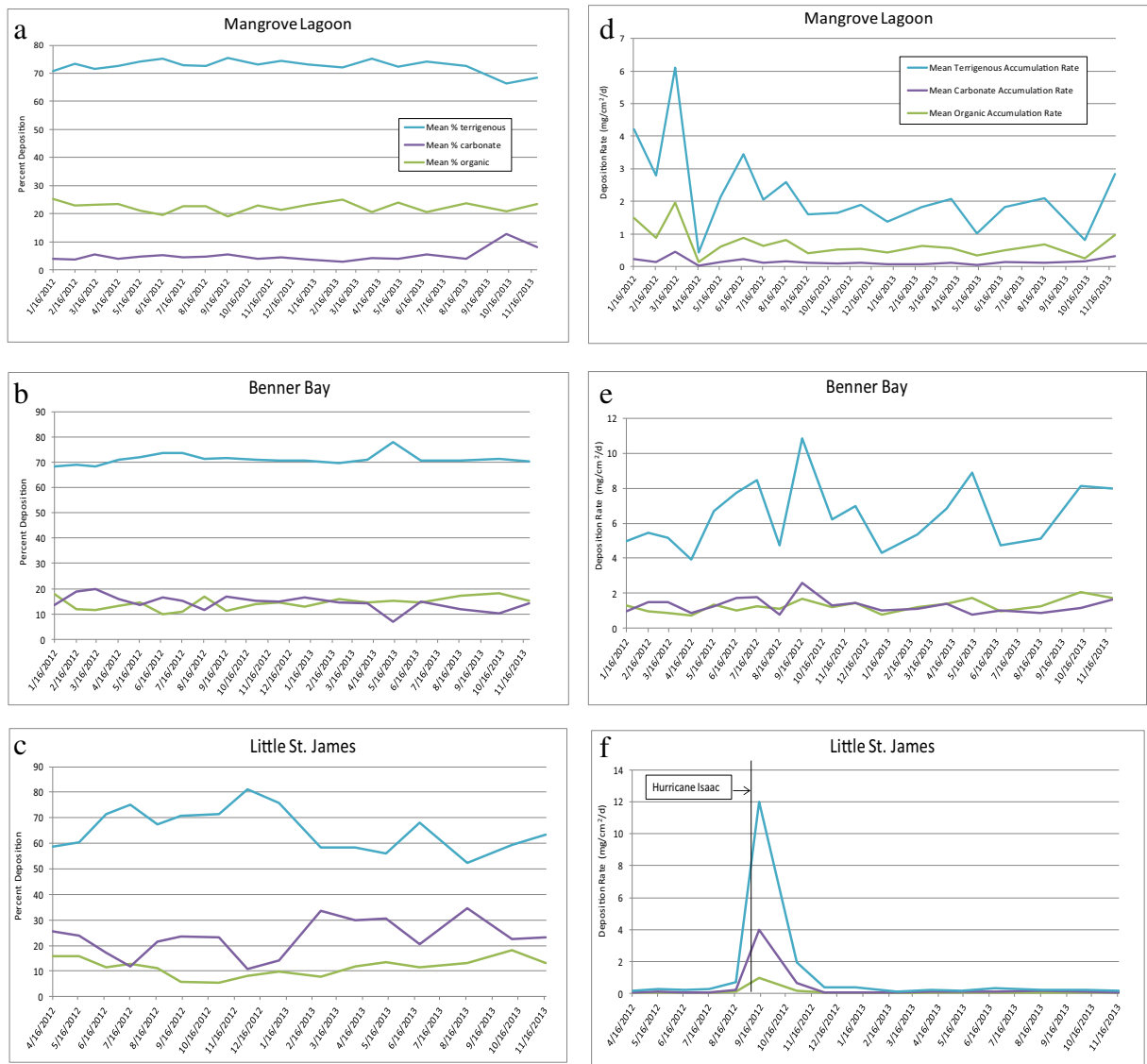
Fig. 3 Percent and rates of deposition for terrigenous, carbonate and organic materials in the sediment traps in the STEER over time for Mangrove Lagoon (**a**, **d**), Benner Bay (**b**, **e**), and Little St. James (**c**, **f**)

wave height increased to nearly 4 m at a wave station just south of St. John (Pait et al. 2015) and likely contributed to the increased sedimentation rate in the traps retrieved in September.

