

Final Report

Combining high-resolution surveys and numerical modeling to optimize water level management and contain Nitrogen accumulation in the Guana Lake

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ABSTRACT

This report summarizes the work conducted by our team in Guana Lake, Florida, USA, during the 2023–2024 study period. The project involved a year-long effort to collect data on water quality and hydrodynamic parameters, aiming to understand how human interventions and seasonal changes in water level, salinity, and temperature affect nitrogen accumulation and other water quality indicators in the lake. Using this data, a coupled hydrodynamic–water quality model was developed to assess potential water level management strategies within existing constraints, with the goal of reducing nitrogen concentrations. The results of this study are intended to assist local lake managers in making informed decisions to improve recreational opportunities, support biodiversity, and enhance flood protection.

1. INTRODUCTION

1.1. OVERVIEW

The Guana Lake is a 950 hectares impounded riverbed within the Guana Tolomato Matanzas (GTM) Estuary in Northeast Florida (Figure 1), receiving freshwater through a weir from the urbanized Ponte Vedra area and saltwater via tidal exchange from the Guana River. The Upper East Coast Watershed is situated along the northeastern coast of Florida, stretching between St. Augustine and Jacksonville, encompassing portions of the Atlantic Intracoastal Waterway (AICW). Covering approximately 189,081 hectares, the basin features coastal lagoons, tidal flats, shallow bays, and numerous creeks, and represents the northernmost extent of mangrove habitat

along the U.S. east coast. Just north of St. Augustine, the AICW merges with the Tolomato River, which subsequently joins the Guana River before draining into the Atlantic Ocean through the St. Augustine Inlet. The Guana River, positioned between the Atlantic Ocean and the AICW, supports one of the largest populations of endangered wood storks and is significant for commercial fishing activities. At the northern boundary of this area lies the Guana Dam, forming Ponte Vedra Lake. Originally constructed to increase upstream flooding and create wintering habitats for waterfowl, the dam now hosts the Guana Tolomato Matanzas National Estuarine Research Reserve (GTMNERR) Environmental Education Center. The Guana River is an integral part of the Guana River Marsh Aquatic Preserve and the larger GTMNERR, established in August 1999. The climate of the Guana River Basin is subtropical, characterized by hot, humid summers and mild, short winters. Summer temperatures typically peak around 32°C, while winter temperatures may drop to around 4°C. Northeast Florida receives an average annual rainfall of approximately 1,346 millimeters, most occurring during the wet season (May to October), which coincides with the hurricane season.

Hydrologically, the Guana River functions as a shallow coastal lagoon located between the AICW and the Atlantic Ocean. It discharges into the Tolomato River before reaching the Atlantic via the St. Augustine Inlet. Waters north of the Guana Dam transition from brackish to freshwater as one moves further north. The river is designated as a Class II water body, although shellfish harvesting has been conditionally approved due to recent water quality concerns. Additionally, the Guana River and its tributaries are designated as Outstanding Florida Waters (OFW), reflecting their ecological significance and the need for stringent water quality protections.

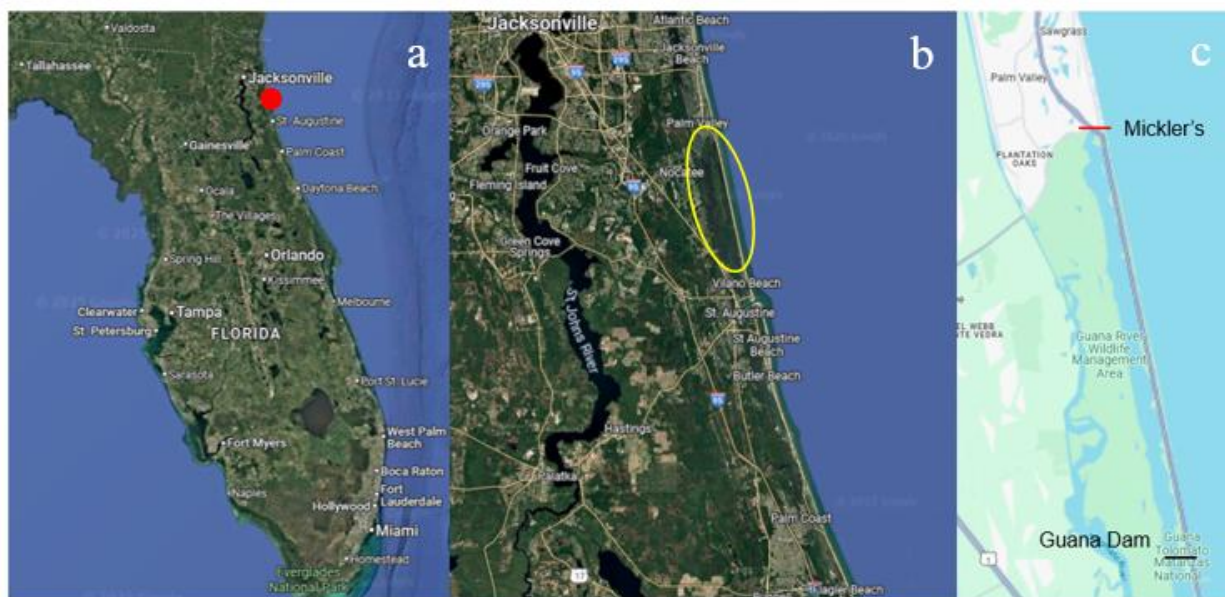


FIGURE 1: A) FLORIDA MAP, WHERE THE GUANA LAKE IS INDICATED WITH A RED DOT. B) THE GUANA LAKE LOCATION WITHIN THE GTM ESTUARY, C) THE TWO ENDS OF THE GUANA LAKE (MICKLER'S - RED LINE AND GUANA DAM – BLACK LINE)

1.1.1 NITROGEN ACCUMULATION IN THE GUANA LAKE

During summer months, saltwater from the estuary is pushed in the lake to the brackish area, causing vegetation death and consequent decomposition. Additionally, water evaporates due to the high temperatures, and the salinity of the lake drastically increases, reaching higher salinity values higher than the estuary. For these reasons, organic matter is released in the water column, promoting organic N accumulation, and the nitrogen cycle altered. Nitrogen accumulation in Guana Lake is primarily influenced by complex biogeochemical transformations carried out by specialized microorganisms, which are subject to environmental stresses. While Nitrogen is essential for primary production in aquatic ecosystems, excessive inputs due to human activities or sudden variations in salinity and temperature can disrupt ecological balance, leading to eutrophication characterized by harmful algal blooms, oxygen depletion (hypoxia), and biodiversity loss (Schlesinger et al., 2006).

The nitrogen cycle in Guana Lake involves several key processes. Nitrogen fixation occurs when prokaryotes convert atmospheric nitrogen (N_2) into ammonia (NH_3) or ammonium (NH_4^+), particularly in sediment associated with vegetation. Assimilation enables primary producers such as phytoplankton, algae, and aquatic plants to incorporate inorganic nitrogen into essential organic molecules. Ammonification (mineralization) releases ammonia back into the environment through microbial decomposition of organic matter, influenced by factors like oxygen availability, temperature, and organic material quality. Nitrification, an aerobic process, further transforms ammonia first into nitrite and subsequently into nitrate, primarily in oxygen-rich environments. Conversely, denitrification is an anaerobic process converting nitrate back to atmospheric nitrogen gas (N_2), effectively removing nitrogen from aquatic systems under oxygen-limited conditions. Anaerobic ammonium oxidation (anammox) also reduces ammonium and nitrite directly to N_2 in low-oxygen environments. Finally, dissimilatory nitrate reduction to ammonium (DNRA) converts nitrate back to ammonium, conserving nitrogen within the ecosystem, especially in environments with high organic carbon-to-nitrate ratios.

1.1.2 DAM AND LAKE WATER LEVEL MANAGEMENT

The water level of the Guana Lake is regulated by the bidirectional Guana Dam. Seasonal tidal inflows significantly increase salinity, prompting vegetation die-off and subsequent decomposition, which elevates concentrations of organic nitrogen and ammonia, adversely affecting both biodiversity and recreational uses. The primary objective of water level management in Guana Lake is to sustain high-quality wetland habitats for a wide range of native wildlife that depend on brackish and freshwater marshes throughout their life cycles. Unlike naturally fluctuating wetlands shaped by seasonal rainfall and drought, impoundments like Guana Lake require strategic manipulation to mimic these dynamic conditions. Without such variation, stagnant water and constant salinity levels can promote undesirable vegetation, muck accumulation, and overall habitat degradation. Seasonal drawdowns expose mudflats, promote native submerged aquatic vegetation, and help control invasive species such as water lettuce, water

hyacinth, and cattails by temporarily increasing salinity. This ecosystem-based approach aims to benefit the entire wetland community, rather than targeting any single species. Water levels follow a general annual cycle, but adjustments are also made in response to rainfall, storm events, and specific ecological goals.

Water level regulation is achieved through the dam structure located at the southern end of the lake. The dam is equipped with seven aluminum gates that allow bi-directional flow: retaining freshwater or allowing saltwater intrusion during high tides from the Guana River Intracoastal Waterway (ICW). These gates are also opened to discharge stormwater runoff, providing both ecological and flood protection functions. As the final drainage point for the Ponte Vedra watershed, the dam helps shed excess rainfall during the hurricane season and prevents storm surge from moving upstream, reducing the risk of flooding in developed areas. The lake's water levels, referenced to NAVD88, are managed according to ecological and operational constraints:

- **Normal Seasonal Levels:** Typically range from **0.41 ± 0.15 m MSL** in spring to **1.07 ± 0.15 m MSL** in late fall. These fluctuations mimic natural conditions, supporting diverse habitat types including salt marsh in the south and fresh-intermediate marsh in the north. They are designed to meet the biological needs of migratory waterfowl and other wetland species.
- **Maximum Permitted Level:** Set at **1.37 m MSL** by the St. Johns River Water Management District. This is used only as a temporary buffer during storm uncertainty or to allow saline water to reach northern sections for vegetation control. It must be avoided if tropical weather is imminent.
- **Storm Buffer Limit:** In late summer and fall (August–October), a maximum of **1.07 m MSL** is typical. However, levels may rise to **1.22 m MSL** if no storms are expected, providing additional buffering capacity.
- **Minimum Lake Level:** **0.41 ± 0.15 m MSL** is the lowest safe threshold under normal conditions, protecting aquatic life from excessive dewatering. Lower levels are only used during full drawdowns for management purposes.
- **Mosquito Control Minimum:** From May to July, water is maintained at or above **0.56 m MSL** to suppress mosquito breeding, although this threshold may also be used at other times if needed.
- **Boat Passage Restriction:** Navigability north of the Six-Mile Boat Ramp is compromised below **0.71 m MSL**, due to shallow channels and a sand ridge. When levels fall under **0.56 m MSL**, water exchange becomes particularly restricted.
- **Flood Control Measures:** During storm season, particularly from August to October, inflow may be limited and discharge increased to prevent lake levels from surpassing regulatory thresholds.
- **Drawdown Targets:**

- *Partial Drawdown*: Aims for **0.46 to 0.61 m MSL**. The higher end supports vegetation control, while the lower end exposes mudflats for sediment oxidation and bird foraging.
- *Complete Drawdown*: Reduces water below **0.46 m MSL**, supporting sediment drying, nutrient cycling, vegetative succession, and seed germination.

Operational decisions are executed using the dam's flap gates and flashboards, based on ecological monitoring, weather forecasts, and seasonal habitat goals. This adaptive approach ensures Guana Lake maintains its ecological integrity while supporting flood resilience and public use.

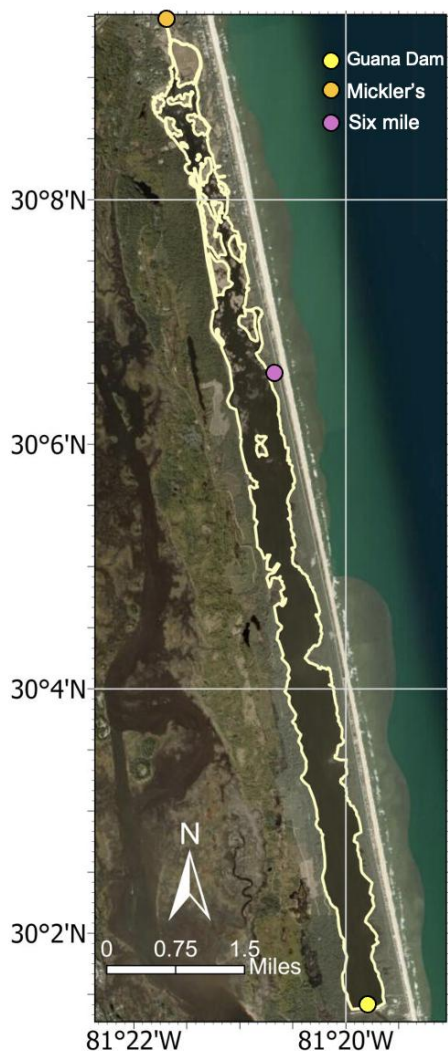


FIGURE 2: THE GUANA LAKE, WHICH BOUNDARIES ARE DEFINED BY THE CONTINUOUS LIGHT-YELLOW LINE. THE LAKE IS CONNECTED TO THE GUANA RIVER IN THE SOUTH, THROUGH THE GUANA DAM (YELLOW DOT) AND IN THE NORTH, THROUGH THE MICKLER'S DAM (ORANGE DOT). THE SIX MILE RAMP IS ALSO INDICATED IN THE MAP (PINK DOT).

1.2. OBJECTIVES

The GTM estuary is a highly flushed ecosystem that rarely experiences negative consequences of eutrophication due to its dynamic hydrology and strong tidal exchange. However, Guana Lake, a semi-impounded subregion of the system, shows pronounced seasonal variability in tidal flushing as a result of managed water level operations intended to balance ecological and recreational needs. This hydrologic modification can increase water residence time, reduce dilution capacity, and elevate the risk of nutrient retention and accumulation, especially in the area between Mickler's weir and Six mile ramp (orange and pink dots in Figure 2). As a result, the Guana Lake provides an ideal natural laboratory for investigating how varying degrees of tidal flushing influence nutrient cycling, eutrophication potential, and water quality dynamics. Understanding these interactions is essential for meeting regulatory water quality standards, maintaining flood protection infrastructure, and preserving the lake's recreational, ecological, and economic value.

As noted by (Dix et al., 2017) a better understanding of the quantity, sources, and transformation of nutrients along the estuarine gradient is urgently needed to design effective mitigation strategies. This knowledge gap has led GTMNERR to prioritize the development of a comprehensive, data-driven hydrodynamic and pollutant-source model. The model is intended to support informed decision-making, assess alternative dam management scenarios, and ultimately reduce nitrogen accumulation in the lake system.

In the next sections, we will present the results obtained during the period September 2023-October, 2024. In particular:

- Twelve months of data collection using the YSI EXO2 and YSI ProDSS.
- Flow discharge measurements at the two ends of the Lake (Guana Dam and Mickler's Weir).
- Twelve months of water sampled collection to quantify Total Nitrogen concentrations.

- Development of a coupled hydrodynamic and water quality model for the Guana Lake and its watershed; Calibration of the model using the collected data. Investigation of alternative Dam managements with the numerical model to reduce Nitrogen accumulation.

2. METHOD

2.1. PROJECT SCHEDULE

The main tasks of the present Guana Project are described below and summarized in Table 1. All tasks were completed in time by our team during the Project. Task 1-4 were submitted in previous reports (Biondi, 2024), (Pinton, 2023)

- Task 5 – Data Collection
- Task 6 – Discharge survey
- Task 7 – Workshop
- Task 8 – Final Report

Table 1. Project schedule and tasks summary.

Task No.	Task or Deliverable Title	Task Start Date	Task End Date	Deliverable Due Date
Task 5	Monthly data collection	September 1 st , 2023	09/30/2024	06/30/2025
Task 6	Discharge survey		09/30/2024	06/30/2025
Task 7	Workshop		02/28/2025	02/28/2025
Task 8	Final Report		06/30/2025	06/30/2025

2.2. TASK 5 AND 6 –MONTHLY DATA COLLECTION

2.2.1. DATA COLLECTED AND INSTRUMENTS USED

In this project, we collected Hydrodynamic and water quality data from the Guana Lake using a Water quality and water velocity data were collected using the SonTek RiverSurveyor M9 Acoustic Doppler Current Profiler (ADCP, Figure 3a), and the YSI/Xylem EXO2 MultiParameter Water Quality Sonde (Figure 3a)) mounted on a YSI HYCAT (Figure 3c) for the months of September 2023 to January 2024. Following a HYCAT failure in January 2024, the Sensors were attached to PVC pipe and carried with the boats. Collected water quality data are water temperature, conductivity, salinity, Dissolved Oxygen (DO), pH, and Chlorophyll-a. NO₃, Nitrite

(NO₂), Ammonia (NH₄), and Total Kjeldahl Nitrogen (TKN) filtered concentrations were also be obtained from water samples collected in the Guana Lake.

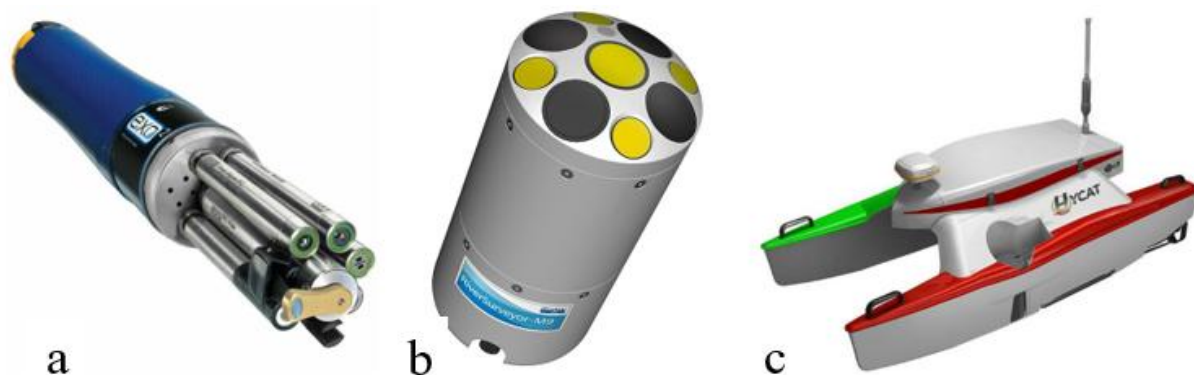


FIGURE 3: THE INSTRUMENTS USED FOR THE SURVEY: A) YSI EXO2, B) SONTEK M9, C) YSI HYCAT.

2.2.2. *FIELDWORK DESCRIPTION*

The survey was conducted as follows: Water quality monitoring utilized a YSI/Xylem EXO2 MultiParameter Water Quality Sonde, which was mounted on the HYCAT platform (**Figure 3c**). On the opposite side of the HYCAT, a Sontek M9 Acoustic Doppler Current Profiler (ADCP) was installed to gather bathymetric data and flow velocity. Data for hydrodynamic and water quality parameters were collected at a sampling frequency of 1 Hz. The survey path was accurately tracked using a Real-Time Kinematic (RTK) GPS system, achieving a horizontal precision of approximately 0.03 m. Following a malfunction of the HYCAT system in January 2024, the YSI/Xylem EXO2 sensor was repositioned onto the side of the survey vessel on a custom mount, complemented by a YSI ProDSS device, which provided GPS coordinates and allowed for data validation. To minimize turbulence and maintain data quality, the vessel was operated at idle speed throughout the survey. Water sample were collected at the same stations every survey. At each sampling location, a dark leak-proof high-density polyethylene (HDPE) bottle will be used to collect a water sample of 500 ml. Bottles will be cleaned and sterilized before each survey. Samples will be manually grabbed at a depth of 0.5 m, and bottles were labeled with the date, time, and number of the sample (progressive, starting from 1 each day). TKN, NO₃, NO₂, and NH₄ samples were filtered through a 0.45-μm filter (using filtration towers that have been acid-washed before the sampling day) and acidified to pH < 2 with H₂SO₄ at the station. Bottles were stored on ice until the end of the daily survey. At the end of the day, samples were stored at a temperature of 4°C, as required by the lab performing the analysis on nutrient concentrations. Samples were delivered to the UF/IFAS Analytical Services Laboratories. Nutrient concentration analysis. According to the procedure indicated in their ANSERV Lab's QA Manual, they will be delivered to ANSERV Lab acidified, at a temperature of 4°C, and in 20 ml scintillation vials. The ANSERV Lab's QA Manual includes information on the MDL/PQL the method of analysis for the bottle

samples collected in the field, the calibration procedures of their instruments, and their Chain of Custody procedures. Details on the ANSERV Lab and the nutrient concentration analysis they perform are reported in the Laboratory Analysis section.

Four HOBO pressure sensors were placed in the Guana Lake and Guana River to monitor water levels. Two sensors were installed near the Guana Dam (one upstream and one downstream, marked with a yellow dot in Figure 5), while another pair was placed near Mickler's Weir (one upstream and one downstream, marked with an orange dot in Figure 5). These sensors recorded water level measurements at 15-minute intervals. The collected data was used to calculate the discharge at both dams using established literature formulations (detailed in Section 2.3.3) and to analyze tidal variations and water levels in the lake. Additionally, two salinity sensors were deployed in at the Guana Dam stations to quantify the saltwater exchange between the lake and the river. These data were also used to prescribe the model boundary conditions.

