Exploring Temporal Trends of Various Water Quality Constituents in the Apalachicola National Estuarine Research Reserve

Final Report

DEP Award Number: ANR03

Project Director:

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June 2025

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1. Overview

1.1. Project description

This project was jointly funded by Florida Department of Environmental Protection (FDEP) Apalachicola National Estuarine Research Reserve (ANERR). Florida State University was the Grantee. The goal of this project was to study trends of water quality parameters and their potential drivers in the Apalachicola Bay in order to identify factors that shape short- and long-term temporal patterns of water quality in the bay. The main tasks included compilation of water quality and other parameters, analysis of trends and creation of reports and/or publications to help disseminate findings to the research community and public. The Grantee focused on compiling data and analyses of trends of water quality parameters, including nutrients (nitrogen and phosphorus) and physical parameters (e.g., dissolved oxygen [DO], chlorophyll-a and total suspended solids). In Year 1, which was under an MOU (DEP agreement # 202301/MOU 28), Grantee explored trends in the water quality parameters. The overarching goal of Year 2 (this agreement ANR03) was to identify drivers of these water quality trends in the Apalachicola Bay. The Grantee completed all the tasks listed and submitted all the deliverables on time. The specific objectives were to: (1) prepare a unified database of the drivers of various water quality constituents; (2) evaluate temporal changes in the drivers in and upstream of the Apalachicola Bay; and (3) investigate plausible reasons for certain temporal changes in the water quality constituents. A set of statistical analyses and experiments has been conducted to achieve the goal and objectives.

1.2. Timeline

The Grantee has adhered to the timeline outlined in Table 1 and successfully completed all tasks and deliverables as scheduled. Note that the dates were slightly updated during the project and some of the updates were communicated in the meetings and through emails. The dates in Table 1 refers to the most updated dates.

Table 1. The corresponding tasks and deliverables and due date.

Task/ Deliverable No.	Task/Deliverable title	Task start date	Task end date	Deliverable due date	Status
1	Data preparation and analyses	7/1/2024	9/30/2024	9/30/2024	Completed
2	Temporal trend analyses of water quality drivers	7/1/2024	3/31/2025	3/31/2025	Completed
3	Identify drivers that explain the temporal trend of water quality constituents	7/1/2024	3/31/2025	3/31/2025	Completed
4	Explore the impact of hydroclimatic extremes on the temporal trend of water quality constituents	3/1/2025	5/31/2025	5/15/2025	Completed
5	Final Report	3/1/2025	6/30/2025		
5a	Final Report Draft			5/27/2025	Ongoing
5b	Final Report			6/15/2025	Ongoing

1.3. Grant award information

Awarding Agency: Florida Department of Environmental Protection (FDEP) and Apalachicola National Estuarine Research Reserve (ANERR).

Grant Number: ANR03

Total award amount: $66,217

1.4. Anticipated benefits

The anticipated benefits are briefly discussed here:

- The project produced well-documented datasets and reusable analysis scripts that will be valuable resources for future related research, regulatory assessments and environmental planning.
- By analyzing approximately two decades of water quality data, the project shed insights about short- and long-term trends of various parameters such as nutrients, chlorophyll-a and key physical parameters at annual and seasonal timescales.
- The identification of driving factors behind observed changes in water quality, such as precipitation, land use and streamflow, provides insights about the relationships between water quality changes and natural/anthropogenic mechanisms, which can potentially support decision-making and adaptive management strategies at the bay.
- The evaluation of how hydroclimatic extreme events (e.g., hurricanes, extreme heat and heavy rainfall) affect water quality parameters contribute to the understanding of the bay vulnerability under future extremes as influenced by climate change and sea level rise, thereby supporting resilience planning.

