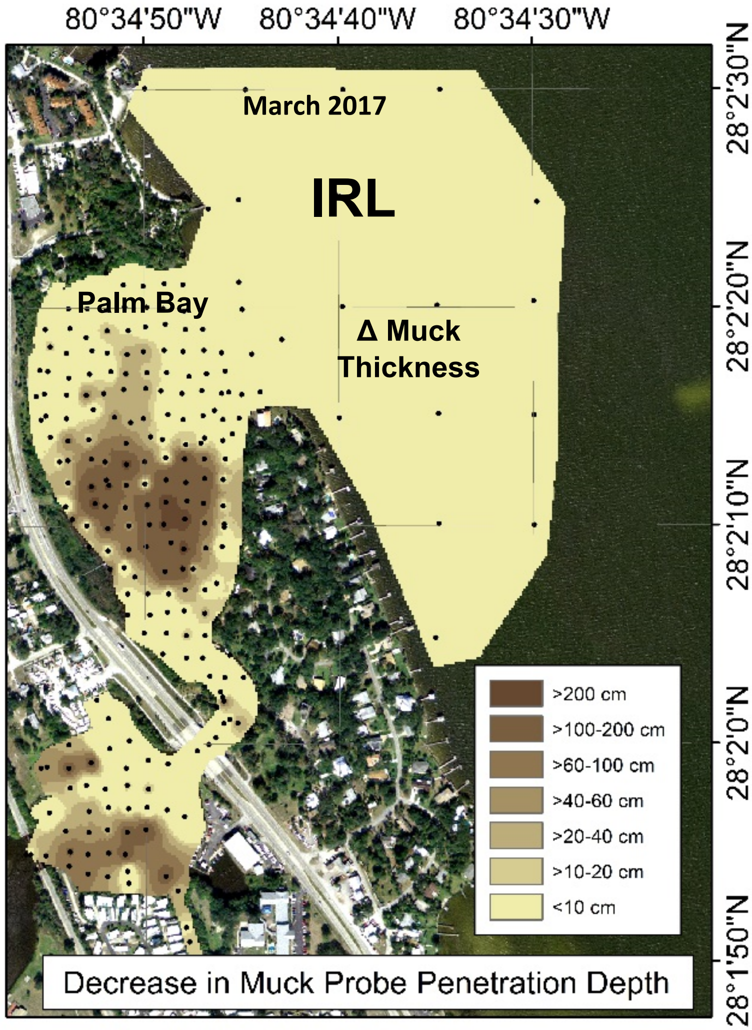
Determining the Effectiveness of Muck Removal on Sediment and Water Quality in the Indian River Lagoon, Florida (Subtask 4a)



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Impacts of Environmental Muck Dredging 2016–2017

Determining the Effectiveness of Muck Removal on Sediment and Water Quality in the Indian River Lagoon, Florida (Subtask 4a)

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Executive Summary

Removal of fine-grained, organic-rich sediments is an integral part of restoring the Indian River Lagoon (IRL) to a healthy ecosystem. This sediment, often referred to as IRL muck, is a concern because it can increase turbidity, consume oxygen, create an inhospitable benthic habitat and is an internal source of dissolved nitrogen (N) and phosphorus (P) that diffuse from muck into the lagoon. Dredging is an effective method for removing large reservoirs of muck with associated N and P; however, there are challenges to dredging and few data are available to quantify the efficacy of environmental dredging in the IRL.

We carried out surveys in Turkey Creek on multiple occasions during the following periods:

- Before dredging from April 2015–January 2016.
- During two separate phases of dredging.
    - Phase I. February 20, 2016–April, 22, 2016 when dredging was carried out for 24 hours/day and then stopped as planned for increased manatee activity.
    - Phase II. September 6, 2016–January 11, 2017 when dredging was carried out for 10 hours/day and alum and flocculants were added.
- After environmental dredging during May 2016–April 2017 (dates varied by area).

The goals of the study were to track changes in (1) the distribution and composition of the muck, (2) benthic fluxes of N and P from muck to the overlying water column and (3) sediment and water quality.

Our pre-dredging sediment survey (February 2015) identified little to no muck in the adjacent IRL; yet, up to 3 m of muck were found between the Florida East Coast Railroad Bridge and the mouth of Turkey Creek. We calculated the pre-dredge volume of muck in Turkey Creek at ~110,000 m^3 (140,000 yd^3) with 83,000 m^3 (~75%) in the portion of the creek selected for dredging. Our post-dredging sediment survey (March 2017) found that 52,000 m^3 of muck and a total of 160,000 m^3 (210,000 yd^3) of wet sediment were removed from the dredged area (i.e., >60% removal efficiency for muck in the dredged area). No significant differences were identified in the chemical composition of muck before versus after dredging.

Observed spikes in turbidity during dredging were driven by an algal bloom and Hurricane Matthew, not the dredging process. Dredging increased water depths and the abundance of saline

water in some locations, a potential benefit to fishes, benthic fauna and seagrass. Benthic fluxes of N and P were ~50% lower at three months after dredging, which if continued would decrease annual releases of dissolved N and P from IRL muck by ~3 tons and ~1 ton, respectively (50% decrease), within the ~0.10 km^2 of Turkey Creek that were dredged. Future trends in benthic fluxes will be monitored.

Monthly water quality surveys (April 2015 to April 2017) showed that the 1- to 2-m deeper water column after dredging contained >2-fold more total dissolved oxygen. This increase in oxygen may enhance resiliency to oxygen depletion events. Before, during and after dredging, values for dissolved ammonium and phosphate were highest in bottom water, consistent with sediments as a continuing source of these nutrients to the overlying water. Secchi depths were significantly deeper and total suspended solids (TSS) were lower after dredging, possibly aided by a prolonged drought after dredging. Overall, Secchi depths and values for TSS followed patterns for rainfall.

Dredged material was transported ~2 km north to a Dredge Material Management Area (DMMA) for settling and dewatering. Clarified water was discharged into the adjacent IRL. Residence times for water in the DMMA were about ~2.5 days during Phase I and ~6 days during Phase II, a response to the rate of filling of the holding area at different dredging rates. The overall retention efficiency for solids was >99% as ~200 tons of N and ~50 tons of P were successfully removed from Turkey Creek. Values for TSS in the outfall from the DMMA to the IRL averaged ~28 mg/L during Phase I and 12 mg/L during Phase II, with four brief episodes of higher values. Background TSS values were 10–20 mg/L in the adjacent IRL. Chemical treatments effectively reduced concentrations of dissolved phosphate from as high as 10,000 µg P/L in the incoming dredged material to <40 µg P/L in clarified water released to the lagoon during Phase II, relative to <50 µg P/L in the lagoon. Total dissolved nitrogen in water released from the DMMA to the IRL was >5 mg N/L throughout the dredging process, relative to <0.8 mg/L in the lagoon. Additional efforts are now underway to decrease concentrations of dissolved nitrogen, mostly as ammonium, during future uses of DMMAs. Nutrient concentrations were at baseline values for the IRL at ~100 m from the outfall. We estimate that ~6 tons of N (~90% dissolved) and ~0.1 ton of P (~30% dissolved) were released from the DMMA during this one-year dredging project. Although unique to this particular IRL area, freshwater discharges annually release ~80 and ~5 tons of N and P, respectively, to Turkey Creek, far more than released from the DMMA.

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Task 4a. Determining the Effectiveness of Muck Removal on Sediment and Water Quality in the Indian River Lagoon, Florida

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Introduction

Eutrophication continues to be a leading environmental challenge to coastal communities worldwide (Diaz and Rosenberg, 2008). Virtually all excess nutrients in the environment originate from anthropogenic nitrogen (N) fixation and phosphorus (P) mining (Howarth and Marino, 2006). Nutrients are released to coastal waters through a variety of mechanisms including, but not limited to: (1) excess fertilizer application and runoff, (2) animal and human waste and improper waste treatment and (3) decomposition of organic matter (OM) from stormwater runoff and yard or agricultural trimmings. Nutrients also are released to the overlying water column when sediment OM decomposes.

The Indian River lagoon (IRL) extends ~250 km along the central east coast of Florida. In the most restricted, northern section of the lagoon, no inlets are present along a 140-km section from Sebastian Inlet to Ponce de Leon Inlet. Since the 1950s, >4 million m^3 (~5.2 x 10^6 yd^3) of fine-grained, organic-rich sediment have accumulated on areas of the once sand- and shell-covered bottom of the northern IRL (Tetra Tech, 2016). Locally called IRL muck, this sediment contains 10–30% OM and >60% silt and clay with a high water content (porosity >0.9). This IRL muck (1) is easily resuspended to block light from seagrass, (2) consumes oxygen, (3) is characterized by a dearth of biota and (4) continually releases large quantities of dissolved N and P.

Management of IRL muck requires a multifaceted approach that addresses both control of upland inputs of N, P and suspended sediments and removal of muck that has already accumulated. Muck removal is an integral part of the ongoing restoration process for the IRL. Although dredging is an effective method for removing large reservoirs of N and P associated with fine-grained silt and clay, numerous challenges and limited data constrain present-day assessments of environmental dredging in the IRL. A study of dredging in Crane Creek identified ~82,000 m^3 of muck in 2002, even though the creek had been dredged four years earlier (Trefry et al., 2004). This observation emphasized issues with incomplete dredging near docks and seawalls as well as post-dredging redistribution of undredged muck.

Dredging in Turkey Creek began (Phase I) on February 20, 2016, with continuous operations (24 hours/day). A planned shutdown for manatee season during May and June was initiated 8 days early (April 22, 2016) because the Dredge Material Management Area (DMMA) reached capacity. Dredging resumed (Phase II) on September 6, 2016, for ~10 hours/day through January 11, 2017. Material dredged from Turkey Creek was transported ~2 km north through a submerged pipe to a DMMA (BV-52) where it was sprayed into the northwest corner of the ~0.04 km^2 retention basin. Clarification was initially accomplished by settling. Beginning on April 7, 2016, alum and proprietary polymers were injected directly into the dredge pipe at the DMMA to test their potential to reduce concentrations of dissolved P and enhance flocculation of suspended solids. A berm near the inflow prevented water from passing directly from the incoming pipe to the weir and the IRL, thereby increasing the residence time for water in the DMMA.

The goals of this project were to (1) determine the efficiency of muck removal, (2) assess the effectiveness of sediment and nutrient retention in the DMMA and (3) quantify any improvements in sediment and water quality after dredging. Turkey Creek was a challenging setting due to its proximity to a large freshwater inflow and the presence of numerous docks and seawalls that limited the spatial extent of dredging. Despite these challenges, environmental dredging in Turkey Creek provided a unique opportunity for intensive evaluation of such efforts in the IRL.

Approach

Muck Survey, Sediment and Water Collection

This study was initiated with a muck survey during February 2015 using a 4-cm diameter, capped polyvinyl chloride (PVC) pole (Figure 1a). The pole, marked in centimeter graduations, was lowered into the water column until the surface layer of sediment was encountered; this depth was recorded as the water depth. The pole was then pushed into the sediment until a firm bottom was struck and the total depth minus the water depth was recorded as the thickness of the muck layer. Usually, muck adhered to the pole along the entire muck interval to help confirm the thickness of the muck layer. The survey included 253 probe measurements (counting duplicates of water depth and muck thickness and IRL data) within a gridded area of the creek (Trefry et al., 2016). The post-dredge survey during March 2017 was conducted ~3 months after dredging was completed and included 249 probe measurements. Data from each survey were tabulated and elevations were normalized to a datum established during the initial survey. Contour maps for water depths, muck distribution, muck thicknesses and changes in waters depth and muck thicknesses were generated using ArcGIS (Version 10.2.2.3552, Esri, Redlands, CA).

Surface sediment samples for chemical analysis were collected at 9 locations before dredging and at 16 locations after dredging using a 0.1 m^2 Ekman grab. Sediment from the top 2 cm was placed in double Ziploc bags for grain size and in polycarbonate vials (~70 mL) for other chemical analyses. Sediment cores were collected at four stations before and after dredging (TC3, TC4, TC5 and TC6, Figure 1b) by divers using 60-cm long, 7-cm diameter cellulose acetate butyrate tubing. One core from each site was sub-sectioned upon return to the laboratory into 2-cm intervals for chemical analysis. Interstitial water was obtained from 16 sections along a 30-cm core using whole-core squeezers (Jahnke, 1998; Trefry et al., 2015).

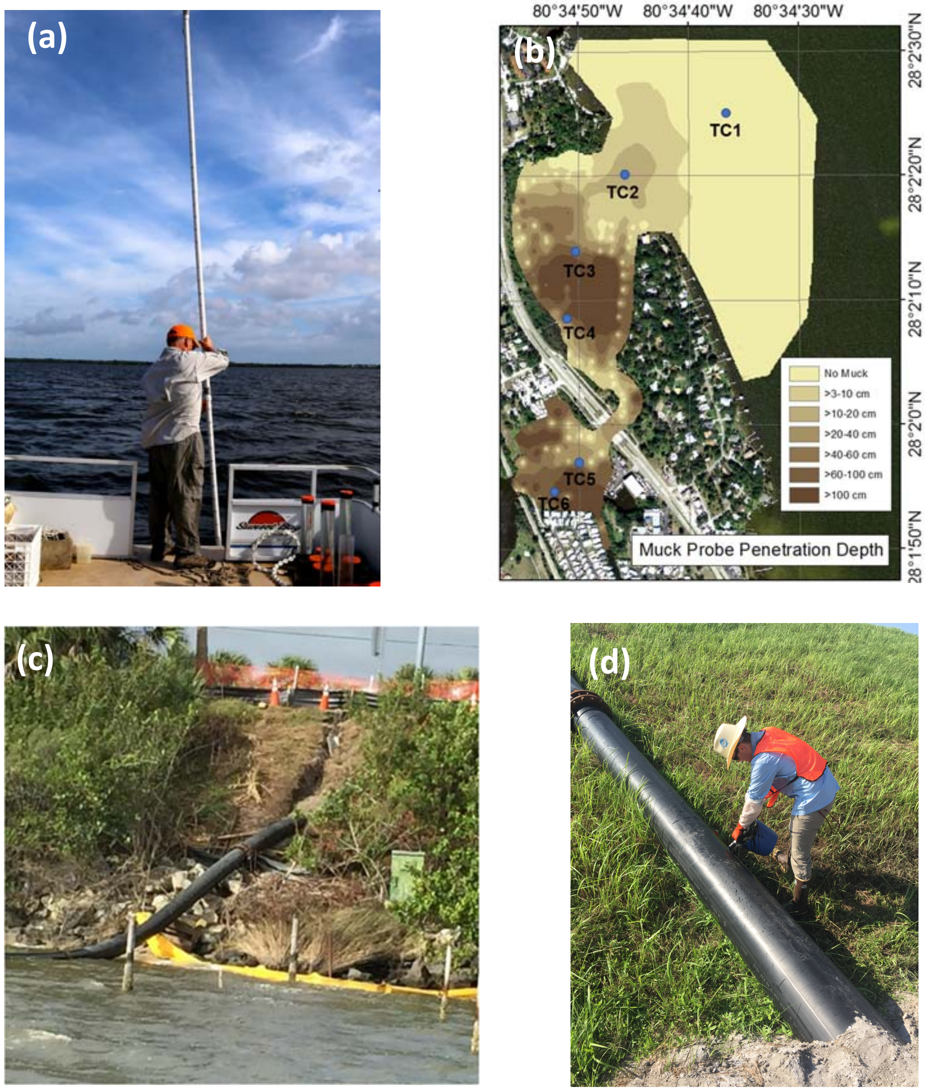


Figure 1. (a) Using a PVC pole to determine water depths and muck thicknesses, (b) contour map with muck distribution and depths before dredging, sampling locations for sediment cores and water (labelled TC1–TC6), (c) incoming and outgoing pipes between the Dredge Material Management Area (DMMA) and the Indian River Lagoon and (d) sampling the incoming pipe to the DMMA just before discharge into the retention area. Facility is located west of Highway US 1 and south of Robert Conlon Boulevard, Palm Bay.

More than 70 core samples for Quick-Flux analysis were obtained using a 0.1 m^2 Ekman grab. The grab was gently lowered into surface sediments to obtain 10–15 cm of stratified sediment and overlying water. Sediment from the center of the grab was collected using a 1.5-cm diameter, mini-piston corer that was made from a plastic syringe. Mini-cores were sealed using Parafilm and stored in a cooler until processing in the laboratory at Florida Institute of Technology (FIT). In the laboratory, mini-cores were extruded into nitrogen-purged tubes and centrifuged at ~2000 RPM for 5 minutes. The supernatant was filtered through 0.45-µm pore size polypropylene filters and stored in low density polyethylene (LDPE) vials. Sulfide analysis was performed immediately (within 10 seconds of filtration).

Ten pre-dredging water quality surveys were carried out from April 2015–January 2016. Water quality surveys also were conducted during, between and after dredging operations from February 2016 to April 2017. Post-dredging water quality surveys began at different dates as a function of when dredging was completed. Therefore, after-dredging surveys began as early as March 2016 near the mouth of the creek to as recently as February 2017 in the area west of Highway US1. Water quality sampling will continue for the foreseeable future. During each survey, water samples were collected at 2–5 depths at the same five stations (TC1–TC5) during each survey (Figure 1b). Vertical profiles for salinity, temperature, pH and dissolved oxygen were obtained using intercalibrated YSI 6600 V2 or YSI ProDSS probes (Yellow Springs Instruments). The sondes were calibrated at the beginning of each day following manufacturer's specifications. Discrete samples were collected through Tygon tubing attached to a peristaltic pump. Samples were placed in acid-washed LDPE bottles and stored in coolers until returned to the Marine & Environmental Chemistry Laboratories at FIT. Samples were then filtered within 2–3 hours.

We sampled the DMMA, weekly, or more often, from (1) the incoming pipe in the northwest corner of the retention basin, (2) the weir near the northeast corner of the basin and (3) the outfall pipe (Figure 1 c, d). Water flow at the outfall was determined for about one month by Brevard County using an ISCO 4250 flow meter; however, the system was damaged in March 2016 and no longer functional. Additional flow measurements were made by FIT using a Global Flow Probe Model FP101.

Samples were filtered, or allowed to settle and then filtered, in the nearby FIT laboratory. On several occasions, we sampled water from the IRL along 50- and 100-m radii from the outfall pipe. We also maintained a station in the IRL at 0.5 and 1 km from the outfall as part of our Turkey Creek sampling program.

Eight representative samples of settled dredge material were collected from the DMMA, four during the dredging hiatus in May 2016 and four after dredging in February 2017. Samples were collected for analysis of water content, OM, total N, total P and 17 metals (Al, As, Ba, Be, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Sb, Sn, Ti, V and Zn). The main goal of these analyses was to determine whether the dredged muck was contaminated with any metals.

Laboratory Analyses: Sediments

All sediment samples, except sub-samples for grain size, were freeze dried using a Labconco FreeZone 6 system and then powdered using a SPEX Model 8000 Mixer/Mill. In preparation for analysis for Al, Fe, Si and P, 10–20 mg of freeze-dried, homogenized sediment or Certified Reference Material (CRM) sediment MESS-3, from the National Research Council of Canada (NRC), were totally digested in sealed Teflon tubes using concentrated, high-purity HF and HNO_3 following methods of Trefry and Trocine (1991). Complete digestion of the sediment was chosen because it accounts for the entire amount of each element in the sample.

Concentrations of Al, Fe and Si in digested sediments were determined by flame atomic absorption spectrometry (FAAS) using a Perkin-Elmer Model 4000 atomic absorption spectrometer following U.S. EPA (1991) methods. Values for P were determined by inductively coupled plasma-mass spectrometry (ICP-MS) based on EPA Method 6020 (U.S. EPA, 1991) using a Varian Model 820-MS instrument. Concentrations of these elements in the sediment CRM MESS-3 were within the 95% confidence intervals for certified values. Analytical precision for individual elements in sediments ranged from 0.7–6% (as relative standard deviation, RSD = [SD/mean] x 100%). Eight sediment samples were completely digested and analyzed for 17 metals using techniques described by Trefry et al. (2014).

Grain size analyses were carried out using the classic method of Folk (1974) that includes a combination of wet sieving and pipette techniques. Loss on Ignition (LOI) at 550˚C was determined following the method of Heiri et al. (2001). Values for LOI estimate the fraction of OM in the sample and were used in conjunction with concentrations of organic C, total N and total P to help characterize sediment composition. Concentrations of $CaCO_3$ were determined by heating the sediment that had been treated for LOI at 550˚C to 950˚C following the method of Heiri et al. (2001).

Concentrations of total organic carbon (TOC) were determined using freeze-dried sediment that was treated with 10% (v/v) hydrochloric acid to remove any inorganic carbon, washed with carbon-free, high purity water (HPLC grade) and dried. Then, approximately 200–800 mg of pre-treated sediment were weighed into ceramic boats and combusted with pure oxygen at 950˚C using a LECO Corporation (St. Joseph, MI) TruMac C/N/S system with quantification of the CO_2 produced using an infrared detection cell. Sediment total N concentrations were determined using separate samples that were untreated prior to analysis to avoid losses of N during acidification. Nitrogen analyses of sediments also were carried out using the LECO system at 950˚C with quantification of the N_2 gas produced via a thermal conductivity detector. Concentrations of C and N in the sediment CRM MESS-3 and LECO reference sample 502-309 were within the 95% confidence intervals for certified values. Analytical precisions (RSD) were 1.5% for TOC and 2% for total N.

Laboratory Analyses: Water

Samples for nutrient analysis were vacuum filtered through polycarbonate filters (Poretics, 47-mm diameter, 0.4-µm pore size) in a laminar-flow hood. Ammonium concentrations were quantified following standard methods (#4500-NH_3, Rice et al., 2012). Standards were prepared from dried ammonium chloride and analyzed at least twice using UV-visible spectrometry with each batch of samples to ensure accuracy. All values were within the 95% confidence interval for the prepared standard. Analytical precision (RSD) for lab duplicates was <3%.