2.2.3. DATA ANALYSIS AND AVAILABILITY

Hydrodynamic and water quality data were analyzed by using python scripts we developed. Data were plotted in 2-dimensional map to capture the spatial variation of the parameters. Water level data are shown in section 3.

The XYZ bathymetric was extracted from the HYCAT using the HYPACK software. The file was then imported in QUICKIN (a Delft3D plugin) to assign the bathymetry to the Delft3D-FLOW (Deltares) numerical model we implemented for this project. Finally, both the files of the water quality parameters were used to calibrate the numerical model. The Total Nitrogen TN was obtained as the sum of the Organic and inorganic components (TKN and NO_x).

All the data collected are available in the google Drive folder shared with this report in xlsx format. The folders are organized as follows:

- *ADCP*: all the discharge and bathymetry data collected with the HYCAT and RSQpod;
- *Calibration logs*: all the calibration and post calibration data collected during the year for the YSI EXO2;
- *EXO2*: water quality data: pH, Salinity, DO, turbidity, CHL-a, temperature, TSS, fDOM;
- *ProDSS*: water quality data: pH, Salinity, DO, CHL-a, temperature;
- *SUNA*: Nitrate (NO_x, μM) data collected for the whole year;
- *Weather Data*: collected air temperature, rainfall, wind speed, solar irradiation and humidity from the GTMNERR meteorological station "Pellicer Creek" (29°39'28" N, 81°13'58" W).
- *Lab Analysis*: this folder includes the chain of Custody, Certified analysis form and the results from the analysis performed at the IFAS laboratory (University of Florida)

2.2.4 TASK 6 - DISCHARGE SURVEY

Flow-discharge measurements were required to calibrate the discharge-rating curves and to estimate annual discharge at both Guana Dam and Mickler's Weir based on water-level readings. In the pre-January 2024 survey at Guana Dam, a one-day field campaign collected velocity profiles on both the inflow and outflow sides of the structure every thirty minutes over a six-hour period, capturing a half tidal cycle that included both high and low tides; these profiles were then used to compute discharge. Simultaneously, an RTK-GPS recorded upstream and downstream water levels relative to the dam crest, allowing correlation of lake level, flow rate, and dam configuration. At Mickler's Weir, being mono-directional and unaffected by tidal oscillations, a single velocity measurement per survey was sufficient to determine discharge. During 2024, a one-day survey at both sites employed a SonTek rQpod R5 acoustic profiler (**Figure 4**, right side), which streamlined and standardized the collection of discharge data at both Guana Dam and Mickler's Weir.

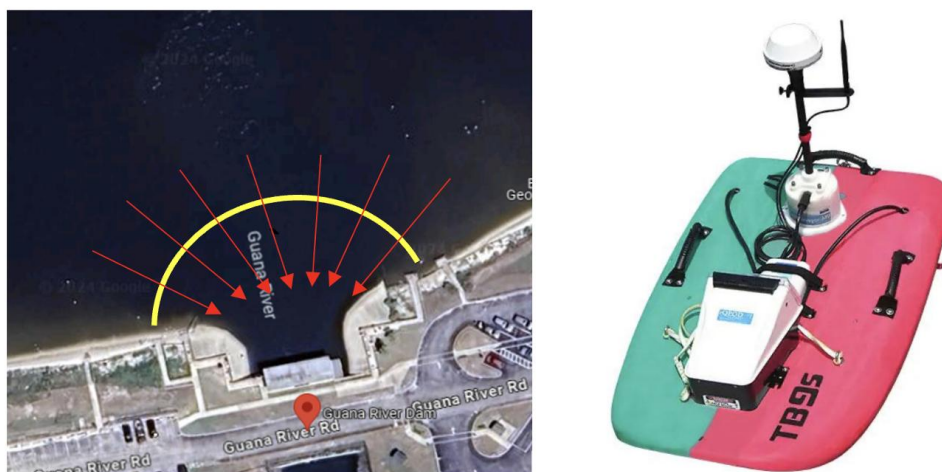


FIGURE 4: THE PATH USED TO MEASURE THE DISCHARGE WITH THE ADCPS (YELLOW LINE) AND THE FLOW LINE EXPECTED FOR AN OUTFLOW OF DISCHARGE (RED ARROWS), LEFT PICTURE. B) THE SONTEK RQPOD (RIGHT PICTURE)

2.3. HYDRODYNAMIC MODEL DETAILS

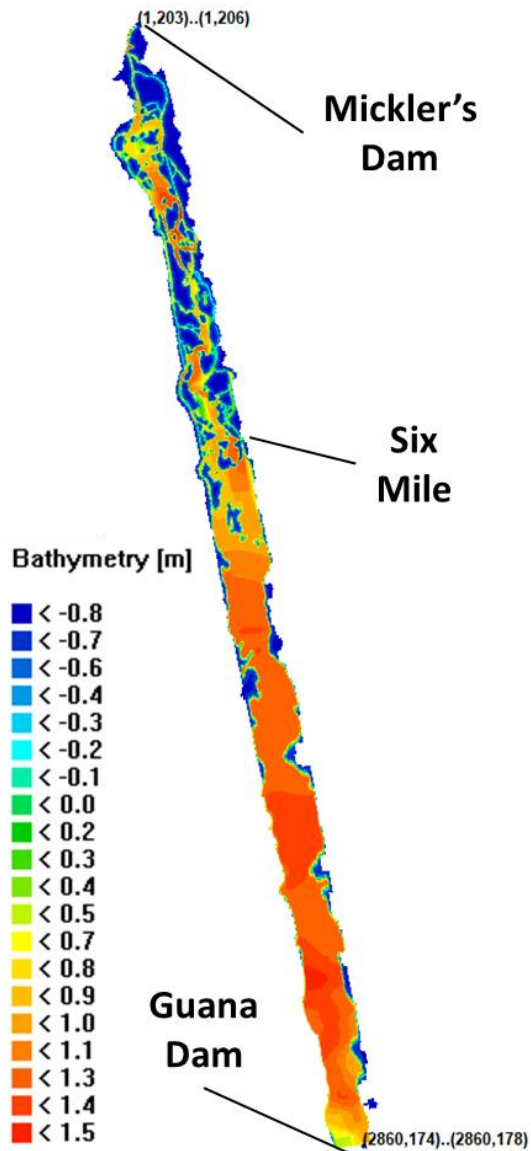


FIGURE 5: GRID AND BATHYMETRY OF THE DELFT-3D MODEL DESCRIBING THE GUANA LAKE. VALUES ARE EXPRESSED IN DELFT3D NOTATION: POSITIVE AND NEGATIVE VALUES INDICATE THE ELEVATION BELOW AND ABOVE THE MSL, RESPECTIVELY.

We used the Delft3D-FLOW model (<https://oss.deltares.nl/web/delft3d>) to solve the hydrodynamics and the water quality in the Guana Lake. It calculates non-steady flow resulting from the hydrodynamic (tide and river flow) and meteorological forcing on a regular, boundary-fitted grid. We used a structured curvilinear grid encompassing approximately 9.50 km² to describe the Guana Lake.

The model domain, shown in **Error! Reference source not found.**, encompasses the Guana Lake, from Mickler's Weir (30°09'39.6" N 81°21'37.4" W) to Guana Dam (30°01'23.7" N 81°19'42.3" W). The grid cell dimensions varied along the lake, growing from approximately 5 m × 25 m at the Guana Dam, in the southern part of the Lake, to about 5 m × 5 m at Mickler's Dam, in the northern part of the Lake.

The bathymetry used in the model is obtained from the survey we conducted in the Lake by using the ADCP. We assigned an elevation equal to 0.80 m to the marshes located in the northern part of the lake (see **Figure 5Error! Reference source not found.**).

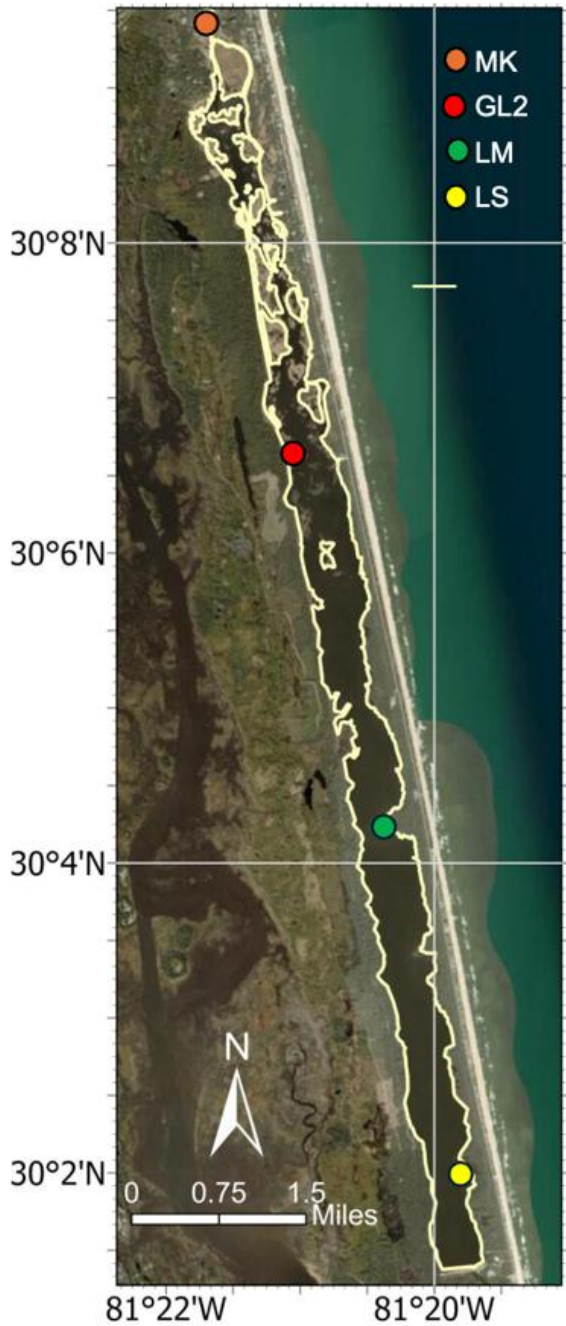
2.3.1. MODEL VALIDATION

To validate the model, we reproduced the water level, temperature, salinity and TN concentration in the Guana Lake. The simulation lasted for 365 days, from Oct 2nd, 2023, to Oct 2nd, 2024. Due to the significant computational demands of simulating an entire year, the model was executed on multiple cores using the HiperGator HPC (High-Performance Computing) system at the University of Florida. The model's scalability reduced the

simulation time by a factor of 8. The total time of calculation is 12 hours with 0.1 minutes time step.

2.3.2 INITIAL, BOUNDARY CONDITIONS AND EXTERNAL FORCES

The initial conditions assigned to the model match the field data collected on Oct 2nd, 2023. The prescribed initial water level in the domain was assigned as the average of the two values recorded at the water level stations inside the lake (one at the Guana Dam, named “Lake South” (LS) with the GTM notation and one at the Mickler’s weir (MK), respectively orange and yellow dot in Figure 5). The assigned uniform initial salinity, water temperature and TN concentration in the Lake are derived from data collection.



The boundary conditions applied to the model are obtained from hydraulic modeling and field observations. At the Guana Dam and Mickler’s weir the prescribed water temperature and salinity were measured at the water level stations sampling one value every 15 minutes. The water discharge at the two boundaries (Guana Dam and Mickler’s weir) was computed as a function of the water levels upstream and downstream, as explained in section 2.3.3.

Finally, we applied the meteorological forcings, corresponding to relative humidity, air temperature, solar irradiation, wind direction, and wind speed to the entire model domain. These data were measured at the GTMNERR meteorological station “Pellicer Creek” (29°39’28” N, 81°13’58” W). All the data are reported in the plots in Figure 6. In the model, 4 observation points are set coinciding with the GTM stations “Guana Lake 2” (GL2) and “Lake Mid” (LM), Lake south (corresponding to the Guana Dam) and Mickler’s weir.

FIGURE 6: THE GUANA LAKE IN PONTE VEDRA, FLORIDA, USA (LIGHT YELLOW LINE). THE ORANGE DOT INDICATES THE LOCATION OF THE MICKLER’S WEIR WATER LEVEL STATION, WHILE THE YELLOW DOT SHOWS THE LOCATION OF ANOTHER WATER LEVEL STATION. THE RED AND GREEN DOTS REPRESENT THE OBSERVATION POINTS GL2 AND LM, RESPECTIVELY.

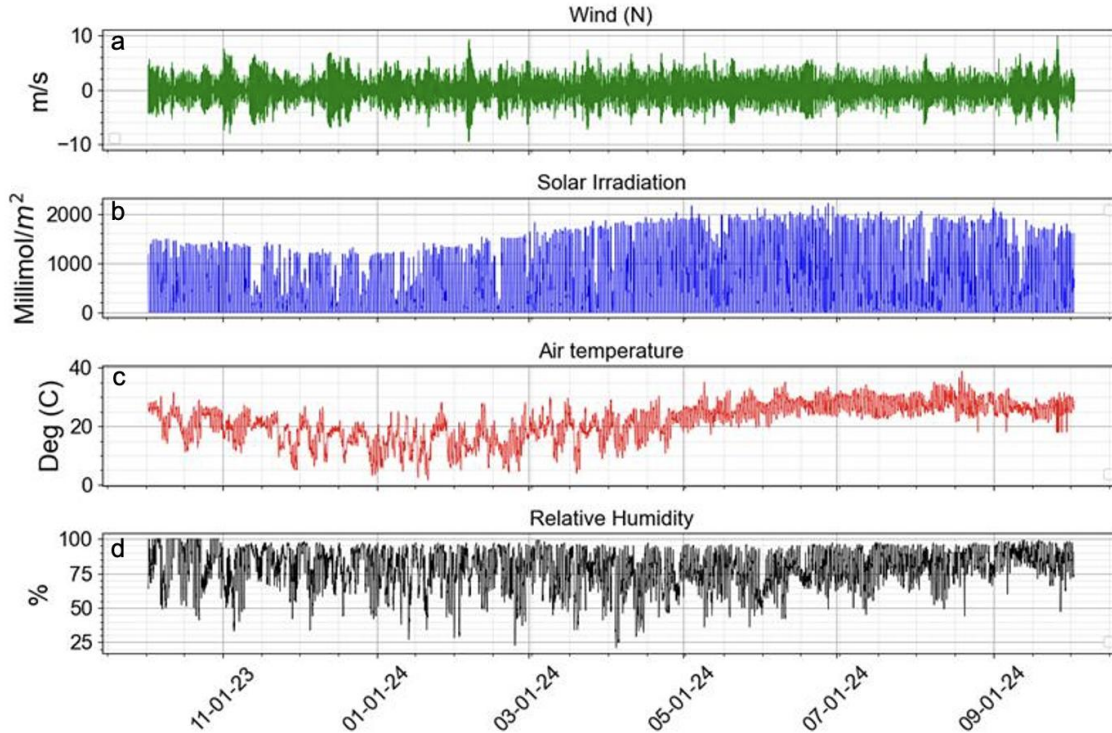


FIGURE 7: EXTERNAL FORCES PRESCRIBED TO THE MODEL. SUBPLOT A) IS THE WIND (REPRESENTED BY THE NORTH COMPONENT IN M/S), B), C) AND D) ARE RESPECTIVELY THE SOLAR IRRADIATION, AIR TEMPERATURE AND RELATIVE HUMIDITY USED TO CALCULATE THE EVAPOTRANSPIRATION IN THE MODEL.

2.3.3. COMPUTATION OF THE WATER DISCHARGE

The Guana Dam allows a bidirectional flow to be established. Water can flow either by spilling over the crest of the weir or passing through mono-directional flap gates. Therefore, the total water discharge Q flowing through the Dam is the sum of two components: the discharge at the gates, Q_g , and the discharge at the spillways, Q_s . We define water outflow from the lake to the estuary (discharge stage, according to FWC nomenclature) as a negative discharge, whereas water inflow from the estuary to the lake (recharge stage) is defined as a positive discharge.

The Guana Dam is equipped with seven spillways (Figure 7a), and each is 1.56 m wide. The elevation of their crest is regulated using flashboards (brown rectangles in Figure 7b, c), which are removed or added (ranging from 0 to 3 boards) by FWC personnel, to control the water level and salinity in the lake gradually. Water exchange between the GTM estuary and Guana Lake depends on the relative water levels of the lake and the Guana River. When the water level in the Lake exceeds both the water level in the Guana River and the elevation of the weir crest, water flows out of the Lake. Conversely, when the water level in the river is higher than both the Lake level and the weir crest, water flows into the Lake. The dam is also equipped with seven $1.44 \text{ m} \times 1.44 \text{ m}$ gates (dark grey squares in Figure 7a), which can be configured to rapidly regulate the water level and the salinity in the lake. These gates can be set by the FWC personnel in two modes: they can

either be fully closed, preventing any flow, or open to allow mono-directional flow either seaward or toward the lake. If open, flow occurs only if the water level gradient aligns with the opening orientation of the gate, enabling the flap to open in the direction of the gradient. The management of the dam was recorded by FWC.

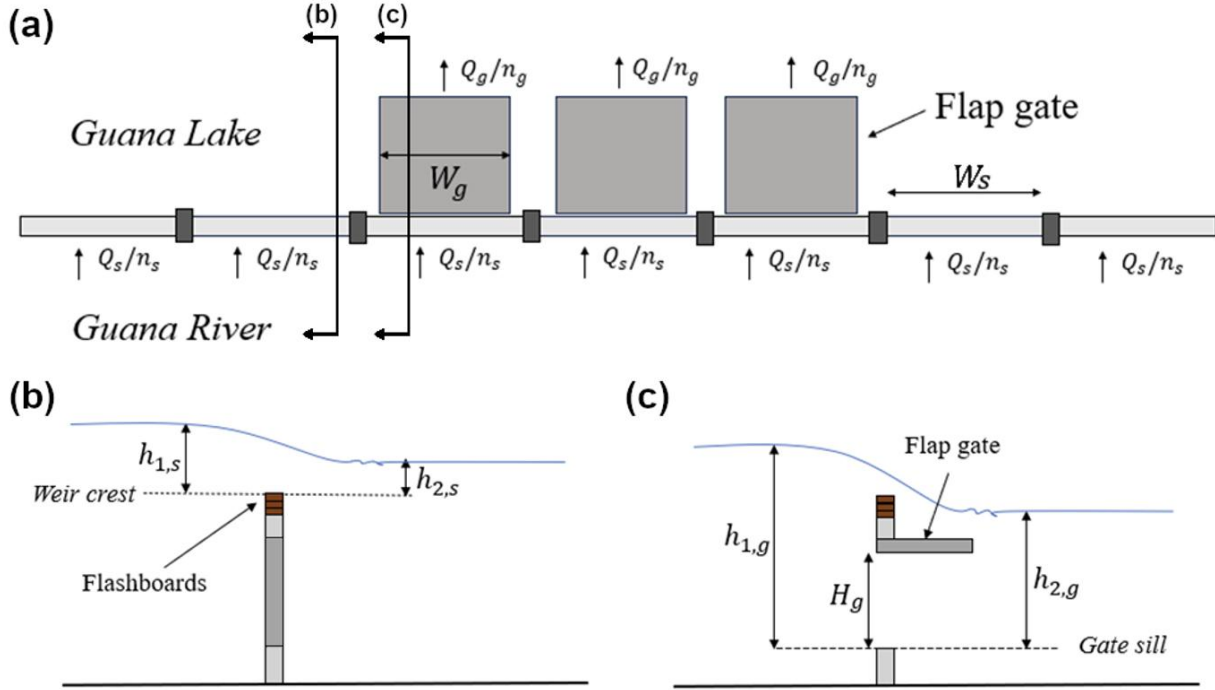


FIGURE 8: (A) TOP VIEW OF THE GUANA DAM. IN THE EXAMPLE SHOWN, THE SQUARE GATES (DARK GRAY SQUARES) ARE OPEN TOWARDS THE LAKE. THIS MEANS THEY ARE SET IN RECHARGE MODE. THE FOUR REMAINING GATES ARE FULLY CLOSED. BOTH THE SPILLED DISCHARGE (Q_s) AND THE TOTAL GATE DISCHARGE (Q_g) ARE EQUALLY DISTRIBUTED AMONG THE SPILLWAYS ($n_s = 7$) AND THE OPEN GATES (n_g , EQUAL TO THREE IN THE EXAMPLE SHOWN). W_g IS THE GATE WIDTH, W_s THE SPILLWAY WIDTH, AND H_g THE GATE HEIGHT. (B) AND (C) SHOW THE SECTIONAL VIEWS OF THE GUANA DAM. NOTE THAT h_1 AND h_2 REFER TO UPSTREAM AND DOWNSTREAM WATER LEVELS, RESPECTIVELY. $h_{1,g}$ AND $h_{2,g}$ ARE, RESPECTIVELY, THE UPSTREAM AND DOWNSTREAM WATER LEVELS RELATIVE TO THE GATE SILL (DASHED LINE IN (B)). $h_{1,s}$ AND $h_{2,s}$ ARE, RESPECTIVELY, THE UPSTREAM AND DOWNSTREAM WATER LEVELS RELATIVE TO THE WEIR CREST (DOTTED LINE IN (C)). FLASHBOARDS PLACED ON TOP OF THE WEIR ARE INDICATED IN BOTH (B) AND (C) USING BROWN RECTANGLES.