2. Project execution

2.1. Executive summary

This project aimed to evaluate long-term trends in water quality and identify key drivers in the Apalachicola Bay system. The Grantee focused on compiling a database of driving variables and applying a series of statistical analyses to assess how these drivers and hydroclimatic extremes may have influenced the bay's water quality over the 2001–2022 period. All five tasks in the Grant Work Plan were completed, submitted and approved by FDEP/ANERR. Task 1 involved compiling historical datasets, including nutrients, hydrology, atmospheric deposition and land surface characteristics. Task 2 applied non-parametric statistical methods to assess temporal trends in environmental drivers, revealing significant shifts in streamflow, land cover and storm surge intensity. Task 3 aligned trends in water quality parameters (e.g., phosphate, nitrite + nitrate, chlorophyll-a and DO) with their potential drivers to identify possible explanatory patterns. Task 4 evaluated the impacts of hydroclimatic extremes, including tropical cyclones, extreme heat and negative storm surge events, on water quality trends. Task 5 is the final report that presented the entire project objectives, methods and results. For each task, Grantee submitted deliverables, such as analysis scripts, summary tables and reports for the review by FDEP/ANERR.

Overall, Grantee found increasing trends in phosphate and chlorophyll-a, declining trends in DO and nitrogen species, and increasing salinity and turbidity at several monitoring stations, particularly after 2015. These changes appeared to be linked to reductions in freshwater input, land cover change and an increase in the frequency and intensity of storm-related disturbances.

2.2. Schedule, deviations and corrections

All tasks outlined in the Grant Work Plan were completed on schedule, with no significant delays or deviations from the original timeline. Data compilation, analyses, report preparation and all associated deliverables were submitted by their respective due dates. Monthly coordination meetings were held as planned to ensure timely progress and alignment with the agreement scope and expectations. No adjustments to the task schedule were required and the project proceeded according to the milestones established at project initiation.

3. Summary of Activities

Grantee successfully completed all the technical tasks outlined in the Grant Work Plan.

3.1. Tasks in Year 1

While Year 1 was fulfilled under another agreement, a brief discussion is provided here to provide context as there is a link between Year 1 and Year 2 products. In Year 1, Grantee first acquired and cleaned the data to build a unified dataset of water quality in the study area. Further, Grantee focused on trend analyses of water quality data from 2002 to 2022. Both monotonic and non-monotonic trends were assessed using the non-parametric Mann-Kendall test (5% significance level). Statistical analyses were conducted on the average, maximum and median values of the 9 water quality parameters (nutrients and physical parameter) at each monitoring station, across annual and seasonal (dry and wet) timescales. All analyses were conducted in R using packages such as dplyr, lubridate, readxl, openxlsx, kendall and changepoint.

Long-term trend analyses required at least 10 years of data and examined overall trends across the full period of record. Mid-term trend analyses used 10-year rolling window (2002–2011, 2003–2012 and so forth) with similar parameter and seasonal breakdowns, requiring 10 consecutive years of data for inclusion. Seasonal analyses only included time series with data available for at least 8 months per year. Changepoint detection was applied to identify shifts in the values of yearly time series (mean, max and median) using 5-year monitoring windows.

3.2. Tasks in Year 2*Task 1: Data preparation and analyses*

A unified database of the water quality drivers was compiled by integrating various variables, including rainfall, wind, air temperature, streamflow, tide, storm surge, land imperviousness and land cover. The data were sourced from public domain repositories such as ANERR, NOAA and USGS. Metadata and quality assurance documentation were also provided.

3.2.2. Task 2: Temporal trend analyses of water quality drivers

Statistical analyses were conducted to assess long-term and short- to mid-term trends in the compiled drivers across seasonal and annual timescales. Both monotonic and non-monotonic trends were evaluated, including changepoint detection and characterization of extreme conditions (e.g., peak air temperatures and dry spells). Deliverables included analysis scripts, summary tables and a technical report.

3.2.3. *Task 3: Identification of drivers explaining temporal trends in water quality parameters*

Using trends from Task 2 and prior Year 1 findings, the Grantee examined associations between water quality constituents (e.g., DO and chlorophyll-a) and environmental drivers. Joint temporal analyses helped identify candidate drivers contributing to observed trends, with results documented in summary tables and reports.

