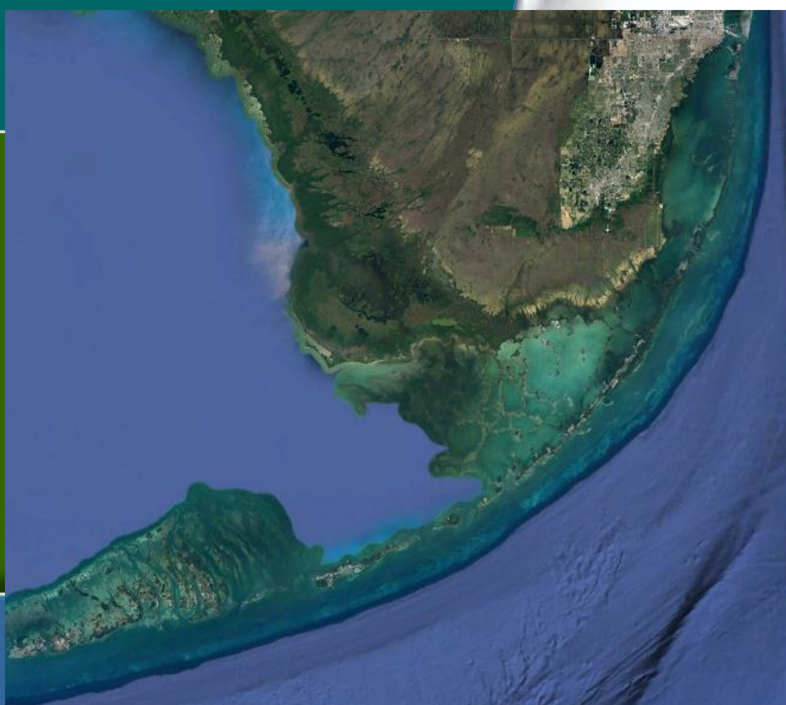
WATER QUALITY MONITORING PROJECT FOR DEMONSTRATION OF CANAL REMEDIATION METHODS: FLORIDA KEYS

Final Report



May 2018

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US EPA Agreement #X7-00049716-0

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WATER QUALITY MONITORING PROJECT FOR DEMONSTRATION OF CANAL REMEDIATION METHODS, FLORIDA KEYS

EXECUTIVE SUMMARY

BACKGROUND

Construction of canals in the Florida Keys was not an environmentally responsible endeavor, especially in the fifties and sixties when environmental concern was practically inexistent. Unfortunately, fill requirements to increase land area for new housing, instead of future water-quality concerns, drove the design of canal geometry. Structural flaws in canal design and building included excessive depths, sills, orientation with respect to winds, as well as extremely long and dead-end canals, all lacking good water circulation and exchange with surrounding marine waters. These flaws increase the flushing time of canal waters and favor the accumulation of seaweed wrack and flotsam. These, in turn, rot and consume oxygen from the water column, depriving organisms of the required levels of oxygen to sustain life. These nutrient-rich waters are eventually exported to nearshore environments.

Environmental degradation affect residents and visitors, and legal conflicts arise because nearshore waters in the Florida Keys are Outstanding Florida Waters (OFW), meaning "…water designated worthy of special protection because of its natural attributes…" (Section 403.061(27), Florida Statutes). Additionally, the Florida Keys National Sanctuary and Protection Act (HR5909; 10/24/1990) designated an area enclosing the entirety of the Florida Keys. This legal status prohibits direct or indirect discharges that would lower ambient water quality, especially from canals.

In 1999, degradation of nearshore water quality prompted the State of Florida to enact House Bill No. 1993. This bill mandated the installation of advanced wastewater treatment systems to eliminate septic tanks, cesspits and ineffective small treatment facilities. Likewise, the Florida Department of Environmental Protection (FDEP) approved the Florida Keys Reasonable Assurance Documentation (FKRAD) in 2008, which defined management activities to address dissolved oxygen (DO) impairments for those waters. Following suit, on March 21, 2012 the Monroe County Board of County Commissioners (BOCC) approved the execution of a series of canal restoration and demonstration projects, extending from Key Largo to Geiger Key to improve water quality in canals. This action is crucial for improving living conditions of the citizens, securing the wellbeing of 2 million tourist who visit the Keys annually, and is essential for protecting the receiving Sanctuary waters.

The main goal of the remediation projects is to augment dissolved oxygen in the water column and reduce nutrient levels. In order to achieve those goals we must increase water circulation and exchange by reducing flushing time (e.g. installing culverts), and/or reducing water depth (e.g. backfilling), and/or keeping seaweed from coming into the canals (e.g. installing weed barriers/air curtains), and/or supplying oxygen directly to the water column (i.e. installing aerators).

The Monroe County, the Water Quality Protection Program Steering Committee and the Canal Subcommittee selected ten (10) canals out of twenty (20) pre-selected sites, for demonstration of restoration technologies. Additionally, seven (7) canals, which would not receive any remediation, were selected as the control canals. The Environmental Protection Agency contracted Florida International University to conduct the monitoring program. During execution of the project, two canal were dropped from the demonstration program.

MONITORING

The main objective of the monitoring program was to provide data needed to make unbiased, statistically rigorous statements about the status and temporal trends of water quality parameters in the remediated canals. The proposed monitoring experiment adopted a Before–and-After Control-Impact Design with multiple sites (BACI experiment). This design entails the collection of data prior to the remediation activity to compare with data after remediation. Data to compare in this report came from vertical profiles of physical-chemical data; 24 to 72 hour continuous logging of physical-chemical properties; and water chemistry (total and dissolved nutrient concentration).

Each remediation method was aimed to a specific target (Fig i). Backfilling was designed to address canal depth, and by doing so, to eliminate the persistence of bottom organic matter, anoxic-reducing waters, and to change the residence time of canal waters while reducing its dissolved organic matter levels. Backfilling doesn't address those issues coupled to incoming seaweed wrack. Culvert installation focus on reducing residence time and dissolved oxygen in the water column. Aerators simply contribute oxygen to the water column. Weed gates and air curtains pretend to stop seaweed wrack to enter the canals, and by doing so, to improve oxygen levels in the water column by hindering accumulation of organic matter on the canal bottom. What is clear from Figure i is that no single method addresses all water quality issues.

This project posed especial challenges given the unpredictable delays and unexpected extent of asynchrony in the implementation of remediation measures. In fact, each remediation project became an individual monitoring project in itself, complicating logistics and forcing stretching of resources. At the end, most remediation actions ended in year 2016, leaving little over one year for post-remediation monitoring (Table i). The first post-remediation simultaneous monitoring of all canals began in June 2017.

While we expected and detected expedite changes in dissolved oxygen, previous experience indicates that not enough time has spanned to achieve water quality changes to assess remediation with certainty, especially regarding nutrient concentrations (Briceño and Boyer 2009).

Landfall of Hurricane Irma in September 2017, interrupted all monitoring plans, and tests performed after Irma, from January to March 2018, indicate that canals had not returned to previous post-remediation status.

__Table i:__ End date of remediation and years lapsed until June 2017, when simultaneous post remediation monitoring began

Canal	Remediation	Years
#29	July 2015	1.9
#137	Nov 2014	2.6
#148	May 2017	0.1
#266	May 2016	1.1
#277	May 2016	1.1
#287	July 2016	0.9
#290	Mar 2016	1.3
#470	May 2016	1.1
#472	May 2016	1.1

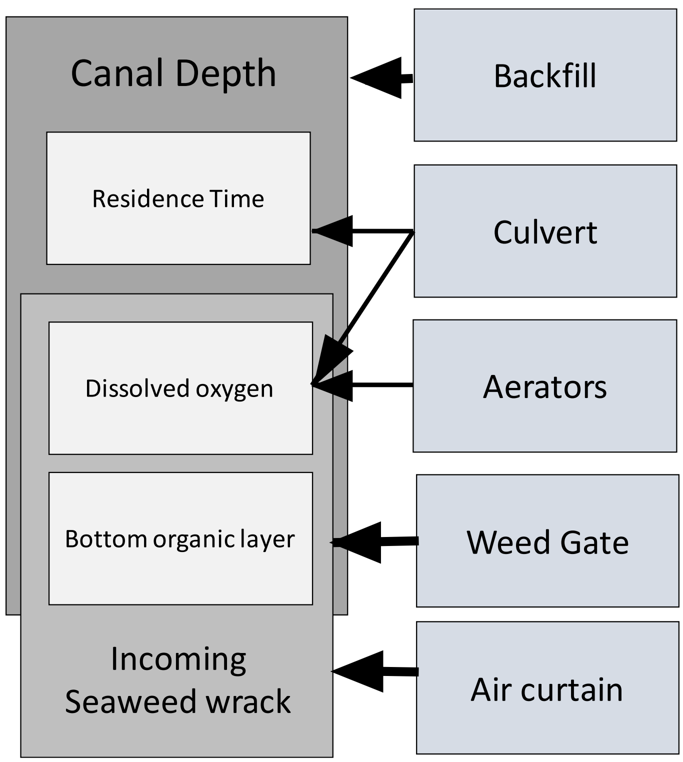

__Figure i:__ Targeted canal issue (left panel) and remediation methods to address it (right panel).

RESULTS

Among the diverse water quality parameters tested, changes in oxygenation of the water column (especially bottom waters) was the fastest metric to signal changes potentially brought about by remediation. We used diel and water profile data (Table iii) for the assessment. Those canals where remediation consisted of improving water circulation and exchange by means of backfilling (#29) or culvert installation (#277, #470 and #472), experienced positive increasing trends in percentage of dissolved oxygen saturation (%DO Sat) after remediation. In these cases, the response was almost immediate, not only in oxygen concentration but also with the arrival of fish and crab to the remediated canals. On the other hand, organic removal and air curtains have not rendered favorable results increasing %DO Saturation yet.

Weed barriers, organic removal and air curtains have not rendered favorable results in %DO Saturation yet. Air curtains coupled with aeration inside the canal seems to partially improve oxygen saturation. Nutrient concentration levels have not declined in any of the remediated canals (Table iii).

***Table iii**: Summary of performance for each Remediation Method*

CANAL	REMEDIATION METHOD	REMEDIATION DATE	PROFILES	DIEL	NUTRIENTS
# 29	Backfilling	July 2015	YES	YES	Not yet
#137	Air Curtain & Aerator	Nov 2014	Not yet	YES	Not yet
#148	Air Curtain	May 2017	Not yet	Not yet	Not yet
#266	Organic Removal & Air	May 2016	Not yet	Not yet	Not yet
#277	Culvert	May 2016	YES	YES	Not yet
#287	Weed Barrier	July 2016	Not yet	Not yet	Not yet
#290	Organic Removal & Air	June 2017	Not yet	Not yet	Not yet
#470	Culvert	May 2016	YES	Not yet	Not yet
#472	Culvert	May 2016	YES	YES	Not yet

All data files generated during this project are freely accessible from the Southeast Environmental Research Center Water Quality Monitoring Laboratory website: http://serc.fiu.edu/wqmnetwork/Canals/index.htm

CONCLUSIONS

The most relevant conclusions derived from the monitoring program are:

- Response to remediation is significantly affected by lagging. Post-remediation monitoring has been too short to detect significant and sustained changes as expected from remediation.
- Nutrient concentrations have not shown any improvement yet, while dissolved oxygen was the only parameter to suggest improvements in water quality in some canal.
- All remediation methodologies, except backfilling, dodged elimination of a fundamental driver of water quality decline, excessive canal depths. Surface waters in most canals have fair quality most of the time. Poor water quality usually sets in for waters deeper than 6 ft.
- Improvements in water oxygenation were more evident and more expedite in those sites where deep stagnant waters were eliminated (backfill) and/or water circulation was enhanced (culvert). These improvements seem to respond to a reduction in residence time due to enhanced tidal flushing.
- Backfilling, the most radical remediation technique rendered immediate positive results in oxygenation. After remediation there were no stagnant, deep, organic-rich waters to consume oxygen, while circulation and exchange with open waters was more expedite.
- Culvert Installation followed backfilling in efficiency to amend oxygenation by improving circulation and exchange. Culverts purpose was stimulating exchange with marine cleaner waters. Hence, culverts are more efficient when connecting canals to open waters.
- Organic removal has not resulted in water quality improvements yet, and canals are being backfilled with rotting seaweed wrack from accumulations at the mouth of canals
- Aeration addresses only oxygenation of the water column. This oxygenation has not proven efficiency to render permanent positive results yet.
- When attempting to remediate deep canals, no permanent solution will be achieved without backfilling. Bottom should be raised to shallower than approximately 7 ft.

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WATER QUALITY MONITORING PROJECT FOR DEMONSTRATION OF CANAL REMEDIATION METHODS, FLORIDA KEYS

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1. Project Background

The Florida Keys form an archipelago of sub-tropical islands at the southernmost tip of the Florida Peninsula, stretching in a NE to SW direction from Miami to Key West and out to the Dry Tortugas (Fig. 1.1). The coral reef tract offshore the Florida Keys is the third largest barrier reef in the world, and the only living barrier reef adjacent to continental US. Approximately 2 million visitors come to the Keys every year to enjoy water sports and entertainment, including fishing and diving. Residents and Keys visitors want waterfront with dock space for boats to enjoy this tourist paradise. That desire drove the construction boom of finger canals in the fifties and sixties, to the point that canals became part of common day life for Key dwellers. Today there are over 480 canals, extending for 170 miles creating over 300 miles of waterfront property.

Nearshore waters in the Keys are Outstanding Florida Waters, meaning "…water designated worthy of special protection because of its natural attributes…" (Section 403.061(27), Florida Statutes). This legal status prohibits direct or indirect discharges to OFWs that would lower ambient (existing) water quality. Additionally, in 1990, President Bush signed into law the Florida Keys National Sanctuary and Protection Act (HR5909) which designated a boundary encompassing >2,800 square nautical miles of islands, coastal waters, and coral reef tract as the Florida Keys National Marine Sanctuary (FKNMS). The Comprehensive Management

Plan (NOAA 1995) required the FKNMS to have a Water Quality Protection Plan (WQPP) thereafter developed by EPA and the State of Florida (EPA 1993). Improving water quality in canals crucial for improving living conditions of the citizens, as well as pivotal for protection of the receiving waters. These waters are part of the Florida Keys National Marine Sanctuary enclosing the Keys.

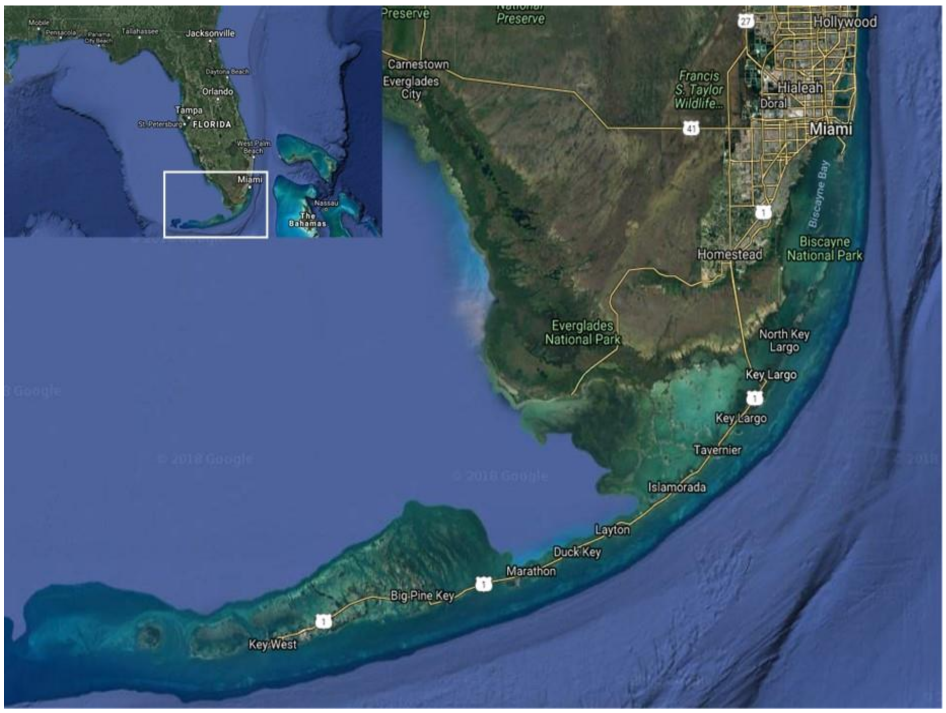


Figure 1.1. *Satellite image showing the Florida Keys (Google 2017)*

Construction of canals was not an environmentally responsible endeavor, especially in the fifties and sixties, when environmental concern was practically inexistent. On the contrary, design of canal geometry was driven by fill requirements to increase land area for new housing, not by future water quality concerns. Structural flaws in canal design and building included excessive depths (Fig 1.2), sills, as well as extremely long and dead-end canals, all lacking good water circulation and exchange with surrounding marine waters. These structures increase the residence or flushing time of canal waters and favor the accumulation of seaweed wrack and flotsam. These, in turn, rot and consume oxygen from the water column, depriving organisms of the required levels of oxygen to sustain life. Under such conditions, fish-kills and proliferation of sulfur-reducing bacteria, rendering smelly waters are the common result.

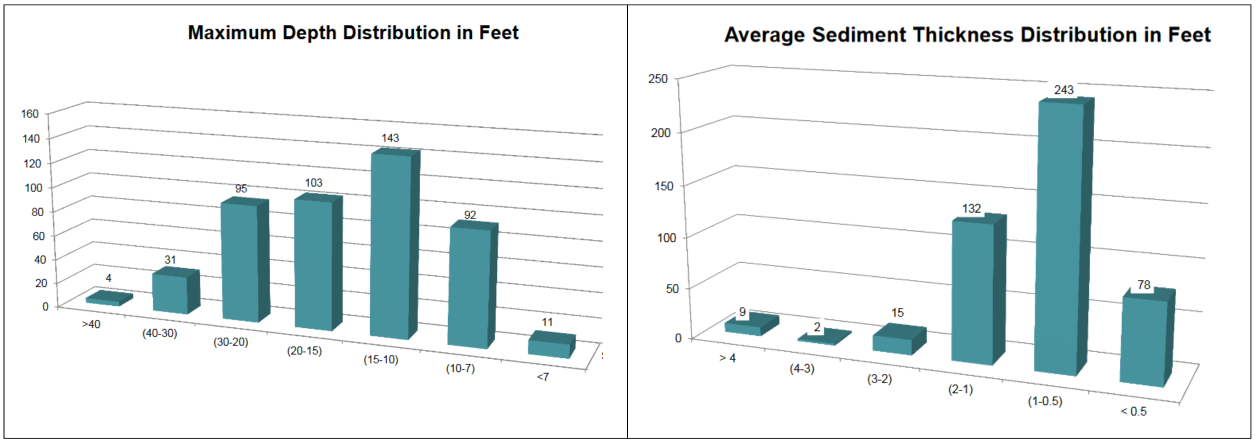


***Figure 1.2**. Distribution of maximum depth and average sediment thickness in Florida Keys canals (after AMEC, 2013a)*

Residence time (flushing time) is a critical parameter affecting water quality. It expresses the time required to purge a waterbody completely (i.e. canal) of its water or a given contaminant. Flushing depends upon canal geometry, length, depth and orientation with respect to wind direction and/or current direction. Hicks et al. (1975) studied water exchange of canals #263 and #258 in Big Pine and found an x 2.6 increase in flushing time by doubling the water depth and x1.7 increase by doubling the canal length.

Canal water is the result of contributions from rain, stormwaters, groundwater and marine waters, as well as human inputs. Contributions from these “endmembers” are continuously driven by tides, wind, currents and storms. To make things more complicated, until recently, most domestic wastewater disposal practices in the Florida Keys were primarily on-site disposal systems, including septic tanks, and shallow injection wells. These poorly treated waters ended-up into the extremely porous and permeable limestone substrate, where they readily moved to adjacent canals. Paul et al. (1995) have measured rates of groundwater migration in Key Largo, ranging from 0.57 to 24.2 meter/hour. Likewise, Briceño et al. (2015) measured rates from 0.9 to 23.2 meters/hour in Cudjoe Key. Similar conditions exist for the rest of the Florida Keys.

Given the high organic matter content in canal waters, especially bottom waters, increasing residence time causes depletion of dissolved oxygen of the water column at a faster rate than that of flushing and replenishing with new oxygen-rich waters. This would lead to hypoxia (oxygen deficiency) or anoxia (absence of oxygen), as observed in deep waters of many canals of the Florida Keys. The main conclusion is that to augment dissolved oxygen in the water column, we must increase water circulation and exchange reducing flushing time (e.g. installing culverts), reduce water depth (backfilling), keep seaweed coming into the canals (i.e. install weed barriers) or reducing canal length.

We have observed elevated nutrient concentrations (DIN, TP and SiO2) in waters close to shore along the Keys, and corresponding responses from the system, such as higher phytoplankton biomass (CHLA), turbidity and light attenuation (Kd), as well as lower oxygenation (DO) and lower salinities of the water column. These changes, associated to human impact, have become more obvious in a new series of stations (SHORE stations. Briceño and Boyer 2017) located very close to shore, near canal mouths and sampled since November 2011 (Fig 1.3). These waters are part of the so-called Halo Zone, a belt following the shoreline which extends up to 500 meters offshore, and whose water quality characteristics are closely related to those in canals and are affected by quick movement of infiltrated runoff and stormwaters, tides and high water tables.

For a long time canal waters have been recognized as contributors of nitrogen and phosphorous loads to Sanctuary waters (Hicks et al. 1975; Kruczynski, 1999; Briceño and Boyer, 2016). Canal waters are low in oxygen content, have high turbidity and are significantly enriched in nutrients as compared to other water bodies of the Sanctuary. Furthermore, most canal waters do not meet the Class III marine surface water quality standards for dissolved oxygen and nutrients (DEP Chapter 62-302, F.A.C.).

Moving forward to confront the water quality decline in some water bodies (segments), the Florida Department of Environmental Protection (FDEP) approved the Florida Keys Reasonable Assurance Documentation (FKRAD) in 2008, which defined management activities to address dissolved oxygen (DO) impairments for those water body segments (WBIDs). Following suit, the Monroe County Board of County Commissioners (BOCC) approved the execution of a series of canal restoration and demonstration projects, extending from Key Largo to Geiger Key, whose results would provide the necessary information to assess restoration costs and efficiency of the diverse methodologies.

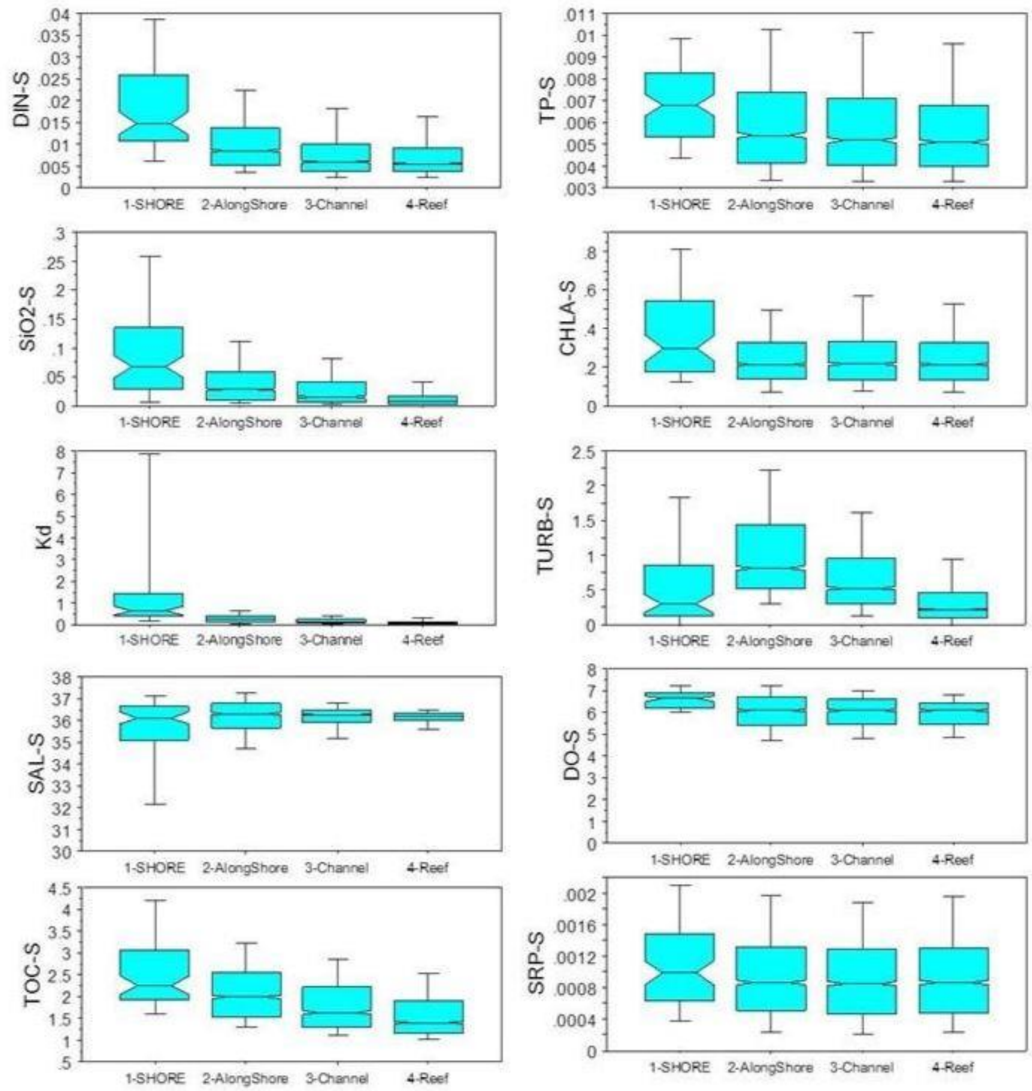


Figure 1.3. *Nutrient and response changes along transect from shore to reef-track in the Florida Keys (Briceño and Boyer, 2017)*

The Monroe County, the WQPP Steering Committee and the Canal Subcommittee have selected ten (11) canals out of twenty (20) pre-selected sites, for demonstration of restoration technologies (See Summary in Table 1.1). Additionally, seven (7) canals, which would not receive any remediation, were selected as control canals. The main objective of this demonstration is to obtain realistic data and costs for future restoration planning and grant application purposes (AMEC 2013a). Those technologies under consideration target two fundamental problems, poor circulation (stagnation) and accumulation of organic matter. Both, poor circulation and accumulation of organic debris, besides run-off and seepage from septic tanks, are the recognized major contributors to water quality degradation in the Florida Keys (Kruczynski, 1999; Briceño and Boyer, 2017), especially to the degradation of canal waters.

TABLE 1.1. Selected Canal Demonstration Projects Monroe County and Village of Islamorada. (Modified after AMEC 2013a)

	Weed Barrier			**Organic Removal**	**Weed Barrier and Organic Removal**	**Pumping**	**Culvert Installation**		**Backfilling**
Remediation Canals	#137 Plantation Key, Treasure Harbor	#148 Lower Matecumbe Key. Mate-Lido Beach	#287 Big Pine Key, Hollerich Subdivision	#290 Big Pine Key, Between Ave I & J	#266 Big Pine Key. Dr Arm Subdividion	#278 Big Pine Key. Eden Pines Colony Subdivision	#277 Big Pine Key. Tropical Bay Subdivision	459 Geiger Key. Boca Chica. Ocean Shores Subdivision	#29 Key Largo. Sexton Cove Estates Subdivision
								#472 and # 470 Geiger Key. Ocean Shores Subdivision	
Control Canals	**#132 Plantation Key**	**#147 Matecumbe K.**	**#293 Big Pine Key**			**#282 Big Pine Key**		**#458 & #460 Geiger Key**	**#28 Key Largo**

As the study progressed we realized the study was a challenging enterprise because of unpredictable delays and unexpected asynchrony in the implementation of remediation measures. Initial characterization was in occasions interrupted because of early remediation activities, while in other canals the beginning of remediation was delayed for more than a year. Finally, overall construction ended on The Environmental Protection Agency (EPA) provided funds and contracted Florida International University (FIU) to design and perform a 2-year monitoring program starting in 2014. The study finally extended up to 4 years.

2. Tested Remediation Technologies

The restoration technologies tested during this project for canal restoration demonstration (Table 1.1) are as follows:

- Reductions in weed wrack loading (using air-bubble curtains, or weed gates)

- Enhanced circulation (using culverts) to reduce hydraulic residence times and eliminate areas of water column stagnation
- Removal of accumulated organic sediments, in areas where the sediments are contributing to the development of phytoplankton blooms, bottom-water hypoxia and excessive hydrogen sulfide production; and
- Backfilling to reduce canal depth, in areas where excessive depth is contributing to poor circulation, bottom-water hypoxia, and other canal management issues.

Initially, pumping was a potential method among the remediation techniques to implement at Canal #278, but it was finally ruled-out. More recently, the installation of six injection wells was proposed as an alternative for Canal #278. Likewise, installation of a culvert in Canal #459 in Geiger Key has been cancelled. No alternative has been proposed for remediation of this canal.

3. Monitoring Objectives

The general objective of water quality monitoring for the demonstration canals is to measure the status and trends of water quality parameters to evaluate progress toward achieving and maintaining water quality standards and protecting/restoring the living marine resources of the Sanctuary, and to objectively compare diverse restoration methodologies used in the demonstration.

Specific objectives are as follows:

- To provide data needed to make unbiased, statistically rigorous statements about the status and temporal trends of water quality parameters in the remediated canals
- To inform management actions and policy development processes for improved water quality in the Sanctuary.

4. Conceptual Guidelines to Canal Monitoring

Monitoring consists of the continued observation of the selected canal waters to determine spatial and temporal variability in water quality. Monitoring involves systematic, long-term data collection and analysis to measure the status of water quality and to detect changes over time. Detecting and quantifying such changes at each specific canal, subjected to a specific remediation methodology, can focus research on quantifying and qualifying those changes to evaluate the success of corrective actions. As shown in Fig 4.1, each ACTION (i.e. Reduce Weed Wrack, Culvert Installation, Removal of Organic Sediments and Backfilling) is expected to lead to the achievement of some desired GOALS established as landmarks by the Canal Subcommittee. Reaching or approaching those GOALS entails important consequences in the canal conditions responding to CHANGES occurring in the water column. Finally, if such changes were to occur, we could detect and quantify them using our analytical toolkit and INDEXES (Fig 1.4) or indicators of environmental conditions (Doren et al 2009).

The proposed monitoring experiment has been conceptually conceived as a Before–and-After Control-Impact Design with multiple sites (BACI experiment; Green, 1979; Smith, 2002). This design entails the collection of data prior to the remediation activity in several sites within the canal to compare with data after remediation. The impact areas (remediated canals) are paired and compared to another canal (non-remediated canal), which is referred to as the "control" canal. Selected canals for remediation and the proposed control canals are shown in Table 1. The BACI experiment allows the application of methods where the data are treated as independent samples and are compared using diverse statistics. Physical-chemical properties of the water column were measured, and selected water samples were collected and analyzed following previous experience characterizing and monitoring canal WQ in Little Venice, Marathon (Briceño and Boyer 2009). In summary, the study was performed in two stages, characterization pre-remediation (BEFORE) and monitoring after remediation (AFTER). When done before remediation it was intended to characterize the system and to capture enough information to account for pre-remediation variability. Post-remediation monitoring was focused on detecting changes potentially linked to remediation.

