Terrestrial Sediment Delivery and Nearshore Water Turbidity – A Case Study From the East End of St. Croix, USVI

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Abstract

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Section 303(d) of the Clean Water Act and the U.S. Environmental Protection Agency's (EPA's) Water Quality Planning and Management Regulations (40 CFR Part 130) require states to develop Total Maximum Daily Loads (TMDLs) for waterbodies that are not meeting their designated uses. In October 2010 EPA published a list of impaired and threatened waters in the USVI that are targeted for the development of future Total Maximum Daily Load (TMDL) limits. The most common reported causes of impairment in near-shore waters were sedimentation, effluent discharges, dissolved oxygen (DO) deficiencies and bacterial contamination (US EPA, 2010). Of the 33 listed sites for St. Croix, 28 or 85% of the reported impairments were associated with high turbidity.

Although increased turbidity, primarily associated with terrestrial sediment delivery, is consistently reported as primary cause of impairment and is an imminent threat to marine ecosystems, very little quantitative data is available. Here, instrumentation designed to collect water quality data was deployed in Boiler Bay to characterize two types of water quality conditions; 1) during dry conditions when no runoff was occurring from the watershed and 2) during sedimentation events resulting from terrigenous inputs (an eroding trial) when runoff was discharging into the bay. Data were collected in high-resolution temporal scales (2 – 5 minute intervals) to characterize the magnitude and duration of changes in water quality during a sedimentation event.

To develop baseline, ambient water quality characteristics in the bay, temperature, DO, pH, salinity and turbidity were collected during two sampling periods, (May 18–November 23, 2012 & April 20–November 4, 2013). Mean values and standard deviations over the two study periods for temperature, DO, pH, turbidity, and salinity were, 28.6 ± 0.4 °C, 6.7 ± 0.7 mg/L, 8.0 ± 0.1, 0.50 ± 0.5 NTU, and 36.1 ± 0.7 ppt, respectively.

In September 2013, Tropical Depression Gabrielle provided the conditions (rainfall magnitude, duration and intensity) that were needed to generate runoff on the eroding trail, which produced a sedimentation event in Boiler Bay. The sediment plume peaked in turbidity at 19.0 NTU. Turbidity remained above the regulatory limit of 3.0 NTU for a continuous 2.5-hour period during the sedimentation event, however NTUs greater than 3.0 occurred intermittently for a 5–6 hour period. Turbidity exceeded 3.0 NTU 105 times, or 24.25% of the time in a 14-hour period (Sept. 6, 0:00:00–14:00:00) following two consecutive hours of rainfall with 1-hr intensities of 4.10 and 4.00 cm/hr. Mean turbidity during the 14-hr period was 2.27 NTU, which was 4.54 times higher than mean turbidity over the study period (0.50 NTU). Turbidity in the bay remained above 0.50 NTU for 81.5% of the time during the 14-hr period.

Results from this study underline the importance of sustaining efforts to upgrade and enforce water quality regulations in the region. Elevated erosion rates observed in the rather arid and pristine east end of St. Croix from a small eroding trail suggest an even greater need for caution and required use of BMPs in the steeper and wetter areas of the USVI and PR, where dirt roads and coastal development continue to expand.
Disclaimer

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1. Introduction
Increased anthropogenic sources of terrestrial erosion have long since been identified as a major factor in water quality and aquatic ecosystem degradation worldwide (Cyrus & Blaber, 1987; Fabricus, 2005; Hutchings, et al., 2005; Crain, et al., 2009; Burke, et al., 2011). Within the Caribbean Region, a decline in live coral cover has been in part attributed to increased sedimentation from land-based sources of pollution that typically accompanies development (Rogers, 1990; Gardner, et al., 2003; Mora, 2007; Rothenberger, et al., 2008). In the U.S. Virgin Islands (USVI) terrigenous sources of sediment also consistently ranks among the greatest threats to coral health (Rogers, et al., 2008; Jeffrey, et al., 2005; Territory of the USVI & NOAA-CRPP, 2010).

Over the past five to six decades, the USVI and Puerto Rico (PR) have experienced rapid coastal development and a growing network of unpaved roads, which contribute to the increase in sediment loading into the surrounding bays (Johnston, 1987; Valdez-Pizzini, et al., 1988; MacDonald, et al., 1997; Oliver, et al., 2012). Landscapes in the USVI and PR are often well connected to seascapes, which have only exasperated these problems. Studies in Puerto Rico found that coral reef degradation is widespread in waters surrounding the island and is generally greatest offshore from watersheds with the greatest amount of urbanization (Larsen & Webb, 2009). Other studies have begun to address the need for empirical data by quantifying the effects of land development on plot- and hillslope-scale sediment production rates in Puerto Rico and throughout the USVI (Ramos-Scharrón and MacDonald, 2005; Gellis, et al., 2006; Ramos-Scharrón, 2010; Ramos-Scharrón, et al., 2014). One study found that the measured and predicted erosion rates indicated that roads are capable of increasing hillslope-scale sediment production rates by up to four orders of magnitude, relative to undisturbed conditions (Ramos-Scharron and MacDonald, 2007a). Another study supports these findings by indicating that relatively undisturbed, vegetated hillslopes on St. John generate runoff only during the largest storm events, and produce very little sediment (MacDonald, et al., 2001; Ramos-Scharron & MacDonald, 2007b).

Studies conducted in the USVI show a clear and significant onshore-offshore sedimentation gradient; nearshore sedimentation rates were six times greater than at mid-shelf reefs, and nearly 50 times greater than at offshore reefs (Rothenberger, et al., 2008). Studies relating landscape development intensity to nearshore coral reef condition in St. Croix found a negative correlation between taxa richness, colony size, colony density and anthropogenic activities (Oliver, et al., 2012). Single-year sedimentation studies conducted in St. John imply that current sediment settling rates at the bottom of bays impacted by development are between 3 and 73 times above undisturbed conditions (Gray, et al., 2008). Furthermore, a similar onshore to offshore gradient was also found in a number of coral health indices, including bleaching prevalence and percentage of old mortality, indicating that sediment deposition may be in part, adversely affecting coral condition (Rothenberger, et al., 2008). It is apparent that clean, clear water is critical to maintaining healthy coral communities and sustaining ecological integrity (Jeffrey, et al., 2005).

Section 303(d) of the Clean Water Act and the U.S. Environmental Protection Agency's (EPA's) Water Quality Planning and Management Regulations (40 CFR Part 130) require states to develop Total Maximum Daily Loads (TMDLs) for waterbodies that are not meeting their designated uses. In October 2010, EPA published a list of impaired and threatened waters in the
USVI that are targeted for the development of future Total Maximum Daily Load (TMDL) limits. The most common reported causes of impairment in near-shore waters were sedimentation, effluent discharges, dissolved oxygen (DO) deficiencies and bacterial contamination (US EPA, 2010). Of the 33 listed sites for St. Croix, 28 or 85% of the reported impairments were associated with high turbidity.