3.2.4. *Task 4: Evaluation of hydroclimatic extremes on water quality trends*

The impacts of extreme events (tropical cyclones, heavy precipitation, low/high flows, El Niño, La Niña and extreme heat) on water quality constituents were assessed through statistical analyses. The timing and frequency of extremes were compared to changes in water quality trends to explore possible links. Findings were delivered as scripts, summary tables and a narrative report.

3.3. Monthly meetings in Year 2

Grantee held regular monthly meetings with the ANERR representative(s). In each meeting, Grantee prepared slides and presented the progress by summarizing key findings, methodologies and results. Grantee then requested for feedback from the ANERR representative(s) in these meetings. The feedback was requested by Grantee and was applied on the next steps of the project.

4. Documentation of work performed

Grantee produced a series of analyses and documentation for the tasks, which included data collection, trend analyses of both water quality and drivers, driver-linkage evaluations and the influence of hydroclimatic extremes on water quality. This section summarizes the data products, figures, tables and supporting materials generated during the implementation of Tasks of the Grant Work Plan. It provides documentation of the analyses conducted, key outputs produced, and relevant attachments submitted to support each task as required in the agreement.

4.1. Tasks in Year 1

As discussed above, Year 1 was fulfilled under another agreement. However, a brief discussion is provided here to provide context as there is a link between Year 1 and Year 2 products.*Summary of work performed*

In Year 1, analyses were conducted to explore long- and mid-term trends of nutrient and physical water quality parameters in the Apalachicola Bay. This work focused on evaluating annual and seasonal changes over the period of 2002–2022 using both monotonic and non-monotonic trend analyses as well as changepoint detection. Mann-Kendall test was applied to assess trends in the annual mean, maximum and median values. Seasonal trends were also evaluated for dry and wet seasons. Ten-year rolling windows were used for mid-term assessments. Changepoint detection was performed on annual series to identify significant shifts in water quality trajectories.

4.1.2. *Figures/tables included*

The results included a large set of trends and changepoint plots for each parameter across multiple monitoring stations. These figures were organized by analysis type and presented in the following categories:

A. Long-term monotonic trends

Annual mean, maximum and median trends for nutrients (e.g., PO_4^{3-}, NH_4^+ and nitrite + nitrate) and physical parameters (e.g., temperature, salinity and DO) at each station.

Deliverable 2.1_MOU28: Pages 8-43.

B. Mid-Term non-monotonic trends (10-year rolling window analysis)

10-year rolling window trends for the same parameters using mid-term data slices.

Deliverable 2.1_MOU28: Pages 44-79.

C. Seasonal trends (dry vs. wet)

Seasonal Mann-Kendall trends for each parameter at each monitoring station

Deliverable 2.1_MOU28: Pages 80-91.

D. Changepoint detection

Detected shifts in the time series of annual mean, median and max values by parameter/station.

Deliverable 2.1_MOU28: Pages 92-127.

E. Summary statistical tables

Tables of Kendall's *tau* and *p*-values for all parameters by station and timescale.

Deliverable 2.1_MOU28: Pages 128-142.

4.1.3. Key findings

Ammonium and nitrite + nitrate levels were decreasing at multiple monitoring stations, while chlorophyll-a levels were increasing. This suggested that nutrient uptake by phytoplankton might be more significant than nitrification-denitrification processes. The increasing phosphate levels, combined with the decreasing ammonium and nitrite + nitrate levels, indicated a potential nutritional imbalance, which might be responsible for increasing chlorophyll-a trends. In regarding the maximum values of water quality parameters, the monotonic trend analyses did not show significant trends. However, the bay's water quality is highly sensitive to hydroclimatic disturbances, including droughts and hurricanes, particularly in a short period that is difficult to be captured by long-term trend analyses.

The seasonal results suggested an upward shift in phosphate level during the wet season. This could be attributed to higher runoff from surrounding watersheds during rainy periods, increasing the phosphate load into the aquatic systems. The seasonal trends in ammonium concentration were generally negative, indicating a potential decrease over time, particularly in the dry season. Chlorophyll-a level exhibited significant positive trends during both dry and wet seasons at a few stations. In comparison, season-specific trends in physical parameters were less consistent and did not provide clear seasonal patterns.