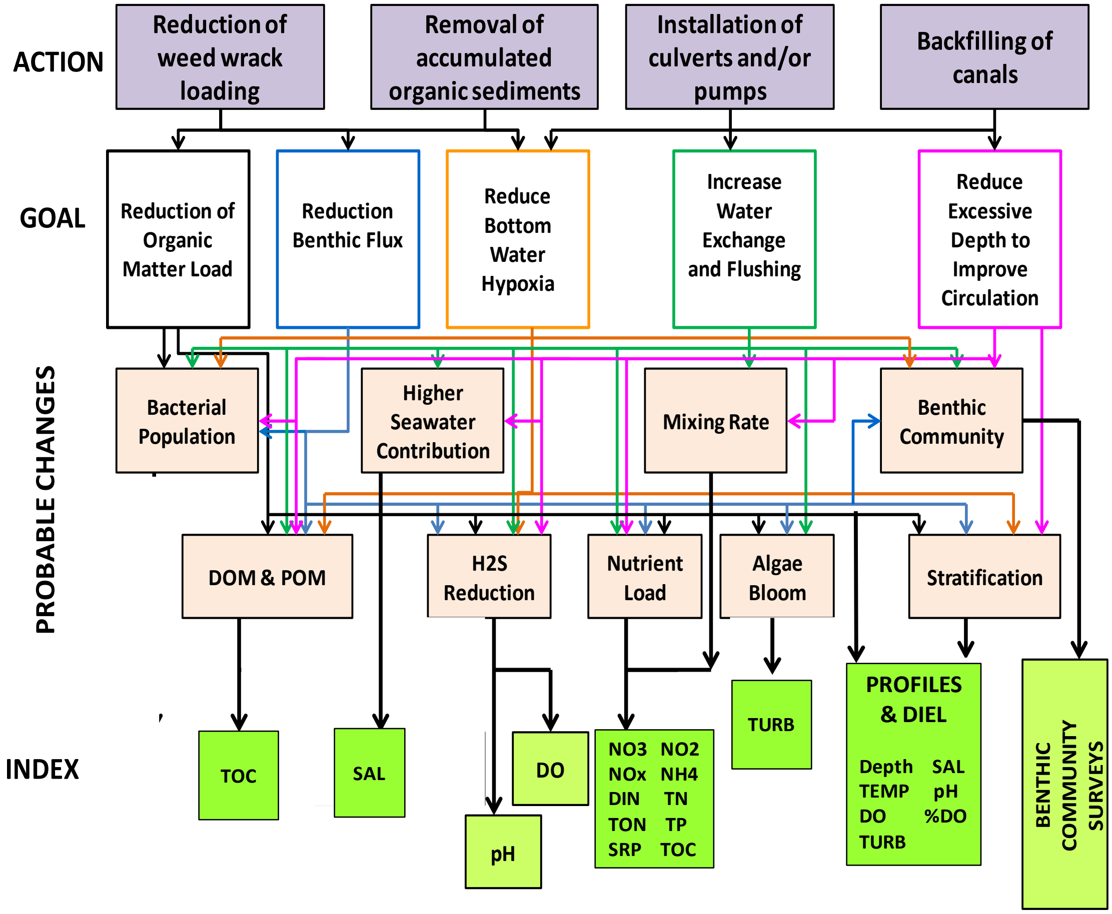


***Figure 4.1**. **Conceptual Monitoring Design**. Indexes used in this study in green boxes. TOC=Total organic carbon; SAL= Salinity; pH=acidity; DO=dissolved oxygen; %DO=% DO saturation; NO3=nitrate; NO2=nitrite; NOx=NO3+NO2; DIN=dissolved inorganic nitrogen; TN=total nitrogen; TON=total organic nitrogen; TP=total phosphorous; SRP=soluble reactive phosphorous; TOC=total organic carbon*

5. Methods

5.1. Field Sampling

Field measurements and grab samples were collected from fixed stations within canals. Depth profiles of temperature (°C), salinity (practical salinity scale), dissolved oxygen (DO, mg l^{-1}), % DO saturation, turbidity (NTU), and depth as measured by pressure transducer, were measured by YSI 6600 casts. The CTD was equipped with internal RAM and operated in stand-alone mode at a sampling rate of 0.5 sec. In order to determine the extent of stratification we calculated the difference between surface and bottom density as DSIGT (kg m^{-3}), where positive values denoted greater density of bottom water relative to the surface. A DSIGT = 0-1 is considered weakly stratified, while instances >1 are strongly stratified. Negative conditions occur rarely and denote an unstable water column where surface is denser than the bottom.

Water was collected from approximately 0.5 m below the surface and at approximately 1 m from the bottom with a Niskin bottle (General Oceanics). Unfiltered water samples were dispensed into 3x sample rinsed 120 ml HDPE bottles for analysis of total constituents (nitrogen, phosphorous, silica and organic carbon). Dissolved nutrients (nitrite, nitrate+nitrite, ammonium and soluble reactive phosphorous) were defined using Whatman GF/F filters with a nominal pore size of 0.7 µm. Water samples for dissolved nutrients were dispensed into 3x sample rinsed 150 ml syringes which were then filtered by hand through 25 mm glass fiber filters (Whatman GF/F) into 3x sample rinsed 60 ml HDPE bottles. All samples were kept on ice in the dark during transport to the laboratory. If not analyzed immediately upon arrival to the lab filtered samples were frozen until further analysis, and samples for totals were just stored under refrigeration.

5.2. Field measurements

Field measurements included vertical profiles and continuous 24-72 hour recording (diel) of physical-chemical properties. We deployed multi-sensor, water quality monitoring instruments (YSI6600) to measure physicochemical parameter profiles at the middle of canals throughout the water column in an effort to generate a depth profile of each parameter. The measured physicochemical parameters included depth (m), salinity (PSU), specific conductivity, temperature (°C), dissolved oxygen (DO in mg l^{-1}), %DO Saturation, and pH.

In order to monitor changes due to tidal cycles or diel variability, two YSI sondes (surface and bottom; Fig 5.3.1) were displayed to collect data (DO, %DO Saturation, Turbidity, Specific Conductivity, Salinity, Temperature and pH) every 15 minutes for up to 72-hour diel experiments.

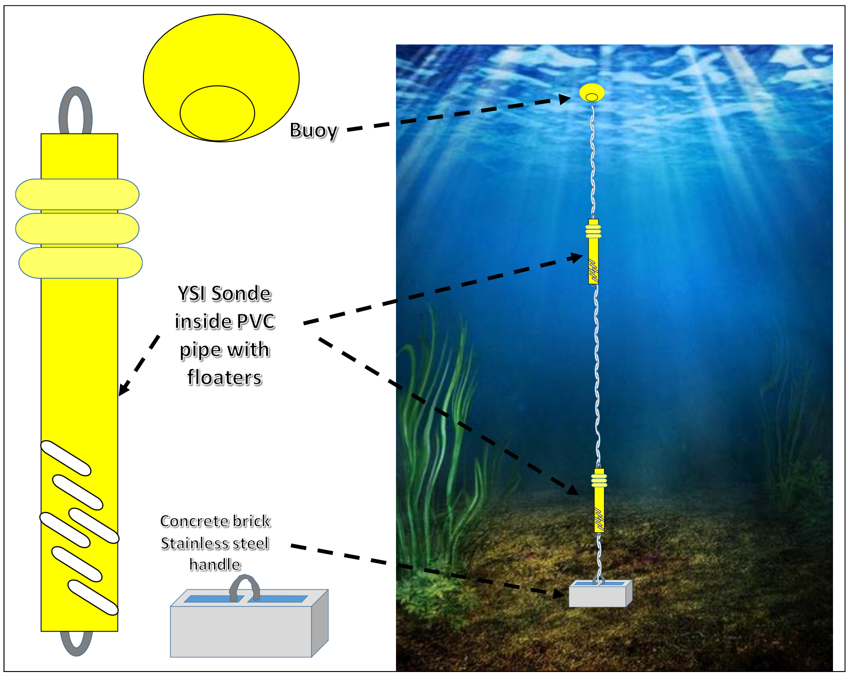


Figure 5.2.1: *Location of YSI sondes for capturing physical-chemical properties of water column in Florida Keys canals.*

5.3. Laboratory Analysis

Samples were analyzed for ammonium (NH4+), nitrate+nitrite (N+N), nitrite (NO2-), total nitrogen (TN), soluble reactive phosphorus (SRP), total phosphorus (TP), total organic carbon (TOC), silicate (SiO2), chlorophyll *a* (CHLA, µg l-1), and turbidity (NTU) using standard laboratory methods. In accordance with EPA policy, the Canal Water Quality Monitoring Program adhered to existing rules and regulations governing QA and QC procedures as described in EPA guidance documents. The FIU-SERC Nutrient Laboratory maintained NELAP certification during this project.

Ammonium ($NH4^+$) was analyzed by the indophenol method (Koroleff 1983). $NO2^-$ was analyzed using the diazo method and N+N was measured as nitrite after cadmium reduction (Grassoff 1983a,b). The ascorbic acid/molybdate method was used to determine SRP (Murphy and Riley 1962). High temperature combustion and high temperature digestion were used to measure TN (Frankovich and Jones 1998; Walsh 1989) and TP (Solórzano and Sharp 1980), respectively. TOC was determined using the high temperature combustion method of Sugimura and Suzuki (1988). Silicate was measured using the heteropoly blue method (APHA 1995). Samples were analyzed for CHLA content by spectrofluorometry of acetone extracts (Yentsch and Menzel 1963). Protocols are presented in EPA (1993) and elsewhere as noted. All elemental ratios discussed were calculated on a molar basis. DO saturation in the water column (%DOsat as %) was calculated using the equations of Garcia and Gordon (1992). Some parameters were not measured directly but calculated by difference. Nitrate ($NO3^-$) was calculated as N+N - $NO2^-$ total dissolved inorganic nitrogen (DIN) as N+N + $NH4^+$, and total organic nitrogen (TON) as TN - DIN. All variables are reported in ppm (mg l-1) unless otherwise noted.

5.4. Monitoring Water Quality

Monitoring during the AFTER Phase began from a few days to several months after Remediation. Water samples and Diel data will be captured for surface and bottom depths at selected stations in each canal (remediated and control. Table 1.1).

We used diverse methods to evaluate changes in biogeochemical water quality after remediation:

a. Comparing B&A mean nutrient concentrations.
b. Comparing before and after (B&A) data from YSI profiles.
c. Comparing B&A data from YSI Diel quarterly experiments
d. Comparing B&A number of %DO Saturation and pH exceedances

These methodologies compare the sites with themselves to track absolute changes in the selected index, disregarding the cause of change. Comparing remediated with control canal help identifying changes potentially related to remediation. Neither one of these methodologies is able to filter-out differentially induced variations such as eventual anthropogenic impacts (i.e. boat discharges, lawn irrigation, etc.) which may occur as confounding effect in any of the paired canals.

5.5. Summary Statistics - Box and Whisker Plots

Typically, water quality data are skewed to the left (low concentrations and below detects) resulting in non-normal distributions. Therefore it is more appropriate to use the median as the measure of central tendency because the mean is inflated by high outliers (Christian et al. 1991). Data distributions of water quality variables are reported as box-and-whiskers plots. The box-and-whisker plot is a powerful statistic as it shows the median, range, the data distribution as well as serving as a graphical, nonparametric ANOVA. The center horizontal line of the box is the median of the data, the top and bottom of the box are the 25th and 75th percentiles (quartiles), and the ends of the whiskers are the 5th and 95th percentiles. The notch in the box is the 95% confidence interval of the median. When notches between boxes do not overlap, the medians are considered significantly different. Outliers (<5th and >95th percentiles) were excluded from the graphs to reduce visual compression.

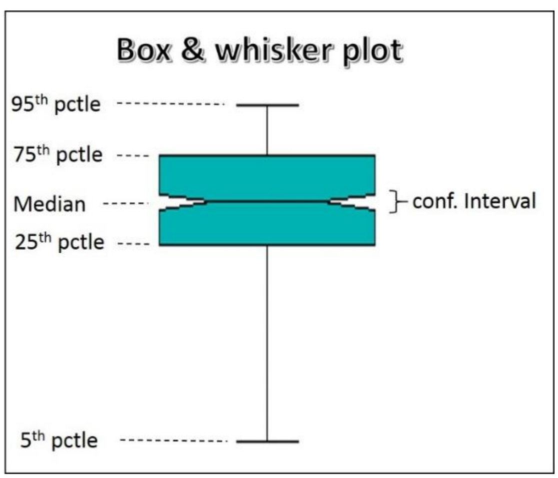


Figure 5.5.1 *Box & Whisker plot displaying the median, range, the data distribution*

6. Results

This project posed especial challenges given the unpredictable delays and unexpected asynchrony in the implementation of remediation measures. In fact, each remediation project became an individual monitoring project in itself, complicating logistics and forcing stretching of resources. Mother Nature conspired to make things even more complicated, and in September 10^{th}, 2017, when the program was near to be finished, Hurricane Irma made landfall in Cudjoe Key as a Category 4 storm. Irma's winds and surge affected all the Florida Keys, causing havoc everywhere and bringing massive amounts of debris to all canals. All monitoring plans programed for September to December 2017 had to be delayed, waiting for the systems to reach some stability and return to previous conditions. Even though the systems were not totally in optimal conditions, the project had to be finished and results delivered. This conditioning may, in some instances, preclude offering a final answer, given the uncertainty of the hurricane impact and the normal lag in system response. This is especially true for expected changes in nutrient concentration, as we have learned from similar monitoring programs in Little Venice, Marathon. After three years of weekly monitoring in Little Venice following installation of sewer system and cancellation of septic tanks there was no definitive improvement in water quality.

Following is a detailed report of results for each remediated canal from the monitoring of water quality in term of nutrients (water sampling and analysis) and physical-chemical properties (profiles and extended diel studies).

6.1 Canal #29.

Canal #29 is located in the Sexton Cove Sub-division, between Bunting & Pigeon Drives, Key Largo. It is a 720 ft long straight canal reaching depths down to 32 ft, and developing a pseudo-fjord profile (Figs 6.1.1 and 6.1.2), which combined with a small tidal range (about 0.5 ft) hinders circulation and replenishment of deeper waters with cleaner, oxygen-rich marine waters. Stagnation of water due to extreme depth is blamed responsible for the poor water quality existing in these canals.

The selected remediation method for Canal #29 was backfilling with crushed carbonate rock from -35 ft Mean Low Water (MLW) to a final mean depth of about -7.7 ft MLW. About 900 truckloads of filling material graded from a maximum diameter of 6 in for the base, to the sub-base with maximum diameter of 3 inches, and final capping with 1' of A3 screening sand (ACME 2013b). The project started on March 2015 and finally completed in July 2015.

6.1.1. Nutrient monitoring

Canal #29 was sampled eight times, three times Before remediation (FKC01 on April 2014 and FKC02 in October 2014), and five times after backfilling during FKC05 (Feb 2016); FKC07 (Nov 2016); FKC08 (June 2017) and FKC09 (March 2018) after Hurricane Irma (Fig. 6.1.3). The monitoring program had to be delayed several months given the extreme turbidity that affected the canal waters right after backfilling.

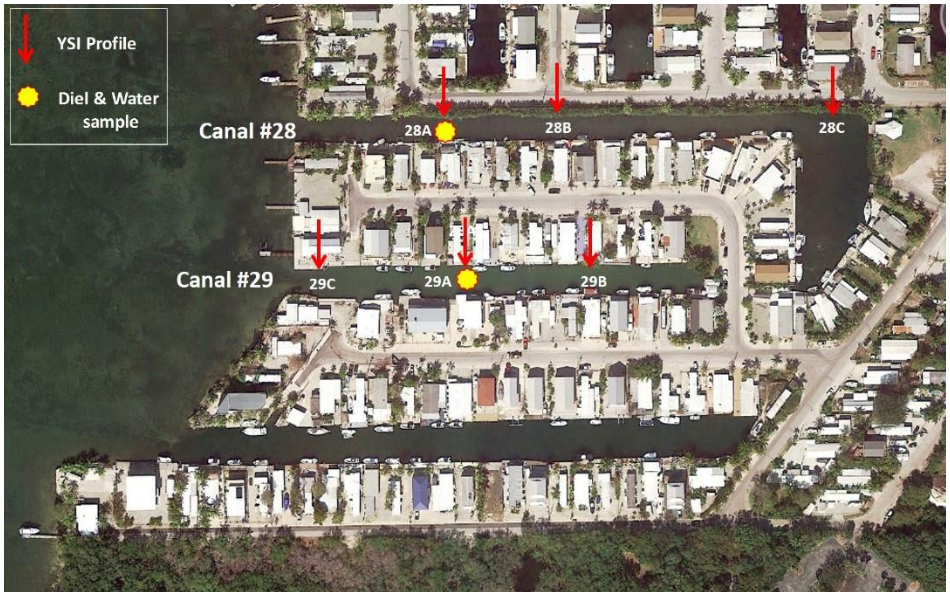


Figure 6.1.1: *Google image rendition of canal #28 (control) and canal #29 (remediation) in Sexton Cove Sub-division, Key Largo.*

NO2, NO3, NOx, and DIN seem to decline AFTER remediation (after FKC05; Fig 6.1.3) and it is a good sign, but this decline is also evident in the control canal, and there were similar concentrations pre-remediation. So, those declines cannot be exclusively ascribed to remediation. NH4 clearly declined after remediation for bottom samples as expected. TN and TON have not improved AFTER backfilling (Fig 6.1.4), and declines in TP and SRP are somehow mimicked in the control canal, ruling out remediation as the exclusive cause of reduction in concentration. Finally, TOC has remained constant through the whole period of record. In summary, there is not conclusive evidence that remediation has driven any significant decline in nutrient concentration in Canal #29.

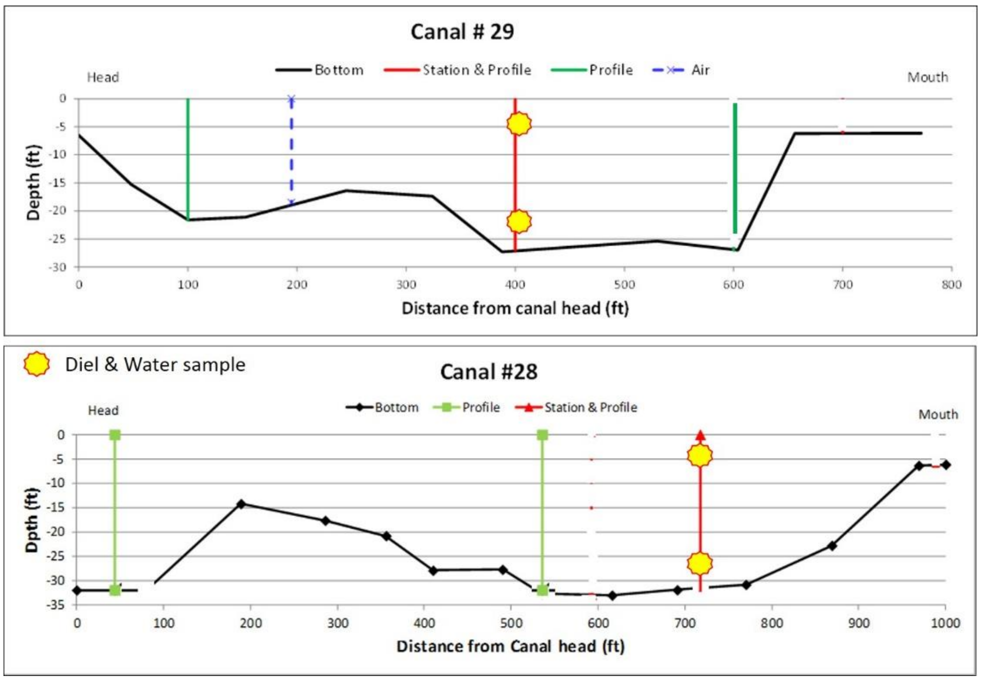


Figure 6.1.2: *Bathymetric profile of canal #28 and canal #29, showing location of sampling and profile measurement sites, as well as location of air bubblers*

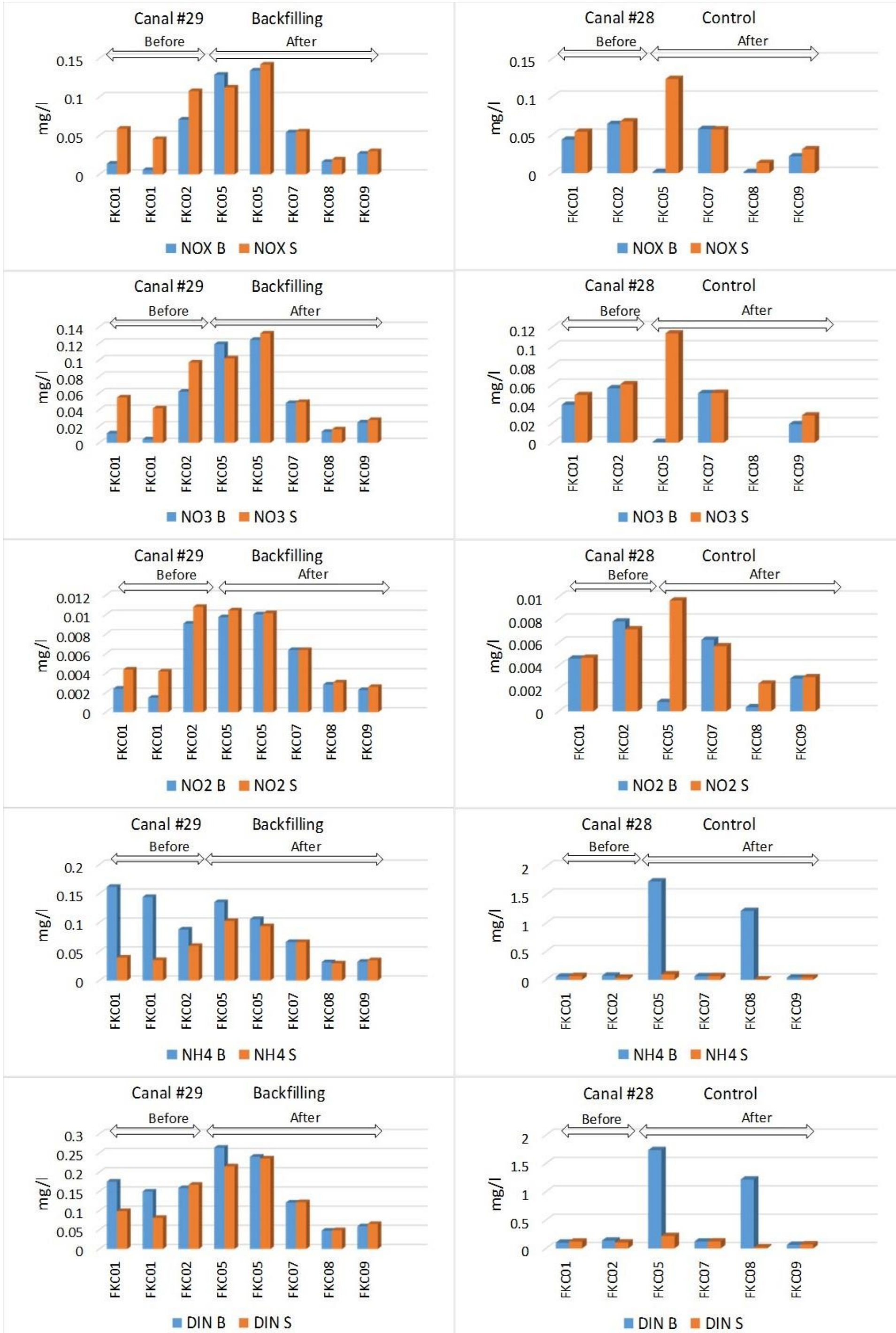


Fig 6.1.3. *Water quality comparison between Before and AFTER sampling, and between remediated Canal #29 and control Canal #28. Dissolved nitrogen species: nitrate+nitrite (N+N), nitrate (NO3), nitrite (NO2), ammonium (NH4) and dissolved inorganic nitrogen (DIN)*

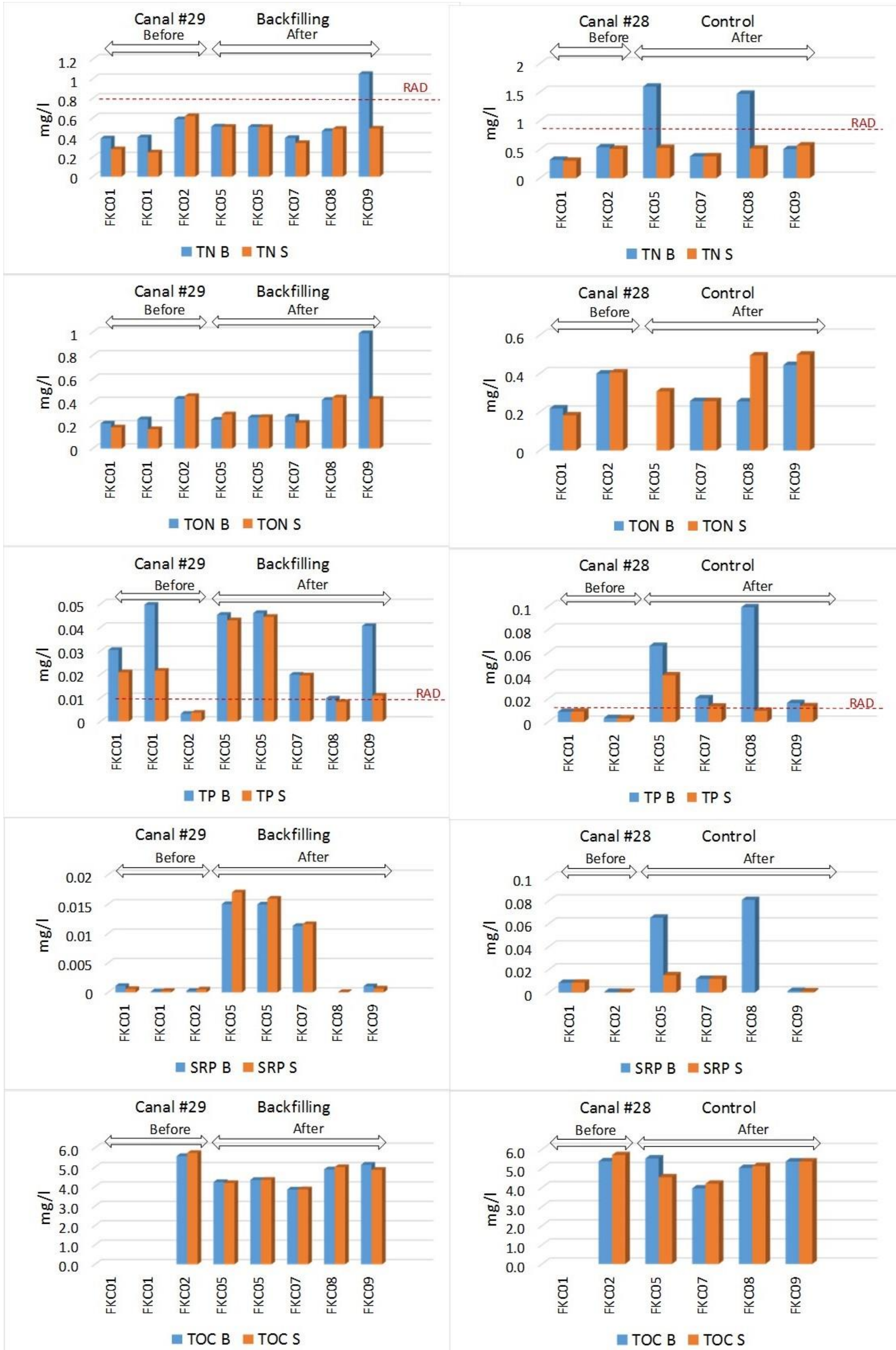


Fig 6.1.4. *Water quality comparison between Before and AFTER sampling, and between remediated Canal #29 and control Canal #28. Dissolved nitrogen species: total nitrogen (TN); total organic nitrogen (TON); total phosphorous (TP); soluble reactive phosphorous (SRP); and total organic carbon (TOC).*

6.1.2 Profiles of water column

Measurements of physical-chemical properties made in Nov 2013 (Fig 6.1.5), exemplify the kind of water quality issues affecting Florida Keys' canals and why remediation is necessary. In most canals, there are significant changes occurring as we go deeper in the canal, especially the development of strong stratification in salinity, pH, dissolved oxygen and photosynthetically active radiation (PAR; radiation useful for photosynthesis). At depth, saltier (denser) waters tend to remain stagnant, while their pHs drop below 7, increasing the dissolution rates of carbonates affecting organisms dependent on calcium-carbonate shell-building, such as zooplankton, coral and oysters. Declines in dissolved oxygen saturations below 42% render waters not suitable for sustaining aquatic life (FDEP, Rule 62-302.533 F.A.C.), and drastic declines in light penetration, specifically of photosynthetically active radiation (PAR), limit the capacity of organism to perform photosynthesis. These conditions conspire to produce a "dead zone" for waters deeper than about 12 ft (4 m)

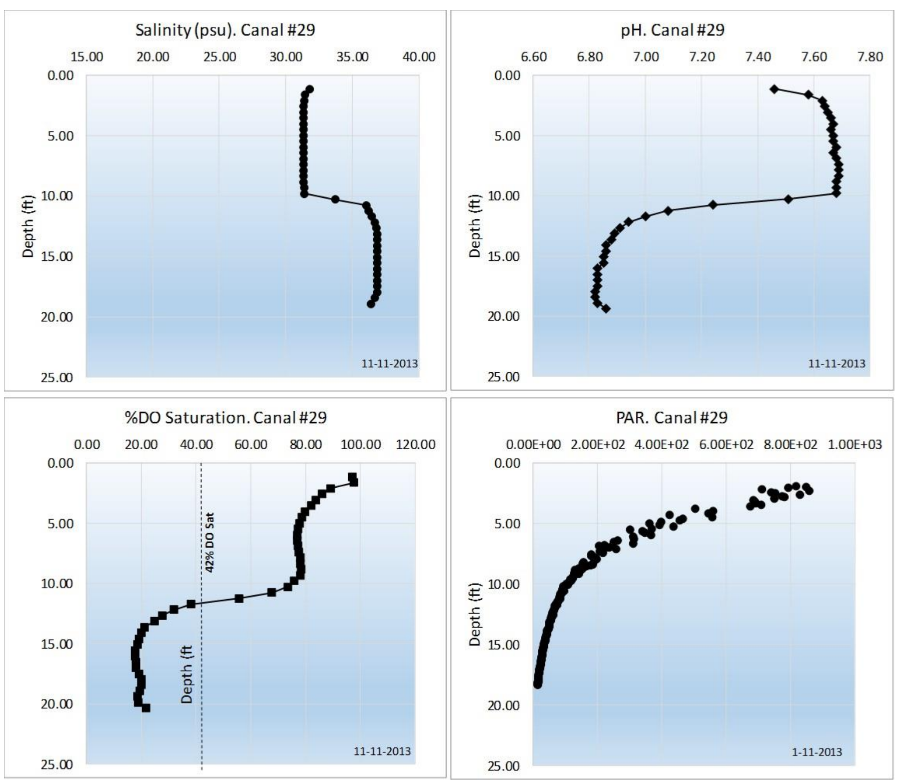


***Figure 6.1.5**. Profiles of physical-chemical variables of water column in Canal #29, measured before backfilling in Nov 2013. Stratification (layering) of water column is well developed*

Temporal changes of physical-chemical properties of waters in Canal #29 were measured in sixteen profiles during 8 surveys as shown in Figure 6.1.6. Backfilling in Canal #29 was completed in July 2015, after survey FKC02. Before remediation %DO sat varied widely, from 17% to 97%, especially at section 29C. After backfilling %DO Sat increased considerably and the median has been above 76.4% in all profiles since then. No measurement has been below 68%DO saturation. Salinity and temperature are extremely varied before and after remediation. Salinity descended right after backfilling, and then increased progressively until Irma's impact. Median salinity before backfilling was relatively high and above 31 psu. After remediation the median salinity oscillated between 25.3 and 37.6 psu. Interesting enough, salinity has been uniform among stations within a given survey, but varied widely among surveys. What this uniformity indicates is a well mixed water column along the canal, suggesting an effective circulation driven by tides.