Concentrations of nitrate + nitrite were determined using a SEAL AA3 HR Continuous Segmented Flow AutoAnalyzer following manufacturer's method G-172-96. The National Institute of Standards and Technology (NIST) traceable Dionex 5-Anion Standard was analyzed as a reference standard with each batch of samples to ensure accuracy; all values were within 10% of the known concentration. Analytical precision (RSD) for lab duplicates was 6 ± 5%.

Concentrations of total dissolved nitrogen (TDN) were determined using a SEAL AA3 HR Continuous Segmented Flow AutoAnalyzer following manufacturer's method G-218-98. Organic and inorganic N compounds were converted to nitrate using UV and persulfate digestion. Nitrate was reduced to nitrite using an in-line cadmium column. Standards were prepared from dried ammonium chloride and analyzed twice with each batch of samples; all values were within 10% of the known concentration. Analytical precision (RSD) for lab duplicates was 2 ± 2%.

Concentrations of ortho-phosphate were determined using a SEAL AA3 HR Continuous Segmented Flow AutoAnalyzer following manufacturer's method G-297-03. The NIST-traceable Dionex 5-Anion Standard was analyzed as a reference standard with each batch of samples to ensure accuracy; all values were within 95% confidence interval for this standard. Analytical precision (RSD) for lab duplicates averaged 1%.

Concentrations of total dissolved phosphorus (TDP) were determined using a SEAL AA3 HR continuous Segmented Flow AutoAnalyzer following manufacturer's method G-219-98. UV and persulfate digestion were used to free organically-bound phosphorus. The NIST-traceable Dionex 5-Anion Standard was analyzed as a reference standard with each batch of samples to ensure accuracy; all values were within 10% of the known concentration. Analytical precision (RSD) for lab duplicates was 3 ± 2%.

Diffusive fluxes of N and P were calculated from gradients of solute concentrations in interstitial water (e.g., Berner 1974; Boudreau and Scott, 1978) and Fick's first law of diffusion (Equation 1). Diffusion coefficients (Ds) were corrected for variations in temperature, salinity and porosity of sediments. Concentration gradients were obtained from (1) discrete samples obtained using whole core squeezers and (2) calculated from integrated sediment samples obtained using the Quick-Flux technique. Standard deviations for detailed interstitial water profiles were calculated based on downcore variability in nutrient concentrations and for Quick-Flux using field replication.

$$\mathrm{F} = -D_S \frac{dc}{dx} \qquad \text{(Equation 1)}$$

Laboratory Analyses: Suspended Matter

Samples of suspended matter were collected by vacuum filtering water through polycarbonate filters (Poretics, 47-mm diameter, 0.4-µm pore size) in a laminar-flow hood in our clean room at FIT. Prior to the field effort, the filters were acid washed in 10% HCl, rinsed three times with deionized water, dried and then weighed to the nearest µg under cleanroom conditions. Precision for replicate filtrations averaged <4% (i.e., ±0.04 mg/L). Samples for particulate organic carbon (POC) were filtered through pre-combusted Whatman Type A/E glass fiber filters mounted on acid-washed filtration glassware within a Class-100 laminar-flow hood. Particle-bearing filters were sealed in acid-washed petri dishes, labeled and then double-bagged in plastic and stored until dried and re-weighed at FIT.

Suspended particles, as well as separate milligram quantities of standard reference material (SRM) #2704, a river sediment issued by the NIST, were digested in stoppered, 15-mL Teflon test tubes using Ultrex II HNO_3 and HF as described by Trefry and Trocine (1991). Concentrations of particulate Al, Fe and Si were determined by FAAS and concentrations of particulate P were determined by ICP-MS. Analytical precision (RSD) for individual elements in sediments ranged from 1–5%.

Concentrations of POC and total N were determined by first treating particles on the glass fiber filter with 10% (v/v) hydrochloric acid to remove any inorganic carbon, and dried. Then, filters with 200–800 mg of pre-treated suspended sediment were weighed into ceramic boats and combusted with pure oxygen at 950˚C using a LECO TruMac C/N/S system. Total N concentrations were determined using separate glass fiber filters that were untreated prior to analysis to avoid losses of N during acidification. Nitrogen analyses of suspended particles also were carried out using the LECO system at 950˚C with quantification of the N_2 gas produced via a thermal conductivity detector. Concentrations of C and N in the sediment CRM MESS-3, SRM #2704 and LECO reference sample 502-309 were within the 95% confidence intervals for certified values. Analytical precision (RSD) was 1.5% for TOC and 2% for total N.

Quality Assurance Plan

The Quality Assurance Plan used in the Marine & Environmental Chemistry Laboratories at FIT was reviewed by Florida Department of Environmental Protection. The plan meets the minimum requirements for description of research field and laboratory procedures according to rule 62-160.600, Florida Administrative Code. Our sediment and water collection and subsequent analysis followed the general guidelines provided below.

(i) *Sample Handling.* Sediment samples were transferred to a refrigerator or if sampled as cores, were immediately processed for sub-sampling (and then refrigerated if necessary). Water samples were collected and preserved using appropriate containers and reagents. Solutes were measured within appropriate holding times. All water samples were kept chilled, either on ice or in refrigerators, until analyzed.

(ii) *Quality Control Measures for Analyses.* Quality control measures included instrument calibration, matrix spike analysis, field replicates, duplicate sample analysis, standard reference material analysis, procedural blank analysis, and standard checks. With each batch of 20 field samples, a procedural blank, standard reference materials, a field and laboratory duplicate, and a matrix spike sample were analyzed. Data quality objectives for these quality control measurements are provided in Table 1.

(iii) *Matrix spike analysis.* A matrix spike sample (method of additions analysis) was run with every batch of 20 samples. Results from the method of additions analysis provide information on the extent of any signal suppression or enhancement due to the matrix. When necessary (spike results outside a recovery of 85–115%), samples were analyzed by methods of additions.

(iv) Duplicate sample analysis. To estimate the precision of the analyses, a duplicate field sample was analyzed with each batch of 20 samples.

(v) *Standard reference material analysis*. A common method used to evaluate the accuracy of environmental data is to analyze standard reference materials, samples for which consensus or accepted analyte concentrations exist. For example, the marine sediment (MESS-3) from the NRC and a river bottom sediment from the NIST (#2704, Buffalo River Sediment) were analyzed with every batch of sediment samples.

(vi) *Procedural blank analysis*. A procedural blank was processed and analyzed with each batch of samples to monitor potential contamination from laboratory reagents, glassware, and processing procedures.

Table 1. Data quality objectives for this study.

QC Measure	Minimum Frequency	Data Quality Objective/Acceptance
Initial Calibration	Standard curve prior to every batch of samples	3–5 point curve depending on the element and a blank; correlation coefficient r ≥ 0.999 for all analytes
Continuing Calibration	Must end every analytical sequence or after every 8–10 samples	% RSD ≤10% for all analytes
Certified and Standard Reference Materials	Two per batch of 20 samples	Within 10% of the accepted values for >85% of the certified analytes
Method Blank	Two per batch of 20 samples	<2 analytes to exceed 5x method detection limit
Matrix Spike and Spike Method Blank	Two per batch of 20 samples	85–115%
Lab Duplicate	Two per batch of 20 samples	RSD <15% for 75% of analytes

Electronic balances used for weighing samples and reagents were calibrated prior to each use with their internal electronic calibration and then verified with certified standard weights (NIST-traceable). All pipets (electronic or manual) were calibrated prior to use. Each of the spectrometers used for metal analysis was initially standardized with a three- to five-point calibration; a linear correlation coefficient of $r \geq 0.999$ was required before experimental samples could be analyzed. Analysis of complete three- to five-point calibrations or single standard checks occurred after every 8–12 samples until all analyses were complete. The RSD between complete calibration and standard checks was required to be <10% or recalibration and reanalysis of the previous samples was performed.

All weighing-related manipulation of the filters used for suspended solids quantification took place under cleanroom conditions, including controlled temperature and relative humidity. Each filter was weighed twice in random order, with a minimum of 5% of the filters being weighed in triplicate. Static effects on filter weight were controlled by the placement of two ^{210}Po anti-static devices near the weighing-pan within the balance. The standard deviation in the weights for each filter had to be <2 μg for the value to be accepted.

Results and Discussion

The Results and Discussion presented below address our goals of determining the effectiveness of muck removal and its impact on sediment and water quality in Turkey Creek by connecting a variety of data sets, timeframes and concepts. We begin with results for the quantity of muck present before and after dredging. Next, we present data for the general composition of sediments, including muck, in Turkey Creek before and after dredging. Then, results for fluxes of dissolved N and P from muck sediments to the overlying water column throughout the dredging process are presented. The flux section is followed by an assessment of changes in water quality parameters during the complete study. Finally, results for our study of the DMMA are introduced and discussed.

Effectiveness of Muck Removal

Water depths and the presence and thickness of muck deposits were determined with ~30-m spatial resolution in Turkey Creek before dredging in February 2015 and after dredging in March 2017. Additional measurements were made with ~150 m resolution in the adjacent IRL (Figure 2). Our surveys spanned Turkey creek from the Florida East Coast (FEC) Railroad Bridge to the mouth of the creek (Figure 2). Dredging was limited by design to ~60% of the 160,000 m^2 of total area in the creek due to obstructions from docks and seawalls or the presence of known sand deposits that did not need to be dredged. Our data for water depths are separated into the (1) dredged area (n = 111) and (2) all of the creek (n = 195, Table 2). Most of our discussion will focus on the dredged area; however, data for the whole creek are included (Table 2 and elsewhere) for completeness. A definition of the dredged area and a pertinent map are presented below with results for the muck survey.

Water depths >4 m were found at <1% (n = 1) of the 111 sites surveyed prior to dredging (Table 2). After dredging, 64% (n = 71) of the same 111 sites had water depths >4 m when elevations were normalized to the initial survey (Table 2). The average water depth for pre- versus post-dredging increased from 2.1 to 3.8 m in the dredged area; maximum water depth increased from 4.4 to 6.0 m in the dredged area (Table 2). Increased water depths in dredged areas can modify water flow, increase bottom water residence times and influence water chemistry as discussed later in more detail.

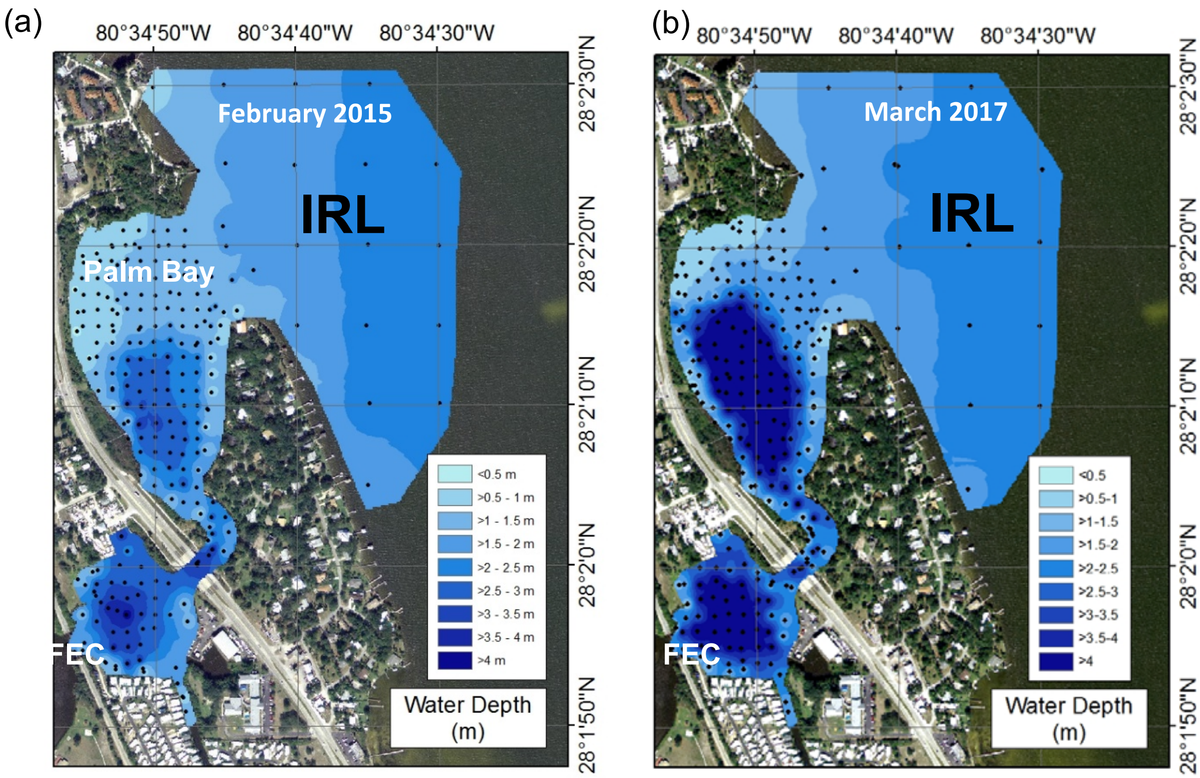


Figure 2. Contour maps of water depths in Turkey Creek from the Florida East Coast (FEC) Railroad Bridge to the adjacent Indian River Lagoon (IRL) during (a) February 2015, prior to dredging and (b) March 2017, ~2 months after dredging. Dots show probing locations.

Table 2. Groupings of normalized water depths for Turkey Creek before (February 2015) and after dredging (March 2017) for (*i*) the dredged area (n = 111) and (*ii*) the entire creek from the Florida East Coast Railroad Bridge to the mouth of the creek (n = 195).

Pre-dredging (February 2015)			**Post-dredging (March 2017)**		
Water Depth (m)	# of Locations		**Water Depth (m)**	# of Locations	
	Dredged Area	Entire Creek		Dredged Area	Entire Creek
0 – 1.0	11	42	0 – 1.0	2	27
>1.0 – 1.5	27	51	>1.0 – 1.5	3	28
>1.5 – 2.0	9	19	>1.5 – 2.0	20	30
>2.0 – 2.5	19	26	>2.0 – 2.5	3	9
>2.5 – 3.0	33	39	>2.5 – 3.0	3	11
>3.0 – 3.5	9	12	>3.0 – 3.5	8	10
>3.5 – 4.0	2	5	>3.5 – 4.0	6	9
>4.0 – 4.5	1	1	>4.0 – 4.5	24	26
>4.5 – 5.0	0	0	>4.5 – 5.0	21	24
>5.0 – 5.5	0	0	>5.0 – 5.5	15	15
>5.5 – 6.0	0	0	>5.5 – 6.0	6	6
Mean (m)	2.1 ± 0.9	1.9 ± 0.9	Mean (m)	3.8 ± 1.4	2.9 ± 1.6

Results from our pre- and post-dredge muck surveys showed that little or no muck was present in the adjacent IRL near the mouth of Turkey Creek (Figure 3a, b). This observation suggests that any muck carried to the mouth of the creek at the IRL was advected away from the immediate area. Likewise, little or no muck was found in shallow water (depth <1 m) at the northern reaches of Palm Bay, just west of the mouth of the creek (Figure 3a, b). In contrast, muck layers as thick as 3 m were found in 2- to 4-m deep water in the southern portion of the creek before dredging (Figure 3a).

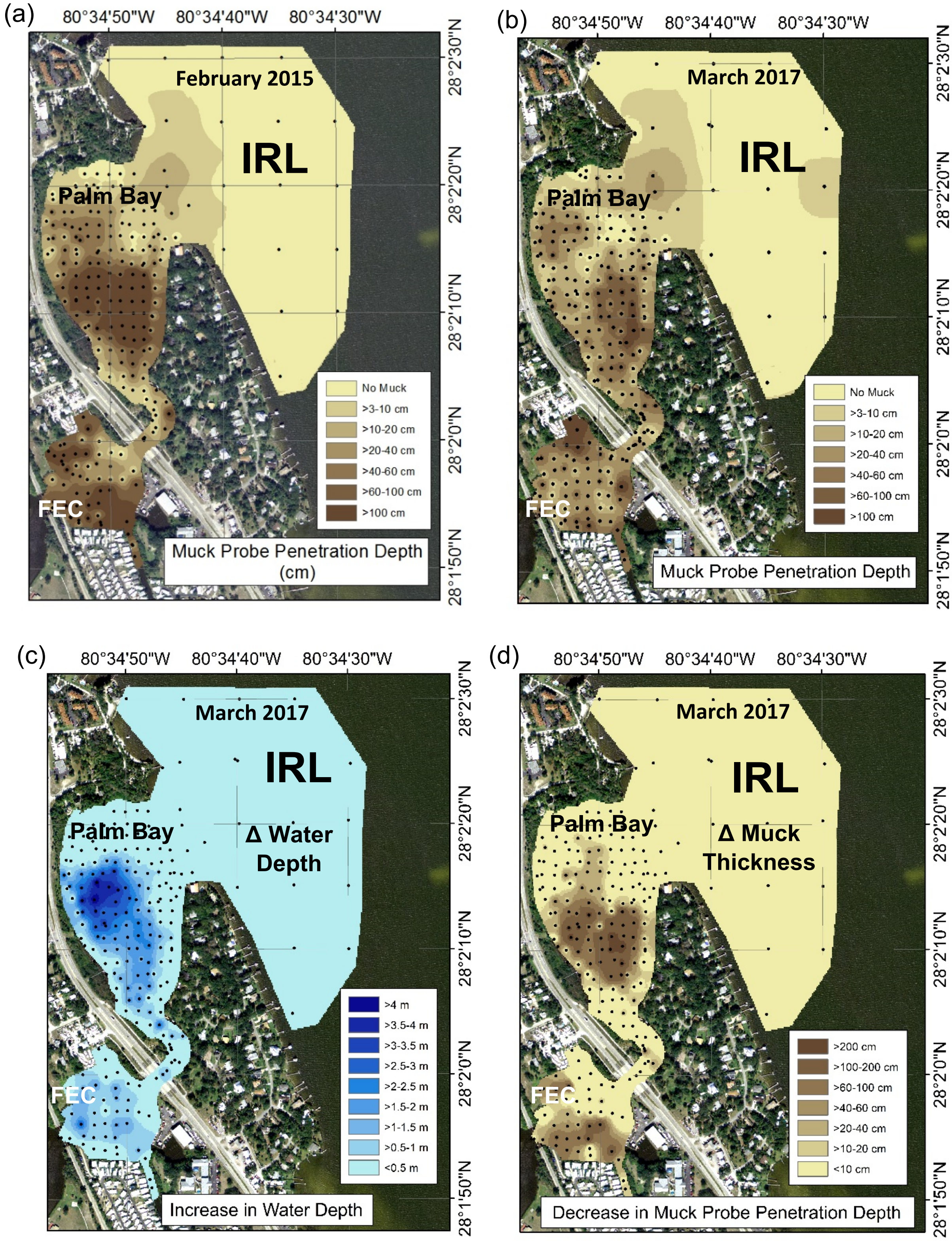


Figure 3. Contour maps of muck thicknesses in Turkey Creek from the Florida East Coast (FEC) Railroad Bridge to the adjacent Indian River Lagoon (IRL) (a) before dredging in February 2015 and (b) ~2 months after dredging in March 2017. Contour maps of (c) increases in water depths and (d) decreases in muck thicknesses (i.e., amount of muck removed) after dredging. Dots show probing locations.

Data for muck thicknesses from our pre-dredge survey (for all wet muck in Turkey Creek from the FEC Railroad Bridge to the mouth of the creek, n = 195) were used to calculate a total muck volume of 110,000 m^3 (~140,000 yd^3) for all of Turkey Creek, including the area to be dredged. Contractors for Brevard County initially determined a total muck volume of 382,000 $yd^3$for the same area based on data from ~40 locations that were obtained using a metal rod that in many cases penetrated 15–30 cm deeper than our PVC pipe, thereby yielding a larger muck volume. Contractors refined their estimate to 140,000 yd^3 for the same area based on data from 13 vibracores. This refined estimate agreed well with our calculation of 140,000 yd^3; however, we identified a different distribution of muck. The contractor used a muck thickness of zero for contouring at the boundary of the contoured areas (orange and yellow areas in Figure 4). This assumption most likely led to an underestimation of the muck present outside the specified dredged area. Our study extended contours from high resolution data (~30 m spacing) to the shoreline, thereby identifying muck adjacent to seawalls throughout Turkey Creek (Figure 5); thus, we calculated that ~30,000 m^3 of muck were initially present outside the area to be dredged.

After dredging, muck thicknesses in the dredged area (as defined on Figure 5) were >1 m in only 5% (n = 6) of the 111 survey sites relative to 28% (n = 31) of the sites before dredging (Table 3). Contour maps showing the increase in water depth and decrease in the muck layer (Figure 3c, d) are relatively well matched with the dredge cuts (Figure 5).

Table 3. Groupings of observed muck thicknesses for Turkey Creek before (February 2015) and after dredging (March 2017) for the dredged area (n = 111) and the entire creek from the Florida East Coast Railroad Bridge to the mouth of the creek (n = 195).