Annual mean chlorophyll-a levels increased after 2006 at West Pass, Pilots Cove and Mid Bay stations, with Dry Bar station showing additional increases after 2016. East Bay station experienced increases after 2006, followed by slight decreases after 2011. For other nutrients, no statistically significant changepoints were detected. However, the data indicated a gradual increase in mean phosphate levels and a gradual decrease in mean ammonium, particularly since 2010-2011.

The streamflow drought years (2006-2009 and 2011-2013) likely contributed to the water quality patterns. During these periods, reduced streamflow led to decreased freshwater inflow into the bay, affecting nutrient delivery and distribution. This can explain the observed gradual decreases in ammonium levels as lower runoff would reduce the input of nitrogen compounds from terrestrial sources. At the same time, the accumulation of phosphate might have occurred due to reduced dilution and changes in biogeochemical cycling under low-flow conditions. Salinity changes in East Bay (EB-s and EB-b) and Dry Bar stations are likely be linked to reduction in freshwater inflow from upstream Apalachicola River into the bay. Variabilities in turbidity, particularly the increases after 2016 and 2020, are likely due to sediment disturbances from extreme weather or land use changes. Stable pH and DO levels suggest consistent buffering and balanced biological processes. Water temperature rises reflect broader and gradual climate warming trends.

The bay's changes in annual maximum turbidity and salinity, particularly the notable increases after 2016, may be linked to the impacts of hurricanes such as Hermine (2016), Irma (2017), Michael (2018) and Sally (2020). These storms likely caused strong mixing, sediment resuspension and altered salinity patterns, contributing to the observed changes in these parameters.

4.2. Task 1 in Year 2: Data preparation and analyses

Grantee compiled a comprehensive dataset of drivers potentially influencing water quality trends in the Apalachicola Bay. Variables included atmospheric deposition (of nitrate and phosphate), meteorological conditions (precipitation, air temperature and wind), freshwater inflows (streamflow), hydrodynamic factors (tide and storm surge) and land surface characteristics (Land cover and surface imperviousness). These drivers were collected at the bay or in the upstream basin—Apalachicola and Apalachicola-Chattahoochee-Flint (ACF) basins. Data spanned 2001–2022 and were sourced from ANERR, NOAA, USGS and NADP (Table 2). A unified database was created in .csv format, accompanied by detailed metadata and QA/QC documentation (see Deliverables 1 in Year 2).

Table 2. Summary of driving factors analyzed, including monitoring period, sampling frequency, data source, measurement units and the contributing fraction to the study area.

Variable	Source	Period	Unit	Time step	Notes
Land cover	USGS NLCD	2001-2021	Percent	Once every few years	For the ACF and Apalachicola Basins
Land surface imperviousness	USGS NLCD	2001-2021	Percent	Once every few years	For the ACF and Apalachicola Basins
Air temperature	NOAA NCEI	2001-2021	°F	Daily	Weather stations US1FLFR0002, USC00080211 and USW00012832*
Precipitation	NOAA NCEI	2001-2021	in	Daily	Weather stations US1FLFR0002, USC00080211 and USW00012832
Streamflow	USGS NWIS	2001-2021	cfs	Daily	Station IDs 02359170 (Apalachicola River near Sumatra) and 02330400 (New River Sumatra)
Storm surge	NOAA Tides & Currents	2001-2021	ft (MLLW)	Daily	Daily max for tidal gauge ID 8728690
Astronomical tide	NOAA Tides & Currents	2001-2021	ft (MLLW)	Daily	Daily min and max for tidal gauge ID 8728690

Variable	Source	Period	Unit	Time step	Notes
Agricultural land	FDACS	2001-2021	Percent	Once every few years	Agricultural land area from FDACS for the Apalachicola Basin
Atmospheric deposition	NADP	2001-2021	kg/ha	Monthly	Monthly atmospheric deposition at station ID FL23 (Sumatra)
Wind	NOAA NCEI	2001-2021	mph	Daily	Station ID USW00012832 (Apalachicola Airport, FL)

* USC00080211 and USW00012832 are at the Apalachicola Airport, while US1FLFR0002 is 0.8 miles West-Northwest of Apalachicola.

