EPA Region 4: Final Report (Award # 02D20622)

Cover Page

Project Title: South Florida Geographic Initiatives Program: Monitoring Water Quality in the Key West Ship Channel and surrounding ecologically and culturally significant coral reefs post-COVID-19 anthropause.

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Executive Summary

The College of the Florida Keys, in partnership with Florida International University's (FIU) Institute of Environment Water Quality Monitoring Laboratory, completed the Key West Water Quality Monitoring Project (KWWQ) under EPA Region 4 Award #02D20622. The project monitored water quality in Key West Harbor, the Key West Shipping Channel, Eastern Dry Rocks Sanctuary Preservation Area, and Western Dry Rocks to better understand the effects of natural and anthropogenic stressors on ecologically significant marine waters surrounding Key West, Florida.

The project was designed to expand the spatial and temporal resolution of long-term water quality monitoring in the Florida Keys National Marine Sanctuary. Monitoring activities included continuous *in-situ* measurements using deployed water quality sondes, monthly field sampling, laboratory analysis of nutrients and water chemistry by FIU's CAChE Nutrient Analysis Core Facility, and targeted observations of cruise ship activity in Key West Harbor. Although the original proposal referenced pre- and post-COVID-19 anthropause conditions, the project began in March 2022, after the primary anthropause period; therefore, the study focused on current water quality conditions, perturbations, and connectivity among harbor, channel, and reef-adjacent waters.

A major accomplishment of the project was the successful deployment of a YSI Turnkey water quality monitoring system on the "Yellowman" mooring station near Mallory Square and Pier B. This location provided near real-time monitoring in the center of Key West Harbor and allowed the research team to collect high-value data in an area where archival sondes and autonomous underwater vehicle deployment proved unsafe or impractical due to vessel traffic, strong currents, turbidity, and low visibility. The system performed reliably through several severe weather events and generated important continuous records of turbidity, conductivity, salinity, dissolved oxygen, depth, and photopigment concentrations.

Results showed that Key West Harbor water quality was affected by both natural and anthropogenic stressors. Severe weather events, including Tropical Storm Debby, Hurricane Helene, and Hurricane Milton, produced the most prolonged impacts, including elevated turbidity, enormous salinity and conductivity changes, and increased chlorophyll-related signals. These storm-related effects often lasted for days and indicated major freshwater and sediment-resuspension influences within the harbor system.

Cruise ship activity was also associated with acute turbidity events. From October 2023 through December 2024, 301 cruise ships visited Key West Harbor, and 35 turbidity events exceeding 29 NTU above background levels were correlated with cruise ship arrival and/or departure. The most extreme recorded event occurred on August 20, 2024, when turbidity reached 200.11 NTU, approximately 191.41 NTU above background and more than six times the Florida water quality criterion threshold. While these cruise ship-related events were generally shorter in duration than storm events, their frequency and magnitude indicate that vessel propwash and sediment resuspension are important recurring stressors in the harbor.

Field measurements and laboratory results further showed that turbidity was highest in Key West Harbor and generally decreased with distance from Key West, with lower values observed offshore near Eastern Dry Rocks and Western Dry Rocks. Temperature, dissolved oxygen, salinity, and conductivity were generally stable across the study area, although periodic conductivity and salinity decreases corresponded with heavy rainfall and storm-related freshwater inputs.

Water chemistry results indicated that the study area is generally phosphorus limited. Soluble reactive phosphorus was frequently below laboratory method detection limits, while total inorganic nitrogen was elevated relative to phosphorus. These findings are consistent with previous research in the Florida Keys showing nearshore phosphorus limitation and elevated nitrogen-to-phosphorus ratios, likely influenced by carbonate sediment phosphorus adsorption, limited riverine phosphorus inputs, and anthropogenic nitrogen sources.

The project also found elevated total organic carbon relative to nitrogen, phosphorus, and silicon across the study area. These elevated carbon ratios may reflect regional organic matter inputs, including sargassum inundation events, which have become an increasing concern in the Florida Keys and broader Caribbean region. No clear relationship was observed between silicon and other nutrients, limiting interpretation of silica-driven food web dynamics within the scope of this study.

Beyond its scientific findings, the project produced significant educational and workforce-development outcomes. The KWWQ project was incorporated into CFK marine science coursework, research diving activities, internships, capstone projects, and research assistantships. It provided valuable hands-on training in water quality monitoring, field sampling, data management, and applied marine resource management. Several student participants advanced into environmental careers or graduate programs, demonstrating the project's value as both a monitoring initiative and an educational platform.

Overall, the project demonstrated that near real-time water quality monitoring is feasible and highly valuable in Key West Harbor when appropriate deployment infrastructure is available. It also showed that Key West Harbor experiences recurring water quality disturbances from severe weather, freshwater inputs, cruise ship activity, and sediment resuspension. Future research should prioritize identifying sources of freshwater entering the harbor during storm events, evaluating the impacts of sargassum influxes on organic carbon and water quality, assessing mitigation options for cruise ship-related turbidity, and establishing biological baselines to support long-term monitoring and impact assessment in the Key West Harbor, Shipping Channel, and adjacent reef ecosystems.

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1.0 Introduction

In 2020, during the height of the Covid-19 pandemic, anecdotal evidence suggested that water quality in the Key West Harbor and Key West Shipping Channel improved substantially due to the lack of anthropogenic activity (e.g. cruise ships). Subsequently, on June 11, 2021, the EPA Region 4 – 2021 Southeast Florida Geographic Program released a Request for Applications (RFA) through Funding Opportunity Number (FON) EPA-R4-SFL-2021-01. The RFA identified five Program Priority Action Items for the Florida Keys National Marine Sanctuary (FKNMS) including Priority Action Item No. 5 – Water Quality Monitoring in the Key West Harbor and the Adjacent Marine Ecosystems. The College of the Florida Keys (CFK) submitted a proposal entitled "Monitoring Water Quality in the Key West Shipping Channel and surrounding ecologically and culturally significant coral reefs pre- and post-COVID-19 Anthropause" (hereto referred to as the KWWQ project) and was awarded funding for the project (EPA Award No. 02D20622). This document represents a comprehensive "Final Report" of the KWWQ water quality monitoring project.

1.1 Project Background

During Fall 2020, in response to the apparent changes in water quality in the Key West Harbor, CFK started conducting water quality monitoring in the Key West Harbor and the Shipping Channel as part of the field sampling exercises for the marine science course OCB 2102C Marine Data Collection. Initial water quality measurements in October of 2020 were very basic and included: (1) temperature, (2) dissolved oxygen (DO), and (3) Secchi depth. The following year (2021) the PI met with Dr. Henry Briceño of Florida International University's (FIU) Institute of Environment Water Quality Monitoring Laboratory after learning about a report entitled "Preliminary Assessment of the Surface Water Clarity Changes in Key West During the Covid-19 Anthropause". The report was based on twenty-five years of baseline water quality monitoring by FIU in the Florida Keys, including the waters surrounding Key West. Given CFK's proximity to the Key West Harbor and Key West Shipping Channel, along with the technical marine science training program at CFK, the PI and Dr. Briceño discussed developing a partnership between FIU and CFK to expand the water quality monitoring program by: (1) increasing the resolution of water sampling from once per quarter to bi-weekly or monthly, and (2) expanding the study area to include Eastern Dry Rocks - Sanctuary Preservation Area (EDR-SPA) and Western Dry Rock (WDR). The PI and Dr. Briceño prepared a water quality monitoring proposal that was submitted to the EPA Region 4 – 2021 Southeast Florida Geographic Program Funding Opportunity Number (FON) EPA-R4-SFL-2021-01 with a focus on Priority Action Item No. 5 – Water Quality Monitoring in the Key West Harbor and the Adjacent Marine Ecosystems. The proposal was awarded (EPA Award No. 02D20622) and work started on March 4, 2022.

1.1.1 Key West Harbor and Shipping Channel - Waterbody Description

The Key West Harbor and Key West Shipping Channel are the primary maritime access points for vessels entering and leaving Key West, Florida. They provide access to the Atlantic Ocean and the Gulf of Mexico via surrounding passages and support commercial, recreational, and military navigation. The Harbor encompasses the protected waters immediately east and southeast of Key West Island; the Shipping Channel extends seaward, connecting the harbor to deeper coastal waters and proximally to nearby areas of ecological concern (e.g. EDR).

1.1.2 Key West Harbor and Key West Shipping Channel - Physical Characteristics

The Key West Main Shipping Channel is approximately 90 - 150 m wide but widens to over 400 m in the Key West Harbor to accommodate large turning areas for cruise ships. The Key West Harbor and the Shipping Channel vary in depth but maintain the federally mandated depth of 10.4 m (34 ft.) in the main shipping channel to the Naval Air Station Truman Annex Mole and then continues at a 30-foot depth until the Key West Bight near the U.S. Coast Guard Station, Sector Key West (U.S. Coast Pilot 5, 2026). The area is surrounded by shallow coastal waters with connections to open oceanic circulation. The channel depth is historically maintained by the U.S. Army Corps of Engineers to allow transit of commercial and naval vessels (USACE, 2023).

1.1.3 Key West Harbor and Key West Shipping Channel- Hydrology

The Key West Harbor experiences semidiurnal tides (i.e. two high and two low tides each lunar day) with tidal ranges influenced by regional coastal dynamics. Tidal exchange drives flushing between the harbor and adjacent waters, including the Florida Current to the south and Florida Bay to the north. Water circulation in the Key West Harbor and the Shipping Channel is influenced by tides, wind, currents, and episodic events (e.g. storms). Water exchange with Florida Straits and local passages helps regulate water quality, which is also often influenced by vessel traffic, marina discharges, and runoff from the City of Key West.

1.1.4 Nearby Sensitive Environmental Areas

Coral reef ecosystems near the Key West Harbor and Key West Shipping Channel including EDR – SPA, WDR, Sand Key Lighthouse, and Western Sambo Reef. These coral reef habitats harbor biodiversity and protect shorelines, however like other coral reefs, they are sensitive to changes in water-quality (Fabricius, 2005; 2010; Cacciapaglia and van Woesik, 2015; MacNeil et al., 2019; Sully and van Woesik, 2020).

1.1.5 Key West Harbor and Key West Shipping Channel – Management and Regulation

The Key West Harbor and Key West Shipping Channel maintenance falls under the jurisdiction of the U.S. Army Corps of Engineers (USACE, 2023); while the U.S. Coast Guard has

jurisdiction over aids to navigation and safety. The National Oceanic & Atmospheric Administration (NOAA) and the Florida Keys National Marine Sanctuary (FKNMS) oversee permitting and marine resource management. The Florida Department of Environmental Protection (FDEP) is the lead state agency responsible for managing and protecting nearshore coastal waters in Florida and compliance with water quality standards; Florida Fish and Wildlife Conservation Commission (FWC) is responsible for law enforcement of marine waterways and works in collaboration with the U.S. Coast Guard on regulation of the Key West Harbor and Key West Shipping Channel. Local management and regulation of the Key West Harbor and Key West Shipping Channel falls under the overlapping jurisdictional authority of Monroe County and the City of Key West, FL.

1.1.6 Key West Harbor and Key West Shipping Channel - Water Quality Concerns

The Florida Keys are designated by the International Maritime Organization (IMO) as a Particularly Sensitive Area (PSA) (U.S. Coast Pilot 5, 2026) and recognized as one of the great recreational and environmental resources of the United States (Halley et al., 1997).

Although there are many stressors associated with water quality issues relevant to the Florida Keys [e.g. wastewater pollution (Griggs et al., 2003; Meyers et al., 2024), contaminants of emerging concern (CECs) (Singh et al., 2010; Castillo et al., 2024; Li et al., 2026), climate change (Manzello, 2015), etc.], some of the primary water quality concerns in the Key West Harbor and Key West Shipping Channel and surrounding areas include but are not limited to: (1) sedimentation, (2) nutrient pollution, and (3) shipping related contamination.

1.2 Purpose of the Project

The original purpose of this project was to monitor water quality in the Key West Harbor and the Key West Shipping Channe pre- and post-COVID-19 anthropause. However, the project did not begin until March 2022, towards the end of the pandemic. Therefore, pre-COVID data was not collected as part of the current project.

The primary goal of the current project was to monitor perturbations in water quality in the Key West Harbor and Key West Shipping Channel and to determine their connectivity with nearby areas of special concern (i.e. EDR). The project was a partnership between CFK and FIU's Institute of Environment, Water Quality Monitoring Laboratory and designed to expand the scope and resolution of FIU's 25+ year water quality monitoring program in the FKNMS in the waters proximal to Key West, Florida.

The project had four objectives with three associated tasks designed to meet the objectives. The deliverables included: (1) an approved Quality Assurance Project Plan (QAPP), (2) deployment of water quality monitoring equipment, (3) water quality field sampling, (4) data analysis, and (5) annual progress and a final report. An additional goal was to incorporate water

quality monitoring operations into the marine science curriculum at CFK and use the project as an educational tool to support student internships and research assistants.

1.2.1 KWWQ Project Objectives:

Objective 1. Deploy additional devices to establish a broad array of continuous water quality monitoring equipment to determine connectivity between Key West Harbor, the Key West Shipping Channel, and surrounding areas of critical concern, especially EDR-SPA.

Objective 2. For one year, perform bi-weekly field measurements and monthly collection of water samples (for lab analysis at FIU) from the waters of the Key West Harbor and along the Shipping Channel at ten predetermined sites.

Objective 3. For one year, perform bi-weekly field measurements and monthly collection of water samples (for lab analysis at FIU) from the waters at EDR and WDR for field and lab analysis to compare to the Key West Harbor and Key West Shipping Channel water samples.

Objective 4. For a period of one year, periodically (i.e. weekly if ships arrive) measure water quality immediately before and after large industrial ships enter and exit the Key West Harbor.

1.2.2 KWWQ Project Outputs and Outcomes

The KWWQ project's main output was important water quality data on chemical and physical properties of the waters within the FKNMS comprising the Key West Harbor, the Key West Shipping Channel, and the surrounding areas of critical concern, including EDR-SPA and WDR. The KWWQ project's main outcome provides useful information for marine resource managers, as well as municipal, regional, state, and federal agencies, and their respective legislators.

1.2.3 EPA Region 4 Relevance

The KWWQ project aligns with EPA Region 4 – 2021 Southeast Florida Geographic Program Funding Opportunity Number (FON) EPA-R4-SFL-2021-01 Priority Action Item No. 5 – Water Quality Monitoring in the Key West Harbor and the Adjacent Marine Ecosystems.

2.0 Project Description

The KWWQ project builds upon a 25+ year water quality database developed for the EPA Region 4 as part of the FKNMS Water Quality Monitoring Program (WQMP) by FIU (Briceño, 2021). The KWWQ project incorporated protocols and procedures directly from the WQMP, including sample sites along the Key West Harbor and Key West Shipping Channel. The WQMP attempts to sample these sites at least once per quarter but often cannot meet the sampling schedule

due to trip cancellation for a variety of reasons (e.g. bad weather). Therefore, given the location of CFK and the technician-level marine science program, the KWWQ project was able to increase the sampling frequency to once per month and expand the monitoring program to include the surrounding areas of critical concern, EDR-SPA and WDR.

2.1 Study Area

The study area lies within the FKNMS, including the Key West Harbor and Key West Shipping Channel, extending to EDR-SPA and beyond to WDR (Figure 1). EDR-SPA was selected because it's of special importance and identified by the FKNMS as one of seven "ecologically and culturally significant coral reefs" (www.fisheries.noaa.gov/iconic-reefs). Located approximately 9 km south-southwest of Key West Harbor and 3.5 km due west of the entrance to the Key West Shipping Channel, EDR-SPA is a critical area within the study region. The WDR site was selected as a control for the project because it is relatively far from Key West Harbor, Key West Shipping Channel, and anthropogenic sources of pollution originating from Key West. Sample sites in Key West Harbor and along the Key West Shipping Channel were provided by FIU (Figure 1).

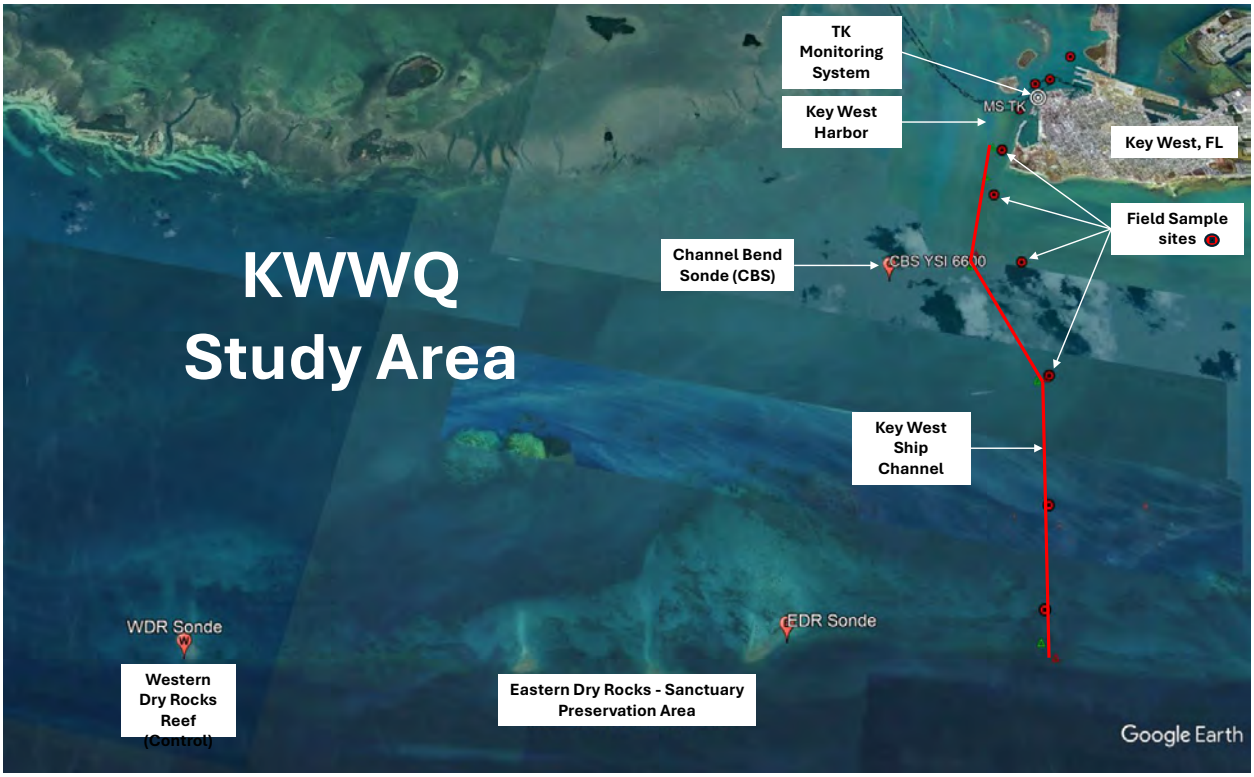


Figure 1. Study area for the Key West Water Quality (KWWQ) monitoring project. The red line indicates the location of the Key West Shipping Channel and red targets indicate the locations for water sample collection for analysis by Florida International University (FIU).

Orange symbols indicate data sonde deployment locations. Note: TK = Turnkey water quality monitoring system at Mallory Square (MS); Channel Bend Sonde (CBS); Eastern Dry Rocks (EDR); Western Dry Rocks (WDR).

2.2 Monitoring Design

The KWWQ project was designed with three tasks intended to meet the project objectives. Each of these tasks are presented below and will be discussed in detail in the following sections.

2.2 Task 1: Deploy additional equipment to form a broad array of continuous water quality monitoring equipment to determine connectivity between the Key West Harbor and the Key West Shipping Channel to surrounding areas of critical concern, especially Eastern Dry Rocks Sanctuary Preservation Area (EDR-SPA).

The KWWQ project deployed water quality monitoring equipment (i.e. data sondes) throughout the study area in a triangular array, extending from the apex at the Key West Harbor to the eastern base angle near EDR and the western base angle near WDR. (Figure 1). However, insurmountable complications arising from recreational and commercial boat traffic near Key West Harbor, strong tidal currents, and extreme turbidity (i.e. cloudiness of the water) created dangerous diving conditions that forced the PI to abandon using archival data sondes (i.e. equipment that monitors water quality and archives the data until divers can retrieve the equipment for data download) proximal to Key West Harbor. Therefore, archival data sondes were subsequently only deployed near EDR and WDR.

The PI was able to identify water quality monitoring equipment that stored data internally (i.e. archived data) but also transmitted the data via cable to a data logger above the water surface (YSI, Inc.) and transmitted data via cellular service to a web-based data management platform (Hydrosphere^{TM}). However, this specific technology (i.e. YSI Turnkey hereafter referred to as the TK System) required a dry place to mount the equipment, which consisted of a solar power supply, 12V battery, a data logger, and a cellular telecommunications device. The PI worked with FKNMS to explore options for mounting the TK System on infrastructure within Key West Harbor and Key West Shipping Channel [e.g. Aids to Navigation (ATONS) and/or private buoys] or on infrastructure surrounding Key West Harbor. With help from the City of Key West, the PI initiated meetings with the Key West Port Authority and developed a plan to install the TK system on City Property on the “Yellowman” mooring station at Mallory Square on October 10, 2023 (Figure 2).

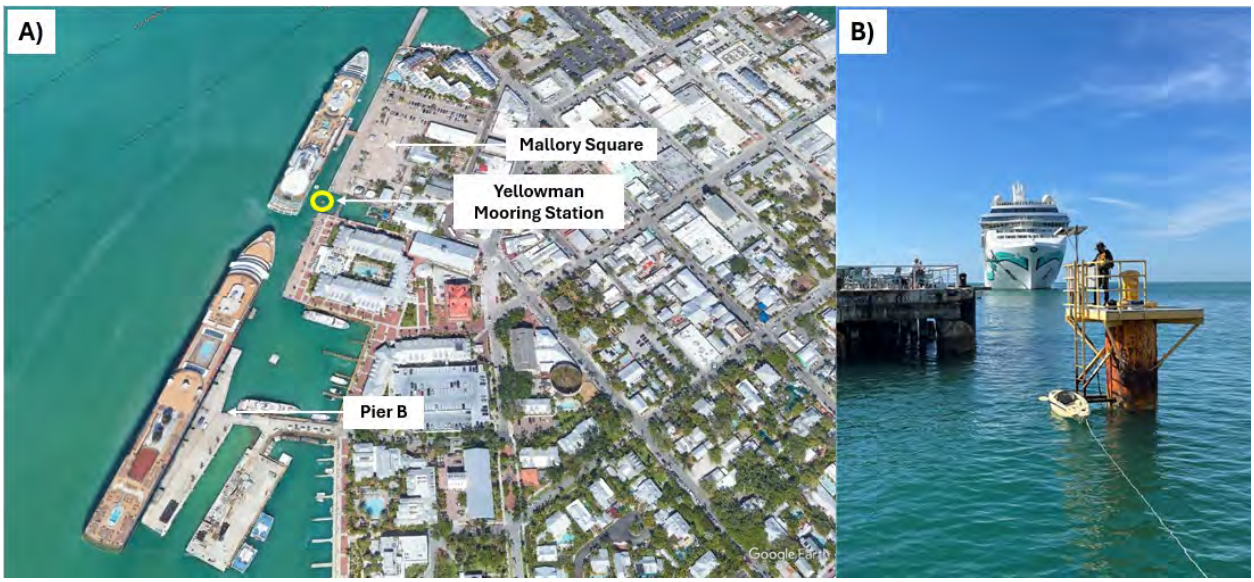


Figure 2. A) An aerial of Mallory Square, Pier B, and the location of the "Yellowman" mooring station in Key West Habor, Florida. B) An image of the "Yellowman" mooring station at Mallory Square Key West, FL with the solar powered Turnkey (TK) water quality monitoring system being serviced by The College of the Florida Keys (CFK) technician. Notice the cruise ship approaching Pier B immediately adjacent to the "Yellowman".

The "Yellowman" mooring station is ideally located for the placement of the TK water quality monitoring equipment in Key West Harbor because: (1) it is located near the middle of Key West Harbor, (2) it stands alone and separate from any docks or piers making it inaccessible to unauthorized people, (3) its proximity to cruise ship docking location between Pier B and Mallory Square docks, and (4) it eliminates the need for diving in the dangerous high boat traffic areas in Key West Harbor.

After several meetings with the City of Key West Port Manager, the College drafted an Inter-Local Agreement (ILA) which was submitted to the City of Key West. The City of Key West unanimously approved the ILA with CFK to create a Water Quality Partnership Program in April 2023. This partnership established a framework for the College to monitor water quality throughout the Key West area. The ILA officially authorized the placement of the TK system on the "Yellowman" mooring station.

2.2.1 The YSI Turnkey (TK) System

The TK system used for the KWWQ project on the "Yellowman" mooring station incorporates two YSI EXO3s data sondes (YSI, Inc.) equipped with sensors for: (1) optical dissolved oxygen (ODO), (2) total algae (TAL) [i.e. a dual-channel fluorescence probe built to detect chlorophyll *a* (green photopigments) and phycoerythrin (a red photopigment)], (3) turbidity (an optical measurement of the clarity and transparency of water reported in Nephelometric Turbidity Units or NTU), (4) conductivity [reported in microSiemens per cm^2 ($\mu S/cm^2$) and a

proxy for salinity], and (5) depth (reported in meters). One of the EXO3s sondes was deployed at approximately 1 m depth (referred to as 'shallow') and the other at approximately 6 m depth (referred to as 'deep') (Figure 3). Prior to deployment, each data sonde was placed inside a 3-inch polyvinyl chloride (PVC) pipe to protect it from chaffing and damage from the straps used to hold the apparatus to the "Yellowman" mooring station underwater (Figure 3B). A through bolt was used to hold the sonde in place inside the PVC pipe. Sensors on the sonde were protected by an antifouling copper-alloy guard (Figure 3C).

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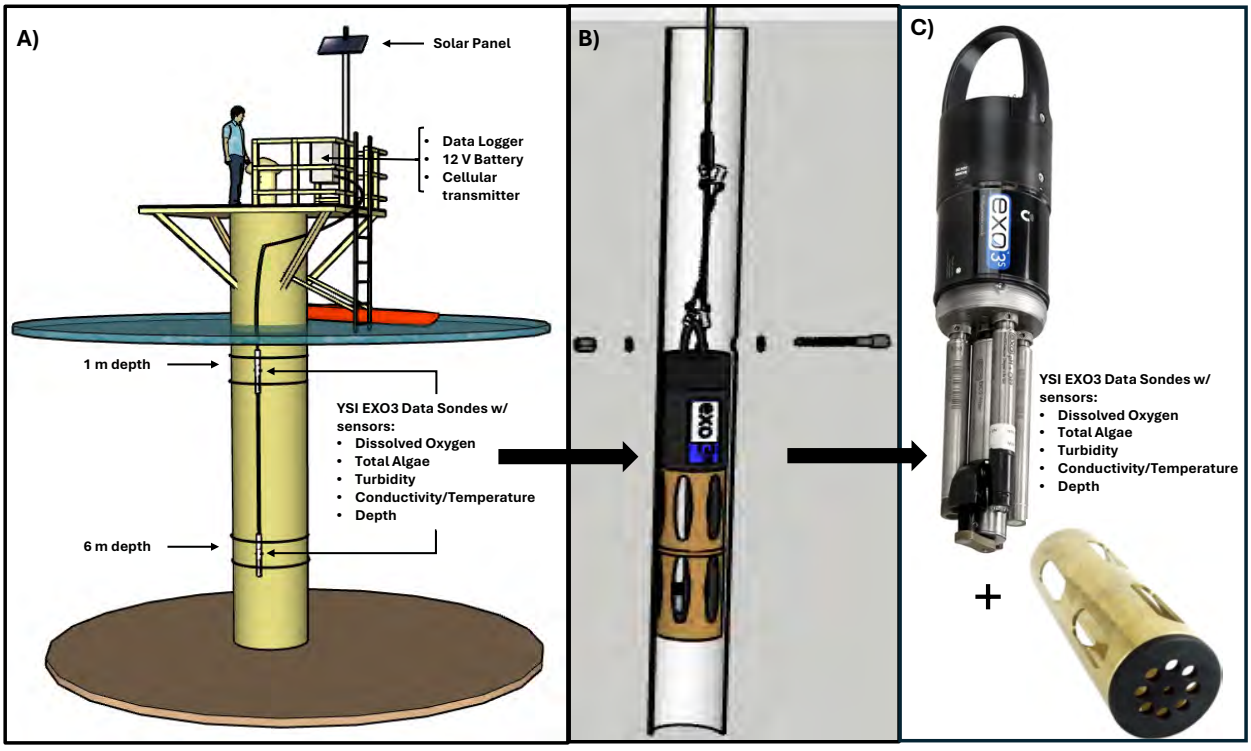


Figure 3. A computer aided design (CAD) rendering of the YSI Turnkey (TK) system deployed on the "Yellowman" mooring station in Key West Harbor near both Mallory Square and Pier B docks. A) a complete view of the TK system deployed on the "Yellowman" from the solar panel to the data sonde deployed at 6 m depth, B) a cross sectional view of the data sonde inside a 3 inch polyvinyl chloride (PVC) pipe including an exploded view of the bolting method used to secure the sonde inside the PVC pipe, and C) an actual image of the YSI EXO3s sonde with the specific sensors and the protective copper housing.

Data sondes were placed near the water surface (1 m) and at depth (6 m) to record any water quality differences between surface and deeper waters. However, there was a secondary reason for placing the equipment at different depths. Data anomalies can occur when something interferes with the optical sensors at the time measurements are taken (e.g. debris in the water column, marine organisms near the sensor, etc.). Therefore, data sondes were placed at different

depths to corroborate water quality measurements since changes in water quality will typically be captured on both sondes. For example, a small fish swimming near a turbidity sensor at the time of measurement may impact the measurement and record a high turbidity reading. The anomaly will only be recorded as a spike on one sensor and not the other, so that data can be evaluated during the quality control process.