Pre-dredging (February 2015)				**Post-dredging (March 2017)**		
Muck Thickness (m)	# of Locations			**Muck Thickness (m)**	# of Locations	
	Dredged Area	Entire Creek			Dredged Area	Entire Creek
0	19	50		0	29	56
>0 – 0.10	16	25		>0 – 0.10	11	17
>0.10 – 0.25	5	13		>0.10 – 0.25	21	35
>0.25 – 0.50	19	28		>0.25 – 0.50	22	39
>0.50 – 0.75	12	21		>0.50 – 0.75	15	24
>0.75 – 1.0	9	14		>0.75 – 1.0	7	14
>1.0 – 1.5	4	15		>1.0 – 1.5	3	5
>1.5 – 2.0	5	7		>1.5 – 2.0	1	2
>2.0 – 2.5	8	8		>2.0 – 2.5	2	3
>2.5 – 3.1	14	14		>2.5 – 3.1	0	0
Mean (m)	0.9 ± 1.0	0.7 ± 0.8		Mean (m)	0.3 ± 0.4	0.3 ± 0.4

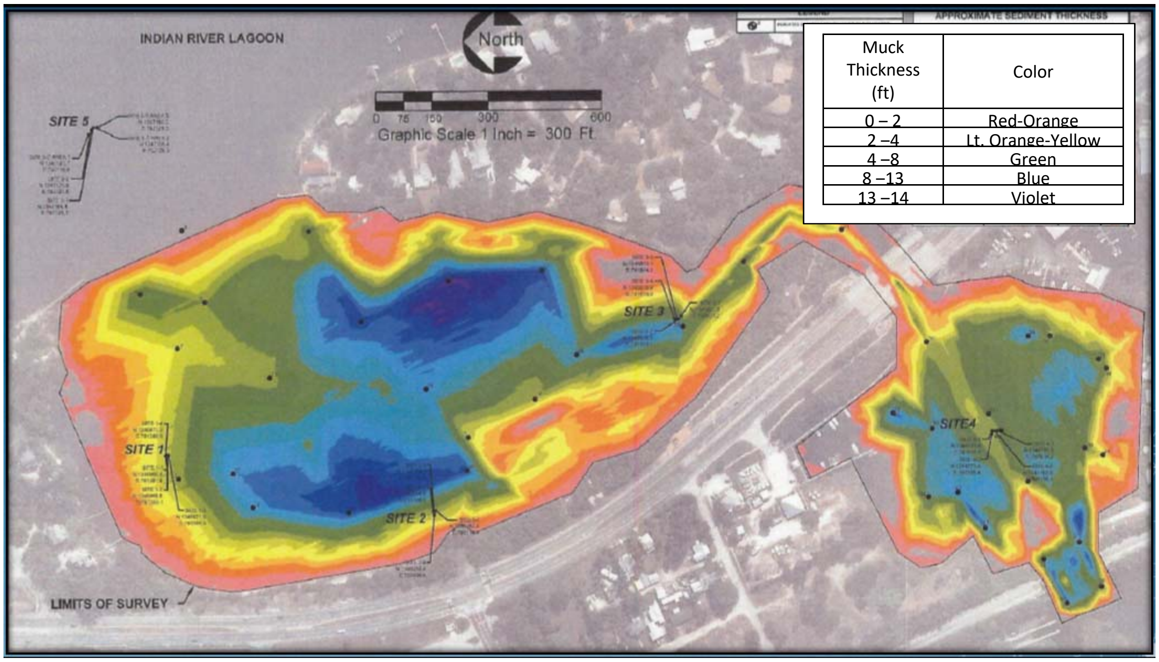


Figure 4. Contour map showing muck thicknesses in Turkey Creek that were used by the contractor to determine dredge cuts. Dots (n = ~40) show coring locations. Image credit: Brevard County Natural Resources.

Our post-dredge survey (March 2017) determined that 52,000 m^3 (78,000 yd^3) of muck, >60% of the pre-dredge muck volume of 80,000 m^3 were no longer present in the dredged area after dredging (Table 4). This removal estimate was likely low because an estimated 1,000 m^3 of muck slumped back into the dredge area prior to our survey influenced by impacts from Hurricane Matthew in early October 2016. We also estimated that as much as greater than half of the total material dredged was lower water content sediments.

Muck remaining in the dredged area was most likely due to (1) not dredging deep enough to remove all the muck (Figure 6a, b) and (2) slumping of muck onto newly exposed sand from areas not dredged deep enough to remove all the muck (Figure 6b, c). Twenty three percent (25/111 stations) of sites located within the dredged area contained muck at water depths shallower than pre-dredge total bottom depths suggesting incomplete dredging. Muck at these sites accounted for ~16,000 m^3 or ~50% of the 31,000 m^3 of muck remaining in the dredged area and ~30% of the 54,000 m^3 of muck remaining in Turkey Creek (Table 4). Muck also was identified at 50% of the locations that were dredged below the bottom of muck layers identified during our pre-dredge survey; this muck most likely slumped in from surrounding areas to cover freshly exposed sand (Figure 6c).

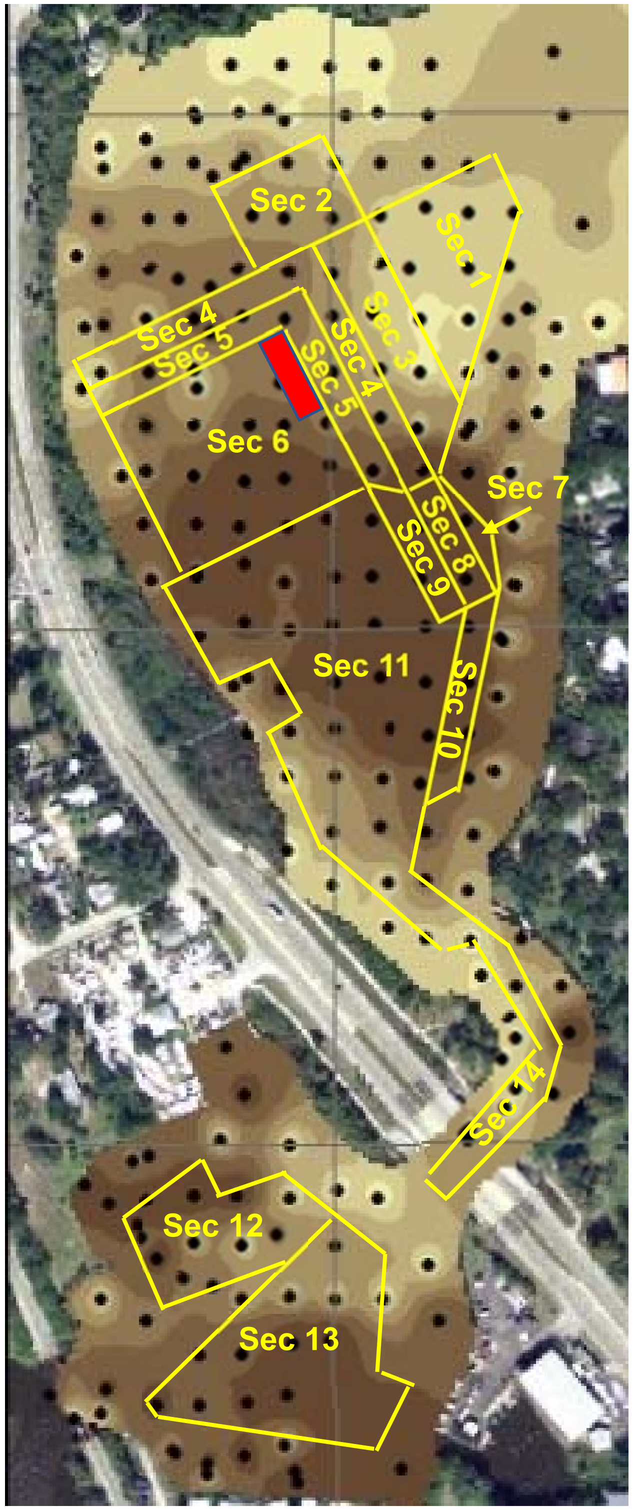
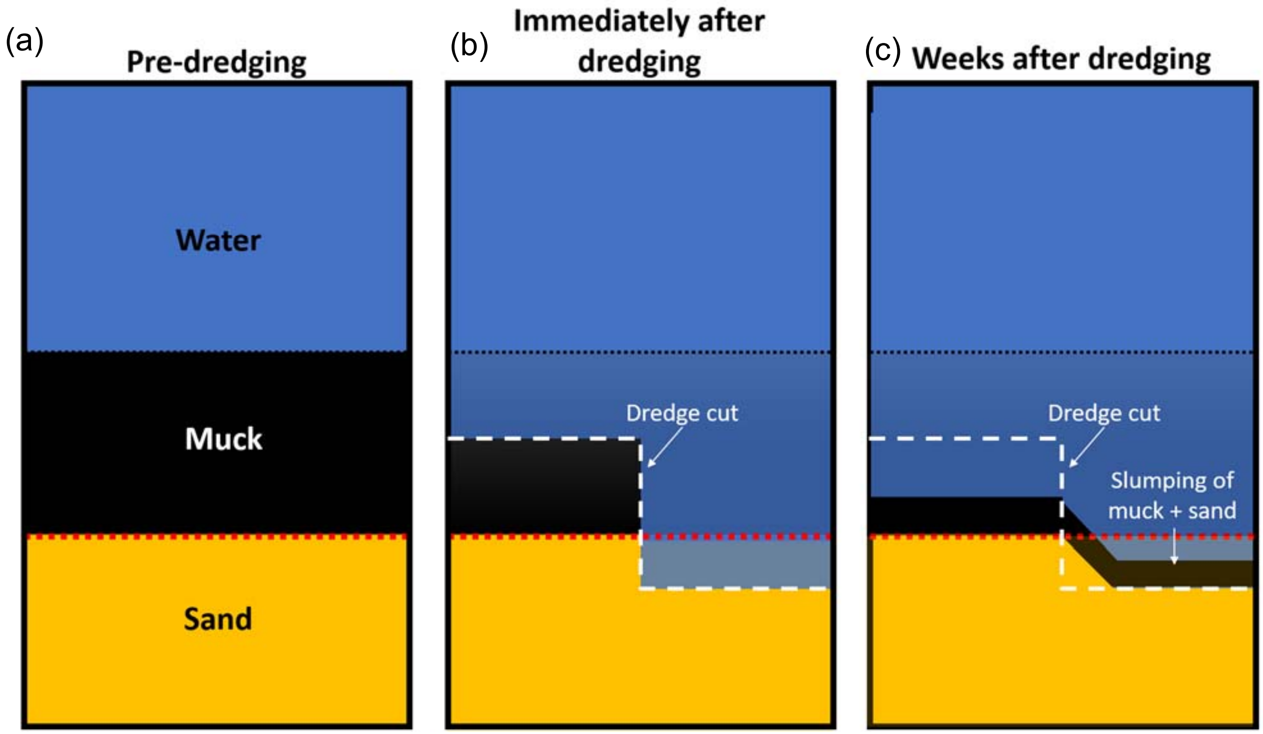


Figure 5. Contour map of muck thicknesses in Turkey Creek before dredging in February 2015 with overlying dredge cuts SEC-1 to SEC-13 (yellow lines). Image credit for dredge cuts: Brevard County Natural Resources. (■) identifies location where image in Figure 6d was obtained.



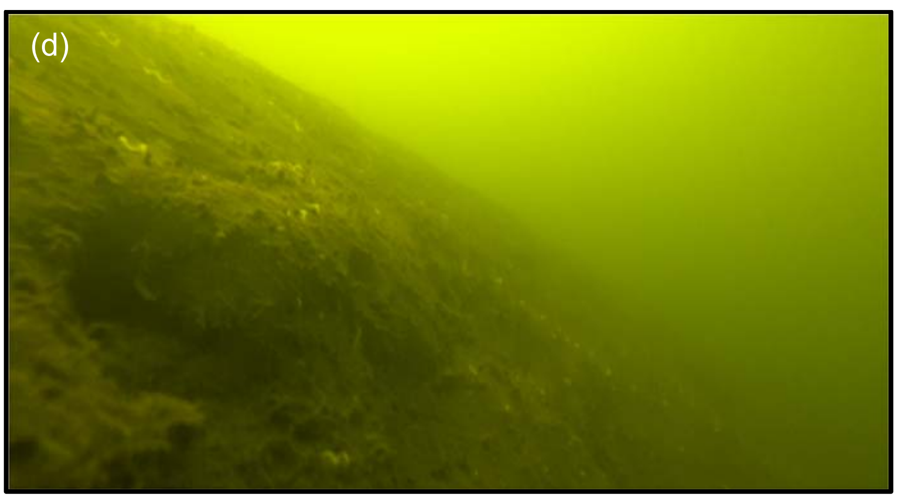


Figure 6. Schematic diagram illustrating sections of vertical and horizontal dredge cuts (white dashed lines) (a) before dredging, (b) after muck was incompletely dredged adjacent to a section where dredging extended deep enough to reach the sand below the muck deposit and (c) slumping of muck along the boundary between sections. (d) Image showing the boundary between SEC-5 and SEC-6 (location shown on Figure 5).

Table 4. Volume of muck in all of Turkey Creek (from the Florida East Coast Railroad Bridge to the mouth of the creek) and in the dredged and non-dredged area of the creek.

Location	Volume (m^3) Before	Volume (m^3) After	Volume (m^3) Removed	% Change
Turkey Creek (n = 195)	107,000	54,000	53,000	-50%
Dredged Area (n = 111)	83,000	31,000	52,000	-63%
Non-Dredged Area (n = 84)	24,000	23,000	1,000	-4%

At least sixty three percent (71/111) of sites were dredged an average of 1m below the muck layer (from our pre-dredge survey) and ~100,000 m^3 (130,000 yd^3) of material were dredged from below muck deposits. Based on our data and a total of 160,000 m^3 of material reported to be dredged (McGarry 2017, personal communication) from Turkey Creek, ~40% of the dredged material was muck (probe penetrable) and 60% was lower water-content sediments dredged from below probe-penetrable muck deposits. About 30% of sites that were dredged below the bottom of the muck deposit retained a sandy bottom after dredging. The net result was migration of muck towards deeper water as shown graphically by the increase in number of sites containing muck in the dredged area with water depths >4 m, an increase from 1 site before dredging (Figure 7a) to 66 sites after dredging (Figure 7b and Table 2).

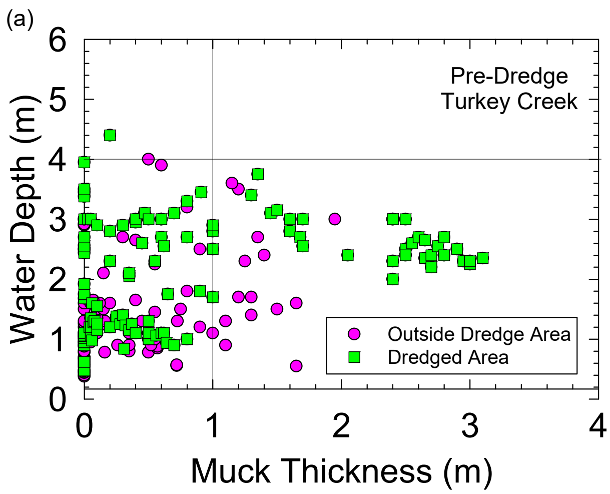


Figure 7. Normalized water depth versus thickness of the muck layer for Turkey Creek (a) before dredging (February 2015) and (b) after dredging (March 2017). Dredged and not dredged sites include 111 and 84 data points, respectively. Vertical solid lines at 1 m (muck thickness) and horizontal lines at 4 m (water depth) were added to help cross reference the graphs.

Sediment Composition

Sediment composition and OM content have long been shown to be important factors in explaining the abundance and diversity of benthic biota (e.g., Stoker, 1981; Graf, 1989). In Turkey Creek, Beckett (2016) and Johnson and Shenker (2016) have demonstrated that muck is essentially uninhabitable, most likely because of very high concentrations of H_2S. In contrast, sandy muck can have significantly greater species abundance and diversity. Therefore, it is important to track changes in sediment composition that accompany dredging.

The water content and chemical composition of surface sediments in Turkey Creek are highly variable as a function of the relative amounts of sand, silt and clay in the sample. For example, the water content of surface sediments in Turkey Creek ranged from ~46% (by volume) in sandy sediments to ~96% in muck (Figure 8). Sediment OM also varied widely from 1.6% in sandy sediments to 22% in muck (Figure 9). Using the 1989 definition of IRL muck (>75% water by weight (90% by volume), >60% silt + clay and >10% OM, Trefry and Trocine 2011), 12 of the 24 samples collected in Turkey Creek before and after dredging fit the parameters listed above for IRL muck (Table 5). No significant differences (i.e., $p < 0.05$) were found in the composition of muck collected before versus after dredging, with the exception of water content (H_2O by mass, 88.2% before and 83.4% after dredging, $p = 0.040$). The lack of differences for most components before and after dredging is reasonable because all muck samples were essentially the same Turkey Creek muck. The significant difference for water content may be due to the removal of a less consolidated layer of muck that exposed a more consolidated, deeper layer with lower water content.

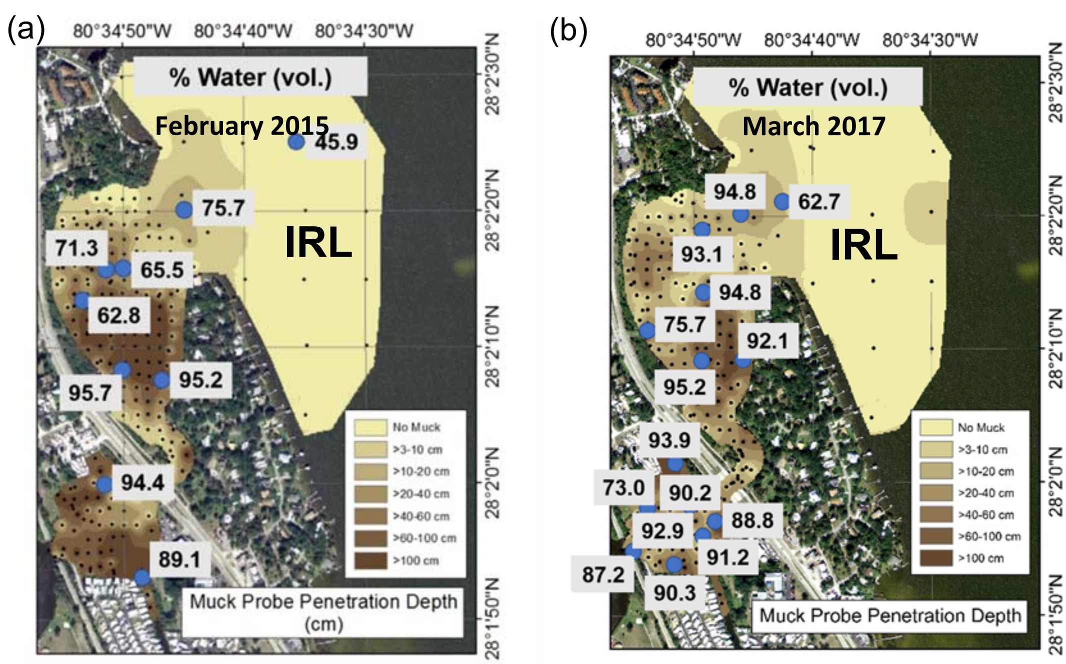


Figure 8. Contour maps for muck thicknesses in Turkey Creek and the adjacent Indian River Lagoon (IRL). Blue dots show where surface sediments were collected. Numbers show % water in sediments by volume (a) before dredging in February 2015 and (b) ~2 months after dredging in March 2017.

Table 5. Averages ± standard deviations for parameters in muck sediment from Turkey Creek (n = 12). (LOI = Loss on Ignition at 550 °C, TOC = Total Organic Carbon)

	Gravel (%)	Sand (%)	Silt + Clay (%)	LOI (%)	$CaCO_3$ (%)	Al (%)
TC Muck	0.5 ± 0.9	13.9 ± 10.8	85.5 ± 10.6	18.9 ± 2.4	13.6 ± 3.9	4.0 ± 0.7

	Fe (%)	Si (%)	TOC (%)	H_2O (wt. %)	H_2O (vol. %)	N (%)	P (%)
TC Muck	3.7 ± 0.7	18.6 ± 2.2	6.7 ± 0.8	84.5 ± 3.7	93.6 ± 1.6	0.70 ± 0.17	0.14 ± 0.02

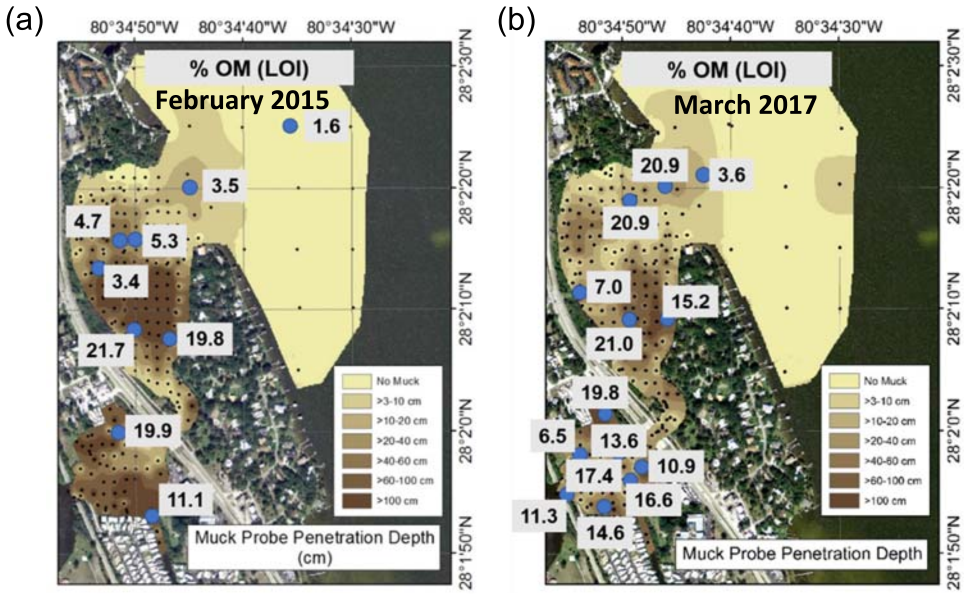


Figure 9. Contour maps for muck thicknesses in Turkey Creek and the adjacent Indian River Lagoon (IRL). Blue dots show where surface sediments were collected. Numbers show % organic matter (OM from LOI at 550ºC) of sediments (a) before dredging in February 2015 and (b) ~2 months after dredging in March 2017.