The Guana Dam gates can hydraulically function in two possible modes, i.e. as orifice or weir. Each mode can, in turn, operate under a free or submerged flow regime. A free flow occurs when the downstream water level $h_{2,g}$ does not influence the discharge, which depends solely on the upstream water level $h_{1,g}$. A submerged flow, instead, occurs when the downstream water level partially or fully submerges the gate or weir crest, affecting the discharge. Here, we measure water levels relative to the gate sill (Figure 7c). For the orifice mode and during the free flow regime, the gate discharge Q_g can be computed as follows (Ryan et al., 2020):

$$Q_g = n_g C_g \sqrt{2gh_{1,g}} H_g W_g, \quad \text{for } H_g > h_{2,g} \text{ and } H_g < \frac{2}{3} h_{1,g}, \quad (1)$$

where n_g is the number of open gates, $C_g = 0.61$ is the discharge coefficient of the gates, g is the gravity, $h_{1,g}$ is the upstream water level, $h_{2,g}$ is the downstream water level, H_g is the height and $W_g (= H_g)$ is the width of the square gate. When the downstream water level rises above the elevation of the opened gate, the flow of water through the gate opening is obstructed. Therefore, the flow regime shifts from free to submerged, and the discharge for the submerged orifice mode reads:

$$Q_g = n_g C_{g,sub} \sqrt{2g(h_{1,g} - h_{2,g})} H_g W_g, \quad \text{for } h_{2,g} \geq H_g \text{ and } H_g < h_{1,g}, \quad (2)$$

where $C_{g,sub} = C_g \left(\frac{h_2}{h_g}\right)^{1.5}$ is the corrected discharge coefficient for a submerged flow (Sanders and Feaster, 2004). When the upstream water depth on the still gate is lower than 3/2 of the gate height, and $\frac{h_{2,g}}{h_{1,g}} < 0.6$, the gate functions as a weir. The discharge through the gates for a free regime can be computed by:

$$Q_g = n_g C_s \sqrt{2g} W_g h_{1,g}^{1.5}, \quad \text{for } \frac{h_{2,g}}{h_{1,g}} < 0.6 \text{ and } H_g > \frac{2}{3} h_{1,g}, \quad (3)$$

where $C_s = 0.4$ is the discharge coefficient of the weir, as suggested in Ryan et al. (2022). If the ratio between the downstream and upstream water depths above the gate sill is larger than 0.6, the flow is affected by downstream water levels, resulting in reduced water fluxes (Sanders and Feaster, 2004). Hence, the flow regime becomes submerged and can be calculated as:

$$Q_g = n_g C_s C_{s,sub} \sqrt{2g} W_g h_{1,g}^{1.5}, \quad \text{for } \frac{h_{2,g}}{h_{1,g}} > 0.6, H_g > \frac{2}{3} h_{1,g}, \text{ and } h_{2,g} < H_g, \quad (4)$$

where $C_{s,sub} = 4.537 - 4.337 \left(\frac{h_{2,g}}{h_{1,g}}\right)$ is a correction to the discharge coefficient for submerged weir flow ((Collins, 1977)

The Guana Dam spillways function always as a weir. During free flow conditions ($\frac{h_{2,s}}{h_{1,s}} < 0.6$), the spilled discharge Q_s can be computed as:

$$Q_s = n_s C_s \sqrt{2g} W_s h_{1,s}^{1.5}, \quad (5)$$

where n_s is the number of spillways, W_s is the spillways width, $h_{1,s}$ and $h_{2,s}$ are the upstream and downstream water elevations on the weir crest, respectively. Analogously to the gate discharge, when the flow becomes submerged ($\frac{h_{2,s}}{h_{1,s}} > 0.6$), the discharge reads:

$$Q_s = n_s C_s C_{s,sub} \sqrt{2g} W_s h_{1,s}^{1.5}. \quad (6)$$

The values of C_s and C_g are consistent with literature values. We also validated the values of C_s and C_g by monitoring water levels upstream and downstream of the dams, and water discharge upstream of the dam in three different days.

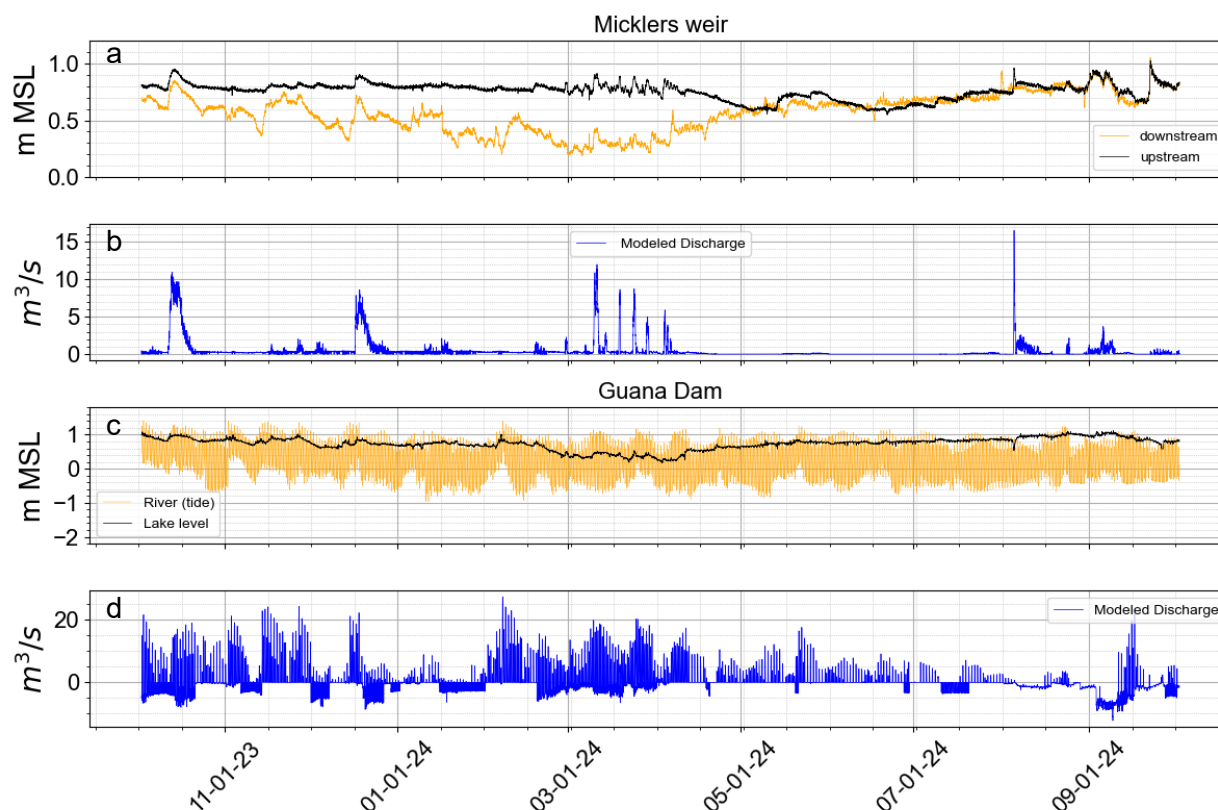


FIGURE 9: THE WATER LEVEL AND DISCHARGE DATA COLLECTED FROM OCTOBER 2, 2023, TO OCTOBER 2, 2024. SUBPLOT (C) DISPLAYS THE WATER LEVELS MEASURED IN THE LAKE AND RIVER (REFERENCED NAVD88), REPRESENTED BY ORANGE AND BLACK LINES, RESPECTIVELY. SUBPLOT (A) PRESENTS THE WATER LEVELS AT MICKLER'S, WITH THE UPSTREAM LEVELS DEPICTED BY THE BLACK LINE AND DOWNSTREAM LEVELS BY THE ORANGE LINE. SUBPLOTS (B) AND (D) ILLUSTRATE THE WATER DISCHARGE CALCULATED USING ESTABLISHED LITERATURE FORMULATIONS, BASED ON THE INPUT WATER LEVELS RECORDED AT MICKLER'S AND GUANA DAM.

Table 2. List of the datasets used in the Delft3D-FLOW model validation, and how they were used in the model.

Source	Dataset	Data Usage
Guana Dam Station	Water temperature	Applied at the Guana Dam boundary to describe the local water temperature
	Water salinity	Applied at the Guana Dam boundary to describe the local water salinity

Modeled with USGS equations	Total Discharge	- Applied to the Guana Dam to prescribe the saltwater exchange - Applied at Mickler to prescribe the freshwater input
GTM dataset	TN concentration	Applied at the two boundaries (Dams) to prescribe the Total nitrogen input in time
GTMNERR weather station – Pellicer Creek	Air temperature	Applied at the entire model domain to calculate the heat fluxes between air and water
	Relative humidity	Applied at the entire model domain to calculate the heat fluxes between air and water
	Wind speed	Applied at the entire model domain to calculate the effect of the wind on the hydrodynamic
	Wind direction	
	Solar irradiation	Applied at the entire model domain to calculate the evapotranspiration (ET)

2.3.4 NITROGEN MODULE FOR DELFT3D

To represent salinity-driven nitrogen release, we implemented a new source term in the Delft3D sediment-transport modules. At each grid cell (x, y) and time t , the total nitrogen source TN_{source} is computed as:

$$TN_{source}(x, y, t) = C_{eropar} (Sal(x, y, t) - Sal_{cr})^m, \quad (7)$$

where C_{eropar} is a calibration constant that scales the overall magnitude of nitrogen release (set to 10^{-5}), m is an exponent controlling how sensitively nitrogen release responds to salinity exceedance (set to 1), and Sal_{cr} is the critical salinity threshold above which freshwater vegetation dies and begins to release nitrogen (set to 1.5 ppt).

This formulation is evaluated at every time step in all cells occupied by freshwater vegetation, thereby simulating spatially and temporally varying nitrogen accumulation driven by local salinity levels.

2.3.5 ATMOSPHERIC-INDUCED SETUP IN DELFT3D-FLOW

Delft3D-FLOW incorporates atmospheric setup (η_{AID}) by adjusting the free-surface elevation according to time-varying air pressure via the inverse barometer principle:

$$\eta_{AID} = -\rho g (P_{atm} - P_{ref}), \quad (8)$$

where ρ is water density, g is gravitational acceleration, P_{atm} is the local atmospheric pressure, and P_{ref} is a reference pressure. The model applies this term in the vertical momentum equation, ensuring proper response of surface heights to atmospheric fluctuations. Wind stress is likewise applied as shear in the horizontal momentum equations, enabling Delft3D to simulate wind-driven currents and surges based on observed meteorological data

2.3.5. EVAPOTRANSPIRATION

Evaporation (E) in Delft3D-FLOW is handled by the integrated ocean model, which calculates evaporative fluxes using surface heat and humidity balance. The computed E is then introduced as a time- and space-dependent sink in the continuity equation:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (H_u) = -E(x, y, t), \quad (9)$$

where η is water surface elevation, η is total depth, and u is the velocity. The E field is dynamically derived using the coupled hydrodynamics and meteorological forcing modules in space (x, y) and time t , drawing on ocean-atmosphere exchange calculations rather than prescribed rates. This ensures evaporation responds realistically to variables like sea surface temperature, humidity, and wind.

2.3.6. PROPOSED ALTERNATIVE MANAGEMENT OF THE GUANA DAM

Two scenarios were analyzed in this study. The first scenario involved increased tidal flushing, achieved by installing an additional flashboard to maintain higher water levels and introducing supplementary discharge and recharge gates operational from June 28th to August 2nd, 2024. The second scenario maintained the number of recharge gates but completely omitted discharge gates, effectively reducing tidal flushing. This changed in this period

	Original Configuration	Increased flushing	Decreased Flushing
Flashboards	3	4	4
Recharge gates	1	2	2
Discharge	0	1	0

The model results indicate that enhanced tidal flushing initially leads to a slight rise in TN concentrations. This initial increase is primarily caused by a rapid reduction in water levels, significantly lowering the lake's total water volume. Following this initial period, however, TN

concentrations decrease due to improved tidal flushing at the dam, which shortens water residence time. Additionally, the enhanced flushing scenario results in lower salinity, as freshwater inflows from Mickler's experience reduced resistance from saline water entering the system. Moreover, lower temperature and salinity conditions in the estuary inhibit the formation of organic nitrogen, contributing to overall improved water quality.

3. RESULTS

3.1. FIELD SURVEY

One of the main outcomes of this project is the acquisition of a comprehensive and high-resolution dataset describing the bathymetry of Guana Lake (**Figure 5**: Grid and bathymetry of the Delft-3D model describing the Guana Lake. Values are expressed in Delft3D notation: positive and negative values indicate the elevation below and above the MSL, respectively.). In addition, monthly water quality data collected using the EXO2 and ProDSS sondes enable the analysis of seasonal trends within the lake. Water samples were also collected and analyzed to complement the in-situ measurements. Furthermore, discharge measurements were obtained using the ADCP. This section presents all the data collected during the study, then discussed in section 4.1.

3.1.1 WATER SAMPLING - TOTAL NITROGEN CONCENTRATION

Water was sampled once per month from the period October 2023- October 2024. The Total Nitrogen was calculated as the sum of ammonium (NH_4), TKN, Nitrate, and Nitrite concentrations. The results show how the area north to the six-mile ramp (where the GL2 station is) is consistently higher in total Nitrogen concentrations.

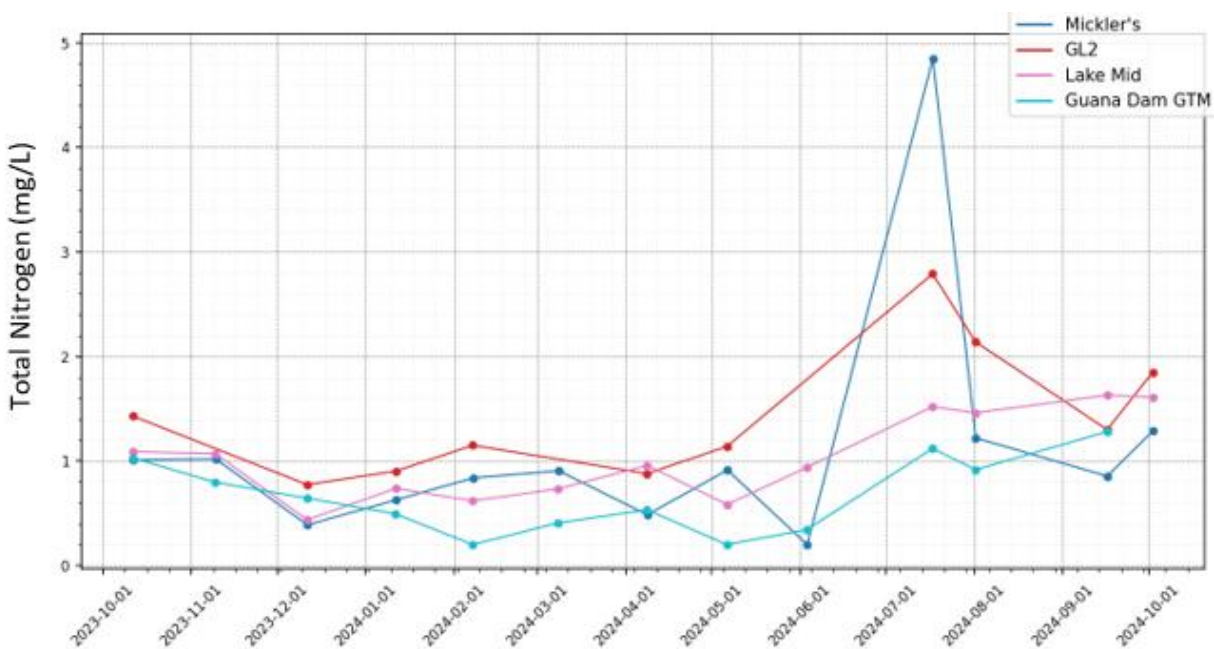


FIGURE 10: TOTAL NITROGEN CONCENTRATION IN THE FOUR OBSERVATION STATIONS, MK (BLUE LINE), GL2 (RED LINE), LM (PINK LINE), AND LS (CYAN LINE).

3.1.2 WATER QUALITY – CHLOROPHYLL-A

Chlorophyll-a concentration data collected in Guana Lake was analyzed. Data are discussed in section 4.1.4.