2.2.2. Archival data sondes

Previous efforts to deploy archival data sondes in Key West Harbor and Key West Shipping Channel during 2020-2021 informed methods and procedures used during the current KWWQ project. The initial objective was to create an array of devices that would cover the study area and track water movement and connectivity between Key West Harbor, the Key West Shipping Channel, and EDR-SPA. However, towards the end of 2022, the strategy was reconsidered for the following reasons: (1) deploying scientific divers in Key West Harbor and Key West Shipping Channel is very dangerous because: (*i*) heavy boat traffic in the area, (*ii*) very strong currents, and (*iii*) very poor visibility. These challenges elevated the risk of not being able to recover water quality monitoring equipment once deployed near Key West Harbor and Key West Shipping Channel. However, these challenges were not an issue for areas near EDR-SPA and WDR. Therefore, rather than purchasing expensive new equipment for deployment in the harbor and shipping channel, the PI opted to purchase older archival data sondes (i.e. YSI 6600) to use with sensors from previous efforts for deployment in this area and used newer model archival data sondes for EDR-SPA and WDR. However, when trying to order the newer data sonde models (i.e. YSI EXO3 multiparameter sondes and sensors), the company (YSI, Inc.) estimated 4-6 months lead time due to supply chain issues caused by the COVID-19 pandemic. These supply chain issues also affected equipment prices and quotations with much of the equipment that was originally proposed (e.g. YSI EXO3 archival data sondes) now out of scope for the KWWQ grant budget. Since the project was only intended to cover a period of one year, these delivery delays and price changes were considered unacceptable. For these reasons, the PI decided to explore: (1) other water quality monitoring equipment suppliers, (2) other deployment options (i.e. something different from archival data sondes like the YSI Turnkey System), and (3) use the YSI 6600 model archival data sondes until new equipment could be purchased.

The PI explored similar equipment from other manufacturers including In-Situ, Inc. and Eureka Water Probes (now Solinist-Eureka). After careful consideration including: (1) the appropriateness of the technology (i.e. is the technology approved by EPA standards), (2) pricing, and (3) lead time for delivery, the PI decided to purchase four water quality data sondes from Eureka Water Probes, Inc. These newer model sondes (Eureka Manta+35) have several improvements over the YSI EXO3 sondes including: (1) availability in approximately six weeks, (2) sensors are in the same plane making it easier for the central swiper to clean the optical sensor heads (Figure 4 A and C), and (2) the sensors are embedded in antifouling material (Figure 4 B).

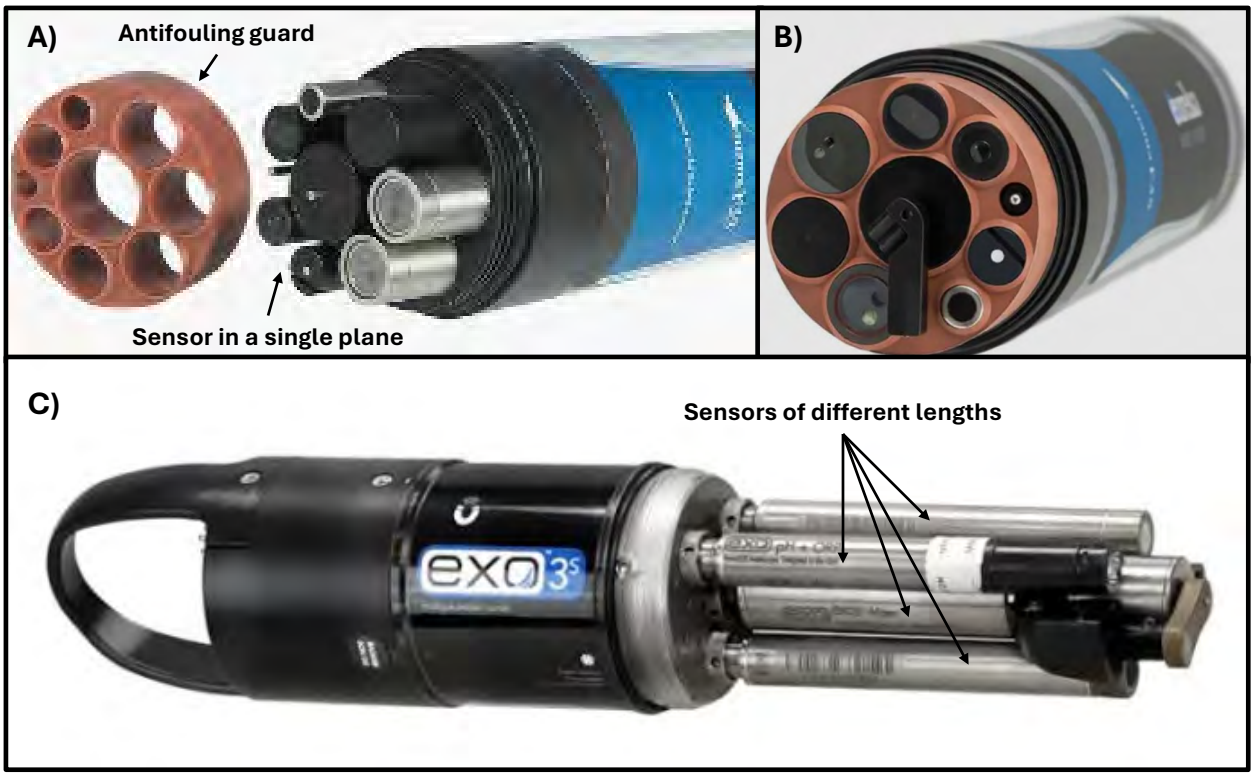


Figure 4. Image of: A) the Eureka Manta+35 showing optical sensors arranged around a central wiper and lying in a single plane and the antifouling material used to protect the sensors from biofouling, B) The Eureka Manta+35 and antifouling unit assembled, and C) the YSI EXO3s data sonde equipped with various sensors of differing lengths arranged around a central wiper.

Having procured the necessary archival data sondes, the next step was to fabricate a robust anchor system to hold the equipment in place in the water column. Three concrete anchors with dimensions 1 m^2 x 10 cm deep were constructed. Each anchor had four eyebolts in each corner and several sections of 5 cm diameter PVC pipe embedded in the concrete (Figure 5).

(Continued on the next page)



Figure 5. Image of the anchors used to hold and suspend water quality monitoring equipment: (Left) the anchor with the YSI 660 sonde, (middle & right) photos of the anchor equipped with Eureka™ Mant+35 model archival data sondes.

The eyebolts served two purposes: (1) attachment locations for a harness to raise and lower the apparatus, and (2) an attachment to connect a chain to secure the equipment to the anchor. Two lateral PVC pipe sections were installed to traverse through the concrete to allow rope to pass through. The ropes were connected to a small 2.5 cm diameter PVC and a series of three Styrofoam buoys (Figure 6). A coil of metal chicken wire was placed on the middle-buoyed rope for each anchor (Figure 6). The purpose of the metal coil was to create a sonar reflective surface to help locate the exact position of the anchor and equipment after deployment.

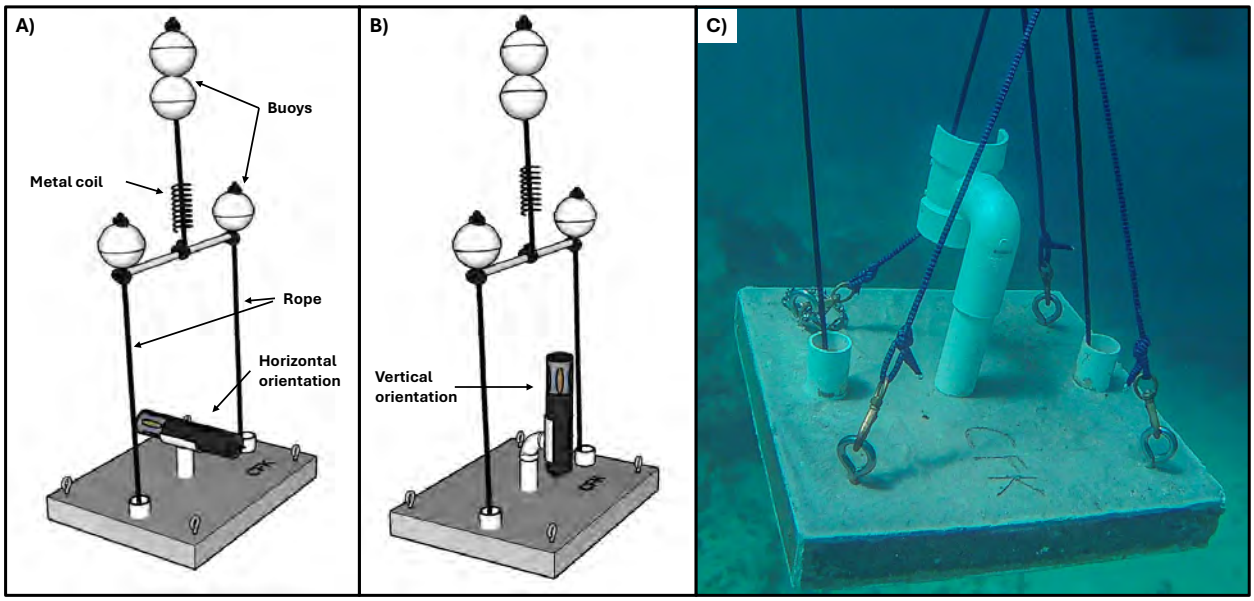


Figure 6. Illustrations of the anchor system employed to hold water quality monitoring archival data sondes. A) shows the anchor with a horizontal bracket holding the water quality data sonde and a buoy system used to hold up the metal coil for increased sonar reflection of the water quality monitoring apparatus. B) shows changes to the apparatus to hold the data sonde in a vertical orientation. C) apparatus being deployed.

The PVC mounting bracket consisted of 7.5 cm PVC, and the initial anchor design constructed the PVC "Tee" crosscut along the length to create a mounting bracket. The data sonde was mounted to the PVC and fastened with large zip-ties and large diameter adjustable hose clamps. The initial design mounted the data sonde in a horizontal orientation (Figure 5 and Figure 6 A). However, discussions with the Florida Department of Environmental Protection (FDEP) suggested that the data sondes should be mounted vertically to be consistent with FDEP data sonde deployment protocols (Figure 6 B).

2.2 Task 2: Water quality monitoring at 10 sites in Key West Habor, Key West Shipping Channel, EDR-SPA and WDR.

2.2.3 Site selection rationale and sampling strategy

In June 2021, CFK partnered with FIU to collect water samples from Key West Harbor and Key West Shipping Channel. The CFK team conducted a ride-along with FIU technicians during quarterly water sample collection as part of the FIU 25+ year long-term water quality monitoring program (Briceño, 2021). Subsequently, the PI worked with FIU to prepare and submit a proposal to EPA Region 4 for the current KWWQ project. The submission proposed to use local science and research academic programs at CFK to increase water quality monitoring efforts in the study area, especially regarding water sample collection frequency (i.e. increasing from quarterly sampling to monthly or bi-weekly if possible). Water sample station locations in Key West Harbor

and Key West Shipping Channel were provided by FIU, and sample locations at EDR-SPA and WDR were determined by CFK (Table 1 and Figure 1).

Table 1. Water quality sample locations		
Site	**Latitude**	**Longitude**
KW01	24°34'8.53" N	81°48'9.69" W
KW02	24°33'49.45" N	81°48'1.59" W
KW03	24°33'44.30" N	81°48'31.47" W
KW04	24°33'24.23" N	81°48'40.28" W
KW06	24°32'53.40 N	81°48'49.52" W
KW07	24°32'21.98" N	81°48'52.25" W
KW09	24°31'40.98" N	81°48'32.03" W
KW12	24°30'34.55" N	81°48'11.29 W
KW14	24°29'21.89" N	81°48'7.32" W
KW16	24°28'27.45" N	81°48'6.24 W
EDR	24°27'48.43" N	81°50'18.12" W
WDR	24°26'43.55"N	81°55'39.34"W

KW01 - KW16 = Sites in the Key West Harbor/Ship Channel
EDR = Eastern Dry Rocks
WDR = Western Dry Rocks

2.2.4 Water Quality Parameters Monitored

Water samples collected during the KWWQ project for laboratory chemical analysis focused on water quality parameters provided by FIU as part of the FIU 25+ year long-term water quality monitoring program (Briceño, 2021) (Table 2.). Specific water sample collection protocols and procedures are reviewed in Section 3.

Table 2. Water sample chemical analysis
Dissolved Inorganic Nutrients (NO2-, NO3-, NH4+, PO4-3)
Total Phosphorus (TP)
Total Nitrogen - ANTEK (TN)
Total Organic Carbon (TOC) and Dissolved Organic Carbon (DOC)
Dissolved Silicate (SI)
Chlorophyll a (GF/F filtered, spectrofluorometric)

In addition to water samples collected for chemical analysis, water quality was measured *in-situ* at each sample location during sample trips and periodically during field labs for marine science courses including OCB2102C Marine Data Collection and ISC 2132 Basic Research Diving. Water quality parameters measured *in-situ* were as follows: (1) water depth (m), (2) temperature (°C), (3) conductivity ($\mu S/cm^2$), (4) optical dissolved oxygen (DO) (mg/l), (5) turbidity (NTU), (6) hydrogen sulfide (H_2S) (ppm), (7) salinity (ppt), (8) pH, and (9) ammonia/ammonium (NH_3/NH_4) (ppm). Specific water sample field measurement protocols and procedures are reviewed in Section 3.

2.2 Task 3: Upgrade Autonomous Underwater Vehicle (AUV) from IVER-2 to EcoMapper

In 2010, CFK acquired an Ocean Server – IVER 2 Autonomous Underwater Vehicle (AUV) as part of a federally funded port security project. The IVER-2 AUV was proposed as a technology that could be used to support the KWWQ water quality monitoring project in Key West Harbor and Key West Shipping Channel. The IVER-2 was equipped with side-scan sonar but lacked the necessary instrumentation for water quality monitoring. Therefore, upgrades to the AUV were required.

3. Methods and Procedures

3.1 Monitoring Key West Harbor

Water quality monitoring in Key West Harbor included: (1) near continuous water quality measurements (i.e. every 5 minutes) recorded by the TK system, (2) monitoring cruise ship traffic in Key West Harbor, (3) monthly water sample collection at sites KW01-KW06 (Figure 1 and Table 1) for chemical analysis, and (4) monthly *in-situ* water quality measurements at the same sites (i.e. KW01-KW06).

3.1.1 The YSI Turnkey (TK) System

Water quality measurements taken by the TK system were: (1) recorded internally on each water quality monitoring data sonde (both shallow and deep), (2) archived internally on the data logger in the dry box above the water surface (Figure 3A), and (3) transmitted via cellular service to YSI Hydrosphere™ - a collaborative, cloud-based data visualization and management platform for environmental monitoring.

Data was downloaded from the sondes and the data logger periodically during routine maintenance and calibrations. Hydrosphere™ was monitored almost daily and delivered the most useful information providing almost immediate feedback on changes in water quality in Key West Harbor near Pier B and Mallory Square until the end of the project on December 31, 2024. The information provided by the TK system was compared with cruise ship activity (e.g. arrival and departure times) in Key West Harbor, and correlations were noted.

3.1.2 Monitoring cruise ship traffic in Key West Harbor

Initially, the cruise ship schedule published online by the City of Key West (https://www.calendarwiz.com/calendars/calendar.php?crd=caribenautical&&jsenabled=1&winh=754&winw=1536&inifr=false) was used track cruise ship activity in the Key West Harbor. However, the arrival/departure times published in the schedule did not correspond with the actual arrival/departure times of the ships at Pier B and Mallory Square docks. Therefore, the PI identified several publicly available websites that broadcast videos of Mallory Square and Pier B docks. The websites were monitored according to the cruise ship schedule. The cameras were able to capture the exact arrival/departure times of the cruise ships at the docks. Screen captures with time stamps were recorded and archived. Then, starting on October 24, 2023, until the end of the project, the exact arrival/departure times of the cruise ships were correlated with data acquired by the TK system and visualized on Hydrosphere™. An information table was created covering cruise ship activities in Key West Harbor from October 13, 2023, through the end of the project (December 31, 2024) and beyond (Appendix A). The table was created to document the date, cruise ship name and capacity, the arrival/departure time, and various environmental conditions including: (1) turbidity, (2) tidal condition (e.g. incoming, slack, or out-going), and (3) wind speed and direction. Relevant notes and special circumstances were noted in a comments section of the table.

3.1.3 Using the Autonomous Under Vehicle (AUV) to monitor water quality in Key West Harbor

Section 2.2 Task 3 outlined the need to upgrade the IVER-2 AUV to accommodate the needs of the KWWQ project. Therefore, the IVER-2 AUV was sent to YSI Inc. to upgrade and install water quality monitoring technology. The resulting upgrades transformed the IVER-2 AUV into an EcoMapper AUV complete with side-scan sonar, internal inertial guidance systems, satellite GPS, and an EXO3 data sonde in the nose cone. Unfortunately supply chain issues associated with the Covid-19 pandemic resulted in extremely long delays (> 1 year) and the new EcoMapper was not received until March 1, 2024. YSI provided classroom and field training onsite at CFK on April 9, 2024 (Figure 7).

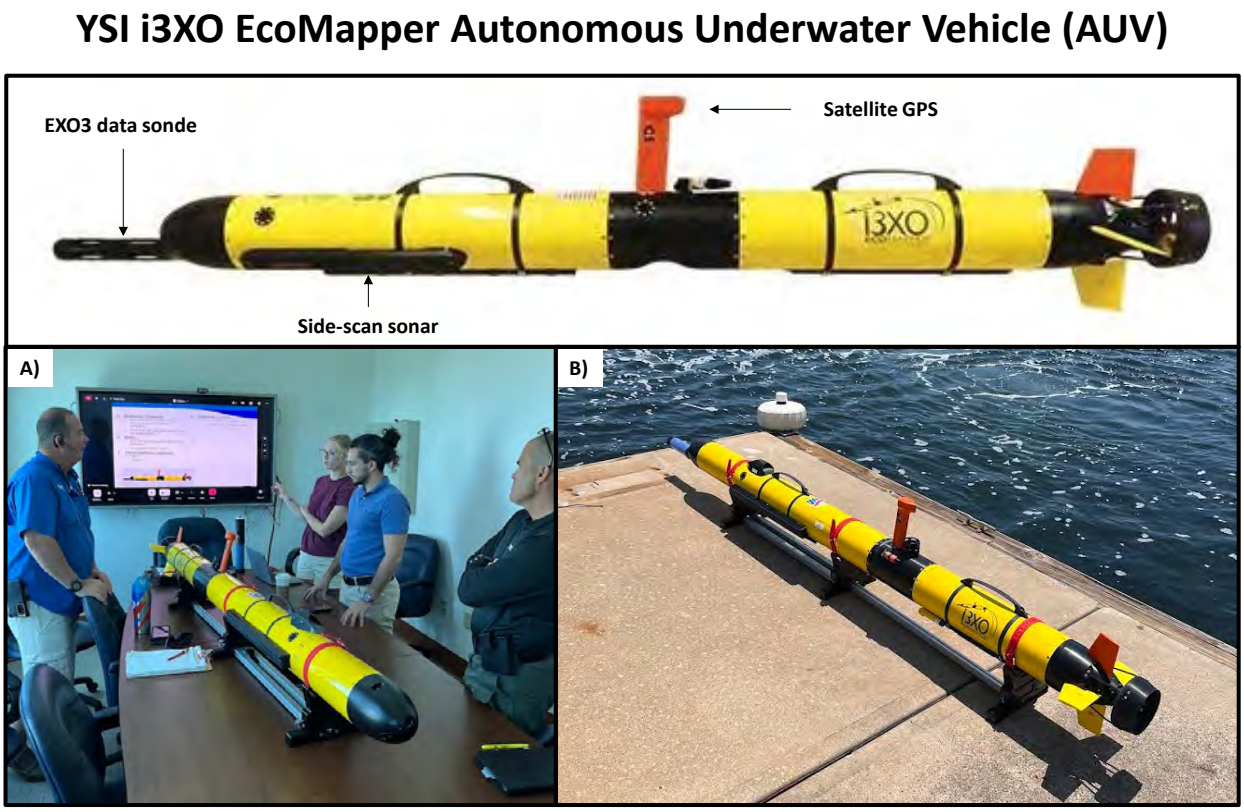


Figure 7. (Top) An image of the EcoMapper AUV with associated water quality and guidance technology, A) classroom training and B) field training.

(Continued on the next page)

The initial plan was to deploy the EcoMapper AUV in Key West Harbor immediately before and after the arrival and departure of a cruise ship. However, after surveys of the proposed study area for deployment and retrieval of the AUV the plan was abandoned for several reasons including: (1) access to the Key West Harbor to deploy the AUV was limited to a small beach at Ft. Zachary Taylor State Park which is not always accessible (Figure 8), and (2) currents in the harbor often exceed the recommended operating speed of the EcoMapper AUV (i.e. >1.5 m/s).

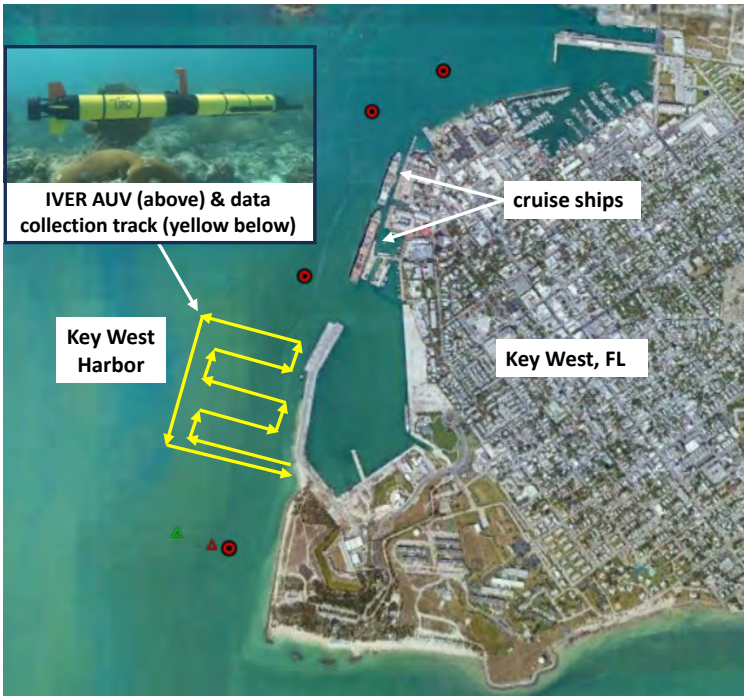


Figure 8. Map of the proposed AUV deployment location and AUV path in the Key West Harbor.

3.1.4 Water samples and in-situ water quality measurements in Key West Harbor

Monthly water samples and *in-situ* water quality measurements were conducted in Key West Harbor from Key West Bight to the entrance of the harbor near Fort Zachary Taylor State Park jetty (Figure 1: KW01-KW06).

Prior to field sampling and *in-situ* water quality measurements, equipment, materials, and supplies were gathered and checked to ensure technicians were properly equipped. High density polyethylene (HDPE) sample bottles and centrifuge tubes (Thermo Fisher Scientific Inc.) were labelled specifically for each sample site. A small dark box (approximately 2 L) was used to store *chlorophyl-a* filtered samples while in the field. Decarbonated fiberglass syringe filters to fit 140 ml screw-lock syringes and screw-lock filter holders were prepared and placed in a field sample kit. Also included in the field sample kit were two pairs of clean (i.e. not rusty) tweezers, 1 gallon of deionized or reverse osmosis deionized (RODI) water, and a 200 ml graduated cylinder.

Also included in the field sampling kit were the equipment, materials, and supplies necessary to conduct *in-situ* water quality measurements (see Section 3.2 below). Immediately prior to departure for each field sampling event, an approximately 50-L cooler was filled with ice to maintain collected samples at the appropriate temperature during transport from the field to the laboratory. Specific methods for field sampling and *in-situ* water quality measurements are presented in 3.1.6 In-situ field measurement methods.

3.1.5 Field Sampling Methods

Field sampling occurred approximately monthly except for April 2024 when two trips were made because the first trip was cut short due to weather conditions (Table 3).

Table 3. Water quality monitoring sampling trip schedule

Date	Vessel	Sample Collection (Y/N)	Field Data Collected (Y/N)
10/30/2020	FKCC-2	No	Yes
6/3/2021	FIU	Yes	Yes
7/1/2021	FKCC-2	No	Yes
7/21/2021	FKCC-2	No	Yes
9/3/2022	Tuga Explorer	Yes	Yes
2/3/2023	Hunter Charters	Yes	Yes
3/13/2023	Hunter Charters	Yes	Yes
4/4/2023	Hunter Charters	Yes	Yes
5/18/2023	Hunter Charters	Yes	Yes
6/6/2023	Tuga Explorer	No	Yes
6/14/2023	Hunter Charters	Yes	Yes
7/30/2023	Hunter Charters	Yes	No
8/25/2023	Hunter Charters	Yes	Yes
9/22/2023	Tuga Explorer	Yes	Yes
11/30/2023	Hunter Charters	Yes	Yes
12/29/2023	Hunter Charters	Yes	Yes
4/17/2024	Hunter Charters	Yes	Yes
4/30/2024	Hunter Charters	Yes	Yes
5/20/2024	Hunter Charters	No	Yes
5/22/2024	Hunter Charters	Yes	No
6/28/2024	Hunter Charters	Yes	Yes
7/22/2024	Hunter Charters	Yes	Yes
8/27/2024	Hunter Charters	Yes	Yes

9/19/2024	Hunter Charters	Yes	Yes
10/23/2024	Hunter Charters	Yes	Yes

All samples collected were stored on ice until brought back to CFK where they were then stored in a -86 °C freezer (K2 Scientific, LLC.). Samples were usually shipped within 48 hours to the FIU Institute of Environment, Center for Aquatic Chemistry Environmental (CAChE) Nutrient Analysis Core Facility. FIU CAChE is a NELAC (National Environmental Laboratory Accreditation Conference) accredited nutrient analysis laboratory which provides direct chemical analysis support for environmental research. Chain of custody (COC) forms were submitted for each set of water samples shipped to CAChE. The CAChE facility analyzed the samples and returned the analysis data accompanied by an updated COC. The data was subsequently used in the data analysis process.

For specific water sample collection procedures and methods, please refer to Appendix B - CFK Water Quality Technician Training Guide and Appendix C – The KWWQ Quality Assurance Project Plan (QAPP).

3.1.6 In-situ field measurement methods

Water samples were collected during field sampling trips (Table 3). Water depth was measured using charts or depth sounding sonar depending on the vessel being used during the trip. Water temperature, conductivity, and DO were measured using a handheld YSI ProSolo Dissolved Oxygen meter. For other parameters, water samples were taken from just below the surface using a Van Dorn water collection apparatus. Samples were collected from just below the surface at approximately 1 m depth. Sample vials and test tubes were washed three times with the sample water before the sample was measured. Turbidity was measured using a turbidimeter (LaMotte 2020t turbidimeter). Hydrogen sulfide was measured using H_2S test strips (Industrial Test Systems, Inc.). Ammonia/ammonium (NH_3/NH_4^+) and pH were measured using a titration method (API Marine Saltwater Master Test Kit).

For specific *in-situ* water quality measuring procedures please refer to Appendix B - CFK Water Quality Technician Training Guide.

3.2 Monitoring water quality along the Key West Shipping Channel

Water quality monitoring in the Key West Shipping Channel included: (1) deployment of archival water quality monitoring equipment, (2) monthly water sample collection at sites KW07-KW016 (Figure 1 and Table 1) for chemical analysis, and (3) monthly *in-situ* water quality measurements at the same sites (i.e. KW07-KW16).

3.2.1 Archival data sondes in the Key West Shipping Channel

During the KWWQ project on October 10, 2023, an older YSI 6600 archival data sonde was deployed near the mouth of Key West Harbor approximately 3 km southwest of the Ft. Zachary Taylor State Park jetty (Figure 7). The data sonde was programed to sample the environment once every thirty minutes. This sampling rate was selected because the energy consumption would allow the device to be deployed for approximately three months before needing to replace batteries. The YSI 6600 data sonde was equipped with sensors similar to the YSI EXO3s on the TK system including: (1) optical dissolved oxygen (ODO), (2) total algae (TAL) [i.e. a dual-channel fluorescence probe built to detect chlorophyll *a* (green photopigments) and phycoerythrin (a red photopigment)], (3) turbidity (an optical measurement of the clarity and transparency of water reported in Nephelometric Turbidity Units or NTU), (4) temperature (ºC) and conductivity [reported in microSiemens per cm^2 ($\mu S/cm^2$) and a proxy for salinity], and (5) depth (reported in meters). The procedure was to conduct routine maintenance and calibration every three months but subsequent trips to recover the equipment were unsuccessful (see 4.2.1 Results for archival data sondes in the Key West Shipping Channel).