Table 6.1.1. Summarized selected profile statistics BEFORE and AFTER remediation. Canal #29

Canal	Parameter	Temp, Before	Temp, After	Salinity, Before	Salinity, After	pH, Before	pH, After	DO%, Before	DO%, After
Canal #29	Mean	26.5	25.4	33.6	30.7	7.5	7.7	62.1	84.4
Canal #29	Std. Dev.	1.6	4.6	2.4	4.5	0.3	0.2	24.9	11.3
Canal #29	Count	149	185	149	185	149	185	149	185
Canal #29	Minimum	24.6	19.7	31.2	25.2	6.8	7.5	17.8	59.7
Canal #29	Maximum	29.9	33.2	36.9	37.7	7.7	8.0	97.8	117.9
Canal #29	Coef. Var.	0.1	0.2	0.1	0.1	0.0	0.0	0.4	0.1
Canal #29	Range	5.3	13.5	5.7	12.5	0.9	0.5	80.0	58.2
Canal #29	Geom. Mean	26.5	25.0	33.5	30.4	7.5	7.7	55.6	83.7
Canal #29	Median	26.3	23.6	32.1	30.7	7.6	7.7	74.2	81.9

Median temperature before remediation varied between 24.9 °C and 26.4 °C. After remediation it oscillated between 20.5 °C and 32.9 °C. As with salinity, variability within surveys is very small, while among surveys changes are extreme. Again, temperature in the post remediation stage suggests that waters are well mixed, not only vertically, but also along the length of the canal. Finally, acidity (pH) has increased since remediation. Before remediation pH varied significantly, reaching values below neutral pH in all 4 profiles. Before remediation median pH oscillated between 7.24 and 7.62. After backfilling median pH increased and has always been above 7.5 units. Furthermore, no individual measurement has been below 7.49 units. In summary, water quality as represented by casts of physical-chemical properties indicate significant improvements after backfilling. Remediation of Canal #29 may be considered a success story.

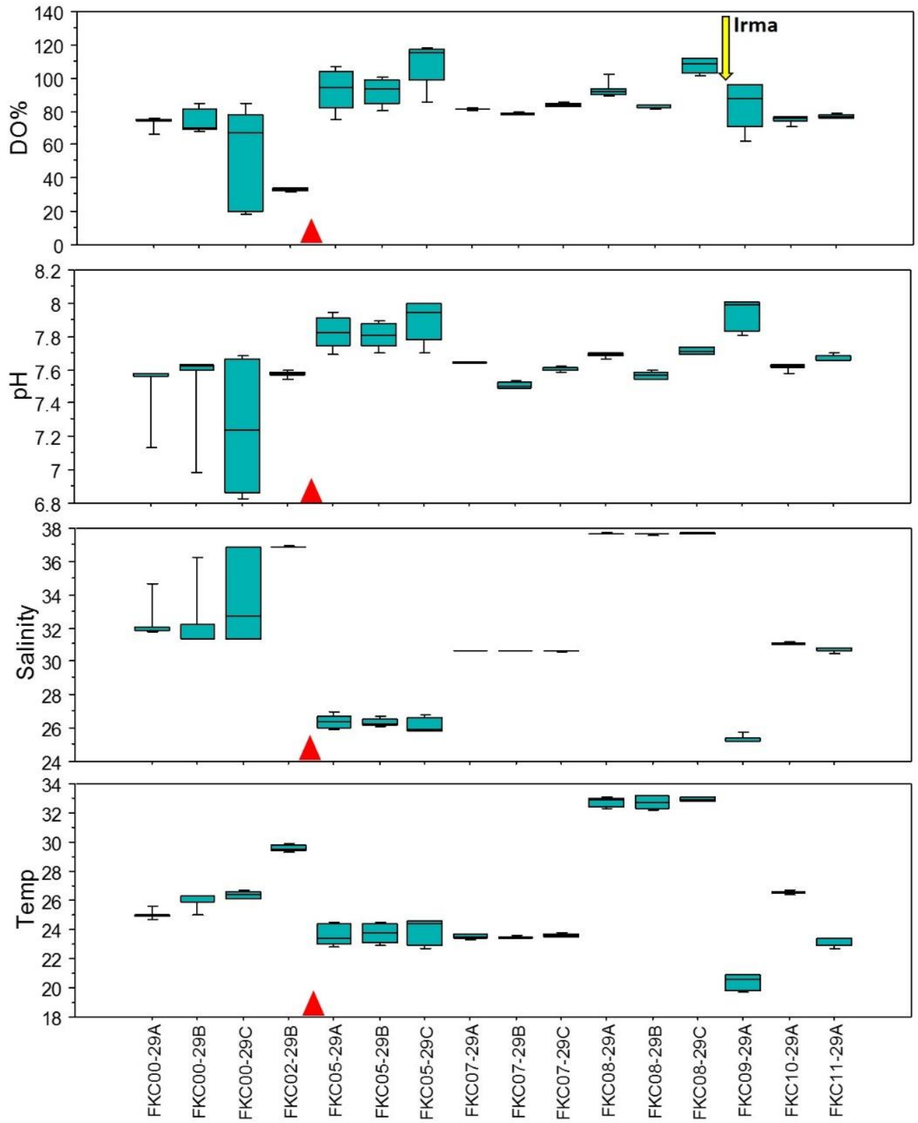


***Figure 6.1.6**. Box-and-Whisker plots of physical-chemical variables measured along depth profiles of the water column in Canal #29. Date of remediation is indicated by the red triangle, and Irma landfall by yellow arrow.*

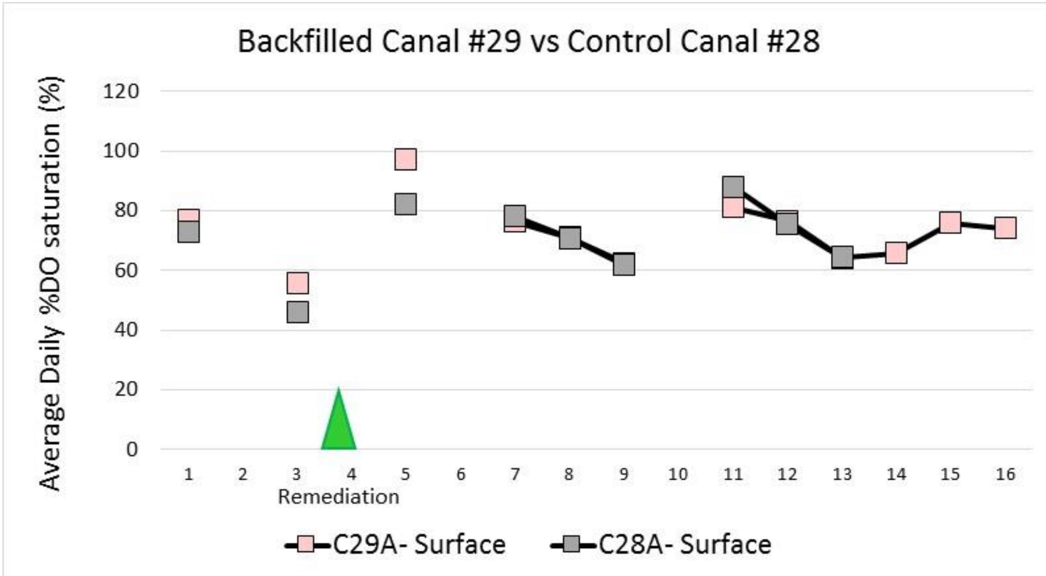
6.1.3 Diel Measurements

Diel observations, meaning twenty four-hours of continuous observation and recording, were performed to trace the relationships among physical-chemical parameters and relevant factors that change along the day, like tides influencing water quality by bringing and withdrawing water from canals, biotic processes in the water column and bottom which are dependent upon sunlight (i.e. photosysnthesis), or even human activities affecting waters, like watering gardens, boating, etc. Furthermore, results from a long series of data are more robust and less uncertain than a measurement from a grab sample. We measured physical chemical variables (temperature, salinity, specific conductance, ph, DO, %DO saturation and turbidity) every 10 minutes, for a daily total of 144 measurements.

Average diel %DO saturation for 13 diel-days for Canal #29 are plotted together with those of its control Canal #28. Three levels of information may be derived from these diagrams, first, how Canal #29 and #28 have changed over time, providing a feeling for the variability present in the dataset. Second, how each one behaved before and after remediation, and third, we may compare how #29 fares with respect to #28 in terms of remediation, given that #28 has not experienced any remediation and #29 was backfilled.

As we can see from surface data (upper plot on Fig 6.1.7) both canals have very similar daily average %DO saturation, concentrations are all above 42% DO sat, and backfilled and control canal do not change significantly from before to after remediation. In fact these two canals do not seem to have surface water problems.

Now, the lower diagram in Fig 6.1.7 show two separate behaviors. Before remediation #29 had lower %DO sat than #28 and after backfilling #28 totally decouples and contains an order of magnitude more %DO saturation than the control canal, and most “diel days” were above 42%. The improvement of water quality conditions of Canal #29 after remediation is evident.



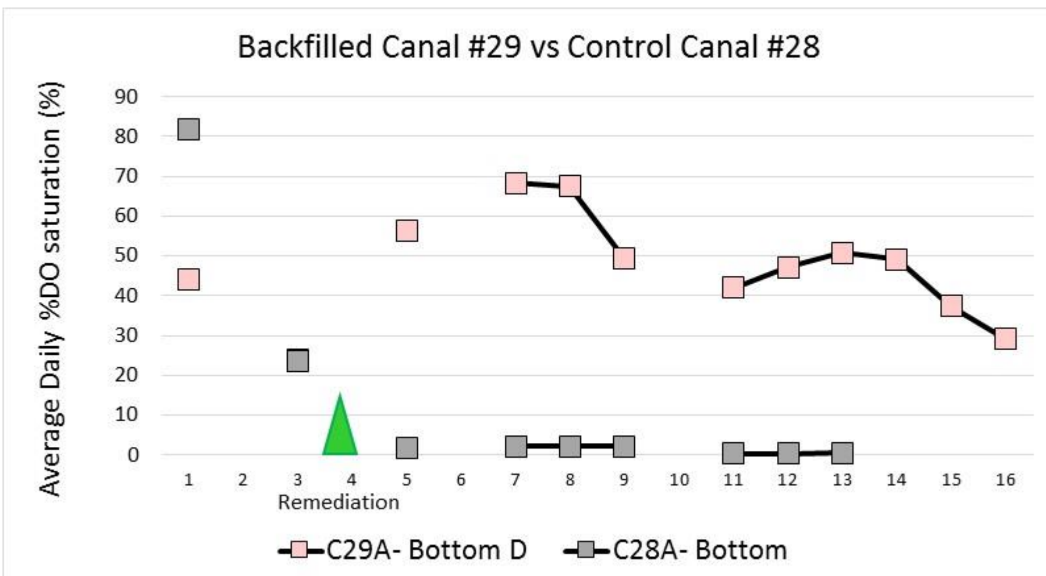


***Figure 6.1.7**. Diel (24 hour) observations of %DO saturation for Backfilled Canal #29 and Control Canal #28, Key Largo. Green triangle indicates when remediation took place.*

6.2 Canal #137.

Canal #137 is located in Treasure Harbor, Plantation Key. It is a 5.7 acre, 1,180 ft long basin-shaped canal, reaching depths down to 14.5 ft (Figs 6.2.1 and 6.2.2), with a narrow entrance, and despite a 2.14 ft tidal range, it lacks enough circulation and replenishment with cleaner, oxygen-rich marine waters. Orientation of the canal inlet with respect to prevailing winds causes seaweed wrack to enter the basin and slowly settle down. As seaweed wrack settles bacterial activity decomposes the organic matter, first by aerobic organisms in the upper, oxygenated portions of the water column, and then at deeper waters by anaerobic bacteria. Oxygen in the upper portions of the water column is consumed during oxidation of organic matter.

Anaerobic sulfur–reducing bacteria in deeper waters use the oxygen from the sulfate to oxidize the organic matter (supplier of hydrogen molecules), while hydrogen sulfide (H2S) is produced (Equation1). The final outcome is an oxygen-depleted water column, where fish-kills are common, and waters smell like rotten-eggs.

$$4H_2 + CaSO_4 \rightarrow H_2S + 2H_2O + 2OH^- + Ca^{2+} \qquad (1)$$

The selected remediation method for Canal #137 was aeration. Installation completed 04 November 2014. Figure 6.2.3 illustrates the BEFORE (2013) and AFTER (2014) lay-out of air bubblers (aerators) in canal #137. Additionally an air curtain was installed at the canal mouth to keep seaweed wrack out of the canal (https://www.vertexwaterfeatures.com/airgate-technology-for-canals-and-marinas)

6.2.1 Nutrient monitoring

Canal #137 was sampled during seven surveys for a total of 24 samples. Four samples collected before remediation (FKC01 on April 2014 and FKC02 in October 2014), and 20 samples after installation of aerators during FKC04 (Jun 2015), FKC05 (Feb 2016); FKC07 (Nov 2016); FKC08 (June 2017), and finally FKC09 after Irma's impact (March 2018) (Fig. 6.2.4).

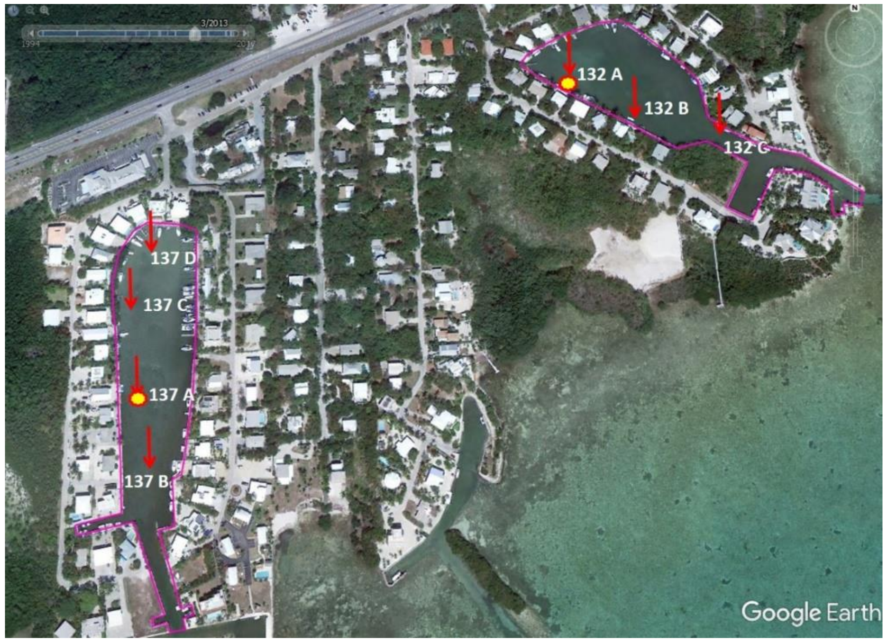


__Figure 6.2.1:__ Google image rendition of canal #132 (control) and canal #137 (remediation) in Treasure Harbor, Plantation Key.

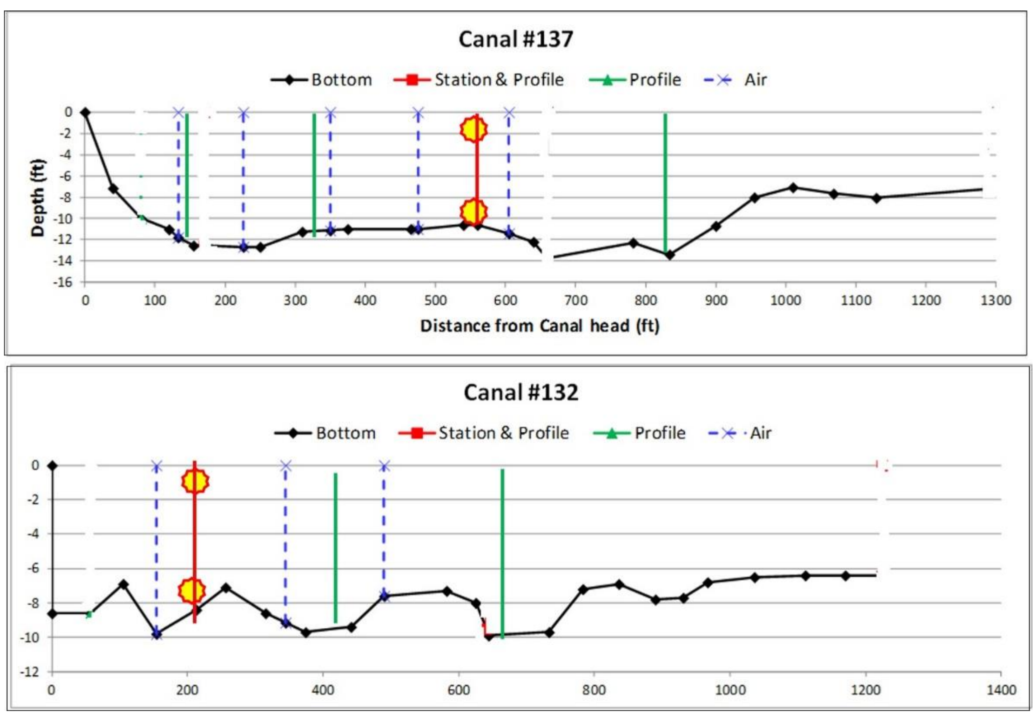


__Figure 6.2.2:__ Bathymetric profile of canal #137 and canal #132, showing location of sampling (yellow circle) and profile measurement sites, as well as location of air bubblers

Canal #137 was sampled during seven surveys for a total of 24 samples. Four samples collected before remediation (FKC01 on April 2014 and FKC02 in October 2014), and 20 samples after installation of aerators during FKC04 (Jun 2015), FKC05 (Feb 2016); FKC07 (Nov 2016); FKC08 (June 2017), and finally FKC09 after Irma's impact (March 2018) (Fig. 6.2.4).

NO2, NO3, NOx, seem to decline after remediation (after FKC07; Fig 6.2.3), but this decline seems to be also in the control canal although not so well defined. NH4 and DIN show a drastic decline with remediation, suggesting improvement, especially since June 2017. It is interesting that results for FKC09, after Hurricane Irma, resulted in declines in NH4 and DIN, suggesting that stirring, erosion and perhaps outflow of organic rich sediments due to winds and storm surge, improved water quality despite the accumulation of debris by the hurricane.

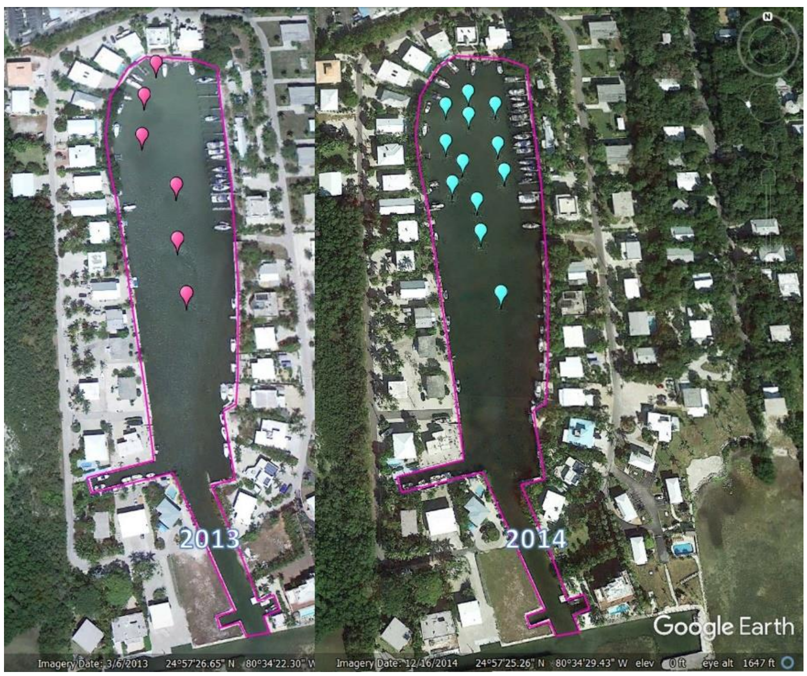


Fig 6.2.3. *Existing six aerators Before remediation, by March 2013 (left panel, magenta), and relocation and installation of 12 new aerators in Canal #137 as of December 2014 (right panel, blue).*

Fig 6.2.4. *Water quality comparison between Before and AFTER sampling, and between remediated Canal #137 and control Canal #132. Dissolved nitrogen species: nitrate+nitrite (N+N), nitrate (NO3), nitrite (NO2), ammonium (NH4) and dissolved inorganic nitrogen (DIN). Survey FKC09 occurred after Irma*

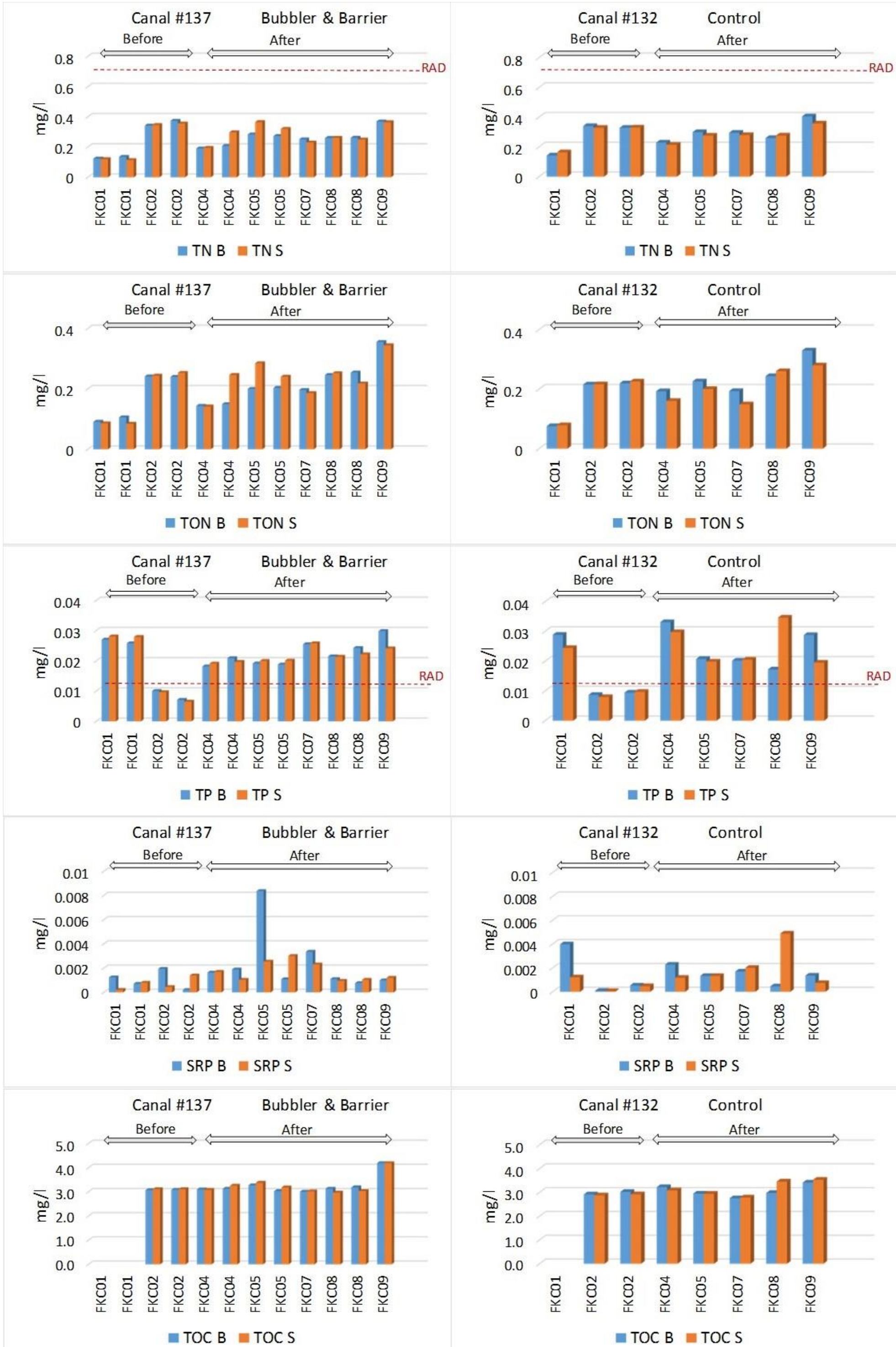


Fig 6.2.5. *Water quality comparison between Before and AFTER sampling, and between remediated Canal #137 and control Canal #132. Dissolved nitrogen species: total nitrogen (TN); total organic nitrogen (TON); total phosphorous (TP); soluble reactive phosphorous (SRP); and total organic carbon (TOC). Survey FKC09 occurred after Irma*

TN and TON have not improved after installation of aerators (Fig 6.2.5), and declines in TP and SRP, especially in FKC08 and 09 are somehow mimicked in the control canal, ruling out remediation as the exclusive cause of reduction in concentration. Finally, TOC has remained constant through the whole period of record. In summary, there is an ill-defined pattern of improvement in nutrient data after remediation, and dissolved nitrogen species, especially NH4 and DIN, seem to be moving in the right direction in Canal #137.

6.2.2 Profiles of water column

Temporal changes of physical-chemical properties of waters in Canal #137 were measured in twenty four profiles during eight surveys as shown in Figure 6.2.6. Installation of aerators and air curtain in Canal #137 was completed in Nov 2014, after survey FKC02. Before remediation median %DO sat varied from 20% to 53%. Right after remediation %DO Sat increased considerably to 59.7% but progressively declined to 36% in FKC07 (Nov 2016). Followed a sudden increase to reach a median of 74% DO sat with elevated variance in January 2018, after Irma . Then, saturation dropped to only 18% by March 2018.

Acidity before remediation was around 7.3 pH units, with moderated variability. Immediately after remediation it was very variable with a median around 7.4 units, then it declined continuously to a minimum median of 6.59 units in June 2017 (FKC08). Since then pH variance increased and values went up and finally down to about neutrality (pH=7) (Fig 6.2.6). pH and %DO saturation were directly correlated

Salinity and temperature are in general varied before and after remediation. Median salinity before aeration was relatively high and above 35 psu. After remediation the median salinity oscillated between 34.7 and 38.0 psu. Salinity and temperature have been uniform among stations within a given survey, but varied widely among surveys. What this uniformity indicates is that any given time there is a well mixed water column along the canal, suggesting an effective circulation driven by tides.

Table 6.2.1. Sumarized selected profile statistics BEFORE and AFTER remediation for Canal #137

Canal	Parameter	Temp, Before	Temp, After	Salinity, Before	Salinity, After	pH, Before	pH, After	DO%, Before	DO%, After
Canal #137	Mean	26.3	26.0	36.4	36.7	7.3	7.1	37.8	45.5
Canal #137	Std. Dev.	2.0	4.1	1.1	1.0	0.1	0.3	15.4	13.6
Canal #137	Count	145	442	145	442	145	442	145	442
Canal #137	Minimum	23.4	20.8	35.1	34.7	7.2	6.2	18.2	8.4
Canal #137	Maximum	28.8	32.8	38.0	38.5	7.5	7.8	77.0	99.6
Canal #137	Coef. Var.	0.1	0.2	0.0	0.0	0.0	0.0	0.4	0.3
Canal #137	Range	5.4	12.1	2.8	3.8	0.3	1.6	58.8	91.2
Canal #137	Geom. Mean	26.2	25.7	36.4	36.7	7.3	7.1	34.7	43.3
Canal #137	Median	26.1	24.2	35.6	36.4	7.3	7.2	40.1	45.0

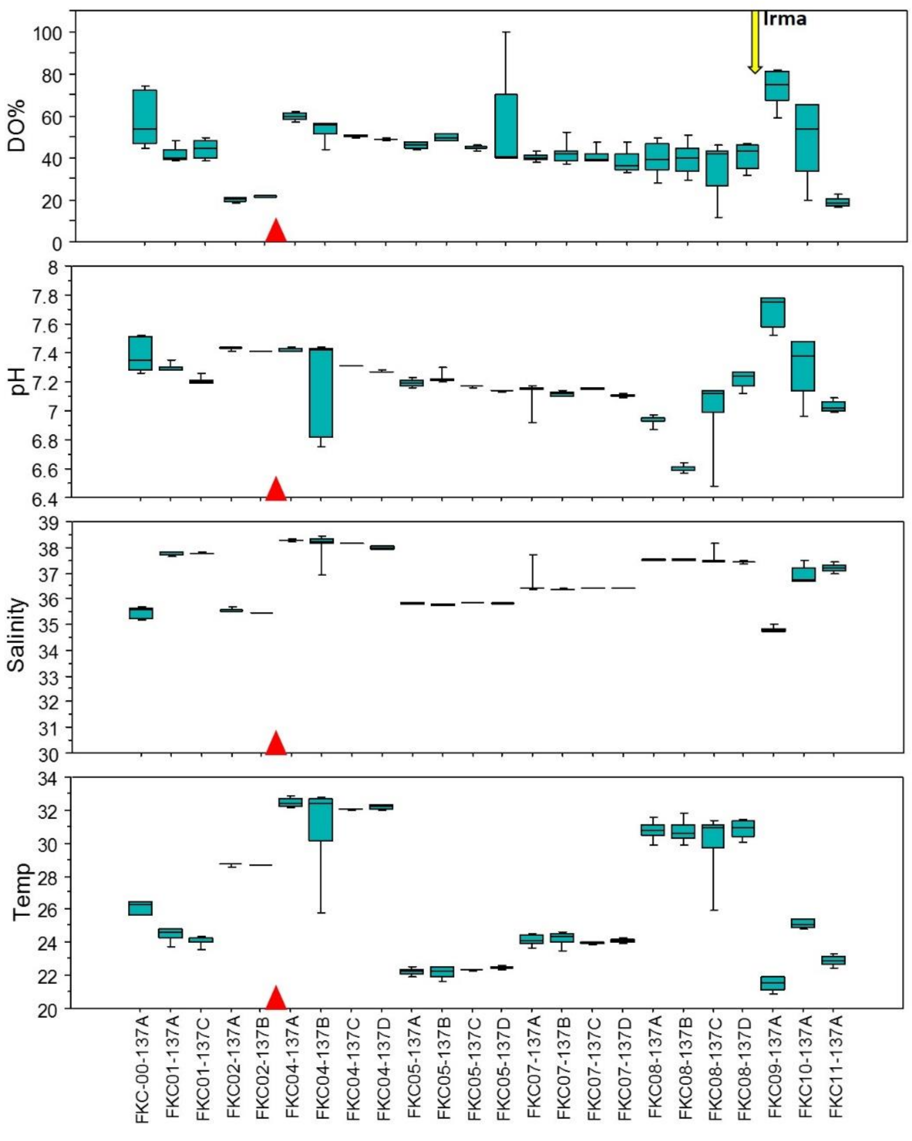
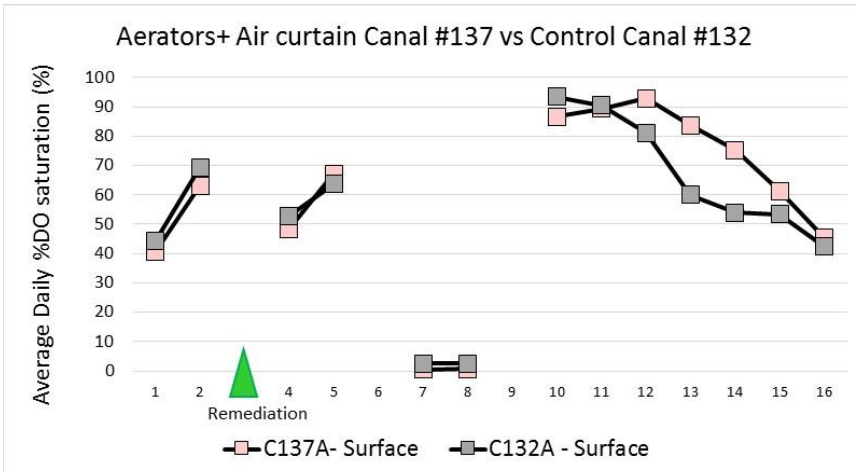


***Figure 6.2.6**. Box-and-Whisker plots of physical-chemical variables measured along depth profiles of the water column in Canal #137. Date of remediation is indicated by the red triangle.*

6.2.3 Diel Measurements

Figure 6.2.7 shows average diel %DO saturation for 13 diel-days for Canal #137 and its control Canal #132. Surface waters (upper diagram) have very similar patterns and concentration levels and do not seem to be significantly affected by remediation, although #137 shows better %DO saturations towards the end of the dataset. There are no issues with %DOsat in surface waters from remediated and control canals.