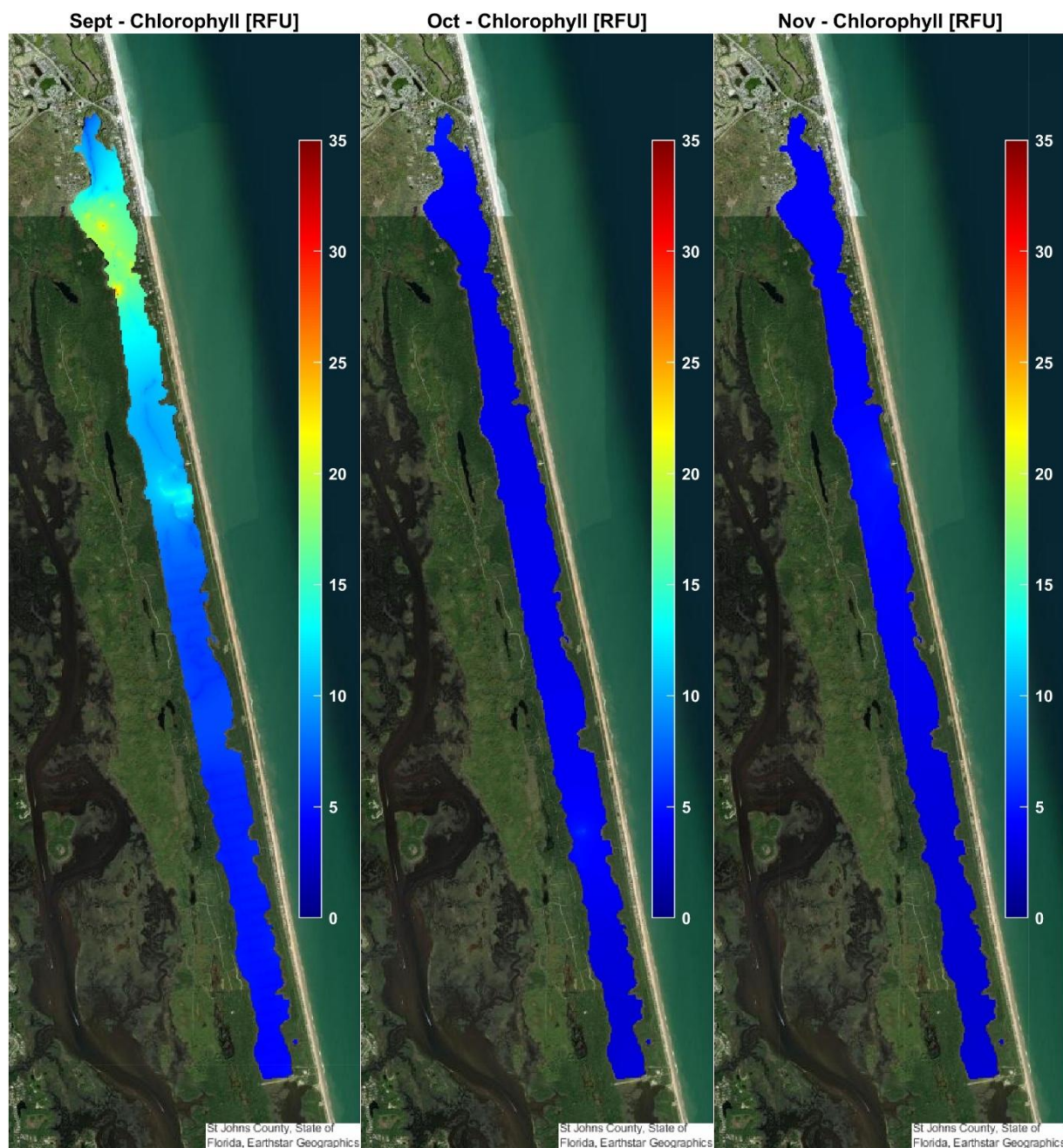


FIGURE 11: CHLOROPHYLL-A SPATIAL DISTRIBUTION DURING THE MONTHS OF SEPTEMBER, OCTOBER AND NOVEMBER 2023

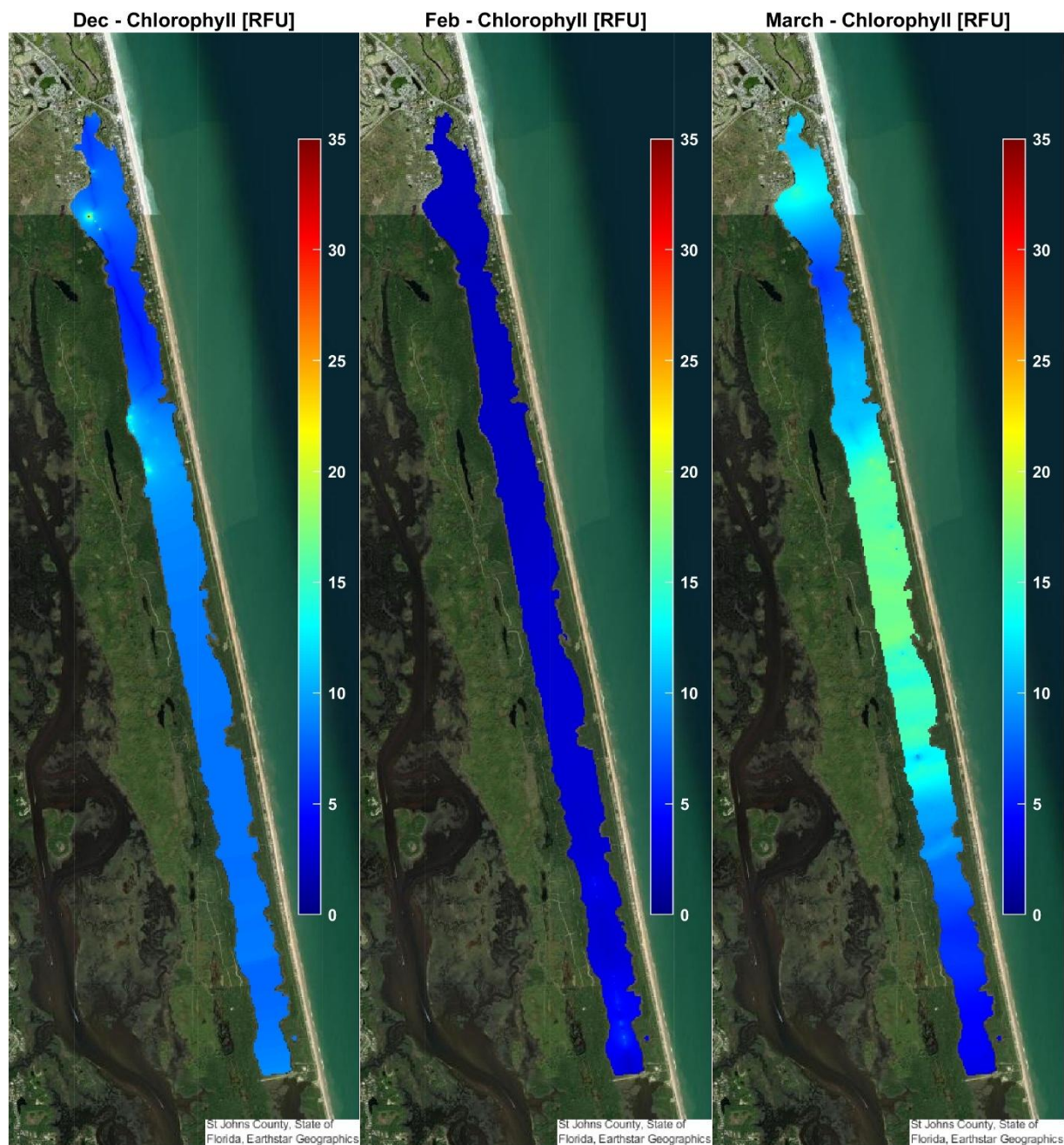


FIGURE 12: CHLOROPHYLL-A SPATIAL DISTRIBUTION DURING THE MONTHS OF DECEMEBR 2023, FEBRUARY AND MARCH 2024

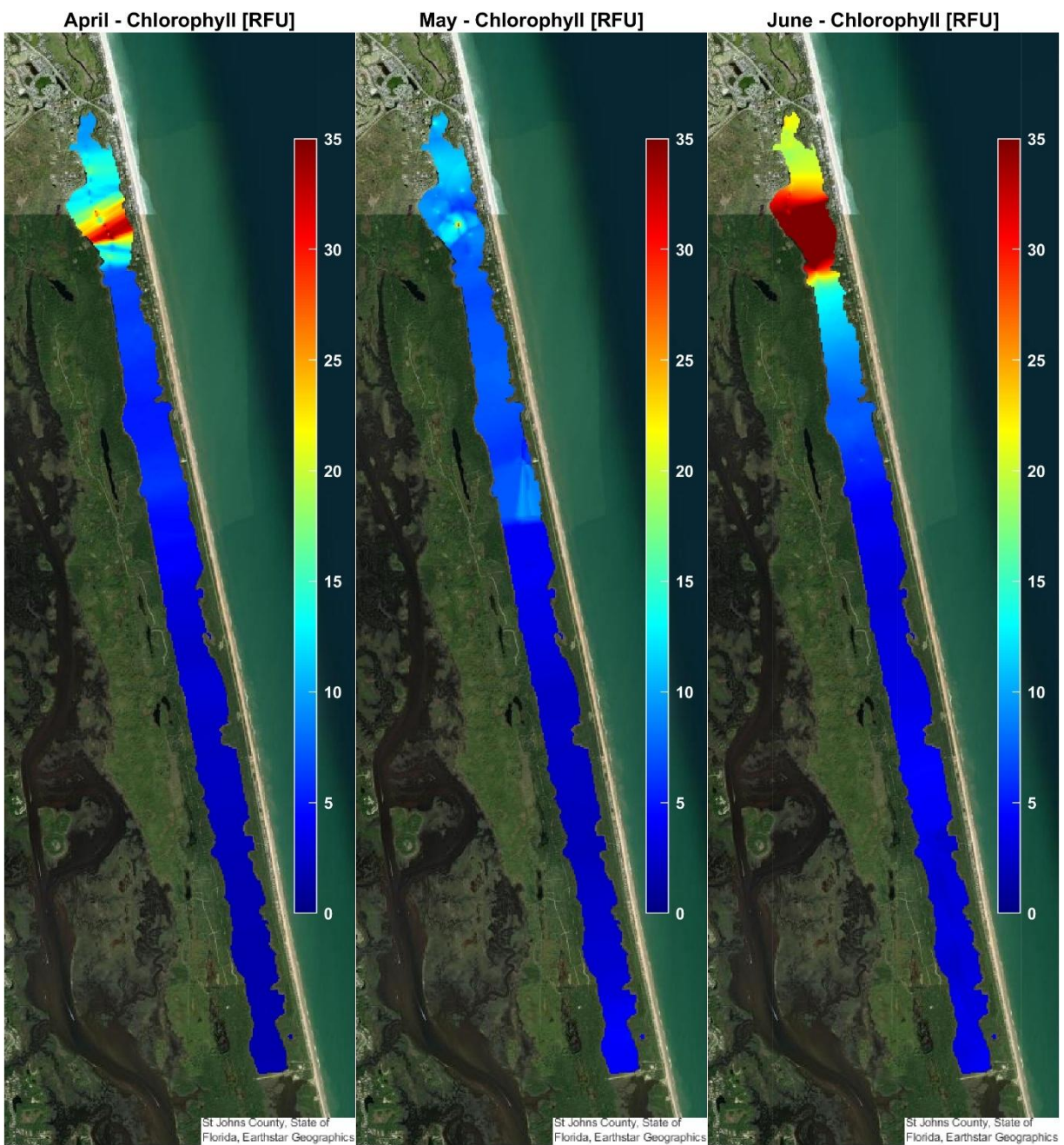


FIGURE 13: CHLOROPHYLL-A SPATIAL DISTRIBUTION DURING THE MONTHS OF APRIL, MAY AND JUNE 2024

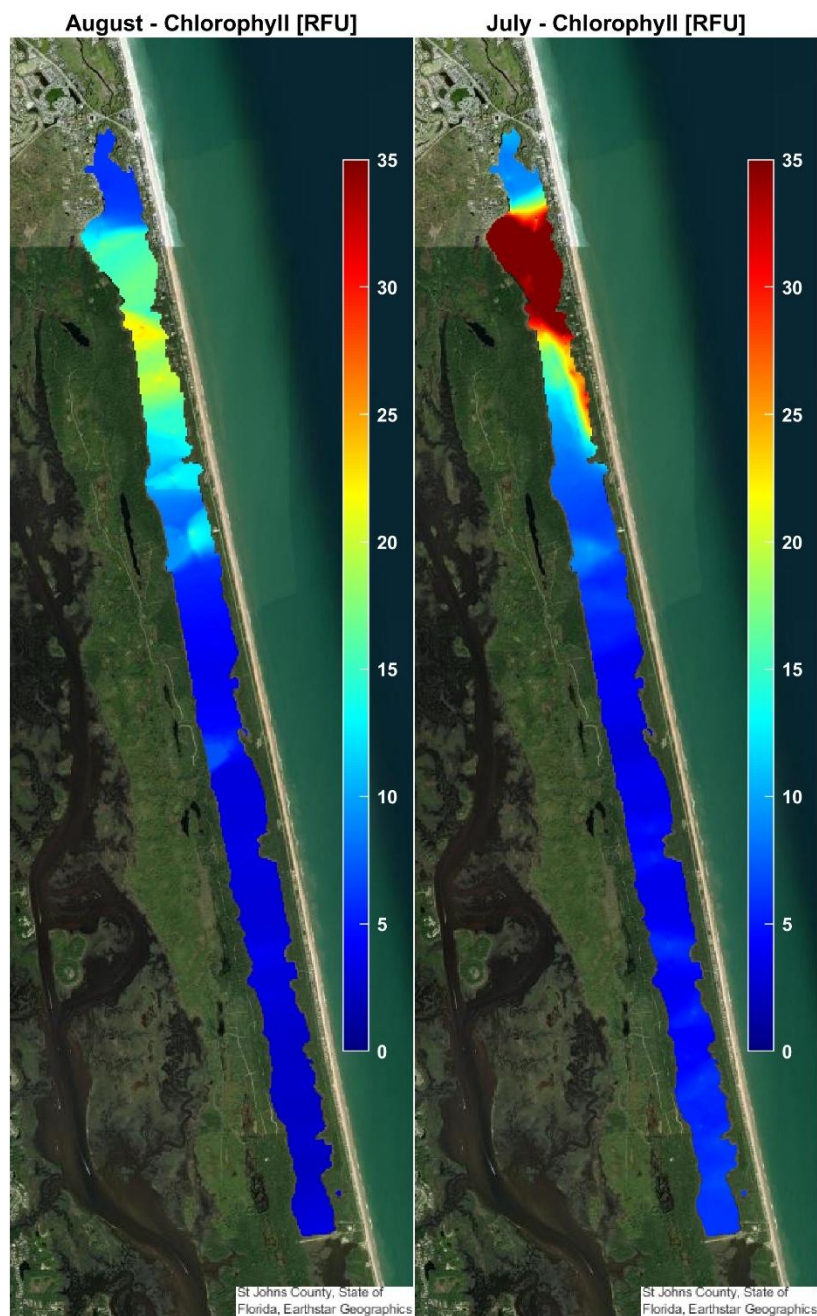


FIGURE 14: CHLOROPHYLL-A SPATIAL DISTRIBUTION DURING THE MONTHS OF JULY AND AUGUST 2024

3.1.3 WATER QUALITY –FDOM

fDOM data collected in Guana Lake were analyzed. Data are discussed in section 4.1.4.