Sediments collected from Turkey Creek showed a predictable continuum of composition (e.g., TOC, TP, TN) in response to the relative amounts of muck and sand. Strong correlations were found between (1) TOC and LOI, (2) total P and TOC, (3) total N and TOC and (4) total P and total N (Figure 10). When data from pre-, mid- and post-dredging surveys were plotted on these four plots, essentially all data fit the trends observed for the pre-dredge muck (Figure 10). These results confirm the previous statement that no significant differences in the chemical composition of unmixed muck were identified, before, during or after dredging.

The plots also show several other insights about muck composition. The slope of the line for TOC versus LOI was 0.35 for the pre-dredge data; this slope suggests that OM collected in Turkey Creek averages ~35% C. Concentrations of TOC correlated very strongly with total P and total N (Figure 10b, c). Muck samples had an average C/P molar ratio of 120, close to the Redfield ratio of 106 (published C/N/P atomic [molar] ratio of 106/16/1 in phytoplankton and in deep seawater by Redfield, 1934, Figure 10b). The C/P ratio for the non-muck samples was less reliable because of the very low amounts of OM present in the sediment. The average molar ratio of 10.6 for N/P was ~35% lower than 16 predicted by the Redfield ratio (Figure 10b). This result supports N release from and depletion in sediment as well as possible precipitation of inorganic P in sediments. The TOC and total N values are for organic C and organic N in sediments whereas total P values include both organic and inorganic P; inorganic P may be associated with weathered phosphorite rock or phosphorus sorbed to inorganic particles and could lead to N/P ratios lower than the Redfield ratio.

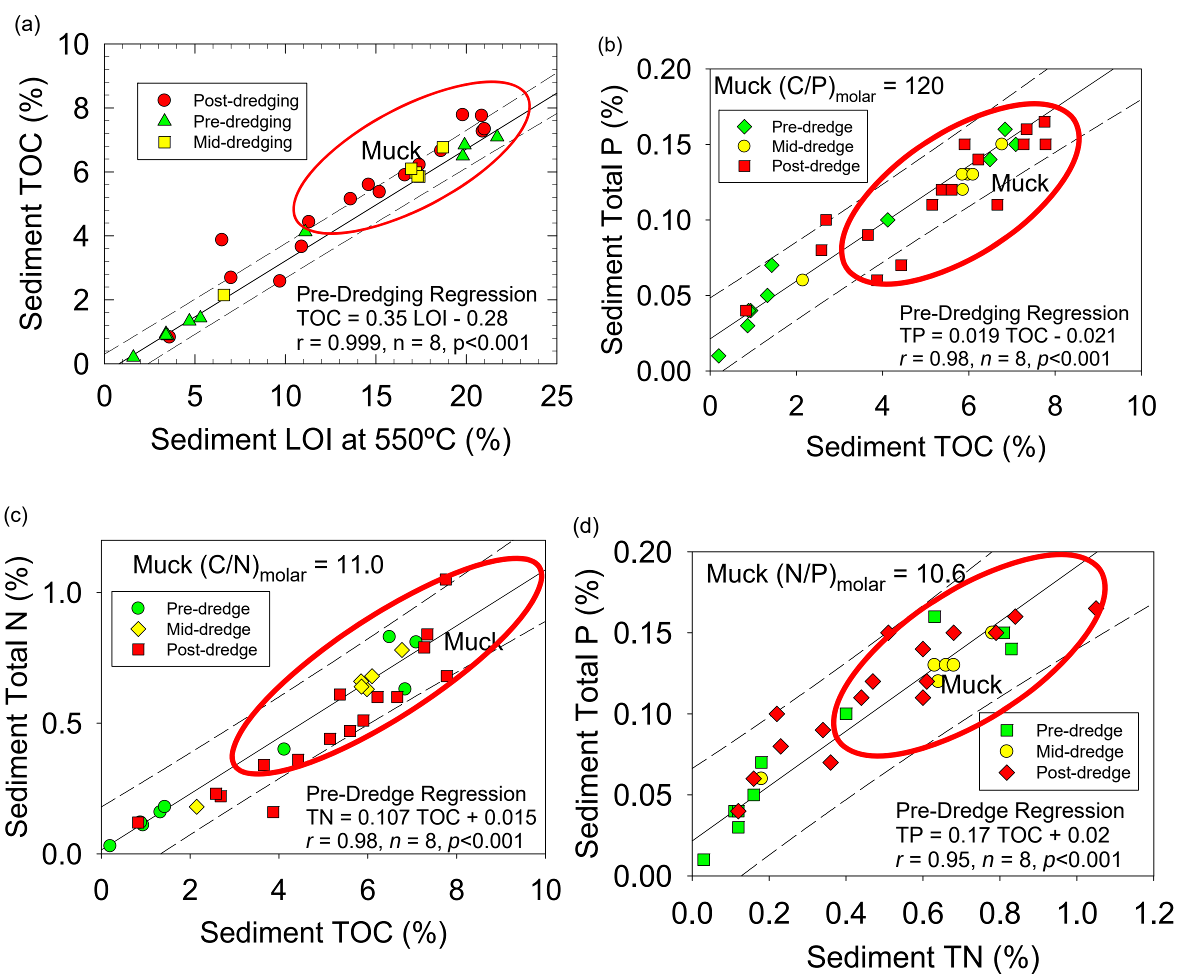


Figure 10 (a) Sediment total organic carbon (TOC) versus sediment Loss on Ignition (LOI) at 550°C, (b) sediment total phosphorus (TP) versus sediment TOC, (c) sediment total nitrogen (TN) versus TOC and (d) sediment TP versus TN. Muck samples plot within the ovals on (a–d). The molar ratio for the muck samples is listed next to each oval. Solid lines and equations on each graph are from linear regression analysis of the re-dredge data, dashed lines show 95% prediction intervals, *r* is the correlation coefficient and *p* is the *p* statistic.

Using average values for surface sediments from Turkey Creek (~85% water by volume and a density of dry sediments of 2.7 g/cm^3), the 160,000 m^3 of wet sediment removed from Turkey Creek had a total mass of ~65,000 metric tons (dry weight). Based on the typical pre-dredging composition of average sediments from Turkey Creek (containing muck, sand and sandy-muck) at 0.36 ± 0.30% N and 0.08 ± 0.05% P, and the removal of 160,000 m^3 of muck, we calculate the removal of ~200 metric tons of N and ~50 metric tons of P from Turkey Creek.

Sediment cores collected at the same four locations before and after dredging showed changes in chemical composition as a function of whether (1) muck was dredged to sand, (2) muck was not completely dredged or (3) sand was dredged, but replaced by muck. Two cores (stations TC5 and TC6) contained muck (high water content) before dredging. After dredging, both stations contained a thin layer (~2 cm) of muck, above ~5–10 cm of muck mixed with sand, and then sand (low water content) deeper in the core (Figure 11a, b). At station TC4, cores from before and after dredging contained muck because this site was only partially dredged (Figure 11c). The fourth site (TC3, original water depth = 1.1 m) contained sand before dredging; however, after dredging to a water depth of 3.8 m, the newly-formed basin accumulated ~30 cm of muck (Figure 11d). Values for the other sediment parameters (e.g., TOC, TN, TP, Al) increased directly with increased muck content as discussed above (Figure 10). Down-core trends in water content are controlled by pressure from sediment accumulation that promotes upward advection of water and a decrease in water content. This loss in water content is accompanied by essentially no changes in concentrations of Al, TOC and other sediment chemicals on a dry weight basis (Figure 12).

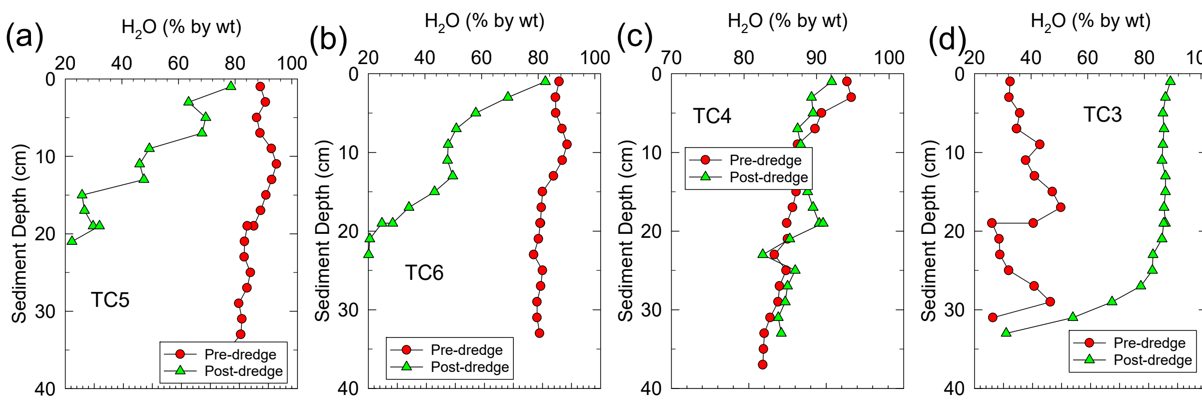


Figure 11. Vertical profiles for water content before and after dredging in sediment cores from stations (a) TC5, (b) TC6, (c) TC4 and (d) TC3. Locations in Figure 1b.

Interstitial Water Composition

Decomposition of organic matter in muck leads to high concentrations of dissolved N and P in the abundant interstitial water of these organic-rich sediments. Higher values of dissolved N in sediments interstitial water, virtually all as ammonium were found deeper than ~10 cm in each core (Figure 13a–d). Ammonium concentrations were lowest in surface sediments before and after dredging due to diffusion of ammonium to the overlying water (Figure 13a–d). Before dredging, concentrations of ammonium were very high in muck (relative to sand) with maximum values of

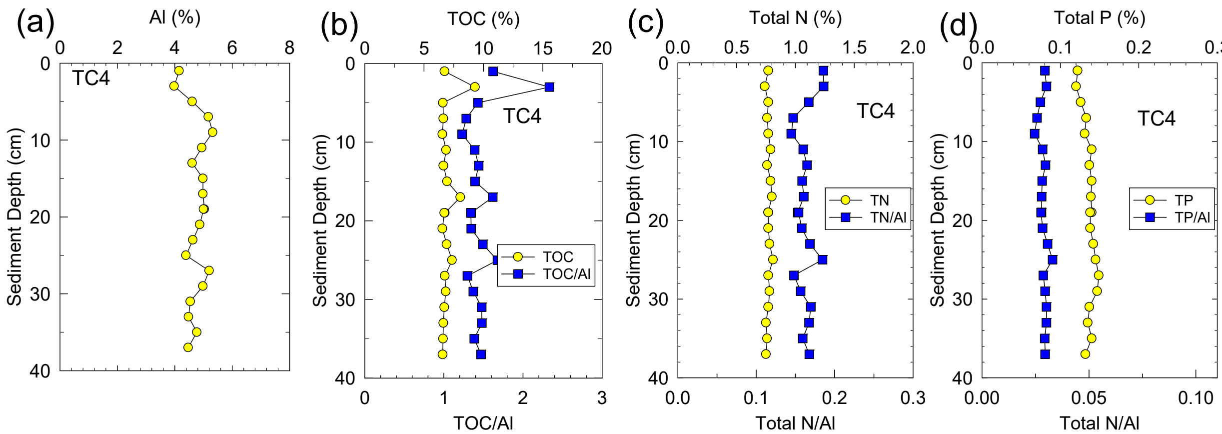


Figure 12. Vertical profiles for (a) aluminum, (b) total organic carbon (TOC), (c) total nitrogen and (d) total phosphorus plus ratios of each component to aluminum (Al) for a sediment core from station TC4.

~2000–6000 µM (28–84 mg N/L; Figure 13a–d). Ammonium concentrations in sandy sediments were all <200 µM (2.8 mg N/L). After dredging, concentrations of ammonium followed patterns for water content with >80% lower values at sites TC5 and TC6 because dredging removed muck and left mostly sand with a surface layer of mixed sand and muck (Figure 13a, b). At station TC4, where muck was not directly dredged, ammonium values in interstitial water were ~50% lower after dredging in March 2017 than in October 2016 before dredging. This observation follows observed seasonal trends where large amounts of ammonium produced during the summer are still present in the interstitial water in October. Then, cooler winter temperatures decrease ammonium production from December to March when the cycle begins again. Highest ammonium values in interstitial water (>10,000 µM) were found in muck that slumped in over the original sandy bottom at station TC3 (Figure 13d).

Interstitial water phosphate distributions before and after dredging followed the same trends observed for ammonium with much higher values in muck than sand or sandy muck (Figure 13e–h). Thus, interstitial phosphate concentrations were much lower at stations 5 and 6 after dredging due to removal of muck, only slightly changed at station 4 and increased in the new muck at station TC3 (Figure 13e–h).

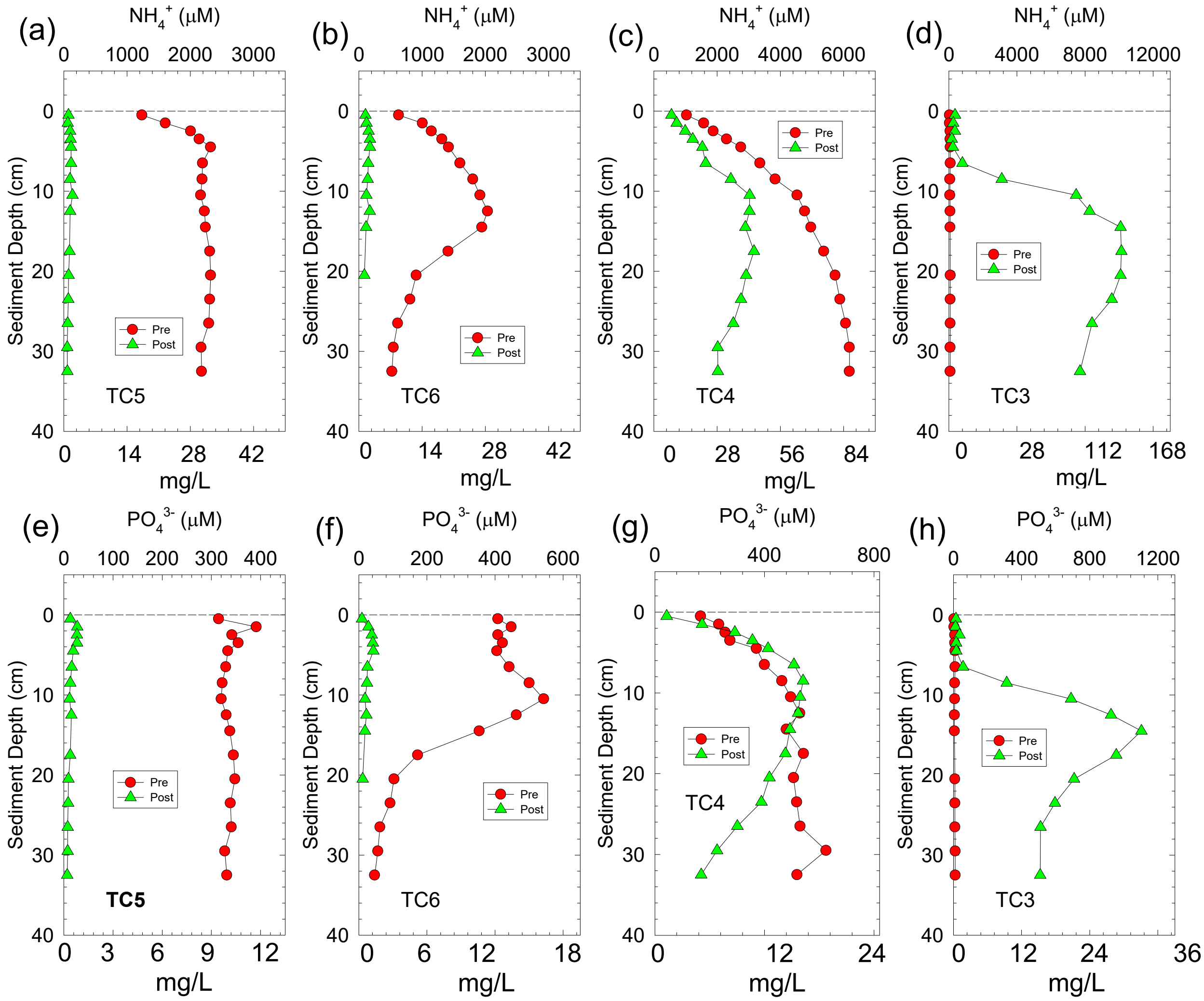


Figure 13. Vertical profiles for (a–d) ammonium and (e–h) phosphate in interstitial water before (pre) and ~3 months after (post) dredging at stations TC5, TC6, TC4 and TC3.

Concentrations of sulfide in interstitial water also were lower after dredging at three of the four stations, excluding sediment from station TC3 where muck covered sand after dredging (Figure 14). Clearly, the sediment redox environment changed. For example, the Eh at station TC4 shifted from -149 to -70 mV after dredging (Table 6) due to downward mixing of oxygenated lagoon water into sediments and cooler temperatures. Similar, but smaller increases in Eh were observed after dredging at stations TC5 and TC6. Oxygen was essentially absent from all muck cores (Table 6). The toxicity of H_2S would be much lower at stations TC4, TC5 and TC6 after dredging, thereby increasing the likelihood of finding benthic biota. These observations are at least partially due to seasonal variations in the composition of interstitial water as described above for ammonium.

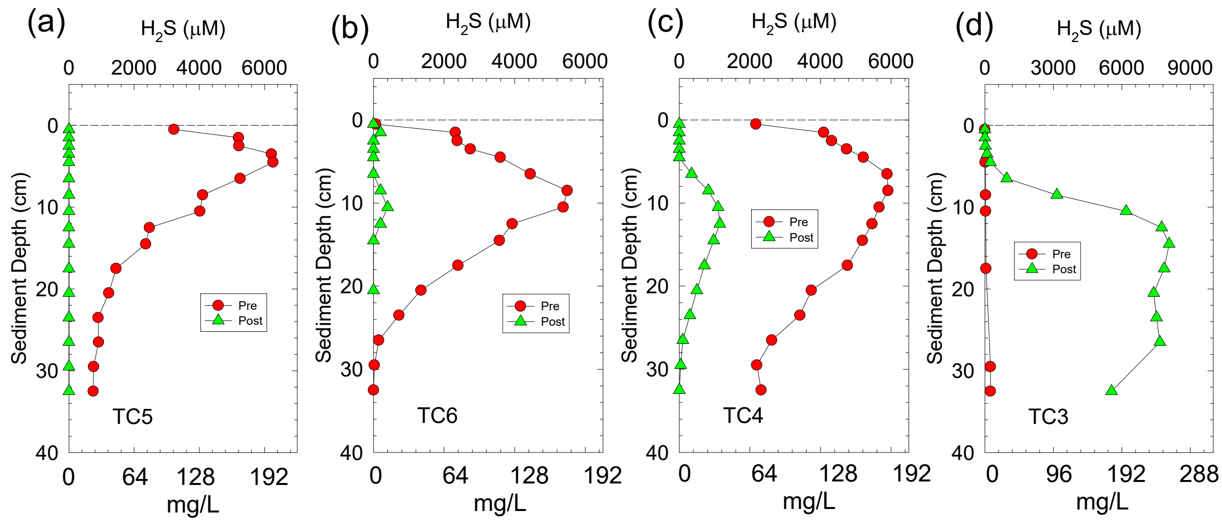


Figure 14. Vertical profiles for sulfide in interstitial water before (pre) and ~3 months after (post) dredging from stations (a) TC3, (b) TC4, (c) TC5 and (d) TC6.

Table 6. Redox potential (Eh) for surface sediments (5 mm) and dissolved oxygen saturation at the sediment-water interface before and after dredging. Values in parenthesis indicate the depth in sediments (mm) that contained oxygen.

	Eh (mV) Before Dredging	Eh (mV) After Dredging	O_2 (% saturation) Before Dredging	O_2 (% saturation) After Dredging
TC3	-116	-126	5 (2 mm)	0
TC4	-149	-70	0	<1 (>5 mm)
TC5	-79	-45	0	0
TC6	-32	-0.4	0	0

Benthic Fluxes of Nitrogen and Phosphorus

Pre-dredging fluxes (releases) of N and P from muck to the overlying water were determined using two different methods (interstitial water profiles and Quick-Flux). Average fluxes ranged from 0.1 mg N/m^2/hr (multiply by 8.8. to obtain tons N or P/km^2/yr) and 0.01 mg P/m^2/hr in sandy sediments at station TC3 to 8.6 mg N/m^2/hr and 1.7 mg P/m^2/hr in muck at station TC6 (Table 7). Fluxes of ammonium and phosphate (TC4, TC5 and TC6) before dredging were relatively uniform among stations containing muck with mean values of 6.9 ± 2.0 mg N/m^2/hr and 1.3 ± 1.1 mg P/m^2/hr. When these values are applied to the entire 0.12 km^2 surface area of muck in Turkey Creek, the pre-dredging fluxes of N and P for the study area in Turkey Creek was 0.8 kg N/hr (7 tons N/year) and 0.2 kg P/hr (1.4 tons P/year), respectively.