The government of the USVI approved legislature that allocated 155.4 km² of offshore marine habitat to the St. Croix East End Marine Park (STXEEMP) to protect the largest island barrier reef system in the Caribbean, which was incorporated into a marine protected area (MPA) in 2003 (DPNR, 2008). Federal and territorial coastal managers consider the watersheds that drain into the STXEEMP to be priorities for protection and restoration (Horsley Witten Group, Inc., 2011). The study presented here was located on the small watershed that discharges into Boiler Bay, St. Croix, USVI, which is located within the STXEEMP. A 180-m long eroding trail has been identified as a chronic source of erosion and sedimentation in Boiler Bay. Recent studies have estimated that the existing trail is capable of delivering 2 metric tons of sediment annually into the Bay (Reale-Munroe, et al., 2011). Boiler Bay is comprised of an array of different aquatic habitats, (seagrass beds, linear reef, sand patches, etc.) which contain protected and endangered species (sea turtles, coral, etc.). Understanding the factors governing erosion and sedimentation in this area is important not only for TMDL development, but also for mitigating the impacts on the existing marine ecosystem.

Although terrestrial erosion and water quality impairments, due to high turbidity are consistently reported as imminent threats to marine ecosystems, very little quantitative data is available. Here, instrumentation designed to collect water quality data was deployed in Boiler Bay to characterize two types of water quality conditions; 1) during dry conditions when no runoff was occurring from the watershed and 2) during sedimentation events resulting from terrigenous inputs (the eroding trial) when runoff was discharging into the bay. Data were collected in high-resolution temporal scales (2–5 minute intervals) to characterize the magnitude and duration of changes in water quality during a sedimentation event.

1.1. Objectives

- To determine ambient marine water quality parameters during dry conditions with no terrestrial inputs from runoff, and
- To assess the magnitude and duration of turbidity during a sedimentation event in Boiler Bay.

2. Site Description
The study site was located on the northeastern side of St. Croix, US Virgin Islands (Lat: 17° 45.552'N; Long: 64° 34.511'W) within the small, approximately, 0.56 km² (0.22 mi²) subtropical watershed that drains into Boiler Bay (Figure 1). Two prior VI-WRRI funded projects have been conducted at this location, (Reale-Munroe, et al. 2010; Reale-Munroe, et al. 2011) where a more comprehensive description of the topography, geology, soils, climate, and vegetation cover can be found.

An abandoned dirt road that is currently used as a foot trail is contributing sediment-laden runoff directly into Boiler Bay. Boiler Bay is a nearshore, open coastal waterbody that is located within a protected, no-take management zone of the STXEEMP (Horsley Witten Group, Inc., 2011). Boiler Bay is comprised of class B waters (DPNR, 2010). Class B waters have been designated "for maintenance and propagation of desirable species of aquatic life (including threatened & endangered species listed, pursuant to section 4 of the federal Endangered Species Act and threatened, endangered and indigenous species listed pursuant Title 12, Chapter 2 of the Virgin Islands Code and for primary contact recreation (swimming, water skiing, etc.) (DPNR, 2010). The bay is not directly impacted by any additional anthropogenic sources of pollution-residential, industrial or otherwise (Figure 1).

Boiler Bay is partially protected by a barrier reef that runs less than 0.25 mile off shore. The area is rich in coral and algal reefoid populations, seagrass beds, and sand chutes (Adey, et al., 1977; Pittman, et al., 2013). The array of aquatic habitats found in Boiler Bay and the rest of STXEEMP support and contain protected and endangered species (sea turtles, coral, etc.) (Horsley Witten Group, Inc., 2011; Pittman, et al., 2013). The ocean current velocities in Boiler Bay run swiftly in a general east to west direction and have good connectivity to the open ocean. Water depths range from approximately 0.25–30 m (0.8–30 ft), with very shallow seagrass beds nearest to shore and hardbottom, sand patches and patch reef communities in the deeper depths as you move towards the fore reef from shore.
Figure 1 Map showing the study site and locations of the rain gauge, sonde and sediment traps (WRRI-B, WRRI-D and WRRI-K).
3. Methods

Methods consisted in monitoring rainfall, quantification of sediment contribution from the trail based on previously collected data, and marine water quality monitoring. A more extensive explanation of the methods, designs and terrestrial monitoring plan can be found in (Reale-Munroe, et al., 2010; Reale-Munroe, et al., 2011). Specific methods applied to this study are outlined below. Rainfall and water quality data were collected over two study periods during 2012 and 2013.

3.1. Precipitation

3.1.1. Onsite Rain Gauge

A HOBO RG3-M Data Logging Rain Gauge system equipped with a HOBO® Pendant Event data logger was installed onsite in May 2012. Data were recorded by the data logger with each tip of a tipping bucket mechanism, which had a resolution of 0.2 mm of rainfall and a maximum rainfall rate of 127 cm/hr. The data were used to determine 1-hr rainfall intensities, to calculate total rainfall for storm events and to summarize monthly rainfall during December 2012–November 2013. The rain gauge was placed on top of a knoll draining to the eroding trail (Lat: 17° 45.532’N; Long: 64° 34.431’W) at an elevation of 15.2 m (50 ft) (Figure 2). Data was downloaded approximately once a month using associated software (HOBOware Pro Mac/Win,) an optic USB Base Station and a HOBO® Waterproof Shuttle in accordance with the user manual. Data collected from the onsite datalogger was intermittent during April–November of 2012, due to technical difficulties and was replaced with data collected at the Very Long Baseline Array (VLBA) weather station.

3.1.2. VLBA Weather Station

Weather data was provided by the National Radio Astronomy Observatory (NRAO), which was collected at the Very Long Baseline Array (VLBA) and used for the first 8 months of the study (April–November 2012). Data were collected in 8 minute intervals with a resolution of 0.1 mm and were also used determine 1-hr rainfall intensities, to calculate total rainfall for storm events and to summarize monthly rainfall. The VLBA is located on Route 82, opposite of Cramers Park (Lat: 17 45.378’ N; Long: 64 35.044’ W) with an elevation of approximately 13.1 m (43 ft.). The VLBA is approximately 1.03 km (0.64 mi) southwest of Boiler Bay (Figure 2).