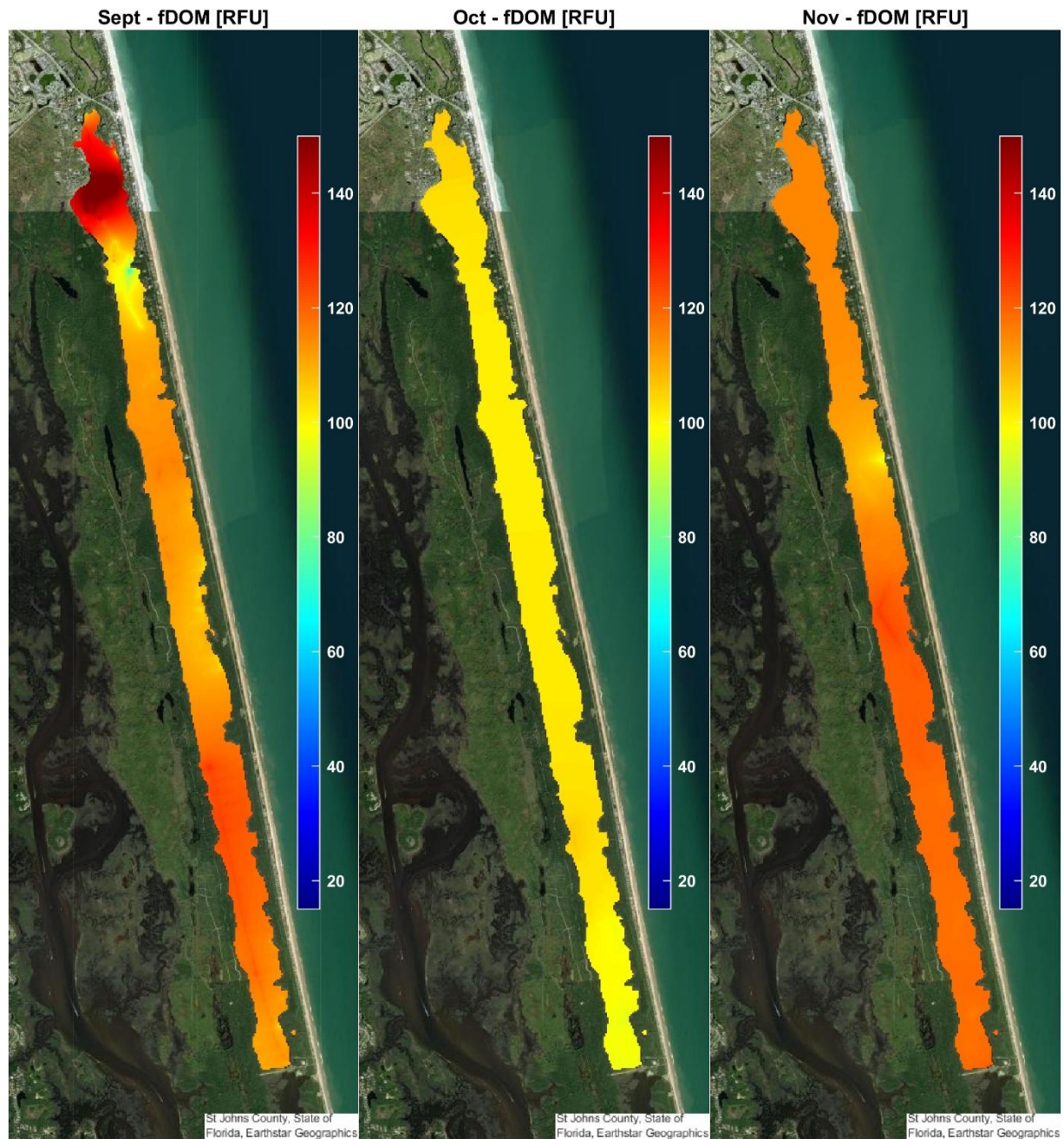


FIGURE 15: FDOM SPATIAL VARIATION DURING THE MONTHS OF SEPTEMBER, OCTOBER AND NOVEMBER 2023

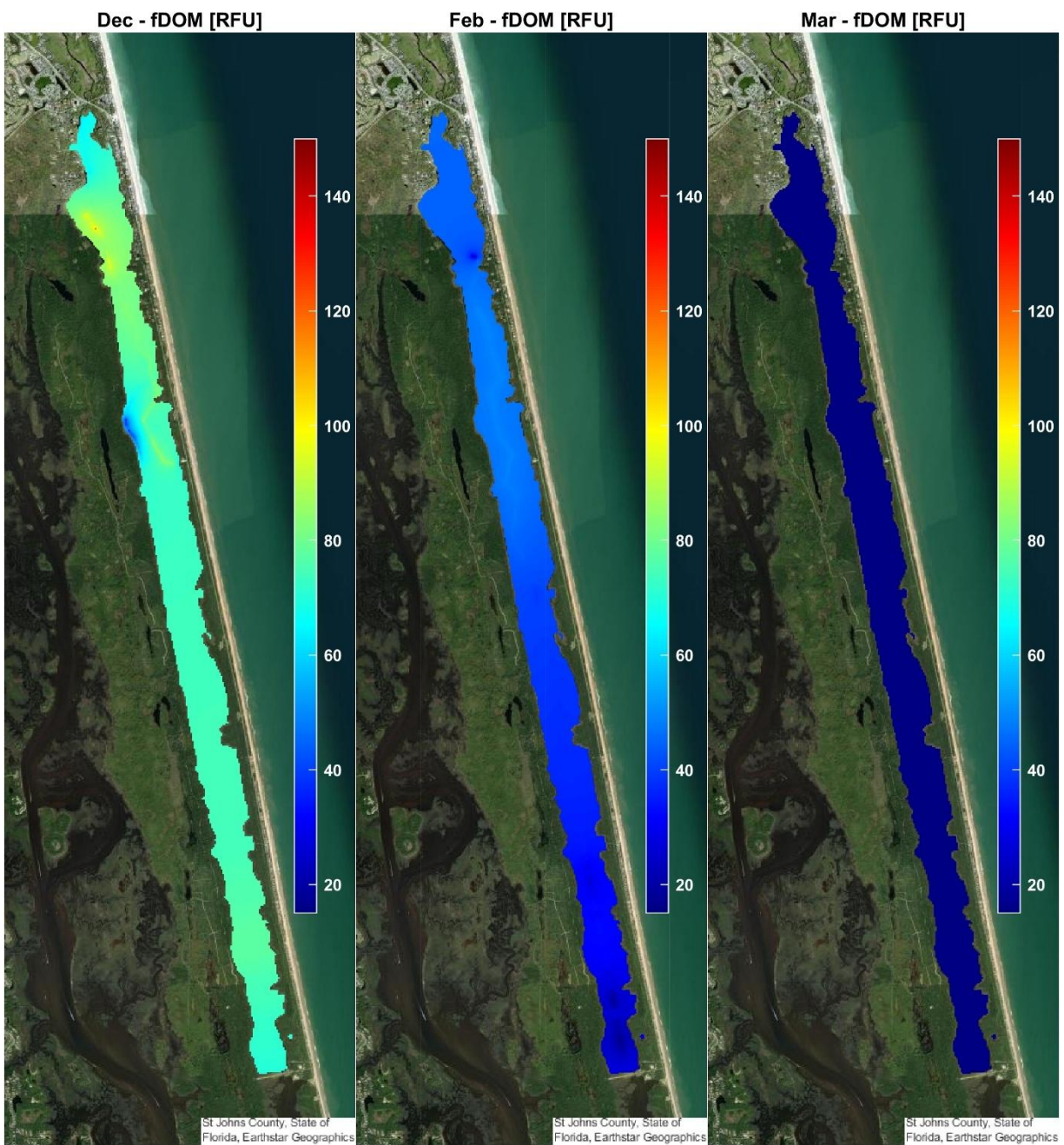


FIGURE 16: fDOM SPATIAL VARIATION DURING THE MONTHS OF DECEMBER 2023, FEBRUARY AND MARCH 2024

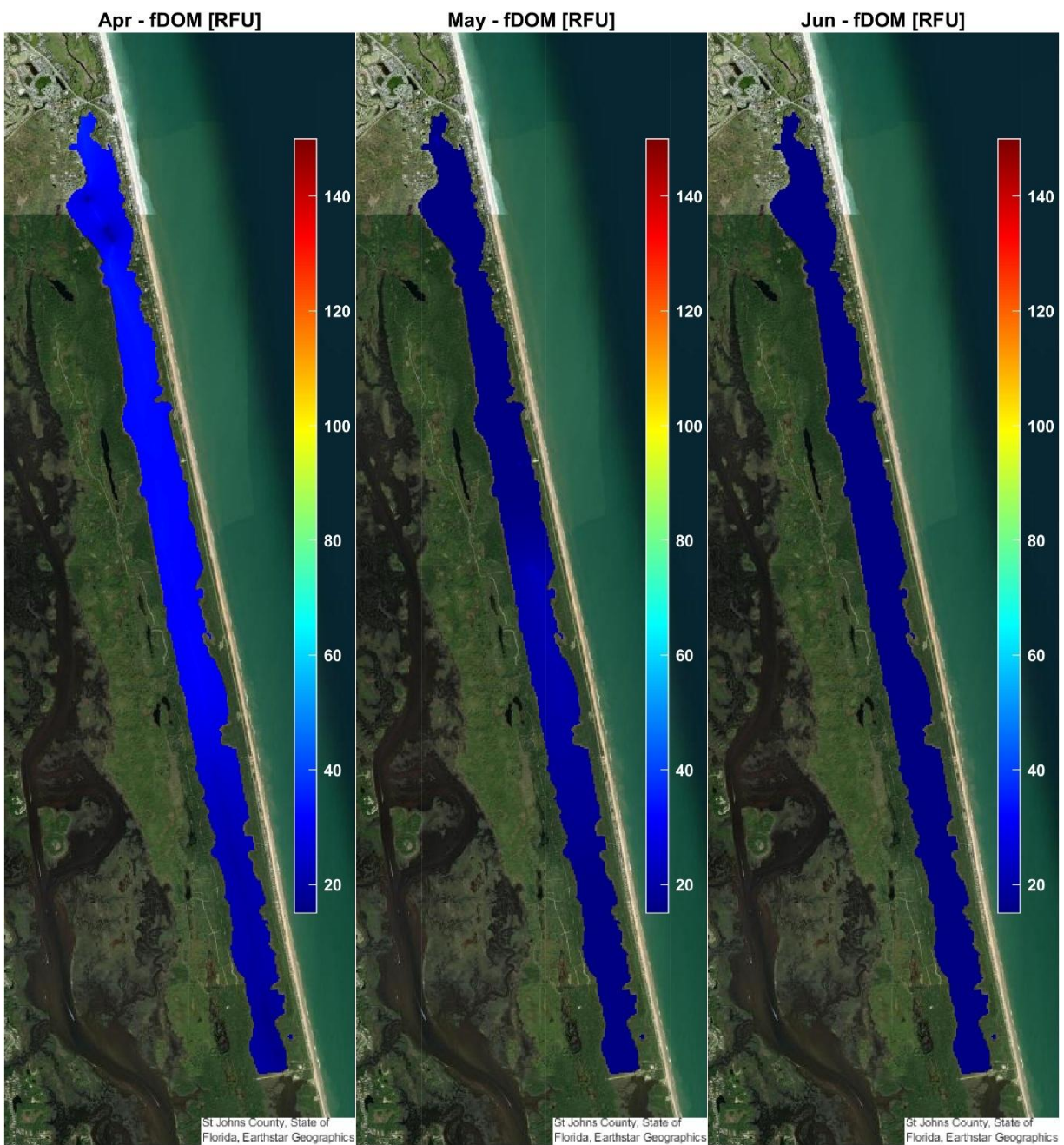


FIGURE 17: fDOM SPATIAL VARIATION DURING THE MONTHS OF APRIL, MAY AND JUNE 2024

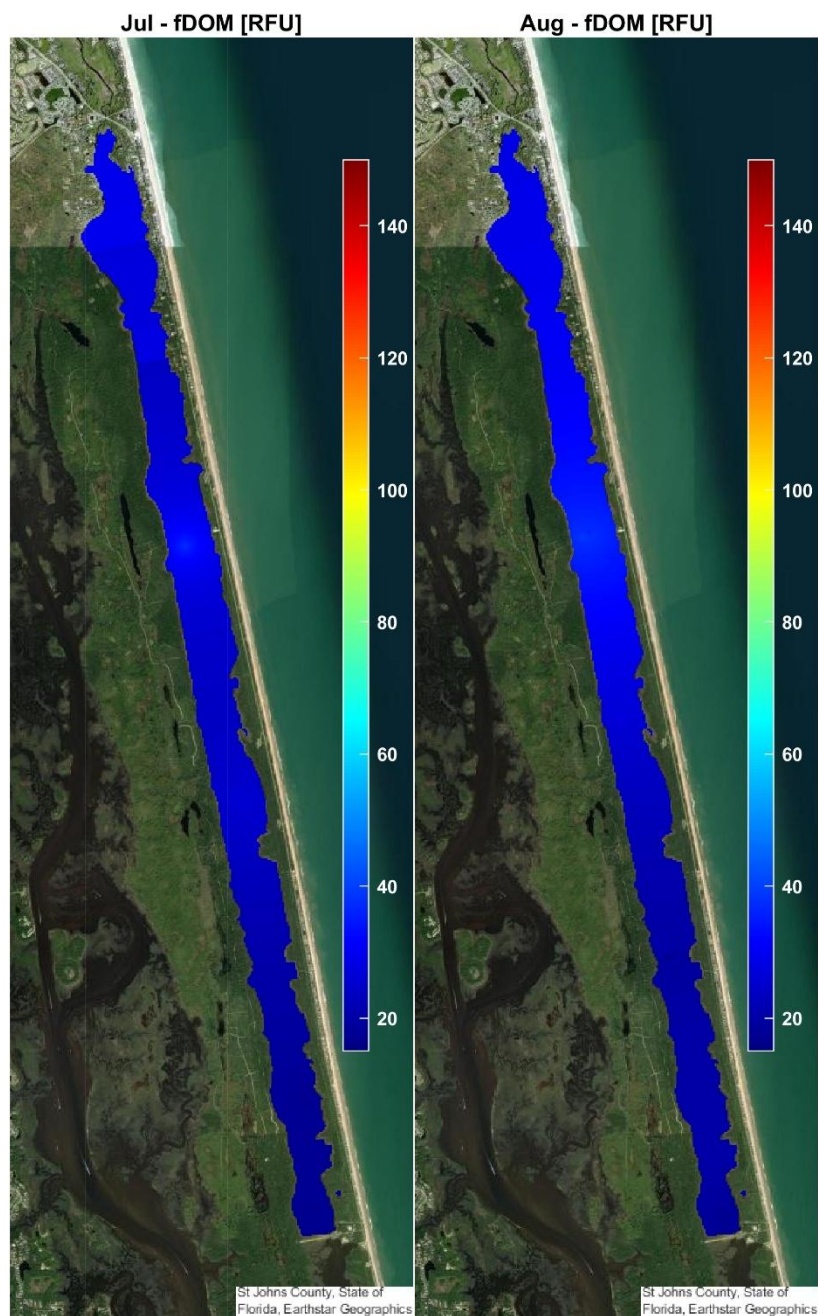


FIGURE 18: FDOM SPATIAL VARIATION DURING THE MONTHS OF JULY AND AUGUST 2024

3.1.4 WATER QUALITY – DISSOLVED OXYGEN (DO)

DO data collected in Guana Lake were analyzed. Data are discussed in section 4.1.4.

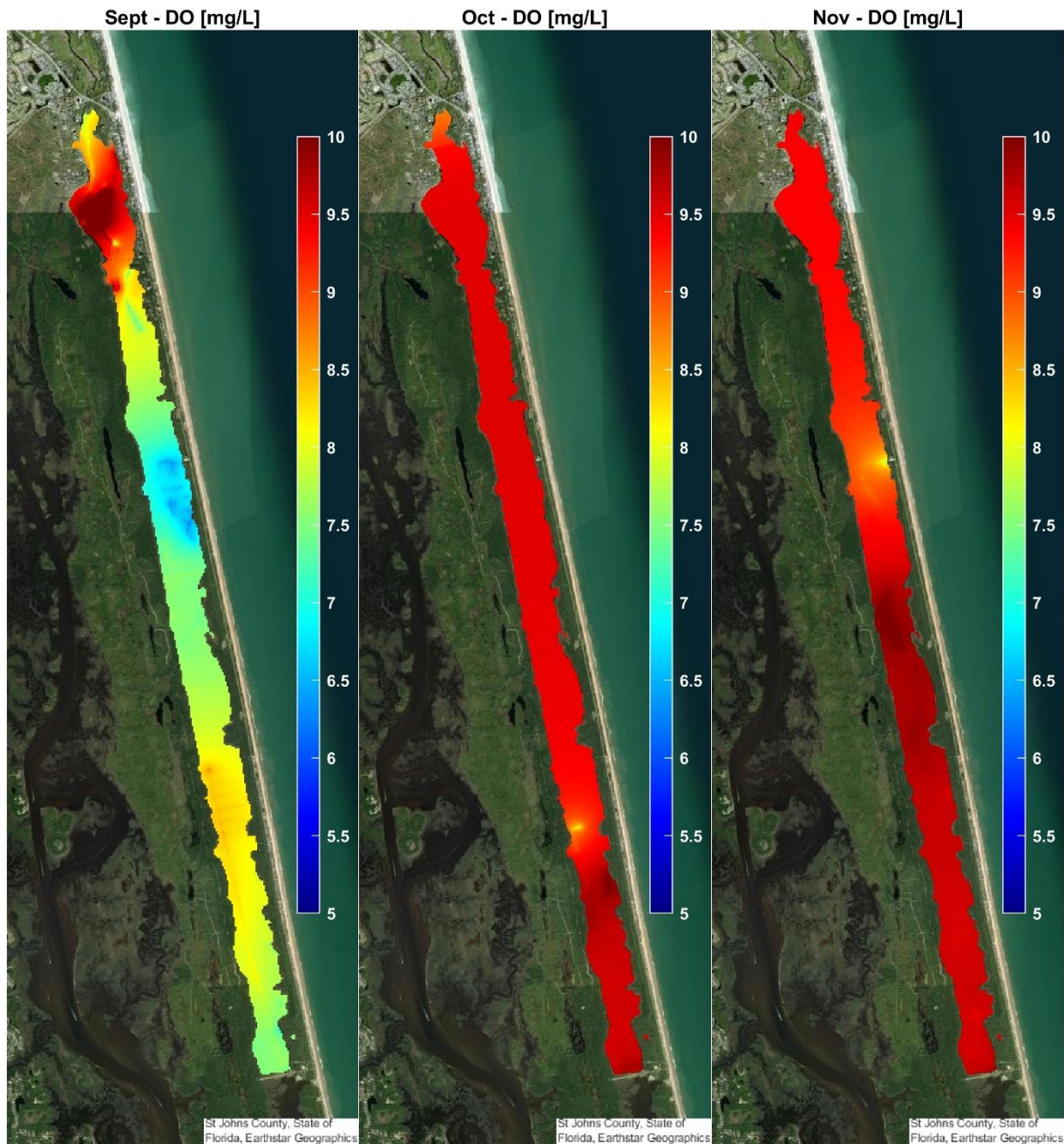


FIGURE 19: DISSOLVED OXYGEN SPATIAL DISTRIBUTION DURING THE MONTHS OF SEPTEMBER, OCTOBER AND NOVEMBER 2023

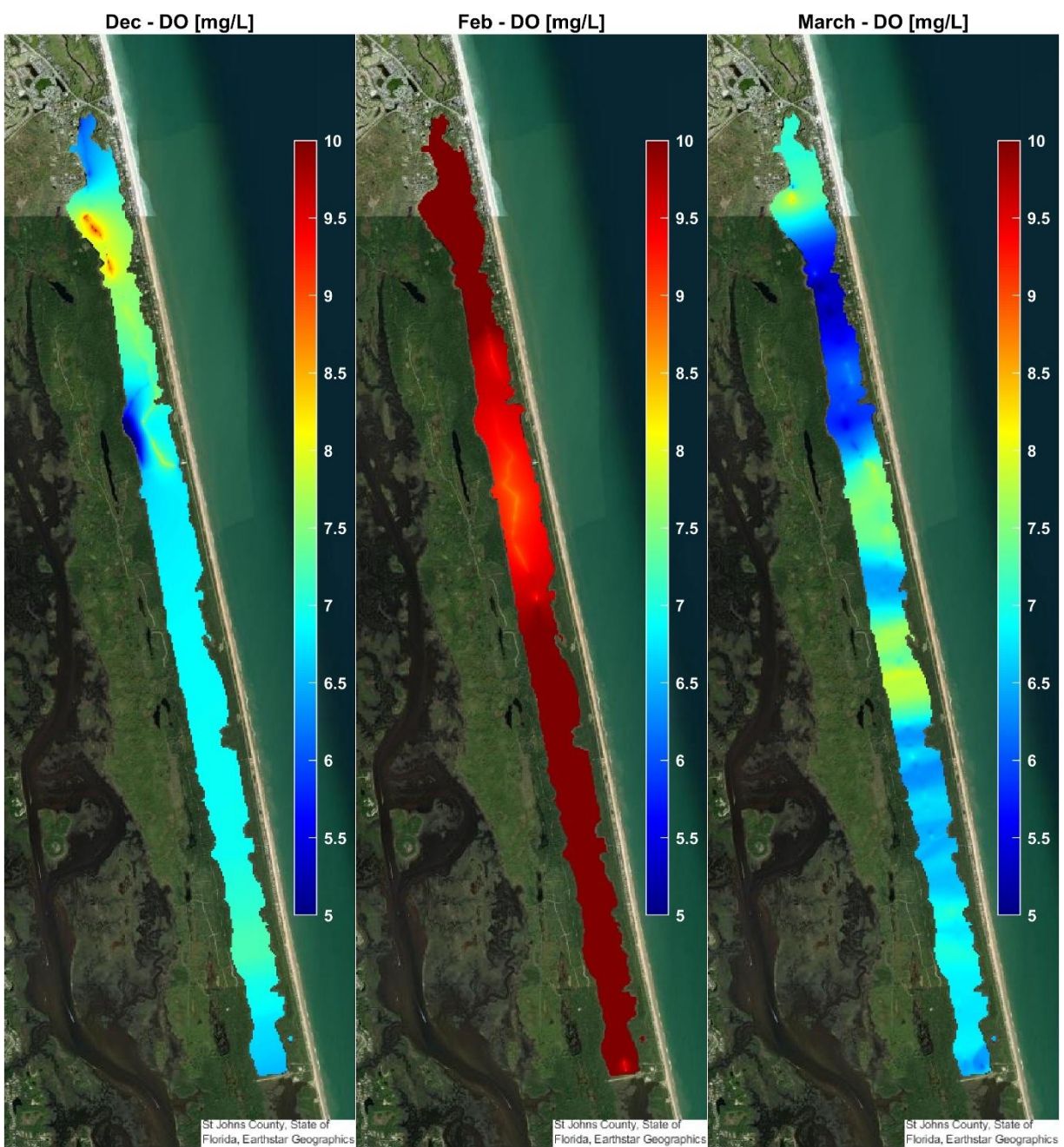


FIGURE 20: DISSOLVED OXYGEN SPATIAL DISTRIBUTION DURING THE MONTHS OF DECEMEBR 2023, FEBRUARY AND MARCH 2024.

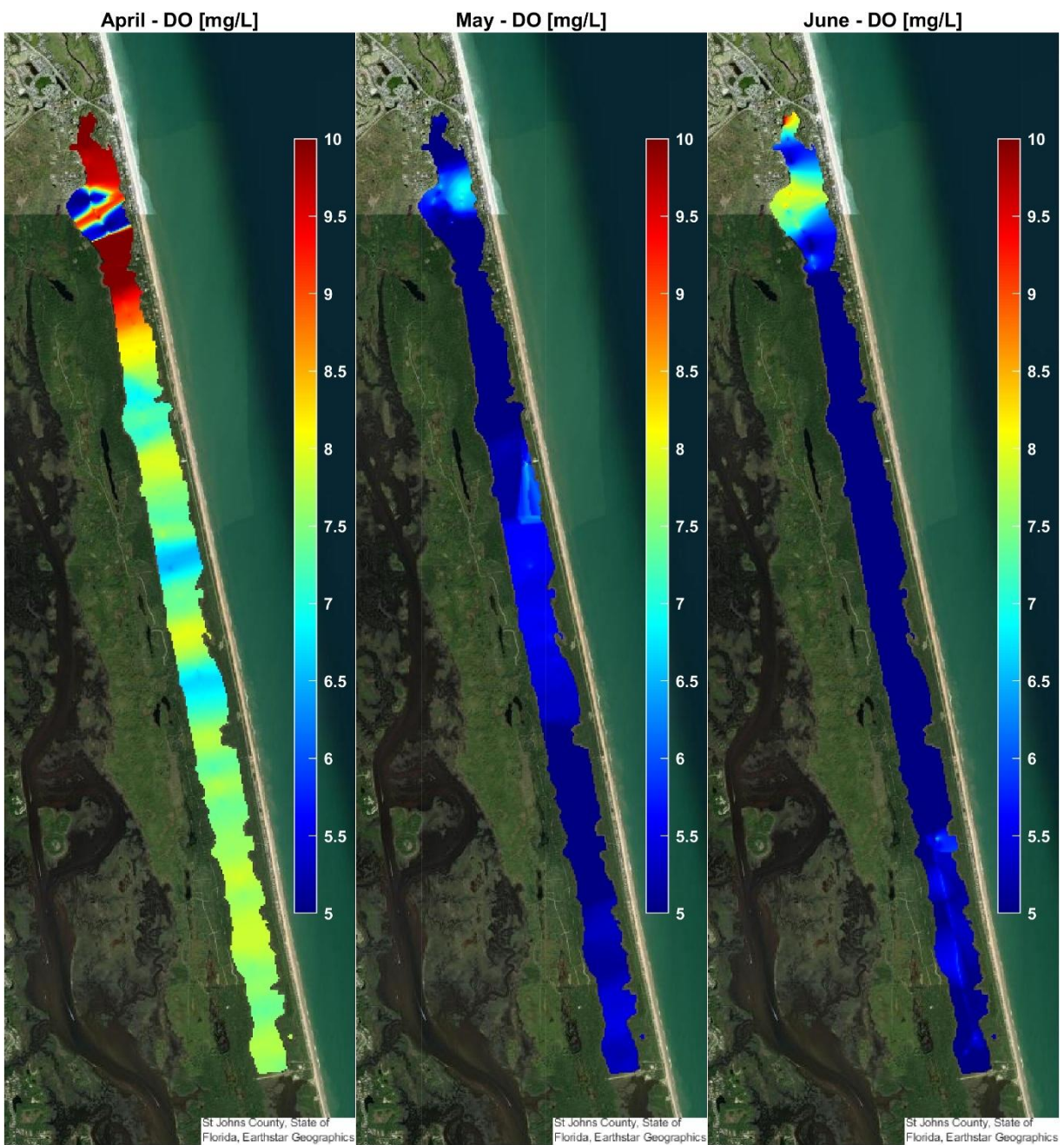


FIGURE 21: DISSOLVED OXYGEN SPATIAL DISTRIBUTION DURING THE MONTHS OF APRIL, MAY AND JUNE 2024.

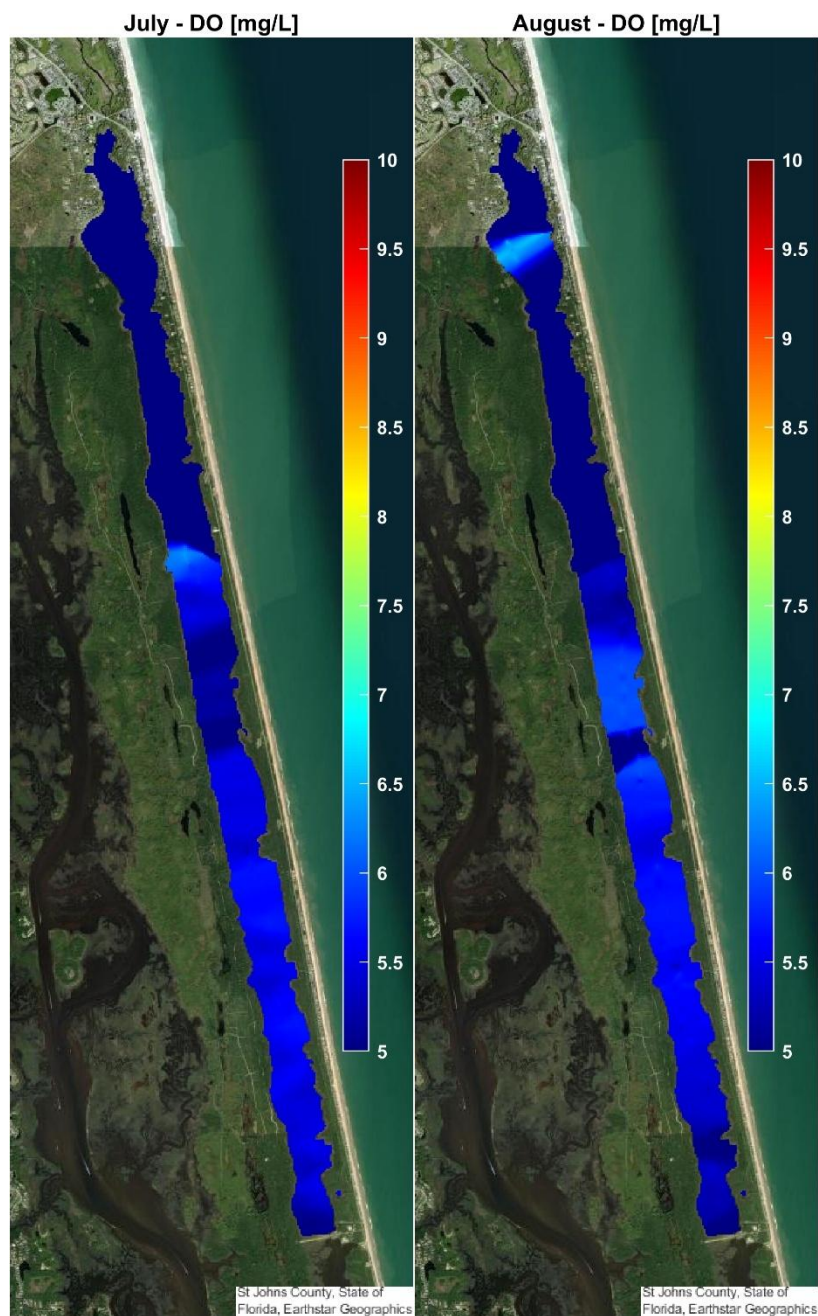


FIGURE 22: DISSOLVED OXYGEN SPATIAL DISTRIBUTION DURING THE MONTHS OF JULY AND AUGUST 2024

3.1.5 WATER QUALITY- PH

pH data collected in Guana Lake were analyzed. Data are discussed in section 4.1.4.