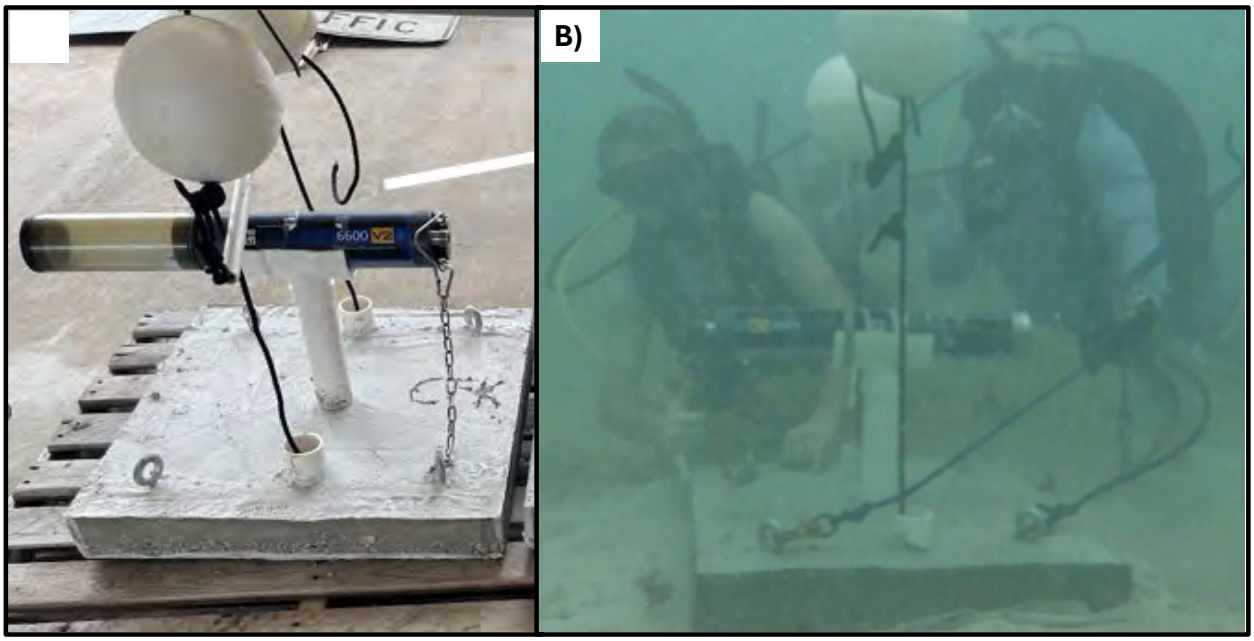


Figure 7. Photos of: A) the YSI 6600 data sonde mounted on the deployment anchor with buoys to support radar reflective material and B) the data sonde system being deployed proximal to the entrance of Key West Harbor on October 10, 2023.

3.2.2 Water samples and in-situ water quality measurements along the Key West Shipping Channel

Monthly water samples and *in-situ* water quality measurements were conducted along the Key West Shipping Channel from Key West Harbor entrance to the shipping channel entrance (Figure 1: KW07-KW16 and Table 1). The same methods described in sections 3.1.5 Field Sampling Methods and 3.1.6 *In-situ* field measurement methods were used to collect water samples for chemical analysis and *in-situ* field measurements.

3.3 Monitoring water quality near EDR and WDR

Water quality monitoring near EDR-SPA and WDR included: (1) deployment of archival water quality monitoring equipment, (2) monthly water sample collection at sites EDR and WDR (Figure 1 and Table 1) for chemical analysis, and (3) monthly *in-situ* water quality measurements at the same sites (i.e. EDR and WDR).

3.3.1 Archival data sondes deployed at EDR and WDR

As discussed in section 2.2.2. Archival data sondes, supply chain issues delayed the procurement and deployment of archival water quality data sondes. Four Eureka Manta+35 water quality data sondes with associated sensors were purchased in late 2023 and two sondes deployed on February 29, 2024 near EDR and WDR (Figure 1). The other two sondes were kept until the next sonde maintenance and calibration event, so that sondes could easily be swapped in the field rather than conducting maintenance and calibration in the field. The data sondes were programed to sample the environment once every thirty minutes. This sampling rate was selected because the energy consumption would allow the device to be deployed for approximately three months before needing batteries to be replaced. The Manta+35 data sondes were equipped with sensors similar to the YSI EXO3s on the TK system including: (1) optical dissolved oxygen (ODO), (2) algae sensors [two fluorometer probes built to detect: (*i*) chlorophyll-*a* (green photopigments) and (*ii*) phycoerythrin (a red photopigment) for blue-green algae or cyanobacteria], (3) turbidity (an optical measurement of the clarity and transparency of water reported in Formazin Nephelometric Units or FNU, which is treated as a one-to-one relation to NTU), (4) conductivity [reported in microSiemens per cm^2 ($\mu S/cm^2$) and a proxy for salinity], and (5) depth (reported in meters).

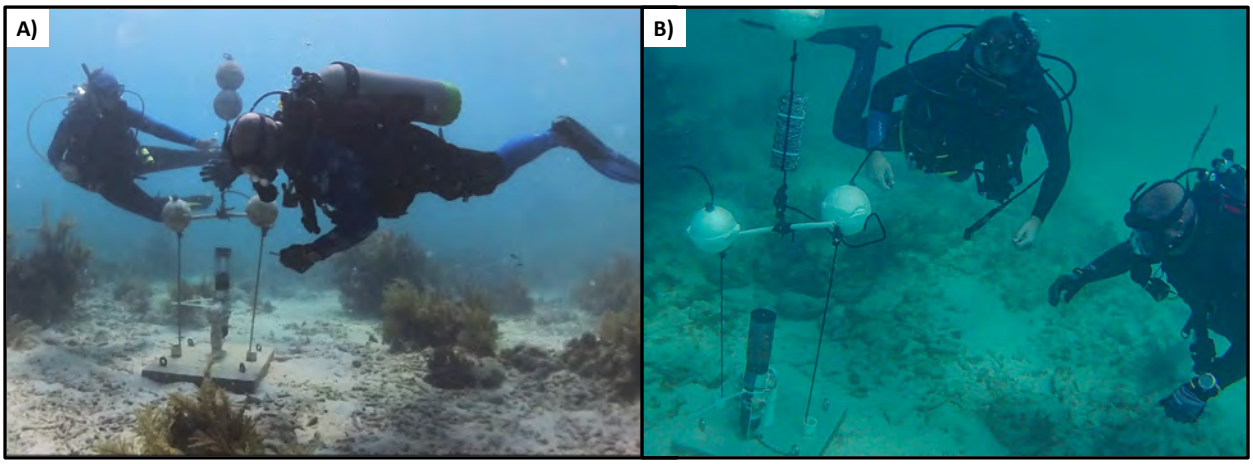


Figure 8. The CFK scientific diving team deploying Eureka Manta+35 data sondes at: A) Eastern Dry Rocks (EDR) and B) Western Dry Rocks (WDR).

Data from archival data sondes was downloaded during routine maintenance and calibration. Data was downloaded onto a dedicated rugged laptop and subsequently copied to the cloud and PI laptop computer, as well as an external data storage device.

3.3.2 Water samples and in-situ water quality measurements near EDR and WDR

Monthly water samples and *in-situ* water quality measurements were conducted near EDR-SPA approximately 3 km west-southwest of the entrance to the Key West Shipping Channel and WDR approximately 13 km further west-southwest (Figure 1: EDR and WDR; and Table 1). The same methods described in sections 3.1.5 Field Sampling Methods and 3.1.6 In-situ field measurement methods were used to collect water samples for chemical analysis and *in-situ* field measurements.

3.4 Quality Assurance Project Plan (QAPP)

All methods, protocols, calibrations, and procedures attempted to follow the approved EPA Region 4 South Florida – Quality Assurance Project Plan (QAPP) (Appendix C). Deviations from the QAPP were documented in annual EPA Region 4 Progress Reports. Deviations mostly resulted when proposed water quality monitoring equipment was not available and alternative technology was used (e.g. Eureka Manta+35 data sondes instead of YSI EXO data sondes).

Regarding data sonde calibration, calibration methods varied depending on the archival data sonde equipment employed. Three types of archival data sondes were used during the KWWQ project including: (1) YSI 6600 model, (2) YSI EXO3s model, and (3) Eureka Manta+35. To the extent possible, each technology was calibrated in accordance with KWWQ QAPP and the specific procedures outlined in the specific sonde User Manual.

CAChE Lab data and *in-situ* field data quality assurance and quality control (QA/QC) processes are outlined below in sections 3.5.2 CAChE Lab Data Conditioning and QA/QC and 3.5.3 In-situ Field Data Conditioning and QA/QC.

3.5. Data Conditioning and QA/QC

Three types of data were generated during the KWWQ project: (1) sonde data, (2) water sample chemical analysis data, and (3) field measurement data. Data was downloaded or reported in spreadsheet format, and each data type required specific data conditioning prior to data analysis.

3.5.1 Sonde Data Conditioning and QA/QC

Sonde data was collected, reported, and stored differently depending on the specific technology employed. Archival data sondes stored information internally, and data was periodically downloaded during routine maintenance and calibration. EXO3s sonde data was collected and stored internally (i.e. archived), transmitted and stored on a data logger (YSI, Inc., Model DL-6) inside the TK system, and transmitted via cellular service to the cloud (Hydrosphere^{TM}). Data was reported on a single master worksheet and protected (i.e. locked) to safeguard it from changes. In all cases, sonde data was downloaded and reported as CSV (comma-separated values) files. The CSV files were converted into a XLSX (Microsoft Excel) workbook.

Sonde data QA/QC was conducted manually for specific dates in accordance with cruise ship activity (Appendix A) or specific data. Spreadsheets were reviewed and graphs were plotted of the sonde data to identify data anomalies. For example, sondes reported -999.9 during calibration periods or periodically presumably during a power loss or other information disruption. Occasionally, other data anomalies appear in the data (e.g. unrealistic data spikes). Consultation with YSI technical support suggested several reasons for these data anomalies including biological interference (e.g. fish, etc.) or debris near the sensor while it was sampling the water column. Therefore, the following criteria for data anomaly deletion were as follows:

1. A data anomaly was defined as a substantial deviation from background data (i.e. data spike or data drop).
2. Were data anomalies reported on both sondes at similar times? The probability of an anomaly caused by sensor interference on both sondes at the same time is very low. If yes, keep the data. If not, move to #3 below.
3. Was the data anomaly unrealistic relative to background data?
4. Was the data anomaly a single data point?
5. If the answer to #3 and #4 was yes, then the data point was removed.

Hydrosphere^{TM} data was extracted (i.e. copied) by month from the master worksheet, and a new workbook for each month was created and locked to protect the data from changes. From this workbook, a specific date to be analyzed was extracted (i.e. copied) onto additional worksheets

and labelled “Raw Data”. Specific data (i.e. the parameter to be analyzed) was extracted and pasted into another worksheet which was used for data analysis.

EXO3s data or DL-6 Data Logger data were archived internally and downloaded to form comprehensive data sets covering the duration of deployment from October 10, 2023, through December 31, 2024. The comprehensive data set was saved to a master datasheet which was locked and protected to avoid changes. From this master datasheet, a specific date to be analyzed was extracted (i.e. copied) onto additional worksheets and labelled “Raw Data”. Specific data (i.e. the parameter to be analyzed) was extracted and pasted into another worksheet which was used for data analysis. Eureka Manta^{+}35 data sonde data was treated similarly to EXO3s data, but the data range was not comprehensive and only covered the deployment duration between routine maintenance and calibration periods.

After calibration occurring February 14-15, 2024, TK system sondes were accidentally switched during redeployment (i.e. deep sonde was deployed shallow and the shallow sonde was deployed deep). The mistake was noticed and the sondes were returned to their original positions on February 27, 2024. Therefore, data conditioning for all TK system data (Hydrosphere^{TM}; EXO3s archived; DL-6 Data Logger) required exchanging the data from this period.

3.5.2 CAChE Laboratory Data Conditioning and QA/QC

The CAChE Laboratory data was reported monthly via email approximately one month after water samples were shipped to FIU. Prior to data analysis, monthly data was combined into a single comprehensive Excel workbook and organized by each sample trip starting with Trip 1 through Trip 20. The CAChE Laboratory provided method detection limits (MDL) for each parameter and qualifying data criteria (Table 4). The CAChE data was reported and values determined questionable or uncertain were flagged according to the qualifying data criteria. CAChE data was examined separately four times to identify anomalies and ensure data quality.

After manual review, CAChE Laboratory Data then underwent additional QC processing through the newly developed “epa_aoc” database using pgAdmin4, an open-source database development and management platform for PostgreSQL. The database included: (1) the comprehensive CAChE Laboratory data table, (2) CAChE Views – information generated by the database management tool serving a distinct purpose in the QC process. The QC CAChE process is as follows:

1. Table information with database syntax:
    a. cache_staging: This table is solely for loading the raw data into the database. The only change that is made is the formatting column headers. The table is loaded and then is used to generate the views below, leaving it untouched.
2. Views information with database syntax:

a. v_cache_mdl_protocol: This view gave every analyte an additional column (ending in _half_mdl). For any sample that returned from the lab with a flag of “T”, “U”, or “ND”, or lab-specific notation of “QT”, the value of ½ the method detection limit (MDL) was substituted in place of the reported value. This is a standard reporting practice that the Florida Department of Environmental Protection uses under the Florida Department of State (62-4.246 Sampling, Testing Methods, and Method Detection Limits for Water Pollution Sources). This view also decreased chances of human error by deduplicating any duplicate trips that could have gone unseen during manual review. Additionally, this view removed pre- and post-control samples from the results, so they would not be included in our graphical analysis. Once developed, this view is untouched and left as a reference.

b. v_processed_cache_results: This view is developed from v_cache_mdl_protocol. The half_mdl column is kept, and for any analyte flagged “T”, “U”,“ND”, or “QT”, ½ the MDL value fills the corresponding analyte column. A Total Inorganic Nitrogen (TIN) column is also added and calculated by (Nitrite + Nitrate) + (Ammonia\ Ammonium). Once developed, there are no more alterations to this view, and it is used as the source for further data analysis.

3. v_processed_cache_results: used to select the processed analyte columns and generate the CAChE Lab figures. No data is ever deleted from the database; it is stored under tables or views. When in the database, one can query any specific QC step and download the data set if they wish. This helps preserve data integrity by decreasing interactions with the raw data file and the chances of human error. It is noted that the TIN values calculated use the ½ MDL protocol, and if one analyte (Nitrite + Nitrate or Ammonia\ Ammonium) could not be reported (e.g.. sample received broken, not collected due to weather, etc.) but the other was, TIN was reported as a value of zero. It is also noted that the ½ MDL protocol was necessary for reporting SRP and is visually reflected in the figures. This is for the purpose of gathering a background assessment on the water quality of the KWWQ study area, and therefore results should be interpreted carefully.

(Continued on the next page)

Table 4. CAChE Nutrient Analysis Laboratory Method Detection Limits (MDL) and data qualifying criteria.

CAChE-NACF METHOD DETECTION LIMITS AND QUALITY CONTROL INFORMATION

Analyses Information										
Method Detection Limits approved and effective as of 8/1/2023										
ANALYSIS	CAChE-NACF	Based on Stand. Method	MDL (µmoles/L)		PQL (µmoles/L)		MDL (ppm)		PQL (ppm)	
	SOP ID		SW	FW	SW	FW	SW	FW	SW	FW
N+N	SOP-004	EPA353.4 Rev. 2.0	0.13	0.124	0.96	0.96	0.00182	0.00173	0.01344	0.01344
NO2-N	SOP-004	EPA353.4 Rev. 2.0	0.013	0.015	0.16	0.16	0.00018	0.00022	0.00224	0.00224
NH4-N	SOP-004	EPA349.0 Rev. 2.0	0.179	0.196	1	1	0.00251	0.00275	0.014	0.014
SRP	SOP-004	EPA365.1 Rev. 2.0	0.046	0.062	0.4	0.4	0.00141	0.00192	0.0124	0.0124
TP Low Curve	SOP-008	EPA365.1 Rev. 2.0	0.028	0.031	0.1	0.1	0.00086	0.00096	0.0031	0.0031
TP High Curve	SOP-008	EPA365.1 Rev. 2.0	0.151	0.099	1.25	1.25	0.00468	0.00308	0.03875	0.03875
TP-persulfate Low Curve	SOP-008P	EPA365.1 Rev. 2.0	0.048		0.25		0.00148		0.00775	
TP-persulfate High Curve	SOP-008P	EPA365.1 Rev. 2.0	0.293		1.25		0.00907		0.03875	
TP- soil*	SOP-008	EPA365.1 Rev. 2.0					0.4402		3.87	
Si	SOP-005	EPA366.0 Rev. 1.0	0.157	0.147	1	1	0.0044	0.0041	0.028	0.028
TOC	SOP-007	SM5310B-1999	10.4		41.67		0.12		0.5	
TN	SOP-006	ASTM D5176-91	3.46		17.86		0.05		0.25	
Chl-a**	SOP-003	SM10200H-1999	0.1				0.1		0.03	
NOTE: Practical Quantitation Limits (PQL) values are established equal to the lowest (non-blank) calibration standard of each analysis. Any reported value below PQL (S1) and above Method of Detection Limits (MDL) will be flagged and considered uncertain, as per LOQ definition TP-soil* reported in µg/g Chl-a** reported in µg/L										

Calculated Data formulas

NO3-N = (N+N) - (NO2-N)	If either N+N or NO2-N is below the PQL, NO3-N will not be calculated due to the uncertainty of any value below PQL.
TIN = (NO3-N) + (NO2-N) + (NH4-N)	If TIN has a negative value, it will be reported as "ND"
TON = TN - TIN	If TON has a negative value (-), it will be reported as "ND"
DIC = TC - DOC	If DIC has a negative value (-), it will be reported as "ND"

Nomenclature

Nitrite (NO2) + Nitrate (NO3) as N+N
Nitrite as NO2-N
Nitrate as NO3-N
Ammonia/Ammonium as NH3/NH4-N
Nitrogen, Total Inorganic as TIN
Nitrogen, Total Organic as TON

Qualifiers

NA	Not applicable, no QC parameter required/reported
*	Not reported due to interference or instrument malfunction
?	Value outside the established quality control criteria
Y	Improperly preserved sample
I	MDL < Value < PQL
J	Value outside the established quality control criteria
O	Sampled, but analysis lost or not performed.
Q	Exceeded Holding Time
T	Value < MDL
U	Analyte Not Detected in Sample
V	Analyte found in Lab Method Blank

3.5.3 In-situ Field Data Conditioning and QA/QC

Field data conditioning consisted of: (1) transcribing field data onto digital spreadsheets, (2) copying raw data into new spreadsheets and locking raw data sheets, (3) copying specific parameters to be analyzed into new spreadsheets, and (4) removing data anomalies. Data anomalies were defined as data reported an order of magnitude greater than background data. This was most likely attributed to human error when recording or transcribing field data.

3.6 Data Analysis

Three types of data were generated during the KWWQ project: (1) sonde data, (2) water sample chemical analysis data, and (3) field measurement data. Data was downloaded or reported in spreadsheet format and each data type required specific data analysis.

3.6.1 Sonde Data Analysis

Sonde data analysis consisted of time series analysis to monitor changes in a specific parameter over time. Data was analyzed by month over the duration of the KWWQ project. Specific time intervals that correlated with cruise ship activity and weather events were plotted and graphed. To determine changes from background environmental conditions for a specific water quality metric, the mean value from all measurements 1 hour prior to the change was used as the background value for comparison. For the dates October 10, 2023 – November 1, 2024, Hydrosphere^{TM} data was used for analysis. For the dates November 3, 2024 - December 31, 2024 internally archived EXO3s data was used due to issues arising from Hydrosphere^{TM} associated with changing daylight savings time on November 3, 2024 at 2:00 AM.

3.6.2 CAChE Lab Data Analysis

CAChE Lab data was uploaded into a database management tool created using Postgres SQL) (pgAdmin4) and water chemistry was analyzed. Specific water chemistry parameters for each sample site were graphed using X-Y scatter plots. Resulting graphs were analyzed to determine if Log_{10} transformations were required to address data outliers and better understand the relationship between specific data parameters. Data trendlines were calculated and plotted. Redfield ratios (Redfield, 1934) were plotted for each water chemistry relationship graph for comparison.

3.6.3 In-situ Field Data Analysis

In-situ field data was analyzed using time series to monitor changes in a specific parameter over the duration of the study. The mean and 95% confidence intervals were calculated for each sample site.

3.7 Permits

One of the first actions after approval the KWWQ QAPP was to apply for a permit to deploy water quality monitoring equipment within the KWWQ study area. On June 29, 2022, a research permit was issued by the Florida Keys National Marine Sanctuary for: (1) the temporary deployment of scientific monitoring equipment on the seafloor, (2) collection of sediment cores from the seafloor, and (3) deployment of an autonomous underwater vehicle (AUVs) (Appendix D).

3.8 Data Management

In addition to data stored locally on water quality monitoring equipment and devices, data was stored on laptop hard drives, in the cloud (Microsoft One Drive), and a 2TB external storage device. Data was also printed on paper and stored in a dedicated KWWQ project file cabinet. Data was reviewed weekly by the KWWQ project team during weekly meetings. Metadata was collected throughout the KWWQ project and stored similarly.

3.9 Statistical Analysis

Data was log transformed and basic descriptive statistical analysis methods were employed where appropriate, including scatter plots with trendline analysis and mean calculations with 95% confidence intervals. Time series analysis was used when appropriate to explore temporal data trends, especially seasonality.

4.0 Monitoring Results

The following section reports results from: (1) monitoring equipment deployed within the KWWQ study area (Figure 1), (2) water samples collected and analyzed by NELAC accredited FIU CAChE Nutrient Analysis Laboratory, and (3) *in-situ* water quality field measurements.

4.1 Key West Harbor Monitoring Results

The following section reports results from the TK system, cruise ship activities, water sample chemical analysis, and field sample measurements in the Key West Harbor.

4.1.1 The YSI Turnkey (TK) System Results

During the fourteen-month monitoring period by the TK system in Key West Harbor near Pier B and Mallory Square docks, most of the water quality metrics measured were within expected values showing only daily (e.g. DO) or seasonal (e.g. conductivity and salinity) fluctuations except for turbidity and photopigment concentrations (e.g. chlorophyll-a). Turbidity and photopigment concentration measurements were strongly correlated to cruise ship traffic and extreme weather events. Turbidity events were defined as >29 nephelometric turbidity units (NTU) beyond background levels. The background level was determined by averaging turbidity readings over the hour leading up to the spike. The 'spike' refers to the difference between the background average and the high turbidity reading. Correlations between turbidity events and chlorophyll-*a* are presented in the following sections.

4.1.1.1 October2023 Turbidity Events >29 NTU

There were no turbidity events > 29 NTU in October 2023 correlated with cruise ship traffic or weather events in the Key West Habor near Pier B and Mallory Square docks.

4.1.1.2 November 2023 Turbidity Events >29 NTU

There were three turbidity events > 29 NTU in November 2023 strongly correlated with cruise ship activity in Key West Habor near Pier B and Mallory Square docks (Figure 9).

On November 16, 2023, there was a turbidity spike of 45.63 NTU that occurred near the time of cruise ship arrival (Figure 9 A). The time of cruise ship arrival on November 16, 2023, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A).

On November 17, 2023, there was a turbidity spike of 35.58 NTU that occurred on the deep sonde near the time of cruise ship arrival (Figure 9 B). Webcam video for November 17, 2023, was not available due to a power outage, therefore cruise ship arrival and departure times were based on the cruise ship schedule online.

On November 26, 2023, there was a turbidity spike of 133.07 NTU that occurred on the deep sonde near the time of cruise ship departure (Figure 9 C). The time of cruise ship departure on November 26, 2023, was determined by observing webcam video of the precise moment the cruise ship departed the dock at Pier B (Appendix A).

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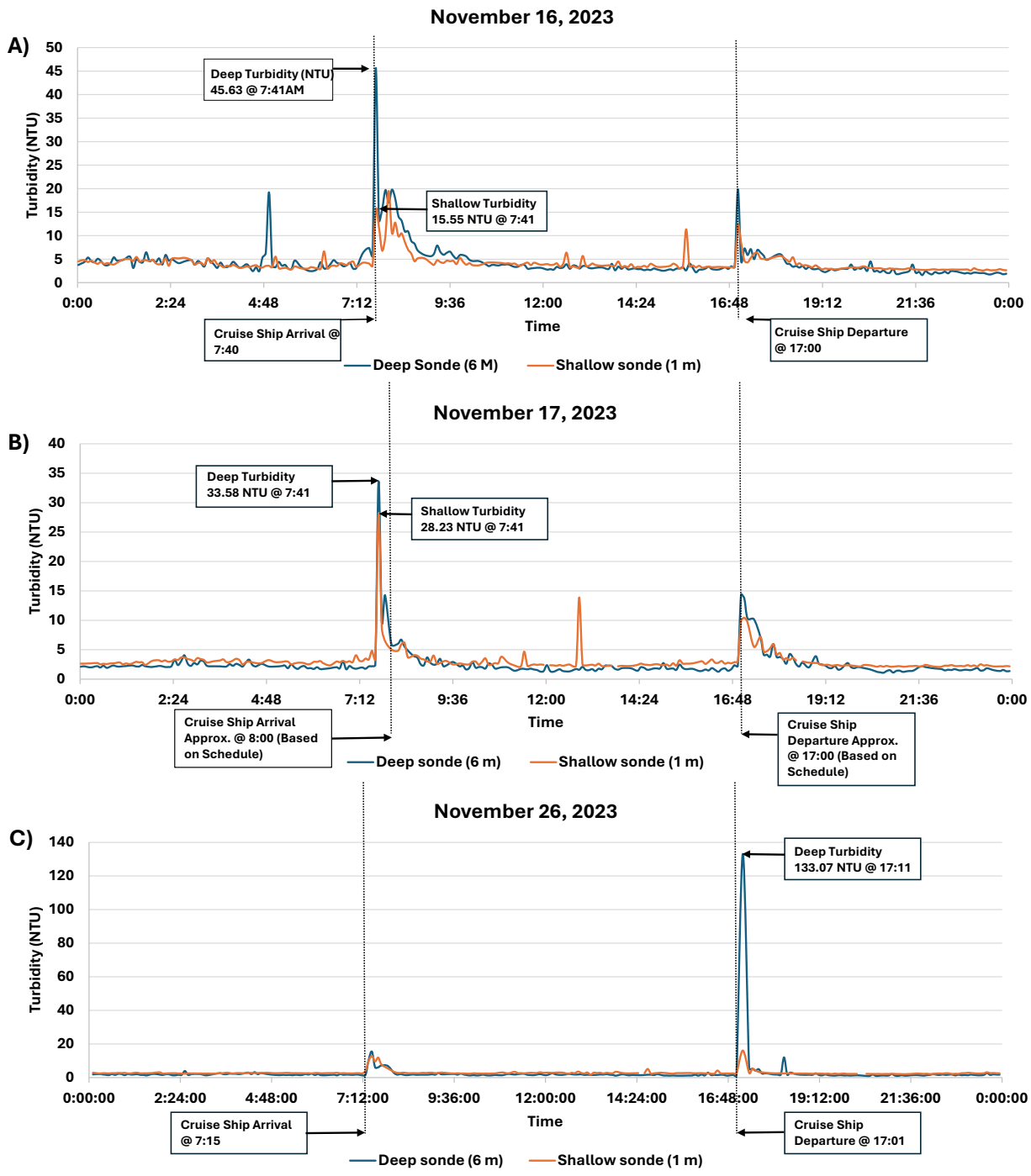
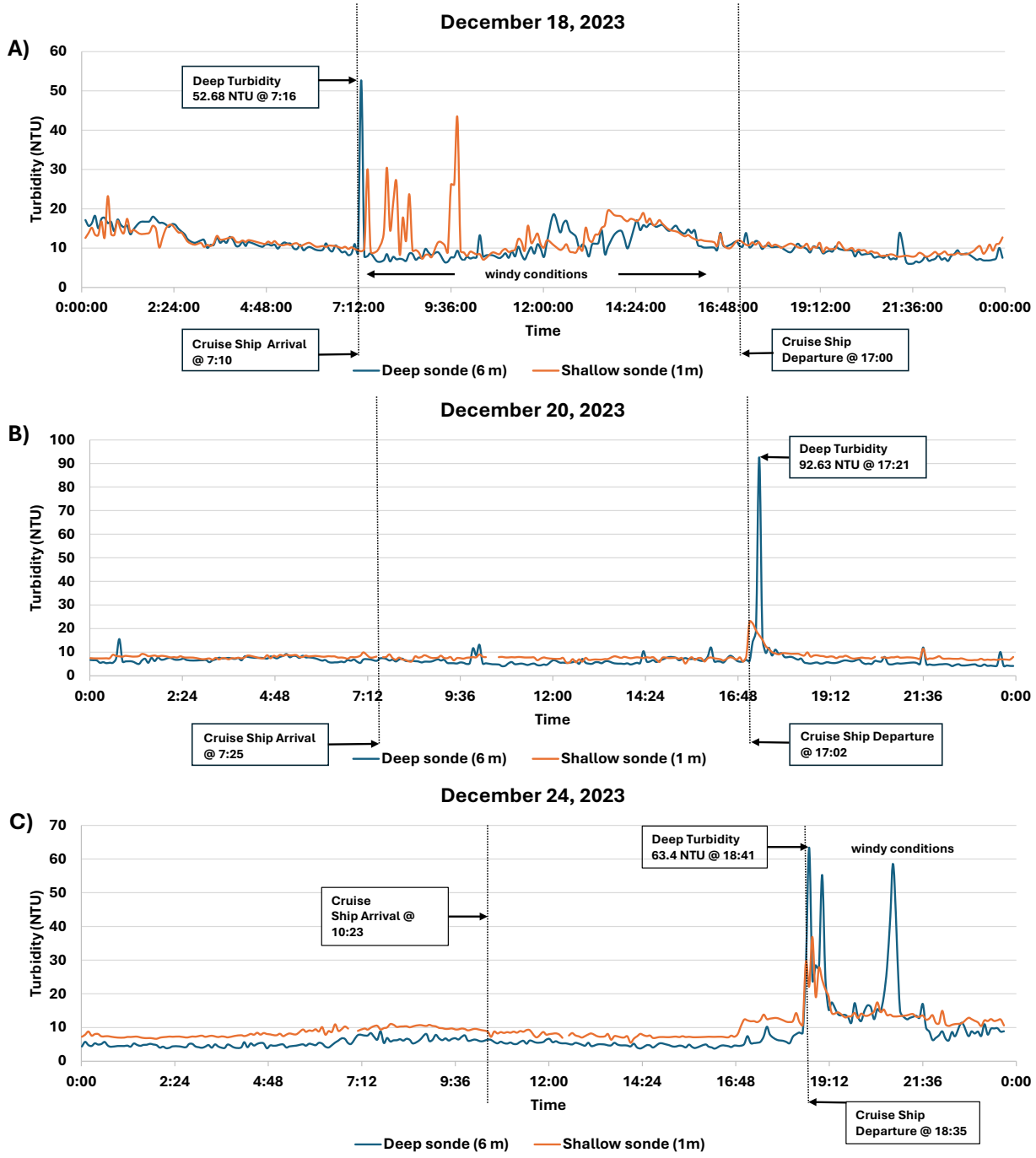


Figure 9. Graphs of turbidity events > 29 NTU in November 2023 recorded by the Turnkey water quality monitoring equipment deployed in the Key West Harbor immediately adjacent to Pier B and Mallory Square dock.