3.1.3. Cotton Valley Station

Thirty-year long-term average rainfall data were obtained to compare relative monthly and seasonal differences observed in Boiler Bay over the study period. Long-term average rainfall values were obtained from the Cotton Valley 2 station (COOP ID: 671810), which were reported in NOAA (2002). The Cotton Valley 2 station is located about 4.51 km (2.80 mi) west of Boiler Bay (Lat: 17° 45.599’N, Long: 64° 37.000’W) with an approximate elevation of 42.7 m (140 ft.) (Figure 2).
3.2. Terrestrial Erosion

As part of a previous study, filter-fabric sediment traps (see description in Ramos-Scharrón et al., 2014) were used to collect sediment from the trail leading to Boiler Bay to determine trail erosion rates with units (kg m\(^{-2}\) yr\(^{-1}\)). The collected sediment was processed to obtain an observed mass of sediment transport per area per unit time over two study periods, which is outlined in detail in the methodology sections of the following final reports (Reale-Munroe, et al. 2010; Reale-Munroe, et al. 2011).

3.2.1. Areally-weighted Erosion Rate Calculations

To link rainfall events in this study to erosion rates in the previous studies erosion rates were instead expressed as a function of precipitation with units (kg m\(^{-2}\) cm\(^{-1}\)). To estimate the sediment yield during sedimentation events in this study, erosion rates were calculated as areally-weighted averages, which considers the erosion rates as a function of the total area that each sediment trap collected sediment from. For instance, the sediment trap WRRI-B had the largest catchment area of 410 m\(^2\), which equates to 86% of the total eroding trail surface leading down to the bay, yet it had the smallest erosion rate. On the other hand, WRRI-K had the smallest catchment area, 19.5 m\(^2\) and the largest erosion rate (Table 1). The calculation integrates these differences according to how large an area each erosion rate represents (Figure 3).
Areally-weighted erosion rates were calculated as:

\[ Er_{\text{area}} = M \cdot L^{-2} \cdot A\% \cdot L^{-1} \]

where the unit erosion rate, \( Er_{\text{area}} \) is the measured rate of removal of rock and soil from the land surface per unit area multiplied by the relative percent each area represents per unit precipitation. This calculation results in the units (kg m\(^{-2}\) cm\(^{-1}\)).

![Figure 3 Catchment areas used to determine areally-weighted erosion rate calculations.](image)

### 3.3. Water Quality

#### 3.3.1. Data Collection and Regulations

Water quality data were collected during two study periods, May–November 2012 and April–November 2013. Data were collected every month during the May–November, 2012 study period. During the second study period (April–June, September and November, 2013), data were collected intermittently, only during storm events in hopes to capture sedimentation events.

A YSI 6920 V2 multiparameter, water quality logging system (sonde) was used for long-term, *in situ* monitoring of Boiler Bay. The sonde was configured to log data in 2–5 minute intervals. The sonde was mounted in a PVC case on a rebar structure (Figure 4). The sonde was mounted approximately 70 m northeast of where runoff from the trail enters the bay. The sonde was mounted approximately 0.5 m from the surface and the bottom (total water depth ~1.0 m) (Lat: 17° 45.606'N; Long: 64° 34.537'W).
Figure 4 YSI 6920 V2 multi-parameter, water quality logging system (sonde) used for long-term, *in situ* monitoring of Boiler Bay.

The sonde was used to characterize water quality parameters during ambient conditions (no terrestrial runoff) and during sedimentation events (with terrestrial runoff). Probes designed to measure water temperature, dissolved oxygen (DO), salinity, pH and turbidity were selected for this study and are defined below:

- **Temperature/Salinity.** Temperature and salinity (derived from conductivity) were both measured using the probe, Model 6560. Temperature is reported here in degrees Celsius (°C) and salinity in parts per thousand (ppt). Temperature is often used as an indicator of aquatic health and processes such as photosynthesis, respiration, changes in community composition, etc. (SOER, 2009a). Changes in salinity are often used to assess the quality of stormwater flow; industrial discharges and is indicative of evaporation and terrestrial freshwater inflow (NERRS, 2014).

- **Dissolved oxygen.** The 6150 ROX Optical DO sensor was used, which uses light wavelength and partial pressure methodology to determine DO in a solution (YSI, 2014). Dissolved oxygen is reported here in units of milligram per liter (mg/L). Dissolved oxygen is an important indicator of water quality as oxygen is essential for all aquatic ecosystems (SOER, 2009b; NERRS, 2014).
• Acidity. A pH electrode probe, Model 6561 was used to measure changes in hydrogen ion concentration in the bay. Variations in pH often indicate changes in primary production and respiration, which can be affected by significant sediment input (SOER, 2009c; NERRS, 2014).

• Turbidity. The Model 6136 optical probe was used to measure the scattering of light off suspended solids (turbidity) in the water column (YSI, 2014). Values are reported in nephelometric turbidity units (NTU). Changes in turbidity resulting from terrestrial sources are indicative of erosion and sediment inputs, which can affect the clarity and quality of receiving water bodies (cite SOER, 2009d; NERRS, 2014).

Data collected were compared to territory water quality regulations. Boiler Bay has been classified as ‘Class B’ waters, where temperature is not to exceed 32 °C, DO is not to fall below 5.5 mg/L, pH is to fall within 7.0–8.3, turbidity is not to exceed 3 NTU and no limits are defined for salinity (Table 1).

Table 1 Regulatory limits for temperature, DO, pH and turbidity for Class B waters. Table adapted from DPNR, 2010.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Class A</th>
<th>Class B</th>
<th>Class C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
<td>In no case shall Class B water quality standards be exceeded.</td>
<td>Not to exceed 32° C at any time</td>
<td>Same as Class B</td>
</tr>
<tr>
<td><strong>Dissolved O2</strong></td>
<td>In no case shall Class B water quality standards be exceeded.</td>
<td>Not &lt; 5.5 mg/l from other natural conditions</td>
<td>Not &lt; 5.0 mg/l from other natural conditions</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td>In no case shall Class B water quality standards be exceeded.</td>
<td>&lt; 8.3 Tolerable Limit&gt;7.0</td>
<td>&lt;8.5 Tolerable Limit&gt;6.7</td>
</tr>
<tr>
<td><strong>Turbidity</strong></td>
<td>In no case shall Class B water quality standards be exceeded.</td>
<td>A maximum nephelometric turbidity unit (NTU) reading of three (3)</td>
<td>Same as Class B, but no NTU standard in Rules &amp; Regulations</td>
</tr>
</tbody>
</table>

3.3.2. Data Quality Assurance and Post-processing

The sonde was retrieved approximately 2-3 times a month for data download, cleaning, maintenance and calibration with standard solutions in accordance with the user manual (YSI, 2014). Long term in situ monitoring of turbidity tends to be problematic and an array of quality assurance and control (QA/QC) procedures have been used by others to ensure that anomalies and spurious data are corrected prior to analysis (CDM, 2009; Horsburgh, et al., 2010; Rasmussen, et al., 2011; Zhu, et al., 2008).