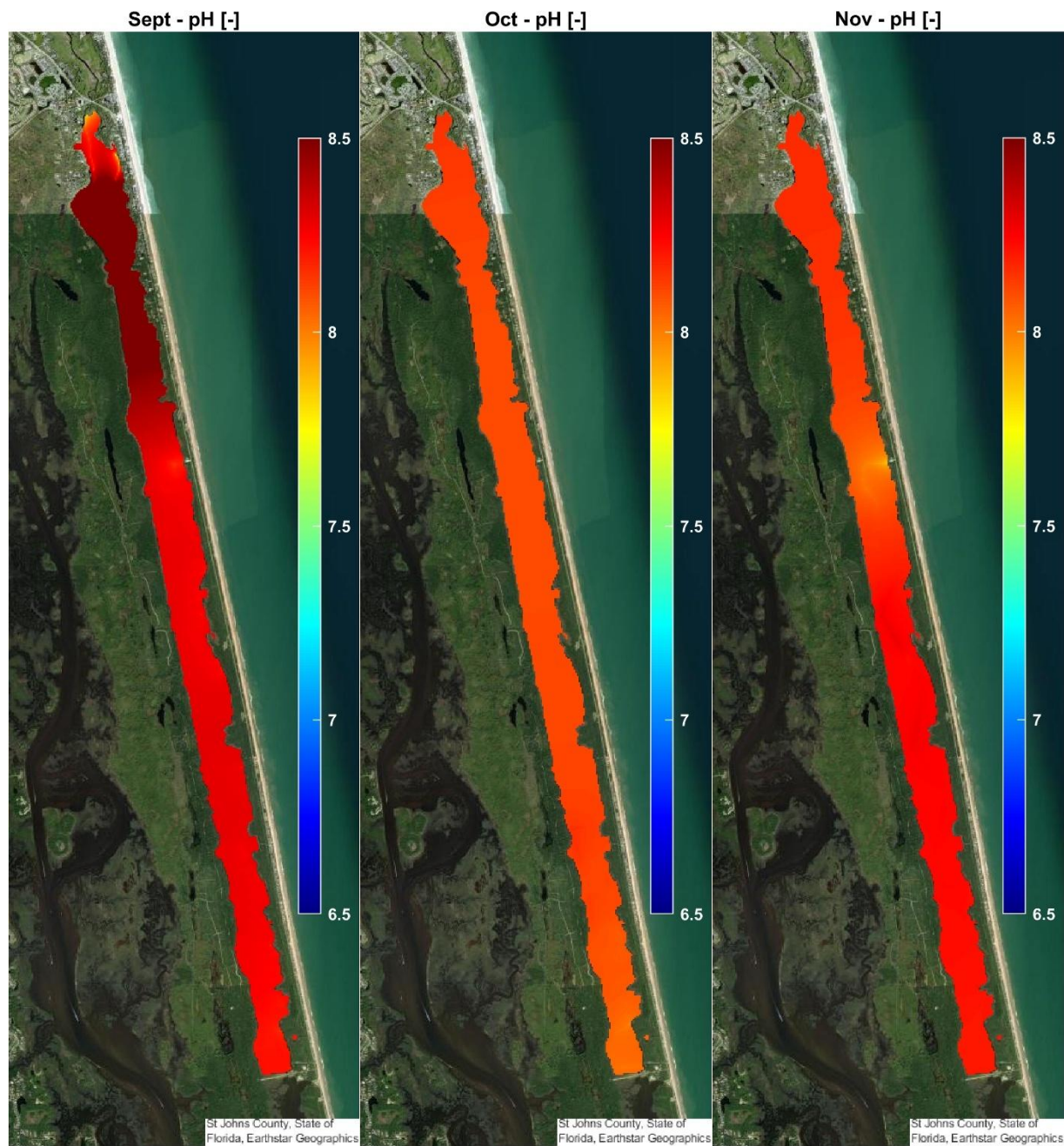


FIGURE 23: PH SPATIAL DISTRIBUTION DURING THE MONTHS OF SEPTEMBER, OCTOBER AND NOVEMBER 2023

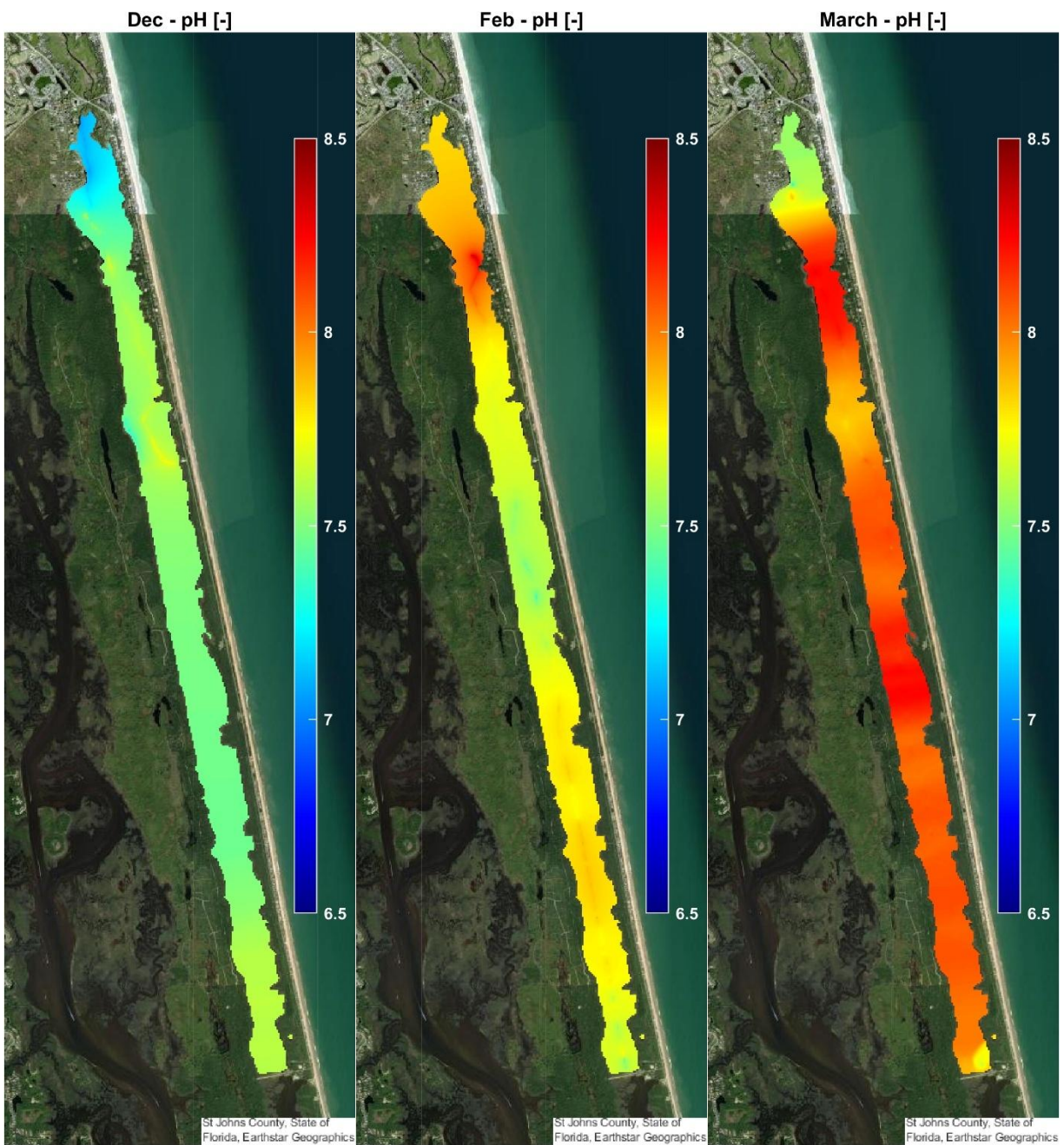


FIGURE 24: PH SPATIAL DISTRIBUTION DURING THE MONTHS OF DECEMEBR 2023, FEBRUARY AND MARCH 2024

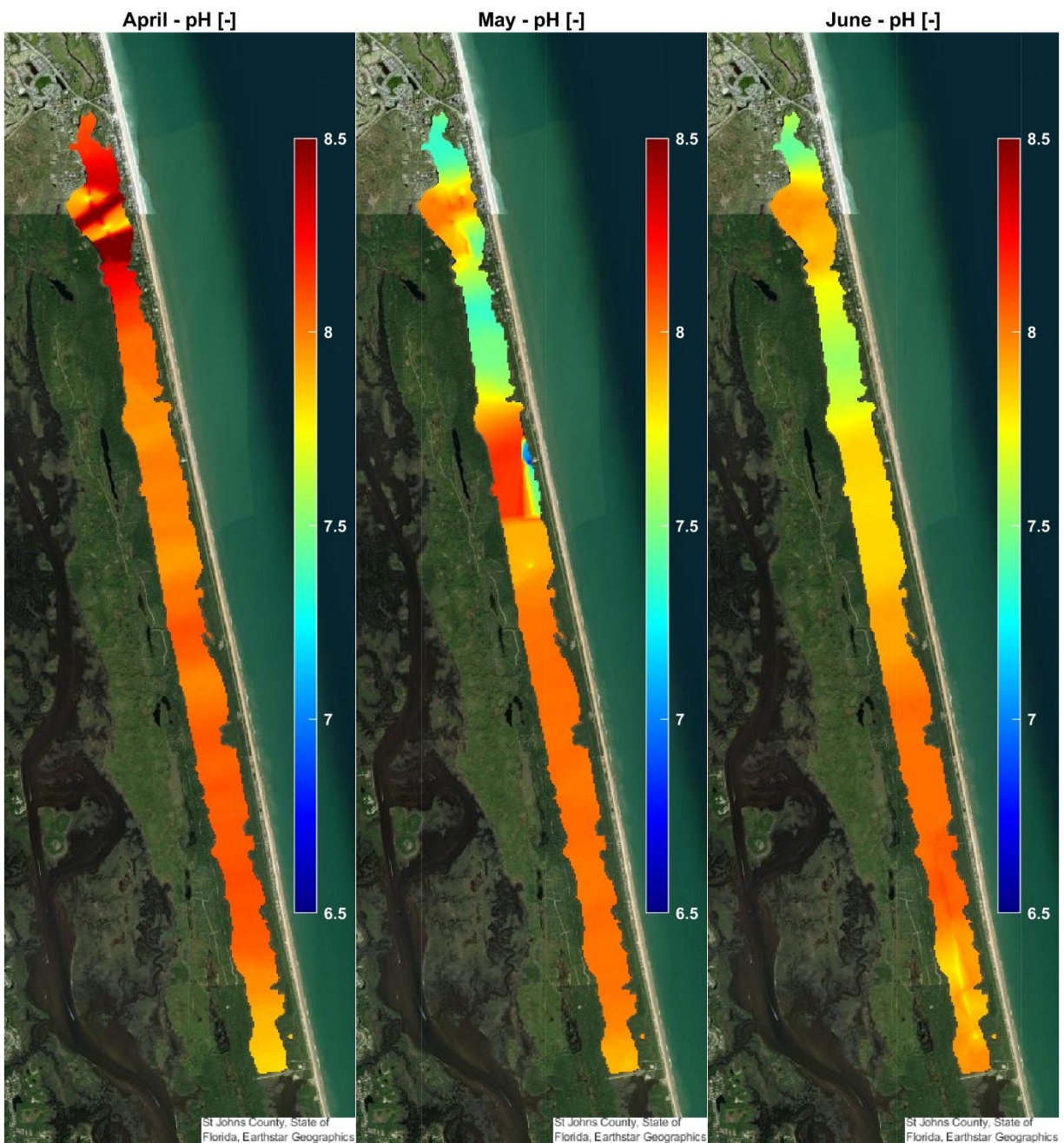


FIGURE 25: PH SPATIAL DISTRIBUTION DURING THE MONTHS OF APRIL, MAY AND JUNE 2024

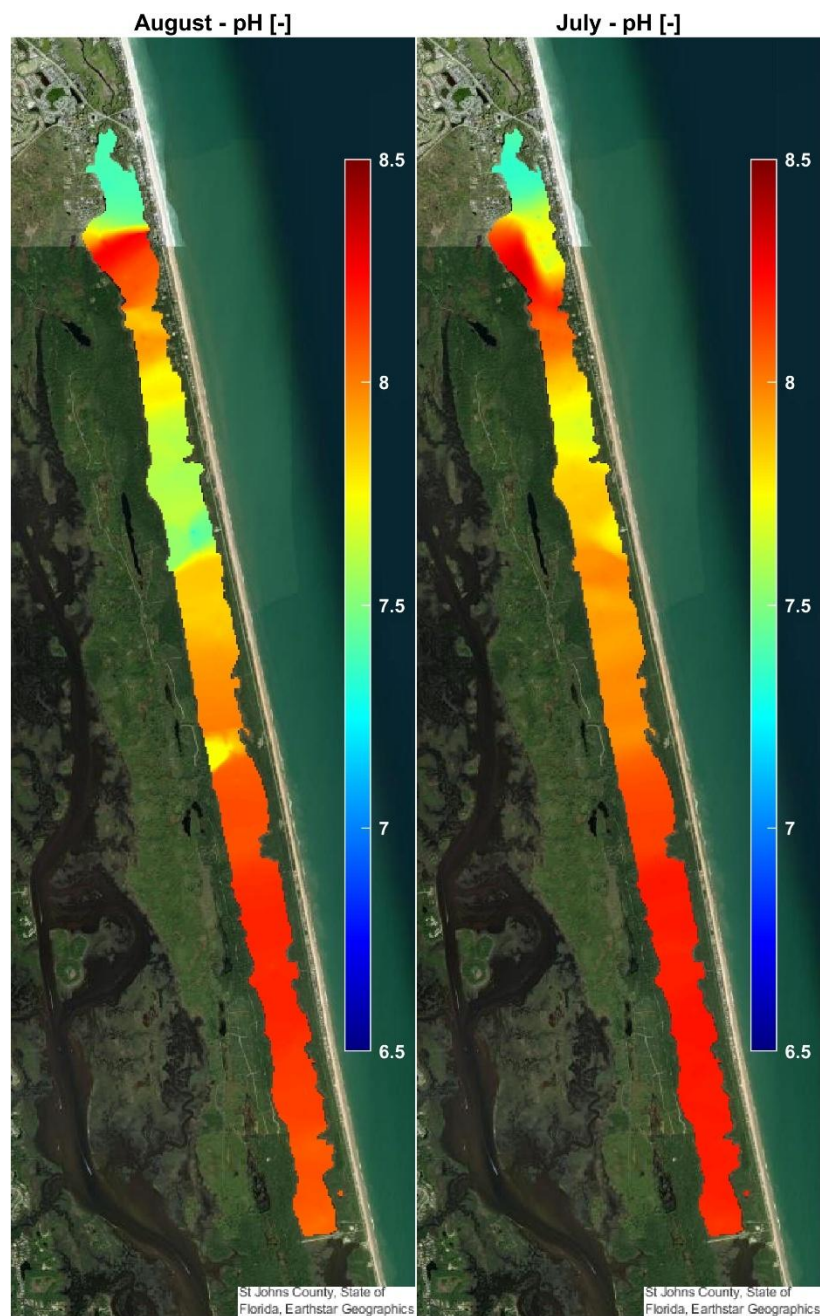


FIGURE 26: DISSOLVED OXYGEN SPATIAL DISTRIBUTION DURING THE MONTHS OF JULY AND AUGUST 2024

3.1.6 SALINITY

Salinity data collected in Guana Lake were analyzed. Data are discussed in section 4.1.4.