Post-dredging, fluxes of N and P from muck averaged 2.3 ± 1.5 mg N/m^2/hr and 0.3 ± 0.3 mg P/m^2/hr, respectively (Table 7). Following dredging, Quick-Flux was used to enhance spatial resolution for flux data with 28 sites throughout Turkey Creek, 19 containing muck. Fluxes of N and P varied spatially with the highest values (>3 mg N/m^2/hr) in the southern portion of Palm Bay between Highway US-1 and the mouth of the creek and high values (>1.5 mg-N/m^2/hr) in pockets of muck that remained after dredging throughout the study area (e.g., Figure 15a). Spatial variations in fluxes were best explained by sediment water content (Figure 15b). Overall, lower fluxes of N and P after dredging result in calculated load reductions of ~3 tons of N and ~1 ton of P annually. Lower calculated fluxes of N and P after dredging were mostly due to lower concentrations of ammonium and phosphorus in interstitial water (Figures 13) because a (<20%) difference in the surface area of muck occurred from dredging. Releases of N and P from muck remaining in Turkey Creek are more likely to vary with time and temperature relative to reductions in flux due to a change in the composition of sediment (e.g., from muck to sand). We will continue to monitor benthic fluxes.

Table 7. Pre- and post-dredging fluxes of N and P determined from interstitial water profiles and the Quick-Flux technique along with supporting information.

Pre-Dredge				Flux (mg/m^2/hr)[1]			
				Ammonium-N		Phosphate-P	
Station	Sediment Type	Date	Temp. (°C)	Interstitial Water	Quick-Flux	Interstitial Water	Quick-Flux
TC3	Sand	Oct 2015	25.0	0.1 ± 0.1	0.1 ± 0.0	0.01 ± 0.02	0.01
TC4	Muck	Oct 2015	25.0	8.6 ± 6.3	5.6 ± 0.0	1.0 ± 0.9	0.77
TC5	Muck	Feb 2016	16.4	8.6 ± 7.8	ND[2]	1.4 ± 1.8	ND[2]
TC6	Muck	Feb 2016	16.4	5.0 ± 3.5	ND[2]	1.7 ± 2.4	ND[2]

[1]Tons/km^2/yr = 8.8 x mg/m^2/hr [2]Not determined.

Post-Dredge				Flux (mg/m^2/hr)[1]			
				Ammonium-N		Phosphate-P	
Station	Sediment Type	Date	Temp. (°C)	Interstitial Water	Quick-Flux	Interstitial Water	Quick-Flux
TC3	Muck	Mar 2017	23.2	1.5 ± 2.5	3.1 ± 1.6	0.09 ± 0.06	0.03
TC4	Muck	Mar 2017	23.3	3.8 ± 3.2	4.4 ± 0.9	0.84 ± 0.12	0.63 ± 0.03
TC5	Sandy-Muck	Apr 2017	25.0	0.4 ± 0.4	1.1 ± 0.3	0.09 ± 0.03	0.08 ± 0.0
TC6	Sandy-Muck	Apr 2017	25.1	0.4 ± 0.4	0.7 ± 0.04	0.06 ± 0.00	0.06 ± 0.0

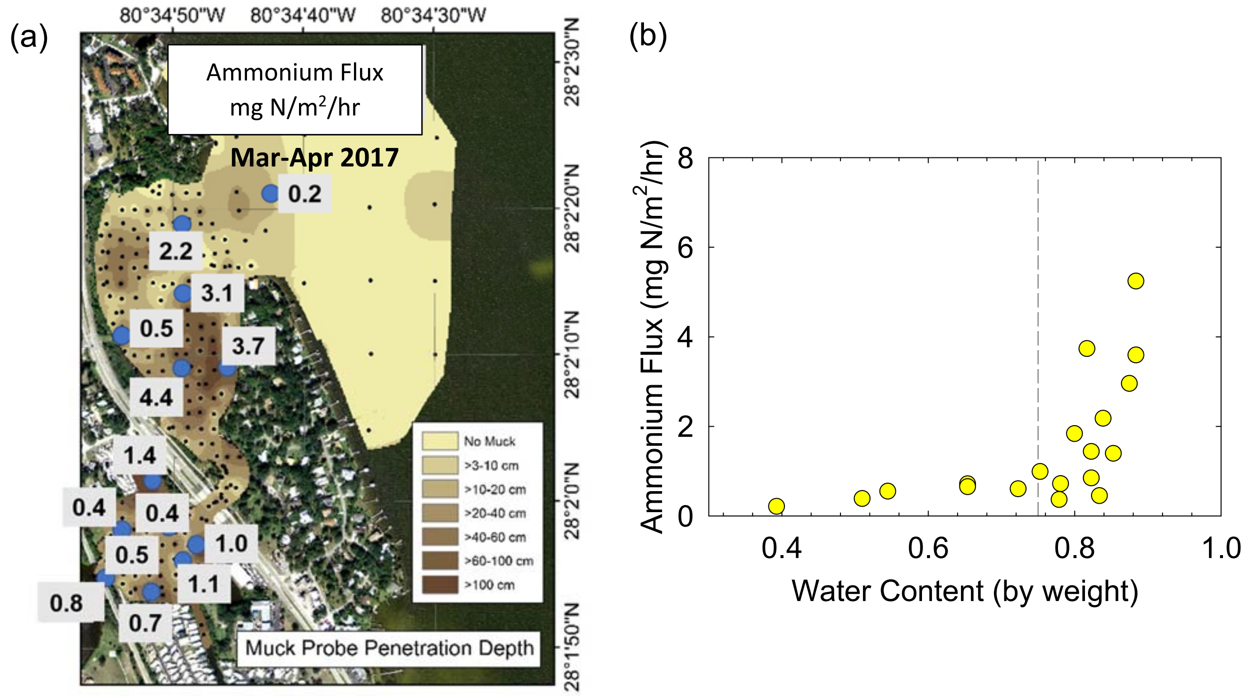


Figure 15. (a) Map showing fluxes of ammonium from sediments at sites with (b) matching data for water content from Turkey Creek after dredging as determined by the Quick-Flux technique that had not been developed and validated before dredging began.

Fluxes of Nitrogen and Phosphorus Over Time.

The convenience of the Quick-Flux technique enabled us to initiate a time series of measurements for benthic fluxes of N and P at stations TC3 and TC5 in September 2016. Station TC3 was dredged during March 2016 and subsequently accumulated a thin layer of muck that spurred fluxes of 3.6 mg N/m^2/hr and 1.1 mg P/m^2/hr in September; these values are >15-times higher than found in the sandy sediments at this site before dredging. Soon after this first sampling of the time series, Hurricane Matthew moved through the area and resuspended muck sediments and caused large-scale erosion in the IRL. Post-hurricane nutrient fluxes at station TC3 peaked at >50 mg N/m^2/hr and >3.5 mg P/m^2/hr in October 2016 (Figure 16a). After this storm-induced peak, fluxes decreased over the winter to 2.9 mg N/m^2/hr and 0.02 mg-P/m^2/hr in April 2017 due to cooler temperatures. Station TC5 was not dredged before Hurricane Matthew, yet fluxes increased following the hurricane and peaked at >5.5 mg N/m^2/hr and >0.4 mg P/m^2/hr, respectively (Figure 16b). Fluxes also decreased over winter at station TC5 (Figure 16b). We are continuing the time series with plans to initiate additional time series and to investigate small-scale variations in nutrient fluxes during the next year.

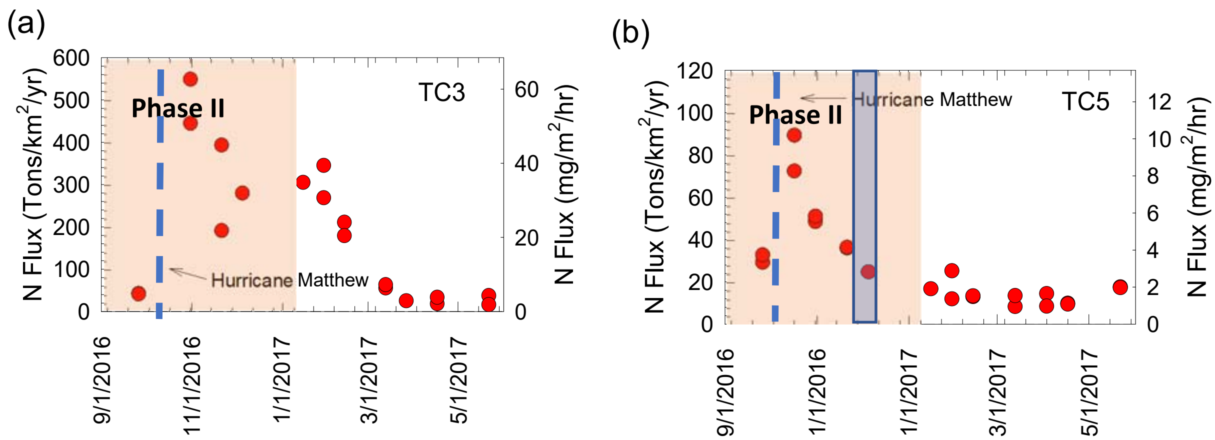


Figure 16. Fluxes of N from sediments over time at stations (a) TC3 and (b) TC5. Dashed vertical lines indicate the passing of Hurricane Matthew (October 6–7, 2016). Dredging took place at station TC3 during March 2016 (not shown on a) and at station TC5 during November–December 2016 (shaded rectangle). Dredging in Turkey Creek began in February 2016 and continued until January 2017 (shaded area).

Water Quality throughout the Dredging Process

Increased turbidity and diminished water quality are concerns typically associated with estuarine and coastal dredging (Morton, 1977; Johnston, 1981; Fisher et al., 2015). For this study, monthly surveys were carried out throughout the dredging process to assess water quality (April 2015–May 2017, stations TC1–TC5; map in Figure 1b, page 3). Salinity, temperature, Secchi depth, TSS, turbidity, dissolved oxygen, pH, dissolved N and P species and other parameters were investigated. Results for turbidity are presented first, followed by salinity, dissolved oxygen and nutrients.

Secchi depth, TSS and turbidity (light scattering) were determined throughout the study to identify anomalous particle plumes. We have previously shown, as part of this and other projects, strong relationships among these three parameters (Trefry et al., 2007, 2016, Figure 17). Secchi depth averaged 110 ± 37 cm before dredging at all locations (Table 8). No significant difference was found for Secchi depth during dredging versus before dredging (Table 8). However, the average Secchi depth after dredging was significantly greater than before or during dredging (Table 8). This simple overview, however, does not adequately describe a data set where Secchi depths ranged from 30–200 cm as a function of several non-dredging related factors (Figure 18).

Coincidently, as Phase I dredging began in February 2016 near station TC3, the Secchi depth at all stations decreased from depths of ~ 100 cm to ~30 cm (Figure 18). This sharp decrease was due to an intense algal bloom (*Aureoumbra lagunensis*) that reached Turkey Creek and the adjacent IRL after a steady southerly progression over the previous two months. The impact of the algal plume was observed throughout the study area (Figure 18 a–c). No particle plumes of dredged material were observed or detected in the area of the dredge that was near station TC3 at the time of the algal bloom.

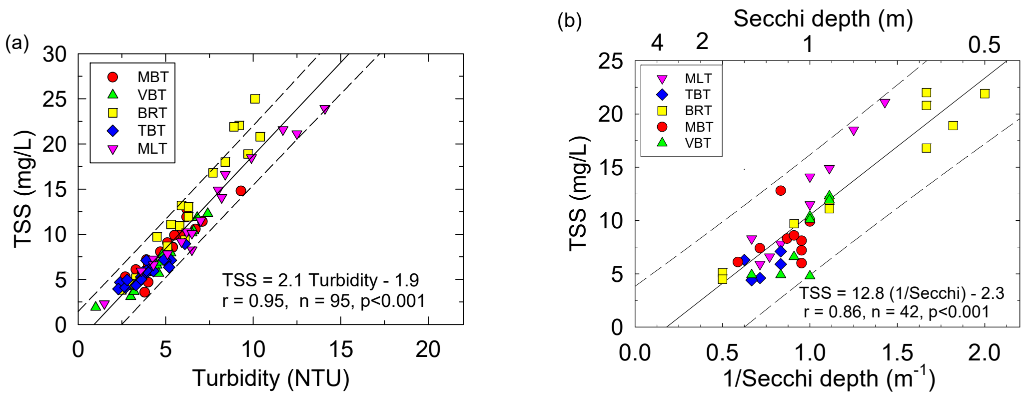


Figure 17. Concentrations of total suspended solids (TSS) versus (a) turbidity and (b) Secchi depth for areas of the Indian River Lagoon. (MBT = Melbourne Transect, VBT = Vero Beach Transect, BRT = Banana River Transect, TBT = Turnbull Creek Transect, MLT = Mosquito Lagoon Transect, data from Trefry et al., 2007). Solid lines and equations on each graph are from linear regression analysis, dashed lines show 95% prediction intervals, r is the correlation coefficient and *p* is the *p* statistic.

Table 8. Means ± standard deviations for Secchi depth and total suspended solids (TSS) in surface and bottom water for each (and all) station(s) during pre- (2015), during (2016) and post-dredging (2016–17) surveys.

Secchi depth (cm)	TC1	TC2	TC3	TC4	TC5	Grand mean
Pre-	127 ± 57	103 ± 33	91 ± 12	103 ± 35	125 ± 28	110 ± 37
During-	136 ± 59	108 ± 41	110 ± 37	115 ± 38	115 ± 31	116 ± 42
After-	178 ± 10	138 ± 5	148 ± 25	143 ± 29	138 ± 17	149 ± 23
Surface TSS (mg/L)	TC1	TC2	TC3	TC4	TC5	Grand mean
Pre-	5.8 ± 2.6	8.2 ± 4.3	8.5 ± 3.0	8.4 ± 3.1	4.2 ± 2.1	7.0 ± 3.4
During-	8.6 ± 8.5	11.8 ± 9.6	7.3 ± 3.3	8.8 ± 7.2	5.1 ± 3.1	8.0 ± 6.7
After-	3.4 ± 0.5	5.5 ± 1.5	4.6 ± 1.4	6.0 ± 1.6	4.6 ± 0.9	4.8 ± 1.4
Bottom TSS (mg/L)	TC1	TC2	TC3	TC4	TC5	Grand mean
Pre-	9.7 ± 4.6	14.7 ± 13.2	30.9 ± 31.8	11.2 ± 12.9	7.3 ± 3.2	11.8 ± 11.6
During-	10.5 ± 7.8	26.2 ± 12.3	16.9 ± 14.4	11.0 ± 9.7	9.2 ± 6.8	13.0 ± 11.0
After-	6.3 ± 5.0	-	7.6 ± 3.1	7.3 ± 3.7	4.6 ± 1.0	6.5 ± 3.5

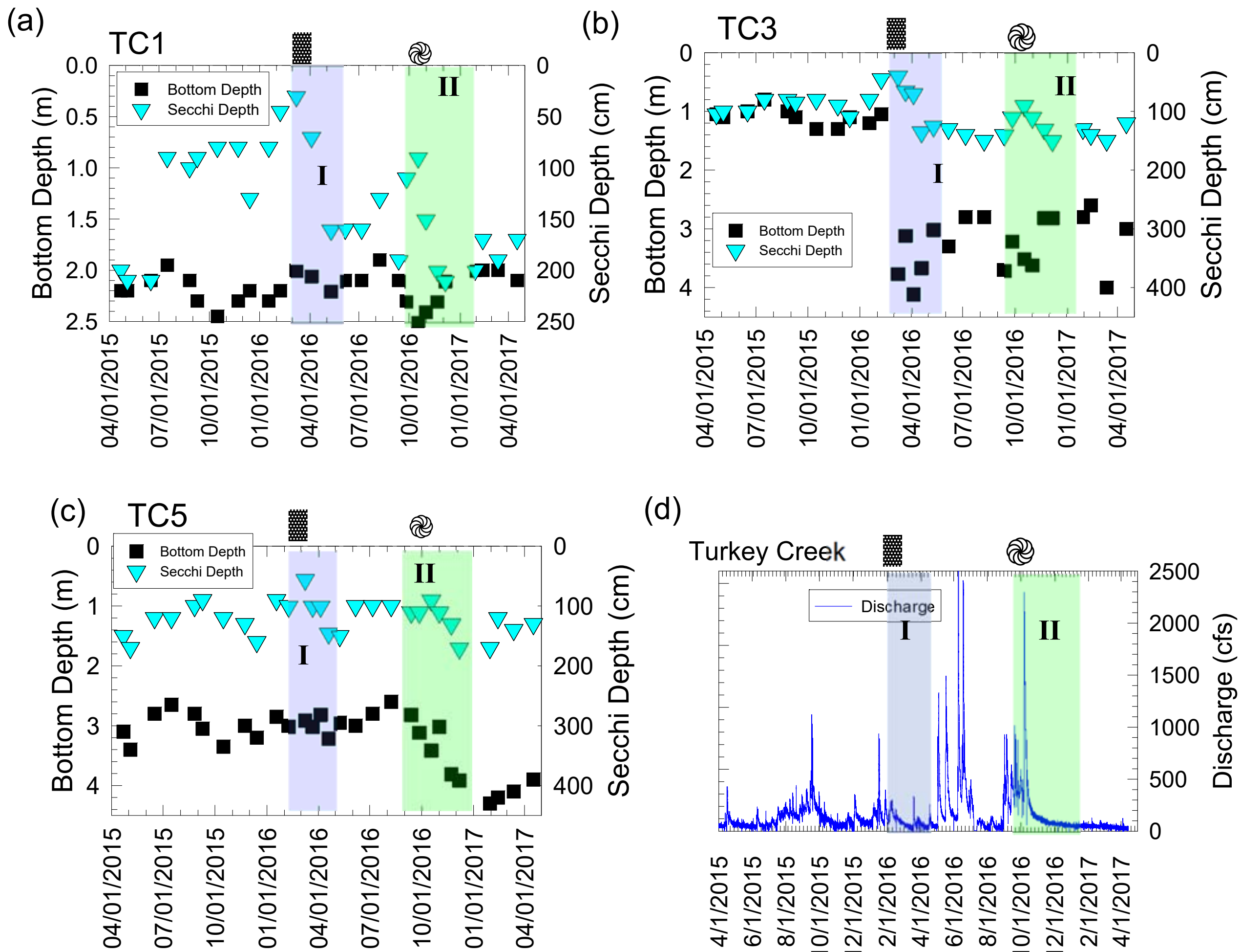


Figure 18. Secchi and water depths at stations (a) TC1 in the IRL near the mouth of Turkey Creek, (b) TC3 in the center of Palm Bay between Highway US-1 and the mouth of the creek and (c) TC5 upstream between the FEC railroad bridge and Highway US-1. (d) Water flow in Turkey Creek at U.S.G.S. gauge. Shaded areas identify dredging Phases I and II, (▓) identifies period of an algal bloom (*Aureoumbra lagunensis*, February and March 2016) and (֍) shows when Hurricane Matthew impacted Turkey Creek (October 6–7, 2016).

Following the bloom, Secchi depths at station TC1 in the IRL, and to a lesser degree at station TC3, increased until October 2016 when the influence of Hurricane Matthew generated increased turbidity and decreased Secchi depths (Figure 18a, b). After the hurricane influence subsided, the Secchi depth at station TC1 increased through April 2017. Similar, but smaller increases were observed at the other stations in response to a prolonged period of drought (Figure 18d). A during-dredging increase in TSS in bottom water at station TC2 (Table 8) may be related to some slumping and movement of muck as described previously or algal particles during the bloom (pages 14–17). In contrast, the observed decrease in TSS at station TC3 during dredging (Table 8) may be due to the much deeper water at that location after dredging that restricted particle resuspension to periodic occurrences (Figure 19b). Our data also show that the only periods of increased values for TSS at station TC4 were during the algal bloom in January-March 2016, even though this station, where dredging did not occur, was very close to dredging activity from February–April 2016 and during September 2016 (Figure 19c). No consistent upstream or downstream trends were identified for Secchi depths or TSS; however, runoff from Turkey Creek, sediment resuspension during storm events, and algal blooms can explain periodic turbidity events that are not linked to dredging activity (Figures 18 and 19).

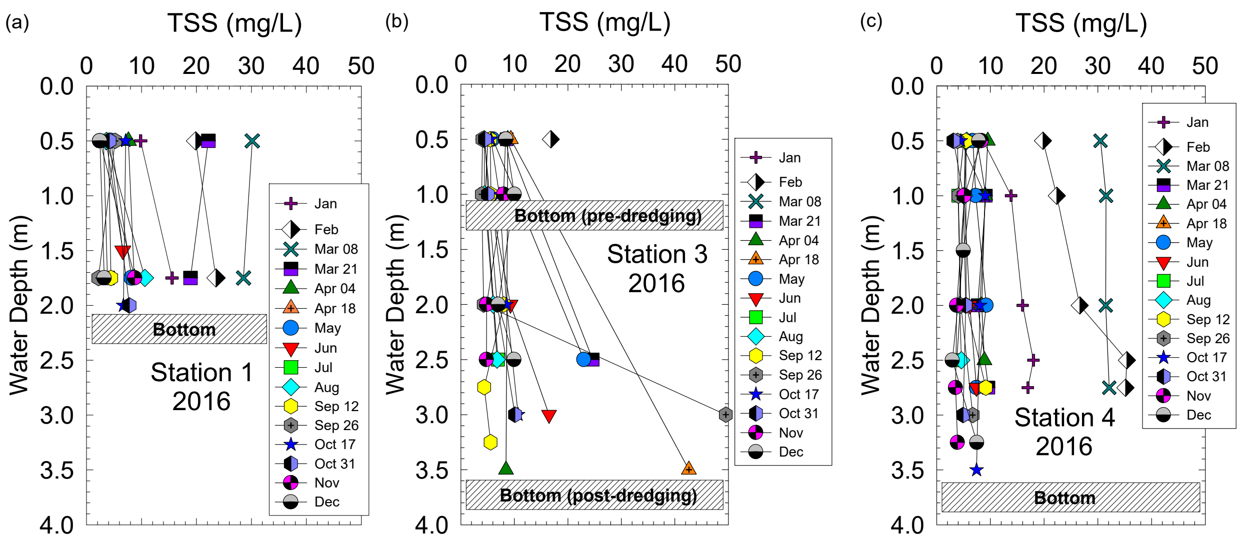


Figure 19. Concentrations of total suspended sediments (TSS) at stations (a) TC1, (b) TC3 and (c) TC4 before, during and after dredging that took place at station TC3 and near (but not at) station TC4 during Phase I.