All data for this study were assessed to detect erroneous data. No corrective measures were taken for temperature, DO, pH or salinity. Turbidity data experienced interference from fouling and
anomalous data spikes that required post-processing. To validate the quality of the turbidity data, it was crosschecked with daily and antecedent hourly rainfall, conductance and temperature to correct invalid data and to determine true sedimentation events.

Two types of data were omitted from the turbidity datasets prior to use in the analysis:

1. Fouled sensor data. Steady increases in turbidity readings near the end of datasets often resulted due to disruption in the optical readings from fouling, despite a built-in sensor wiper. Increases also can arise due to sensor drift in between re-calibration times.

2. Isolated spikes. Spikes occurred as a result of interference from marine life and large particles or debris near the sensor during data logging intervals, even with the use of a protective cage.

Once erroneous turbidity data were identified and crosschecked with antecedent precipitation, conductance and temperature, they were processed based on the set of parameters outlined below.

- Calibration accuracy. If the turbidity value was less than 0 (margin of calibration error) then the negative value was assumed to be 0 NTU.

- Daily antecedent precipitation. If precipitation was less than 0–2.00 cm (0–0.79 in) during a previous 24-hour period and a turbidity value was greater than 5 NTU, then that value was omitted, i.e., not used as part of the dataset.

- Hourly antecedent precipitation. If a turbidity value was greater than 5 NTU and there was less than 2.00 cm in five antecedent hours, then the value was also omitted.

A 5 NTU threshold during periods of no terrestrial runoff was chosen based on averaging 24-hour means of each dataset directly following cleaning, calibration and re-deployment of the sonde. Anomalous data spikes and fouling were minimal during the first 24 hours of data logging, as new recruits of juvenile fish, octopus, algae, etc. had not settled in yet. Based on the 24-hour subsets of data, NTU values rarely were greater than 1 NTU and never exceeded 2 NTU. Although Boiler Bay is classified as Class B waters, which have a maximum of 3 NTU, a maximum criterion of 5 NTU was selected to account for potential natural variation.

A rainfall intensity of 2.00 cm/hr (0.79 in/hr) for five antecedent hours was determined by analyzing observed precipitation events required to generate runoff at Boiler Bay. On several occasions 1-hr rainfall intensities ranging between 1.00–2.00 cm/hr occurred with no observed runoff from the watershed and no increase in water turbidity:

- September 13, 2012: 1.12 cm/hr,
- November 7th, 2012: 1.90 cm/hr, followed by 1.00 cm/hr, and
- June 19th, 2013: 1.10 cm/hr.

On two occasions, 1-hr intensities greater than 2.00 cm/hr generated runoff on the trail, however they did not result in significant terrestrial delivery into the bay.
1. On May 4, 2013, three consecutive hours of rainfall with 1-hr intensities, 2.14, 1.9 and 3.14 cm/hr resulted in terrestrial runoff with volume and velocities needed to push through the beach berm separating the watershed from the bay. Peak turbidity values reached 5.60 NTU.

2. On Sept. 5, 2013 (TD Gabrielle), 2.14 cm/hr followed by 0.88 cm/hr generated runoff from the watershed, creating a pool of water at the base of the trail on the beach, however it did not completely flush the beach out and connect with the bay. Peak turbidity from this event was 3.20 NTU.

Based on these events, it was determined that at least 1-hr rainfall intensities of 2.00 cm/hr were needed to produce runoff from the watershed and discharge into Boiler Bay.

4. Results and Discussion

4.1. Precipitation

Average annual rainfall at Boiler Bay was expected to be similar to that in Cotton Valley, which has a 30-yr mean of 72.6 cm/yr (28.6 in/yr) (NOAA, 2002). Monthly precipitation data was graphed in (Figure 5) along with the mean 30-yr Cotton Valley data (NOAA, 2002). A continuous 20-month record (April 2012–November 2013) of rainfall was recorded by the VLBA station and onsite rain gauges. Total precipitation over the 20-month period was 139 cm (54.7 in). Total precipitation between April and December 2012 was 10.6% lower than the long-term (30-yr) average at Cotton Valley. In contrast, 23% more rainfall than the 30-yr average at Cotton Valley was registered at Boiler Bay from January to November 2013. The National Weather Service (NWS) reported that 2012 ended as the eighth driest year on record at the Christiansted Airport, which generally receives more precipitation than the relatively drier east end of the island where Boiler Bay is located (NOAA, 2012). This study was intended to be completed in 2012, however due to the dry conditions we were unable to capture a single runoff delivery event between April-November 2012. An extension was granted to continue intermittent monitoring in 2013 (June– November), when storm events were expected to occur.
4.2. Terrestrial Erosion

Previous studies began to quantify the total sediment produced by the eroding trail at Boiler Bay in 2010, which suggested that the 478-m² trail surface produced 1,978 kg (4,361 lbs) of sediment over a one-year period (Reale-Munroe, et al., 2011). Based on sediment trap data, erosion rates were calculated and summarized in (Table 2). A normalized erosion rate (a function of precipitation) for the eroding trail surface in Boiler Bay was 1.0E-01 kg m⁻² cm⁻¹ (Reale-Munroe, et al., 2011).

Table 2 Summary data used to calculate total normalized erosion rates on the trail leading to Boiler Bay. Data adapted from (Reale-Munroe, et al., 2011).

<table>
<thead>
<tr>
<th>East End Bay Trap ID</th>
<th>Monitoring Period</th>
<th>Total Sed. Production (kg)</th>
<th>Catchment Area (m²)</th>
<th>Total Precip (cm)</th>
<th>Ave. Erosion Rate (kg m⁻² yr⁻¹)</th>
<th>Normalized Erosion Rate (kg m⁻² cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WRRI-D</td>
<td>4 June 2010 – 24 June 2011</td>
<td>937</td>
<td>48</td>
<td>181</td>
<td>1.9E+01</td>
<td>1.1E-01</td>
</tr>
<tr>
<td>WRRI-K</td>
<td>4 June 2010 – 24 June 2011</td>
<td>702</td>
<td>19.5</td>
<td>181</td>
<td>3.4E+01</td>
<td>2.0E-01</td>
</tr>
</tbody>
</table>

To estimate sediment yields produced by the trail and discharged into Boiler Bay during this study, the normalized erosion rates generated above in (Table 2) were modified to account for the percentage of sediment that each portion of the trail contributed, resulting in an areally-weighted erosion rate of 2.4E-02 kg m⁻² cm⁻¹(Table 3).
Table 3 Data used to determine an areally-weighted trail erosion rate in Boiler Bay.