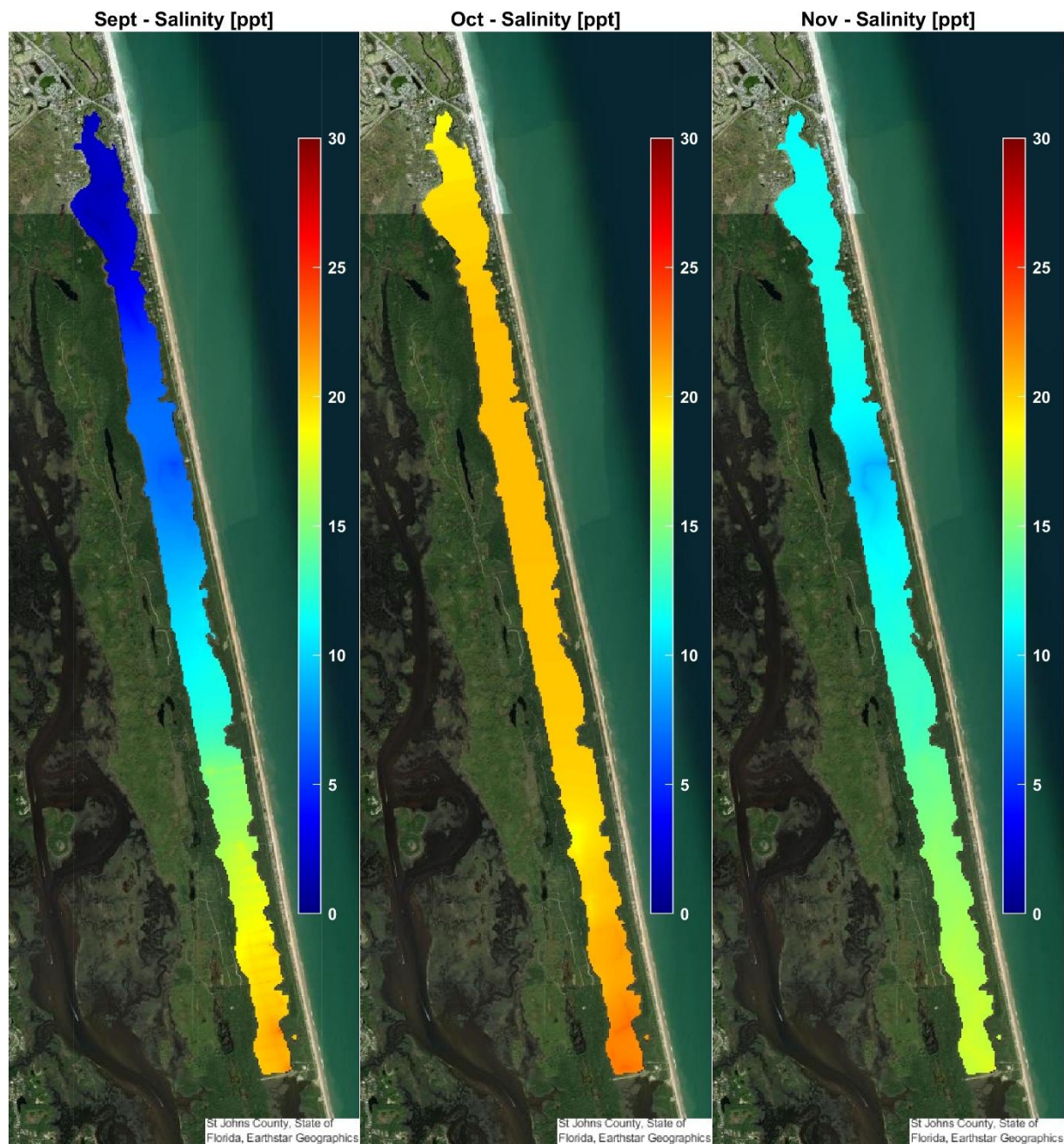


FIGURE 27: SALINITY SPATIAL VARIATION DURING THE MONTHS OF SEPTEMBER, OCTOBER AND NOVEMBER 2023

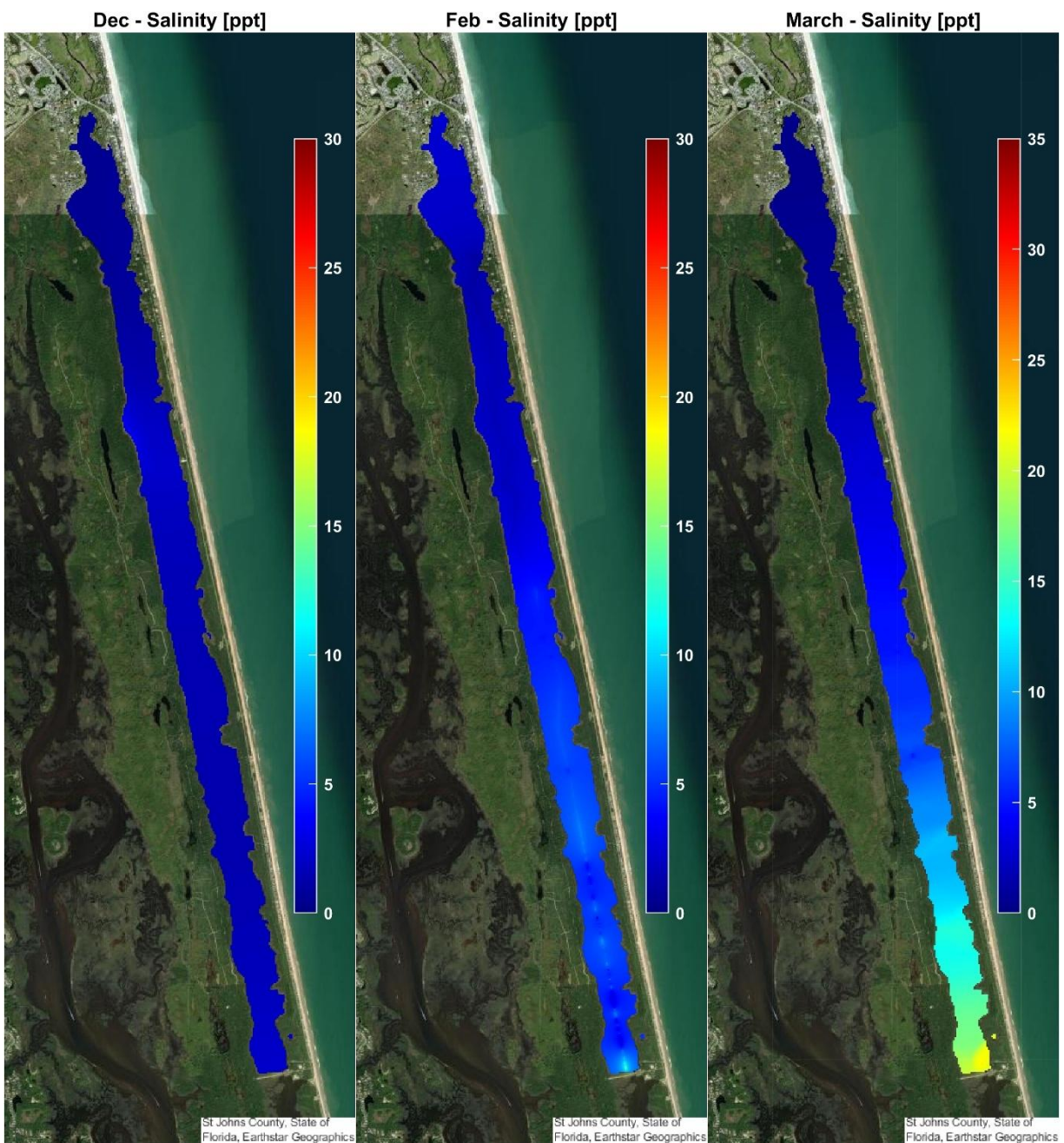


FIGURE 28: SALINITY SPATIAL VARIATION DURING THE MONTHS OF DECEMBER 2023, FEBRUARY AND MARCH 2024

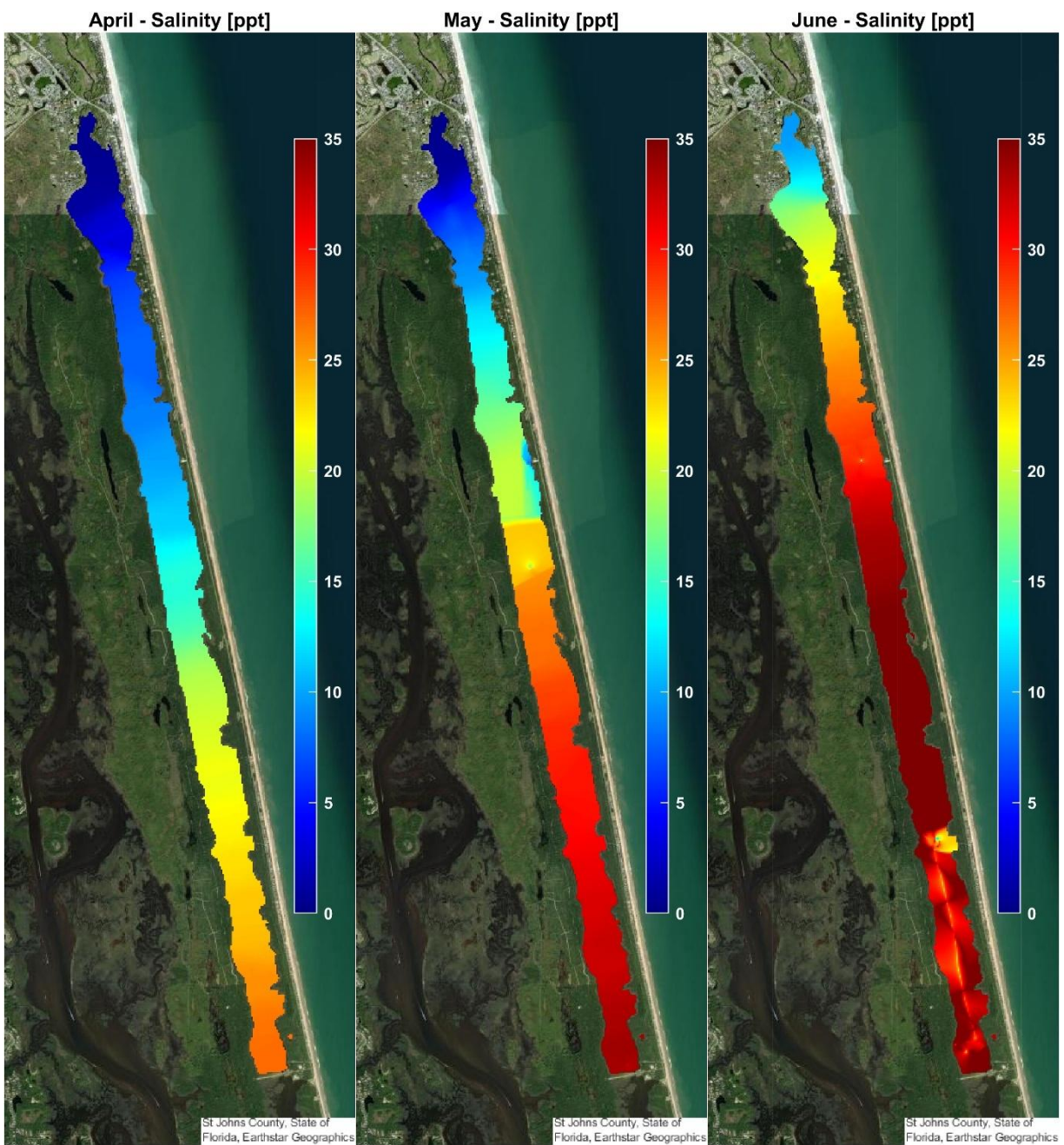


FIGURE 29: SALINITY SPATIAL VARIATION DURING THE MONTHS OF APRIL, MAY AND JUNE 2024.

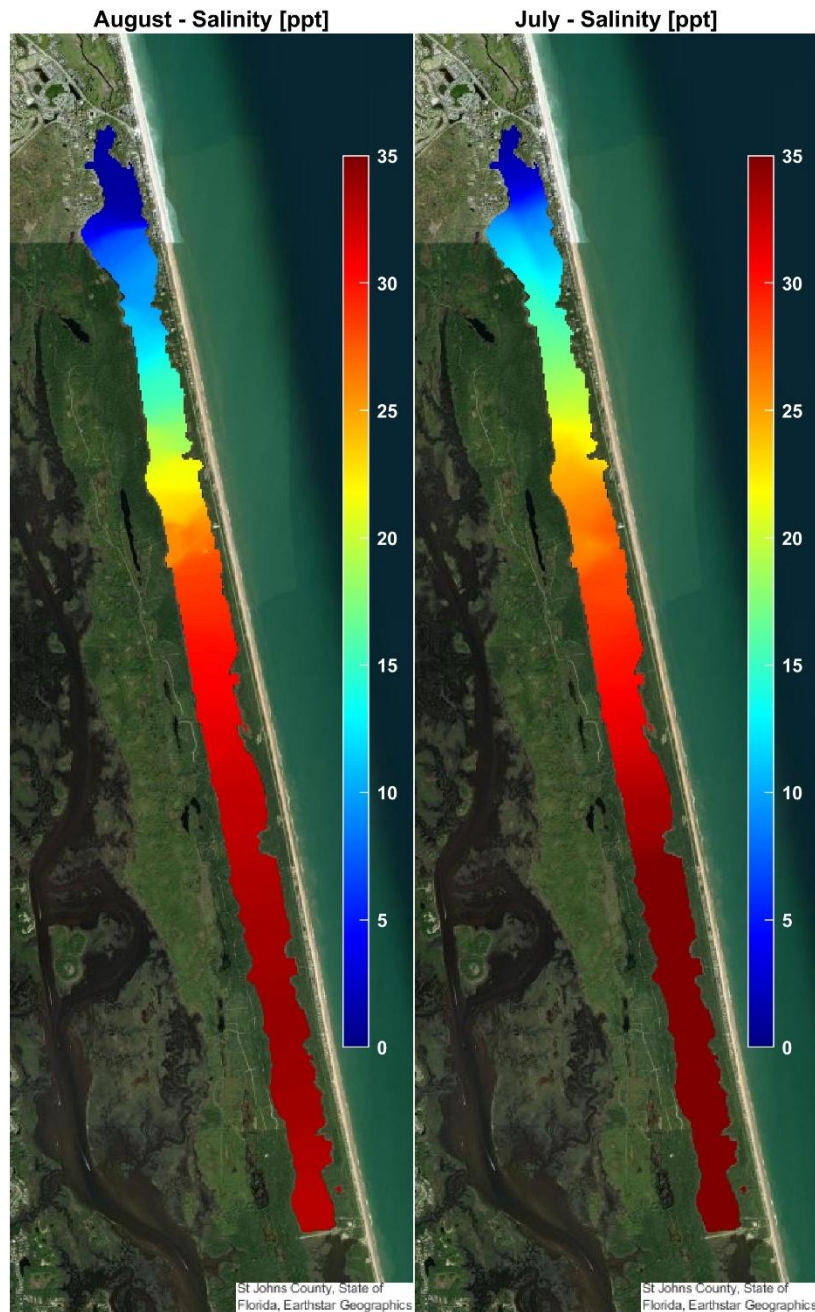


FIGURE 30: SALINITY SPATIAL VARIATION DURING THE MONTHS OF JULY AND AUGUST 2024.

3.1.7 WATER LEVEL STATIONS

The water level in Guana Lake ranged from approximately 0.25 m above mean sea level (MSL) during the complete drawdown period (February to April 2024) to a peak of 1.20 m MSL during Hurricane Helene (September 24–27, 2024). These fluctuations are largely driven by dam management operations. Water levels decrease rapidly during discharge phases, while they rise more gradually during recharge phases, which are typically managed by adding flashboards or

keeping 2 to 3 recharge gates open. On average, each added flashboard contributes to a weekly water level increase of about 0.12 to 0.15 m. Meanwhile, tidal influence at the dam ranges from approximately -0.8 m to 1.4 m MSL. Comparison of water level station data with wind measurements highlights the role of wind shear stress in affecting lake surface inclination. Analysis shows that during severe storm conditions, such as Hurricane Helene, wind-induced setup can reach up to 0.6 m. Under calm conditions or in the absence of strong north-south wind patterns, the lake surface remains nearly level, with no significant gradient observed. Additionally, wind affects the tidal signal at the dam. As shown in Figure 31, strong winds can enhance tidal setup, increasing the hydraulic gradient between the estuary and the lake. This, in turn, leads to higher recharge discharges into the lake due to the amplified head difference.

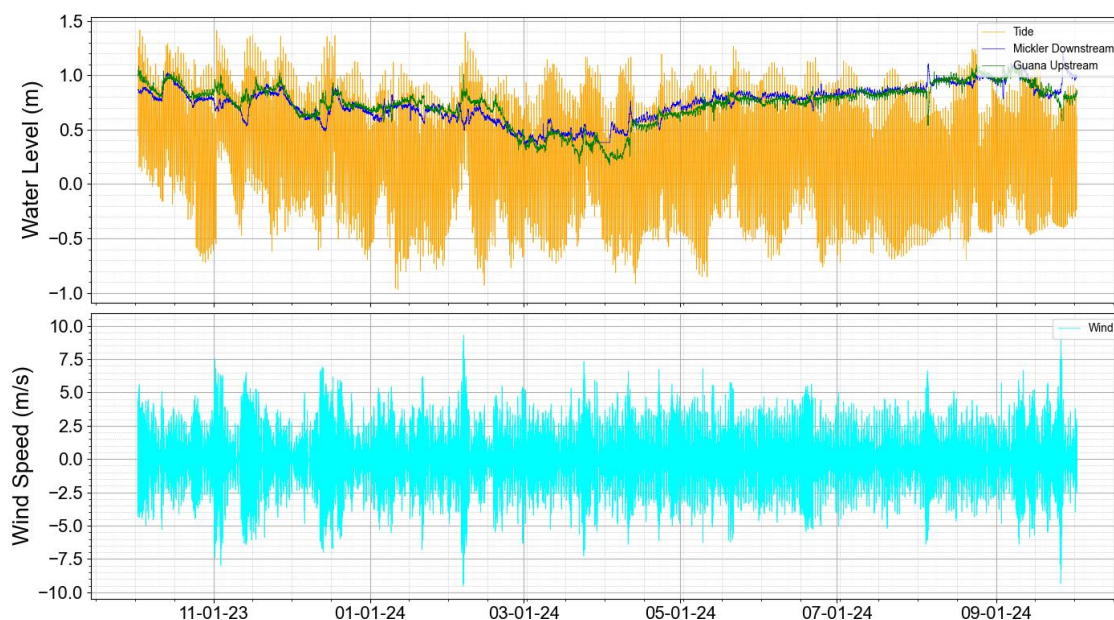


FIGURE 31: UPPER SUBPLOT: THE WATER LEVEL MEASURED SOUTH TO THE GUANA DAM, IN THE GUANA RIVER (ORANGE LINE). THE BLUE LINE SHOWS THE WATER LEVEL IN THE LAKE IN THE MICKLER'S WEIR PROXIMITY, WHILE THE GREEN LINE REPRESENTS THE WATER LEVEL IL THE LAKE IN THE LAKE SOUTH STATION. LOWER SUBPLOT) THE NORTH COMPONENT OF WIND MEASURED IN THE PELLICER CREEK STATION.

Salinity and temperature data were also extracted and compared from the water level stations. During the summer months, salinity in the river shows a noticeable decrease, likely due to increased freshwater input or stratification effects. In contrast, the lake experiences elevated salinity levels driven by high evaporation rates associated with increased temperatures. These conditions can result in hypersaline environments, occasionally exceeding the upper conductivity

detection limit of the HOBO sensor. Additionally, water temperature in the lake exhibits greater diurnal variability compared to the estuary, reflecting stronger heating and cooling cycles.

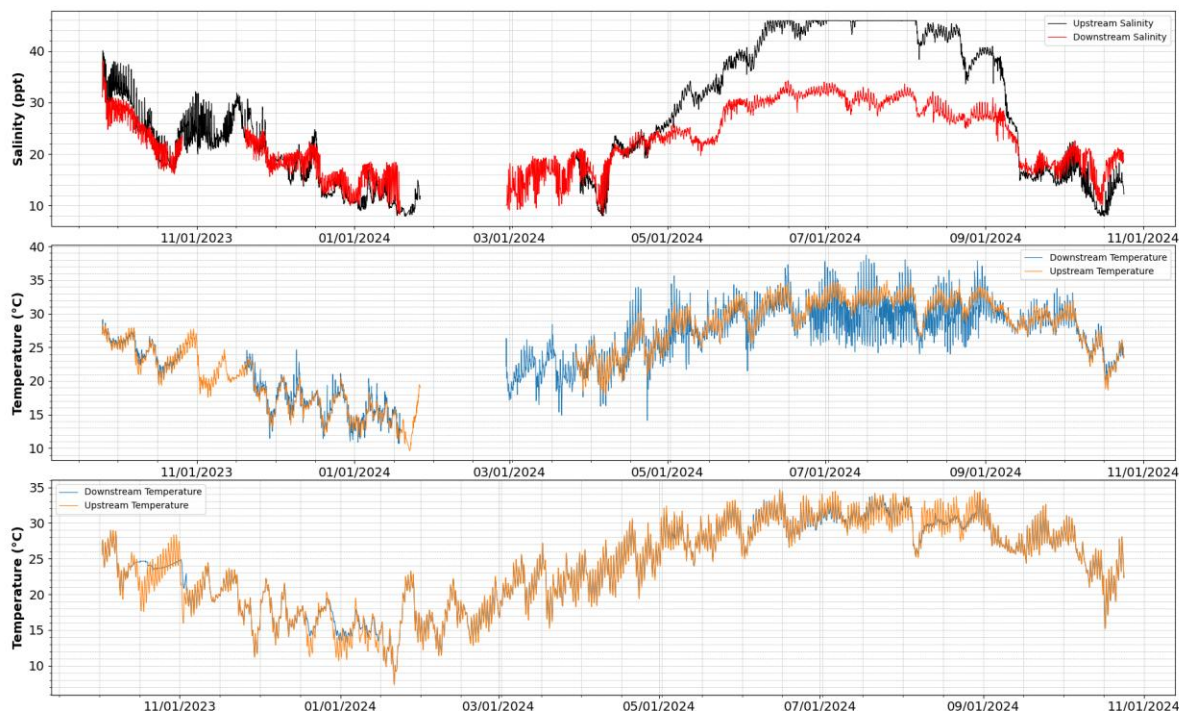


FIGURE 32: MEASURED SALINITY AND TEMPERATURE AT THE FOUR STATIONS DEPLOYED IN THE LAKE. FROM THE TOP, THE FIRST PLOT SHOWS SALINITY INSIDE THE LAKE (BLACK LINE) AND IN THE ESTUARY (RED LINE). THE SECOND PLOT SHOWS WATER TEMPERATURE IN THE LAKE (BLUE LINE) AND IN THE ESTUARY (ORANGE LINE). THE THIRD PLOT SHOWS WATER TEMPERATURE AT THE TWO STATIONS AT MICKLER'S WEIR, WITH THE ORANGE LINE REPRESENTING THE UPSTREAM SENSOR AND THE BLUE LINE REPRESENTING THE DOWNSTREAM SENSOR.

3.1.8 DISCHARGE MEASUREMENTS

Discharge at both ends of Guana Lake was measured using the ADCPs. At the southern end near Guana Dam, discharge values reached a maximum of approximately $15 \text{ m}^3/\text{s}$. These results align with estimates obtained using similar water level and dam geometry inputs in the equations detailed in Section 2.3.4.

At Mickler's Weir, discharge was measured under steady flow conditions, eliminating the need for multiple measurements. The average flow at this northern outlet throughout the year was approximately $0.2 \text{ m}^3/\text{s}$. No discharge data were collected during overflow events across the wider spillway at Mickler's, as the ADCP propeller was unable to pass through the dense vegetation commonly present during high-flow periods. This vegetation is typically transported from the northern area of Ponte Vedra and accumulates near the weir during such events. All discharge data are available in the shared Google Drive folder. The data were used to calibrate the parameters

C_s , $C_{s,sub}$, C_g , and $C_{g,sub}$ in eq.s (1), (2), (3), (4), (5) (values obtained for this calibration are available in section 2.3.3).

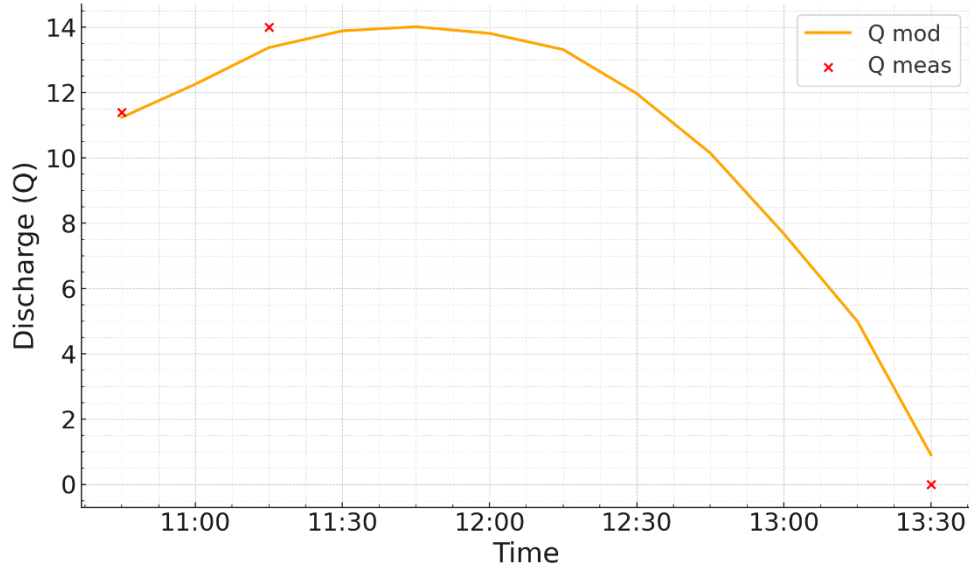


FIGURE 33: MEASURED DISCHARGE IN APRIL 2024. THE YELLOW LINE IS THE MODELED DISCHARGE WITH EQ. (3). THE RED CROSSES REPRESENT THE VALUES RECORDED DURING THE SURVEY WITH THE SONTEK RS5

3.2. NUMERICAL MODEL

In this section, the results of the numerical model are presented. First, the model is validated through comparison with field-collected data. Then, alternative scenarios are explored to evaluate how different dam management strategies could influence nutrient accumulation in the lake.

3.2.1. MODEL VALIDATION

We used the numerical model Delft3D-FLOW to reproduce the water temperature, salinity, TN concentration and water level in Guana Lake during the period October 2nd, 2023, to October 2nd, 2024. Saltwater enters and leaves the Lake through the Guana Dam based on the flow calculated as in section 2.3.2. Consistently with this application, we applied a consistent flow of freshwater at Mickler's Dam. The plots obtained from the model are shown in Figure 13 for the temperature, salinity, water level and TN concentration, respectively. The Observation points locations are shown in Figure 4.