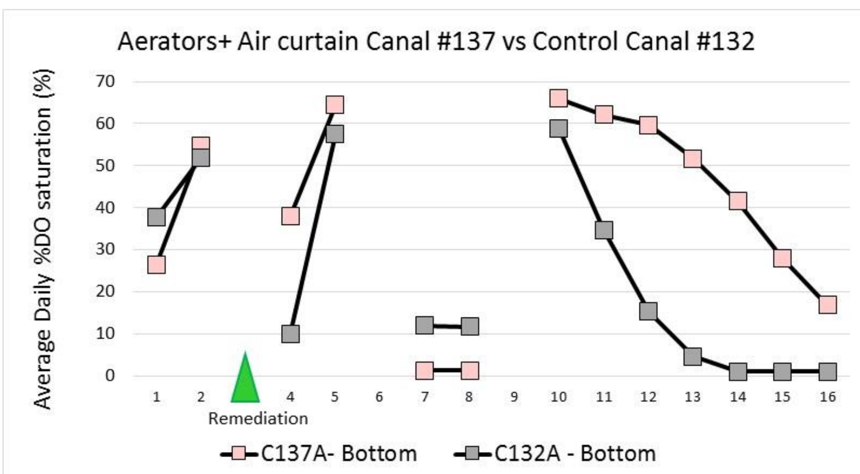


***Figure 6.2.7**. Diel (24 hour) observations of %DO saturation for BackfilledCanal #137 and Control Canal #132, Treasure Harbor, Plantation Key. Green triangle indicates when remediation took place.*

Bottom plot of Figure 6.2.7 shows similar behavior for both canals until about the 10th diel. From then on, Canal #137 seem to decouple, and despite suffering from a common decline affecting both canals, it remains substantially richer in dissolved oxygen than the control canal.

It may be an indication of improvement brought about by remediation, but more observations are necessary to confirm the suspected improvement.

6.3 Canal #148.

Canal #148 is located on the ocean side of Lower Matecumbe Key. It is a 0.99 acre, 918 ft long straight canal, reaching depths down to -9 ft (Figs 6.3.1 and 6.3.2). Its bottom is covered with a 1.5 ft thick organic-rich sediment layer. Orientation of the canal (azimuth=135 degrees) with respect to prevailing winds (122.5 degrees; Fig 6.3.3) facilitates seaweed wrack to enter the basin and slowly settle down. As in other canals, bacterial activity and natural oxidation decompose the organic matter, depleting the water column of oxygen and increasing its nutrient content. Likewise, anaerobic bacteria reduce sulfate to obtain oxygen when consuming the organic matter, while forming hydrogen sulfide (H2S) as by-product. The final outcome is an oxygen-depleted water column, where fish-kills are common, and waters smell like rotten-eggs. The selected remediation method for Canal #148 was installation of an air curtain, whose installation was completed in May 2017. Unfortunately Hurricane Irma damaged the air curtain system and as this report is being written (May 2018), a new fish-kill event is occurring, because of massive amounts of seaweed invaded the canal.

6.3.1 Nutrient monitoring

Canal #148 was sampled during six surveys for a total of 14 samples. Ten samples collected before remediation during FKC01 (April 2014), FKC02 (Oct 2014), FKC04 (Jun 2015), and FKC05 (Feb 2016); and four samples collected after installation of aerators during FKC08 (June 2017) and FKC09 (March 2018). This last survey was performed after Irma damaged the air curtain (Fig. 6.3.4).

NO3, NOx, NO2, NH4, DIN do not show significant changes after remediation, except for some occurring after Irma's impact (FKC09; Fig 6.3.4), which cannot be ascribed to a differential response to Irma due to remediation, because similar changes are also observed in the control canal data. As shown in Figure 6.3.5, TN, TON, TP and SRP are non-diagnostic either. Finally, TOC has remained constant through the whole period of record. In summary, there is not clear pattern of improvement in nutrient data AFTER remediation. Not enough samples have been collected and analyzed, and not enough time has elapsed since remediation to detect significant changes.

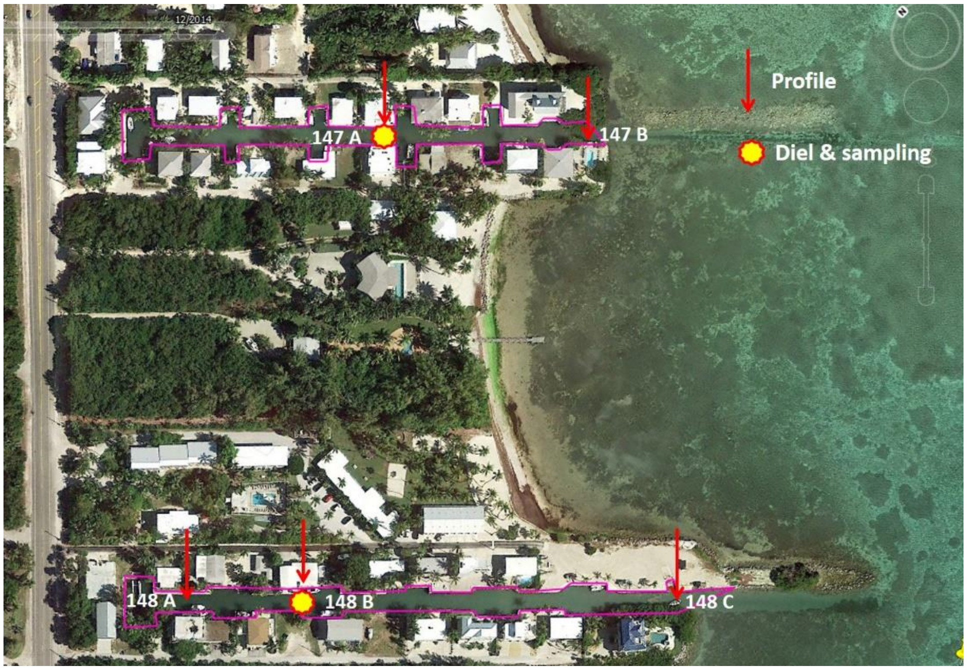


Figure 6.3.1: Google image rendition of canal #147 (control) and canal #148 (remediation) in Lower Matecumbe Key.

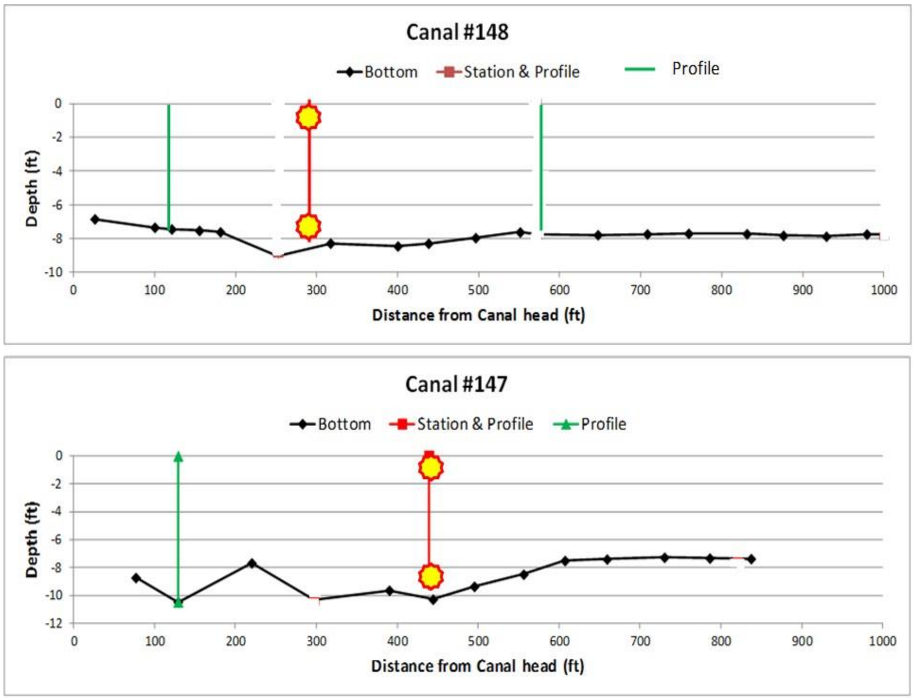


Figure 6.3.2: Bathymetric profile of canal #147 and canal #148, showing location of sampling (yellow circle) and profile measurement sites, as well as location of air bubblers

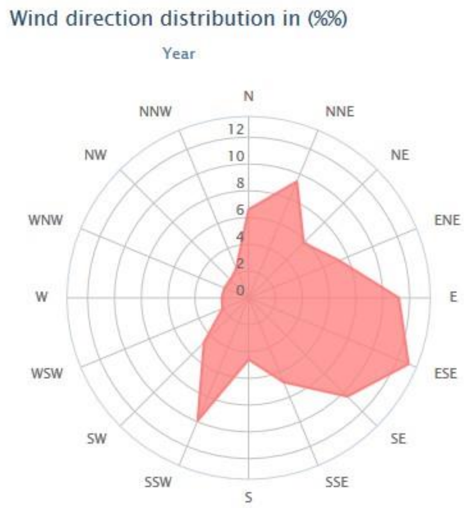


Figure 6.3.3: *Prevailing yearly wind direction in Islamorada, Florida Keys (https://www.windfinder.com/windstatistics/islamorada)*

Fig 6.3.4. *Water quality comparison between Before and AFTER sampling, and between remediated Canal #148 and control Canal #147. Dissolved nitrogen species: nitrate+nitrite (N+N), nitrate (NO3), nitrite (NO2), ammonium (NH4) and dissolved inorganic nitrogen (DIN). Survey FKC09 occurred after Irma.*

Fig 6.3.5. *Water quality comparison between Before and AFTER sampling, and between remediated Canal #148 and control Canal #147. Dissolved nitrogen species: total nitrogen (TN); total organic nitrogen (TON); total phosphorous (TP); soluble reactive phosphorous (SRP); and total organic carbon (TOC). Survey FKC09 occurred after Irma*

6.3.2 Profiles of water column

Temporal changes of physical-chemical properties of waters in Canal #148 were measured in fifteen profiles during nine surveys as shown in Table 6.3.1 and Figure 6.3.6. Installation of a weed barrier at the mouth of Canal #148 was completed in May 2017, after survey FKC05.

Before remediation, variability of median %DO sat was extreme, from practically anoxic condition at 4.8% to oversaturation around 138%. The occurrence of these extremely high %DO sat values is not a sign of good water quality, on the contrary, the cause of those extremely high values is a overwhelming abundance of planktonic organisms (dinoflagellates?), which generate abundant oxygen during sunny days but consume whatever oxygen is in the water column during night respiration (Haraguchi et al. 2010) as we will see when discussing diel data. After installation of the weed barrier median saturation values ranged from 30% to 105%, a more adequate regime for sustainig healthy aquatic life.

Acidity (pH) was relatively high during the Before stage, ranging from 7.3 to 8 pH units. After remediation individual profiles had higher variance and overall values have ranged from 7.2 to 7.8 pH units. Salinity and temperature display similar range of variability before and after remediation (aprox. 34.8 to 37.7). Before remediation temperature in Canal #148 was rather uniform within individual surveys, and among surveys temperature ranged from 25ºC to 32ºC. After remediation in general the temperature has been lower, more varied and ranging from 22.4ºC to 29.7ºC

Table 6.3.1. Selected profile statistics BEFORE and AFTER remediation for Canal #148

Canal	Parameter	Temp, Before	Temp, After	Salinity, Before	Salinity, After	pH, Before	pH, After	DO%, Before	DO%, After
Canal #148	Mean	26.9	25.2	36.4	36.6	7.8	7.6	80.5	62.3
Canal #148	Std. Dev.	3.2	3.1	1.0	0.9	0.3	0.4	56.7	32.3
Canal #148	Count	153	127	153	127	153	127	153	127
Canal #148	Minimum	22.4	21.1	34.8	35.1	7.3	6.8	4.5	8.6
Canal #148	Maximum	31.8	30.2	37.9	37.5	8.1	7.9	151.0	108.6
Canal #148	Coef. Var.	0.1	0.1	0.0	0.0	0.0	0.0	0.7	0.5
Canal #148	Range	9.4	9.1	3.0	2.4	0.8	1.2	146.5	100.0
Canal #148	Geom. Mean	26.7	25.0	36.4	36.5	7.8	7.6	43.5	50.4
Canal #148	Median	26.9	24.8	36.7	37.0	7.9	7.7	105.0	71.7

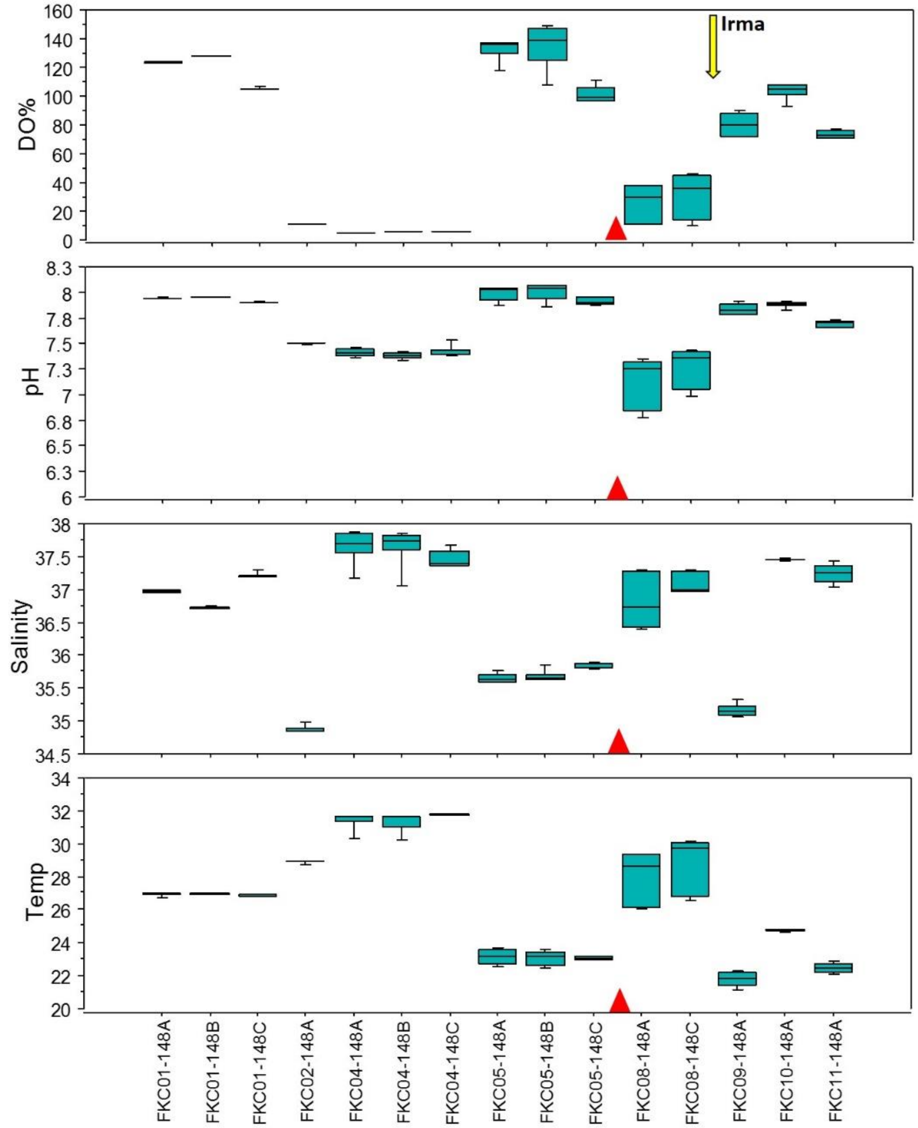
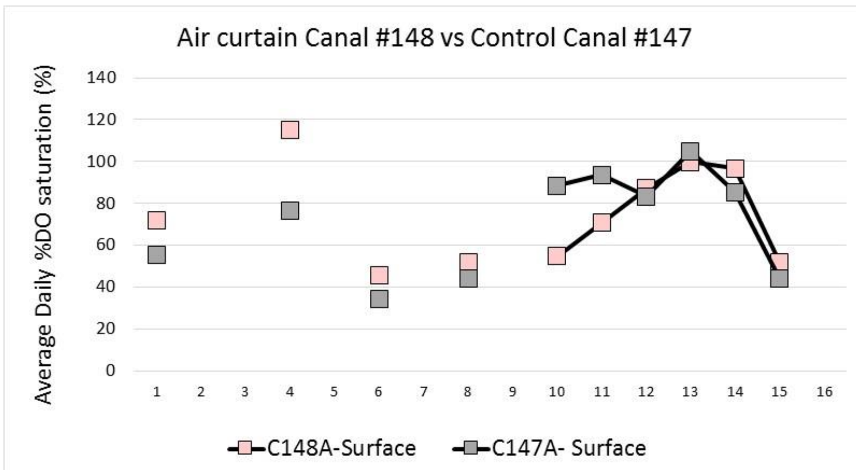


***Figure 6.3.6**. Box-and-Whisker plots of physical-chemical variables measured along depth profiles of the water column in Canal #148. Date of remediation is indicated by the red triangle.*

In summary, water quality as represented by casts of physical-chemical properties in Canal #148 do not suggest improvement in water quality after installation of weed barriers. Nevertheless, as this report is being written, given that hurricane Irma damaged the air curtain system and it has not been repaired, a massive amount of seaweed invaded Canal #148 causing a major fish-kill.

6.3.3 Diel Measurements

Installation the air curtain in Canal #148 was in May 2017. Given that we wait for several months after remediation, to give some time for the system to equilibrate, the first round of After observations was planned for Nov-Dec 2017. Unfortunately Irma arrived first on Sep 10th. In consequence, we have not after remediation measurements, all diel measurements presented below have been obtained before remediation. The utility of these diagrams is that they help understanding the co-variation of these canals and will play an important role in determining decoupling after remediation. For the time being, these diagrams show high similarity in surface waters, but not so for bottom waters.



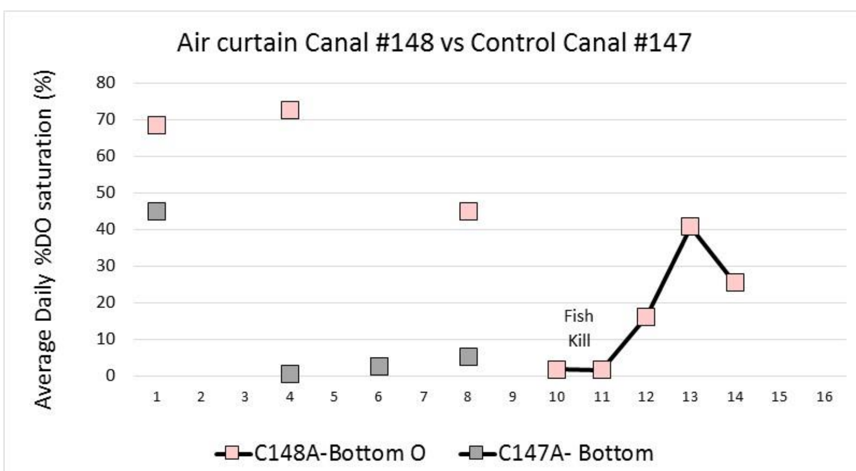


Figure 6.3.6*. Diel (24 hour) observations of %DO saturation for remediated (air curtain) Canal #148 and Control Canal #147, Lower Matecumbe Key. No after remediation data yet.*

6.4 Canal #266.

Canal #266 is located in Dr. Arm's Subdivision between Witters & Bailey Lanes, Big Pine Key. It is a 1.1 acre, 1,280 ft long straight canal, reaching depths down to -11 ft (Figs 6.4.1 and 6.4.2). Its bottom was covered with a several feet of an organic-rich sediment layer. Orientation of the canal is due East (azimuth=90 degrees) and prevailing winds in Big Pine area are from the East-Northeast (Fig 6.4.3). Hence, wind readily pushes seaweed wrack into Canal #266, to be accumulated forming a dense layer several feet thick. Decomposition of this organic matter depletes the water column of oxygen and releases nutrient. Likewise, anaerobic bacteria reduce sulfate to obtain oxygen when consuming the organic matter, while forming hydrogen sulfide (H2S) as by-product. The final outcome is an oxygen-depleted water column, where fish-kills are common, and waters smell like rotten-eggs. The selected remediation method for Canal # 266 includes hydraulic removal of 5 ft of decomposing organic debris (seaweed) and muck and placement of a sand capping layer 6 inches thick, and installation of an air curtain at the mouth of the canal to prevent future seaweed loading. Hydraulic removal began in April 2015, while air curtain installation started in April 2016. Overall construction ended in May 2016

6.4.1 Nutrient monitoring

Canal #266 was sampled during six surveys for a total of 12 samples. Six samples collected before remediation during FKC01 (April 2014), and FKC02 (Oct 2014); and six samples collected after installation of aerators during FKC07 (Dec 2016), FKC08 (June 2017) and FKC09 (March 2018) (Fig. 6.4.4 and Fig. 6.4.5).

NO3 and NOx increase significantly right after remediation to drastically drop in 2018 (FKC09). NO2 on the other hand, following a dramatic increase right after remediation, progressively dropped until 2018. NH4 and DIN do not show a consistent trend after remediation (Fig 6.4.4). As shown in Figure 6.4.5, TN, TON, and TP drop significantly immediately after remediation, but continuously increase afterward. SRP behaves just like NO2, it increases right after remediation and progressively drops afterward, with a trend opposite to TN, TON and TP. Finally, TOC has remained constant through the whole period of record.

__Figure 6.4.1:__ Google image rendition of canal #293 (control) and canal #266 (remediation) in Dr. Arm's Subdivision, Big Pine Key.

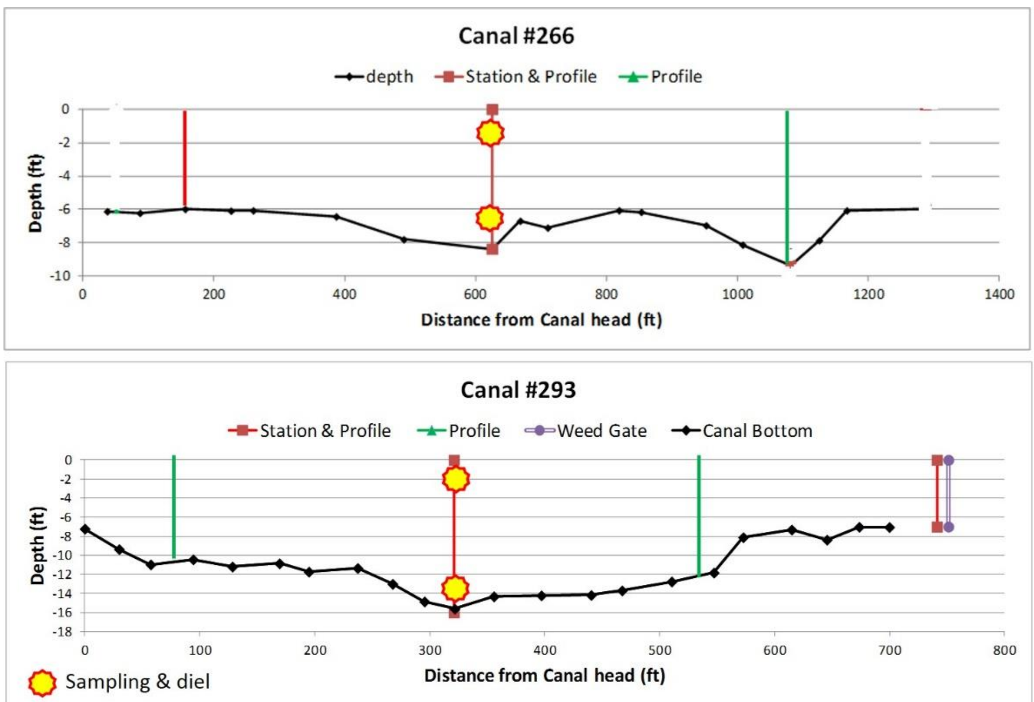


__Figure 6.4.2:__ Bathymetric profile of canal #266 and canal #293, showing location of sampling and diel measurements (yellow circle), profile measurement sites, as well as location of air bubblers

In summary, there is not clear pattern of improvement for most nutrient species after remediation. NO2 and SRP seem to experience a strong increase due to the disturbance of muck removal and a progressive decline to reach similar concentration levels as those observed during the Before stage. In summary, as of today, there is not clear improvement in nutrient water quality in Canal #266 which could be ascribed to remediation.

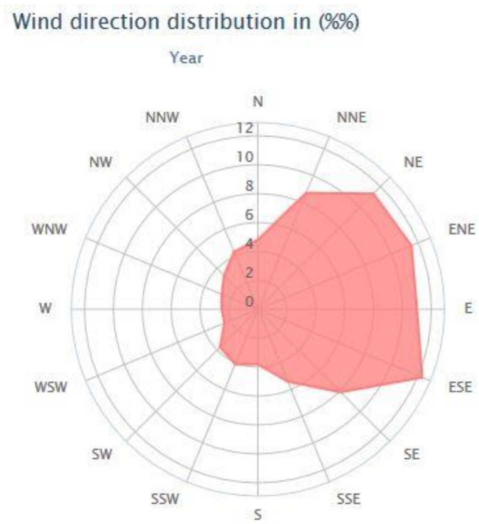


Figure 6.4.3: *Prevailing yearly wind direction in Big Pine Key, Florida Keys (https://www.windfinder.com/windstatistics/big_pine_key)*

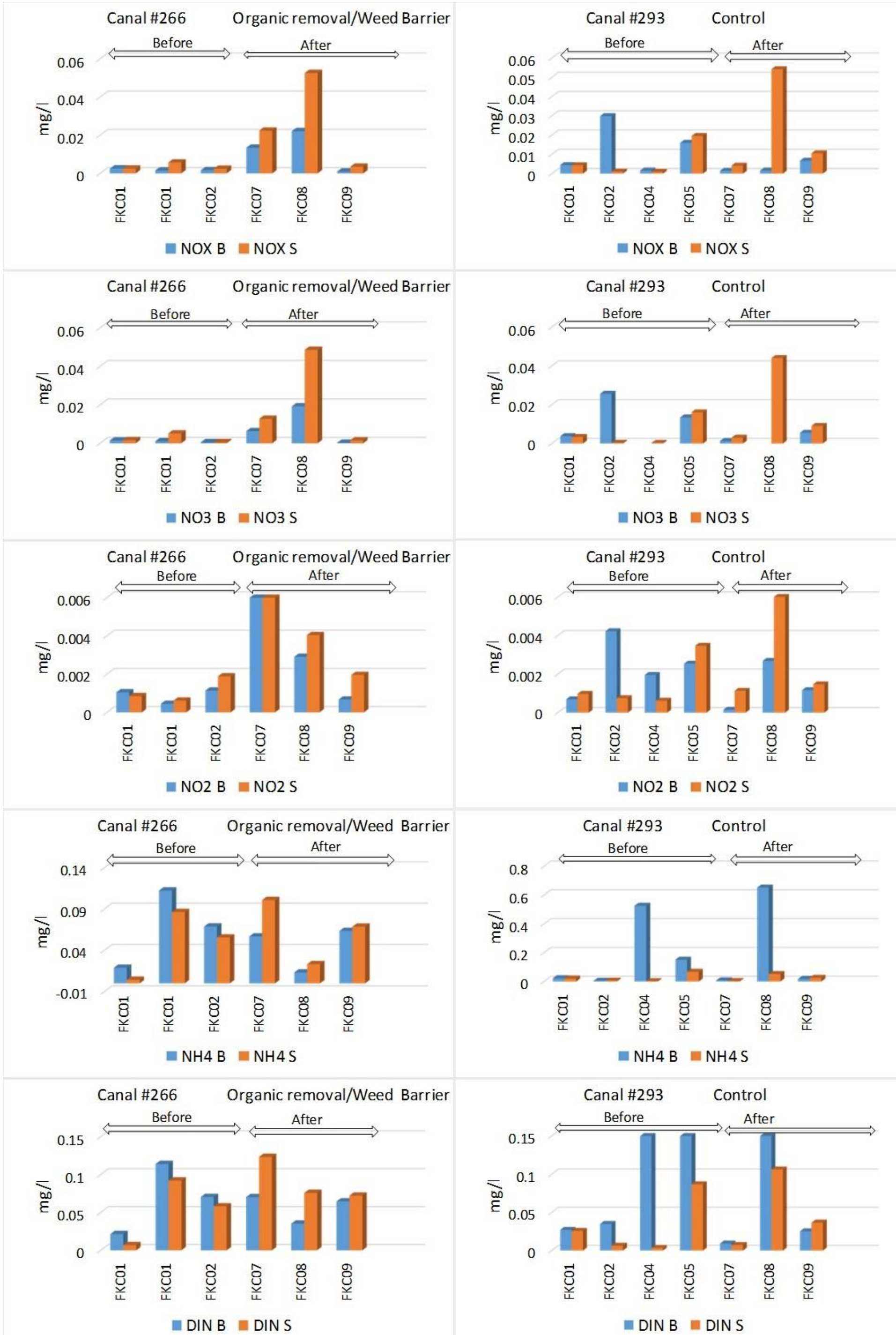


Fig 6.4.4. *Water quality comparison between Before and After sampling, and between remediated Canal #266 and control Canal #293. Dissolved nitrogen species: nitrate+nitrite (N+N), nitrate (NO3), nitrite (NO2), ammonium (NH4) and dissolved inorganic nitrogen (DIN). Survey FKC09 occurred after Irma*

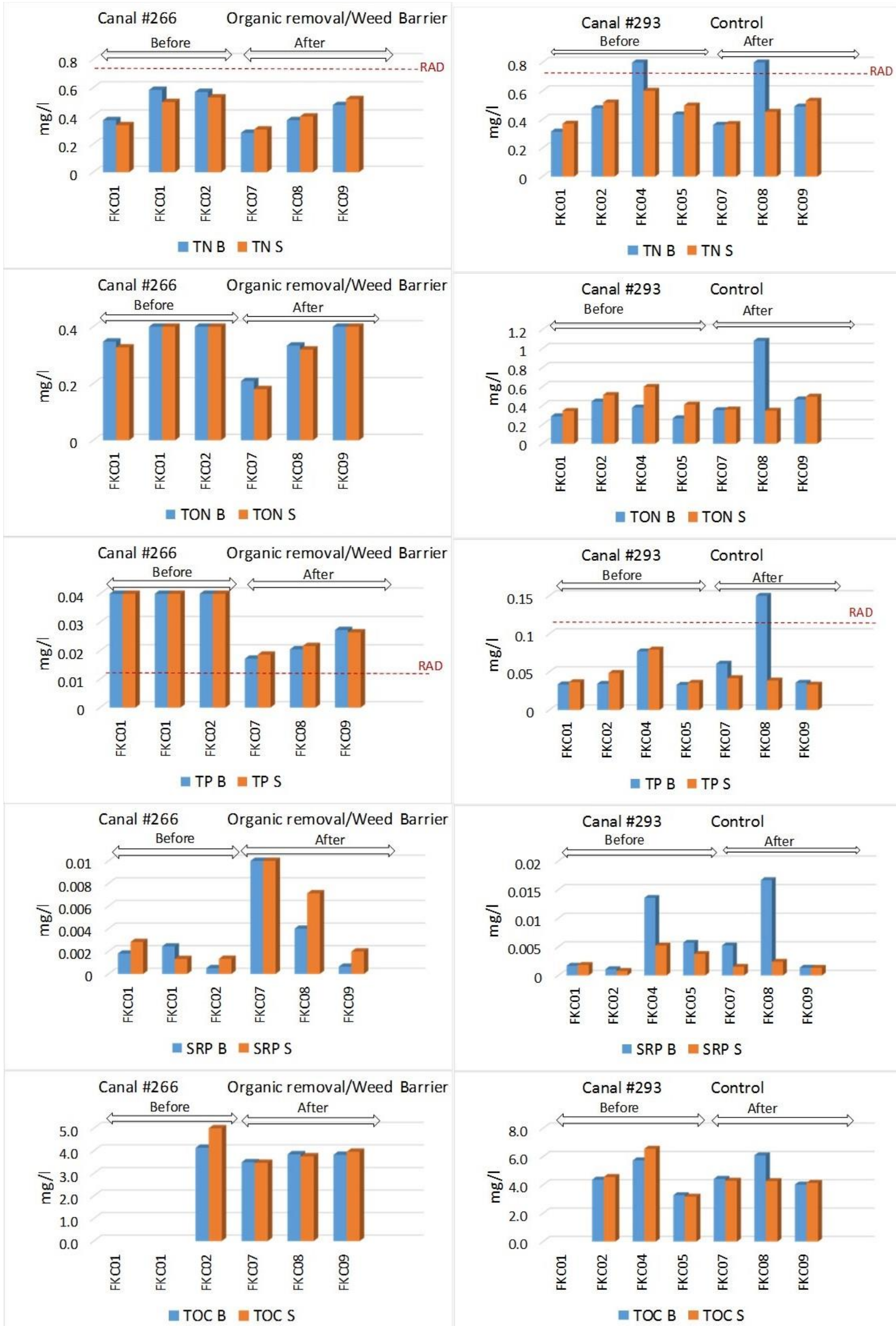


Fig 6.4.5. *Water quality comparison between Before and After sampling, and between remediated Canal #266 and control Canal #293. Dissolved nitrogen species: total nitrogen (TN); total organic nitrogen (TON); total phosphorous (TP); soluble reactive phosphorous (SRP); and total organic carbon (TOC). Survey FKC09 occurred after Irma*

6.4.2 Profiles of water column

Profiles of physical-chemical properties of waters in Canal #266 were measured 13 times in 7 surveys. Organic removal and installation of air curtain at the mouth of the canal were completed in May 2016. Median %DO saturation was in general above 51% before remediation. After remediation %DO saturation started with very low concentrations of dissolved oxygen (16% to 20%DO sat) and high variance in the measured profiles. By Dec 2017, even after Irma's impact, %DO saturation was at a very high level of 72%, but dropped drastically to only 7% DO saturation in Feb 2018 and 10% in March (Table 6.3.1 and Fig 6.3.6). Since Irma the canal has been full of debris with abundant dead seagrass and the water color green. These conditions explain the swinging saturations, caused by a very productive water column affected by eutrophication. The occurrence of these extremely high %DO sat values is not a sign of good water quality, on the contrary, the cause of those extremely high values is a overwhelming abundance of planktonic organisms (dinoflagellates?), which generate abundant oxygen during sunny days but consume whatever oxygen is in the water column during night respiration (Haraguchi et al. 2010).