<table>
<thead>
<tr>
<th>Boiler Bay Trap ID</th>
<th>Source area (m²)</th>
<th>Normalized Ave. Er Rate (kg m² cm⁻¹)</th>
<th>Percent of trail surface area (%)</th>
<th>Ave. Er * % Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>WRRI-B</td>
<td>410</td>
<td>9.3E-01</td>
<td>86</td>
<td>5.3E-03</td>
</tr>
<tr>
<td>WRRI-D</td>
<td>48.0</td>
<td>1.9E+01</td>
<td>10</td>
<td>1.1E-02</td>
</tr>
<tr>
<td>WRRI-K</td>
<td>19.5</td>
<td>3.4E+01</td>
<td>4</td>
<td>8.1E-03</td>
</tr>
</tbody>
</table>

Areally-weighted Erosion Rate: 2.4E-02 kg m² cm⁻¹

The areally-weighted trail erosion rate calculated was compared to a study in East End Bay, St. Croix, USVI in (Table 4). The erosion rate observed on the actively used foot trail leading to Boiler Bay was found to be in the range of other actively used trails in East End Bay. The actively used foot trails in East End Bay with sparse vegetation were reported to have an erosion rate of 20 Mg ha⁻¹ yr⁻¹, while the trails with dense vegetation cover had an erosion rate of 6.6 Mg ha⁻¹ yr⁻¹ (Ramos-Scharrón, et al., 2014). The erosion rate determined for the sparsely vegetated trail surface in Boiler Bay was 13.5 Mg ha⁻¹ yr⁻¹, which was seemingly supported by the findings in East End Bay. The studies in East End Bay and Boiler Bay used analogous methodologies and were conducted in areas similar in climate, usage and topography, which allowed for a useful comparison.

Table 4 Comparison between Boiler Bay and East End Bay trail erosion rates.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Location</th>
<th>Location Description</th>
<th>Areally-weighted Erosion Rate</th>
<th>Common Units (Mg ha⁻¹ yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramos-Scharrón et al., 2014</td>
<td>East End Bay, St. Croix, USVI</td>
<td>Newly constructed, actively used foot trail, very sparse vegetation, 5 – 9% slopes</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Actively used foot trail, sparse vegetation, 14 – 21% slopes</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Actively used foot trail, dense vegetation, 14 – 19% slopes</td>
<td>6.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unused foot trail, dense vegetation, 16 – 21% slopes</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>This study</td>
<td>Boiler Bay, St. Croix, USVI</td>
<td>Actively used foot trail, sparse vegetation, 7 – 15% slopes</td>
<td>2.4E-02 kg m² cm⁻¹</td>
<td>13.5</td>
</tr>
</tbody>
</table>

4.3. Water Quality

4.3.1. Ambient Water Quality Parameters

Five water quality parameters: temperature, DO, pH, salinity and turbidity were collected in Boiler Bay during two sampling periods, (May 18–November 23, 2012 & April 20–November 4, 2013). Data were collected every month within the May 18–November 23 sampling period. Data were collected intermittently during the April 20–November 4, 2013 sampling period. Although Boiler Bay is located in a relatively pristine area with very little anthropogenic inputs other than the trail, it has been classified as ‘Class B’ waters where temperature is not to exceed 32 °C, DO
is not to fall below 5.5 mg/L, pH is to fall within 7.0–8.3, turbidity is not to exceed 3 NTU and no limits are defined for salinity.

A total of 45,687 data points were logged in 2–5 minute intervals over the two sampling periods for the following three parameters: temperature, DO, and salinity. Monitoring of pH did not begin until October 2011, resulting in 31,211 logged data points. Mean, minimum and maximum values were summarized by the corresponding months that the samples were logged, which are reported in (Table 5). Turbidity data were corrected for anomalous spikes and sensor fouling prior to analysis, reducing the number of samples from 45,687 to 39,190 (Table 6).

The minimum and maximum values for temperature, pH and salinity never fell below or exceeded acceptable regulatory limits, however, DO and turbidity data were noted to oscillate outside of the regulatory criteria (Tables 5 & 6). Dissolved oxygen (DO) concentrations fluctuated between 3.42–11.26 mg/L, with 96.8% of the measurements above the current regulatory limit of 5.5 mg/L. Processed turbidity data ranged from 0–19.0 NTU, with 98.5% of the values less than 3.00 NTU.

Table 5 Mean, minimum and maximum values for temperature, DO, pH and salinity during the two study periods in Boiler Bay.

<table>
<thead>
<tr>
<th>Monitoring Logged</th>
<th>Temp (°C)</th>
<th>DO (mg/L)</th>
<th>pH</th>
<th>Salinity (ppt)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Periods (Intervals)</td>
<td>Samples n</td>
<td>Mean</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>---------------------</td>
<td>-----------</td>
<td>------</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>May 18 – 27, 2012 (5-min. intervals)</td>
<td>2586</td>
<td>27.9</td>
<td>27.3</td>
<td>29.1</td>
</tr>
<tr>
<td>June 8 – 20, 2012 (5-min. intervals)</td>
<td>3441</td>
<td>28.9</td>
<td>27.9</td>
<td>30.1</td>
</tr>
<tr>
<td>July 6 – 17, 2012 (5-min. intervals)</td>
<td>3098</td>
<td>28.9</td>
<td>28.2</td>
<td>29.9</td>
</tr>
<tr>
<td>Aug. 13 – 18, 2012 (5-min. intervals)</td>
<td>1399</td>
<td>29.1</td>
<td>28.4</td>
<td>30.1</td>
</tr>
<tr>
<td>Sept. 1 – 14, 2012 (5-min. intervals)</td>
<td>3955</td>
<td>29.3</td>
<td>28.4</td>
<td>31.6</td>
</tr>
<tr>
<td>Oct. 1 – 9, 2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct. 12 – 25, 2012 (5-min. intervals)</td>
<td>7233</td>
<td>29.3</td>
<td>28.4</td>
<td>30.7</td>
</tr>
<tr>
<td>Oct. 27 – 31, 2012 (5-min. intervals)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov. 1 – 8, 2012 (5-min. intervals)</td>
<td>6149</td>
<td>28.8</td>
<td>28.2</td>
<td>30.1</td>
</tr>
<tr>
<td>Nov. 9 – 23, 2012 (5-min. intervals)</td>
<td>1176</td>
<td>26.7</td>
<td>26.0</td>
<td>27.6</td>
</tr>
<tr>
<td>April 20 – 24, 2013 (5-min. intervals)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May 2 – 6, 2013 (5-min. intervals)</td>
<td>5049</td>
<td>28.0</td>
<td>26.9</td>
<td>29.6</td>
</tr>
<tr>
<td>June 4 – 10, 2013 (5-min. intervals)</td>
<td>4515</td>
<td>28.0</td>
<td>27.3</td>
<td>29.2</td>
</tr>
<tr>
<td>June 19 – 29, 2013 (5-min. intervals)</td>
<td>3645</td>
<td>28.7</td>
<td>28.0</td>
<td>29.9</td>
</tr>
<tr>
<td>Sept. 4 – 9, 2013 (2-min. intervals)</td>
<td>3441</td>
<td>28.6</td>
<td>28.0</td>
<td>29.3</td>
</tr>
<tr>
<td>Total</td>
<td>45,687</td>
<td>28.5</td>
<td>6.70</td>
<td>7.90</td>
</tr>
</tbody>
</table>