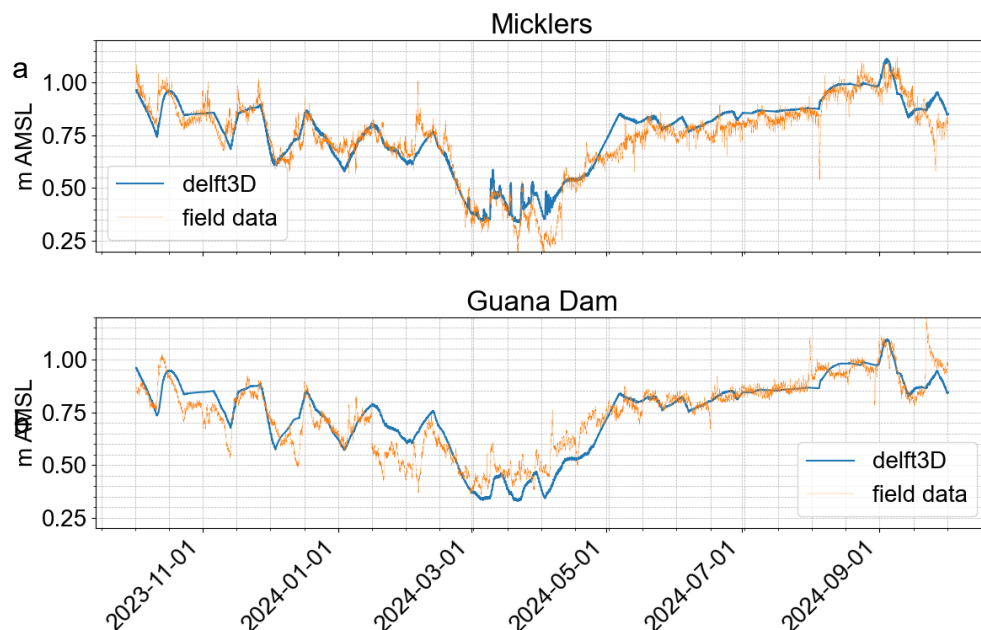


FIGURE 34: COMPARISON BETWEEN MODELED AND MEASURED WATER LEVEL AT MICKLER'S (A) AND GUANA DAM (B), FROM OCTOBER 2ND, 2023, TO OCTOBER 2ND, 2024. IN BOTH PLOTS, THE BLUE LINE REPRESENTS THE WATER LEVEL MODELED WITH DELFT3D, WHILE THE ORANGE LINE DERIVES FROM DATA COLLECTED WITH HOBO WATER LEVEL SENSORS.

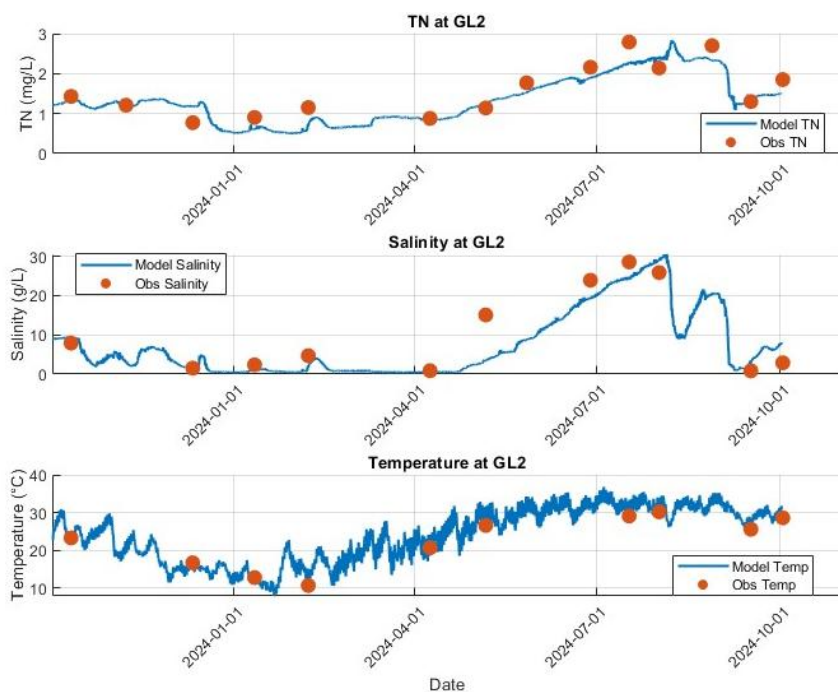


FIGURE 35: COMPARISON BETWEEN MODELED AND MEASURED TOTAL NITROGEN, SALINITY, AND WATER TEMPERATURE FROM OCTOBER 2ND, 2023, TO OCTOBER 2ND, 2024. IN

THE PLOTS, THE BLUE LINE REPRESENTS THE GL2 STATION DATA AS MODELED BY DELFT3D, WHILE THE ORANGE DOTS CORRESPOND TO THE COLLECTED SAMPLES FROM THE SAME LOCATION.

3.2.2. MODEL ALTERNATIVE DAM MANAGEMENT

After validation, the model was utilized to explore different management scenarios for the Guana Dam. The key boundary condition adjusted was the total discharge at the dam. To achieve this, the discharge was modified by increasing and decreasing the number of gates and flashboards at the dam. This approach enables the visualization of how variations in saltwater inflow or outflow impact TN concentrations across the lake. The considered boundary discharge allows to maintain the water level in the lake withing the constraint levels needed for water fowling, recreational activities and flood protection.

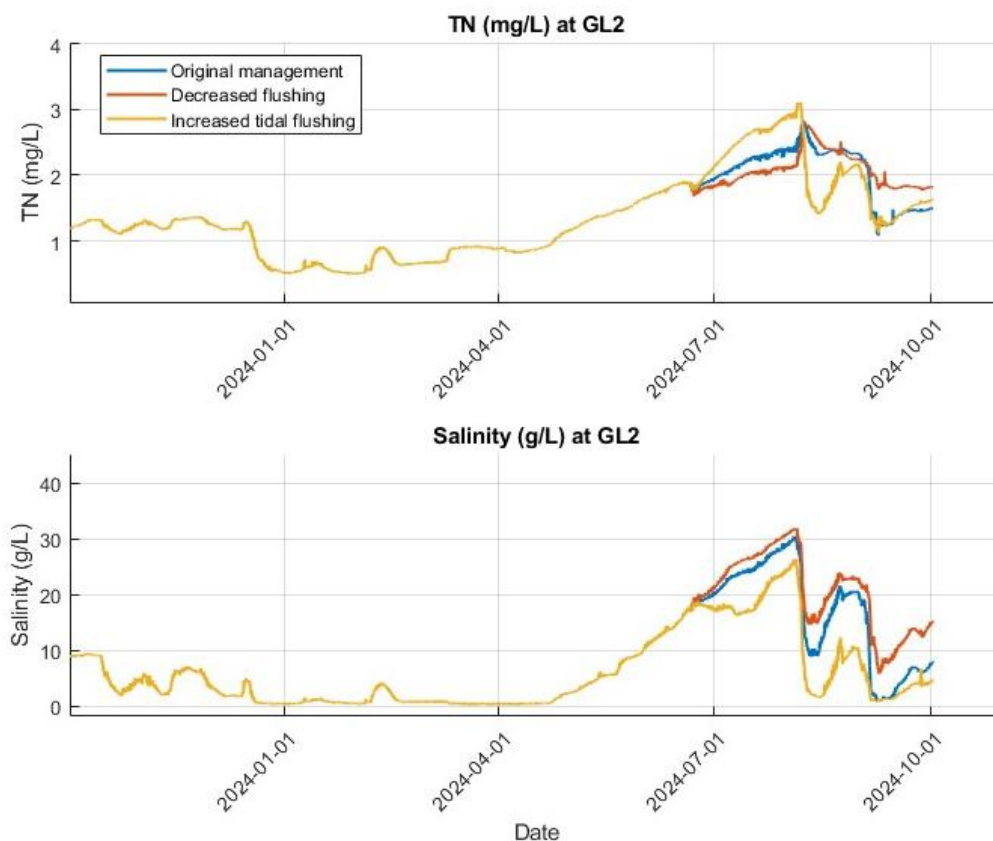


FIGURE 36: HOW DIFFERENT MANAGEMENT AFFECTS TOTAL NITROGEN AND SALINITY CONCENTRATION VARIATIONS IN THE GL2 STATION FROM OCTOBER 2ND, 2023, TO OCTOBER 2ND, 2024. IN THE PLOTS, THE BLUE LINE REPRESENTS THE ORIGINAL MANAGEMENT PERFORMED BY FWC, WHILE THE ORANGE LINE SHOWS THE CASE WHERE THE TIDAL FLUSHING IS REDUCED. THE YELLOW LINE SHOWS HOW THE CONCENTRATIONS VARY WITH INCREASED TIDAL FLUSHING.

4. DISCUSSIONS

The maps reported in Section 3 show the spatial distribution of the variables measured in the Guana Lake during our fieldwork. Data observed in the maps are described and discussed in the following sections.

4.1. FIELD SURVEY

4.1.1. SALINITY

From September to November 2023, salinity in Guana Lake shows marked spatial variability. In September, the lake is highly stratified, with low salinity values around 5 ppt near Mickler's Weir and much higher concentrations, up to 25–30 ppt, near Guana Dam. This pronounced gradient suggests strong saltwater intrusion from the estuary. Although October data is unavailable, November indicates a general reduction in salinity throughout the lake. The northern region near Mickler's Weir and the center around Lake Mid remain fresh, with values close to 0–5 ppt, while the southern portion near Guana Dam still shows moderately elevated salinity levels, just above 15 ppt, likely due to reduced freshwater inflow or limited flushing. During winter, from December 2023 to February 2024, the lake transitions to a nearly freshwater system. In December, salinity levels are close to 0 ppt across the entire lake, reflecting a period of high rainfall and increased freshwater input. While January data is unavailable, February marks the return of salinity gradients. Salinity remains below 5 ppt from Mickler's Weir through Lake Mid, but increases near Guana Dam up to 12 ppt. This shift indicates the beginning of brackish water intrusion as discharge through the dam decreases. Spring conditions from March to May 2024 show a gradual increase in salinity, particularly in the southern reaches of the lake. In March, values begin to rise near Guana Dam, reaching approximately 15 ppt, while most of the lake remains relatively fresh. By April, a more defined gradient develops, with the southern half of the lake (from Lake Mid to Guana Dam) experiencing salinity levels between 20 and 30 ppt. Meanwhile, Mickler's Weir continues to maintain fresh conditions below 5 ppt. The pattern intensifies in May, with salinity exceeding 30 ppt near Guana Dam, ranging between 10–20 ppt around Lake Mid, and remaining under 5 ppt in the north. These observations reflect estuarine water pushing inland, combined with flashboard additions that restrict freshwater outflow. From June to August 2024, salinity peaks across the lake, with July and August showing the most extreme conditions. Salinity levels surpass 30–35 ppt throughout the southern and central regions, indicating widespread saltwater intrusion. Although Mickler's Weir remains relatively buffered, salinity levels still rise to 10–15 ppt by midsummer. These high concentrations are driven by a combination of intense evaporation, minimal rainfall, and restricted dam outflow, all of which enable saline estuarine water to penetrate further upstream. By August, salinity approaches marine levels across the entire lake, underscoring the cumulative effect of sustained dry conditions and estuarine influence.

4.1.2. DISSOLVED OXYGEN (DO)

In September, DO values range widely, from under 6 mg/L in the Guana Dam region (south) to over 9.5 mg/L near Mickler's Weir (north). This gradient suggests higher productivity or oxygen depletion in the southern end. In October and November, DO becomes more spatially uniform, with most of the lake exhibiting concentrations above 8 mg/L, especially near the Guana Dam and Lake Mid, likely due to cooler air temperatures and increased wind-driven mixing. Winter months show the highest DO concentrations throughout the lake. In February, nearly all regions (from Mickler's Weir to Guana Dam) reach values near 10 mg/L, indicating full oxygen saturation and active vertical mixing. December and January also exhibit elevated DO values, with only small, localized variations. DO concentrations start to decline beginning in March, particularly in Lake Mid and Guana Dam, where values drop to 6–7 mg/L. This trend continues into April and May, with extensive zones in the southern half (Lake Mid to Guana Dam) showing DO between 5–6 mg/L, which may indicate increased microbial activity, organic matter decomposition, or incipient thermal stratification. Notably, Mickler's Weir region remains slightly better oxygenated during these months. The lowest DO levels are observed during summer. In July and August, almost the entire lake (especially from Lake Mid to Guana Dam) drops below 6 mg/L, with large areas registering around 5 mg/L, indicating potential hypoxic conditions. Mickler's Weir region retains marginally higher values, suggesting stronger wind influence or inflow mixing.

4.1.3. PH

From September to November 2023, pH levels across the lake are generally high, with most areas ranging between 8.0 and 8.5. In September and November, the pH is uniformly elevated throughout the lake, suggesting consistent buffering capacity and low acidic inputs. In contrast, December 2023 shows a sharp drop in pH in the northern sector (near Mickler's Weir), where values dip below 7.0, while the rest of the lake maintains moderately alkaline conditions, likely due to dilution from rainfall and inflow. February 2024 exhibits a spatial gradient, with Mickler's Weir reaching peak pH values (>8.2), whereas pH gradually decreases toward Guana Dam, falling below 7.5 in the southern reach. This may reflect biological activity and localized buffering in the north, contrasting with acidic loading or reduced photosynthesis in the south. In March and April, the lake returns to more uniform conditions with moderately high pH (mostly 7.8–8.2), and some localized patches of slightly lower values, particularly in the central section during April. May displays pronounced spatial heterogeneity: values near Mickler's Weir and Lake Mid fluctuate from 7.0 to 8.0, with a narrow acidic plume (pH < 7) visible near Lake Mid, potentially from organic decomposition or localized discharge. From June to August, the lake exhibits stratified pH conditions. June and July show elevated values in the south (>8.0), while the north remains more neutral (7.0–7.5), possibly indicating enhanced photosynthetic activity under warmer, sunnier conditions. August sees a notable drop in pH near Mickler's Weir (as low as 7.0), while the rest of

the lake retains alkaline conditions, maintaining the pattern of spatial divergence due to temperature, biological uptake, and hydrologic variability.

4.1.4. CHLOROPHYLL-A

The monthly maps of chlorophyll-a concentration across Guana Lake show clear spatial and seasonal trends. During the summer months, particularly in June and July, chlorophyll-a levels are highest, with values exceeding 30 RFU in the northern portion of the lake. This area is likely influenced by limited water exchange, elevated temperatures, and nutrient availability, all of which favor algal productivity. As the season progresses into late summer and early fall, such as in August and September, chlorophyll-a levels remain elevated but begin to decline in the southern sections, indicating the gradual dissipation of blooms. By contrast, during the winter and early spring months—February, March, and November—chlorophyll concentrations are significantly lower, generally below 10 RFU. This pattern aligns with cooler water temperatures and reduces primary productivity during these periods.

The maps also reveal inconsistencies related to instrument limitations. In some months, such as April and May, chlorophyll-a concentrations display abrupt transitions or grid-like patterns that are not expected in natural systems. These visual artifacts may be attributed to sparse data collection or partial sensor exposure during shallow conditions or rapid vessel movement. This is particularly relevant for the EXO2 sonde, which may underperform in low-depth areas or where the water column is disturbed. Compared to literature values, which suggest that chlorophyll-a in estuarine and brackish systems typically ranges from 5 to 30 $\mu\text{g/L}$ during productive seasons, the observed values fall within expected bounds. However, spatial gaps and irregularities in the dataset limit the resolution and accuracy of these interpolations, underscoring the importance of maintaining sensor stability and consistent spatial coverage during future surveys.

4.1.5 fDOM

The fDOM distribution over the monitoring period reveals both seasonal patterns and technical limitations in the instrumentation. In September, values are exceptionally high in the northern portion of the lake, exceeding 140 RFU near Mickler's Weir and progressively decreasing toward the south. This pattern reflects organic matter loading during late summer, likely due to rainfall-driven runoff and decaying vegetation. In November, fDOM remains elevated throughout the lake, particularly concentrated in the central and southern areas, suggesting persistent organic inputs or limited flushing.

December data indicate a sharp drop in fDOM, with values returning to moderate or low levels (~60–100 RFU) and a visible central depression in concentration. This shift could reflect increased flushing due to winter rainfall and stronger freshwater inflow. However, from January to August (especially from March onward), almost all maps show uniformly low values (<60 RFU), with the lake appearing homogeneously blue in the maps. This consistency raises concerns about

instrument limitations rather than environmental stability. Literature indicates typical fDOM concentrations in similar brackish or freshwater environments can exceed 100–200 RFU during periods of runoff or biological activity (e.g., Guo et al., 2014; Fellman et al., 2010), yet these values are not captured after December.

A plausible explanation is that the EXO2 probe, when carried by hand or mounted on a moving boat, might have experienced reduced sensitivity or data loss due to turbulence, fouling, or calibration drift. The uniform readings, particularly in summer months when fDOM should peak due to evaporation and organic decay, strongly suggest a limitation in detection or data recording capacity rather than actual homogeneity. Future deployments should ensure proper sensor stabilization, regular calibration, and post-survey QA/QC checks to address these inconsistencies and improve spatial accuracy.

4.2. NUMERICAL MODEL

4.2.1. MODEL VALIDATION

Measured data and numerical model outputs show good agreement. In Figure 13 it is shown the comparison between measured water level and numerical model. The model reproduces correctly the water level evolution throughout the year. The model lacks in reproducing the short-term oscillations measured with the water level sensors, which are due to several more factors (particularly wind waves), which are not considered in this model.

The measured salinity in the lake and model output has good agreement (Figure 14). The evolution of salinity in the northern part of the lake is accurately captured. However, a notable discrepancy occurs in the southern part, near the Guana Dam, where saltwater naturally accumulates during summer months. In this region, salinity levels rise to values that are challenging to replicate using only the assumptions of saltwater input and evapotranspiration. Further investigation is necessary to address this issue.

Temperature follows the seasonal trends and reflects the field measurements (Figure 15). At this stage, modeled temperature does not influence the TN concentration evolution during the year.

Variation in TN concentrations during the year were reproduced in the GL2 station and at the Guana dam (labeled “LS”), Figure 16. Peaks at GL2 were fairly reproduced by adding a source term of TN that activates depending on a critical salinity (as explained in section 2.3.4). The process mimics the freshwater vegetation death due to salinity variation. TN concentrations peak during the summer months due to reduced freshwater input, which increases salinity in the northern area. This rise in salinity leads to the die-off of freshwater vegetation, causing nutrient release. During the wet seasons, this peak diminishes but does not drop significantly, as increased flow at Mickler’s Weir carries a substantial amount of freshwater vegetation into the lake. Following this period, in spring, the concentrations stabilize, exhibiting more consistent values (around 0.8 mg/L).

4.2.2 MODEL ALTERNATIVE DAM MANAGEMENT

The variation in TN concentration in response to changes in discharge at the Guana Dam is shown in Figure 15. The results show that salinity and tidal flushing are key drivers of nutrient accumulation in Guana Lake. Reducing discharge increases TN concentration, as the outflow from the lake surpasses inflow, leading to saltwater accumulation and nutrient release from decaying vegetation. Conversely, increasing discharge enhances tidal flushing, introducing water with lower TN concentrations, which dilutes the overall nutrient levels. Temperature may influence plant decay and the nutrient cycle, though this effect requires further investigation. It is important to note that the application of tidal flushing is inherently limited by constraints on how much the water level can be raised or lowered. Consequently, optimal management would aim to maximize water level fluctuations to enhance flushing, particularly during the summer months when nutrient accumulation is higher due to reduced water flow and increased salinity.

5 CONCLUSIONS

This project provided a comprehensive assessment of Guana Lake's hydrodynamics and nutrient dynamics through one year of field data collection and advanced numerical modeling. The integration of spatially distributed water quality data and a calibrated Delft3D model allowed us to identify critical zones of nitrogen accumulation, particularly near the GL2 station, where reduced flushing and high salinity promote vegetation decay and nutrient release. The study demonstrated that seasonal dam operations significantly influence salinity gradients, water residence times, and ultimately, nitrogen cycling in the lake. Enhanced tidal flushing was shown to reduce TN concentrations over time, despite an initial spike due to rapid water level reduction. Conversely, reduced flushing exacerbates nutrient accumulation and raises the risk of eutrophication. These results show the importance of dynamic dam management strategies that mimic natural variability to maintain water quality and ecosystem health.

The project highlights the importance of maintaining robust and reliable field instrumentation. After the HYCAT failure, data quality declined in some variables (notably fDOM and chlorophyll-a), limiting the reliability of certain interpolations. This emphasizes the need for improved QA/QC protocols and backup deployment strategies in future monitoring efforts. Moreover, while the model performed well overall, discrepancies near the Guana Dam suggest that additional drivers, such as wind-driven circulation, stratification, and sediment–nutrient interactions, should be further investigated.

The key actionable recommendation is that water level and salinity management at Guana Dam should be adapted seasonally to enhance flushing during the summer and early fall when nutrient

release risk is highest. This could involve temporary increases in discharge gate operations or flashboard adjustments to reduce residence time. Additionally, future monitoring programs should incorporate biological indicators such as phytoplankton biomass or species composition to better assess ecological impacts. Real-time data integration and scenario testing could further improve the model's utility for decision support. Ultimately, this framework offers a scalable tool for lake managers to balance habitat conservation, flood control, and water quality in complex, semi-impounded estuarine systems.

6 FUNDING AMOUNT AND SOURCES

Florida Department of Environmental Protection's Office of Environmental Accountability and Transparency (OEAT)- \$228,184 and National Oceanic and Atmospheric Administration Coastal Zone Management Estuarine Research Reserves- \$71,820.

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