Finally, Rogers (1990) suggested that sedimentation rates above 10 mg/cm^2/day were high, and that heavy sedimentation is associated with impacts to the structure and function of coral reefs. Research by Smith et al. (2008) and Nemeth and Nowlis (2001) have shown this value may be useful at least in the USVI. None of the sites in this study had a mean rate above this, although

Benner Bay (9.02 mg/cm^2/day) was close. There were nine occasions during the course of the monthly monitoring when a site exceeded this value. Benner Bay exceeded the threshold on six occasions, and Rotto Cay, St. James (September 2012), and Little St. James (September 2012) each exceeded the threshold once. Additional work is needed to better describe sedimentation throughout Benner Bay and to assess where sedimentation should be reduced. In addition, it would also be useful to understand the association between coral species richness/diversity and sedimentation in Benner

Bay and throughout the Reserves, in order to assess how sedimentation may be affecting the distribution of individual coral species.

Conclusions

The results from this part of the STEER integrated assessment project involving NOAA and local partners, indicated elevated levels of nutrients in the western portion (Mangrove Lagoon and Benner Bay) of STEER. These areas contain higher densities of residential housing, most of which have septic systems, and many that are likely failing (HWG 2013). There is also a horse racetrack and the Bovoni Landfill adjacent to Mangrove Lagoon, as well as live-aboard boats in Benner Bay, all of which likely contribute to higher concentrations of nutrients in this part of STEER. Ammonium, nitrite, and dissolved inorganic nitrogen (DIN) were higher in Benner Bay and Mangrove Lagoon than the other sites in STEER. For DIN, both Mangrove Lagoon and Benner Bay had significantly higher levels than the other four sites.

A significant relationship between rainfall and nutrients, although expected, was not found. Because there are no active stream gauges in the watershed draining to STEER, rainfall was used a proxy for streamflow. The reason for the lack of correlation between rainfall and nutrients was not clear.

Nutrient values in STEER appeared slightly higher than in St. John and St. Croix, USVI. Approximately, 60% of the nutrient samples analyzed from STEER were above a proposed threshold (Lapointe 1997) for coral reefs for orthophosphate, with a slightly higher number within the western portion of the study area. For DIN, the mean exceedance across STEER was 55%.

Results from the monitoring of sedimentation indicated that terrigenous material accounted for roughly 60–70% of the material found in the sediment traps, highlighting the role of terrestrial inputs to STEER. The percent terrigenous material in the sediment traps was higher in the western portion of the study area, particularly in Benner Bay, compared to other locations in STEER. It is likely that in addition to inputs of sediment from the surrounding watershed, resuspended sediments as a result of storm (wave and wind activity) or boat traffic (Benner Bay) are likely contributing to the material found in the traps as well.

The average daily accumulation rates in the sediments traps were higher in Benner Bay then at all the other sites in STEER, including Mangrove Lagoon. As with nutrients, there did not appear to be a good correlation between sediment deposition and rainfall. A stream gauge in the watershed would help with understanding the relationship between streamflow, rainfall, and sediment delivery.

None of the sites monitored in STEER had an average sediment deposition rate above the "normal" value for coral reefs (10 mg/cm^2/day, Rogers 1990), although Benner Bay (9.02 mg/cm^2/day) was fairly close. Additional work is needed to better understand the patterns and possible effects of sedimentation throughout Benner Bay, including associations between coral species richness/diversity and sedimentation.

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