Table 6 Mean, minimum and maximum values for turbidity data during the two study periods in Boiler Bay.
<table>
<thead>
<tr>
<th>(Intervals)</th>
<th>Samples (Processed Data)</th>
<th>(Processed Data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 18 – 27, 2012</td>
<td>2582</td>
<td>0.01 0.00 4.00</td>
</tr>
<tr>
<td>June 8 – 20, 2012</td>
<td>2683</td>
<td>0.73 0.00 4.90</td>
</tr>
<tr>
<td>July 6 – 17, 2012</td>
<td>1522</td>
<td>0.004 0.00 4.00</td>
</tr>
<tr>
<td>Aug. 13 – 18, 2012</td>
<td>681</td>
<td>0.013 0.00 3.00</td>
</tr>
<tr>
<td>Sept. 1 – 14, 2012</td>
<td>1359</td>
<td>0.30 0.00 4.80</td>
</tr>
<tr>
<td>Oct. 1 – 9, 2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct. 12 – 25, 2012</td>
<td>7064</td>
<td>0.38 0.00 4.80</td>
</tr>
<tr>
<td>Oct. 27 – 31, 2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov. 1 – 8, 2012</td>
<td>5906</td>
<td>0.93 0.20 4.80</td>
</tr>
<tr>
<td>Nov. 9 – 23, 2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>April 20 – 24, 2013</td>
<td>1176</td>
<td>0.05 0.00 3.70</td>
</tr>
<tr>
<td>May 2 – 6, 2013</td>
<td>5004</td>
<td>0.16 0.00 5.60</td>
</tr>
<tr>
<td>June 4 – 10, 2013</td>
<td></td>
<td></td>
</tr>
<tr>
<td>June 19 – 29, 2013</td>
<td>4499</td>
<td>0.57 0.00 4.80</td>
</tr>
<tr>
<td>Sept. 4 – 9, 2013</td>
<td>3557</td>
<td>0.78 0.00 19.0</td>
</tr>
<tr>
<td>Nov. 2 – 7, 2013</td>
<td>3157</td>
<td>1.86 1.0 4.90</td>
</tr>
<tr>
<td>Total</td>
<td>39,190</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Total means and standard deviations encompassing both sampling periods are illustrated in (Figure 6). Mean values and standard deviations for temperature, DO, pH, turbidity, and salinity were, 28.6 ± 0.4 °C, 6.7 ± 0.7 mg/L, 8.0 ± 0.1, 0.50 ± 0.5 NTU, and 36.1 ± 0.7 ppt, respectively.
Monthly mean values for all of the water quality parameters tested never exceeded or fell below established standard criteria for Class B waters (Table 1).

![Figure 6](image)

**Figure 6** Mean values and standard deviations of water temperature, DO, pH, salinity and turbidity during both study periods in Boiler Bay.

To depict temporal variation, monthly means and respective standard deviations were graphed in the figures below. For relative comparison, a solid, red line indicates regulatory criteria for the water quality parameter, if one is available. Mean monthly temperatures ranged from 26.7–29.3 °C and never exceeded the 32 °C criterion. Temperature exhibited typical seasonal trends for the region, increasing in the summer months and decreasing in the winter months (Figure 7).

![Figure 7](image)

**Figure 7** Monthly means and standard deviations for water temperature in Boiler Bay. Regulatory limit, 32 °C (red line).

Monthly means for DO ranged between 6.4–7.9 mg/L, which is well above the 5.5 mg/L regulatory minimum limit (Figure 8). Boiler Bay is exposed to easterly prevailing trade winds, which promotes wave action and supports circulation and aeration of the water column.
Mean monthly pH values ranged from 7.0–8.2, which are within the regulatory limits of 7.0–8.3 (Figure 9). For unknown reasons, monthly pH was higher and more variable in November, 2012. Although, October and November exhibited higher variation than the remainder of the months, pH was relatively constant, never exceeding ± 1.00 unit of measure.

Monthly means for salinity ranged from 33.4–39.3 ppt (Figure 10). Although salinity is significantly affected by terrestrial freshwater inflow in nearshore environments, from both ground and surface water sources, changes in monthly mean salinity did not correlate with
monthly rainfall. Connectivity to open ocean presumably influenced changes in salinity on a larger, monthly scale. Ocean currents and deeper water are in very close proximity, which could contribute to long-term changes in salinity based on temperature gradients.

Figure 10 Monthly means and standard deviations for salinity in Boiler Bay. No established regulatory limit.

Monthly mean turbidity ranged from 0.004–1.86 NTU (Figure 11). Monthly, mean turbidity data never exceeded the regulatory limit of 3.0 NTU for any of the monitored months and was less than 1.0 NTU 91.7% of the time. The algorithm used to process the turbidity data allowed values to be as high as 4.9 NTU, regardless of precipitation. As a result, mean monthly values in the water column may be even lower than what is reported here.

Figure 11 Monthly means and standard deviations for turbidity in Boiler Bay. Regulatory limit, 3.0 NTU (red line).
4.3.2. Sedimentation Events

4.3.2.1. TD Gabrielle

The only storm during the study period that produced enough precipitation to deliver significant amounts of terrigenous sediment into Boiler Bay was Tropical Depression (TD) Gabrielle. On September 4, 2013, Tropical Storm Gabrielle was downgraded to a tropical depression as it approached the USVI and PR (Avila, 2013). The system associated with Gabrielle moved slowly over the eastern Caribbean in a northeast direction and released copious amounts of rainfall. The National Weather Service reported 6–8 inches of rainfall accumulation from Gabrielle in a 48-hour period (September 5–6, 2013) across the USVI and eastern PR (NOAA, 2013).

4.3.2.2. Precipitation

Small amounts of daily precipitation (<2 cm/day) had fallen intermittently over the previous months (Figure 12), allowing for vegetation to be green. The 14 antecedent days prior to TD Gabrielle, conditions were relatively dry with a cumulative sum of 0.86 cm (0.34 in) of rain. In the three days leading up to TD Gabrielle, 0.72 cm (0.28 in) of precipitation had developed. September 2013 at Boiler Bay was 45% wetter than the 30-yr long-term mean for September in Cotton Valley, with a total rainfall of 15.7 cm (6.18 in) and 8.71 cm (3.43 in), respectively. Tropical Depression Gabrielle produced 87% of the total monthly rainfall during September 5–6, 2013 (48-hr period).