Salinity profiles throughout the dredging process showed the marked stratification of this salt wedge estuary with a well-defined freshwater layer upstream (Figure 20). Trends for bottom water salinity, even at IRL station TC1 (Figure 20a, b), followed patterns for precipitation and flow in Turkey Creek with lower salinities identified during and after periods of enhanced stream discharge (Figure 21). During dredging, the main impact on salinity occurred in surface water when booms diverted freshwater around the dredging operation and surface salinities within the restricted area tended to be a slightly higher (10–20% or a salinity increase of 2–6).

The main impact of dredging on salinity occurred after dredging when increased bottom depths allowed more saline water to move into Palm Bay. A striking example is shown for station TC3 where an added water depth of 2.5 m created a sizeable saline water mass (Figure 20 c, d). This saline water mass can serve as a buffer against the impacts of freshwater on fishes, benthic infauna and seagrass.

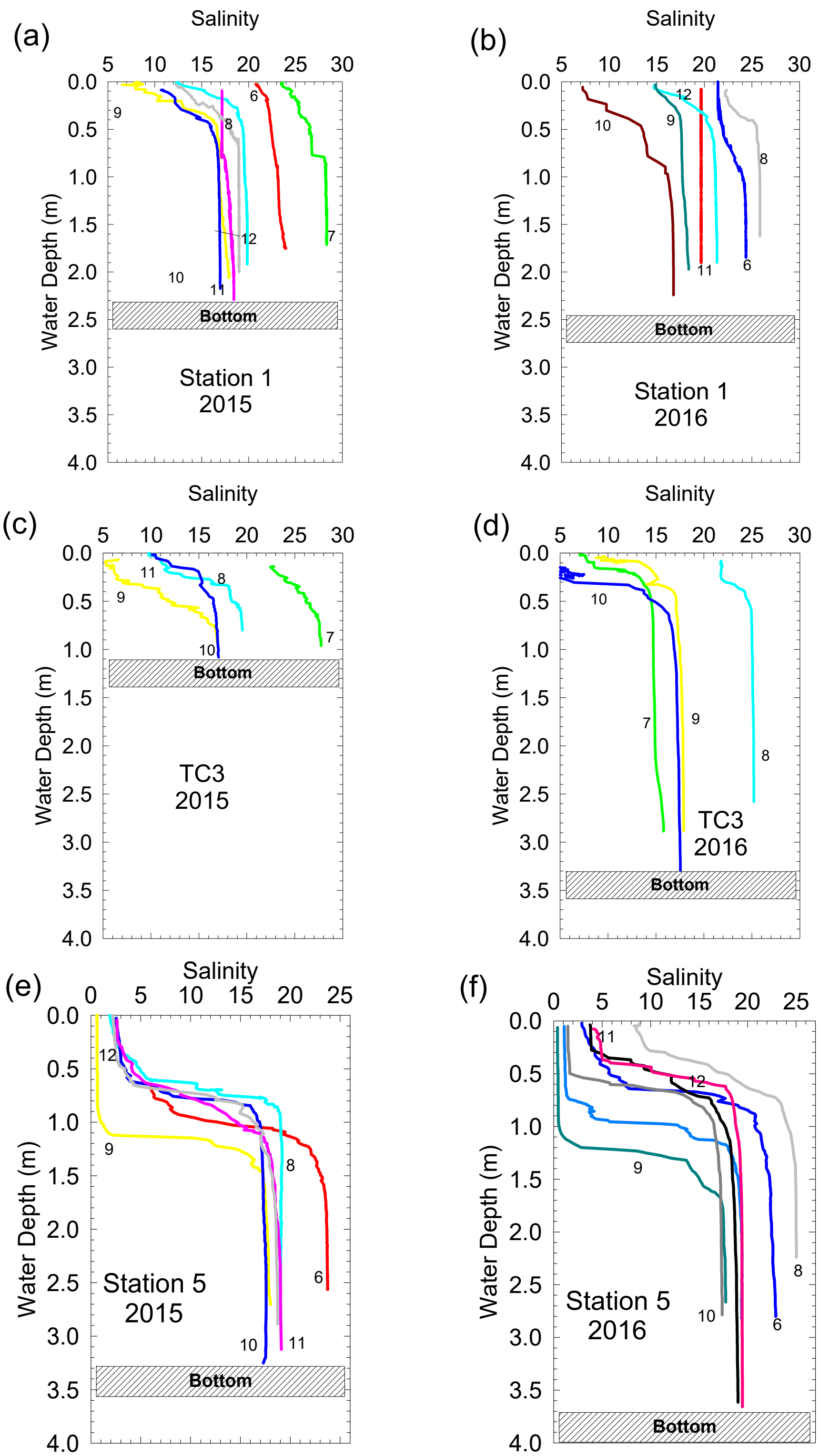


Figure 20. Vertical profiles for salinity at stations (a and b) TC1, (c and d) TC3 and (e and f) TC5 for selected months in 2015, before dredging and in 2016 during and after dredging. Station locations on Figure 1b, page 3.

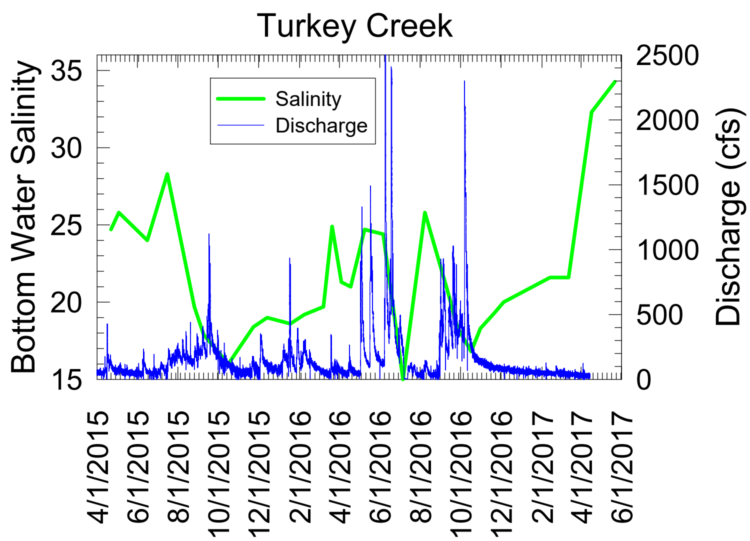


Figure 21. Bottom water salinity at station TC1 and freshwater discharge from Turkey Creek for April 2015 through May 2017. (Flow data from U.S.G.S., 2017)

Concentrations and the percent saturation of DO followed patterns for water temperature with no discernable difference in DO before, during, or after dredging for station TC1 outside the immediate dredged area. At stations where dredging was carried out (e.g., stations TC3 and TC5), DO in surface water increased after dredging regardless of the pre- and post-dredging bottom type, likely related to the increase in water depth (Figures 22, 23). Garcia (1998) reported similar observations after dredging in Crane Creek, except for deeper basins. As predicted, DO was lower in bottom water at stations TC3 and TC5 after dredging due to a combination of oxygen uptake by residual muck and limited circulation and flushing of water at depths below ~2 m.

Even though oxygen concentrations were lower in bottom water after dredging, the low oxygen conditions replaced layers that were previously anoxic sediments. The net result was an increase in the total integrated amount of dissolved oxygen. For example, the integrated amount of oxygenated water at station TC3 increased from ~0.8 mg/cm^2 to ~2 mg/cm^2 due to the transition from 2–3 m of sediments with no DO in interstitial water to >2 m of oxygenated water (Figure 24). This increase in total oxygen provides an added resilience to oxygen depletion events; however, a semi-permanent hypoxic zone at the bottom of the water column may inhibit or slow recovery of benthic fauna within the dredged area.

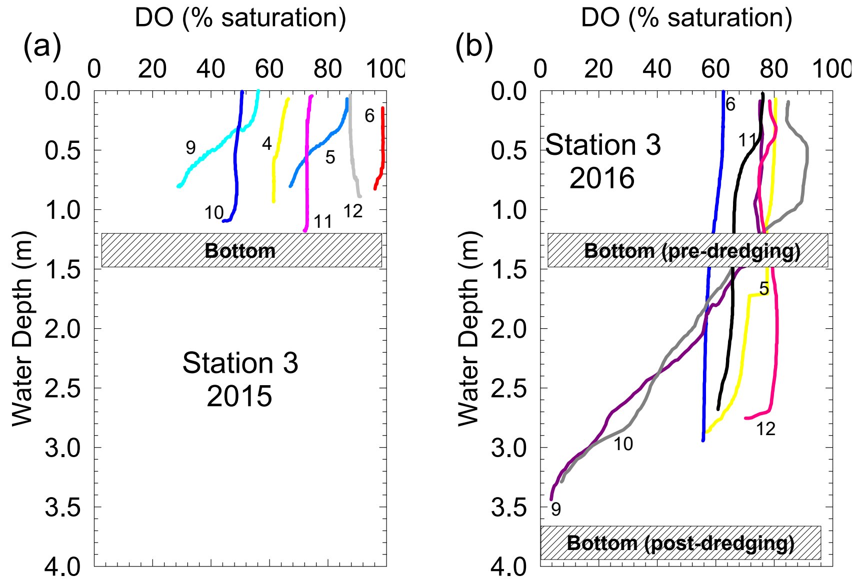


Figure 22. Vertical profiles for percent saturation for dissolved oxygen (DO) at station TC3 located in Palm Bay between US-1 and the mouth of the Turkey Creek in 2015 (pre-dredging) and 2016 (during and post-dredging). Pre-dredge bottom depths on (b) are included for reference. Station TC3 was dredged during March 2016.

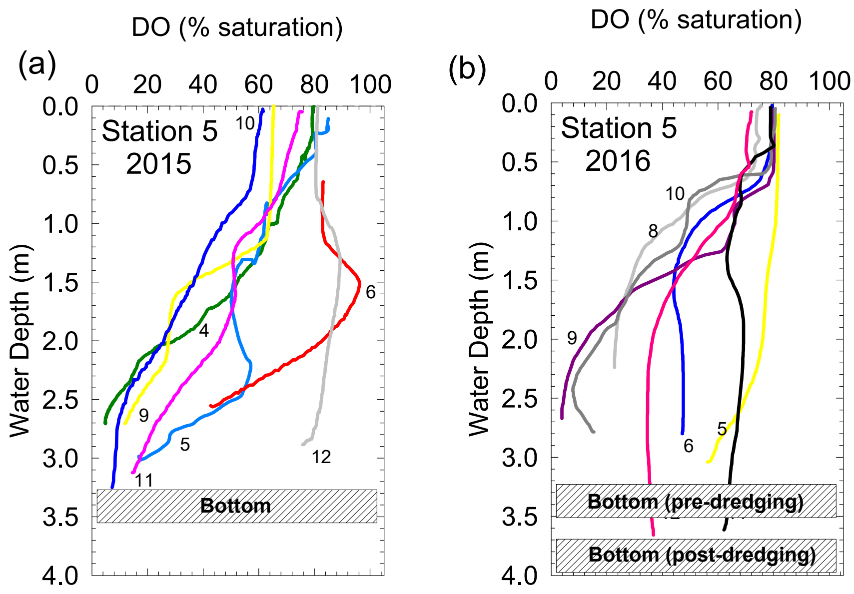


Figure 23. Vertical profiles for percent saturation for dissolved oxygen (DO) at station TC5 located between Highway US 1 and the FEC Railroad Bridge (a) before dredging in 2015 and (b) during and after dredging in 2016. The pre-dredge bottom depths on (b) and (d) are included for reference. Station TC5 was dredged during November – December 2016.

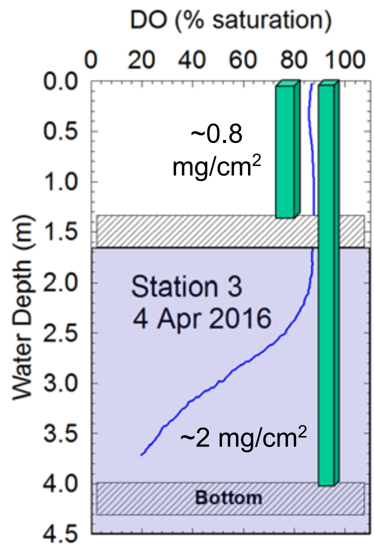


Figure 24. Integrated concentrations of DO before (0.8 mg/cm^2) and after dredging (2 mg/cm^2).

Vertical profiles for ammonium (Figure 25) and phosphate followed predicted trends with lower concentrations in surface water due to uptake during primary production and higher values in bottom water due to the benthic flux from sediments, especially above muck deposits. No discernible differences in dissolved nutrient profiles (e.g., ammonium in Figure 25) during dredging could be identified due to large variations in nutrient concentrations, the Phase I algal bloom and disturbances from Hurricane Matthew. Nevertheless, a strong signal for muck as a source of nutrients was identified throughout this study. Concentrations of dissolved ammonium in bottom water followed patterns for water temperature with highest concentrations of ammonium when temperatures were >30ºC (summer and early fall) and lowest concentrations during cooler months in winter and spring (Figure 25). Concentrations of N and P in bottom water reached maximum values during October 2016 (Figure 25 b, d) in response to sediment disturbance from Hurricane Matthew as previously discussed. At station TC5, dredged during November–December, 2016, ammonium values in surface water during the complete study (Figure 26) were typically <0.5 mg N/L (<35 µM) with exceptions during Phase I (most likely the algal bloom) and Phase II (either Hurricane Matthew or dredging). Ammonium values in bottom water at station TC5 were highly variable as a function of temperature (high in summer and early fall) and stratification of the water column (Figure 26).

At locations where water depths increased and muck slumped in over sand, such as at station TC3, the flux of ammonium and phosphate from the sediments increased and concentrations of these two nutrients in the bottom water increased (Figure 25). In contrast, where dredging removed muck from the bottom, fluxes of ammonium and phosphate greatly decreased (Figure 13). One long-term goal of dredging is to minimize benthic nutrient fluxes and decrease nutrient concentrations in the water column.

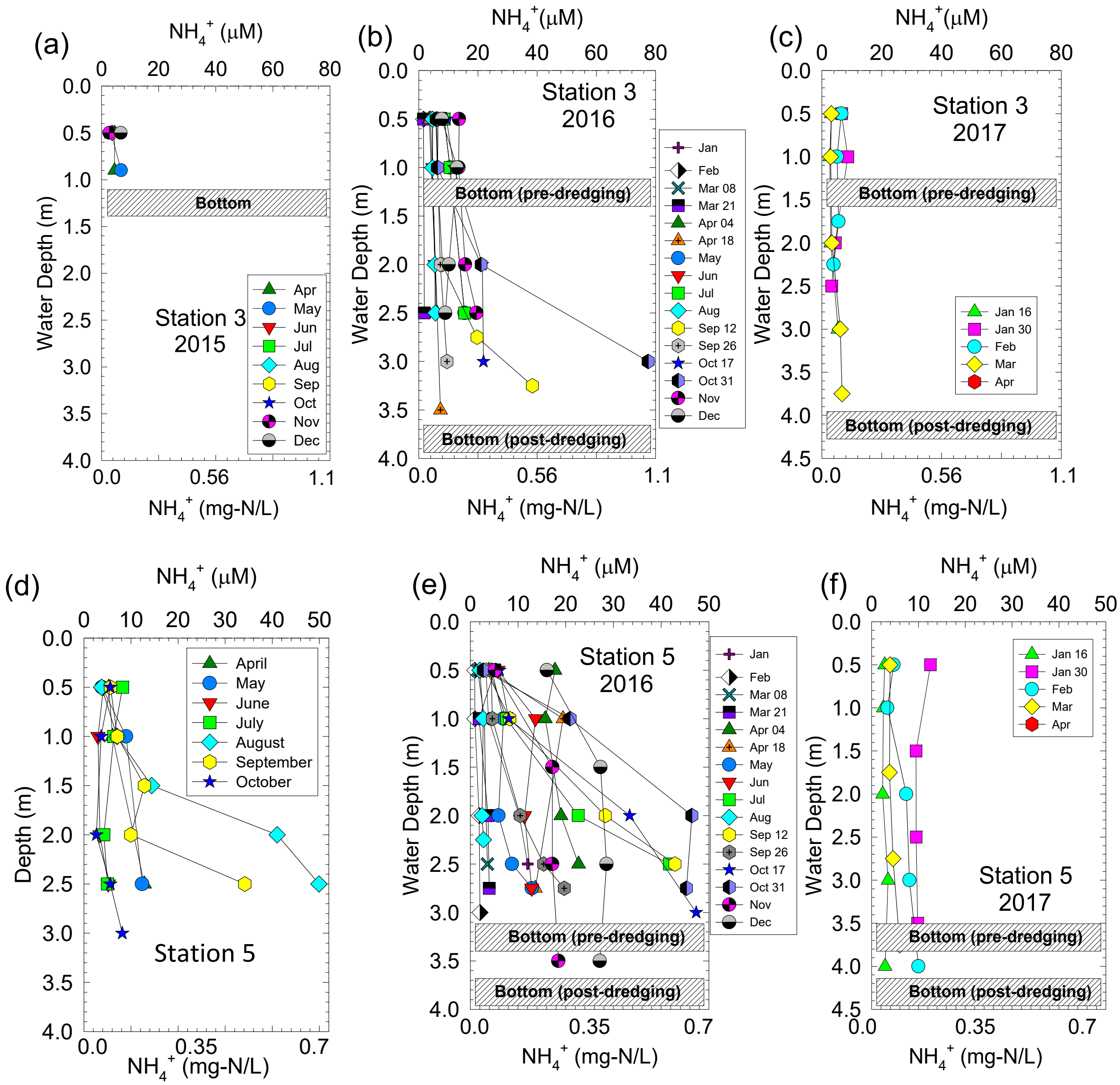


Figure 25. Selected vertical profiles for concentrations of ammonium at station (a, b, c) TC3 and (d, e, f) TC5 for 2015, 2016 and 2017.

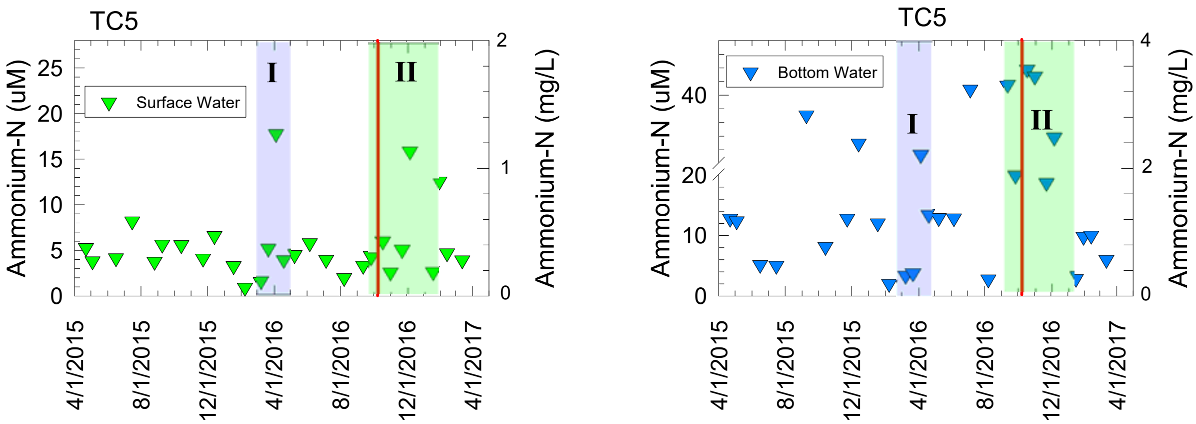


Figure 26. Concentrations of ammonium at station TC5 (A) surface and (b) bottom water for April 2015 – April 2017; dredging occurred during November–December, 2016. Shaded areas identify dredging Phases I and II and solid red line indicate Hurricane Matthew (October 6–7, 2016).

Sediment and Water Assessment of the Dredge Material Management Area

All dredged material from Turkey Creek was pumped ~2 km north to a DMMA (Figure 27). During Phase I (February 20–April 22, 2016), pumping was 24 hours/day and in Phase II (September 6–January 11, 2017), pumping was 10 hours per day. During Phase II, flow out of the DMMA back to the IRL followed a diurnal cycle, increasing during the morning, stabilizing in the afternoon before slowing overnight. From April 7, 2016, until very near the end of dredging (when chemicals were depleted), alum and flocculant were added to the incoming pipe ~300 m before dredged material was discharged into the DMMA. Water that was clarified in the DMMA flowed over boards at a weir near the eastern end of the reservoir and then through a pipe to an outfall to the IRL (Figure 27).

This assessment of the DMMA begins with comparison of the incoming dredged material from Turkey Creek during Phase I (untreated) with Phase II (treated). Familiarity with the composition and reactions of the incoming material is needed to better understand subsequent processes in the reservoir and releases from the DMMA to the IRL. Then, the clarification and flocculation process is further evaluated with data from samples collected at the weir, just prior to discharge to the IRL. Next, we evaluate discharges from the outfall and, finally, we trace discharges from the outfall to the adjacent IRL.