Table 6.4.1. Selected profile statistics BEFORE and AFTER remediation for Canal #266

Canal	Parameter	Temp, Before	Temp, After	Salinity, Before	Salinity, After	pH, Before	pH, After	DO%, Before	DO%, After
Canal #266	Mean	28.8	27.2	38.0	35.8	7.4	7.5	55.6	28.6
Canal #266	Std. Dev.	1.1	3.1	1.0	1.7	0.1	0.2	6.3	21.5
Canal #266	Count	65	182	65	182	65	182	65	182
Canal #266	Minimum	26.9	19.7	36.9	27.3	7.2	7.1	42.7	5.1
Canal #266	Maximum	30.2	31.7	39.2	38.1	7.7	8.0	69.6	80.5
Canal #266	Coef. Var.	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.7
Canal #266	Range	3.3	12.0	2.3	10.8	0.5	0.9	26.9	75.4
Canal #266	Geom. Mean	28.8	27.0	38.0	35.8	7.4	7.5	55.2	21.5
Canal #266	Median	28.4	27.1	37.6	36.4	7.4	7.5	53.5	21.0

Acidity (pH) has remained between 7 and 8 units before and after remediation.There was an increase in variance after remediation, except for the last three surveys when only one each time station was surveyed. Likewise, salinity has declined after remediation, while the variance increased, except for the last three surveys. In summary, water quality as represented by casts of physical-chemical properties in Canal #266 do not give a solid tendency towards improvement of quality. If there was an incipient improvement in dissolved oxygen content and pH after organic removal and air curtain, Hurricane Irma caused total disturbance of the system. We will have to wait until impacts dissapear

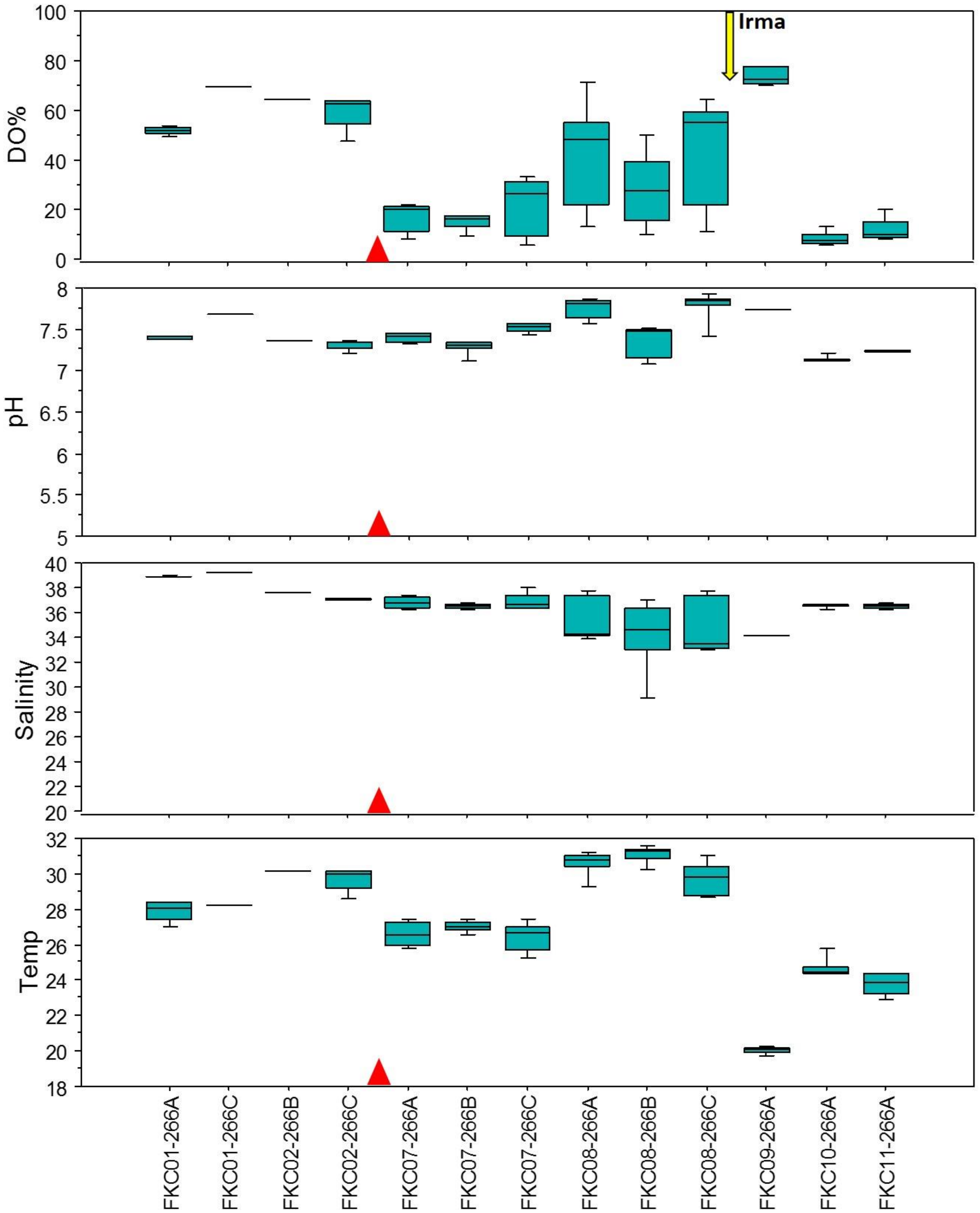


Figure 6.4.6. *Box-and-Whisker plots of physical-chemical variables measured along depth profiles of the water column in Canal #266. Date of remediation is indicated by the red triangle.*

6.4.3 Diel Measurements

Diel data before remediation shows high similarity between surface water in #266 and those from #293, followed by a clear decoupling starting in diel 11 and staying around 40% saturation. Still, surface waters in Canal #266 have not achieved the expected levels of quality. Bottom waters have improved in Canal #266 slightly over the control canal after remediation, but it is still at compromised levels below 20% DO saturation. It seems that we will have to wait longer to observe substantial improvement.

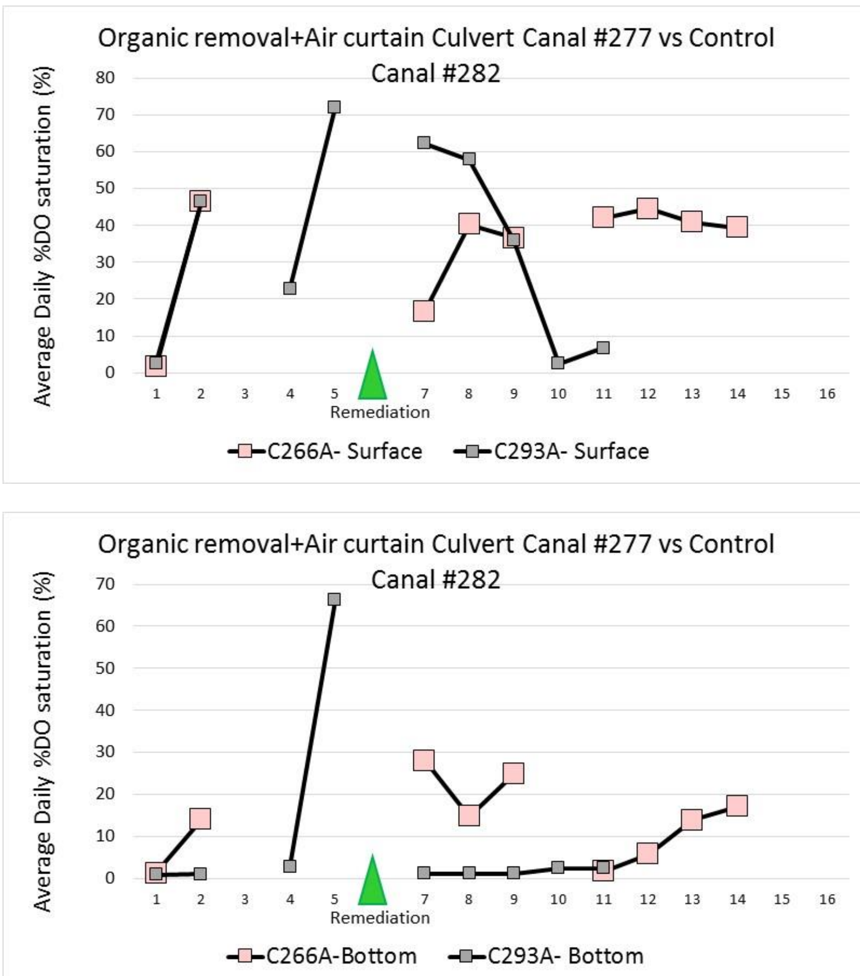


***Figure 6.34.7**. Diel (24 hour) observations of %DO saturation for remediated (organic removal and air curtain) Canal #266 and Control Canal #293, Big Pine Key. Green triangle indicates when remediation took place.*

6.5 Canal #277.

Canal #277 is located in Tropical Bay Estates, between Watson Blvd and Sunrise Drive, Big Pine Key. It is a large 5.4 acre, 1,870 ft long and complex canal, reaching depths down to -21 ft, and tidal range of just 0.69 ft (Figs 6.5.1 and 6.5.2). Orientation of the canal's entrance is due East (azimuth=90 degrees) and prevailing winds in Big Pine area are from the East-Northeast (Fig 6.4.3). Hence, wind readily pushes seaweed wrack into Canal #277. Decomposition of this organic matter depletes the water column of oxygen and releases nutrients. Likewise, anaerobic bacteria reduce sulfate to obtain oxygen when consuming the organic matter, while forming hydrogen sulfide (H2S) as a by-product. The final outcome is an oxygen-depleted water column where waters smell like rotten-eggs. The selected remediation method for Canal # 277 was the construction of a 200 foot 60" concrete culvert connecting the eastern and western branches of the canal. Construction began in March 2016 and ended May 2016.

6.5.1 Nutrient monitoring

Canal #277 was sampled during seven surveys for a total of 20 samples. Twelve samples collected before remediation during FKC01 (April 2014), FKC02 (Oct 2014), FKC04 (Jun 2015), and FKC05 (Feb 2016); and eight samples collected after installation of the culvert, during FKC07 (Dec 2016), FKC08 (June 2017), and FKC09 in March 2018, after Irma's landfall (Fig. 6.5.3 and Fig. 6.5.4).

All dissolved nitrogen species (NO2, NO3, NOx, NH4 and DIN) increase significantly (about 3X) right after remediation to progressively drop to about pre-remediation levels or slightly higher (Fig 6.5.3). There is total decoupling with the control canal behavior. TN and TON developed an increasing trend since remediation peaking in 2018, after Irma's landfall. TP has remained about constant since remediation, at a slightly lower concentration than that before culvert installation. SRP has been increasing since pre-remediation, in 2015, until 2017 (FKC08). Concentration dropped drastically in 2018 to pre-remediation levels (Fig 6.5.4). Finally, TOC has remained practically constant through the whole period of record. In summary, still there is no significant declining trend in nutrient levels in Canal #277 after remediation.

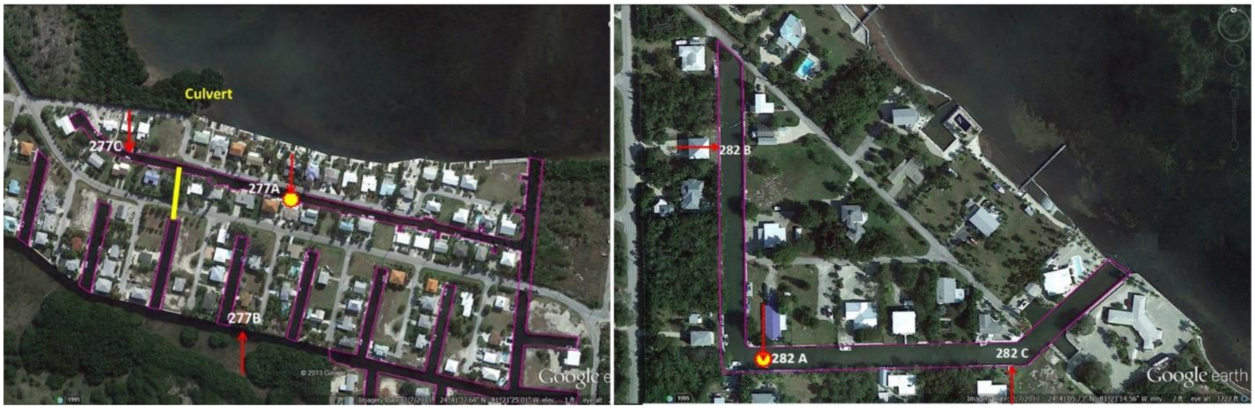


Figure 6.5.1: *Google image rendition of canal #282 (control) and canal #277 (remediation) in Tropical Bay Estates, Big Pine Key.*

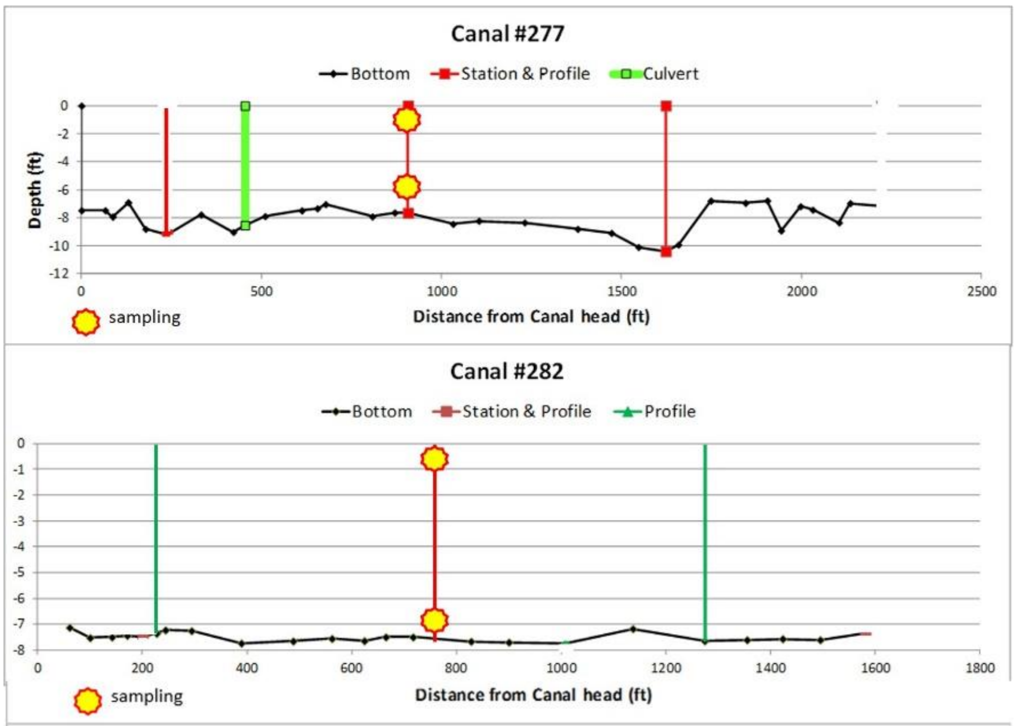


Figure 6.5.2: *Bathymetric profile of canal #277 and canal #282, showing location of sampling and diel measurements (yellow circle), and profile measurement sites.*

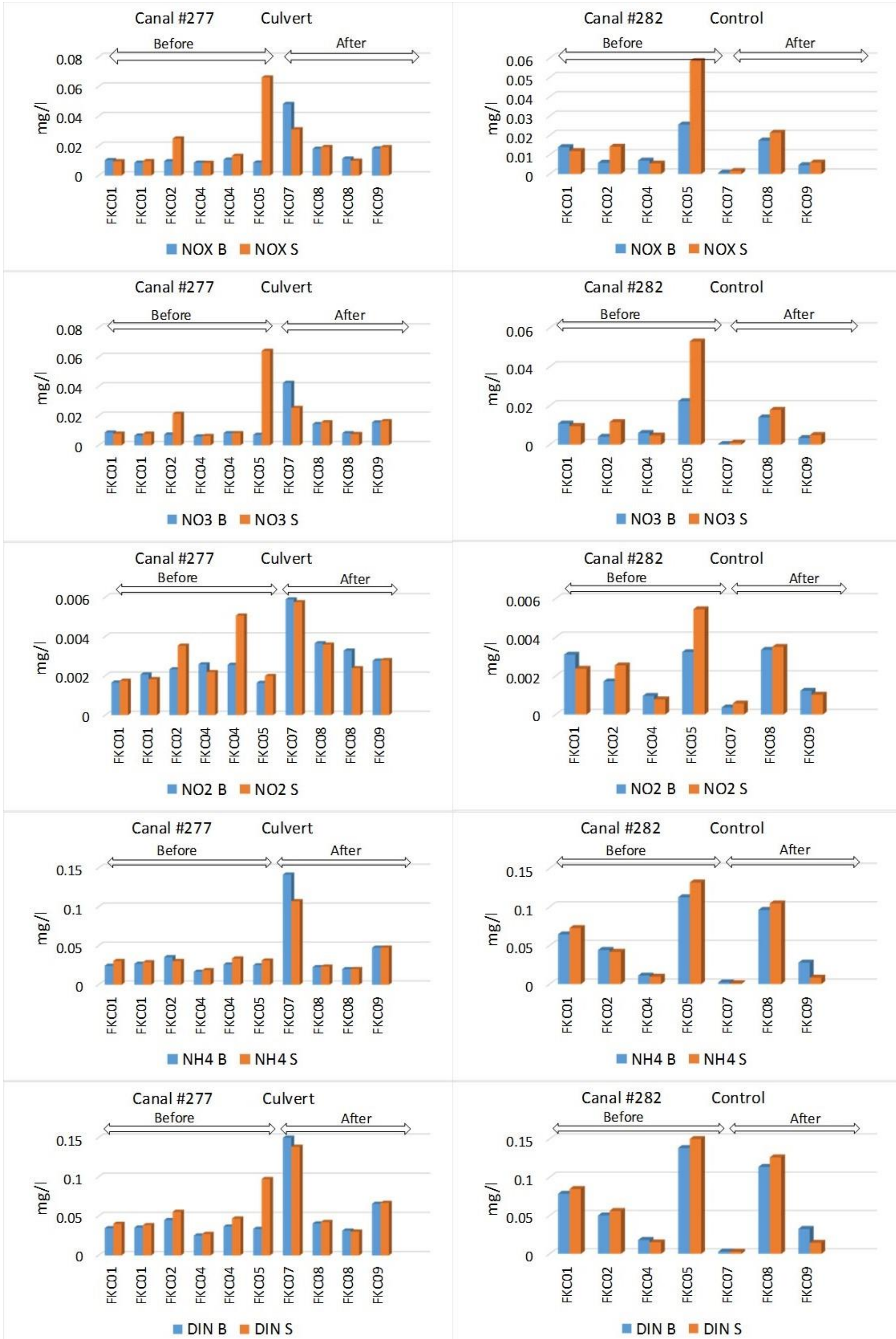


__Fig 6.5.3.__ Water quality comparison between Before and After sampling, and between remediated Canal #277 and control Canal #282. Dissolved nitrogen species: nitrate+nitrite (N+N), nitrate (NO3), nitrite (NO2), ammonium (NH4) and dissolved inorganic nitrogen (DIN). Survey FKC09 occurred after Irma

Fig 6.5.4. Water quality comparison between Before and After sampling, and between remediated Canal #277 and control Canal #282. Dissolved nitrogen species: total nitrogen (TN); total organic nitrogen (TON); total phosphorous (TP); soluble reactive phosphorous (SRP); and total organic carbon (TOC). Survey FKC09 occurred after Irma

6.5.2 Profiles of water column

Profiles of physical-chemical properties of waters in Canal #277 were measured 18 times during 9 surveys. Installation of a culvert connecting two branches of the canal was completed in May 2016 (Fig 6.5.1).

Median %DO saturation ranged between 40.7% and 83% before remediation. Right after remediation values were low, down to 29% DO sat, but there was an important increase since FKC08 (June 2017) when all readings were above 63% DO sat. Meanwhile, pH dropped from about 7.6 to 7.1 units from Before to After remediation. Values have returned to higher levels (7.5-7.8) after Irma (Fig 6.5.5). Salinity was relatively high before remediation, reaching hypersalinity levels. Just before remediation salinity dropped to marine water levels and stayed like that at the beginning of the After stage. Following a small drop, salinity went back to marine water levels after Irma.

Profiles data do not define a definitive improving water quality trend yet. What looked like an advance in %DO saturation was suddenly interrupted by Hurricane Irma. There are still some visible debris in the canal. Good signs not reflected in the data is the good water flow through the culvert and the low turbidity, and the abundance of crab and fish that were not in the canal before installation of the culvert.

Table 6.5.1. Selected profile statistics BEFORE and AFTER remediation for Canal #277

Canal	Parameter	Temp, Before	Temp, After	Salinity, Before	Salinity, After	pH, Before	pH, After	DO%, Before	DO%, After
Canal #277	Mean	26.8	26.4	38.2	35.3	7.6	7.3	60.8	71.2
Canal #277	Std. Dev.	4.5	3.2	2.2	1.3	0.1	0.3	12.4	27.3
Canal #277	Count	246	197	246	197	246	197	246	197
Canal #277	Minimum	20.7	19.9	35.7	32.9	7.3	6.9	37.6	27.9
Canal #277	Maximum	32.6	31.4	40.9	37.5	7.8	7.8	84.2	124.7
Canal #277	Coef. Var.	0.2	0.1	0.1	0.0	0.0	0.0	0.2	0.4
Canal #277	Range	12.0	11.5	5.2	4.6	0.4	0.9	46.6	96.8
Canal #277	Geom. Mean	26.4	26.2	38.2	35.2	7.6	7.3	59.5	65.5
Canal #277	Median	28.0	26.2	37.4	35.0	7.6	7.2	60.3	73.7

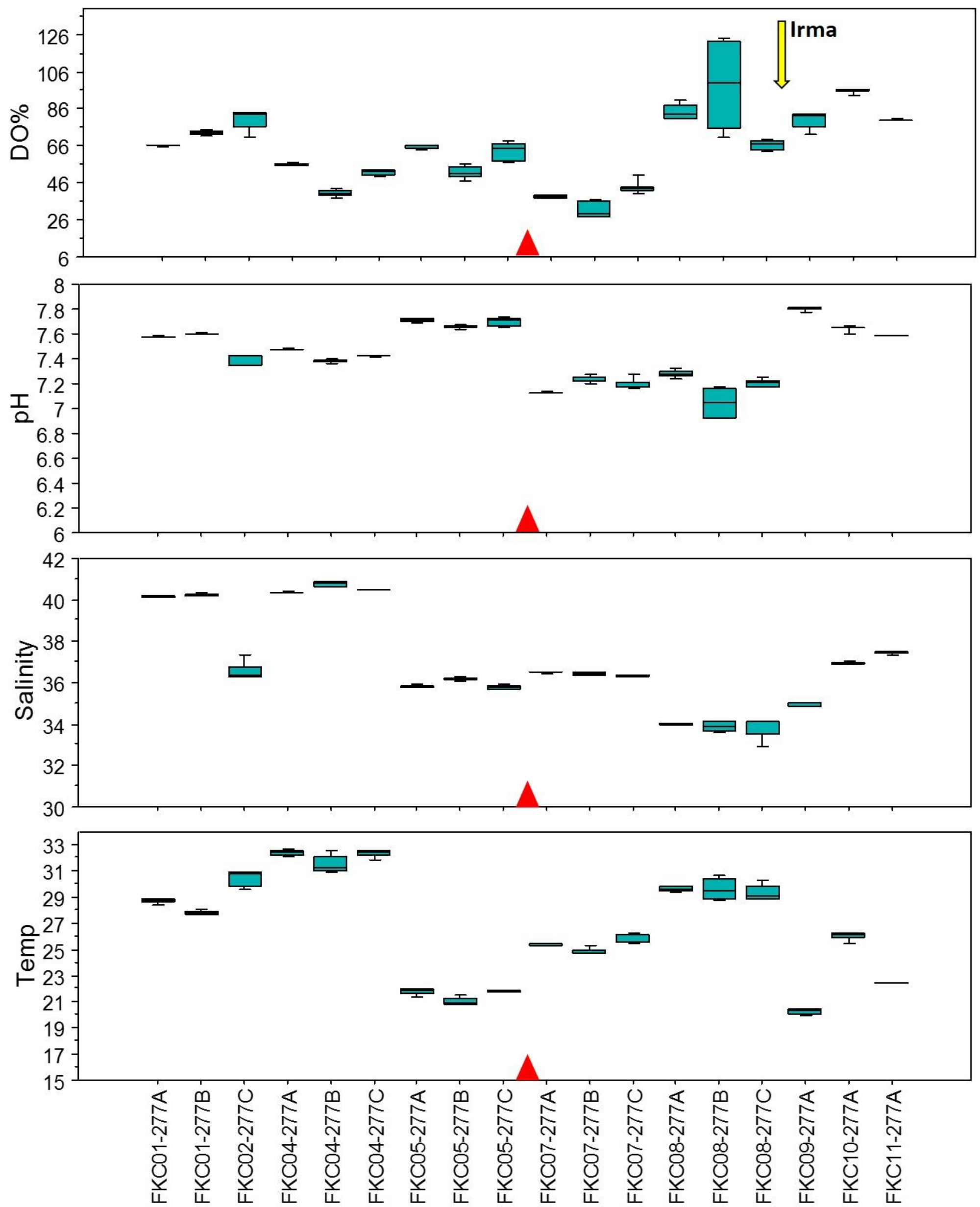


Figure 6.5.5*. Box-and-Whisker plots of physical-chemical variables measured along depth profiles of the water column in Canal #277. Date of remediation is indicated by the red triangle.*

6.5.3 Diel Measurements

Installation of the culvert connecting branches of Canal #277 was concluded in May 2016. Four diels had been measured before remediation and five more were obtained after remediation. Control and remediated canal had similar surface water characteristics before remediation (upper plot on Fig 6.5.6), but Canal #277 decoupled significantly from the control canal and rendered better concentrations of dissolved oxygen after remediation. Bottom waters confirm what was said for surface waters and shows the continuous improvement of %DO saturation after installation of the culvert.

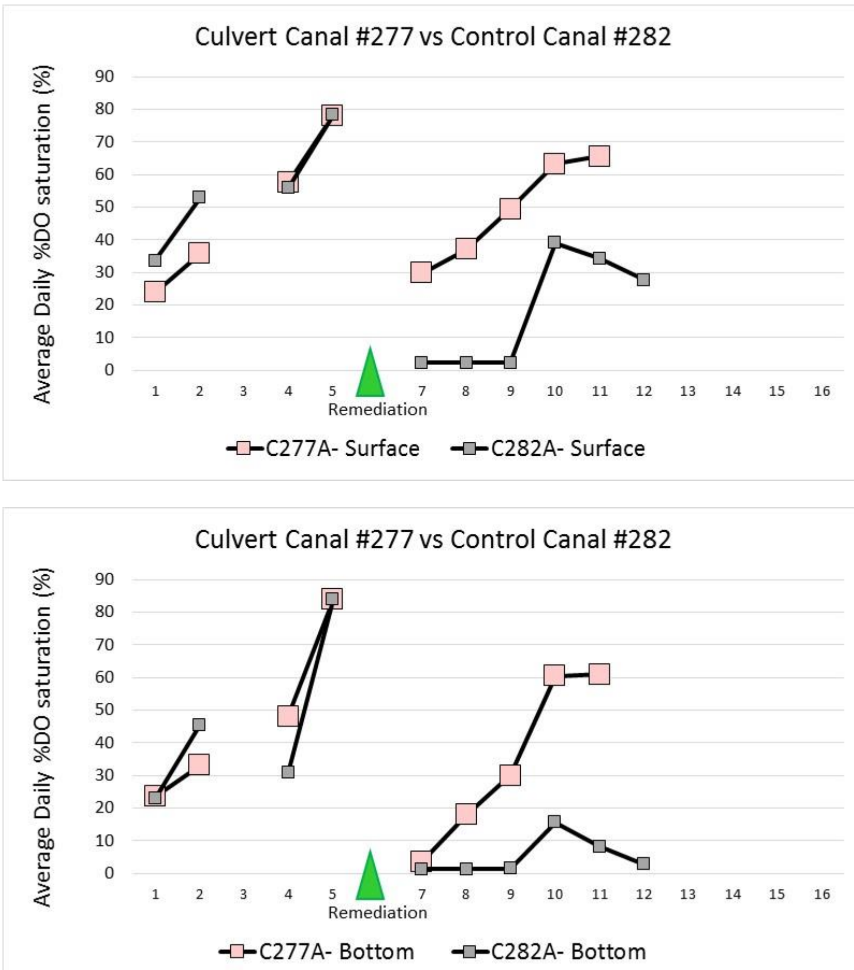


Figure 6.5.6*. Diel (24 hour) observations of %DO saturation for remediated (culvert installation) Canal #277 and Control Canal #282, Big Pine Key. Green triangle indicates when remediation took place*

6.6 Canal #287.

Canal #287 is located in Atlantic Estates, between Hollerich and Atlantic drives, Big Pine Key. It is a 1.4 acre, 1,080 ft long straight canal, reaching depths down to -14 ft, and tidal range of just 0.69 ft (Figs 6.6.1 and 6.6.2). Orientation of the canal's entrance is due East (azimuth=90 degrees) and prevailing winds in Big Pine area are from the East-Northeast (Fig 6.4.3). Hence, wind brings seaweed into Canal #287, where it decomposes depleting the water column of oxygen while nutrients are released. When water conditions become anaerobic, bacteria resort to sulfate as a source of oxygen, reducing sulfate and forming hydrogen sulfide (H2S) as a by-product. The selected remediation method for Canal # 287 was the installation of an air curtain at the mouth of the canal to reduce the organic loading. Construction began in May 2016 and ended July 2016.

6.6.1 Nutrient monitoring

Canal #287 was sampled during six surveys for a total of 12 samples. Eight samples collected before remediation during FKC01 (April 2014), FKC02 (Oct 2014), FKC04 (Jun 2015), and FKC05 (Feb 2016); and four samples collected after installation of the culvert, during FKC08 (June 2017) before Irma and FKC09 (March 2018) after Irma (Fig. 6.6.3 and Fig. 6.6.4).