![Figure 12 Daily precipitation prior to and including TD Gabrielle at Boiler Bay. (July 1–September 9, 2013).](image)

The total rainfall associated with TD Gabrielle was 13.7 cm over 48-hours (5.4 in/48 hr) and primarily occurred during two significant pulses of rain. The first pulse had a max 1-hr intensity of 2.1 cm/hr (0.83 in/hr) and occurred on September 5 at 03:00 AM. The second pulse had a 4.1 cm/hr (1.6 in/hr) max 1-hr intensity and occurred approximately 24 hours later on September 6 at 03:00 AM (Figure 13).
The pattern, intensity and duration of precipitation caused by TD Gabrielle created runoff from the watershed, completely penetrated the beach and produced a sedimentation event in Boiler Bay (Figure 14).
The first pulse of precipitation on the morning of September 5 produced a cumulative sum of 4.4 cm (1.7 in) of rain over a nine-hour period of time. The first pulse of precipitation likely saturated the soil and regenerated groundwater levels enough to produce some runoff at the site, however, there was not enough discharge to push completely through the sandy beach that separated the watershed from the bay. Physical observations of the site following the first pulse of rain revealed standing water on the trail and a pool of water at the base of the trail where the sandy beach began, however the beach had not been visibly flushed out. Although the beach was not visibly penetrated, it is believed that some flushing occurred, causing an increase in turbidity in the bay (Figure, 15). The second major pulse of precipitation on the early morning of September 6 resulted in a total accumulation of 9.1 cm (3.6 in) in an eight-hour period, which completely pushed through the beach and a significant sedimentation event occurred (Figure 15).

Figure 15 Precipitation patterns and turbidity during terrestrial sediment delivery in Boiler Bay.

To assess the duration and intensity of the sediment plume generated by the second pulse of precipitation, a 14-hr (0:00:00–14:00:00, September 6, 2013) dataset was analyzed. At 01:00:00 precipitation began with an intensity of 0.3 cm/hr and increased to 4.1 cm/hr, followed by an additional 4.0 cm/hr, which resulted in a sedimentation plume with a peak turbidity value of 19.0 NTU (Figure 16). During this time, turbidity exceeded 3.0 NTU (indicated by a red line) 105 times, or 24.25% of the 14-hour period. Turbidity remained above 3.0 NTUs for a continuous 2.5-hour period during the sedimentation event, however, turbidity values greater than 3.0 NTUs occurred intermittently for a 5–6 hour period. Mean turbidity during the 14-hr period was 2.27 NTU, which was 4.54 times higher than mean turbidity over the study period (0.50 NTU). Turbidity in the bay remained above 0.50 NTU for 81.5% of the time during the 14-hr period (indicated by a blue line).
4.3.2.3. Terrestrial Erosion

An areally-weighted erosion rate for the eroding trail that leads to Boiler Bay was calculated above to be 2.4E-02 kg m⁻²cm⁻¹. During the 48-hour period that TD Gabrielle was active over the USVI, 13.7 cm of precipitation fell on the watershed that drains into Boiler Bay. The total surface area of the eroding trail was 478 m². Based on the calculated areally-weighted erosion rate, the trail alone in Boiler Bay generated an estimated 159 kg (351 lbs) of sediment that was potentially discharged directly into Boiler during TD Gabrielle.

4.3.2.4. Water Quality

Mean, minimum and maximum values for temperature, DO, pH and salinity during TD Gabrielle (48-hrs) were summarized in Table 7 and turbidity in Table 8, below. Total mean values for temperature, DO, pH, salinity and turbidity were 28.7 ±0.31°C, 7.45 ±0.46 mg/L, 7.9 ±0.04, 34.7 ±0.83 ppt and 1.08 ±1.70 NTU, respectively.

Mean DO during TD Gabrielle (7.45 mg/L) was 10.1% higher than total mean DO over the entire study period (6.72 mg/L). Increased wave-action from winds during TD Gabrielle undoubtedly increased aeration and circulation of DO in the bay. A 3.88% decrease in salinity during TD Gabrielle (34.7 ppt) was also observed compared to the overall mean of 36.1 ppt, which is likely attributed to fresh water inflow and direct precipitation onto the bay.
Mean turbidity over the 48-hour period during TD Gabrielle increased 54.7% (1.08 NTU) relative to the total mean encompassing the entire study period (0.50 NTU). The increase in turbidity was a direct effect of terrigenous sediment delivery and also presumably the resuspension of bottom sediments in the bay during increased surge and wave-action. Although, mean turbidity more than doubled, it remained below the 3.00 NTU regulatory standard. The 48-hour average is too coarse to see acute changes in turbidity during sedimentation events.

Table 8 Mean, minimum and maximum values for turbidity during TD Gabrielle.

<table>
<thead>
<tr>
<th>Monitoring Period (48 hrs)</th>
<th>Logged Samples</th>
<th>Turbidity (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept. 4 – 6, 2013 (2-min. intervals)</td>
<td>1415</td>
<td>1.08 0.00 19.0</td>
</tr>
</tbody>
</table>

5. Conclusions

Data that quantifies sediment transport from eroding watersheds into receiving water bodies is critical to support informed management decisions in the revision of water quality regulations and the development of TMDL limits. The case study presented here illustrates the kinds of erosion and sedimentation issues that all too commonly occur in the USVI and PR. The type of high-resolution water quality data provided by this study is commonly discussed as an important, but lacking source of information in Local Action Strategy meetings conducted by NOAA, the VI-DPNR, and PR-DNER. The co-PIs of this project are active participants in those local meetings and efforts, and these include the development of watershed plans for the USVI, such as those for the Fish Bay and Coral Bay areas of St. John (NOAA-ARRA; NOAA-LAS), Lameshur Bay and Salt Pond Bay in St John (VI National Park), STX East End (Horsley-Witten Group), and in Puerto Rico in Culebra (PR-DNER, NOAA-Coral Reef Restoration), Bahía Mosquito-Vieques (EPA, Vieques Conservation and Historical Trust), Fajardo (NOAA-LAS, Caribbean Coral Reef Institute), La Parguera (NOAA-CRES, CCRI, NOAA-LAS), Cabo Rojo (PR-DNER, NOAA-LAS), and El Río Grande de Añasco (UPR-Sea Grant). The results of this study can thus serve not only to understand the local water turbidity dynamics at Boiler Bay, but could also guide future monitoring efforts for projects having similar objectives in other parts of the USVI and Puerto Rico.
5.1. Precipitation

The intensity and duration of precipitation needed to generate runoff in watersheds is a complex relationship between factors such as, watershed relief, aquifer characteristics, geology, soils, land use, climate, and vegetation cover. The steep topography, short distance to the bay, shallow surficial soils and vegetation typical of subtropical climates (shrubby, dry deciduous forest) create an environment where surface runoff is easily generated and capable of flowing directly into Boiler Bay. Repeated observations of rainfall intensities during this study indicated that an estimated 2.1–4.1 cm/hr (0.83–1.61 in/hr), depending on antecedent precipitation and duration of storm, were needed to generate enough runoff to flush through the beach into Boiler Bay. With the presence of an eroding trail that channels flow from land to sea, runoff discharged into Boiler Bay is sediment laden and poses an imminent threat to the fragile ecosystems present in the bay.