4.1.1.3 December 2023 Turbidity Events >29 NTU

There were seven turbidity events in December 2023 that were strongly correlated with cruise ship activity in Key West Habor near Pier B and Mallory Square docks (Figure 10).



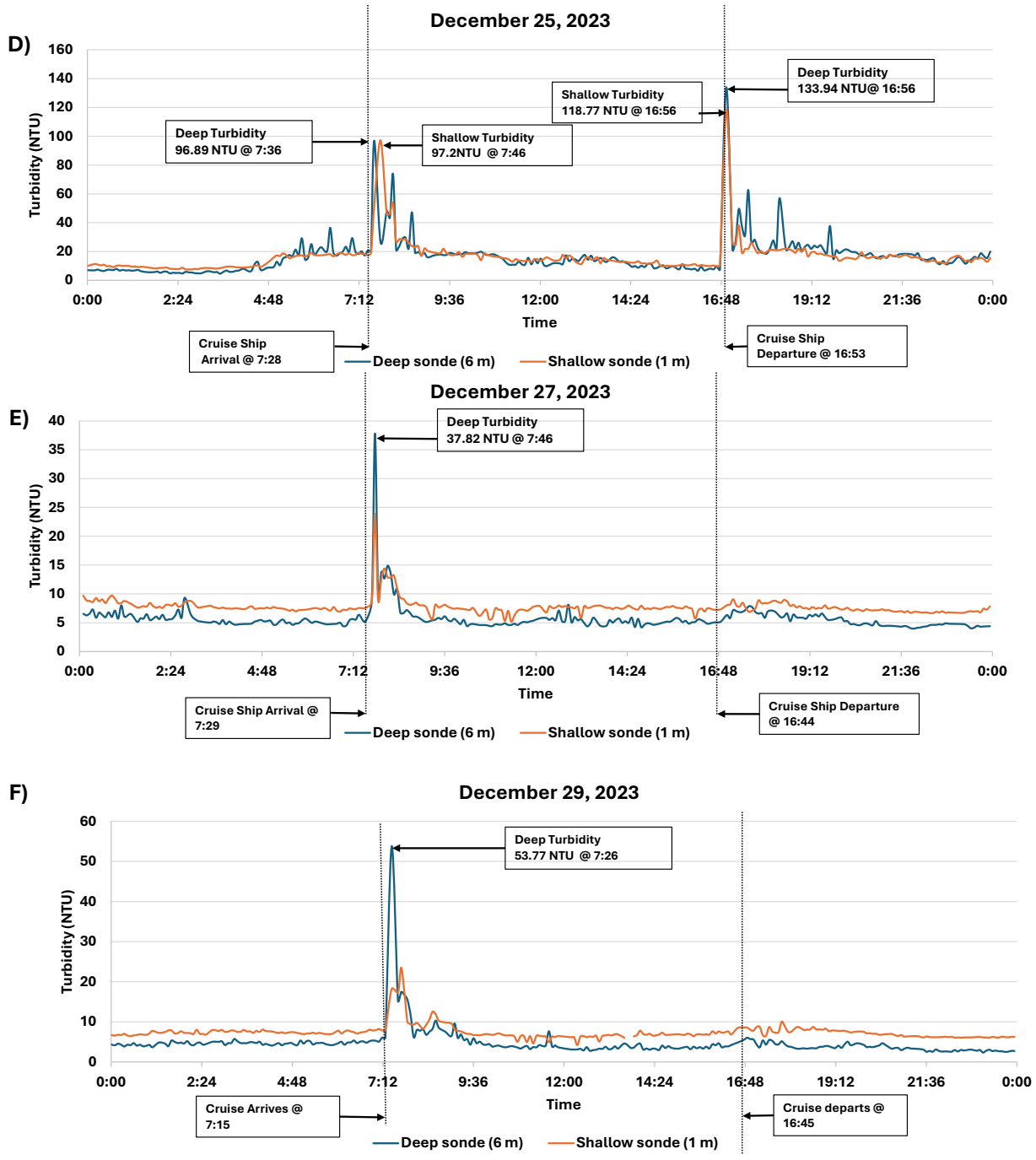


Figure 10. Graphs of turbidity events > 29 NTU in December 2023 recorded by the Turnkey water quality monitoring equipment deployed in Key West Harbor immediately adjacent to Pier B and Mallory Square docks.

On December 18, 2023, there was a turbidity spike of 52.68 NTU on the deep sonde near the time of cruise ship arrival (Figure 10 A). The time of cruise ship arrival on December 18, 2023, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A). There were also turbidity events that occurred throughout the

day with a turbidity spike (43.24 NTU) at approximately 9:30 AM. At the same time on December 18, 2023, Key West experienced breezy conditions under the tail end of a strong East Coast storm system December 17-18 (NOAA - National Weather Service: https://www.weather.gov/ilm/Dec2023CoastalStorm).

On December 20, 2023, there was a turbidity spike 92.63 NTU on the deep sonde near the time of cruise ship departure (Figure 10 B). The time of cruise ship departure on December 20, 2023, was determined by observing webcam video of the precise moment the cruise ship departed the dock at Pier B (Appendix A).

On December 24, 2023, there was a turbidity spike of 63.4 NTU on the deep sonde near the time of cruise ship departure (Figure 10 C). The time of cruise ship departure on December 24, 2023, was determined by observing webcam video of the precise moment the cruise ship departed the dock at Pier B (Appendix A). Elevated turbidity occurred throughout the evening with a turbidity spike (57.74 NTU) at 8:51 PM. At the same time on December 24, 2023, it was very windy with the average wind speed 14.3 mph and strong gusts up to 35.1 mph out of the southeast (NOAA National Centers for Environmental Information; https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily).

On December 25, 2023, there was a turbidity spike of 96.89 NTU on the deep sonde and 97.2 NTU on the shallow sonde near the time of cruise ship arrival. There was also a higher turbidity spike of 133.94 NTU on the deep sonde and 118.77 NTU on the shallow sonde near the time of cruise ship departure (Figure 10 D). The time of cruise ship arrival and departure on December 25, 2023, was determined by observing webcam video of the precise moment the cruise ship reached and departed the dock at Pier B (Appendix A).

On December 27, 2023, there was a turbidity spike of 37.82 NTU on the deep sonde near the time of cruise ship arrival (Figure 10 E). The time of cruise ship arrival on December 27, 2023, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A).

On December 29, 2023, there was a turbidity spike of 53.77 NTU on the deep sonde near the time of cruise ship arrival (Figure 10 F). The time of cruise ship arrival on December 29, 2023, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A).

4.1.1.4 January 2024 Turbidity Events >29 NTU

There were two turbidity events > 29 NTU on a single day in January 2024 that were strongly correlated with cruise ship activity in the Key West Habor near Pier B and Mallory Square docks (Figure 11).

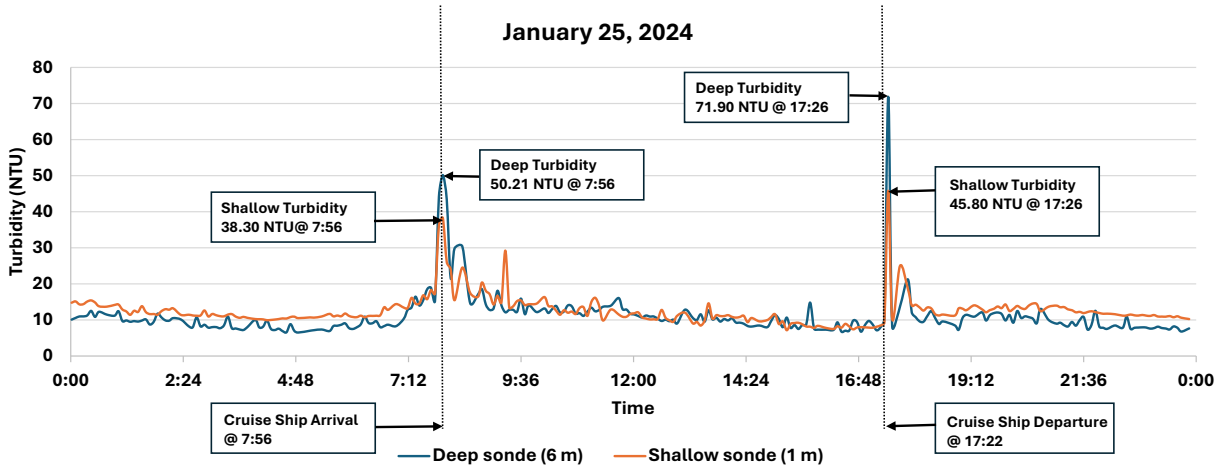


Figure 11. Graphs of turbidity events > 29 NTU in January 2024 recorded by the Turnkey water quality monitoring equipment deployed in Key West Harbor immediately adjacent to Pier B and Mallory Square docks.

On January 25, 2024, there was a turbidity spike of 50.21 NTU on the deep sonde and 38.30 NTU on the shallow sonde near the time of cruise ship arrival. There was also a higher turbidity spike of 71.90 NTU on the deep sonde and 45.80 NTU on the shallow sonde near the time of cruise ship departure (Figure 11). The time of cruise ship arrival and departure on January 25, 2024, was determined by observing webcam video of the precise moment the cruise ship reached and departed the dock at Pier B (Appendix A).

4.1.1.5 February 2024 Turbidity Events >29 NTU

There were two turbidity events > 29 NTU in February 2024 strongly correlated with cruise ship activity in Key West Habor near Pier B and Mallory Square docks (Figure 12).

On February 12, 2024, there was a turbidity spike of 42.29 NTU on the deep sonde near the time of cruise ship arrival (Figure 12 A). The time of cruise ship arrival on February 12, 2024, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A). Notice the variability associated with the background data in Figure 12 A compared to previous months. When this type of erratic data is observed, it indicates that the equipment requires routine maintenance and calibration. Therefore, both shallow and deep sondes were removed from the Yellowman mooring station on February 14, 2024, brought back to the laboratory at CFK, cleaned and calibrated and reinstalled on the Yellowman mooring station the next day on February 15, 2024. There was no cruise ship activity during the maintenance and calibration period. This type of data observation illustrates a notable advantage of the TK system over archival sonde technology.

On February 23, 2024, there was a turbidity spike of 49.58 NTU on the deep sonde near the time of cruise ship departure (Figure12 B). The time of cruise ship departure on February 23, 2024, was determined by observing webcam video of the precise moment the cruise ship

departed the dock at Pier B (Appendix A). Notice the stability of the data after sondes were cleaned and calibrated.

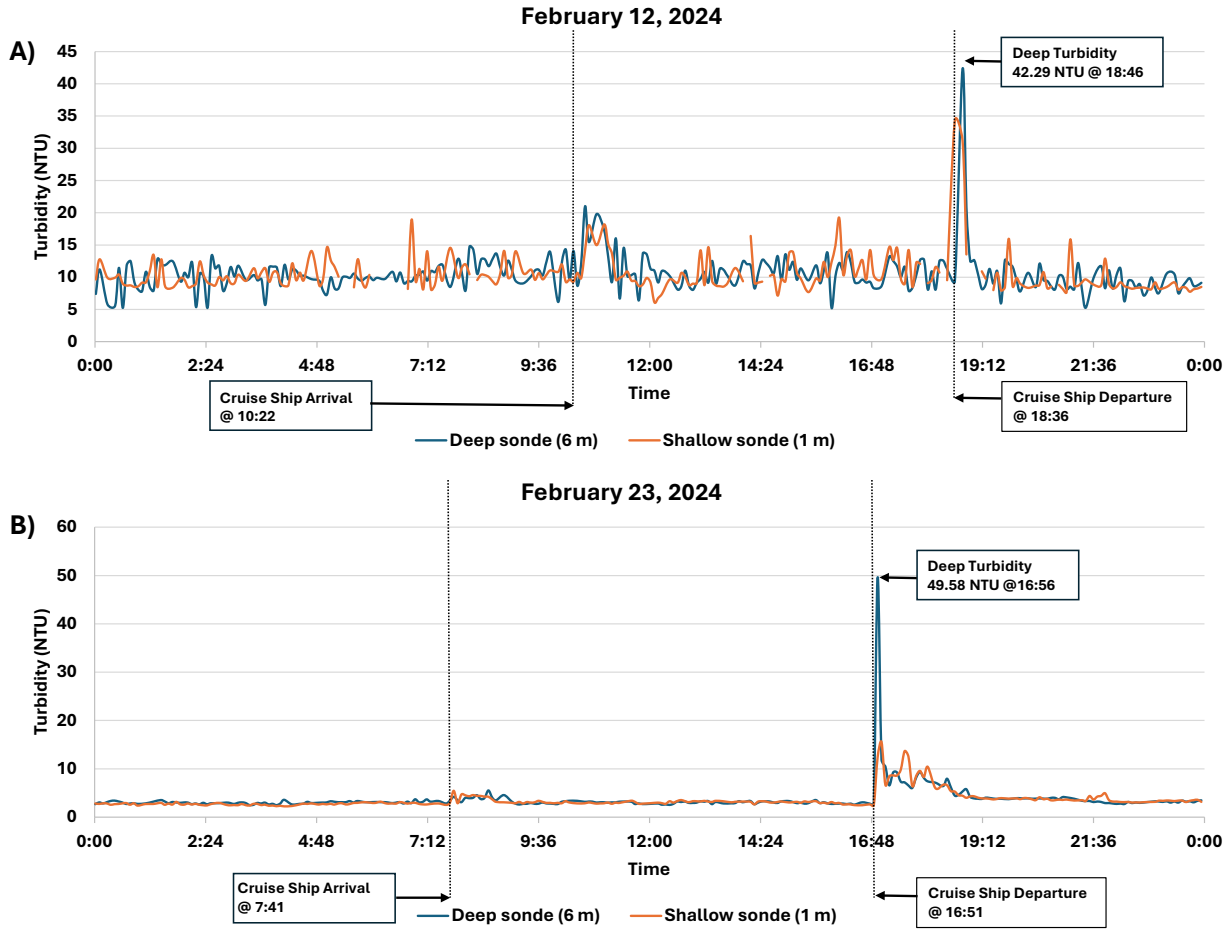


Figure 12. Graphs of turbidity events > 29 NTU in February 2024 recorded by the Turnkey water quality monitoring equipment deployed in Key West Harbor immediately adjacent to Pier B and Mallory Square docks. Notice – data variability in the top graph before routine maintenance and calibration compared to less variability in the bottom graph after routine maintenance and calibration.

4.1.1.6 March 2024 Turbidity Events >29 NTU

There were two turbidity events > 29 NTU in March 2024 strongly correlated with cruise ship activity in Key West Habor near Pier B and Mallory Square docks (Figure 13).

On March 24, 2024, there was a turbidity spike of 74.23 NTU on the shallow sonde and a corresponding spike of 38.98 NTU on the deep sonde near the time of cruise ship arrival (Figure13 A). Webcam video for March 24, 2023, was not available for the cruise ship arrival, therefore the arrival time was based on the cruise ship schedule online.

On March 25, 2024, there was a turbidity spike of 51.87 NTU on the shallow sonde and a corresponding spike of 39.75 NTU on the deep sonde near the time of cruise ship arrival (Figure13 B). The time of cruise ship arrival on March 25, 2024, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A).

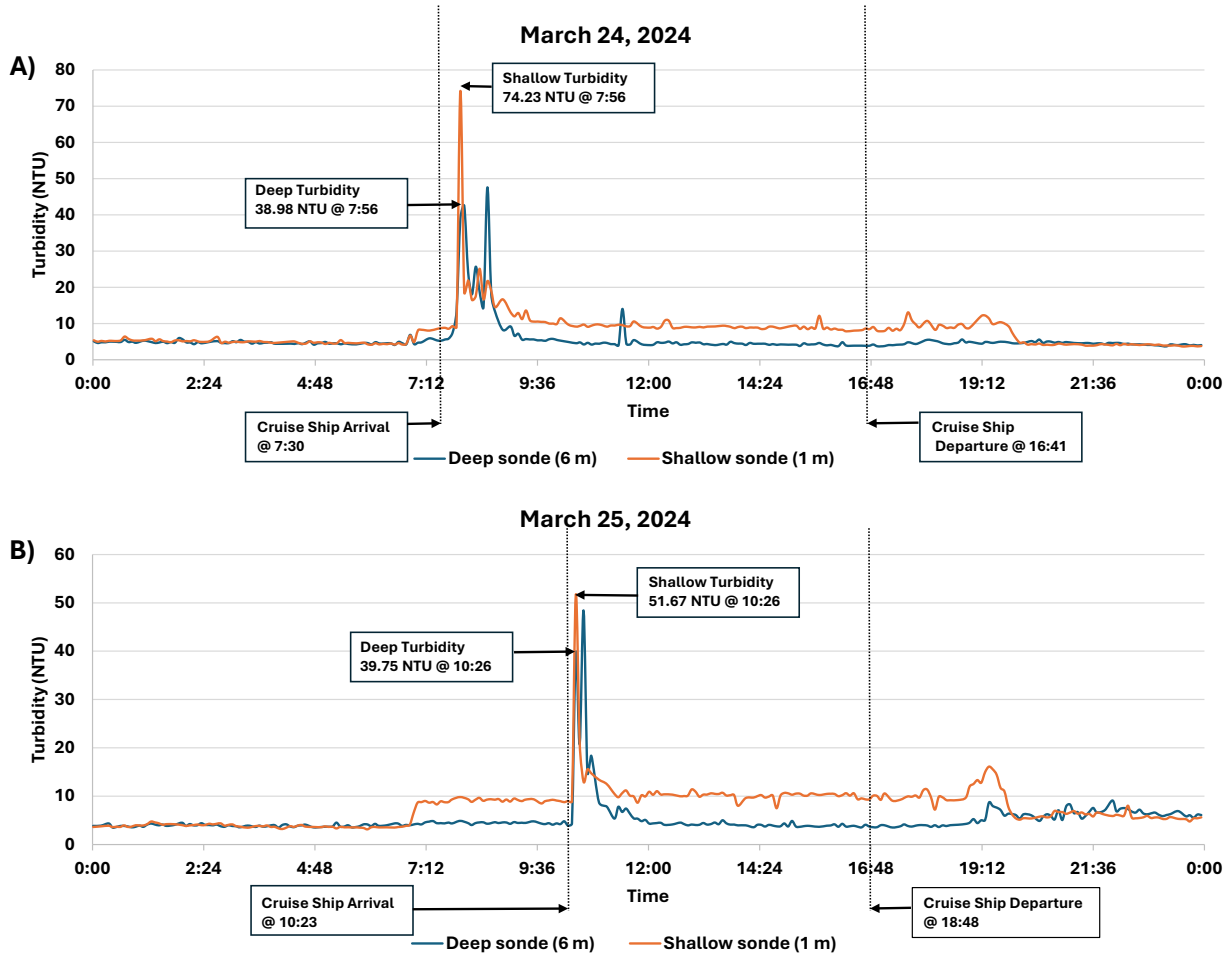


Figure 13. Graphs of turbidity events > 29 NTU in March 2024 recorded by the Turnkey water quality monitoring equipment deployed in Key West Harbor immediately adjacent to Pier B and Mallory Square docks.

4.1.1.7 April 2024 Turbidity Events >29 NTU

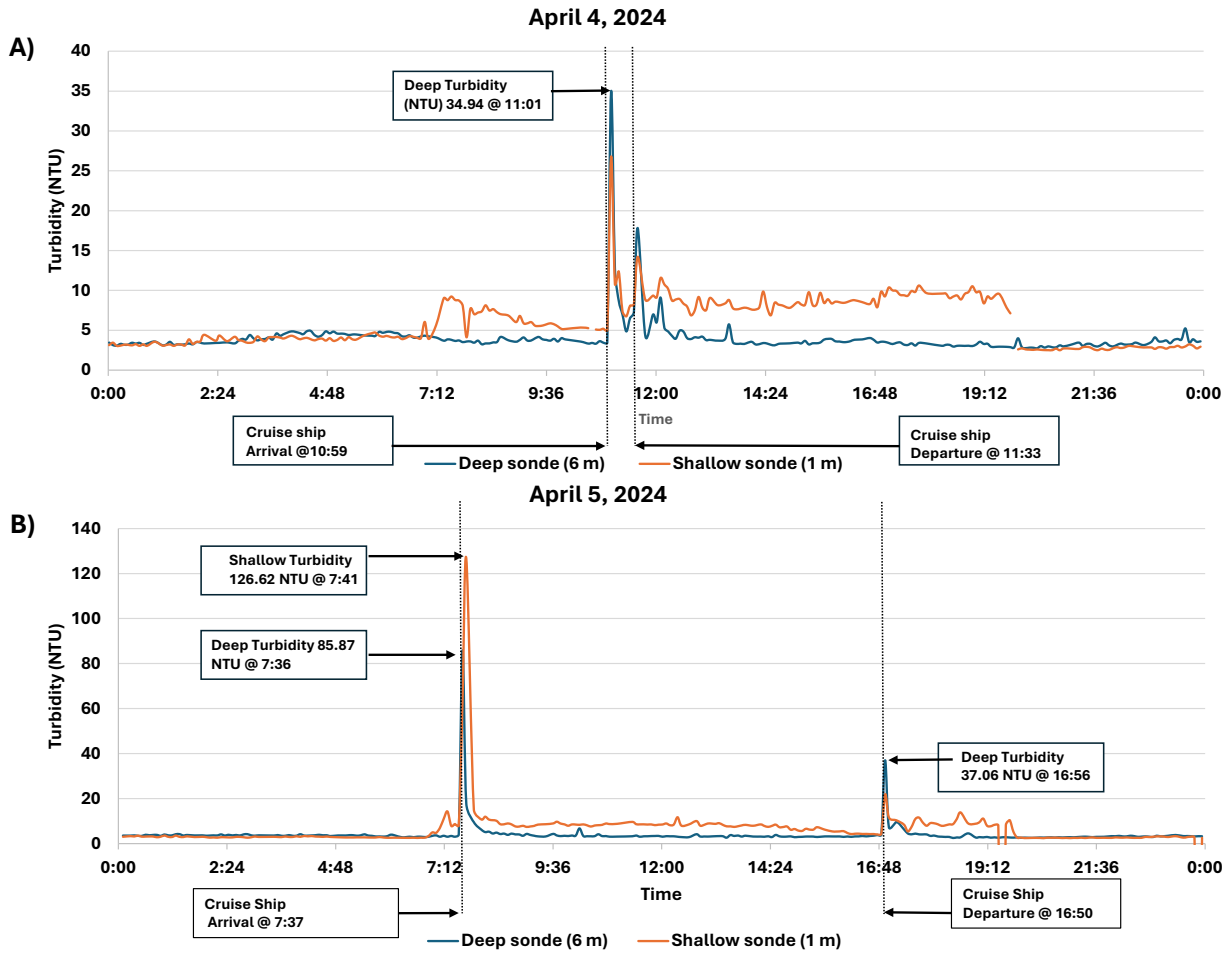
There were four turbidity events > 29 NTU in April 2024 strongly correlated with cruise ship activity in Key West Habor near Pier B and Mallory Square docks (Figure 14).

On April 4, 2024, there was a turbidity spike of 34.94 NTU on the deep sonde near the time of cruise ship arrival (Figure14 A). The time of cruise ship arrival on April 4, 2024, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A).

On April 5, 2024, there was a turbidity spike of 126.62 NTU on the shallow sonde and a corresponding spike of 85.87 NTU on the deep sonde near the time of cruise ship arrival (Figure14 B). The time of cruise ship arrival on April 5, 2024, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A).

On April 12, 2024, there was a turbidity spike of 47.36 NTU on the deep sonde and a corresponding spike of 33.44 NTU on the shallow sonde near the time of cruise ship arrival (Figure14 C). The time of cruise ship arrival on April 12, 2024, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A).

On April 30, 2024, there was a turbidity spike of 60.19 NTU on the deep sonde near the time of cruise ship departure (Figure14 D). The time of cruise ship departure on April 30, 2024, was determined by observing webcam video of the precise moment the cruise ship departed the dock at Pier B (Appendix A).



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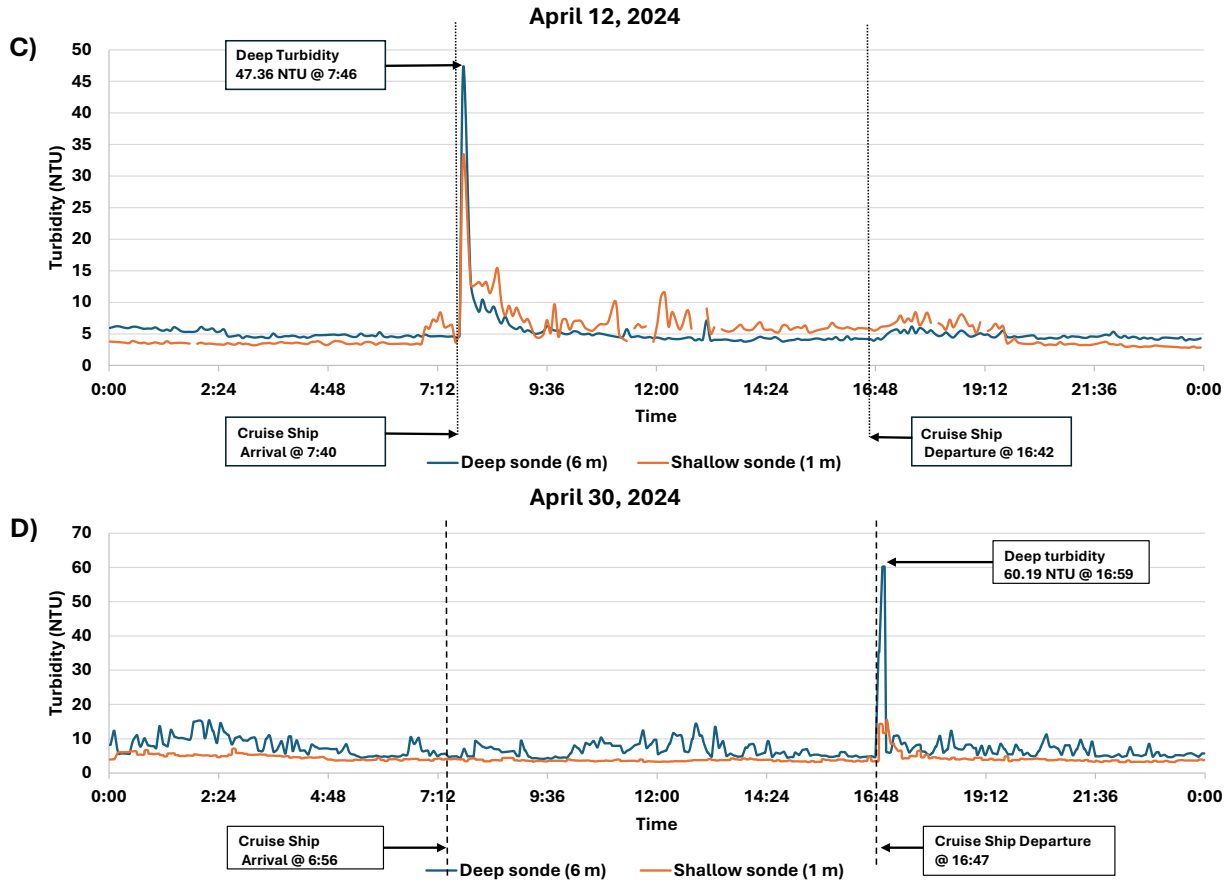


Figure 14. Graphs of turbidity events > 29 NTU in April 2024 recorded by the Turnkey water quality monitoring equipment deployed in Key West Harbor immediately adjacent to Pier B and Mallory Square docks.

4.1.1.8 May 2024 Turbidity Events >29 NTU

There were no turbidity events > 29 NTU in May 2024 strongly correlated with cruise ship activity or weather events in Key West Habor near Pier B and Mallory Square docks.

Data reported in May 2024 exhibited noticeable fluctuations for both data sondes deployed near Pier B and Mallory Square. Therefore, data from May 2024 was excluded from analysis. The sondes were removed from the Yellowman mooring station and brought back to the CFK laboratory for cleaning and recalibration on May 13, 2024, and reinstalled on the Yellowman on May 16, 2024. One ship visited Key West during the maintenance and recalibration period on May 14, 2024.

4.1.1.9 June 2024 Turbidity Events >29 NTU

There were two turbidity events > 29 NTU in June 2024 correlated with cruise ship activity or weather events in Key West Habor near Pier B and Mallory Square docks (Figure 15).