NO2, NO3, NOx and DIN increase concentration right after remediation and then drop to about pre-remediation levels or slightly lower (Fig 6.6.3). In general the behavior is similar to that of the control canal. NH4 has an opposite pattern, it is low after remediation (FKC08) and then increases at the end of the monitoring period (FKC09). TN and TON show an increasing trend since remediation peaking in 2018 (FKC09) after Irma's landfall. TP has remained about constant without significant differences between Before and After remediation. SRP declined just after Irma's impact (FKC09) (Fig 6.5.4). Finally, TOC has remained practically constant through the whole period of record. Still, there is no clear improving trend in nutrient content in canal #287 after air curtain installation.

Figure 6.6.1: *Google image rendition of canal #293 (control) and canal #287 (remediation) in Big Pine Key.*

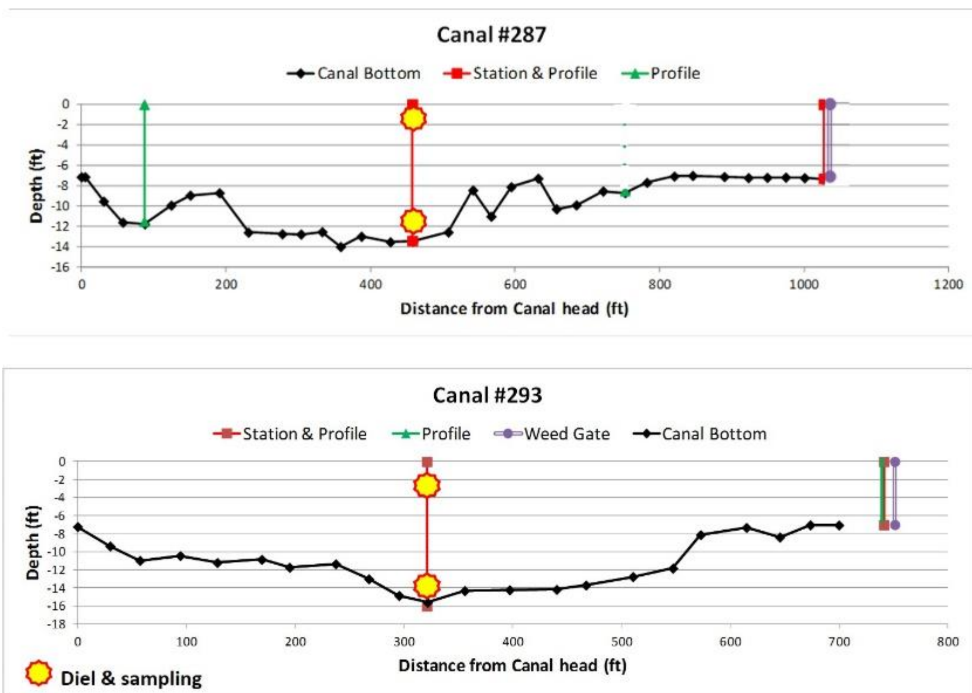


Figure 6.6.2: *Bathymetric profile of canal #287 and canal #293, showing location of sampling and diel measurements (yellow circle), and profile measurement sites, as well as location of air bubblers*

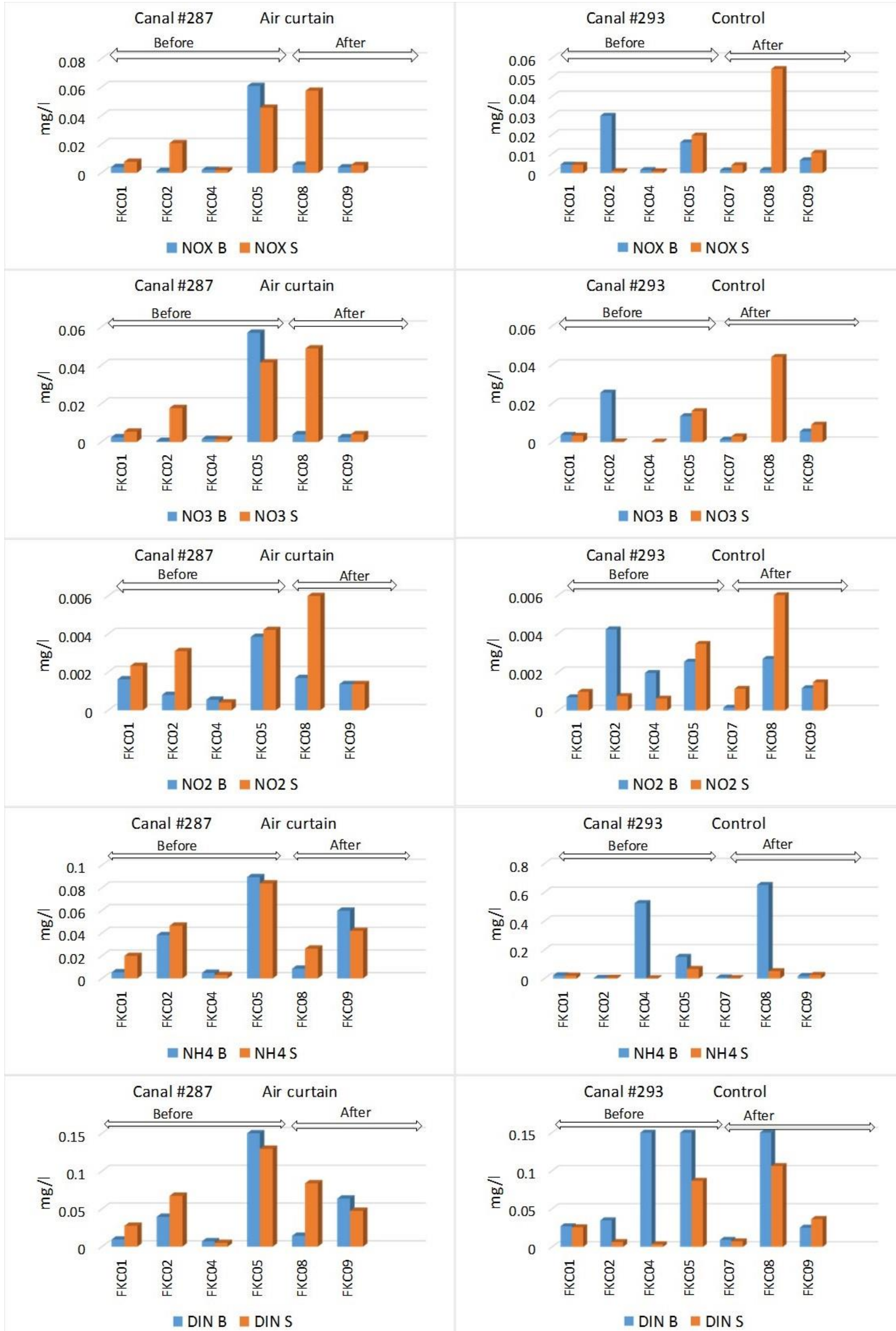


Fig 6.6.3. *Water quality comparison between Before and After sampling, and between remediated Canal #287 and control Canal #293. Dissolved nitrogen species: nitrate+nitrite (N+N), nitrate (NO3), nitrite (NO2), ammonium (NH4) and dissolved inorganic nitrogen (DIN)*

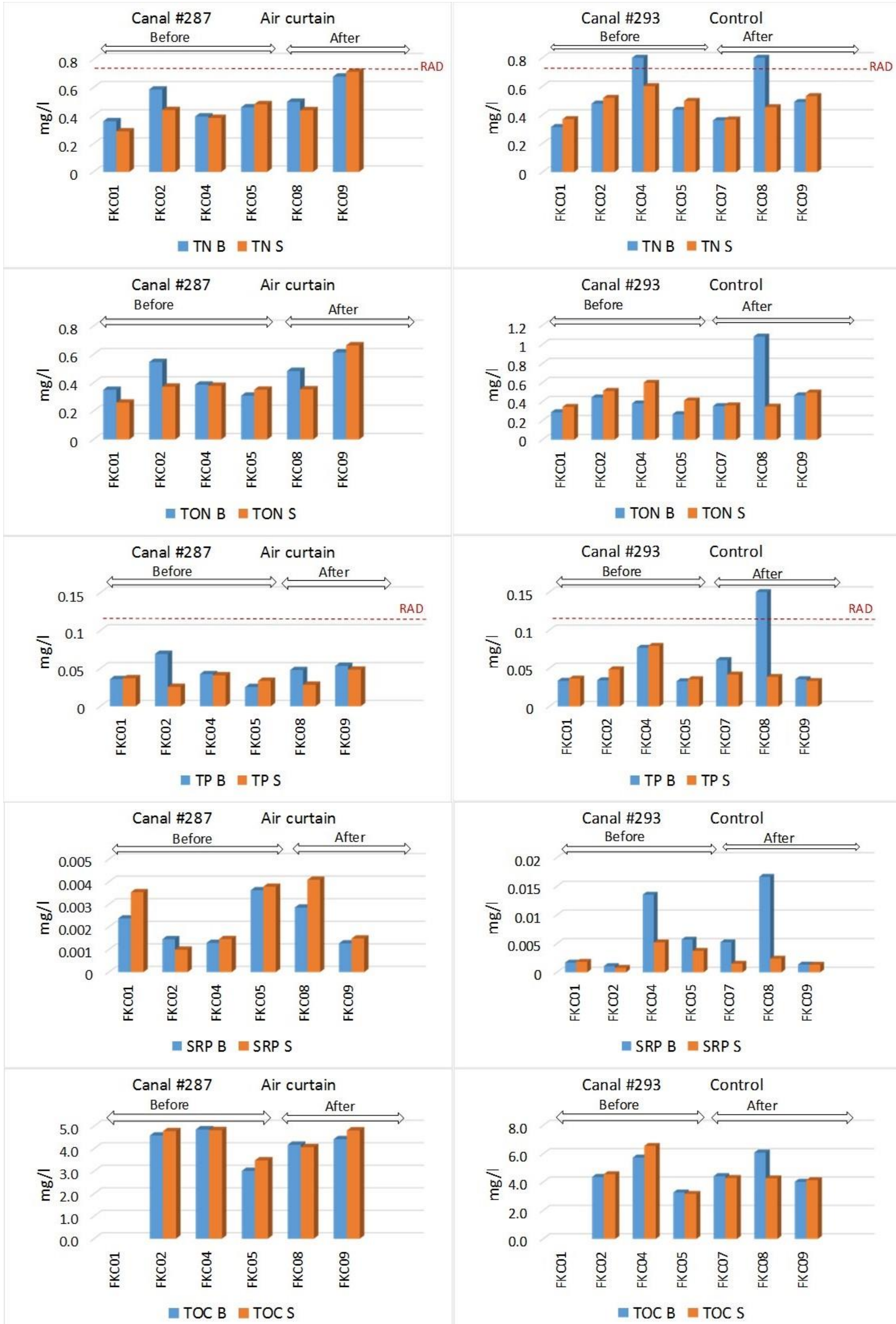


Fig 6.6.4. *Water quality comparison between Before and After sampling, and between remediated Canal #287 and control Canal #293. Dissolved nitrogen species: total nitrogen (TN); total organic nitrogen (TON); total phosphorous (TP); soluble reactive phosphorous (SRP); and total organic carbon (TOC).*

6.6.2 Profiles of water column

Profiles of physical-chemical properties of waters in Canal #287 were measured 14 times during 7 surveys. Eight profiles were measured before and six after remediation. Selected remediation method was the installation of an air curtain at the mouth of the canal. Construction was completed in July 2016.

Low median %DO saturation (about 46%) prevailed just before remediation (Table 6.6.1 and Fig 6.5.5). Following installation of the air curtain, %DO sat experienced a strong increase, reaching median values between 87% and 94%. This apparent improvement was dismantled by Irma. Post Irma values show extreme variance (range up to 68%) while medians dropped significantly and minima fell to 10%DO saturation levels. pH displays an increase in dispersion just before remediation, which continues after remediation, while experiencing a small decline. Salinity was high at the beginning of monitoring (39 psu; 2014 to 2015), suggesting strong evaporation and stratification of the water column. This pattern changed just before remediation when salinity dropped to about 35 psu (Fig 6.5.5). A mild increase occurs in Feb 2018.

Table 6.6.1. Selected profile statistics BEFORE and AFTER remediation for Canal #287

Canal	Parameter	Temp, Before	Temp, After	Salinity, Before	Salinity, After	pH, Before	pH, After	DO%, Before	DO%, After
Canal #287	Mean	26.5	23.9	37.3	34.9	7.4	7.3	54.3	57.3
Canal #287	Std. Dev.	5.1	5.0	2.1	0.8	0.1	0.2	15.1	31.7
Canal #287	Count	133	136	133	136	133	136	133	136
Canal #287	Minimum	21.1	17.7	35.0	34.1	7.2	7.0	17.4	10.1
Canal #287	Maximum	33.5	31.1	39.6	36.8	7.6	7.6	87.3	114.8
Canal #287	Coef. Var.	0.2	0.2	0.1	0.0	0.0	0.0	0.3	0.6
Canal #287	Range	12.3	13.4	4.6	2.7	0.3	0.6	69.9	104.7
Canal #287	Geom. Mean	26.0	23.4	37.2	34.9	7.4	7.3	52.2	46.0
Canal #287	Median	28.4	22.3	38.3	34.5	7.5	7.4	51.2	67.6

Finally, besides having low variability within surveys, temperature does not define a significant pattern relevant to remediation, except for larger dispersion of values after Irma. We have observed a significant increase in turbidity, reaching up to 14.7 NTU, when before Irma values were never went over 4.8 NTU. In summary, it seems that expected changes after remediation have not had time to mature, and if something was developing, like in dissolved oxygen, it was seriously disturbed by hurricane impact in 2017.

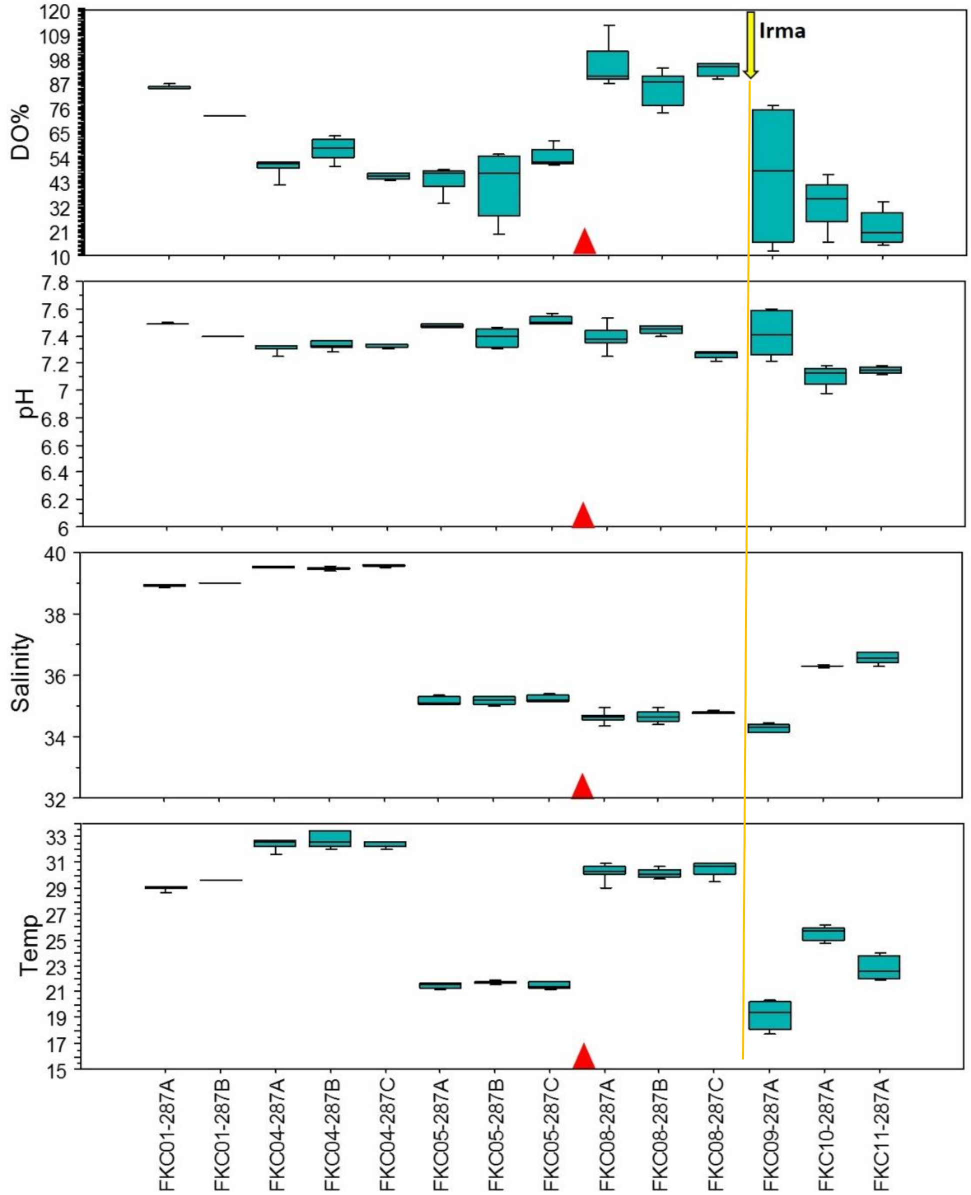
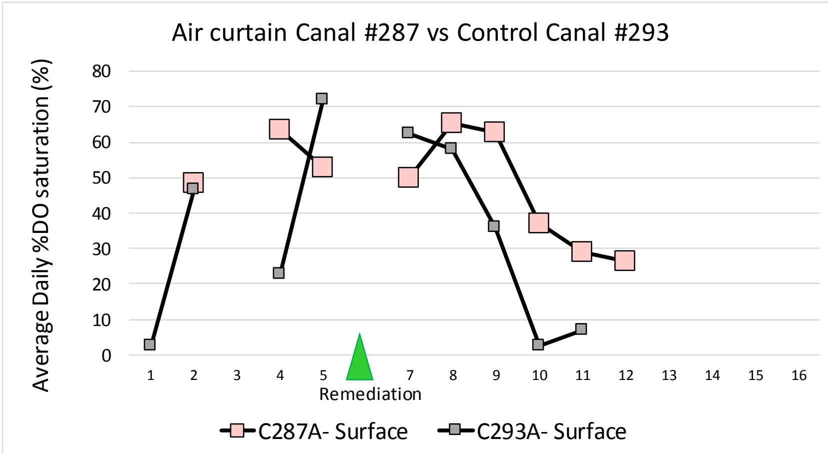


***Figure 6.6.5**. Box-and-Whisker plots of physical-chemical variables measured along depth profiles of the water column in Canal #287. Date of remediation is indicated by the red triangle*

6.6.3 Diel Measurements

Installation of the air curtain concluded in July 2016. Four diel had been measured before remediation and six more were obtained after remediation (Fig 6.6.6). Control and remediated canal did not have similar surface water characteristics before remediation (upper plot on Fig 6.5.6), and after remediation #287 as followed the pattern of the control canal but with better %DO saturation. Bottom waters decoupled a little after remediation but joined the poor water quality of the control canal at the end of monitoring. The diel data indicate that the air curtain may be helping with a slight improvement in %DO saturation, but still Canal #287 does not show signs of achieving good water quality



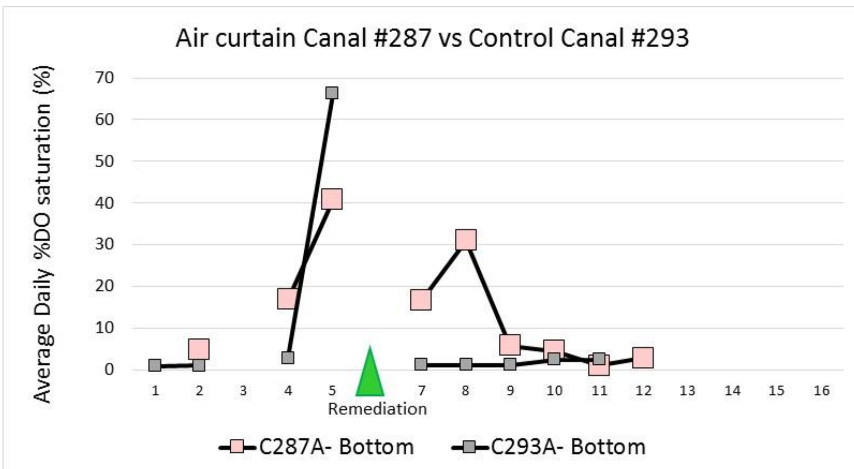


Figure 6.6.6. *Diel (24 hour) observations of %DO saturation for remediated (air curtain) Canal #277 and Control Canal #282, Big Pine Key. Green triangle indicates when remediation took place*

6.7 Canal #290.

Canal #290 is located between Avenue I and J, Big Pine Key. It is a small 0.6 acre, 623 ft long straight canal, reaching depths down to -8 ft, and a experiencing a small tidal range of 0.69 ft (Figs 6.7.1 and 6.7.2). As most canals on Big Pine Key, orientation of the canal’s entrance is due East (azimuth=90 degrees) and prevailing winds in Big Pine area are from the East-Northeast (Fig 6.4.3). Hence, a significant organic load is brought into Canal #290 by winds, where it rots. Oxidation or organic matter depletes the water column of oxygen while enriching waters with released nutrients. When water conditions become anoxic, anaerobic bacteria resort to sulfate as a source of oxygen, reducing sulfate and forming hydrogen sulfide (H2S) as a by-product. The selected remediation method for Canal # 290 was hydraulic removal of 5' of decayed seaweed and muck and placement of 6" sand layer. Additionally, an air curtain was reinstalled at the mouth of the canal to reduce future organic loading. Organic Removal started December 2015 and completed March 2016, but installation of the air curtain ended in June 2017.

6.7.1 Nutrient monitoring

Canal #290 was sampled 14 times during seven surveys for a total of 24 samples. Sixteen samples were collected before remediation during FKC01 (April 2014), FKC02 (Oct 2014), FKC04 (Jun 2015), and FKC05 (Feb 2016); and four samples collected after removal of organic-rich sediments and muck, and sand cap installation, during FKC07 (Dec 2016), FKC08 (June 2017) and FKC09 (March 2018; post-Irma). The air curtain was installed two weeks before FKC08 (Fig. 6.7.3 and Fig. 6.7.4).

NO2, NO3, and NOx begin with low concentrations right after organic removal. Then, there was an increase in concentration in FKC08 (June 2017), just two weeks after air curtain installation. Finally concentrations drop in 2018 to pre-remediation levels. In general the behavior is similar to that of the control canal (#293), which also shows a sudden increase in NO2, NO3 and NOx in FKC08 (Fig 6.7.3). NH4 has a similar pattern before and after remediation, with the exception of an extremely high concentration of a surface sample in FKC08. Other values are not too different from pre-remediation concentrations. DIN concentrations are higher after remediation.

Figure 6.7.1: *Google image rendition of canal #293 (control) and canal #290 (remediation) in The Avenues, Big Pine Key.*

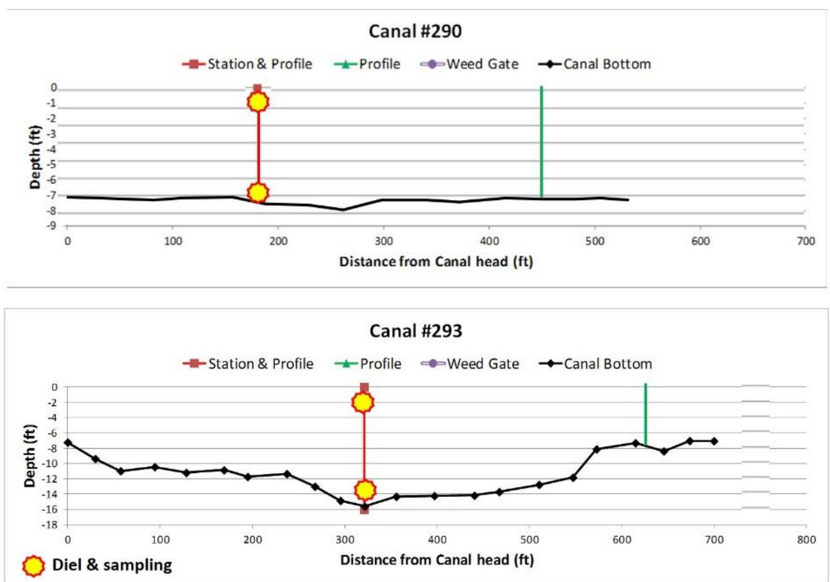


Figure 6.7.2: *Bathymetric profile of canal #290 and canal #293, showing location of sampling and diel measurements (yellow circle) and profile measurement sites.*

__Fig 6.7.3.__ Water quality comparison between Before and After sampling, and between remediated Canal #290 and control Canal #293. Dissolved nitrogen species: nitrate+nitrite (N+N), nitrate (NO3), nitrite (NO2), ammonium (NH4) and dissolved inorganic nitrogen (DIN)

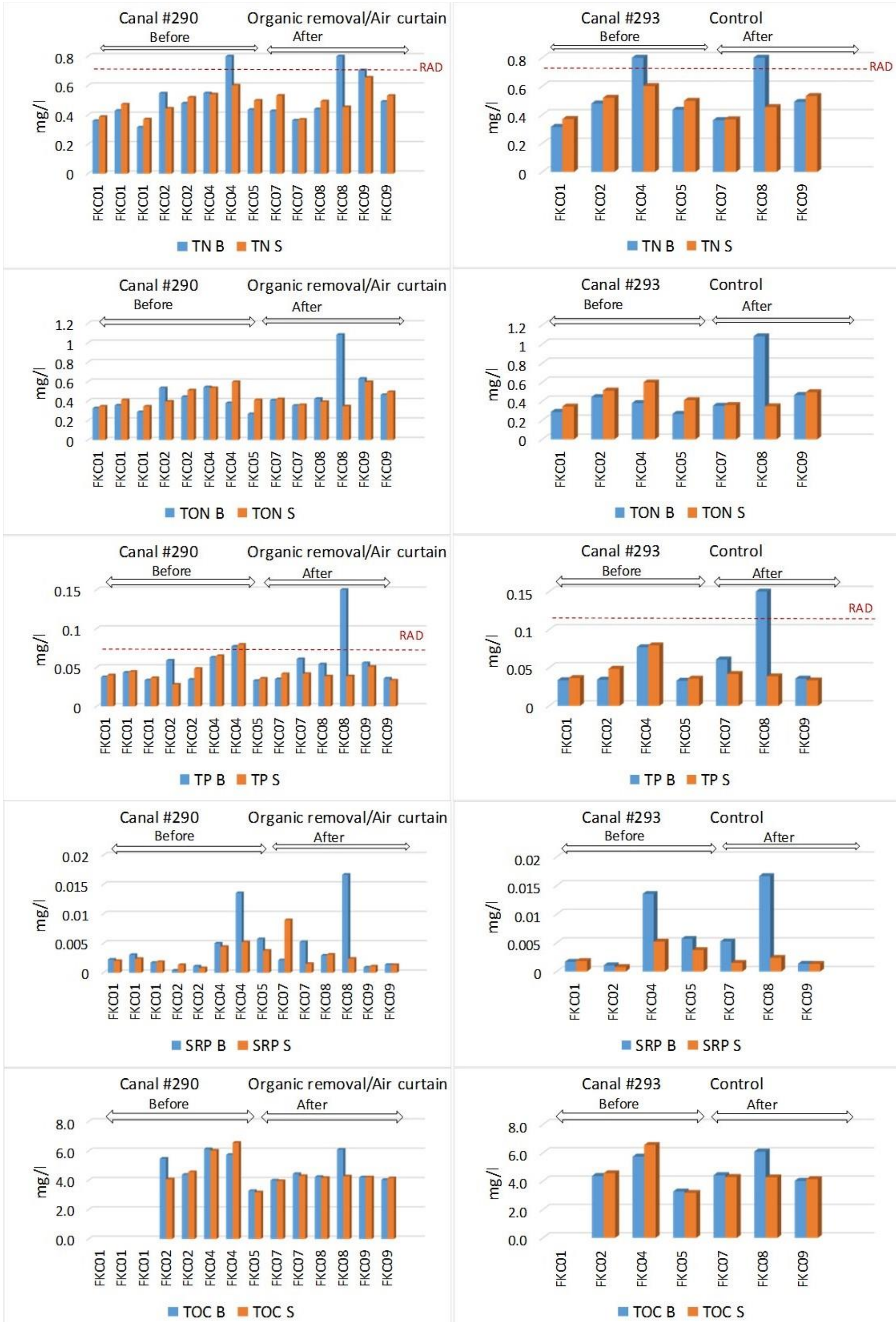


Fig 6.7.4. *Water quality comparison between Before and After sampling, and between remediated Canal #290 and control Canal #293. Dissolved nitrogen species: total nitrogen (TN); total organic nitrogen (TON); total phosphorous (TP); soluble reactive phosphorous (SRP); and total organic carbon (TOC).*

TN, TON and TP are practically the same Before and After remediation. SRP seems to be declining except for a high value in FKC08 (Fig 6.7.4). TOC has remained practically constant since remediation, and slightly lower than before remediation. In summary, after just 8 month since remediation, there is no clear improving trend in nutrient content after organic removal and air curtain installation.

6.7.2 Profiles of water column

Profiles of physical-chemical properties of waters in Canal #290 were measured 15 times during 8 surveys. Six profiles were measured before and nine after remediation. Selected remediation method was Organic Removal and the installation of an air curtain at the mouth of the canal. Construction was completed in June 2017.

After remediation stage began with a drastic drop in %DO saturation from 20%-40% Before to 5% DO saturation After remediation in Dec 2016. There was an increase in 2017 (FKC08) but with a large range of variability, especially at station 290B. Values drop again in Feb and March 2018. pH declined consistently during Before stage and into After stage, with low values occurring in FKC07 (Dec 2016). Most values in 2017 and 2018 remained around neutrality. On the other hand, salinity during the Before stage was in general elevated (>38 psu). After remediation salinity has been declining continuously until reaching 34-35 psu in 2017. Data from 2018, after Irma, suggest an increase back to levels around 36 psu. Finally, temperature does not define systematic changes or trends. By March 2018 we observed most debris had been removed from the canal and two weed gates were operational. In summary, profile data for canal #290 do not indicate any clear improvement trend.