5.2. Terrestrial Erosion

An areally-weighted erosion rate observed on the trail leading to Boiler Bay was found to be 2.4E-02 kg m⁻² cm⁻¹. Relating this calculation to precipitation events provides linkages needed to quantify the mass of sediment generated by the trail. The study site in Boiler Bay provided an environment where the source of sediment (the trail) could be isolated to effectively evaluate resulting turbidity without interference from other non-point or point sources of pollution. The data was used to directly evaluate the effects of runoff on water quality parameters during a sedimentation event.

5.3. Water Quality

Results from this study provided high temporal resolution water quality data during both dry (ambient) and wet conditions when runoff was discharging into the bay (sedimentation). Since in situ monitoring for this project was located in the relatively pristine area of the STXEEMP, ambient data could be used as an established baseline to compare acceptable limits of change to in other areas of similar classification (Class B). This dataset could also be used to quantify potential impacts on marine ecosystem health during sedimentation events.

5.3.1. Ambient Water Quality

Data were collected in 2–5 minute intervals over two study periods, resulting in 31, 211–45, 687 logged samples. Total mean values and standard for temperature, DO, pH, turbidity, and salinity were, 28.6 ± 0.4 °C, 6.7 ± 0.7 mg/L, 8.0 ± 0.1, 0.50 ± 0.5 NTU, and 36.1 ± 0.7 ppt, respectively. Total mean values for all of the water quality parameters tested never exceeded or fell below established standard criteria for Class B waters.

5.3.2. Sedimentation Events

Tropical Depression, Gabrielle provided the conditions (rainfall magnitude, duration and intensity) that were needed to generate runoff on an eroding trail, which produced a sedimentation event in Boiler Bay. The sediment plume peaked in turbidity at 19.0 NTU. Turbidity remained above the regulatory limit of 3.0 NTU for a continuous 2.5-hour period during the sedimentation event, however NTUs greater than 3.0 occurred intermittently for a 5–
6 hour period. Turbidity exceeded 3.0 NTU 105 times, or 24.25% of the time in a 14-hour period (September 6, 0:00:00–14:00:00) following two consecutive hours of rainfall with 1-hr intensities of 4.10 and 4.00 cm/hr. Mean turbidity during the 14-hr period was 2.27 NTU, which was 4.54 times higher than mean turbidity over the study period (0.50 NTU). Turbidity in the bay remained above 0.50 NTU for 81.5% of the time during the 14-hr period.

The intensity and duration of the sediment plume resulting from TD Gabrielle may be relatively conservative from other events that often occur in the territory. The sonde was placed slightly up-current and further away from the point of discharge than was desired. Boiler Bay has a swift current that is not typical of other bays surrounding St. Croix. The current and connectivity to open ocean is capable of flushing the sediment down current relatively rapidly. As a result of flushing down-current, the bulk of the sediment plume may not have been recorded by the sonde. Additionally, the duration of the plume may be much longer in areas with less current, as the same amount of flushing will not occur and the settling time of fine particulates will linger in the water column much longer.

6. Recommendations

6.1. Management Applications

Results from this study underline the importance of sustained efforts to upgrade and enforce water quality regulations in the region. Elevated erosion rates observed in the rather arid and pristine east end of St. Croix from a small eroding trail suggest an even greater need for caution and required use of Best Management Practices in the steeper and wetter areas of the USVI and PR, where dirt roads and coastal development continue to expand. It is urged that financial resources continue to promote wide-spread educational efforts to inform and remind the general public, land developers, construction businesses, etc. of the consequences irresponsible land-use has on the degradation of our water resources.

Recent studies conducted by (Oliver, et al., 2012; Pittman, et al., 2013) have begun to spatially characterize seascape condition within the STXEEMP and quantify species’ biodiversity and abundance. These studies relate biodiversity to landscape patterns and nearshore biological community composition, including those found in Boiler Bay. Data provided by this study could be used to link and actually quantify the impact that turbidity has on a given species of interest. For instance, coral species such as: *Acropora palmata* (Elkhorn Coral), *Diploria strigosa* (Symetrical Brain Coral), *Favia fragum* (Golfball Coral), *Montastrea annularis complex* (Boulder Star Coral), *Porites porites* (Finger Coral), *Porites astreoides* (Mustard Hill Coral), etc., are present in Boiler Bay and each one presumably has a specific tolerance (time and duration) to turbid water before it is detrimental to the organism. Because the condition and distribution of these species have been quantified (Oliver, et al., 2005; Oliver, et al., 2006; Oliver, et al., 2012; Pittman, et al., 2013) and the impact of erosion and sedimentation events, which have been quantified by this study and inferences and direct linkages between landscape and seascape may be possible (Reale-Munroe, et. al., 2010; Reale-Munroe, et. al., 2011).

Furthermore, funding made available to reduce sediment input from the eroding trail into Boiler Bay would be beneficial to the myriad of nearshore habitats and organisms that are present.
Conceptual engineering designs have been developed for the trail leading to Boiler Bay in past student projects. Restoration of the trail could be made possible by the collaboration between students at the University of the Virgin Islands, engineering and/or environmental consulting firms and management and regulatory agencies at the local and federal level.

### 6.2. Technical Notes on Turbidity

Long-term, *in situ* monitoring using a YSI Sonde and turbidity probe proved to be problematic. It is recommended to limit the duration of continuous deployments to less than 7 days, otherwise fouling, despite a built-in wiper, tended to anomalous data. Also, it is recommended to use a protective cage that has smaller slots to house the probes during deployments. Aquatic life (juvenile fish, octopus, etc.) was drawn to the structure (sonde and mounting device) and sought protection inside the protective cage.

Post processing is time consuming, tedious and requires a knowledgeable person to determine erroneous data caused by calibration and hardware malfunction, sensor drift or the myriad of environmental factors that could affect data output. Development of automated algorithms and software that were capable of auto-correlating environmental factors, such as precipitation and salinity to determine erroneous data spikes would perhaps be useful.
7. References Cited


Horsley Witten Group, Inc. 2011. St. Croix East End Watersheds Management Plan (pp. 52). Sandwich, MA.


Valdez-Pizzini, M., Chaparro, R., & Gutierrez, J. 1988. Assessment of access and infrastructure needs of Puerto Rico and the United States Virgin Islands in order to support increased marine recreational fishing. National Fisheries Service, Washington, DC.