On June 1, 2024, there was a turbidity spike of 41.5 NTU on the deep sonde near the time of cruise ship departure (Figure15 A). The time of cruise ship departure on June 1, 2024, was determined by observing webcam video of the precise moment the cruise ship departed the dock at Pier B (Appendix A).

On June 28, 2024, there was a turbidity spike of 34.96 NTU on the deep sonde near the time of cruise ship departure (Figure15 B). The time of cruise ship departure on June 28, 2024, was determined by observing webcam video of the precise moment the cruise ship departed the dock at Pier B (Appendix A).

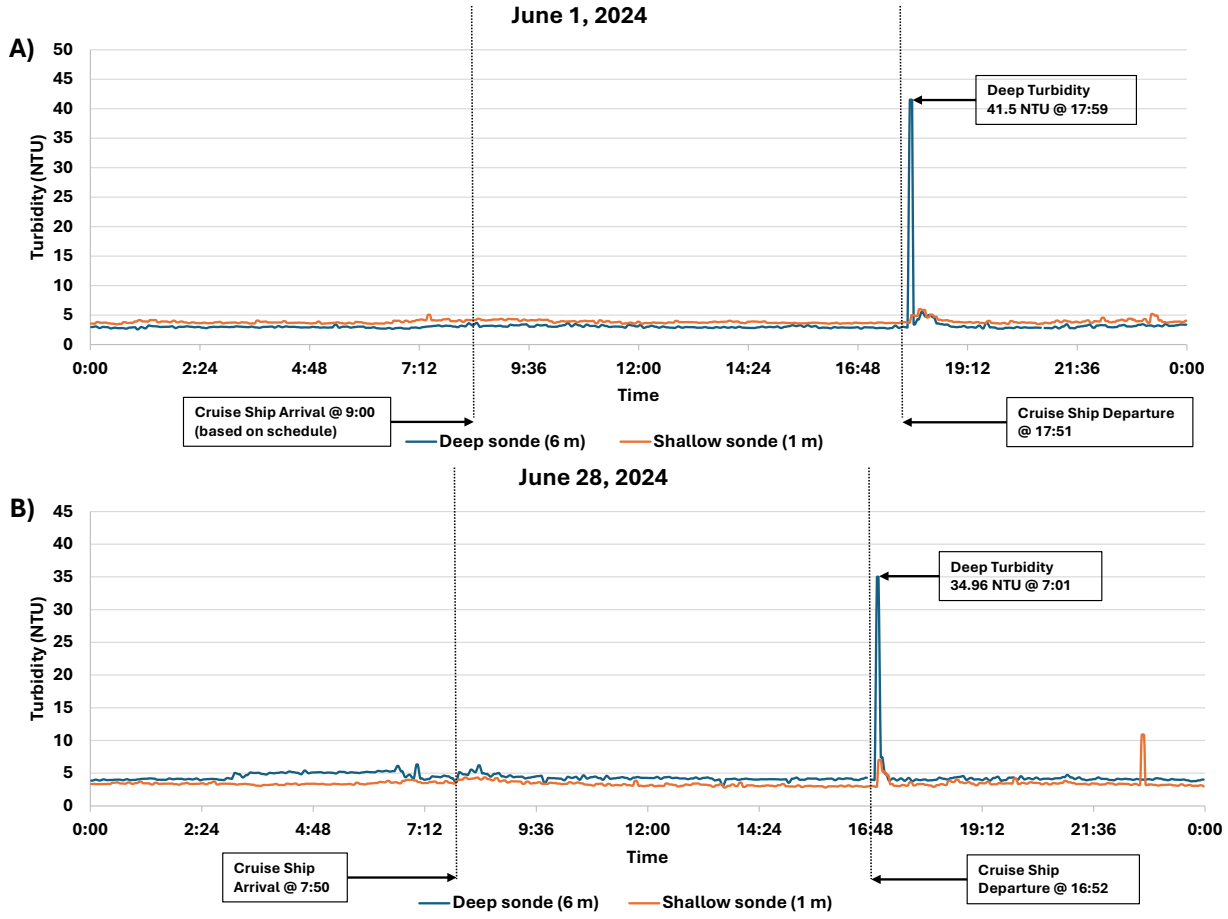


Figure 15. Graphs of turbidity events > 29 NTU in June 2024 recorded by the Turnkey water quality monitoring equipment deployed in Key West Harbor immediately adjacent to Pier B and Mallory Square docks.

4.1.1.10 July 2024 Turbidity Events >29 NTU

There were two turbidity events > 29 NTU in July 2024 strongly correlated with cruise ship activity or weather events in Key West Habor near Pier B and Mallory Square docks (Figure 16).

On July 15, 2024, there was a turbidity spike of 35.57 NTU on the deep sonde near the time of cruise ship departure (Figure16 A). There was also another turbidity spike of 57.14 NTU on the deep sonde at 6:58 AM. However, there was no associated spike on the shallow sonde nor any temporally associated cruise ship activity. The time of cruise ship departure on July 15, 2024, was determined by observing webcam video of the precise moment the cruise ship departed the dock at Pier B (Appendix A).

On July 20, 2024, there was a turbidity spike of 140.03 NTU on the shallow sonde near the time of cruise ship departure (Figure16 B). The time of cruise ship departure on July 20, 2024, was determined by observing webcam video of the precise moment the cruise ship departed the dock at Pier B (Appendix A).

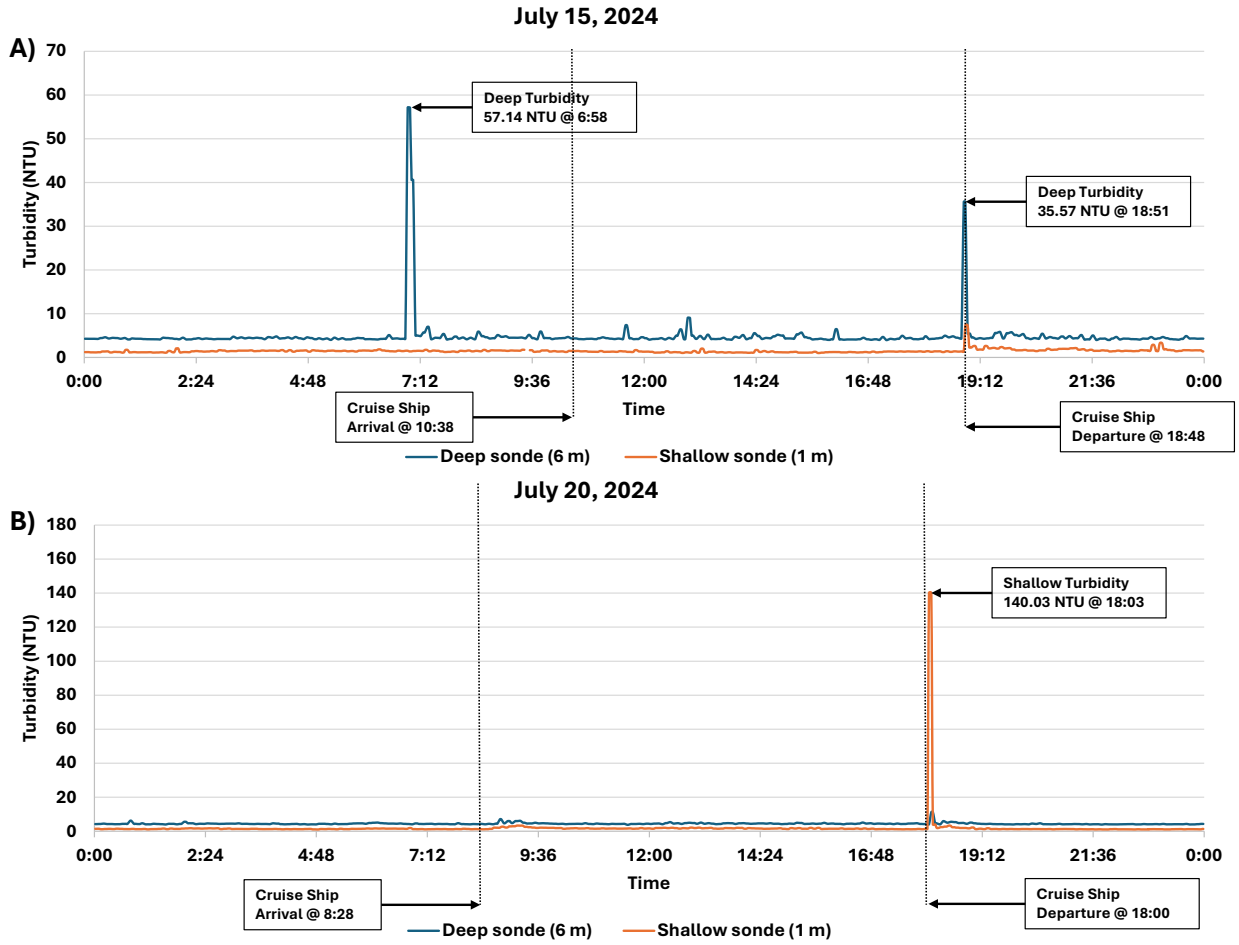


Figure 16. Graphs of turbidity events > 29 NTU in July 2024 recorded by the Turnkey water quality monitoring equipment deployed in Key West Harbor immediately adjacent to Pier B and Mallory Square docks.

4.1.1.11 August 2024 Turbidity Events >29 NTU

There were two turbidity events > 29 NTU in August 2024 strongly correlated with cruise ship activity or weather events in Key West Habor near Pier B and Mallory Square docks (Figure 17).

On August 9, 2024, there was a turbidity spike of 51.29 NTU on the deep sonde near the time of cruise ship departure (Figure17 A). The time of cruise ship departure on August 9, 2024, was determined by observing webcam video of the precise moment the cruise ship departed the dock at Pier B (Appendix A).

On August 20, 2024, there was a turbidity spike of 200.11 NTU on the deep sonde near the time of cruise ship departure (Figure17 B). This was the most substantial turbidity spike observed during the KWWQ project. The time of cruise ship departure on August 20, 2024, was determined by observing webcam video of the precise moment the cruise ship departed the dock at Pier B (Appendix A).

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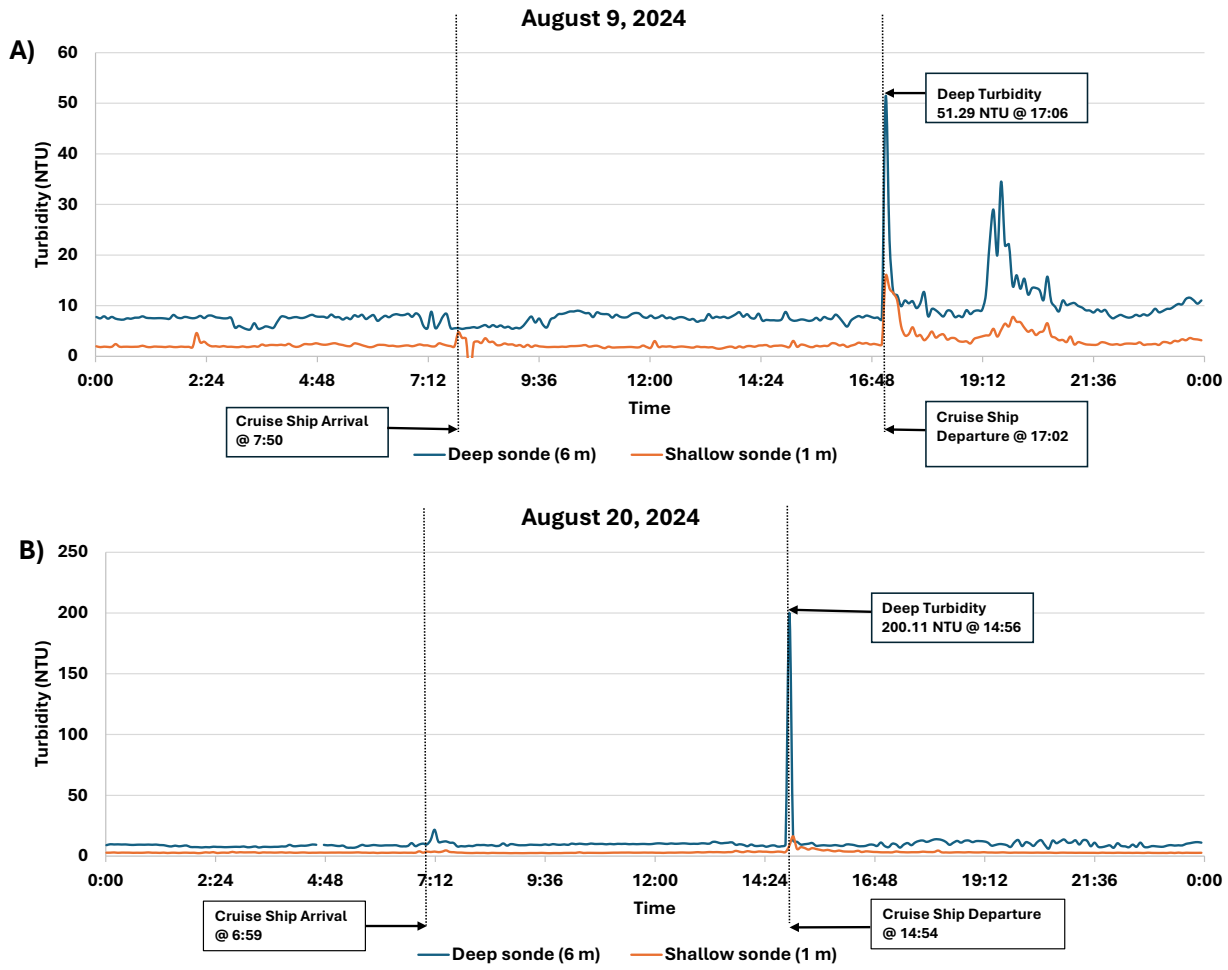


Figure 17. Graphs of turbidity events > 29 NTU in August 2024 recorded by the Turnkey water quality monitoring equipment deployed in Key West Harbor immediately adjacent to Pier B and Mallory Square docks.

4.1.1.12 September 2024 Turbidity Events >29 NTU

There were no turbidity events in September 2024 correlated with ship activity in Key West Habor near Pier B and Mallory Square docks. There were turbidity events associated with severe weather in September 2024 (See Section 4.1.1.16).

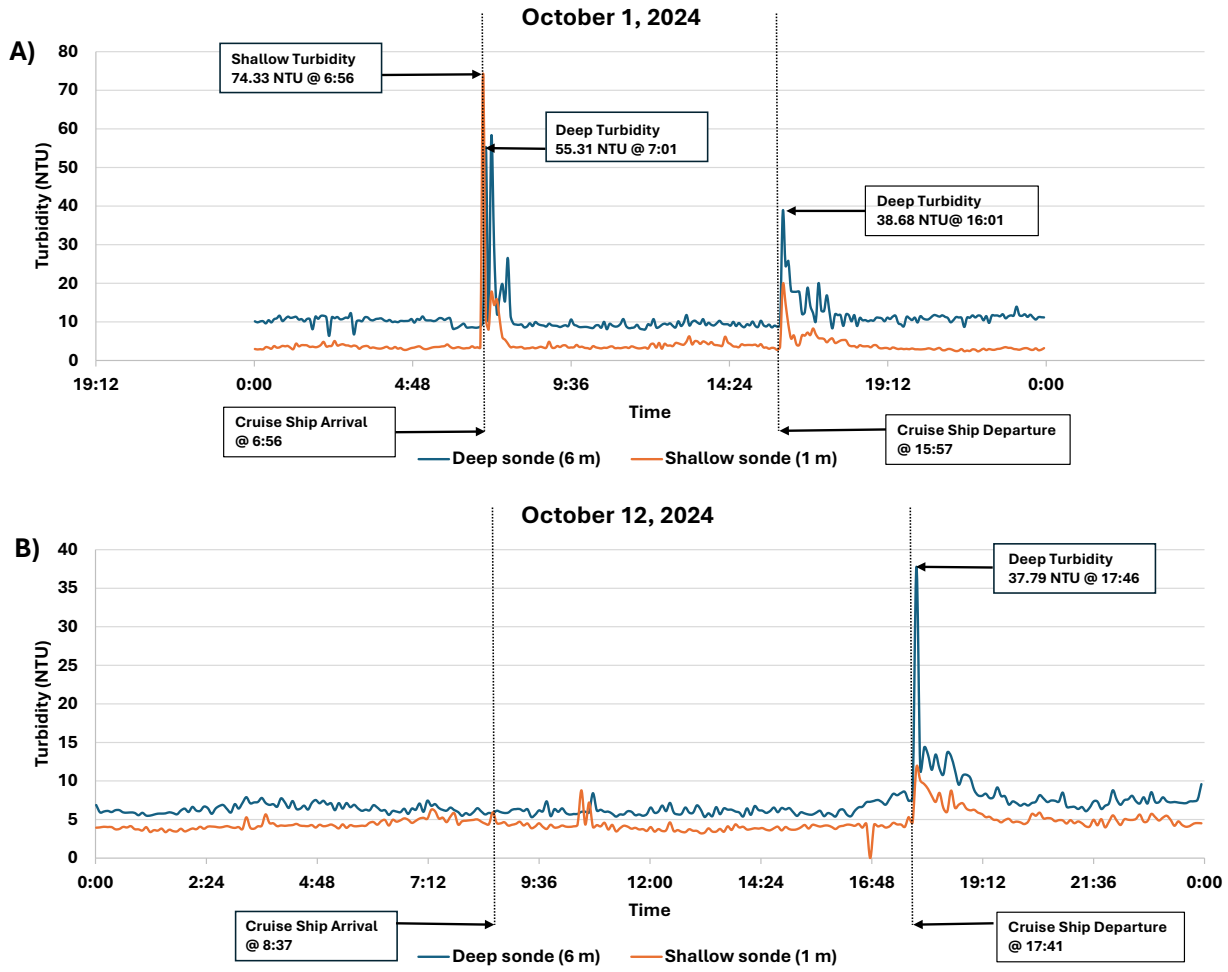
4.1.1.13 October 2024 Turbidity Events >29 NTU

There were five turbidity events > 29 NTU in October 2024 strongly correlated with cruise ship activity or weather events in Key West Habor near Pier B and Mallory Square docks (Figure 18).

On October 1, 2024, there was a turbidity spike of 74.33 NTU on the shallow sonde and an accompanying turbidity spike of 55.31 NTU on the deep near the time of cruise ship arrival.

There was also a small yet significant turbidity spike of 38.68 NTU on the deep sonde near the time of cruise ship departure (Figure18 A). The time of cruise ship arrival and departure on October 1, 2024, was determined by observing webcam video of the precise moment the cruise ship reached and departed the dock at Pier B (Appendix A).

On October 12, 2024, there was a turbidity spike of 37.79 NTU on the deep sonde near the time of cruise ship departure (Figure 18 B). The time of cruise ship departure on October 12, 2024, was determined by observing webcam video of the precise moment the cruise ship departed the dock at Pier B (Appendix A).



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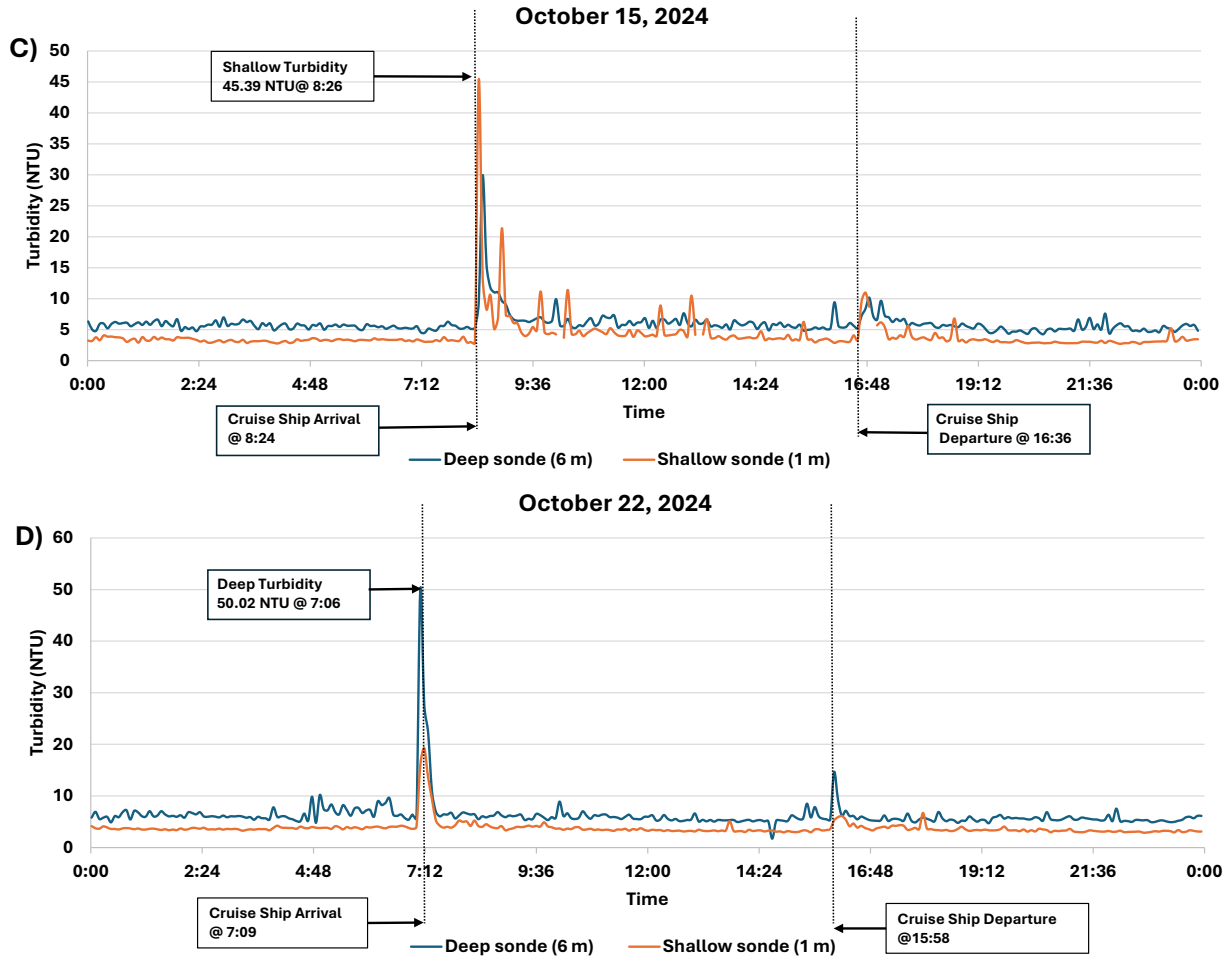


Figure 18. Graphs of turbidity events > 29 NTU in October 2024 recorded by the Turnkey water quality monitoring equipment deployed in Key West Harbor immediately adjacent to Pier B and Mallory Square docks.

On October 15, 2024, there was a turbidity spike of 45.39 NTU on the shallow sonde near the time of cruise ship arrival (Figure 18 C). The time of cruise ship arrival on October 15, 2024, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A).

On October 22, 2024, there was a turbidity spike of 50.02 NTU on the deep sonde near the time of cruise ship arrival (Figure 18 D). The time of cruise ship arrival on October 22, 2024, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A).

4.1.1.14 November 2024 Turbidity Events >29 NTU

There were two turbidity events > 29 NTU in November 2024 strongly correlated with cruise ship activity or weather events in Key West Habor near Pier B and Mallory Square docks (Figure 19).

On November 1, 2024, there was a turbidity spike of 52.24 NTU on the shallow sonde and a corresponding turbidity spike of 48.86 NTU on the deep sonde near the time of cruise ship arrival (Figure 19 A). The time of cruise ship arrival on November 1, 2024, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A).

On November 26, 2024, there was a turbidity spike of 42.61 NTU on the deep sonde near the time of cruise ship departure (Figure 19 B). The time of cruise ship departure on November 26, 2024, was determined by observing webcam video of the precise moment the cruise ship departed the dock at Pier B (Appendix A).

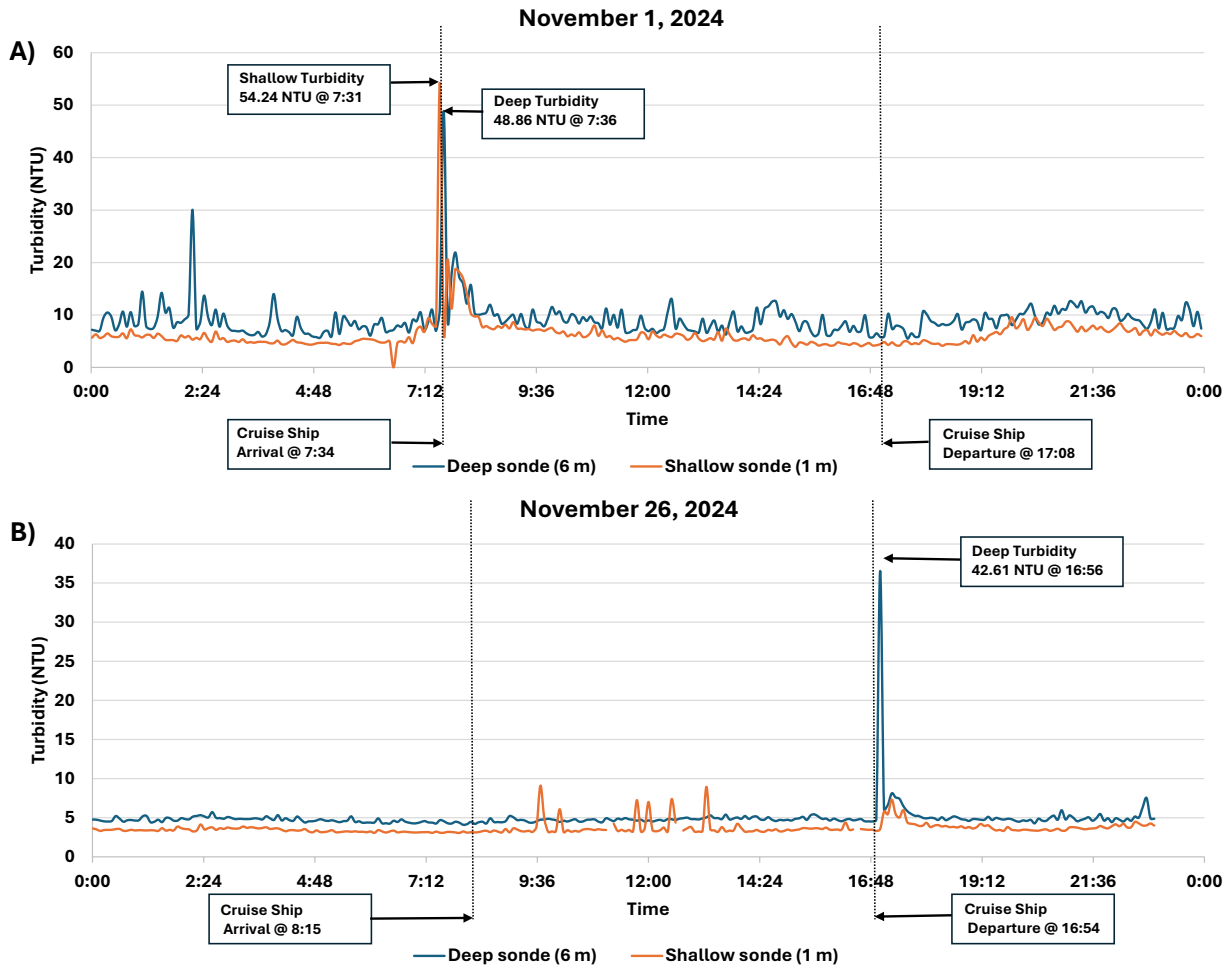


Figure 19. Graphs of turbidity events > 29 NTU in November 2024 recorded by the Turnkey water quality monitoring equipment deployed in Key West Harbor immediately adjacent to Pier B and Mallory Square docks.

4.1.1.15 December2024 Turbidity Events >29 NTU

There was a single turbidity event > 29 NTU in December 2024 strongly correlated with cruise ship activity or weather events in Key West Harbor near Pier B and Mallory Square docks (Figure 19). However, there was a turbidity spike of 50.84 NTU on the shallow sonde at 13:20 which was not associated with any cruise ship activity or weather events.

On December 12, 2024, there was a turbidity spike of 35.84 NTU on the deep sonde near the time of cruise ship arrival (Figure 20). The time of cruise ship arrival on December 12, 2024, was determined by observing webcam video of the precise moment the cruise ship reached the dock at Pier B (Appendix A).

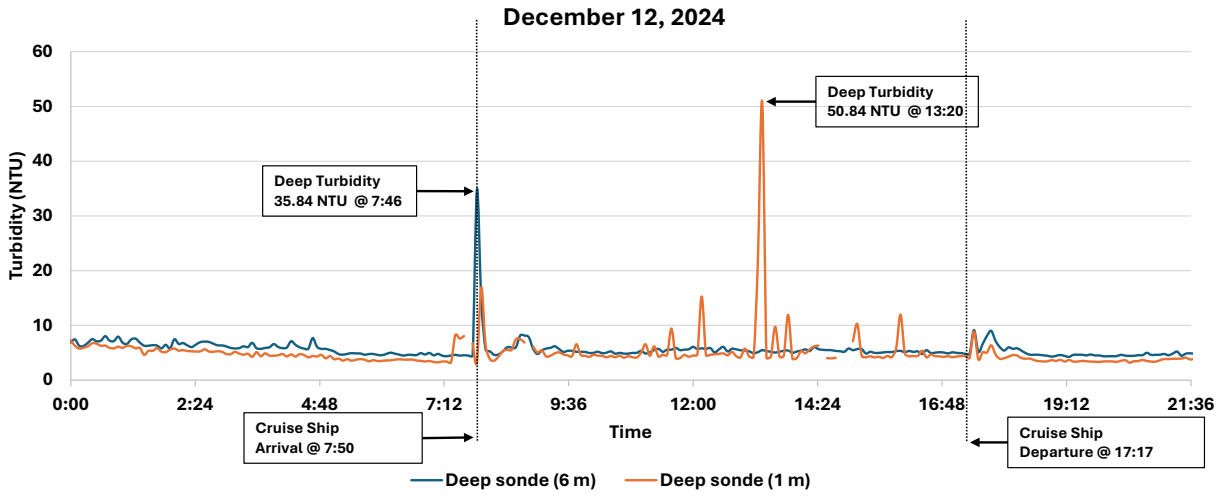


Figure 20. Graphs of turbidity events > 29 NTU in December 2024 recorded by the Turnkey water quality monitoring equipment deployed in Key West Harbor immediately adjacent to Pier B and Mallory Square docks.