Table 6.7.1. Selected profile statistics BEFORE and AFTER remediation for Canal #293

Canal	Parameter	Temp, Before	Temp, After	Salinity, Before	Salinity, After	pH, Before	pH, After	DO%, Before	DO%, After
Canal #290	Mean	30.2	25.8	38.2	36.4	7.3	7.0	48.9	30.1
Canal #290	Std. Dev.	1.8	2.1	1.4	1.3	0.2	0.3	27.8	36.1
Canal #290	Count	94	223	94	223	94	223	94	223
Canal #290	Minimum	28.2	21.9	34.8	33.2	6.8	6.4	14.9	3.1
Canal #290	Maximum	34.5	31.1	39.8	38.4	7.5	7.7	97.2	104.1
Canal #290	Coef. Var.	0.1	0.1	0.0	0.0	0.0	0.0	0.6	1.2
Canal #290	Range	6.3	9.2	5.1	5.3	0.7	1.4	82.3	101.0
Canal #290	Geom. Mean	30.1	25.8	38.2	36.3	7.3	7.0	41.1	13.7
Canal #290	Median	29.4	25.5	38.9	36.6	7.3	7.0	36.8	7.9

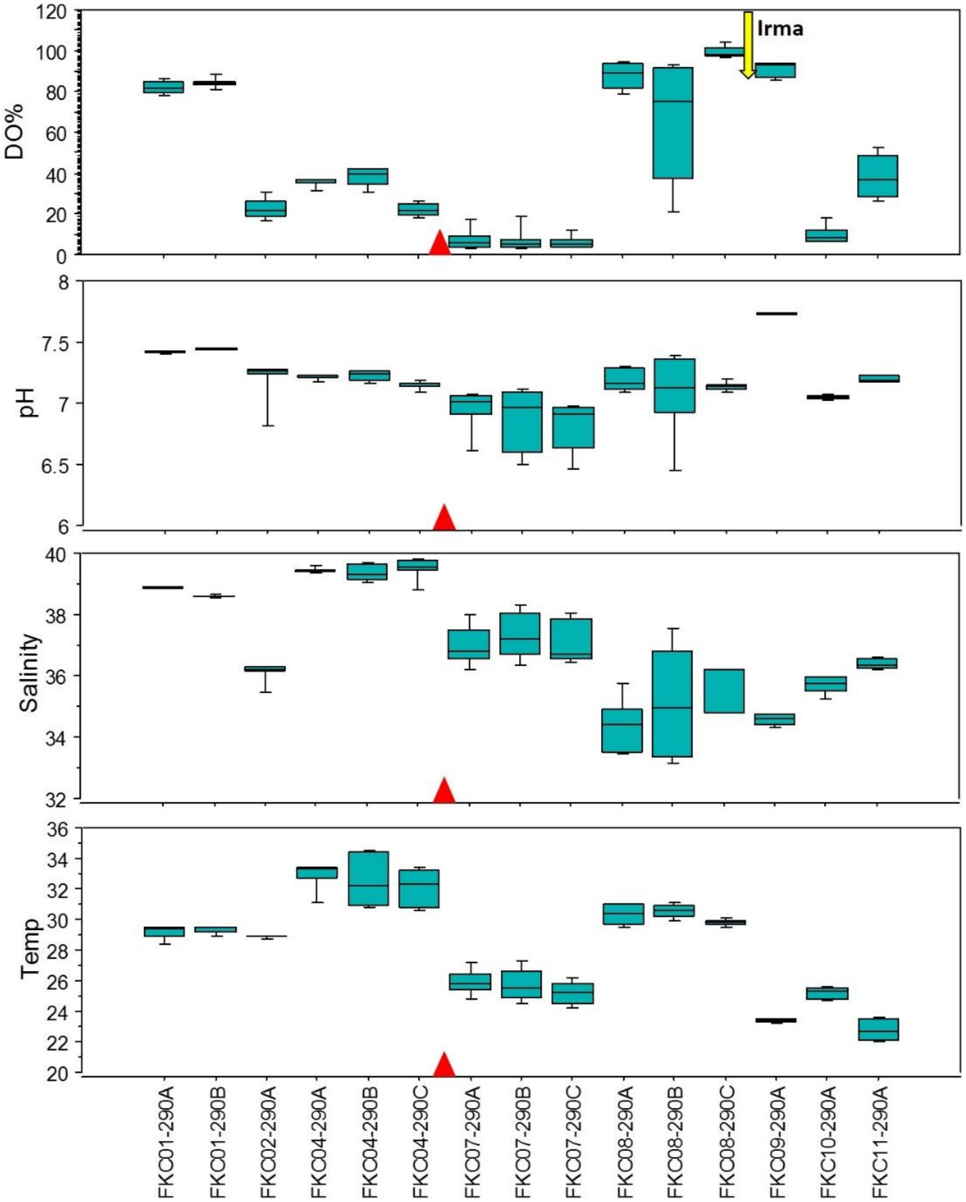
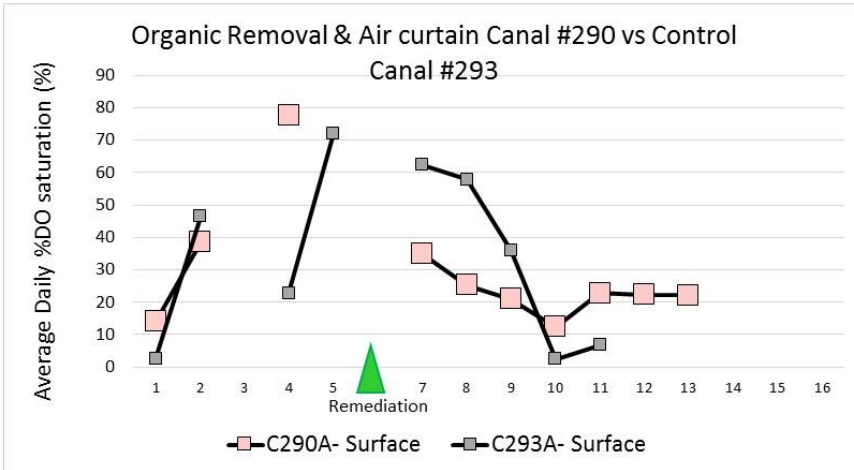


***Figure 6.7.5**. Box-and-Whisker plots of physical-chemical variables measured along depth profiles of the water column in Canal #290. Date of remediation is indicated by the red triangle.*

6.7.3 Diel Measurements

Remediation of Canal #290 consisted of organic removal and installation of an air curtain. Installation concluded on March 2016. three diel were measured Before and seven After remediation. Surface waters for the two canals do not look alike, and after remediation

%DO sat in #290 remained below 40% DO sat. Canal #290 bottom waters Before were better than those after remediation, which simply became anoxic in all diel measurements. From these data, remediation has not rendered favorable results yet



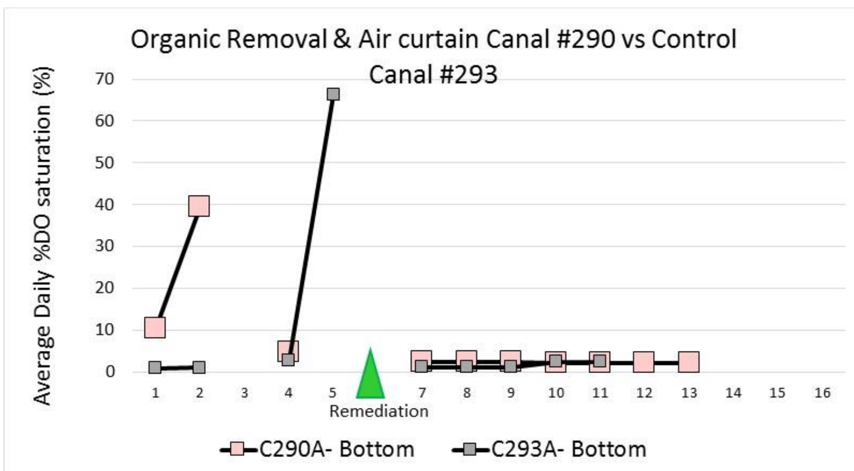


***Figure 6.7.6**. Diel (24 hour) observations of %DO saturation for remediated (organic removal & air curtain) Canal #290 and Control Canal #293, Big Pine Key. Green triangle indicates when remediation took place*

6.8 *Canal #472.*

Canal #472 is located in Boca Chica, Geiger Key, facing the Atlantic Ocean. Canal #472 is a small 0.6 acre, 623 ft long straight canal, reaching depths down to -15 ft, and experiencing a small tidal range of 0.79 ft (Figs 6.8.1 and 6.8.2). Canal #472 is affected by windblown seaweed which rots and degrades water quality. As observed elsewhere in the Keys, oxidation of organic matter depletes the water column of oxygen while enriching waters with released nutrients.

When water conditions become anoxic, anaerobic bacteria resort to sulfate as a source of oxygen, reducing sulfate and forming hydrogen sulfide (H2S) as a by-product. Canal #472 had very poor water quality, with low dissolved oxygen content.

The selected remediation method for Canal # 472 and #470 combined was the installation of a 112 foot 24” by 38”concrete culvert connecting the two dead ends of the canals to enhance natural tidal flushing. Installation was completed on April 2015. Accumulation of seaweed in #472 in late May 2015 made neighbors complain that the culvert was trapping the seaweed. The culvert was plugged on July 2015 to evaluate the situation. Finally the culvert was re-opened in May 2016.

6.8.1 Nutrient monitoring

Given the issues with opening and closing of the culvert, monitoring has been quite fragmentary, but all stages and conditions were sampled at least once. As shown in Figure 6.8.4, and 6.8.5 below, Canal #472 was sampled 8 times during six surveys for a total of 16 samples. Six samples were collected before remediation during FKC01 (April 2014) and FKC02 (Oct 2014); four samples were collected after the first opening of the culvert during FKC03 (Apr 2015); two samples collected while the culvert was plugged in FKC04 (Jun 2015); and finally, four samples were collected after the last culvert opening during FKC07 (Dec 2016) and then after Irma in FKC09 (March 2018).

Figure 6.8.1: *Google image rendition of canal #472 (remediation) and canal #458 (control) in Boca Chica, Geiger Key*

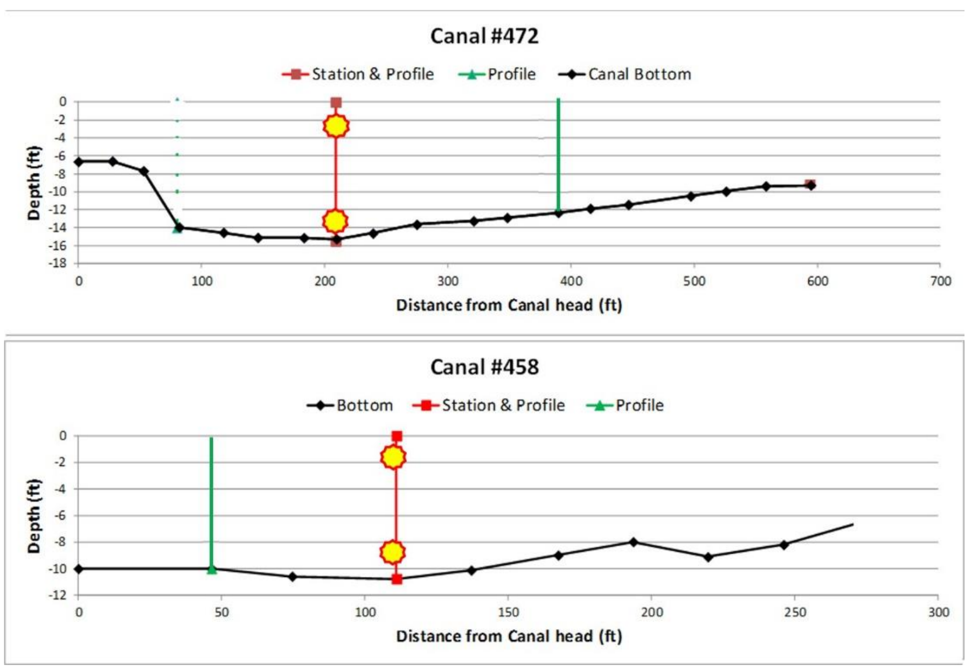


Figure 6.8.2: *Bathymetric profile of canal #472 and canal #458, showing location of sampling and diel measurements (yellow circle) and profile measurement sites.*

NOx and NO3 since first opening of the culvert are slightly higher than previous Before samples (FKC01). NO2, NH4 and DIN do not change significantly from Before to After installation of the culvert (Fig 6.8.4). Likewise, there is no significant change in TN, TON and TOC (Fig 6.8.5). TP, on the other hand, seems to decline slightly down to about 0.01 ppm when the culvert is open (Fig 6.8.5). Finally, SRP stays about the same Before and After culvert opening, except for a high surface value in Dec 2016 (FKC07). In summary, after a little less than two years since culvert installation, there is no clear improving trend yet in nutrient content in Canal #472.

Figure 6.8.3: *Google image rendition of canal #472 (remediation) and canal #470 (remediation) and the location of the culvert connecting them. Boca Chica, Geiger Key.*

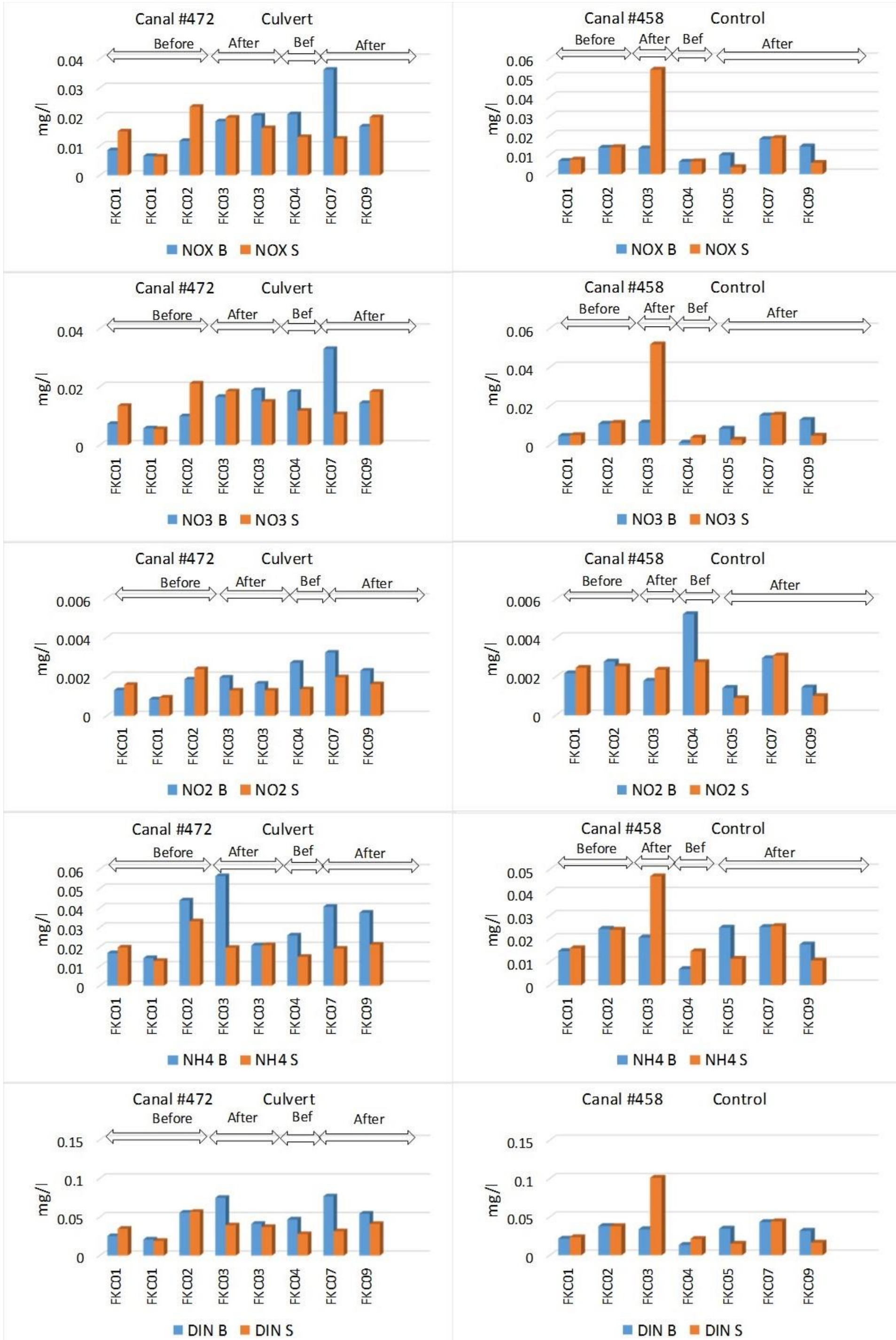


Fig 6.8.4. *Water quality comparison between Before and After sampling, and between remediated Canal #472 and control Canal #458. Dissolved nitrogen species: nitrate+nitrite (N+N), nitrate (NO3), nitrite (NO2), ammonium (NH4) and dissolved inorganic nitrogen (DIN)*

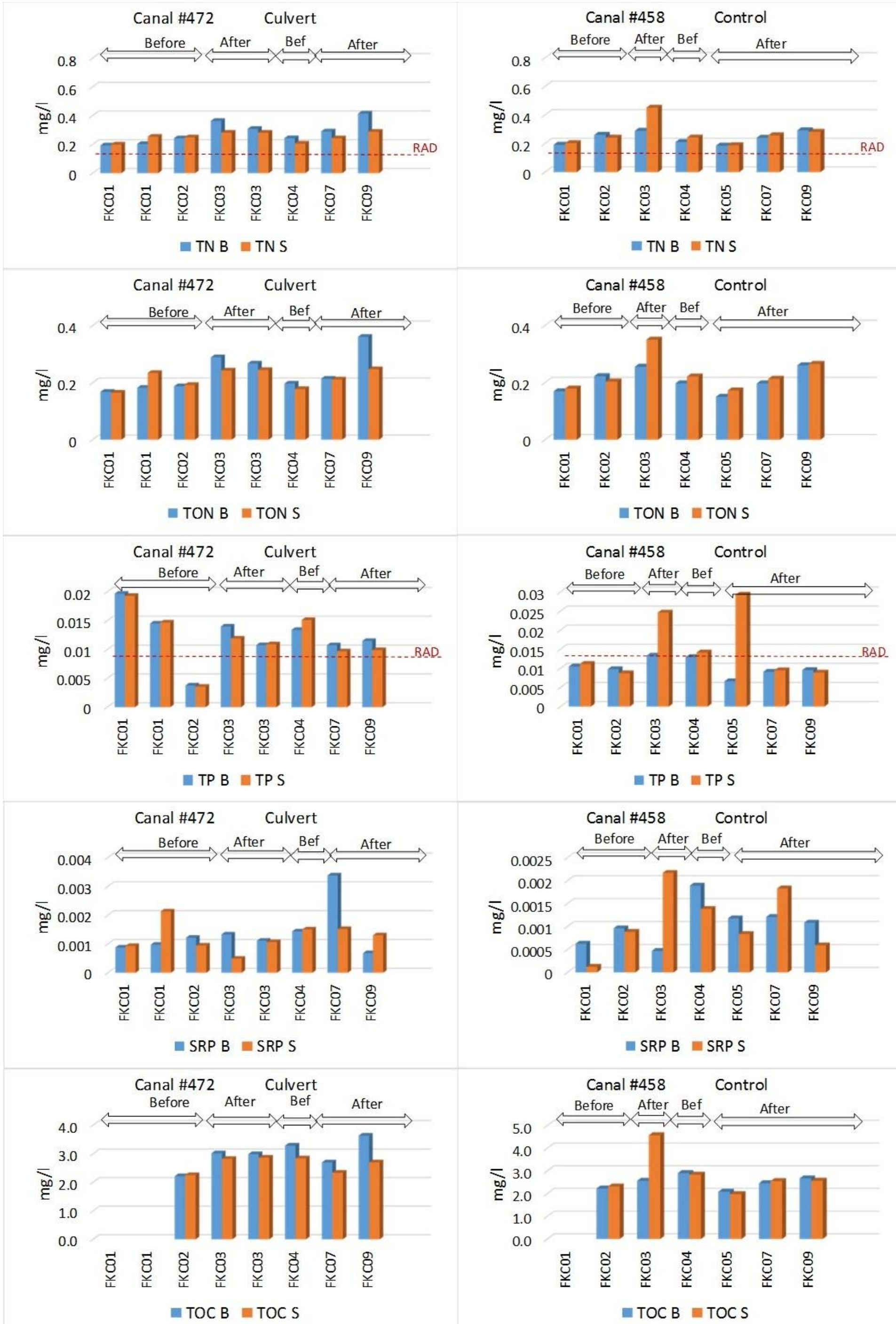


Fig 6.8.5. *Water quality comparison between Before and After sampling, and between remediated Canal #472 and control Canal #458. Dissolved nitrogen species: total nitrogen (TN); total organic nitrogen (TON); total phosphorous (TP); soluble reactive phosphorous (SRP); and total organic carbon (TOC).*

6.8.2 Profiles of water column

Temporal changes of physical-chemical properties of waters in Canal #472 were measured in thirteen profiles during seven surveys as shown in Table 6.8.1 and Figure 6.8.6. Two profiles were measured before remediation and eleven were measured when the culvert functioning. Installation of a culvert connecting Canal #472 with Canal #470 was completed in April 2015. The culvert was plugged from July 2015 to May 2016, when it was definitively open. Survey FKC02 was measured before installation of the culvert. FKC03 and FKC04 were measured while the culvert was open for the first time. Finally, FKC07 to FKC11 were measured after the culvert was unplugged.

Before remediation, median %DO sat were very low (34% and 21% DO sat). Readings right after installation of the culvert render median saturations above 56% DO sat, whith profiles showing low variability and no value was below 49.8%. In other words, the culvert brought inmediate increase with 100% compliance (>42%) in all readings. These results contrasted with those profiles inmediately after the unplugging of the culvert, characterized by large dispersion and higher medians. Finally, recent measurements in 2018 confirm the increasing trend in %DO saturation of a water column, with abundant fish and crab.

Table 6.8.1. Selected profile statistics BEFORE and AFTER remediation for Canal #472

Canal	Parameter	Temp, Before	Temp, After	Salinity, Before	Salinity, After	pH, Before	pH, After	DO%, Before	DO%, After
Canal #472	Mean	29.3	29.0	36.3	38.4	7.6	7.5	27.7	66.3
Canal #472	Std. Dev.	0.3	3.3	0.5	1.9	0.3	0.3	7.3	20.0
Canal #472	Count	53	226	53	226	53	226	53	226
Canal #472	Minimum	28.5	24.1	35.8	35.3	6.6	6.3	17.6	7.3
Canal #472	Maximum	29.7	34.2	37.7	42.2	7.8	7.8	42.3	109.2
Canal #472	Coef. Var.	0.0	0.1	0.0	0.0	0.0	0.0	0.3	0.3
Canal #472	Range	1.1	10.1	1.9	6.9	1.2	1.5	24.7	101.9
Canal #472	Geom. Mean	29.3	28.8	36.3	38.3	7.6	7.5	26.7	62.3
Canal #472	Median	29.4	27.0	36.2	38.1	7.8	7.6	29.4	61.5

Acidity (pH) in the first profile before remediation drops drastically from 7.8 to 6.6 units as depth increases beyond 10 ft. In general, median pH has been above 7 units except for station 472C during FKC08 which dropped to 6.4 units. Salinity increased from Before values close to 36 psu to hypersaline levels of about 40 psu. This seems to be caused by the exchange with more saline waters of Canal #470. Since Dec 2016 (FKC07), salinity has declined slightly to levels between 35 psu and 39 psu were. Temperature has been unremarkably and trendless.

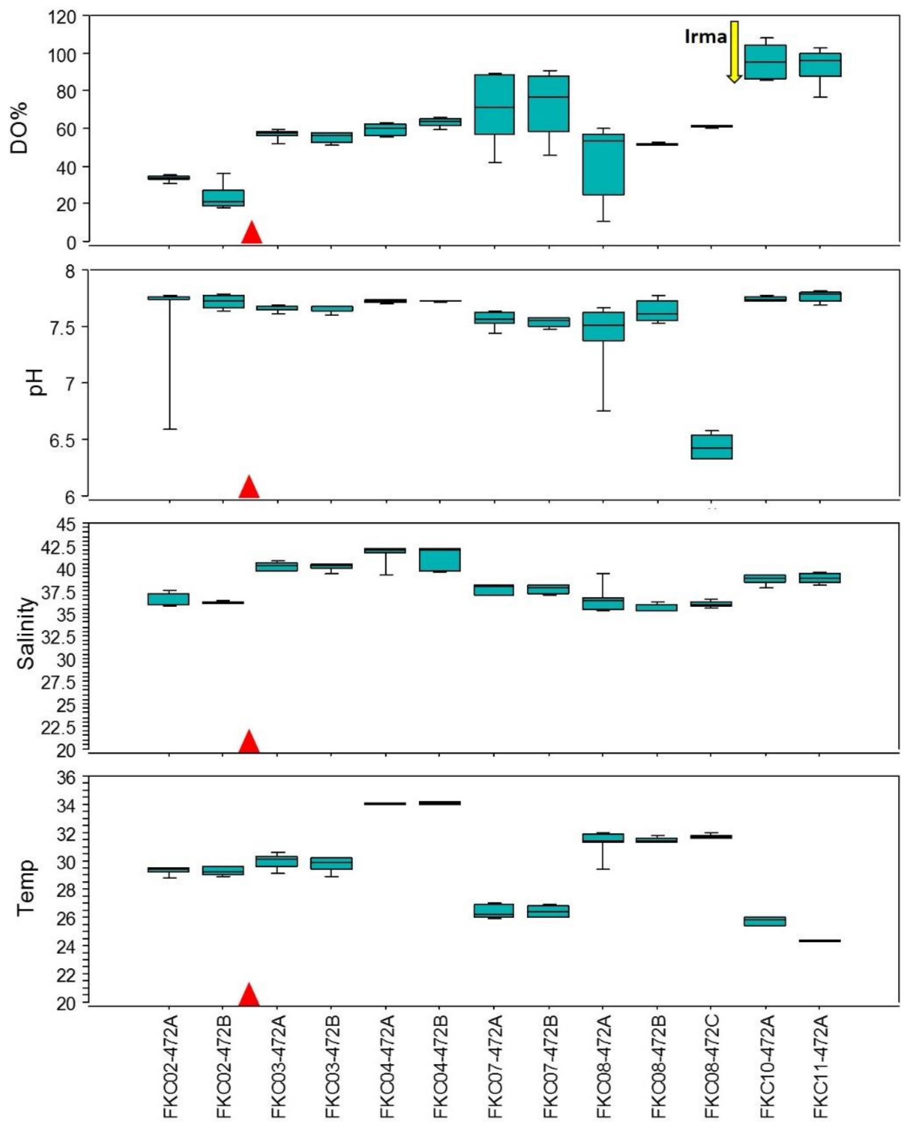


***Figure 6.8.6**. Box-and-Whisker plots of physical-chemical variables measured along depth profiles of the water column in Canal #472. Date of remediation is indicated by the red triangle.*

In summary, from the perspective of physical-chemical properties of the water column, dissolved oxygen content, the fundamental problem affecting waters in Canal #472 seem to be remediated with the installation of the culvert. After three years since remediation and 226 %DO saturation readings along profiles, only 14 (6%) have been below 42% DO sal. All except one readings before remediation were below the 42% DO saturation normative level.

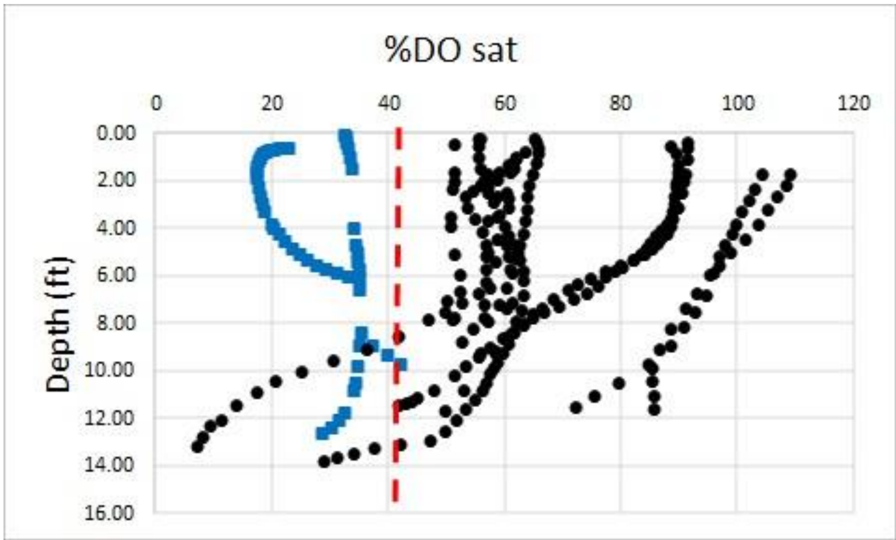
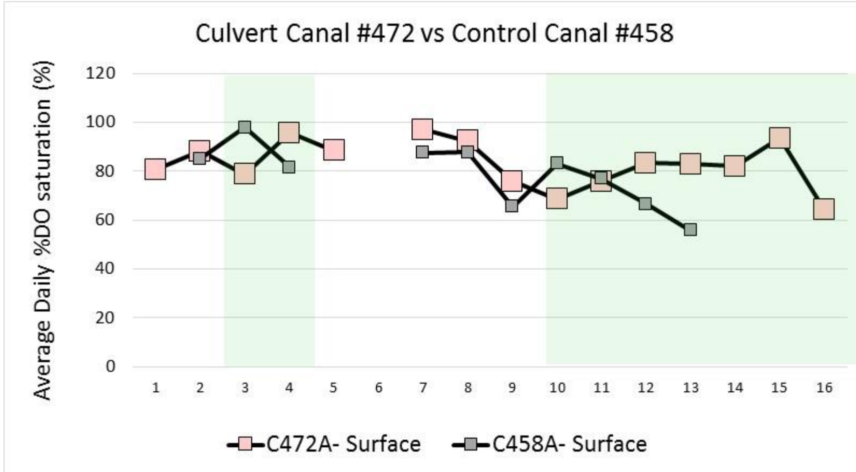


__Figure 6.8.7__. Profiles of %DO saturation for Before (blue squares) and After (black circles) remediation in Canal #472

6.8.3 Diel Measurements

Remediation history of Canal #472 has been complicated. Installation of the culvert was completed on April 2015. The culvert was later plugged on July 2015 and then re-opened in May 2016. Green shaded areas in the diagrams of Figure 6.8.8 are the periods when the culvert has been functioning. Diel data for surface water is rather similar for remediated and control canal. Furthermore, both canals have good quality surface waters. In the lower plot, for the bottom waters, there are again some initial similaritiesasured, which did not lasted beyond the re-opening of the culvert. What is interesting is how all #472 diel measured when the culvert was closed render very low %DO saturation, and how rapidly this canal reacts to improve its bottom waters. Also, bottom waters of Canal #472 are always richer in dissolved oxygen than those of the control canal. The culvert is doing its job in Canal $472 satisfactorily.



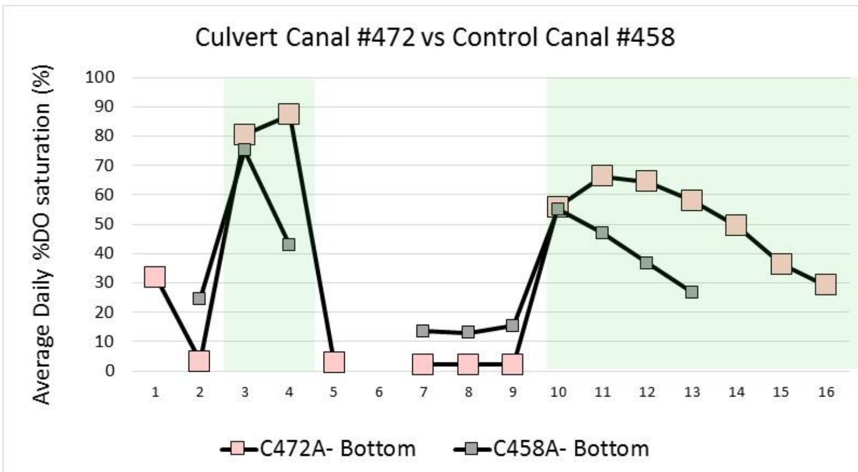


Figure 6.8.8. *Diel (24 hour) observations of %DO saturation for remediated (culvert) Canal #472 and Control Canal #458, Geiger Key. Green rectangles indicate when the culver was open*

6.9 Canal #470.

West of Canal #472 is Canal #470 (Fig 6.8.3), a finger-canal, which opens into a marsh east of the Naval Air Station Key West. Canal #470 has a total combined area of 3.6 acres and length of 1,607 ft. Maximum depth is -22 ft and experiences a tidal range of 0.79 ft. Canal #470 has a poor water quality, reaching anoxic conditions in deeper waters.

The selected remediation method for Canal #470 was the installation of a 112 foot 24" by 38"concrete culvert connecting the two dead ends of #472 and #470 to enhance natural tidal flushing. Installation was completed on April 2015. Accumulation of seaweed in #472 in late May 2015 made neighbors complain that the culvert was trapping the seaweed. The culvert was plugged on July 2015 to evaluate the situation. Finally the culvert was re-opened in May 2016.

6.9.1 Nutrient monitoring

As explained in our discussion of Canal #472, the issues with opening and closing of the culvert, rendered a fragmentary monitoring, but all stages and conditions were sampled at least once. As shown in Figure 6.9.1, and 6.9.2 below, Canal #470 was sampled 4 times during three surveys for a total of 8 samples. Four samples were collected when the culvert was plugged during FKC04 (Jun 2015); and four samples were collected after the last culvert opening during FKC07 (Dec 2016) and FKC09 (March 2018).

NOx, NO2, NO3, NH4 and DIN went higher than Before, following the last opening of the culvert and then declined to previous levels during FKC09 (March 2018; Fig 6.9.1). Likewise, there is an increase in TN and TON since the canal was re-opened (Fig 6.9.2). TP and SRP remained about the same after re-opening of the culvert except for some high values in FKC07 (Fig 6.9.2). Finally, TOC has been about the same Before and After re-opening of the culvert. In summary, there is no clear improving trend yet in nutrient content in Canal #470 after remediation.