Composition of Incoming Dredged Material

Incoming dredged material from Turkey Creek was sampled through a port in the pipe just before it was discharged into the northwest corner of the DMMA (Figures 27 and 1d). During Phase II, samples also were collected from the incoming pipe prior to addition of alum and flocculant (Figure 28b).

Figure 27. Satellite image of the Palm Bay Dredge Material Management Area (DMMA, BV-52) with arrows and text identifying some of its components and the adjacent Indian River Lagoon (IRL).

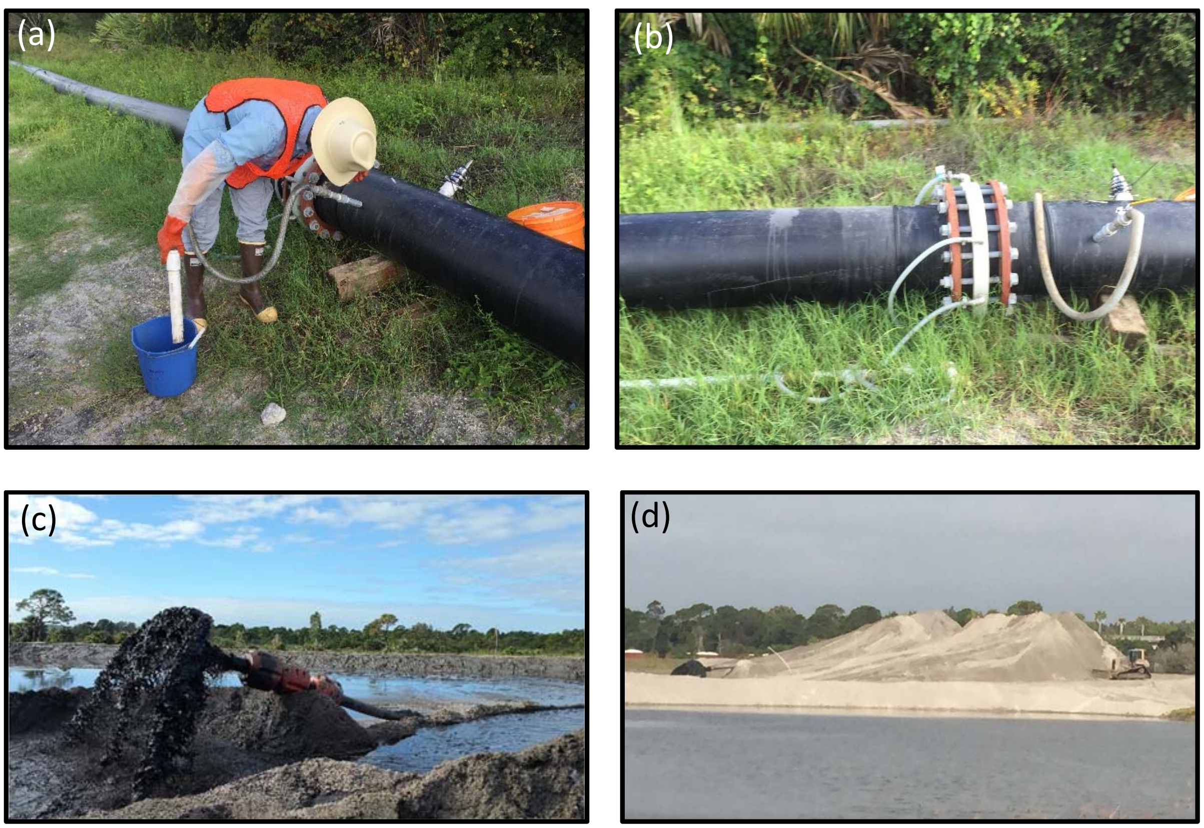


Figure 28. (a) Sampling incoming dredged material prior to addition of alum and flocculant, (b) port for injecting alum and polymer into the dredge pipe, (c) discharge of dredged material into the DMMA and (d) piles of sand at the DMMA recovered from dredged sediment in Turkey Creek.

Concentrations of TSS in dredged material from the incoming pipe ranged from ~9,000–251,000 mg/L with a median of ~50,000 mg/L (Figure 29a). Variations in values for TSS were linked to the material being transported (i.e., water, sand, muck) near the time of sampling. To obtain TSS values higher than ~150,000 in the dredge pipe, the dredge material must contain some fraction of coarser-grained sediments with lower water content (Figure 30). The incoming material from the pipe contained 90.7–99.9% water by volume with an average of 97.7 ± 2.4%. Surface sediments from Turkey Creek contained 47–98% water by volume with a mean 85 ± 15%. Using an average water content (by volume) of 85% for Turkey Creek sediments and 97.7% for material in the dredge pipe, lagoon water on average accounted for ~87% of the water in the pipe (i.e., 13% interstitial water) with a minimum of <1% lagoon water (i.e., essentially 100% interstitial water) when only muck was in the dredge pipe (e.g., March 17, 2016, Figure 29a). Ambient suspended particles in water from Turkey Creek accounted for <2% of the solids in the typical pipe sample because the average TSS in Turkey Creek water was ~5 mg/L. Therefore, the dominant solid material carried to the DMMA was Turkey Creek sediment.

Our results show that high values of TSS (>100,000 mg/L) were supported by increased transport of sand (SiO_2) that has a higher Si/Al ratio (>12) than the clay (aluminosilicates) found in muck (Si/Al = 6 ±3; Figure 29b). We estimated that as much as 60% of the dredged material was sand or non-muck material (page 16), an estimate that seems to be supported by the large amounts of sand recovered at the DMMA (Figure 28d). When the sand content of the dredged material increased, the organic carbon content of particles decreased from >10% to <3%.

Values for TDN in samples from the incoming pipe varied from 1–124 mg N/L with a median of 3.5 mg N/L (Figure 29c); however, TDN accounted for only ~4.0% of the TN (dissolved + particulate) due to the very high concentrations of TSS (Figure 29a). Ammonium, DON and nitrate + nitrite accounted for an average of 77%, ~32% and ~1% of the TDN, respectively. The relative abundance of ammonium to the other N species was directly related to the ratio of lagoon water to interstitial water in the dredge pipe because the TDN in interstitial water is virtually all ammonium, as previously discussed, and because Turkey Creek water contains an average of only ~9% ammonium (Trefry et al., 2016). For example, the sample with the highest TDN in the dredge pipe (124 mg N/L) was obtained on March 17, 2016 and contained >99% ammonium, as well as 92.6% water by volume (Figures 29c and 31a); these values are consistent with sediment and interstitial water from Turkey Creek muck. Concentrations of TDN (p = 0.60), NH_4^+ (p = 0.71) and NO_3^- + NO_2^- (p = 0.82) were not significantly different between paired, pre-treated (n = 9) and treated (n = 9) pipe samples and thus no influence by chemical flocculants (alum or polymer) was observed for particulate or dissolved N.

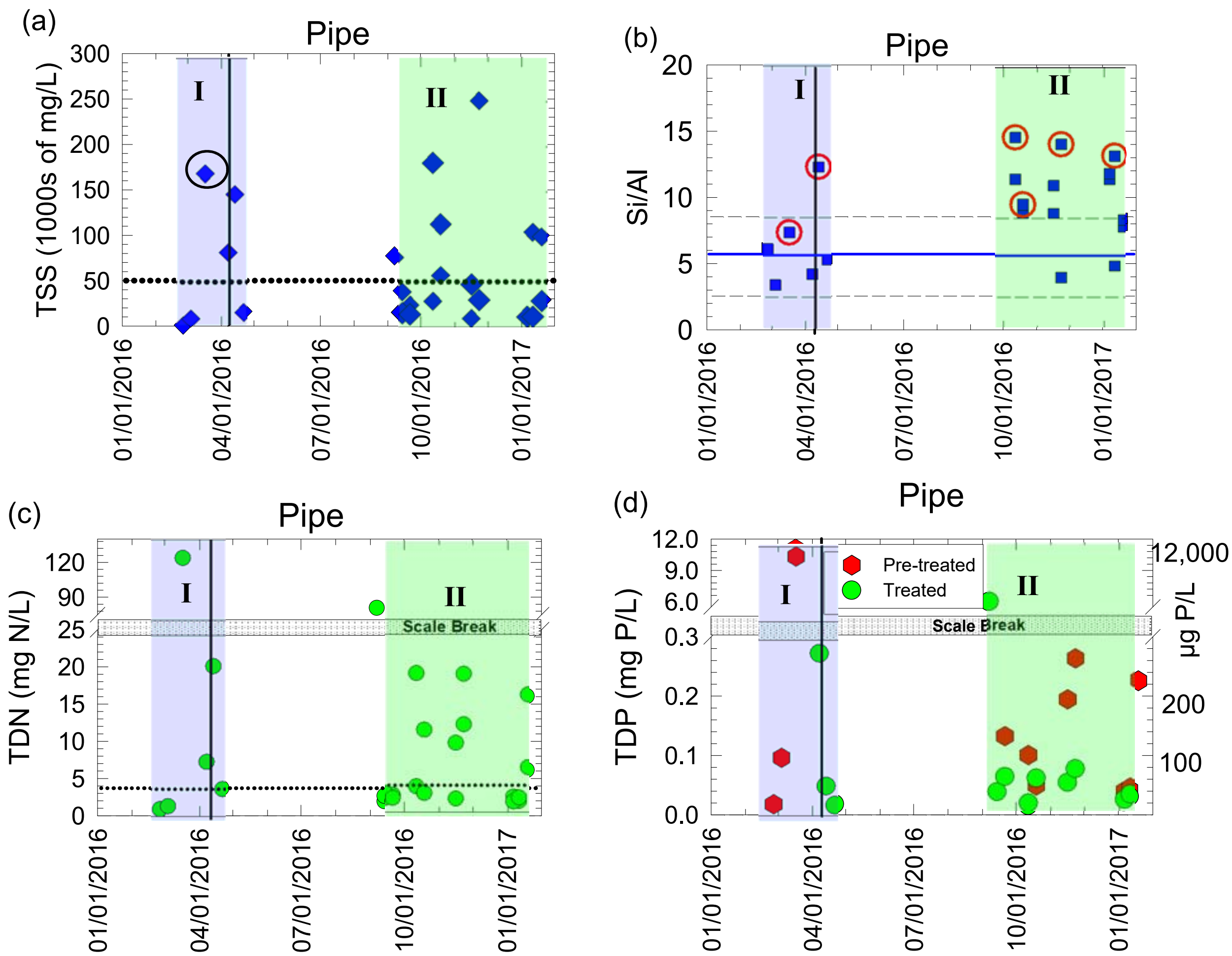


Figure 29. Results for dredge pipe by date showing (a) Total suspended solids (TSS), horizontal dotted line shows median of 50,000 mg/L, circled marker shows March 7, 2016 with only muck in the pipe and (b) silicon vs. aluminum ratio of solids, horizontal line shows average Si/Al ratio in Turkey Creek muck, dashed lines show ± 1 standard deviation. Markers circled show samples with TSS > 100,000 mg/L. Concentrations of (c) total dissolved nitrogen (TDN), horizontal dotted line shows median of 3.5 mg/L, and (d) total dissolved phosphorus (TDP). On all graphs, solid vertical lines show April 7, 2016 when flocculant was first added to the dredge pipe; shaded areas show dredging Phases I and II.

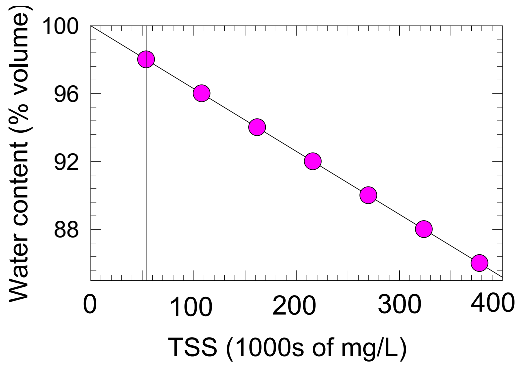


Figure 30. Calculated water content (% volume) versus total suspended solids (TSS). Vertical line indicates the TSS for muck with the highest water content (98% water by volume) identified for Turkey Creek. As TSS values increase above 150,000 mg/L, a coarse-grained sediment (i.e., sand) is required to keep water content lower.

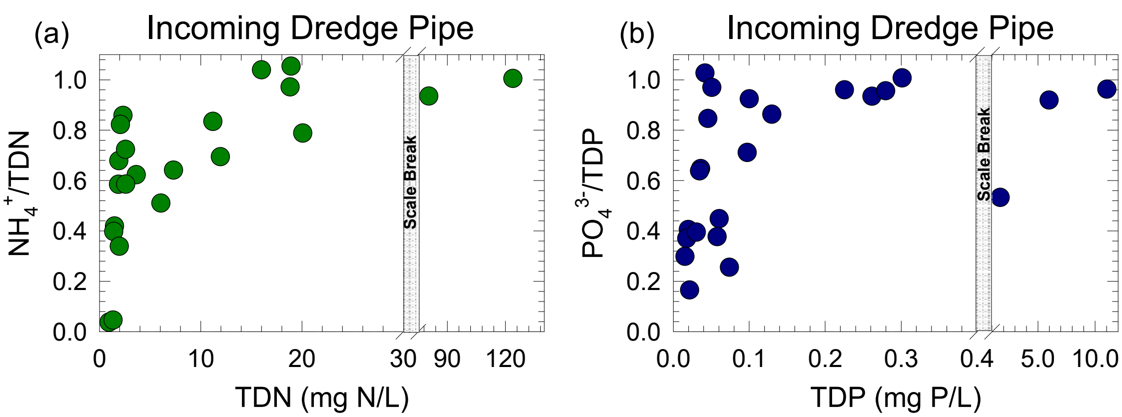


Figure 31. (a) Ratio of ammonium to total dissolved nitrogen (i.e., fraction of TDN that is ammonium) versus TDN and (b) ratio of phosphate to total dissolved phosphate (i.e., fraction of TDP that is phosphate) versus TDP for samples collected from the incoming dredge pipe from Turkey Creek. Interstitial water from Turkey Creek contains TDN and TDP at ~100% ammonium and phosphate, respectively.

Concentrations of TDP varied from 16–11,000 µg P/L (0.16–11 mg P/L) with a median of 115 µg P/L for pre-treated samples (Phase I) and 51 µg P/L for treated samples (Phase II, Figure 29d). TDP accounted for only 1.3% of the TP (dissolved + particulate) for the incoming, high TSS dredged material. Ortho-phosphate (PO_4^{3-}) made up an average of 71 ± 30% of the TDP and the ratio of phosphate to TDP increased with the fraction of interstitial water contained in the dredge pipe (Figure 31b). Values for phosphate and TDP were significantly lower ($p = 0.023$ and 0.013, respectively) in treated pipe samples relative to paired pre-treated pipe samples. Phosphate accounted for only 46 ± 30% of the TDP in treated pipe samples because additions of flocculant produced an average 84% reduction in phosphate and a 70% reduction in TDP in the dredge pipe (Figure 32).

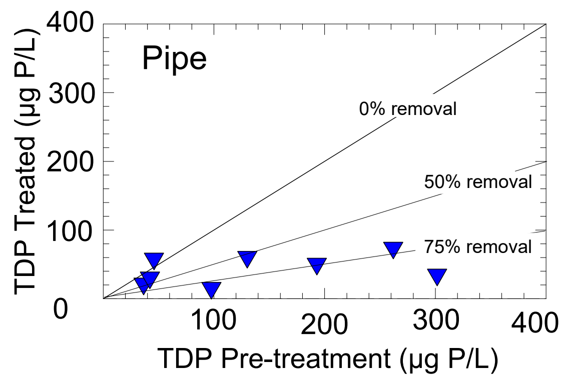


Figure 32. Total dissolved phosphorus (TDP) for paired pipe samples (treated and pre-treated). Solid lines indicate a 1:1 ratio for treated/pre-treated samples and 50% and 75% removal of phosphorus. Data points below the 1:1 line indicate P removal onto particles.

Concentrations of POC (as % dry weight) for the incoming dredge material ranged from ~3–13% with a median of 5.9% (i.e., 18% OM, where OM = 2.8 x TOC, Figure 10a). At the median TSS for material discharged from the pipe into the DMMA (~50,000 mg/L), C, N and P concentrations were 2,950, 250 and 45 mg/L, respectively. No significant differences were identified for TSS or the C, N or P content of particles following addition of flocculants on April 7, 2016. This result was expected because particulate phosphorus accounted for >98% of the TP (dissolved + particulate). Even if all the dissolved phosphorus was sorbed onto particles, no significant difference in the already high concentrations of particulate phosphorus would be identified.

Water Quality at the Weir

Clarified water was collected near the weir in the northeast corner of the DMMA (Figures 27 and 33a). The median TSS value at the weir was 19 mg/L which is ~2,600 times less than the median TSS for pipe samples (50,000 mg/L). Thus, a >99.9% reduction of solids was achieved in the reservoir relative to the incoming dredged material. In contrast to data for the pipe, samples from the weir were influenced by chemical processes and the residence time of water in DMMA.

Figure 33. (a) Three weirs located in the northeast corner of the DMMA where clarified water flowed over boards into a pipe to the IRL and (b) sampling in the IRL along 50- and 100-m radii from the outfall.

Results for water quality parameters in the weir samples improved significantly from Phase I to Phase II because (1) alum and flocculants were added to the incoming dredged material and (2) the decrease in pumping time from 24 to 10 hours per day led to ~2.4-fold longer residence time for water clarification in the DMMA.

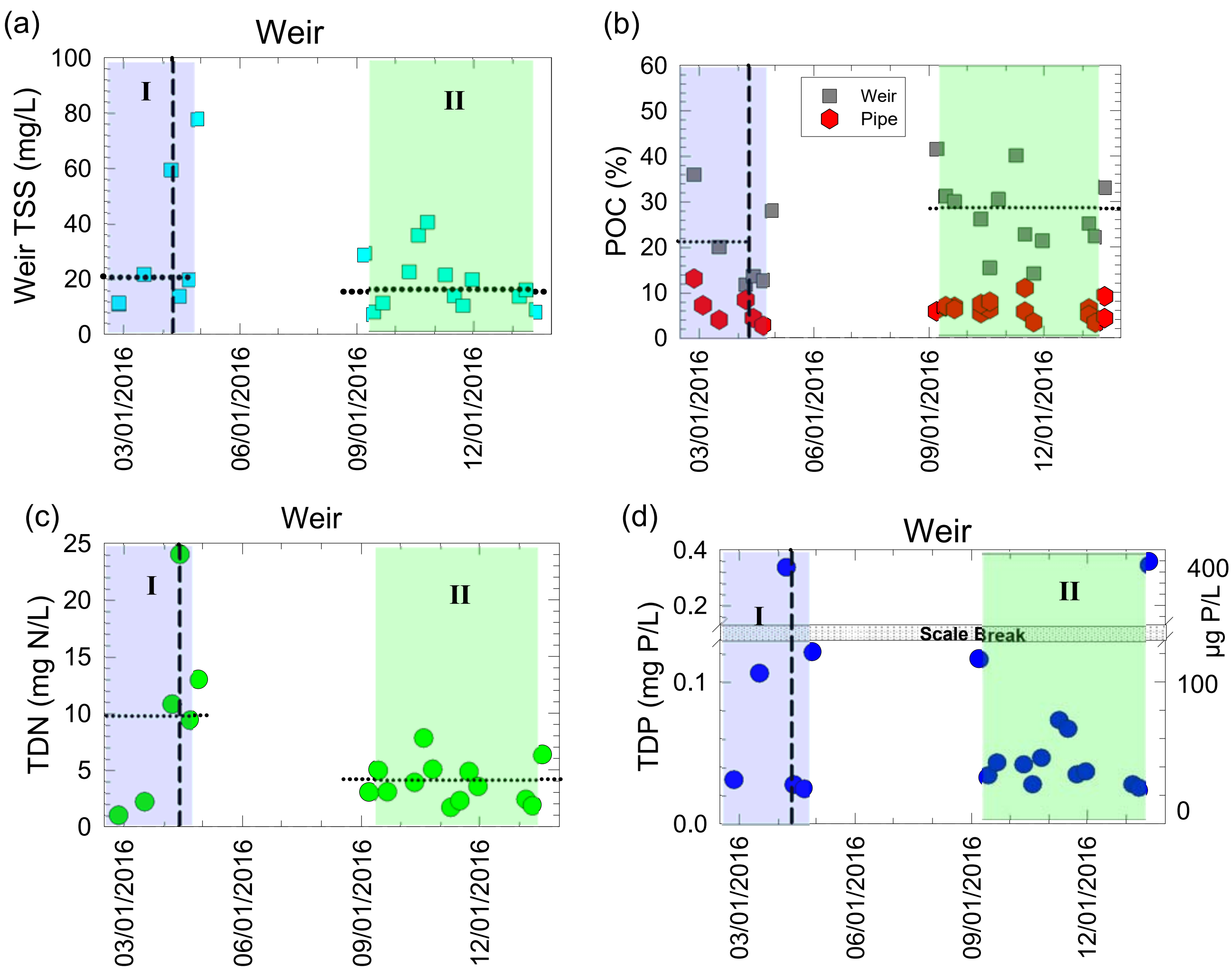


Figure 34. Values for (a) total suspended solids (TSS), (b) particulate organic carbon (POC), (c) total dissolved nitrogen (TDN) and (d) total dissolved phosphorus (TDP) at the weir versus date. Horizontal dotted lines show median. On all graphs, dashed vertical lines indicate April 7, 2016 when flocculant was added to the dredge pipe, shaded areas identify dredging Phases I and II.