4.1.1.16 Weather Effects on Water Quality in Key West Harbor

Weather events, especially wind and rain, impacted environmental conditions in Key West Harbor. The TK system remained operational during three major storm events in 2024 including Tropical Storm Debby (August 4, 2024), Hurricane Helene (September 26, 2024), and Hurricane Milton (October 9, 2024). The storms brought strong winds that impacted turbidity in Key West Harbor (Figure 21). Elevated turbidity readings from August 3-6, 2024, were associated with Tropical Storm Debby with some readings as high as 76 NTU beyond background measurements (Figure 21 A). Elevated turbidity readings from September 26-29, 2024, were associated with Hurricane Helene with some readings as high as 67 NTU beyond

background measurements (Figure 21 B). Elevated turbidity readings throughout the day of October 9, 2026, were associated with Hurricane Milton with some readings as high as 61 NTU beyond background measurements (Figure 21 C). Elevated turbidity levels typically lasted for several days after the storm events.

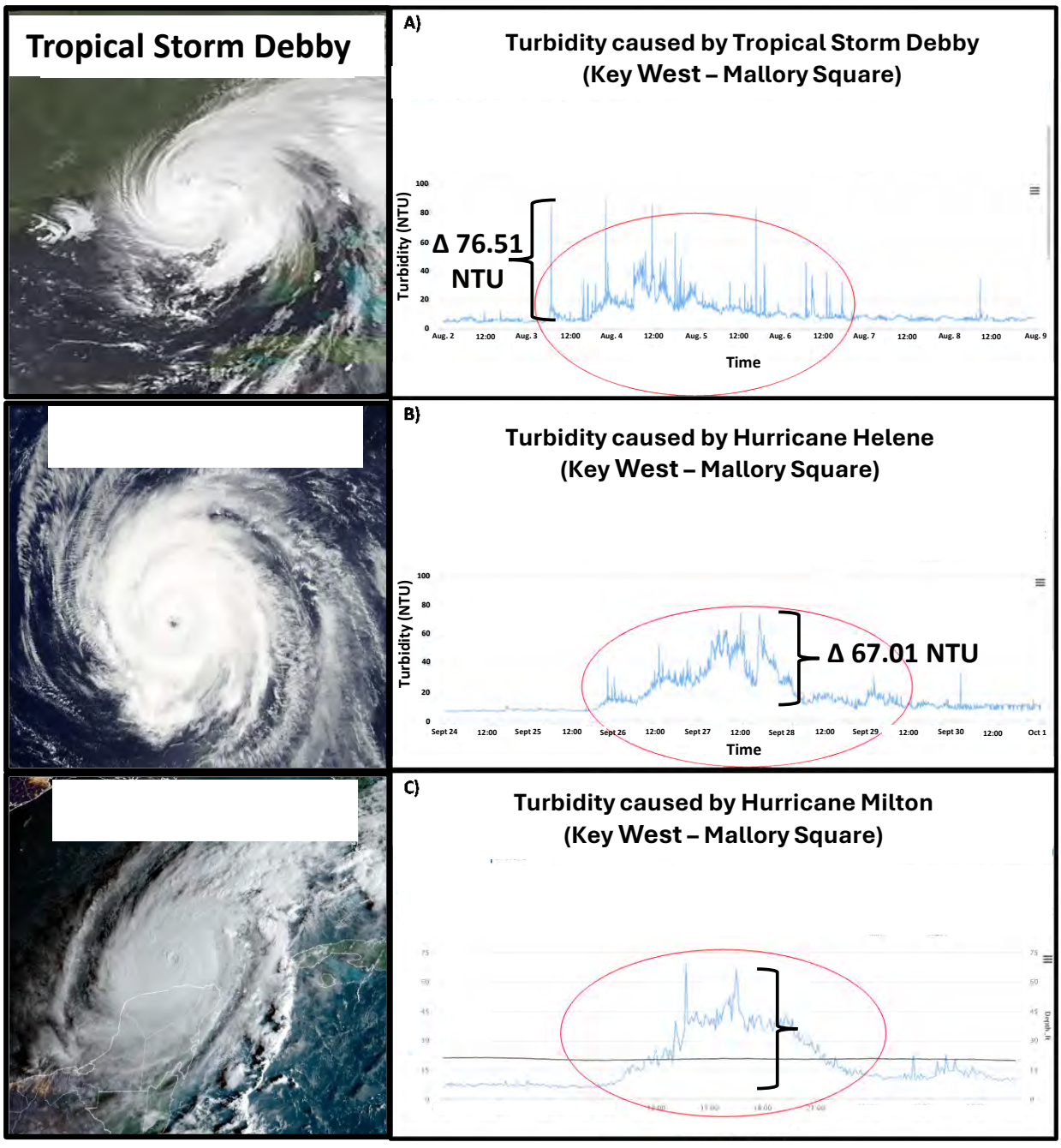


Figure 21. Images and graphs of storm events impacting the turbidity of Key West Harbor. A) a graph of turbidity levels during Tropical Storm Debby showing the elevations from background turbidity levels (Δ 76.51 NTU), B) a graph of turbidity levels during Hurricane Helene showing the elevations from background turbidity levels (Δ 67.01), and C) a graph

of turbidity levels during Hurricane Milton showing the elevations from background turbidity levels (Δ 76.51 NTU). NTU = nephelometric turbidity units.

There was also a strong relationship between elevated turbidity levels and chlorophyll-*a* measurements (Figure 22). Chlorophyll-*a* measurements mirrored turbidity measurements closely during Tropical Storm Debby (Figure 22 A), Hurricane Milton (Figure 22 C), and, to a lesser extent, during Hurricane Helene (Figure 22 B). Chlorophyll-*a* measurements were also mirroring turbidity events associated with cruise ship activity (Figure 22 A).

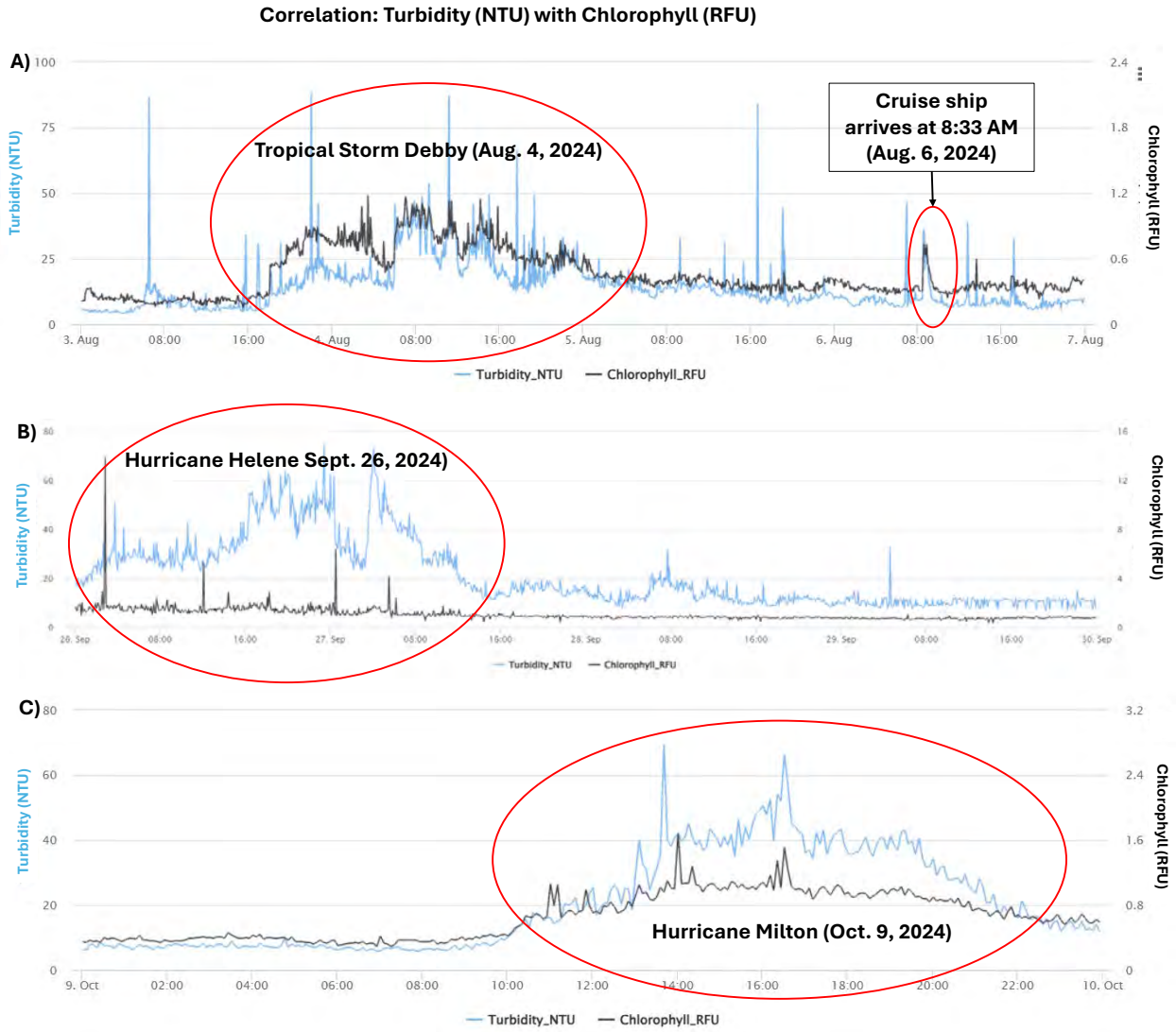


Figure 22. Graphs of turbidity and chlorophyll measurements in Key West Harbor in 2024 during: A) Tropical Storm Debby, B) Hurricane Helene, and C) Hurricane Milton.

Storm events also influenced conductivity/salinity measurements in Key West Harbor (Figure 23). Conductivity readings on the deep sonde (6 m depth) decreased by about 66% during rain events recorded during September and October 2024 (Figure 23). However, there were not

similar measurements recorded on the shallow sonde (1 m depth) during this time period, nor were their similar conductivity decreases measured during August 2024 rain events (i.e. Tropical Storm Debby).

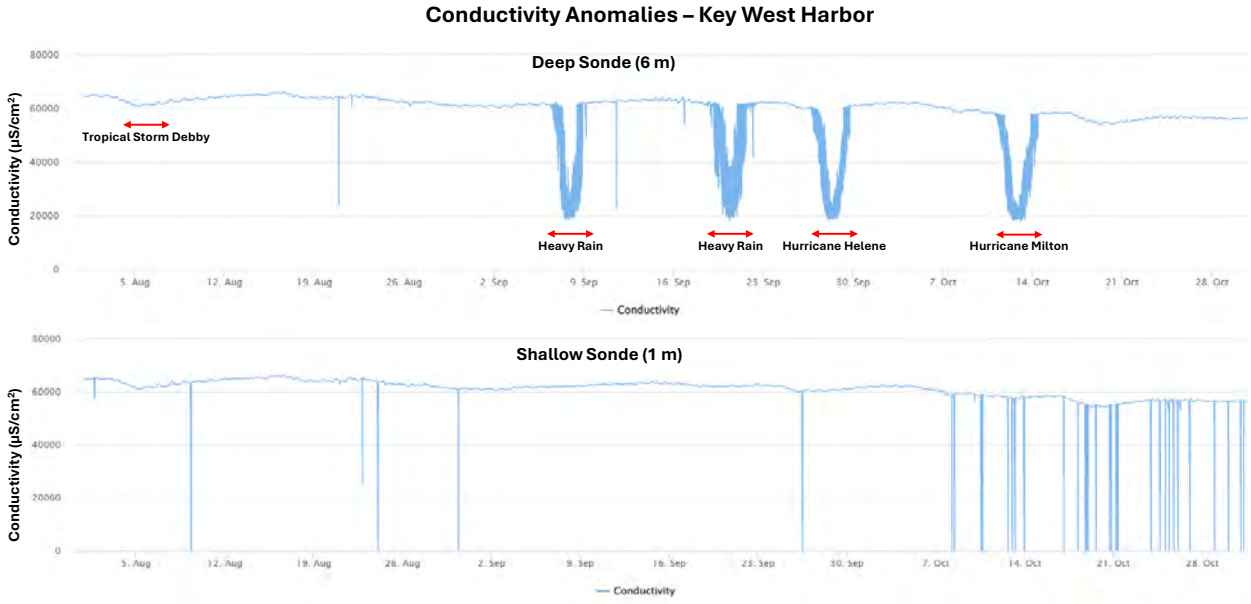


Figure 23. Graphs of conductivity measurements recorded on the deep and shallow sondes deployed on the Yellowman mooring station in Key West Harbor. Notice substantial decreases in conductivity associated with rain events.

4.1.2 Monitoring results for cruise ship traffic in Key West Harbor

There were thirty-five turbidity events >29NTU beyond background turbidity levels correlated with cruise ship activity in the Key West Harbor (Table 5).

Table 5. Turbidity events correlated with cruise ship activity.

Date	Ship Arrival or Departure Time	Turbidity		
		Before	After	Change
11/16/2023	7:40	4.5	45.63	41.13
11/17/2023	8:00	2.06	33.58	31.52
11/26/2023	17:01	1.69	133.07	131.38
12/18/2023	7:10	9.59	52.68	43.09
12/20/2023	17:02	8.33	92.63	84.3
12/24/2023	18:35	9.27	63.4	54.13
12/25/2023	7:36	20.29	96.89	76.6

12/25/2023	16:53	8.19	133.94	125.75
12/27/2023	7:29	5.5	37.82	32.32
12/29/2023	7:15	5.22	53.77	48.55
1/25/2024	7:56	17.1	50.21	33.11
1/25/2024	17:22	8.39	71.9	63.51
2/12/2024	18:36	10.4	42.29	31.89
2/23/2024	16:51	2.77	49.85	47.08
3/24/2024	7:30	8.07	74.23	66.16
3/25/2024	10:23	9.03	51.67	42.64
4/4/2024	10:59	3.59	34.94	31.35
4/5/2024	7:37	6.18	126.62	120.44
4/5/2024	16:50	3.33	37.06	33.73
4/12/2024	7:40	4.63	47.36	42.73
4/30/2024	16:47	7.8	60.19	52.39
6/1/2024	17:51	2.87	41.5	38.63
6/28/2024	16:52	4.11	34.96	30.85
7/15/2024	18:48	4.48	35.57	31.09
7/20/2024	18:00	1.28	140.03	138.75
8/9/2024	17:02	7.45	51.29	43.84
8/20/2024	15:54	8.7	200.11	191.41
10/1/2024	6:56	3.4	74.33	70.93
10/1/2024	15:57	9.2	38.68	29.48
10/12/2024	17:41	7.7	37.79	30.09
10/15/2024	8:24	5.97	45.39	39.42
10/22/2024	7:09	6.98	50.02	43.04
11/1/2024	7:34	5.91	54.24	48.33
11/26/2024	16:54	4.81	42.61	37.8
12/12/2024	7:49	3.69	131.59	127.9
Total = 35 events				

4.1.3 Field Sampling Results in Key West Harbor, Key West Shipping Channel, EDR and WDR

Results from CAChE Laboratory data were analyzed by sample site. Specific water quality metrics were plotted against each other to determine how the relationship compared to Redfield Ratios. Results for the Key West Harbor sample sites (KW01-KW06) are presented along with the Key West Shipping Channel (KW07-KW16) and EDR and WDR.

4.1.3.1 Soluble Reactive Phosphorus (SRP) versus Total Inorganic Nitrogen (TIN)

Scatter plot analysis indicated outliers for both SRP and TIN, therefore the data was Log_{10} transformed on both axes to reduce the impact of outliers on the trendline. In most cases SRP values were below the Method Detection Limits (MDL) indicating low levels of SRP, so ratio variance was driven mostly by changes in TIN measurements. The SRP:TIN ratio (i.e. phosphorus to nitrogen) was graphed with Log_{10}SRP on y-axis and Log_{10}TIN on the x-axis (which is the inverse of the typical presentation of the N:P Redfield ratio) to better represent the data and trendline analysis. The SRP:TIN ratio values and associated trendlines for all sample sites were below the inverse Redfield ratio (P_1:N_{16}). At all sample sites there was a slightly positive correlation between SRP:TIN with the trendlines and associated positive slopes. As TIN values increased, SRP values were stable or only increased slightly. However, the trendline slope for samples taken from WDR was greater than other sample sites and closer to the Redfield Ratio slope (Figure 23; bottom right corner).

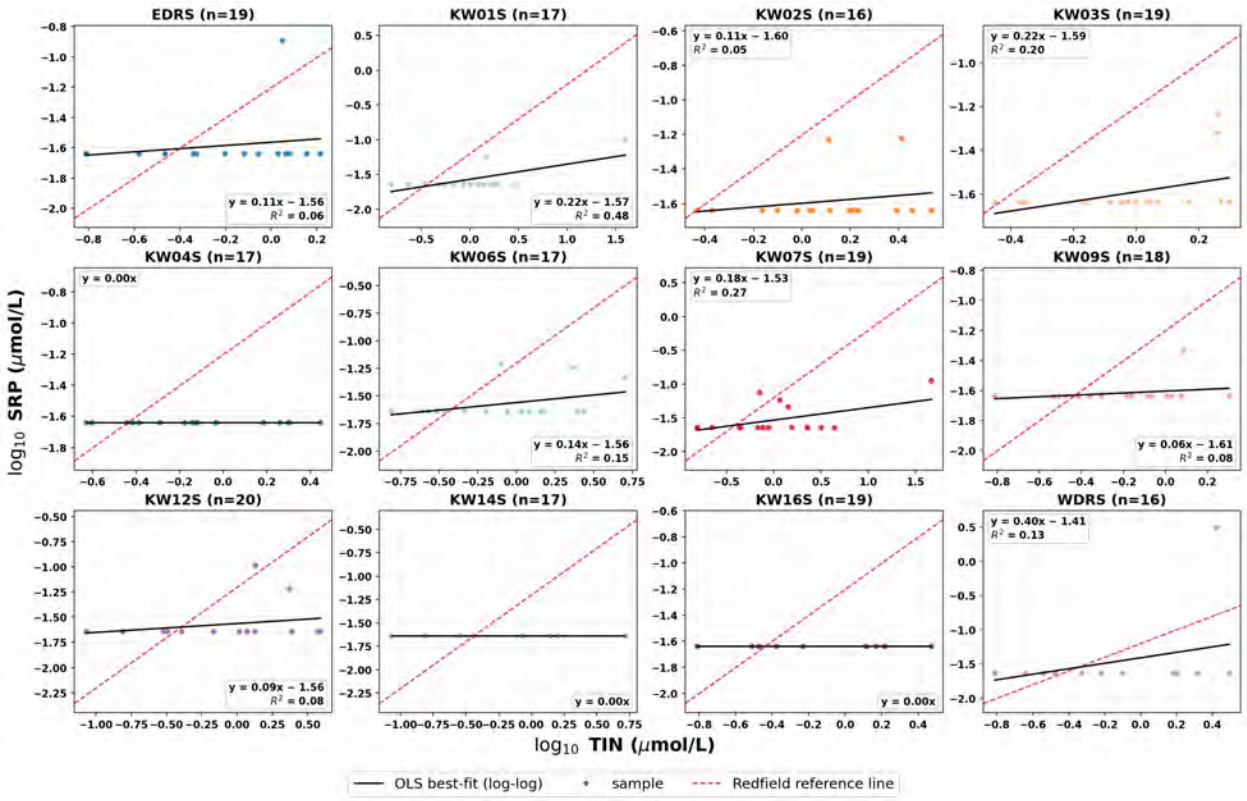


Figure 23. Graphical representation of the relationship between soluble reactive phosphorus (SRP) and total inorganic nitrogen (TIN) at each water sample site during the KWWQ project. Red dotted lines indicate the inverse Redfield Ratio for phosphorus to nitrogen (P_1:N_{16}).

4.1.3.2 Total Organic Carbon (TOC) versus Total Inorganic Nitrogen (TIN)

Scatter plot analysis indicated outliers for both TOC and TIN, therefore the data was Log_{10} transformed on both axes to reduce the impact of outliers on the trendline. The TOC:TIN ratio (i.e. carbon to nitrogen) was graphed with Log_{10}TOC on y-axis and Log_{10}TIN on the x-axis (consistent with the typical presentation of the C:N Redfield ratio). The TOC:TIN ratio values and associated trendlines for all sample sites were above the Redfield ratio (C_{106}:N_{16}). Trendlines at most sights had a slightly negative slope or neutral correlation between TOC:TIN. As TIN values increased, TOC values were constant or only decreased slightly.

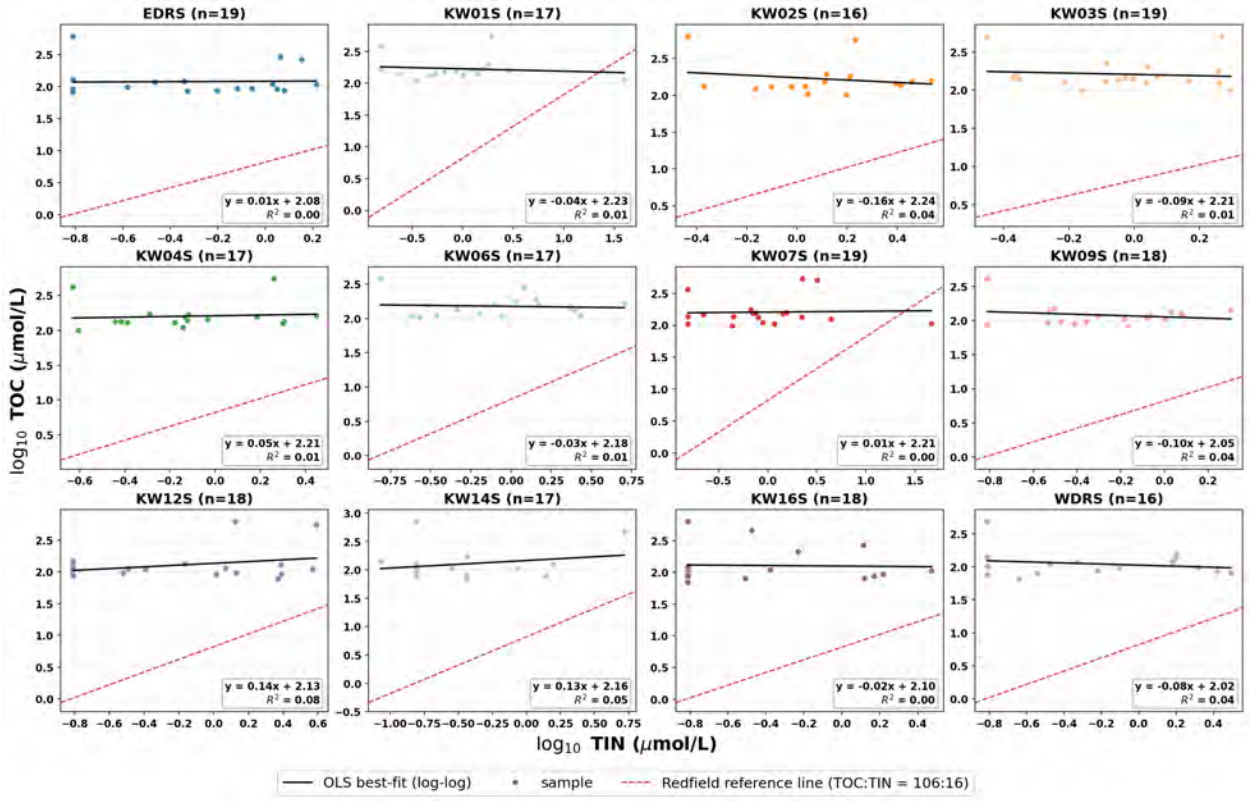


Figure 24. Graphical representation of the relationship between total organic carbon (TOC) and total inorganic nitrogen (TIN) at each water sample site during the KWWQ project. The red dotted lines indicate the Redfield Ratio for carbon to nitrogen (C_{106}:N_{16}).

4.1.3.3 Total Organic Carbon (TOC) versus Soluble Reactive Phosphorus (SRP)

Scatter plot analysis indicated outliers for both TOC and SRP, therefore the data was Log_{10} transformed on both axes to reduce the impact of outliers on the trendline. In most cases, SRP values were below the Method Detection Limits (MDL), indicating low levels of SRP, so ratio variance was driven mostly by changes in TOC measurements. The TOC:SRP ratio (i.e. carbon to phosphorus) was graphed with Log_{10}TOC on y-axis and Log_{10}SRP on the x-axis (consistent with the typical presentation of the C:P Redfield ratio). The TOC:SRP ratio values and associated trendlines for all sample sites were above the Redfield ratio (C_{106}:P_1). Trendline slopes were near zero with neutral correlation between TOC:SRP. As TOC values increased, SRP values were constant.

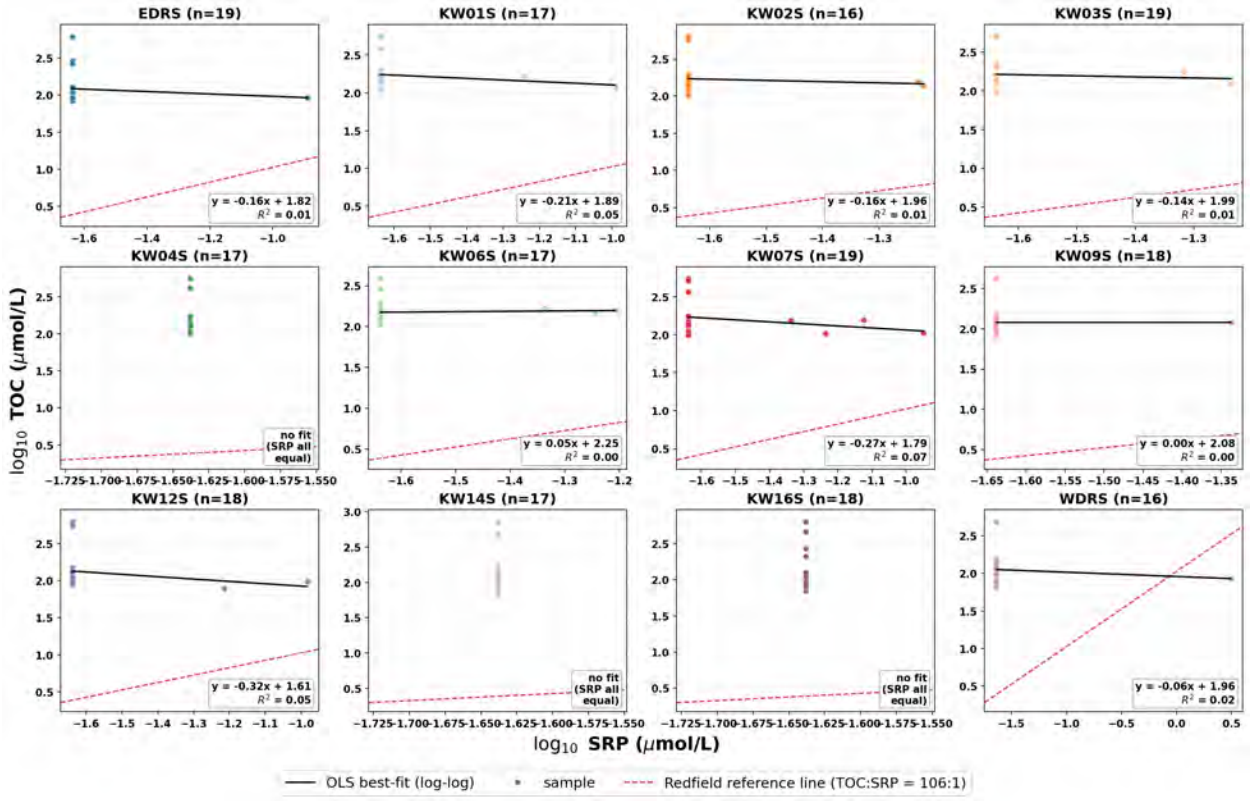


Figure 25 Graphical representation of the total organic carbon (TOC) to soluble reactive phosphorus (SRP) relationship at each water sample site during the KWWQ project. The red dotted lines indicate the Redfield Ratio for carbon to phosphorus (C_{106}:P_1).

4.1.3.4 Total Organic Carbon (TOC) versus Silicon (Si)

Scatter plot analysis indicated outliers for both TOC and Si, therefore the data was Log_{10} transformed on both axes to reduce the impact of outliers on the trendline. The TOC:Si ratio (i.e. carbon to silicon) was graphed with Log_{10}TOC on y-axis and Log_{10}Si on the x-axis (consistent with the typical presentation of the C:Si Redfield ratio). The TOC:Si ratio values and associated

trendlines for all sample sites were above the Redfield ratio (C_{106}:Si_{15}). Trendlines at most sights were near zero with almost no slope. As Si values increased, TOC values were nearly constant.