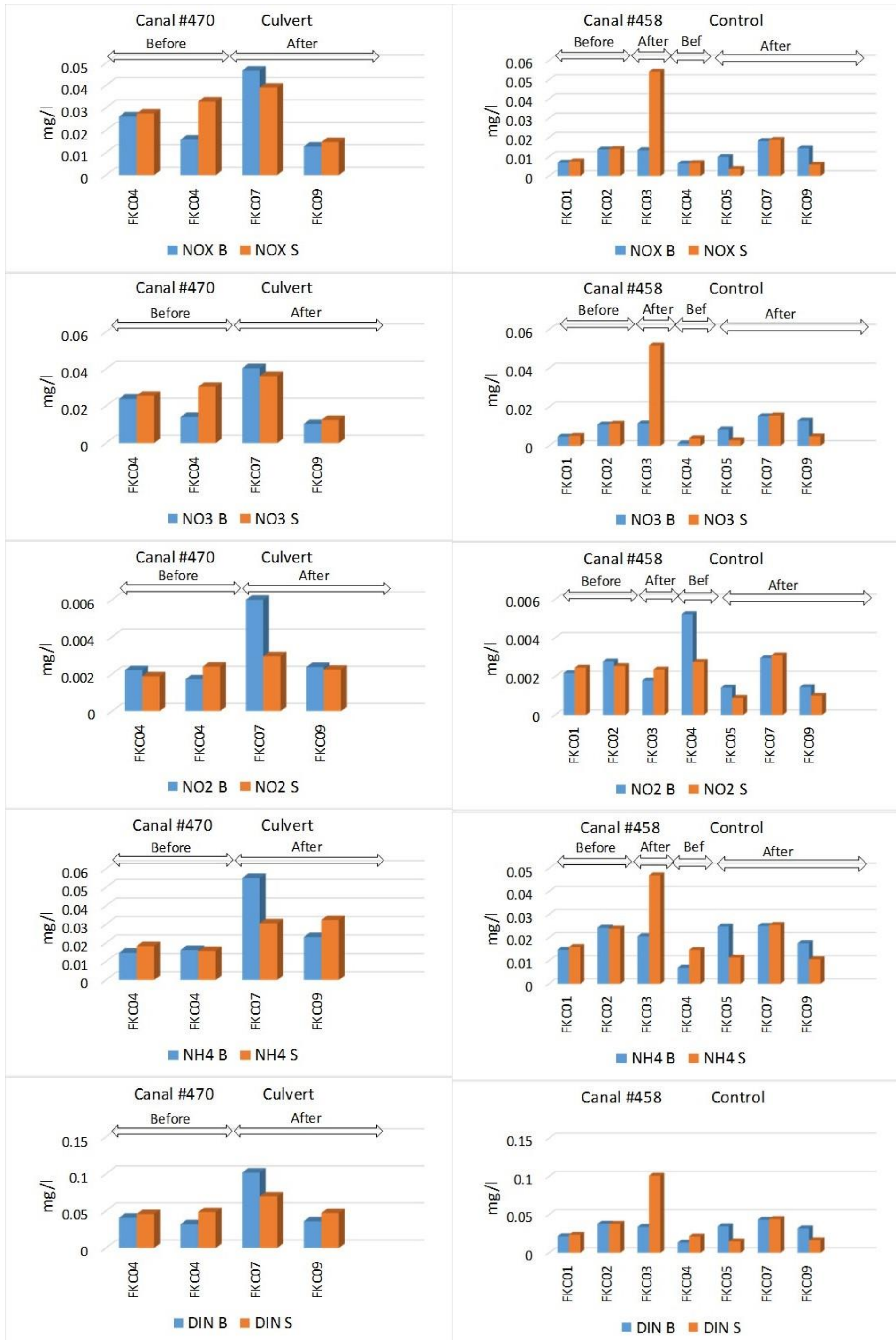


Fig 6.9.1. *Water quality comparison between Before and After sampling, and between remediated Canal #470 and control Canal #458. Dissolved nitrogen species: nitrate+nitrite (N+N), nitrate (NO3), nitrite (NO2), ammonium (NH4) and dissolved inorganic nitrogen (DIN)*

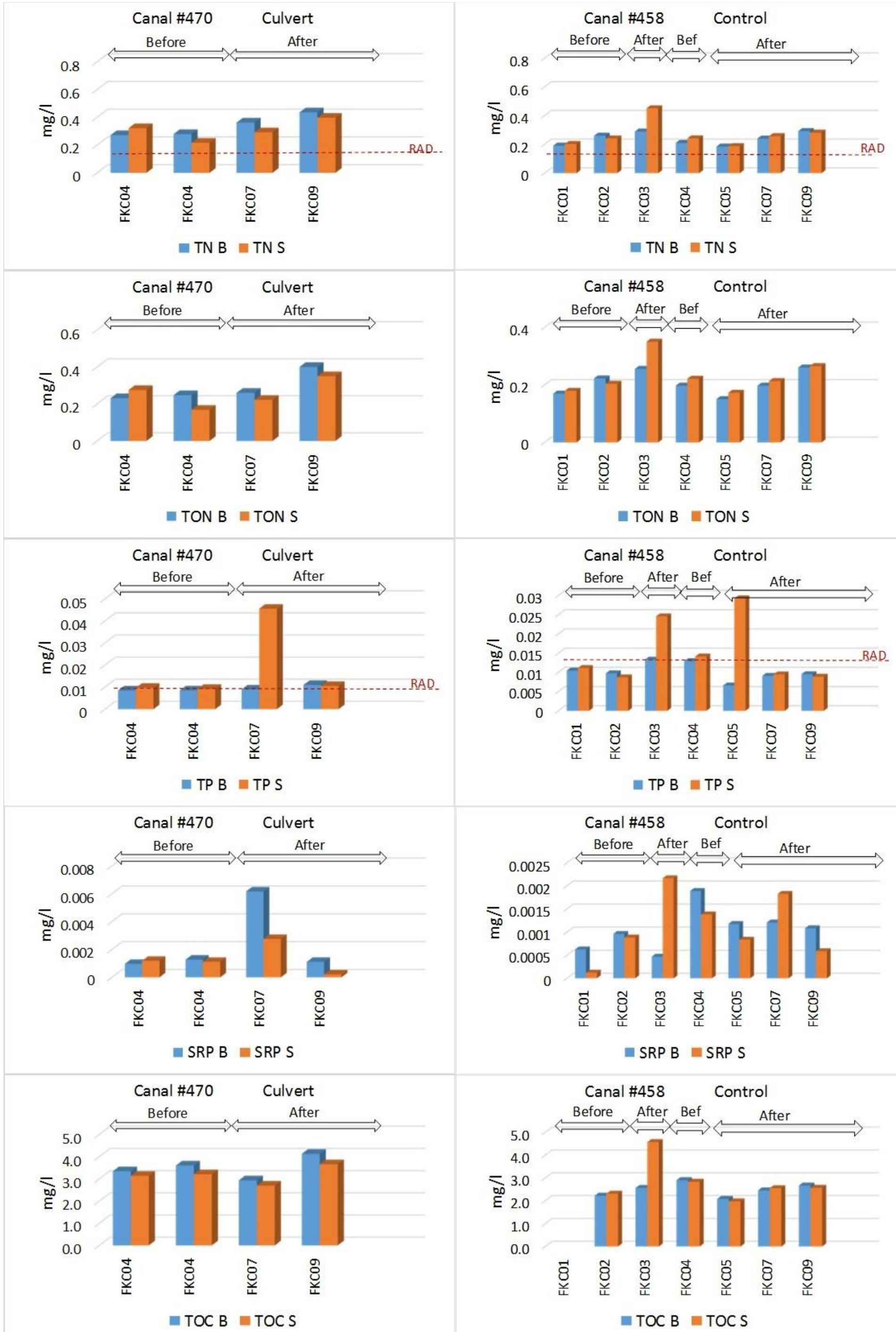


__Fig 6.9.2.__ Water quality comparison between Before and After sampling, and between remediated Canal #470 and control Canal #458. Dissolved nitrogen species: total nitrogen (TN); total organic nitrogen (TON); total phosphorous (TP); soluble reactive phosphorous (SRP); and total organic carbon (TOC).

6.9.2 Profiles of water column

Temporal changes of physical-chemical properties of waters in Canal #470 were measured in nine profiles during six surveys as shown in Table 6.9.1 and Figure 6.9.3. Two profiles were measured before remediation (FKC04) and seven were measured when the culvert was functioning (FKC07 to FKC11). Installation of the culvert connecting Canal #472 with Canal #470 was completed in April 2015. The culvert was plugged from July 2015 until May 2016, when it was definitively open.

Before remediation, median %DO sat were high (78.9% and 77.6% DO sat) without readings below 65%DO sat. First readings after installation of the culvert (Dec 2016) rendered median saturations a little lower than Before, but an increasing trend with medians above 71% DO sat began, which extended until 2018. In other words, although the culvert brought inmediate decline in saturation, the following increase caused 100% compliance (all readings >42%). As in the connected canal #472, water quality in terms of oxygen content has improved since installation of the culvert. Acidity has not changed significantly from Before to After stage, always remaining above pH=7. Salinity was above 42 psu before remediation and has decline slightly to a range between 37psu and 40 psu, while temperature has declined slightly after remediation. In summary, although Canal #470 did not suffer from poor water quality, it has improved since remediation.

Table 6.9.1. Selected profile statistics BEFORE and AFTER remediation for Canal #470

Canal	Parameter	Temp, Before	Temp, After	Salinity, Before	Salinity, After	pH, Before	pH, After	DO%, Before	DO%, After
Canal #470	Mean	33.7	27.7	42.9	39.0	7.8	7.7	78.1	74.1
Canal #470	Std. Dev.	0.3	4.8	0.4	1.5	0.0	0.2	6.1	14.1
Canal #470	Count	66	232	66	232	66	232	66	232
Canal #470	Minimum	33.3	19.6	42.1	36.7	7.8	7.3	65.4	36.5
Canal #470	Maximum	34.4	36.7	43.3	43.1	7.9	8.2	94.3	95.6
Canal #470	Coef. Var.	0.0	0.2	0.0	0.0	0.0	0.0	0.1	0.2
Canal #470	Range	1.0	17.1	1.2	6.4	0.1	0.9	28.9	59.1
Canal #470	Geom. Mean	33.7	27.3	42.9	39.0	7.8	7.7	77.8	72.7
Canal #470	Median	33.7	25.8	43.0	39.0	7.8	7.7	78.0	72.5

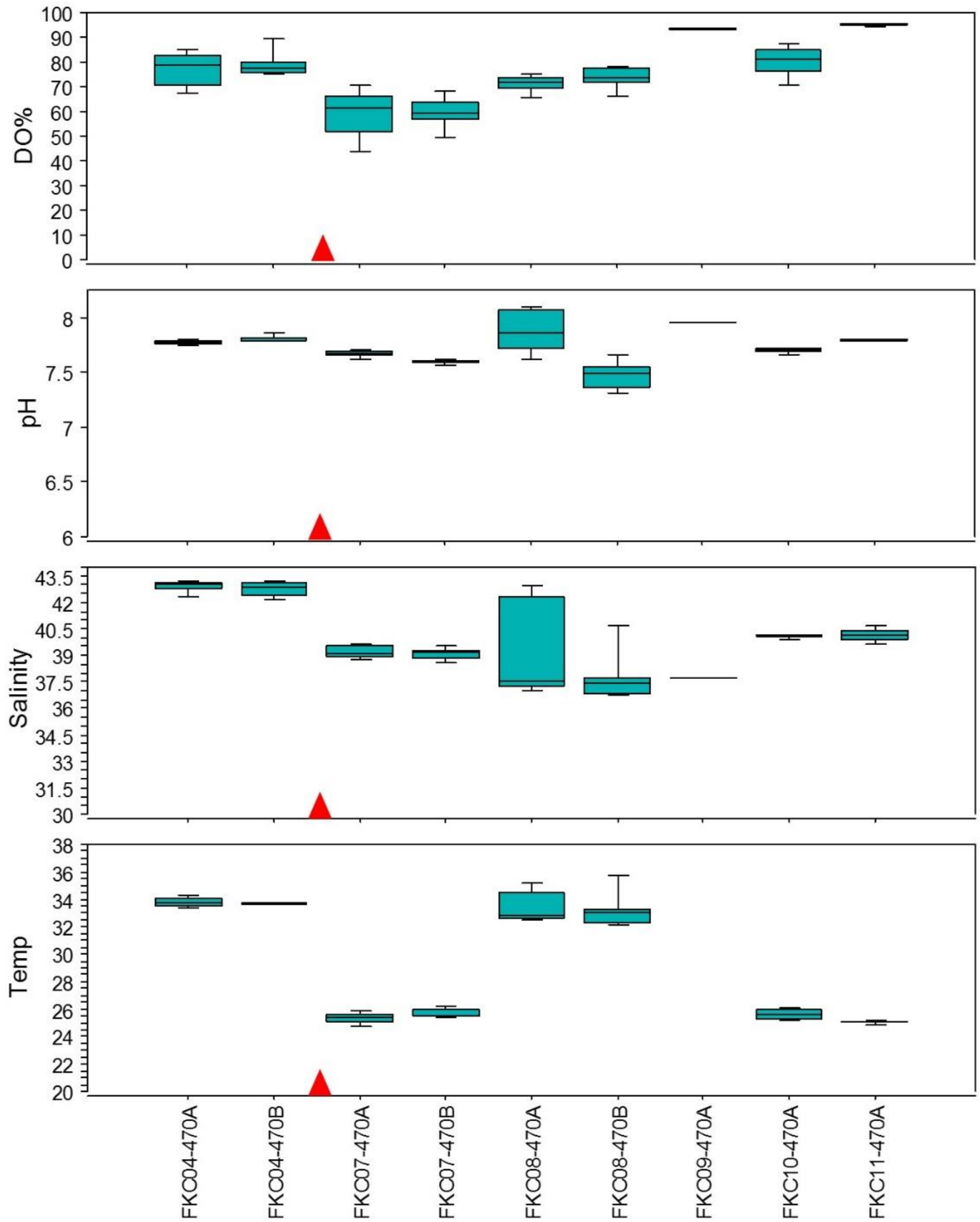


***Figure 6.9.3**. Box-and-Whisker plots of physical-chemical variables measured along depth profiles of the water column in Canal #470. Date of remediation is indicated by the red triangle.*

6.9.3 Diel Measurements

Response of canal #470 contrasts with the excellent results obtained in Canal S472 with the culvert connecting them. Initially, when the culvert was open, measurements in #470, were good, but the last three measurements were rather poor. Curiously enough, measurements with the culvert plugged were excellent but ACME had ranked this canal poor. There are other indexes indicating improvement, like the increasing amount and variety of fish and crab, which are thriving in both canals since installation of the culvert, and how turbidity and odors have receded. Complex behavior may result from the complexity of this canal, and it will necessary to let the system equilibrate for some time before giving a final assessment.

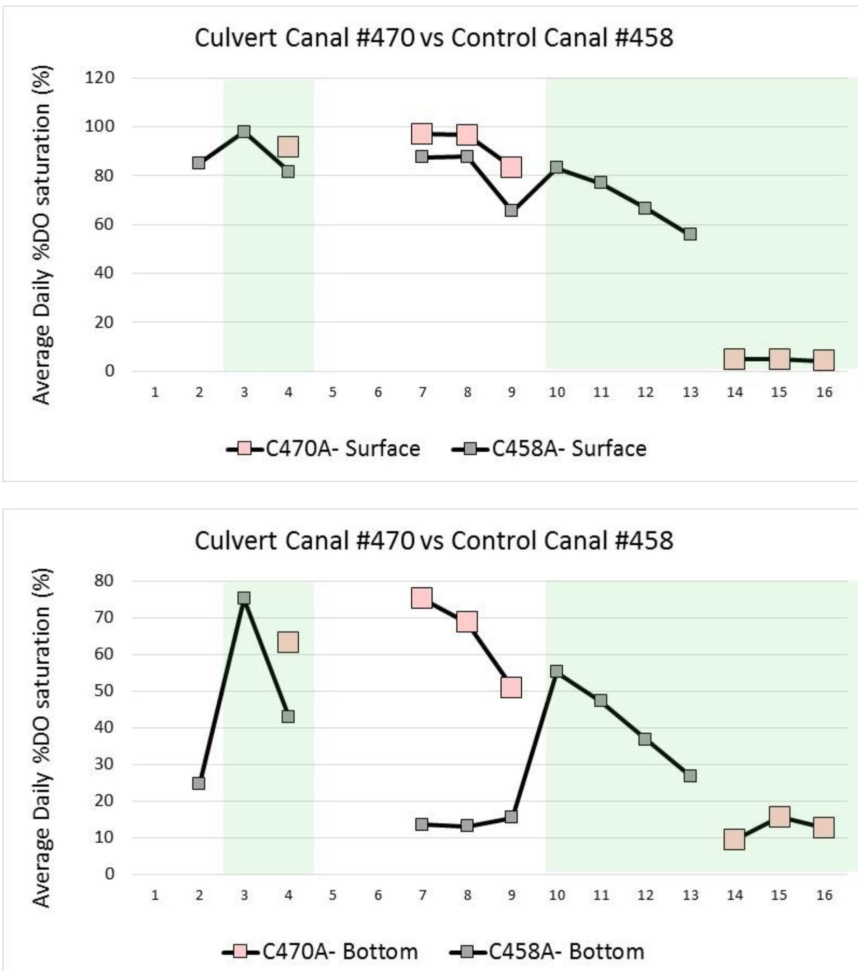


Figure 6.9.4. *Diel (24 hour) observations of %DO saturation for remediated (culvert) Canal #470 and Control Canal #458, Geiger Key. Green rectangles indicate when the culver was open*

7. Discussion of Results

This project posed especial challenges given the unpredictable delays and unexpected asynchrony in the implementation of remediation measures. In fact, each remediation project became an individual monitoring project in itself. Mother Nature conspired to make things even more complicated when in September 10th 2017, Hurricane Irma made landfall in Cudjoe Key as a Category 4 storm. Irma's winds and surge affected all the Florida Keys, causing havoc everywhere and bringing massive amounts of debris to all canals. At the end, most remediation actions ended by mid-2016, leaving little over one year for post-remediation monitoring (Table 7.1). The first post-remediation simultaneous monitoring of all canals began in June 2017.

Table 7.1: *End date of remediation and years lapsed until June 2017, when simultaneous post remediation monitoring began for all canals*

Canal	Remediation	Years
#29	July 2015	1.9
#137	Nov 2014	2.6
#148	May 2017	0.1
#266	May 2016	1.1
#277	May 2016	1.1
#287	July 2016	0.9
#290	Mar 2016	1.3
#470	May 2016	1.1
#472	May 2016	1.1

Each remediation method was aimed to a specific target (Fig 7.1). Backfilling was designed to address canal depth, and by doing so, to eliminate the persistence of bottom organic matter, stagnant anoxic-reducing waters, and to change the residence time of canal waters while reducing its dissolved organic matter levels. Backfilling doesn't address those issues coupled to incoming seaweed wrack. Culvert installation focus on reducing residence time and dissolved oxygen in the water column. Aerators simply contribute oxygen to the water column. Weed gates and air curtains pretend to stop seaweed wrack to enter the canals, and by doing so, to improve oxygen levels in the water column by hindering accumulation of organic matter on the canal bottom. What is clear from Figure 7.1 is that no single method addresses all water quality issues.

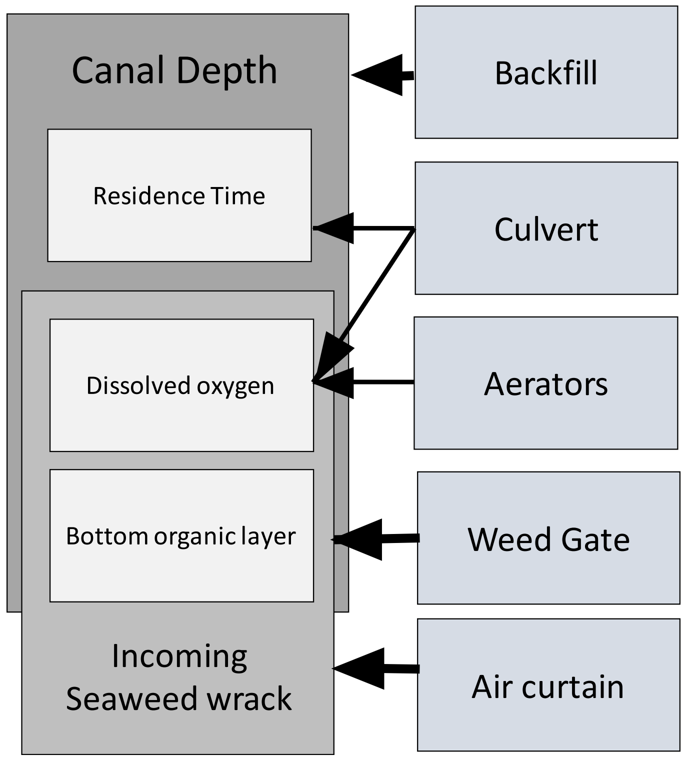


Figure 7.1: *Targeted canal issue (left panel) and remediation methods to address it (right panel).*

Monitoring was initially programmed to begin in early 2014 and to be executed in two years. It finally lasted four years. Given the lessons learned from monitoring remediated canals in Little Venice, we expected that significant changes in nutrient content would take several years to materialize. That experience, budgetary constraints and the need to extend the project to accommodate delays in remediation resulted in increasing the time between sampling, and planning for at least one sampling as close as possible to the end of the program. All of this on the hope that given more time would allow the system to respond, so positive changes in composition would be detected. Except for canal #470, which was included later in the program, waters from all sites were sampled at least twice before remediation (Table 7.2).

TABLE 7.2: Water sampling events.

	WATER SAMPLING					
	BEFORE		AFTER		Post-IRMA	
Canal	Events	Samples	Events	Samples	Events	Samples
#29	2	6	3	8	1	2
#137	2	8	4	14	1	2
#148	4	10	1	2	1	2
#266	3	8	1	2	1	2
#277	4	12	2	6	1	2
#287	4	8	1	2	1	2
#290	3	8	2	4	1	2
#470	1	4	2	4	1	2
#472	4	12	2	4	1	2

Emphasis was focused on profiles and diel logs because parameters like DO, %DO saturation and pH respond faster to induced changes. As expected, nutrients were the most resilient to changing conditions while diel and profile measurements were the most sensible. Diel and profiles indicate that backfilling and culvert installation are the remediation methods driving fastest positive response of the water column (Fig 7.2). Aeration in canal #137 is also beginning to show increases in %DO Sat.

Water acidity (pH) is another potential index of water quality, which covariates with dissolved oxygen concentrations, especially for %DO Sat larger than 20%. However, pH is not as efficient indicator of improvement as dissolved oxygen. In canal systems, higher pHs (above 7.5) are usually indicators of better water quality, and low pHs (usually below 6.65) are usually linked to anoxia or hypoxia and to increasing rates of sulfate reduction by anaerobic bacteria. Figure 7.3 summarizes diel results for pH at each canal and remediation method.

There is no evidence that remediation has driven declines in nutrient concentration in any canal. Some apparent improvements are ruled out when the control canal shows similar pattern as that of the remediated canal, suggesting conditions driven by a common external factor, different from remediation. Similar outcome is observed for some species, like TN, TON, TP and SRP which seem to be slowly moving in the right direction in Canal #148, but without conclusive results.

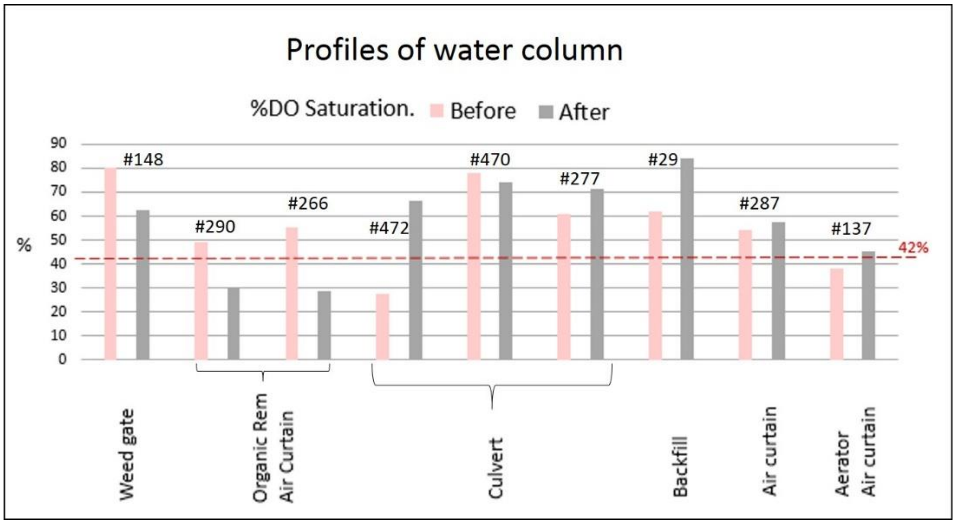


Figure 7.2. *Summary of changes in Dissolved Oxygen Saturation in the water column of remediated canals. Red stippled line marks the 42% DO Saturation limit, below which conditions are not appropriate for development of aquatic life.*

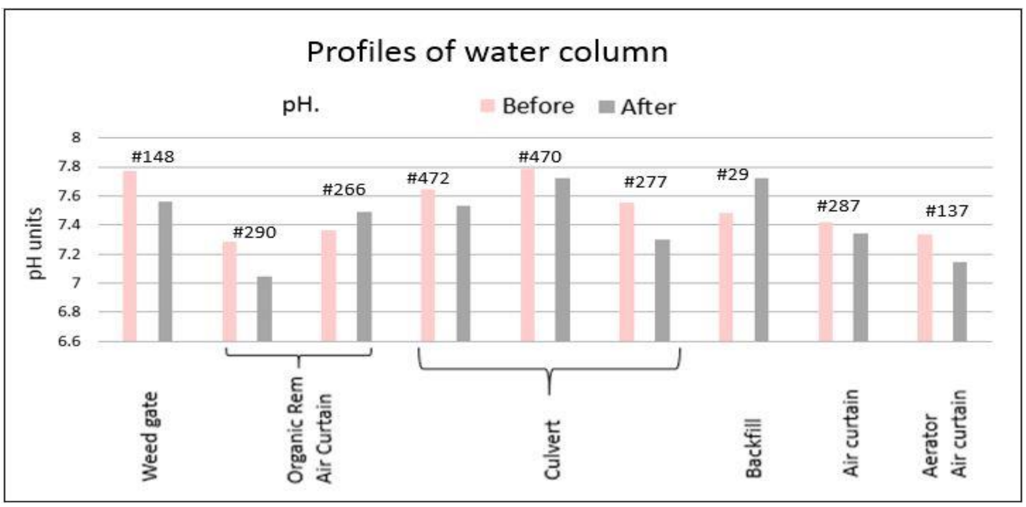


Figure 7.3. *Summary of changes in pH in the water column of remediated canals.*

Among the diverse water quality parameters tested, changes in oxygenation of the water column (especially bottom waters) was the fastest metric to signal changes potentially brought about by remediation. We used diel and water profile data (Table 8.1) for the assessment. Those canals where remediation consisted of improving water circulation and exchange by means of backfilling (#29) or culvert installation (#277, #470 and #472), experienced positive increasing trends in percentage of dissolved oxygen saturation (%DO Sat) after remediation. In these cases, the response was almost immediate, not only in oxygen concentration but also with the arrival of fish and crab to the remediated canals. On the other hand, organic removal and air curtains have not rendered favorable results increasing %DO Saturation yet.

Weed barriers, organic removal and air curtains have not rendered favorable results in %DO Saturation yet. Air curtains coupled with aeration inside the canal seems to partially improve oxygen saturation. Nutrient concentration levels have not declined in any of the remediated canals (Table 8.1).

	REMEDIATION	PROFILES	DIEL	NUTRIENTS
# 29	Backfilling	YES	YES	Not yet
#137	Air Curtain & Aerator	Not yet	YES	Not yet
#148	Air Curtain	Not yet	Not yet	Not yet
#266	Organic Removal & Air Curtain	Not yet	Not yet	Not yet
#277	Culvert	YES	YES	Not yet
#287	Weed Barrier	Not yet	Not yet	Not yet
#290	Organic Removal & Air Curtain	Not yet	Not yet	Not yet
#470	Culvert	YES	Not yet	Not yet
#472	Culvert	YES	YES	Not yet

Figure 8.1. *Summary of performance of remediation methods.* ***YES****= strong evidence of improvement driven by remediation method;* ***Not yet****= No evidence of change driven by remediation method*

All data files generated during this project are freely accessible from the Southeast Environmental Research Center Water Quality Monitoring Laboratory website: http://serc.fiu.edu/wqmnetwork/Canals/index.htm

8. Conclusions

In summary, the most relevant conclusions derived from the monitoring program are:

- Surface waters in most canals have fair quality most of the time. Poor water quality usually sets in for waters deeper than 6 ft.
- Post-remediation monitoring has been too short to detect significant and sustained changes as expected from remediation.
- Response to remediation is significantly affected by lagging. Nutrient concentrations have not shown any improvement yet, while dissolved oxygen was the only parameter to suggest improvements in water quality in some canal.
- All remediation methodologies, except backfilling, dodged elimination of a fundamental driver of water quality decline, excessive canal depths.
- Improvements in water oxygenation were more evident and more expedite in those sites where deep stagnant waters were eliminated (backfill) and/or water circulation was enhanced (culvert).
- These improvements seem to respond to a reduction in residence time due to enhanced tidal flushing.
- Backfilling, the most radical remediation technique rendered immediate positive results in oxygenation. After remediation there were no stagnant, deep, organic-rich waters to consume oxygen, while circulation and exchange with open waters was more expedite.
- Culvert Installation followed backfilling in efficiency to amend oxygenation by improving circulation and exchange. Culverts purpose was stimulating exchange with marine cleaner waters. Hence, culverts are more efficient when connecting canals to open waters.
- Organic removal has not resulted in water quality improvements yet, and canals are being backfilled with rotting seaweed wrack from accumulations at the mouth of canals

- Aeration addresses only oxygenation of the water column. This oxygenation has not proven efficiency to render permanent positive results yet.
- Remediation in shallow canals, less than 8 ft, may render positive results with the combination of organic matter removal from canal bottoms and efficient aeration, while keeping new seaweed from entering the canal with gates or air curtains.
- When attempting to remediate deep canals, no permanent solution will be achieved without backfilling. Bottom should be raised to shallower than approximately 7 ft.

The main corollary we can derive is, it seems that expected changes after remediation have not had the time to mature, and if something was developing, it was seriously disturbed by hurricane impact in 2017. After any environmental intervention, there is a lag time for the system to show a response. The lag time, meaning…. "*The time elapsed between adoption of management changes and the detection of measurable improvement in water quality in the target water body"* (Meals et al 2010) is a critical factor to consider in environmental interventions. Remediation projects may be well designed and fully implemented, but expected changes may not show conclusive results. Remediation design and implementation, monitoring period, and sampling frequency may not be sufficient to address the lag between treatment and response.

> *"The main components of lag time include the time required for an installed practice to produce an effect, the time required for the effect to be delivered to the water resource, the time required for the water body to respond to the effect, and the effectiveness of the monitoring program to measure the response."* (Meals et al 2010)… We must wait…

9. Acknowledgements

We would like to extend a recognition and my sincere gratitude to Mr. George Nugent, Mr. Gustavo Rios, Ms. Jennifer Derby, Dr. John Hunt, Mr. Charles Causey, Ms. Jennifer Shadle, Dr. Billy Causey, Mr. Jon Iglehart, Ms. Rhonda Haag, and especially to Mr. Steven Blackburn. The dedication and professionalism of my technical crew, Jeff Absten, Breege Boyer and Sandro

Stump made this project possible. Thanks are given to SERC's CAChE Nutrient Analysis Core Facility personnel for the excellence of their work. This is contribution number 885T from the Southeast Environmental Research Center in the Institute of Water & Environment at Florida International University

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