Median values for TSS decreased by ~30% (21 to 15 mg/L) from Phase I to Phase II. TSS values during Phase II were likely decreased by longer residence times and addition of flocculants, but increased by enhanced primary productivity in the reservoir (Figure 34a). The carbon content of particles at the weir during Phase II averaged 26% (~70% OM) relative to 6.2% (~18% OM) in the pipe samples; these Phase II values for POC were ~20% higher than at the end of Phase I (Figure 34b). The higher organic content of particles during Phase II was consistent with chlorophyll *a* values at the weir that were >200 µg/L. Enhanced primary productivity during Phase

II may have been at least partially due to the longer residence time for water in the DMMA that may have increased the fraction of the benthic nutrient flux retained in the reservoir.

During Phase I, concentrations of TDN at the weir (median 10 mg/L, Figure 34c) followed patterns for TDN in the pipe samples (Figure 29c), but at lower concentrations. For example, one extreme TDN value in the pipe (124 mg N/L, Figure 29c) preceded a maximum TDN value of 24 mg N/L at the weir (Figure 43c). Following this initial pulse, values for TDN in the pipe and at the weir decreased appreciably (Figures 29c and 34c). Ammonium, DON, and nitrate + nitrite accounted for 65%, 35% and <1%, respectively, of the TDN at the weir, similar to proportions in the corresponding pipe sample (77%, 32%, 1%). During Phase II, values for TDN at the weir were lower and more uniform at 4.0 ± 1.9 mg/L (Figure 34c).

With the addition of alum and polymer during Phase II, concentrations of TDP at the weir (40 ± 16 µg P/L) were not significantly different from those in the treated pipe samples (43 ± 21 µg P/L); however, they were ~ 2-fold lower than observed in the weir during Phase I (Figures 29d and 34d). Phosphate accounted for 21% of the TDP during Phase II, a sharp decrease from 40–45% phosphate during Phase I. Excluding the first (just getting going) and last (chemicals depleted) samples of Phase II, mean values (n = 11) for TDP and phosphate at the weir were 40 ±16 µg P/L (Figure 34d) and 8 ± 8 µg P/L (Figure 35c), respectively. Low concentrations of phosphate during Phase II were successfully achieved by use of flocculants.

Water Quality in the Outfall

Water samples were collected weekly, or more often, at the outfall to the IRL (Figures 27 and 1c on page 3). Salinities in the outfall samples were ~10–15% (2-4 ‰ as salinity) lower than in the weir due to dilution of the weir samples with freshwater from a contributing drainage ditch; this mixing led to corresponding lower values for numerous parameters in the outfall samples. During Phase I, values for TSS averaged 28 ± 19 mg/L for 12 typical surveys (Figure 35a). On one occasion in March and two in April, large turbidity events led to very high concentrations of TSS (>2000 mg/L, Figure 34a); these episodes were linked to (1) high flow rates, (2) high water levels in the DMMA during wind events and (3) a pipe failure in the DMMA. Successful responses to these events by the contractor occurred within hours. Concentrations of TSS were lower and more stable at 12 ± 5 mg/L (n = 9) during Phase II with one exception when a vortex at the weir induced resuspension of bottom sediments and TSS values increased to 205 mg/L. The significant decrease in TSS during Phase II is clearly related to the decrease in dredging operations from 24 to 10 hours per day and the resulting increase in residence time for water in the DMMA.

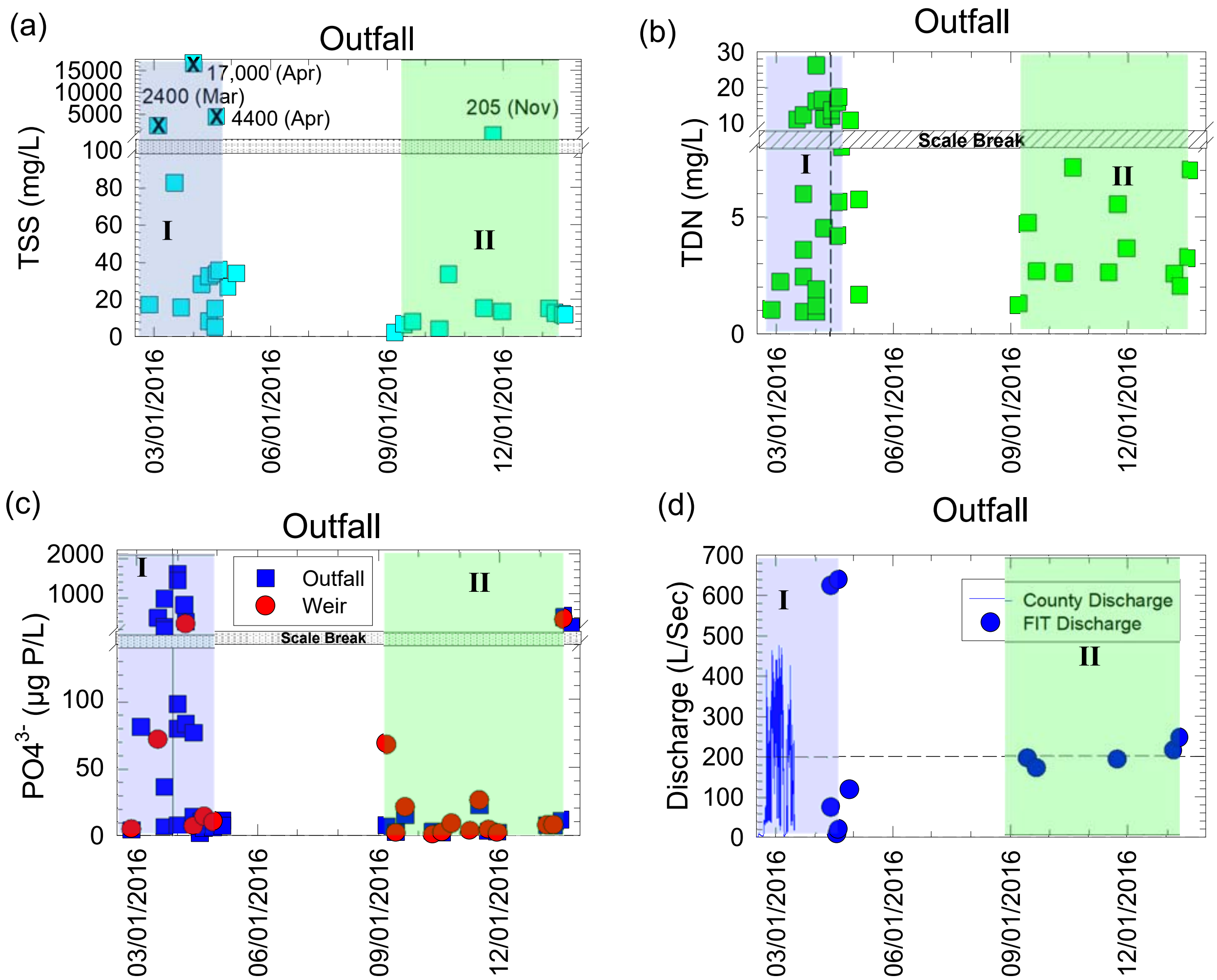


Figure 35. Concentrations of (a) total suspended solids (TSS), (b) total dissolved nitrogen (TDN) and (c) dissolved phosphate in the outfall from the DMMA to the IRL. (d) Flow rates at the outfall from the DMMA from the Brevard County in situ meter and discrete measurements by Florida Institute of Technology. On all graphs, dashed vertical lines indicate April 7, 2016 when flocculant was added to the dredge pipe, shaded areas identify dredging Phases I and II and (x) identified turbidity events.

Values for TDN at the outfall were higher and more variable during Phase I than Phase II (Figure 35b, Table 9). Water leaving the outfall during Phase I had concentrations of TDN at ~1 to >26 mg N/L with a median of 5.9 mg N/L (Figure 35b). During Phase II, concentrations of TDN in the outfall were more uniform and typically <5 mg N/L with a median of 2.9 mg N/L (Figure 35c). Variability during each phase resulted in no significant difference in average values for TDN despite a lower median during phase II (Table 9).

Table 9. Median values for selected parameters in the outfall from the DMMA during Phase I and II of dredging of Turkey Creek. The range of values is large as shown on Figure 35.

Location	TSS (mg/L)	TDN	NH_4^+	DON	N + N	PON		TDP	PO_4^{3-}	PP
		(mg N/L)						(µg P/L)		
Outfall Phase I (n = 26)	33	5.9	3.8	2.2	0.03	0.5		51	57	72
Outfall Phase II (n = 13)	12.5	2.9	2.3	0.86	0.06	0.63		32	8	65

The relative abundance of ammonium, DON and nitrate + nitrate in the outfall varied greatly with average values of ~80%, ~20% and <1%, respectively (Figure 36a). Variations in the percentages of ammonium and DON correspond with the relative amounts of lagoon versus interstitial water being added to the DMMA. Turkey Creek, on average has 82% DON, 13% ammonium and 2% nitrate + nitrite; interstitial water contains >99% of its dissolved N as ammonium (Trefry et al., 2017). The fraction of ammonium was >50% in more than 60% of the outfall samples in support of significant, but not dominant transport of muck. In contrast with the pipe samples, the outfall (and the weir) were characterized by much greater dissolved than particulate N (Figure 37a).

The median concentration of TDP in the outfall during Phase II was 32 µg P/L which was ~40% lower than during Phase I (Table 9). Median phosphate concentrations decreased from 57 µg P/L during Phase I to 8 µg P/L during Phase II (Table 9) with all but the final two samples at values <30 µg P/L. The relative abundance of phosphate typically ranged from 60–90% of TDP (Figure 36b) and no trend was identified for an increase or decrease in TDP throughout Phase II. Near the end of Phase I, after the flocculants were added, concentrations of phosphate decreased to <20 µg P/L (Figure 35c). Thus, concentrations of particulate P were typically >4-fold higher than TDP (Figure 37b).

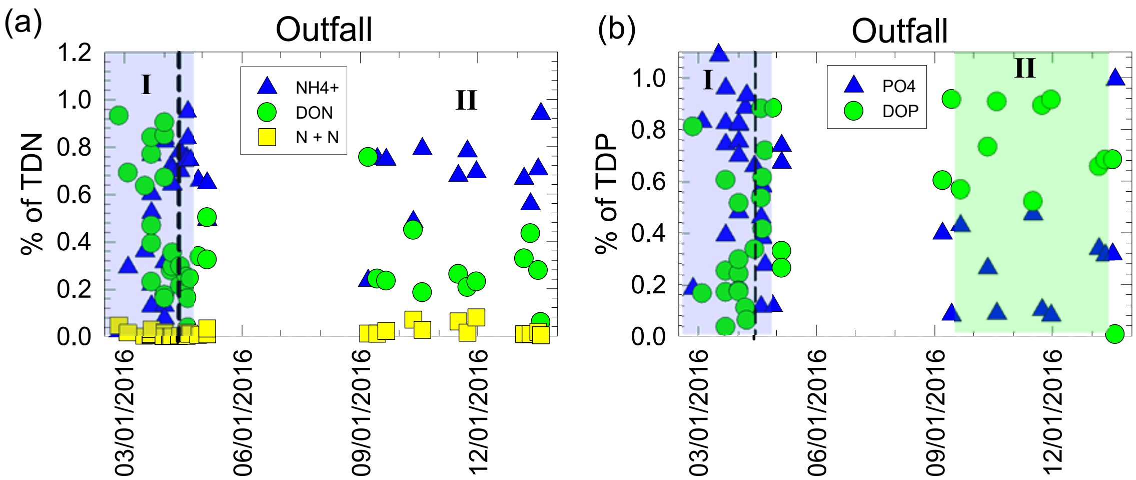


Figure 36. The relative abundances of (a) ammonium (NH_4^+), dissolved organic nitrogen (DON) and nitrate + nitrite (n + N) as % of the total dissolved nitrogen (TDN) and (b) phosphate and dissolved organic phosphorus (DOP) as % of the total dissolved phosphorus (TDP). On both graphs, dashed vertical lines indicate April 7, 2016 when flocculant was added to the dredge pipe, shaded areas identify dredging Phases I and II.

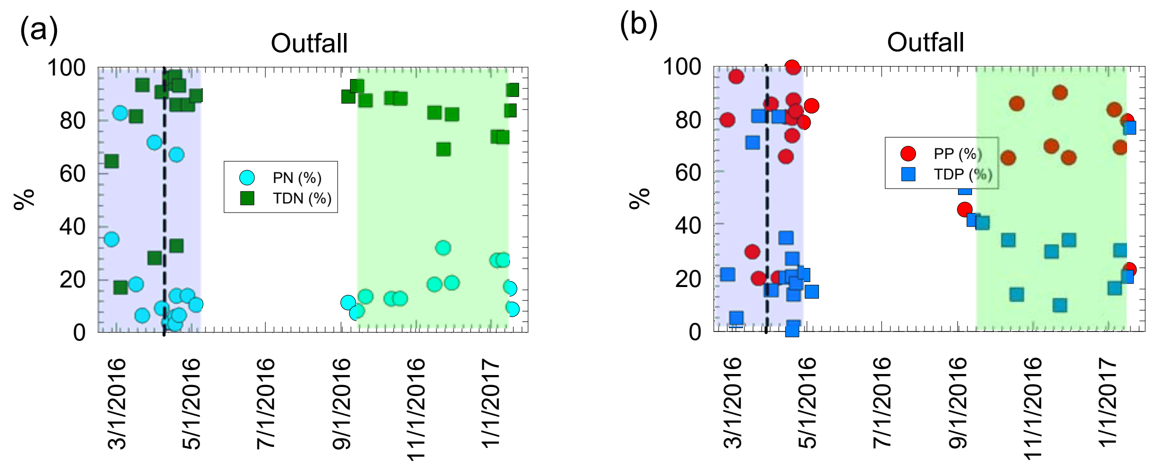


Figure 37. The percent of total (particulate + total dissolved) (a) organic nitrogen (PON) phosphorus (PP and TDP) in samples from the outfall.

Water Quality in the Adjacent IRL

Water samples were collected along 50- and 100-m radii from the outfall of the DMMA into the IRL on nine occasions (n = 23). We also sampled five times at control stations located ~0.5 and 1 km offshore from the outfall near the Intracoastal Waterway (ICW). At our control stations, values for TSS averaged 6.9 mg/L; however, the standard deviation was high and TSS was not significantly different than at 100 m (Table 9). Typical TSS values for the IRL range from 2–25 mg/L with an average of 9 ± 5 mg/L (Trefry et al., 2007).

Mean concentrations of TDN were 0.9 and 0.60 mg N/L at 50 and 100 m from the outfall in the IRL, respectively; 5–7 times lower than the values for the outfall and within the mean ± SD or our control stations (Table 10). On average, ammonium, DON and nitrate + nitrate accounted for ~7%, ~90% and ~2% of the TDN at 50 and 100 m from the outfall, values consistent with the open lagoon and dominated by DON. Overall TDN and PN accounted for ~75% and ~25% of the TN (dissolved + particulate), respectively. The median TDP at our control stations was 29 µg/L, 1.3-times lower than the overall median value at the outfall. At our control station, phosphate accounted for only ~1% of the TDP and TDP and PP each accounted for ~50% of the TP (dissolved + particulate). Water quality along a 100-m radius from the outfall was not significantly different from our control site.

Table 10. Mean values for all outfall samples and means ± standard deviations for samples from the adjacent Indian River Lagoon at 50, 100 and 500 m from the outfall to the lagoon.

Location	TSS (mg/L)	TDN	NH_4^+	DON	N + N	PON	TN		TDP	PO_4^{3-}	PP	TP
		(mg N/L)							(µg P/L)			
Outfall (n = 39)	22	4.4	4.0	3.0	0.05	0.55	5.5		40	32	70	140
50 m (n = 13)	12.0 ± 35.0	0.93 ± 0.63	0.13 ± 0.41	0.61 ± 0.24	0.05 ± 0.04	0.39 ± 0.39	1.4 ± 0.8		28 ± 10	10 ± 7	57 ± 55	81 ± 54
100 m (n = 12)	14.9 ± 66.8	0.62 ± 0.31	0.11 ± 0.21	0.48 ± 0.11	0.005 ± 0.004	0.27 ± 0.74	1.0 ± 0.8		18 ± 5	4 ± 5	24 ± 69	43 ± 68
IRL Control (n = 5)	6.9 ± 11.0	0.62 ± 0.32	0.05 ± 0.03	0.47 ± 0.09	0.01 ± 0.09	0.23 ± 0.27	0.9 ± 0.6		29 ± 17	12 ± 4	25 ± 24	51 ± 40

Discharges from the DMMA

Total inputs of dredged material to the DMMA were calculated using TSS values for samples from the dredge pipe and the total volume of sediment removed from Turkey Creek. If dry sediments accounted for on average 13% of the material contained in the dredge pipe for the removal of 210,000 yd^3 of sediments (160,000 m^3); then, 1,840,000 yd^3 of water + solids are calculated to have traveled through the dredge pipe from Turkey Creek during the project. Based on the composition of material in the pipe versus the outfall, 1,600,000 yd^3 (1,230,000 m^3) of clarified water was discharged to the lagoon. Using this discharge and median values for TSS, TN and TP at the weir during normal discharge (excluding turbidity events) ~23 tons of solids from Turkey Creek were discharged from the DMMA. This mass of solids (with water) would carry (1) ~6 tons of N with ~90% as dissolved N (TDN = 5.4 tons, PN = 0.7 tons) and (2) >0.1 ton of P with ~30% as dissolved P (TDP = 0.05 tons, PP = 0.9 tons) from the DMMA to the IRL. The discharge of material during turbidity events is significant; yet difficult to quantify and not included in calculations presented here.

Composition of Sediments in the DMMA

Eight representative samples of dredge material were collected from the DMMA, four during the dredging hiatus in May 2016 and four after dredging in February 2017. Samples were analyzed for water content, TOC, OM (LOI), $CaCO_3$, total N, total P, Al, As, Ba, Be, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Sb, Sn, Ti, V and Zn. All metal concentrations (Table 11) were consistent with values previously reported for lagoon sediments (Table 11). Sediment quality guidelines have been used to determine whether sediments with above natural concentrations of metals may have adverse biological effects (e.g., Long et al. 1995). Long et al. (1995) introduced an Effects Range Low (ERL) and an Effects Range Median (ERM) that were set at the 10th and 50th percentile, respectively, from an ordered list of concentrations of metals in sediments with an associated biological effect.

None of the sediment metals in our study exceeded realistic values for the ERM or ERL as defined by Long et al. (1995) and further refined by O'Connor (2004) and Trefry et al. (2014). Several authors state that sediment quality guidelines should be used cautiously. For example, O'Connor (2004) noted that the ERL is a concentration at the low end of a continuum that links metal values with toxicity and that these criteria call attention to a specific site where additional study, such as determining benthic community structure, may be warranted. None of the samples contained metal concentrations at >ERL and therefore should not be considered as harmful to lagoon biota. Previous studies of IRL sediments have shown similar results for organic substances (Trefry et al., 2008).

Table 11. Composition of sediments sampled from the Dredge Material Maintenance Area (DMMA, this study) and IRL plus values for the Effects Range Low (ERL) and Effects Range Median (ERM).

	TOC (%)	TN (%)	TP (%)	Al (%)	As (ppm)	Ba (ppm)	Be (ppm)
DMMA	4.8 ± 1.5	0.46 ± 0.16	0.11 ± 0.03	4.1 ± 1.3	6.2 ± 2.1	109 ± 31	0.86 ± 0.26
IRL[1]	5.0 ± 2.3	-	-	4.4 ± 1.4	6.9 ± 3.5	-	-
ERL[2]	-	-	-	-	8.2	-	-
ERM[2]	-	-	-	-	70	-	-
	Cd (ppm)	Cr (ppm)	Cu (ppm)	Fe (%)	Hg (ppm)	Mn (ppm)	Ni (ppm)
DMMA	0.29 ± 0.09	59 ± 20	27 ± 14	3.1 ± 1.1	0.09 ± 0.03	233 ± 74	14.0 ± 4.3
IRL	0.28 ±0.15	58 ± 20	44 ± 34	2.6 ± 1.3	0.10 ± 0.09	232 ± 70	15 ± 6
ERL	1.2	81	70[3]	-	0.15	-	20.9
ERM	9.6	370	270	-	0.71	-	51.6
	Pb (ppm)	Sb (ppm)	Sn (ppm)	Tl (ppm)	V (ppm)	Zn (ppm)	$CaCO_3$ (%)
DMMA	25 ± 8	0.26 ± 0.09	2.0 ± 0.06	0.26 ± 0.09	50 ± 17	91 ± 29	12.2 ± 2.2
IRL	33 ± 16	0.26 ± 0.09	2.4 ± 1.1	-	59 ± 21	95 ± 50	5.0 ± 2.3
ERL	46.7	-	-	-	-	150	-
ERM	218	-	-	-	-	410	-

[1]Trefry and Trocine (2011).
[2]Long et al. (1995).
[3]O'Connor (2004).

Conclusions

The conclusions from this study of the effectiveness of dredging in Turkey Creek are presented below as a series of bulleted items:

- Dredging reduced the volume of muck in the dredged area by >60%.
- Dredging decreased the surface area of muck in the dredged area by <20%.
- The volume of water in the dredged area increased by 160,000 m^3 after dredging.
- Muck, where present, did not change in composition during or following dredging.
- Fluxes of N and P were >50% lower within three months after dredging, likely related to mixing during dredging and Hurricane Matthew.
- The total amount of DO in Turkey Creek increased after dredging due to a deeper water column and a larger volume of water.
- Increased turbidity during the beginning of dredging during Phases I and II were due, respectively, to a large algal bloom and resuspension of sediment during Hurricane Matthew.
- The DMMA retained >99.9% of the solids pumped in from Turkey Creek.
- Chemical treatments effectively controlled concentrations of dissolved phosphate in the DMMA.
- Concentrations of nutrients in water discharged from the DMMA were not identifiable above background at 100 m from outfall.

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