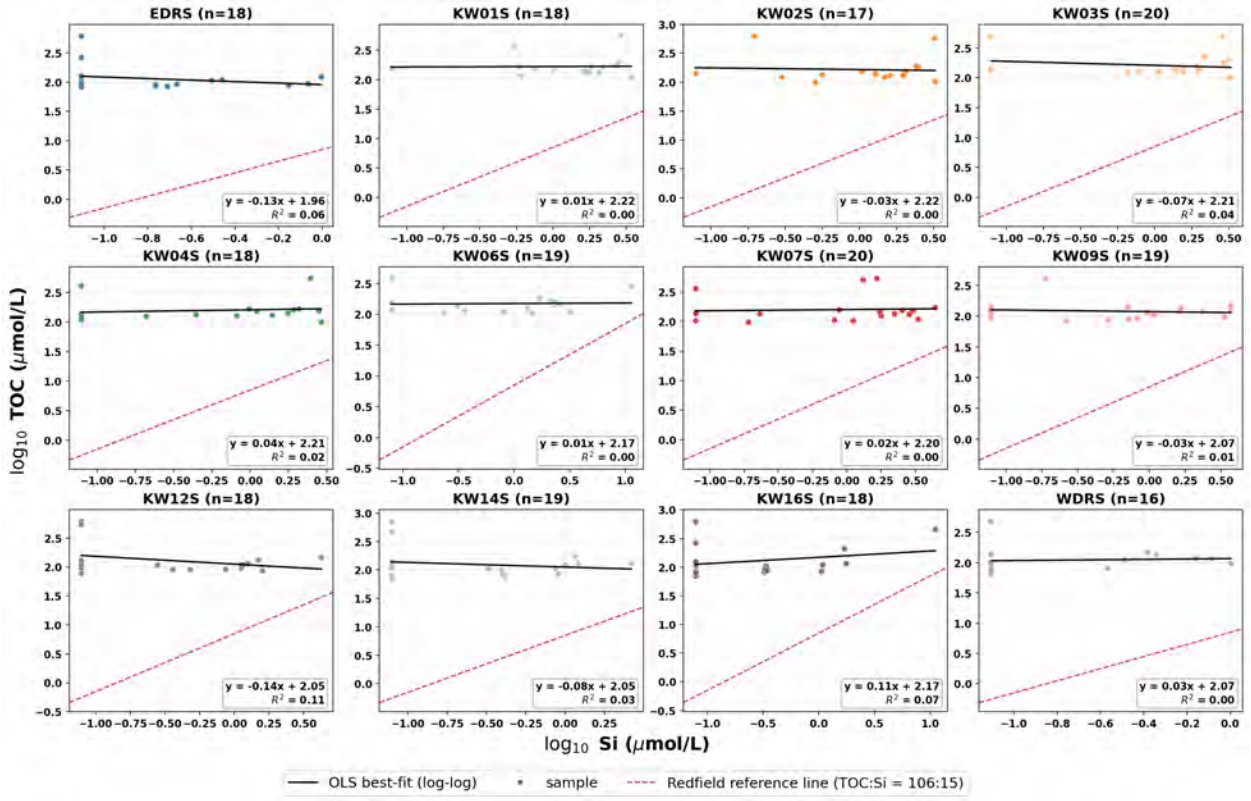


Figure 26. Graphical representation of the silicon (Si) to total organic carbon (TOC) relationship at each water sample site during the KWWQ project. Red dotted lines indicate the Redfield Ratio for (C_{106}:Si_{15}).

4.1.3.5 Total Organic Nitrogen (TIN) versus Silicon (Si)

Scatter plot analysis indicated outliers for both TIN and Si, therefore the data was Log_{10} transformed on both axes to reduce the impact of outliers on the trendline. The TIN:Si ratio (i.e. nitrogen to silicon) was graphed with Log_{10}TIN on y-axis and Log_{10}Si on the x-axis (consistent with the typical presentation of the N:Si Redfield ratio). With the exception of WDR, the TIN:Si ratio values and associated trendlines for all sample sites were above the Redfield ratio (C_{106}:Si_{15}). Trendline slopes were highly variable between sights. Both Si and TIN values were highly variable.

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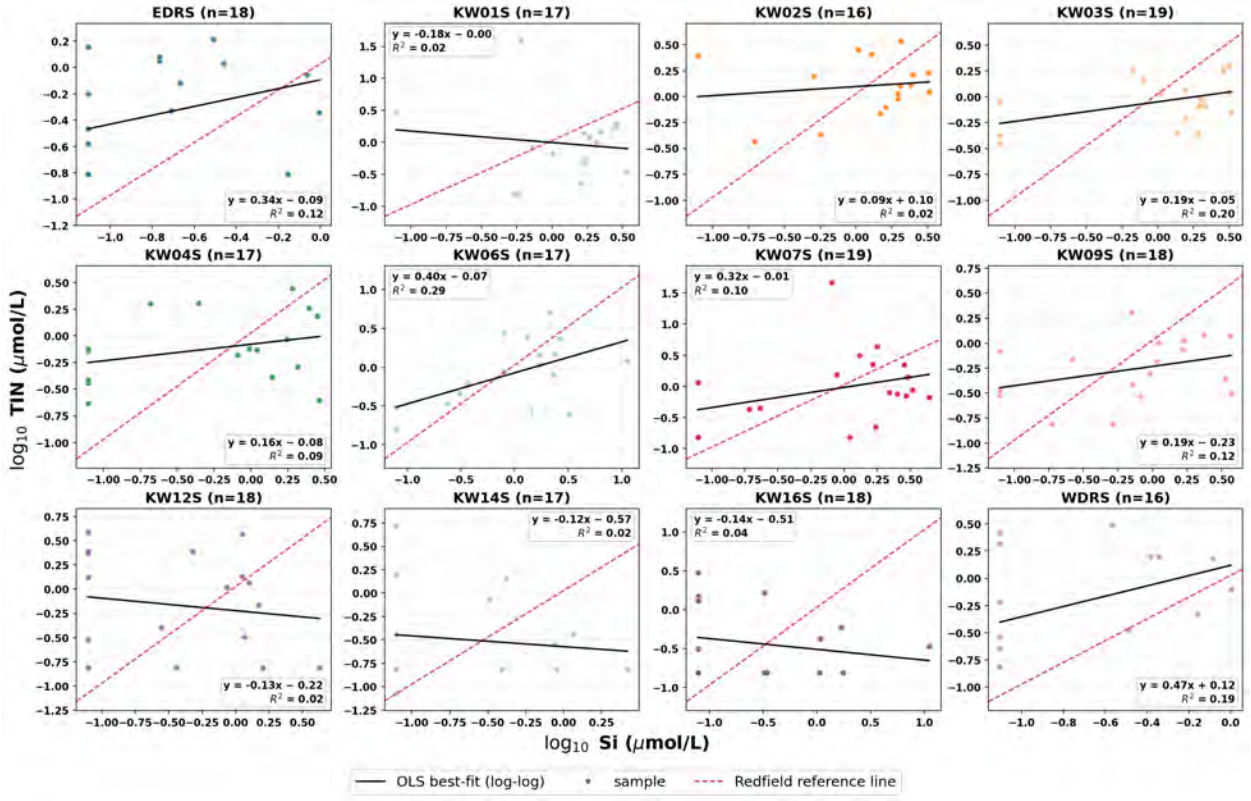


Figure 27. Graphical representation of the silicon (Si) to total inorganic nitrogen (TIN) relationship at each water sample site during the KWWQ project. Red dotted lines indicate the Redfield Ratio for (N_{16}:Si_{15}).

4.1.3.6 Silicon (Si) versus Soluble Reactive Phosphorus (SRP)

Scatter plot analysis indicated outliers for both Si and TIN, therefore the data was Log_{10} transformed on both axes to reduce the impact of outliers on the trendline. In most cases SRP values were below the Method Detection Limits (MDL) indicating low levels of SRP, so ratio variance was driven mostly by changes in Si measurements. The SRP:Si ratio (i.e. phosphorus to silicon) was graphed with Log_{10}SRP on y-axis and Log_{10}Si on the x-axis (consistent with the typical presentation of the Si:P Redfield ratio). The TIN:Si ratio values were highly variable with variation driven almost entirely by changes in Si values. Often there were no trendlines calculated because SRP values were identical for each sample and there was no clear relationship between Si:SRP values relative to the Redfield ratio (Si_{15}:P_1).

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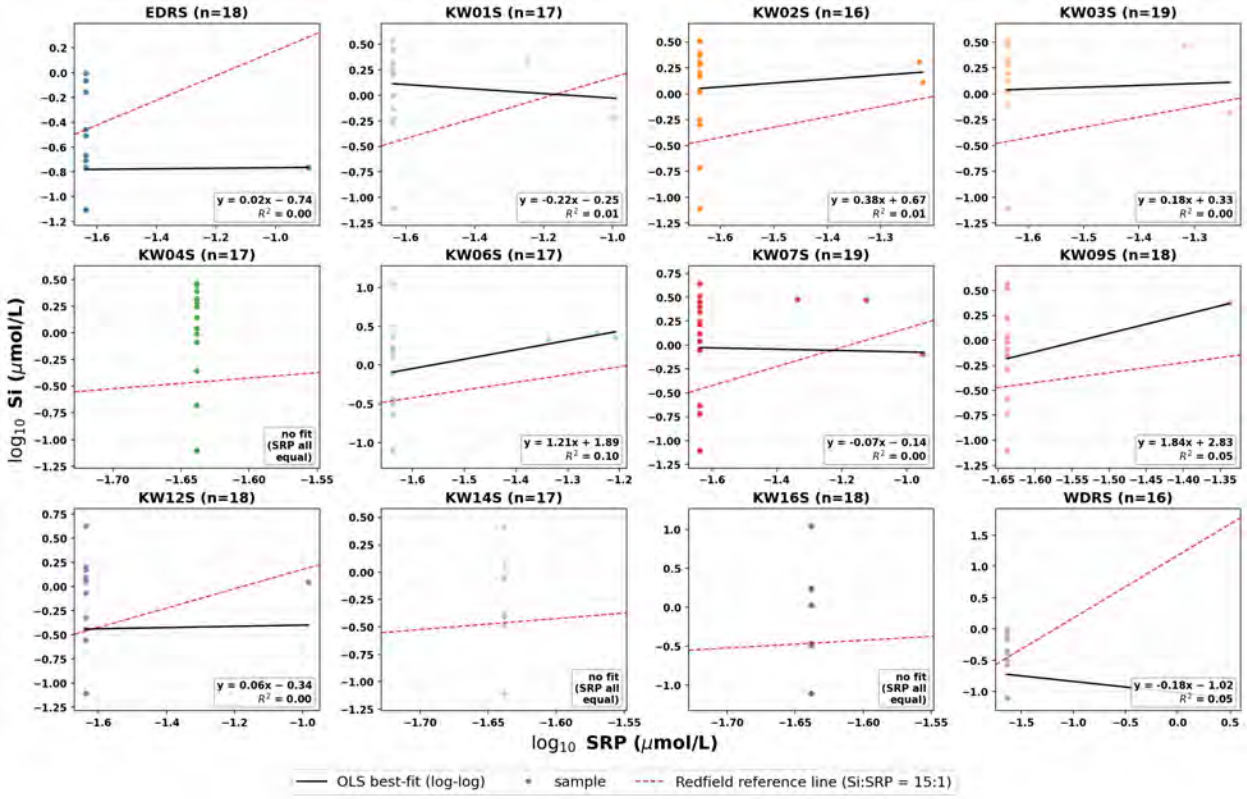


Figure 28. Graphical representation of the silicon (Si) to total soluble reactive phosphorus (SRP) relationship at each water sample site during the KWWQ project. Red dotted lines indicate the Redfield Ratio for (Si_{15}:P_1).

4.1.3.7 Chlorophyll-a versus Total Inorganic Nitrogen (TIN)

Scatter plot analysis indicated outliers for TIN but not for chlorophyll-*a*, therefore TIN data was Log_{10} transformed to reduce the impact of outliers on the trendline but chlorophyll-*a* values were not. The relationship between chlorophyll-*a* and TIN was graphed with chlorophyll-*a* values on y-axis and Log_{10}TIN on the x-axis. Data values and trendlines showed no clear relationship between chlorophyll-*a* and TIN. Trendlines between sample sites were highly variable.

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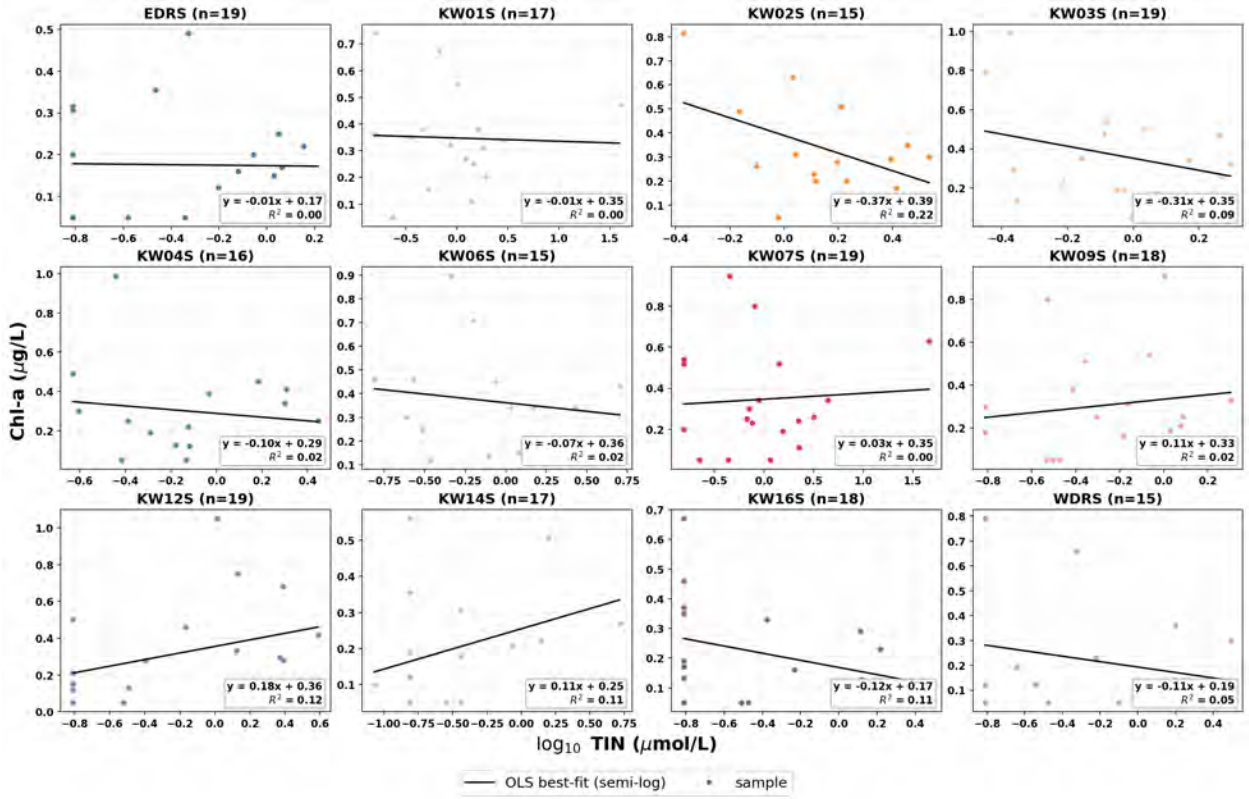


Figure 29. Graphical representation of the chlorophyll-*a* **to total inorganic nitrogen (TIN) relationship at each water sample site during the KWWQ project.**

4.1.3.8 Chlorophyll-a versus Soluble Reactive Phosphorus (SRP)

Scatter plot analysis indicated occasional outliers for SRP values but not for chlorophyll-*a* values, therefore SRP data was Log_{10} transformed to reduce the impact of outliers on the trendline and chlorophyll-*a* values were not. In most cases SRP values were below the Method Detection Limits (MDL) indicating low levels of SRP, so parameter variances were driven mostly by changes in chlorophyll-*a* values. The relationship between chlorophyll-*a* and SRP was graphed with chlorophyll-*a* values on y-axis and Log_{10}SRP on the x-axis. Data values and trendlines showed no clear relationship between chlorophyll-*a* and SRP. Trendlines between sample sites were highly variable.

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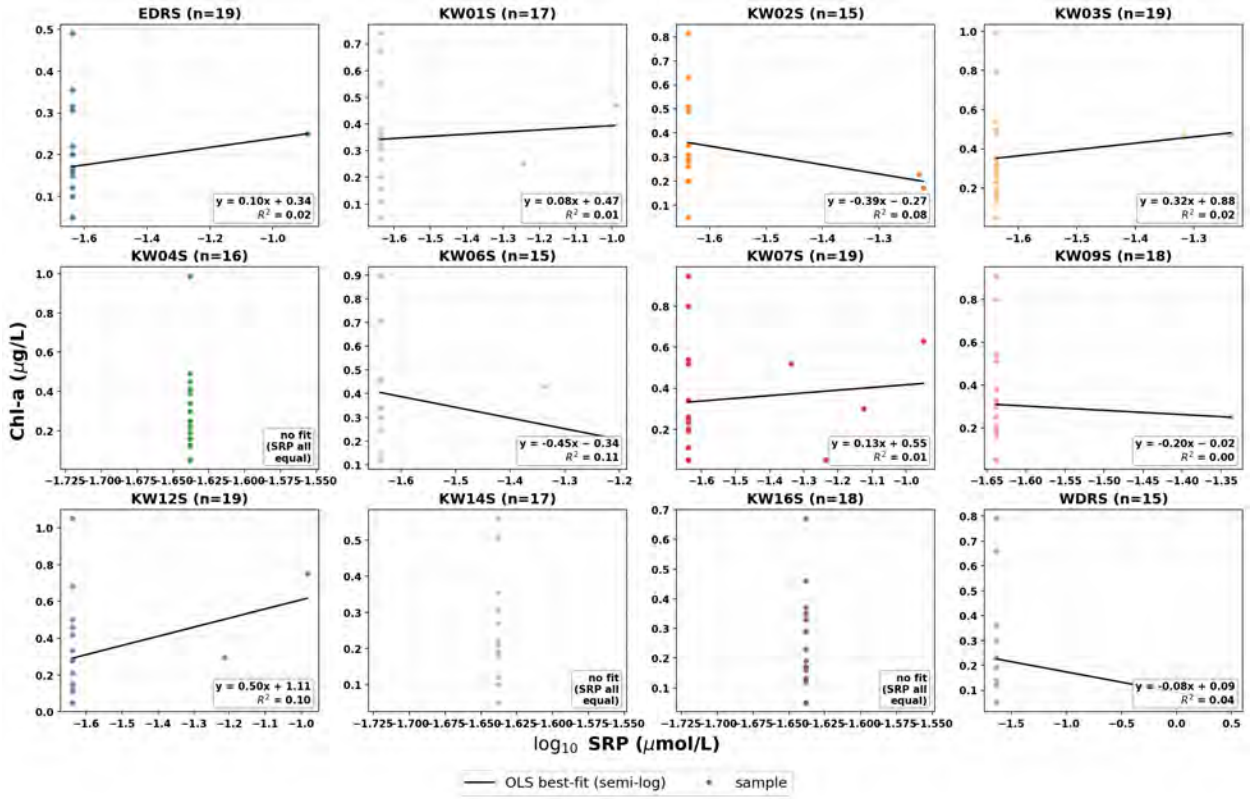


Figure 30. Graphical representation of the chlorophyll-*a* **to soluble reactive phosphorus relationship at each water sample site during the KWWQ project.**

4.1.4 In-situ field measurement results in Key West Harbor, Key West Shipping Channel, EDR and WDR

Results from *in-situ* field water quality measurement data were analyzed by sample site. The mean value for specific water quality metrics were plotted for each sample site with a 95% confidence interval. Results for the Key West Harbor sample sites (KW01-KW06) are presented along with the Key West Shipping Channel (KW07-KW16), EDR, and WDR.

The mean temperatures recorded in the study area over the duration of the KWWQ project were slightly cooler closer to Key West but not to any significant degree (Figure 31).

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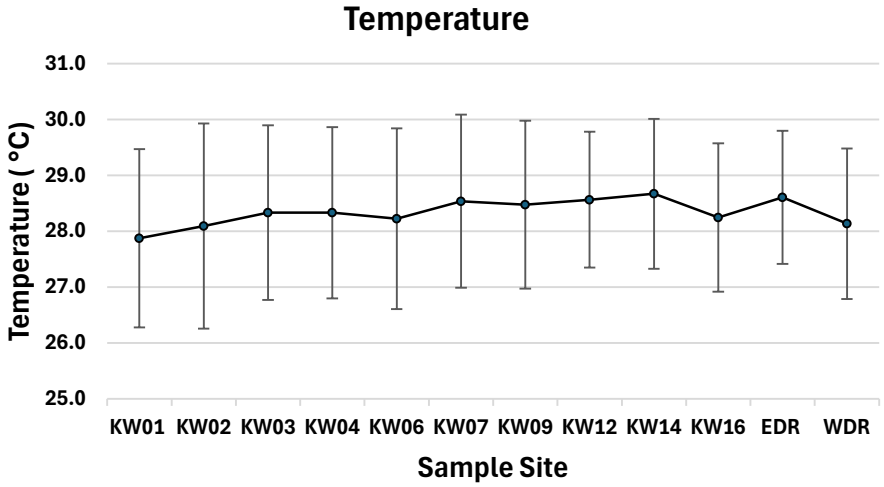


Figure 31. A plot of mean temperature (°C) with 95% confidence intervals for each water measurement site with distance from Key West Harbor increasing on the x-axis.

The mean dissolved oxygen values for each sample site were also relatively stable, fluctuating between approximately 6.2 mg/L and 6.4 mg/L (Figure 32).

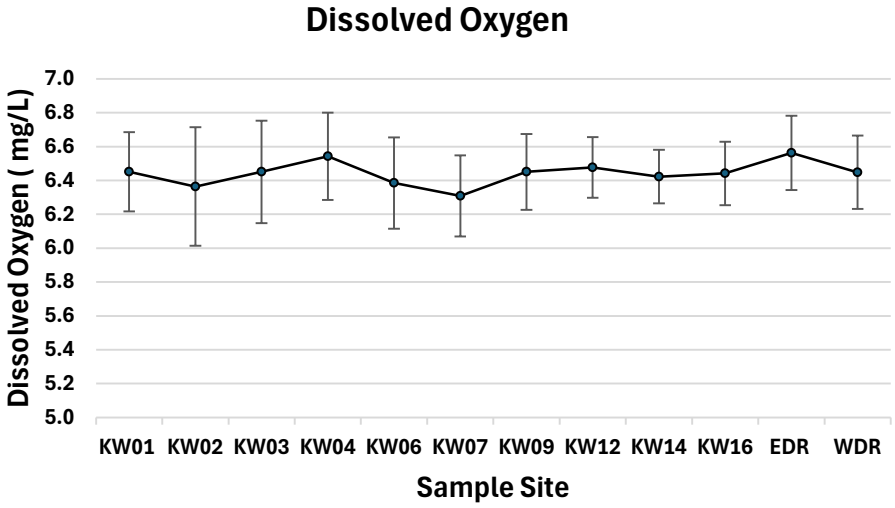


Figure 32. A plot of mean dissolved oxygen values (mg/L) with 95% confidence intervals for each water measurement site with distance from Key West Harbor increasing on the x-axis.

Although turbidity readings are generally low (i.e. <2NTU), an inverse relationship exists between turbidity and the distance from Key West with mean turbidity readings highest in Key West Harbor (KW01-KW06) and decreasing offshore with the lowest mean values reported at EDR and WDR (Figure 33).

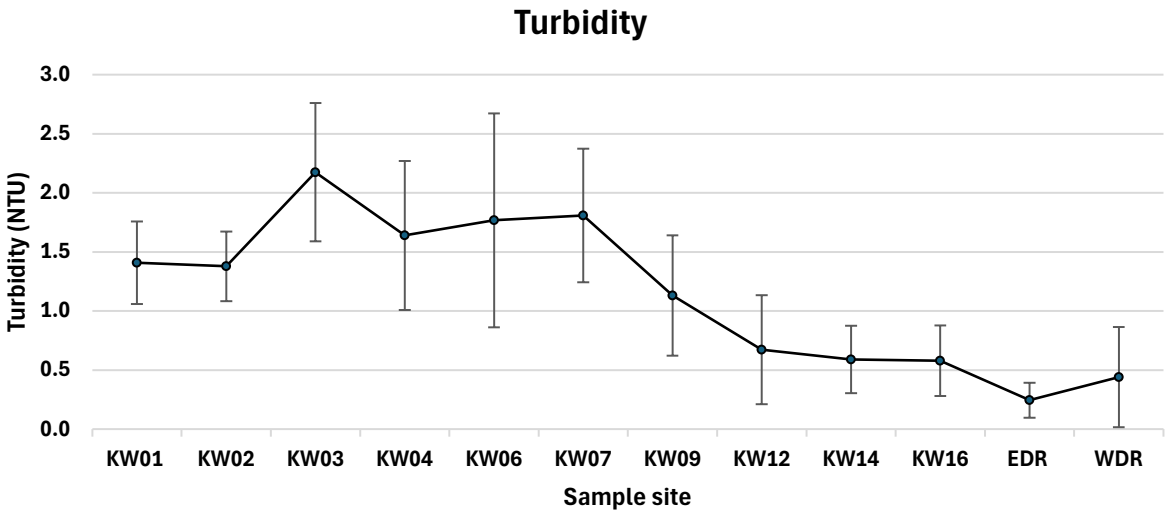


Figure 33. A graph of mean turbidity (NTU) with 95% confidence intervals for each water measurement site with distance from Key West Harbor increasing on the x-axis.

Salinity and conductivity where relatively stable fluctuating between 34-36 ppt and 52,000-56,000 µS/cm^2, respectively. There were periodic decreases in mean salinity and conductivity reported (Figure 34). Decreases in both salinity and conductivity were reported for KW07 with low values occurring for Trip 9 (September 22, 2024). There were also low values for conductivity at KW02 (Trip 9 and Trip 10 – November 30, 2024) and KW14 (Trip 9). These values correspond with extreme decreases in conductivity reported in the Key West Harbor from the TK system and heavy rain events reported for the period (Figure 34).

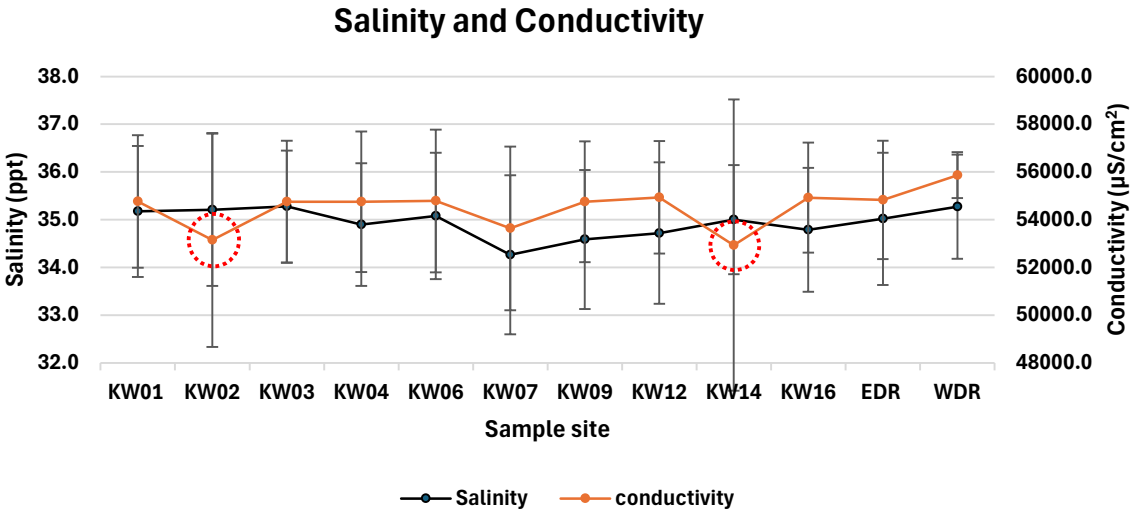


Figure 34. A plot of mean salinity (ppt) and conductivity (µS/cm^2) with 95% confidence intervals for each water measurement site with distance from Key West Harbor increasing on the x-axis. Red dotted circles indicate drops in conductivity associated with heavy rain events.

4.1.5 Archival sonde results in the Key West Shipping Channel, EDR, and WDR

Archival sondes were deployed near: (1) the Key West Shipping Channel (CBS Sonde), (2) EDR, and (3) WDR (Figure 1). There was limited success using archival sonde technology during the KWWQ project. Results are presented in the following sections.

4.1.5.1 Archival data sondes in the Key West Shipping Channel

Deployment, maintenance, and retrieval of water quality monitoring equipment near the Key West Shipping Channel and entrance to Key West Harbor was very problematic. Diving conditions in the area were extremely dangerous due to: (1) vessel traffic, (2) strong currents, and (3) low visibility.

A YSI 6600 model archival data sonde was deployed on October 10, 2023 to monitor water quality conditions in the area. The equipment was scheduled to be deployed during slack tide around 2:00 PM, however, deployment occurred after slack tide at 2:31 PM and the outgoing current was stronger and faster than anticipated. Therefore, there was uncertainty associated with deployment coordinates recorded during the process.

Due to dangerous vessel traffic in the area, the U.S. Coast Guard Auxiliary Service (Key West, FL) assisted with equipment recovery efforts by blocking vessel traffic around the equipment deployment area. However, efforts to retrieve the equipment were unsuccessful even though sector-scan and side-scan sonar units were employed during search and recovery efforts. Poor visibility and strong currents contributed to the dangerous diving conditions and, combined with uncertainty associated with GPS coordinates, were attributed as the primary reasons for lack of success.

4.1.5.2 Archival data sondes deployed at EDR and WDR

Archival data sondes were deployed near EDR and WDR on February 29, 2024. Sondes were recovered on April 6, 2024. The WDR sonde was in good condition, downloaded, and provided valuable water quality data for the area which is considered as a control for comparison to other water quality measurements in the study area.

The mean turbidity during the spring 2024 was 2.2 NTU. There were turbidity events in March 2024 and April 2024 that occurred during strong wind events (Figure 35).

(Continued on the next page)

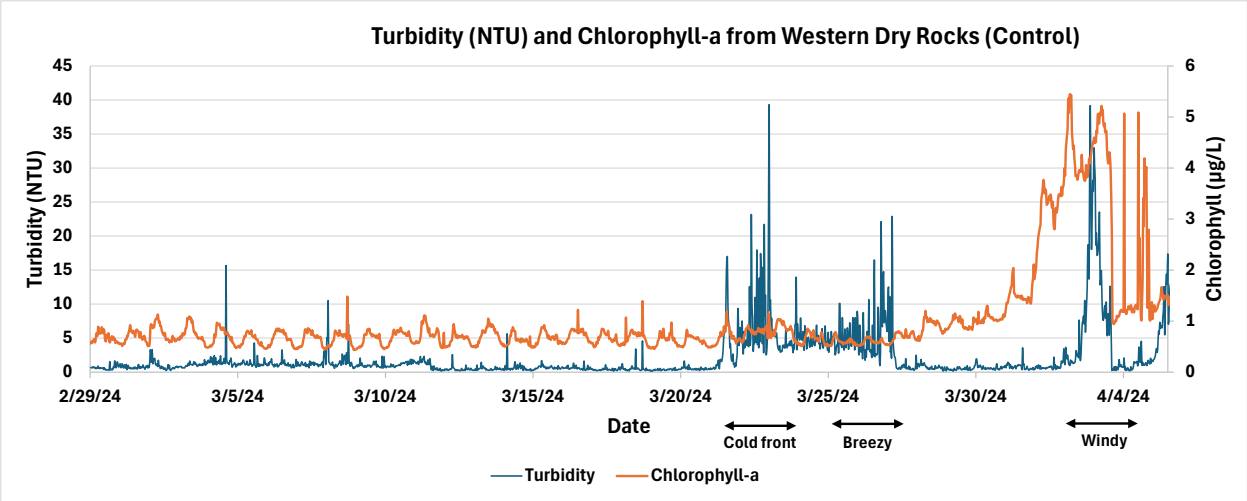


Figure 35. Turbidity (NTU) and chlorophyll (µg/L) measurements recorded at Western Dry Rocks (WDR) from 2/29/2024 through 4/4/2024. Corresponding weather events are also presented during periods with high readings.

Mean chlorophyll during spring 2024 was 1.0 µg/L at WDR. Chlorophyll measurements fluctuated daily around 1.0 µg/L but mirrored elevated turbidity readings during storm events (Figure 35).

Dissolved oxygen and pH had daily fluctuations but were relatively stable between 6-8 mg/L and 8.2-8.4 pH units, respectively during spring 2024 at WDR (Figure 36).

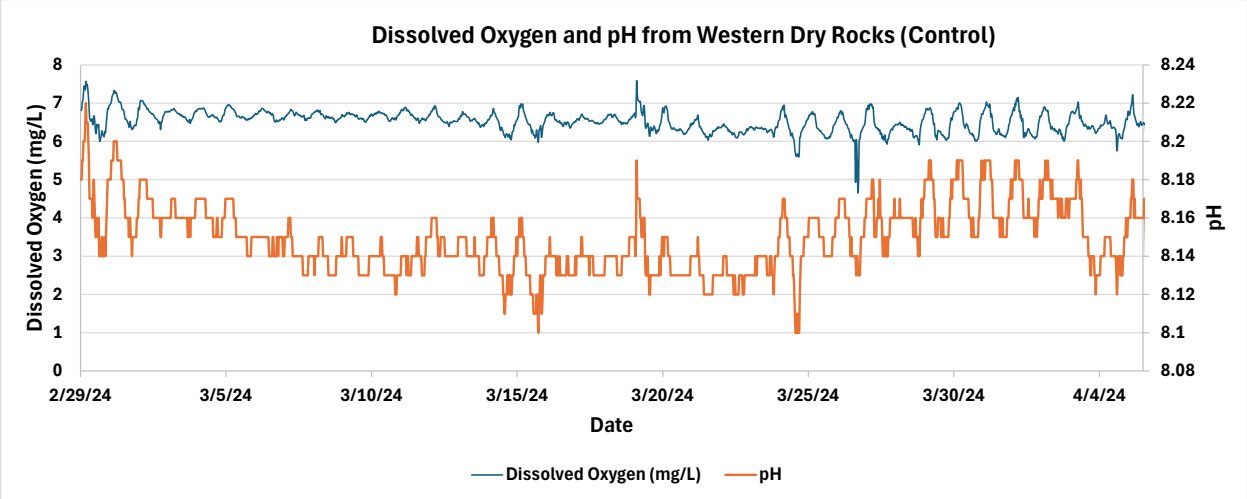


Figure 36. Dissolved oxygen (mg/L) and pH measurements recorded at Western Dry Rocks (WDR) from 2/29/2024 through 4/4/2024.

Temperature increased steadily from 2/29/2024 – 4/4/2024 from about 23°C to about 24.5°C. Conductivity was high but appeared very stable around 60,000 µS/cm^2 (i.e. 41 ppt)

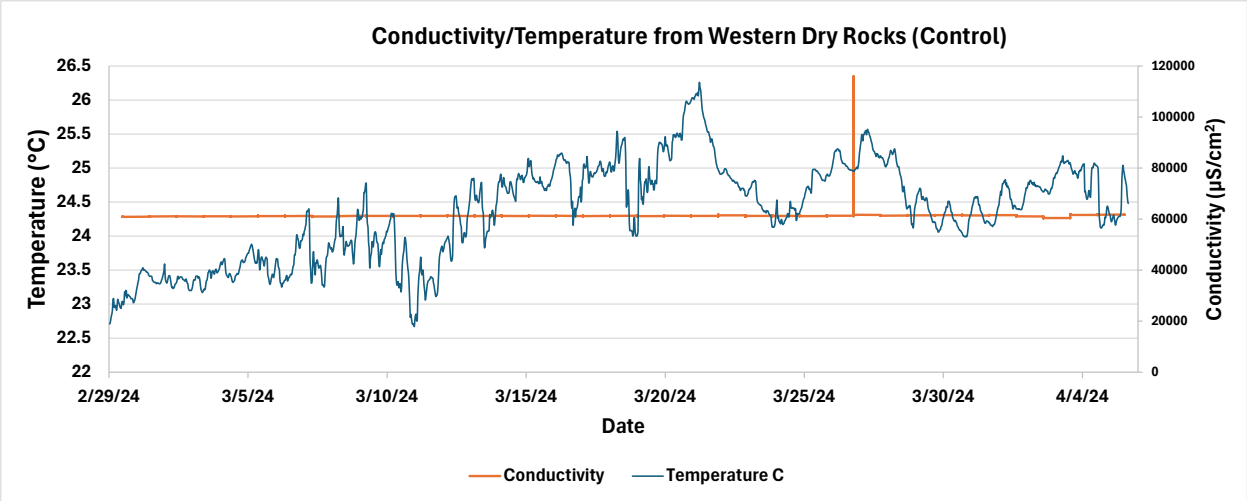


Figure 37. Temperature (°C) and conductivity (µS/cm^2) measurements recorded at Western Dry Rocks (WDR) from 2/29/2024 through 4/4/2024.

Unfortunately, the EDR sonde had water intrusion and was not functional. The damaged EDR sonde was sent back to Eureka to see if the data was salvageable but unfortunately it was not. The equipment was under warranty, so a new sonde was delivered. A backup sonde to replace the damaged EDR sonde and the still functioning WDR sonde were calibrated and prepared for deployment. Both the WDR and new EDR sondes were subsequently redeployed on June 28, 2024.

Recovery efforts in August 2024 for routine maintenance and recalibration were delayed by severe weather conditions (i.e. Tropical Storm Debby). Subsequent recovery efforts revealed that the storm caused damage to equipment deployed at WDR including damage to the sonde anchor system (Figure 38). The WDR sonde was removed but was severely damaged and not functional. Therefore, no data could be downloaded. The EDR sonde experienced similar damage and was also not functional therefore, no data could be downloaded. Both units were sent back to Eureka, but data could not be recovered.

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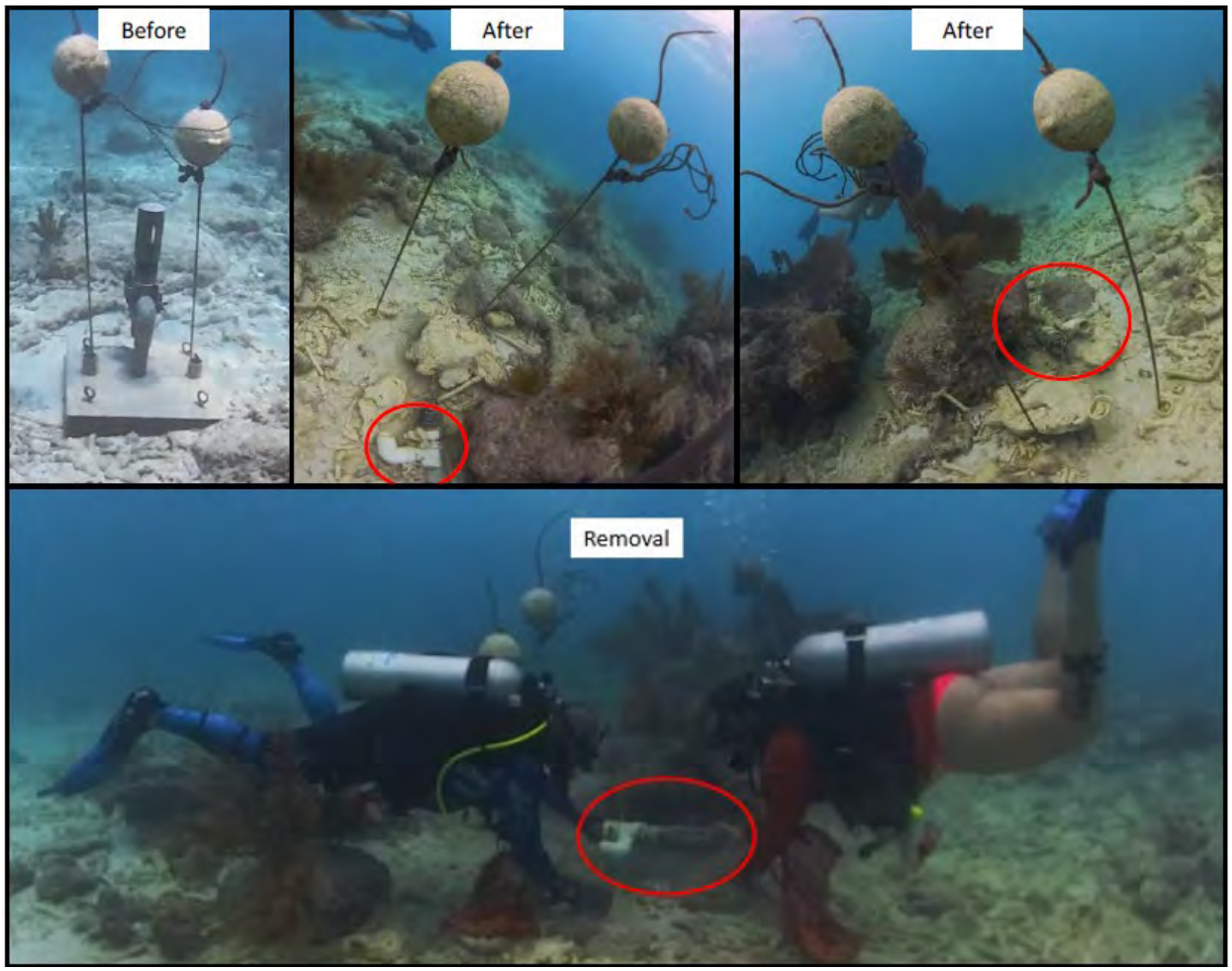


Figure 38. Images of the WDR sonde before and after Tropical Storm Debby. (Bottom) The PI and scientific diver removing the equipment from the location near WDR.

5.0 Discussion

Monitoring water quality in the waters around Key West is essential to provide marine resource managers with the necessary information to effectively balance anthropogenic environmental stressors (e.g. vessel traffic and tourism) with the protection of water quality and vital marine habitats. The KWWQ project was intended to provide useful data to inform these important environmental decisions.

The water quality monitoring equipment deployed in Key West Harbor and Shipping Channel combined with monthly waters samples and *in-situ* field measures were the mechanisms employed to achieve the goals and objectives of the project. The project was also a valuable educational and training tool for marine science students at CFK supporting many research assistantships, internships, volunteers, and student research capstone projects.

The KWWQ project faced many challenges over the project performance period, but those challenges forced the researchers to adapt and overcome with creative alternatives, which often

yielded better outcomes than originally proposed. For example, the many issues that complicated deployment and retrieval of water quality monitoring equipment near Key West Harbor and the Key West Shipping Channel (e.g. dangerous diving, strong currents, low visibility, etc.) forced the researchers to explore other water quality monitoring options appropriate for the area. This led to the discovery of the TK system and exploring options and partnerships to deploy the equipment. The CFK research team was able to negotiate a partnership with the City of Key West to deploy the equipment of city property on the Yellowman mooring station immediately adjacent to Pier B and Mallory Square cruise ship docks. The TK system performed extremely well providing near real-time water quality monitoring data in an area ideally suited for this purpose. Moreover, the TK system survived several severe weather events that destroyed other water quality monitoring equipment deployed in the study area.

5.1 Monitoring water Quality in the Key West Harbor

The water quality in Key West Harbor was impacted by a variety of environmental stressors over the duration of the study. Sever weather events like Tropical Storm Debby, Hurricane Helene, and Hurricane Milton, had the most apparent impacts on water quality in the harbor having substantial impacts on turbidity, salinity, and chlorophyll concentrations.

TK measurements during these severe storm events indicated prolonged elevated turbidity occasionally spiking > 75 NTU from background values. To put this in perspective, these turbidity readings are more than twice the allowable threshold value set by Florida Administrative Code (F.A.C.) 62-302.530 (Effective 8/4/2016) which states the criteria for surface water quality as “the maximum not to be exceeded at any time” as >29 NTU from background levels.

Similar to turbidity readings during these storm events, chlorophyll measurements closely paralleled elevated turbidity readings. This is important because chlorophyll concentration is the most common method for the determination of phytoplankton biomass (Holm-Hansen et al., 1965; Davies et al., 2018) and an important indicator of: (1) primary productivity, (2) harmful algal blooms (Anderson et al., 2021), (3) water quality (LaPointe et al., 1992; Boyer et al., 2009), and even for (4) natural disaster monitoring, especially droughts (Behera et al., 2025). There are a variety of methods used to detect and estimate chlorophyll concentrations in marine waters including: (1) various types of fluorometry (Holm-Hansen et al., 1965), inclusive or fluorescence spectroscopy (Zhu et al., 2026), (2) high performance liquid chromatography (HPLC) (Milenković et al., 2012), and (3) hyperspectral satellite imagining (Zhang et al., 2022), and more. The method for determining chlorophyll concentrations by the TK system EXO3s sondes during the KWWQ project employs fluorescence spectroscopy. Therefore, it is important to know how turbidity caused by the resuspension of benthic sediments would impact results associated with this technology.

Although chlorophyll itself is not a stable molecule when outside the cell and rapidly degrades upon phytoplankton cell death and sinking, the core structural backbone (i.e. tetrapyrrole) is a very stable molecule allowing chlorophyll degradation products like chlorins and porphyrins

to persist in marine sediments for long geological timescales (Chen et al., 2000; Szymczak-Żyła et al., 2011). Chlorins and porphyrins are natural fluorophores (i.e. fluorescent chemical compounds that absorb light energy at a specific wavelength and re-emit it at a longer wavelength) and both interfere with fluorescence spectroscopy (ICES, 2022; Lennon et al., 2002). This may have serious implications for chlorophyll analysis that utilizes fluorescence spectroscopy, especially when benthic sediments are resuspended into the water column (e.g. severe weather, ship prop wash, etc.).

One type of chlorophyll degradation product, a chlorin called pheophytin, is one of the most significant and common interference molecules during chlorophyll detection methods and methods for its removal from samples (i.e. acid washes) are considered standard (FDEP; DEP-SAS-002/10, 2011). However, there are many chlorophyll degradation products in marine sediments (Zhoa et al., 2025) that may interfere with chlorophyll detection methods. Although the CAChE Nutrient Analysis Laboratory corrects for pheophytin using sample acidification, they don't correct for other potential chlorins or porphyrins that may interfere with chlorophyll analysis. However, CAChE does use narrow bandwidth fluorometers, that minimize interference (Dr. Yan Ding, Director CAChE Nutrient Analysis Core Facility, pers. com.). This may explain the variability reported for chlorophyll in the KWWQ project (Figures 29 and 30). Moreover, chlorins and porphyrins have been shown to interfere with other chlorophyll detection methods: (1) liquid chromatography (Fyrestam et al., 2015), and (2) hyperspectral remote sensing (Tran et al., 2025). Therefore, consideration of the chlorophyll degradation products (i.e. chlorins and porphyrins) from environments exposed to both anthropogenic and natural disturbances that resuspend benthic sediments into the water column is critical when analyzing water samples from those environments for chlorophyll.

In addition to periodic elevated turbidity and chlorophyll measurements, Key West Harbor also experienced extreme fluctuations in conductivity (a proxy for salinity) (Figure 23) and salinity (Figure 34) associated with weather events, especially during hurricane season 2024. Conductivity readings from the TK system in Key West Harbor during this time dropped by >60% from background measurements indicating enormous influxes of freshwater. Interestingly, the low conductivity readings occurred on the deep sonde (6m depth) and were barely perceptible on the shallow sonde (1m depth). This is counter intuitive because freshwater is lighter than saltwater and would float near the surface and more exposed to the shallow sonde than the deep sonde. This indicates that the source of the freshwater originates near the bottom of Key West Harbor.

Anthropogenic stressors such as elevated turbidity from cruise ship propwash also periodically impacted water quality in the Key West Harbor although the events were typically of short duration relative to turbidity events associated with severe weather (<2 hours). During the KWWQ project from October 24, 2023 – December 31, 2024, three-hundred and one cruise ships visited Key West Harbor and docked at Pier B or Mallory Square docks (Appendix A). During that time thirty-five turbidity events >29 NTU beyond background levels and corresponding to cruise ship arrival and/or departure occurred (11.6 %). On three occasions, turbidity events >29 NTU

beyond background levels occurred twice in a single day upon both vessel arrival and departure (Figures 10D, 11, and 14B) and several vessel had repeated incidents during the study. The most egregious turbidity event associated with cruise ship activity occurred on Augus 20, 2024 with turbidity readings of 200.11 NTU which was 191.41 NTU beyond background level and 660% higher than allowed by Florida Administrative Code (F.A.C.) 62-302.530 (Appendix A).

Mean turbidity was the highest in the Key West Harbor relative to the Key West Shipping Channel, EDR, and WDR and turbidity decreased with the distance from Key West (Figure 33). This is most likely due to anthropogenic activity rather than weather related events because weather events would impact the entire KWWQ study area. Although only 35 turbidity events associated with cruise ship arrival and/or departure were beyond the allowable limits (i.e. >29 NTU), cruise ship arrival and/or departures were frequently associated with measurable elevations above background turbidity levels (Figure 9A,B, and C; Figure12A; Figure 17B; and Figure 18C and D). Regular resuspension of benthic sediments into the water column by cruise ship propwash likely contributes to the higher mean turbidity readings in the Key West Harbor and the decreasing turbidity gradient with distance from Key West and nearshore waters.

5.2 KWWQ Water Chemistry

Anthropogenic sources of nutrients in the Florida Keys are usually treated at on-site sewage disposal systems (OSDS) (Fourqurean and Zieman, 2002). These systems discharge treated water into the groundwater which is then forced through porous limestone by tides and currents. This freshwater discharge is often buoyed to the surface where it enters into nearshore waters (LaPointe, 1990; Myers et al., 2024). However, as the water travels through the porous limestone, phosphorus is mostly adsorbed although concentrations are still environmentally significant (Myers et al., 2024). Therefore, nutrient inputs from leakage into nearshore waters are characterized by high N:P ratio (Fourqurean and Zieman, 2002).

The KWWQ study area was characterized as a phosphate limited environment, with the majority of water samples collected reporting concentrations below the CAChE Laboratory method detection limit (MDL). Inorganic nitrogen (TIN) levels were high relative to phosphate (SRP) levels. These results are consistent with other studies and reports suggesting waters surrounding the Florida Keys are phosphate limited (LaPointe et al., 1990; Fourqurean and Zieman, 2002; Boyer and Briceño, 2012; Bacchus et al., 2014; Krause et al., 2022). Fourqurean and Zieman (2002) sampled 504 sites in the Florida Keys and found nearshore waters to be phosphorus limited with the ratio of nitrogen to phosphate decreasing with the distance from shore. However, Fourquean and Zieman (2002) also found that the stochiometric balance of the system shifted from phosphorus limited to a nitrogen limited environment with distance from shore (approximately 10 km). This is similar to the findings of the KWWQ study, where all sample sites indicated phosphorus limited environments but the farthest site from Key West (WDR about 15 km south-southwest) exhibited a trendline slope closer to the Redfield ratio indicating a less phosphorus limited environment relative to other sample sites. There are several possible

explanations for the phosphate limited environment reported in the KWWQ study area including: (1) distance from any riverine inputs (a natural source of phosphorus), (2) removal of phosphorus by carbonate sediments (e.g. limestone) and primary producers (Fourqurean and Zieman, 2002), and/or (3) nitrogen loading from anthropogenic sources (LaPointe et a., 1990; Fourqurean and Zieman, 2002; LaPointe et al., 2004; Rios et al., 2012). Likely, all of these factors contribute to the phosphorus limited environment observed in the KWWQ study area.

The KWWQ study area was characterized by high carbon levels (TOC) relative to other nutrients studied [i.e. total inorganic nitrogen (TIN); soluble reactive phosphorus (SRP); silicon (Si)]. This is important because the TOC:TIN, TOC:SRP, and TOC:Si ratios act as indicators of water quality. In the Florida Keys there is a nutrient balance between offshore coral reef environments, which trend toward oligotrophic conditions, and nearshore seagrass beds and mangroves which are typically much higher in nutrients. Therefore, the TOC:TIN, TOC:SRP, and TOC:Si ratios can indicate whether the specific ecosystem is healthy or trending towards eutrophication. In the KWWQ study area all sample sites exhibited high TOC:TIN, TOC:SRP, and TOC:Si ratios above the Redfield ratio. There were no apparent relationships between TOC:TIN, TOC:SRP, and TOC:Si ratios and the distance from Key West which would be expected if the source of TOC was land based. However, large influxes of organic matter (e.g. sargassum) and the associated decomposition may explain the high TOC levels. Sargassum influxes have been linked to serious marine environmental concerns including the release of toxins, hypoxia or anoxia, as well as elevated carbon levels and marine stochiometric imbalances (Rodriguez-Martínez et al., 2025; Molina-Cora et al., 2025). There were multiple notable sargassum inundation events (SIEs) in the Florida Keys occurring between 2020 - 2024 with the most severe occurring during the KWWQ project in early 2023. The source of the sargassum influx is the Great Atlantic Sargassum belt (Rodriguez-Martínez et al., 2025; Méndez-Tejada and Ayala, 2026) which continues to grow and forebodes additional SIEs in the future. Therefore, understanding the relationship between SIEs and TOC is critically important and the ratios of TOC to other nutrients may provide information on the magnitude and extent of SIE impacts.

The silicon to nitrogen to phosphorus (Si:N:P) ratio is important because it helps control ecosystem food webs. If Si is high relative to other nutrients then diatoms dominate, however, if Si concentrations are low relative to other nutrients, then other phytoplankton may bloom (e.g. dinoflagellates) which can cause harmful algal blooms (e.g. red-tides) (Lu et al., 2020). Moreover, silica and diatoms act as regulators of atmospheric carbon as evidenced by the silica hypothesis which suggests that wind-borne and riverine silica inputs into the ocean during the last inter-glacial period reduced atmospheric carbon by 40% resulting in the last ice age (Tréguer, 2002). However, in the KWWQ project there was no clear relationship between Si and other nutrients (TIN and SRP), so inferences about water quality relative to Si cannot be postulated.

6.0 Conclusions

There were many outcomes and lessons learned during the KWWQ project including: (1) applicability of the project as an educational tool, (2) technological limitations, (3) the impacts of environmental stressors on water quality in the study area, and (4) water chemistry in the study area. Each of these are discussed in the following sections.

Perhaps the most substantial outcome of the KWWQ project was the value of the project as an educational tool. The College of the Florida Keys has a robust undergraduate marine science program that utilizes marine science research as an educational tool. Over the years, the primary focus of the research has been on marine biology. However, in 2020 CFK launched the Bachelor of Science in Marine Resource Management (MRM) program, and the KWWQ project provided the perfect research opportunity for students in that program. The KWWQ project was incorporated into the curriculum for several classes including OCB2102C Marine Data Collection and ISC 2132 Basic Research Diving. The project supported many research assistants (RAs), scientific divers, internships, and capstone class projects. Several of the RAs have been hired by Florida Department of Environmental Protection (FDEP) while others have been accepted into graduate degree programs, one of which is focused on water quality research.

There were important lessons learned regarding the appropriate technology to be used for the project. The use of AUV technology or archival data sondes near Key West Harbor and Key West Shipping Channel was not suitable due to dangerous diving conditions, low visibility, and strong currents. However, the decision to use shore based water quality monitoring equipment (i.e. the TK system) was extremely advantageous and the equipment provided some of the most valuable information for the KWWQ project, especially during severe weather events. Unfortunately, the equipment is limited to shore based deployments and not suitable for remote deployments. Future research efforts for remote deployments in the study area should focus on buoyed technology that can transmit data periodically via cellular services. The primary advantages are: (1) near real-time data monitoring, and (2) transmitted data is immediately stored in the cloud, so data is not lost if the equipment is lost, damaged, or malfunctions.

There are many environmental stressors impacting water quality in Key West Harbor. Although severe weather was the most impactful, with durations lasting for days and substantial drops in salinity, the events appear limited to hurricane season. Disturbances associated with cruise ship activities occurred more frequently and, in terms of turbidity, were significantly more acute, with some turbidity events exceeding allowable standards by more than sixfold.

Water chemistry in the KWWQ study area appears consistent with previous studies being phosphorus limited, and nitrogen elevated with anthropogenic inputs as the most likely drivers of the environmental conditions. Elevated organic carbon levels are concerning and may be driven by enormous influxes of sargassum seaweed into region.

Future research in the KWWQ study area should focus on: (1) the sources of freshwater associated with severe rain events, (2) assessment and mitigation of sargassum influxes, and (3) biological assessments to determine baseline information for future monitoring and impact assessments relative to these and other water quality stressors.

7.0 Financial Summary

Initial compilation of financial documents was completed by reviewing the online data storage (Microsoft OneDrive) for project-related invoices and receipts. To verify all financial records were obtained, a search of the CFK vendor pay system - Accounts Payable Requests, was conducted. Upon logging into the system, one can search 'All Requests' and filter the requests by specific fields. The search was filtered using the Organization code for the EPA KWWQ grant (Org. #211204).

Each request in the system contains the invoice for the specific purchase in question, as well as the CFK Purchase Order (PO) used to pay the invoice. The invoice and PO for each grant-related request was downloaded and printed, with the hard copy being filed in a binder. Additionally, a report for the Organizational account 211204 within the Accounts Payable Requests system was downloaded which lists the PO, vendor name, invoice number, amount, and request date for each purchase. This was used to confirm all invoices that were paid by purchase order. However, purchases paid via credit card are not processed in the Vendor Pay System and therefore do not appear in the financial report.

Furthermore, financial records were monitored monthly by the Grants Analyst who completed the Project Disbursement Report per Florida Department of Education criteria. This report tracks the expenditures for each account within the project. Hard copies of the monthly reports were filed in the binder alongside individual invoices, showing how each purchase directly impacted the accounts within the project budget.

8.0 Acknowledgements

The KWWQ project was a team effort consisting of contributions from: (1) CFK staff, students, and volunteers, (2) researchers from FIU, (3) FKNMS, and (4) a variety of contractors.

Research Assistants provide the primary support for the KWWQ project and contributed at every level from data collection, analysis, and reporting. Their contribution cannot be overstated and often went far beyond expectations. Students and volunteers also provide tremendous support, especially during data analysis and reporting.

Florida International University was very instrumental with the KWWQ experimental design and development of the KWWQ QAPP. The FIU CAChE provided NELAC certified water chemistry data and helpful knowledge during the data analysis.

The Florida Keys National Marine Sanctuary (FKNMS) was very helpful during the initial phases of the KWWQ project acting as the primary liaison between CFK and other water quality stakeholders in the Florida Keys including the FKNMS Water Quality Protection Program (WQPP). The FKNMS provided the necessary permit for the KWWQ project and also influential in garnering support for the KWWQ project from the National Parks Service (NPS). The NPS

donated the initial water quality monitoring technology (i.e. YSI 6600 data sondes), which were used during the initial stages of the KWWQ project.

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10. Appendices

Appendix A — Cruise Ship Activity in Key West Harbor (Oct. 10, 2023 – Dec. 31, 2024)

Appendix B — CFK Water Quality Technician Training Guide

Appendix C — The KWWQ Quality Assurance Project Plan (QAPP)

Appendix D — FKNMS Permit

Appendix E — Equipment Calibration Records