4.3. Task 2 in Year 2: Temporal trend analyses of drivers*Summary of Work Performed*

Grantee explored potential reasons for certain trends in water quality parameters—ammonium, nitrite + nitrate, total nitrogen (TN), ortho-phosphate and chlorophyll-a in addition to a series of physical parameters—in Year 1. The objective of this task was to analyze temporal trends in the drivers of water quality in Apalachicola Bay. For long-term (monotonic) trend analyses, the Mann-Kendall test was conducted. Mid-term trends were evaluated on the rolling 5- and 10- year averages of the variables. After discussing with the representative from ANERR, Grantee added the analysis of calendar seasons (spring, summer, fall and winter) alongside the wet and dry seasons.

4.3.2. Key findings

Some statistically significant trends were summarized in Fig. 1, detailed analysis can be seen in "Deliverables 2 Task_2_Report.pdf". The analysis revealed statistically significant decreasing trends in the atmospheric nitrate deposition, particularly during the wet season. Meteorological factors showed spatial and temporal variability, with significant changes in precipitation and air temperature. The streamflow analyses showed multiple changepoints correlated with drought periods, while storm surge showed a significant positive trend. Wind patterns showed seasonal variability, with significant trends in the wet season for both wind speed and direction. The analyses of land cover indicated an increase in Developed land and imperviousness along with a decrease in forest, wetland and open water. The findings highlighted complex interactions between various drivers and their potential impacts on water quality parameters in the Apalachicola Bay. The identified critical time windows and changepoints provide insights into further analyses to detect factors responsible for trends of water quality.

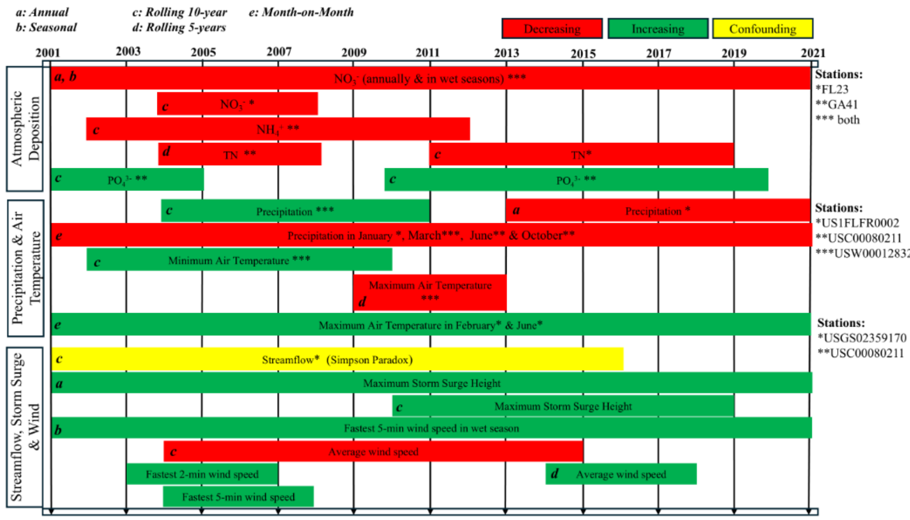

Fig. 1. Statistically significant monotonic and non-monotonic trends in the drivers of water quality parameters in the Apalachicola Bay.

4.4. Task 3 in Year 2: Drivers explaining trends in water quality

4.4.1. Summary of work performed

The objective of Task 3 was to identify potential relationships between the trends of key water quality parameters (nutrients and physical-chemical parameters) and drivers (atmospheric deposition of nutrients, meteorological, hydrodynamic and hydrologic variables and land surface). Consistencies between drivers and water quality alongside the underlying linkages and processes were used to explain detected water quality trends. Drivers were matched with nutrients (e.g., PO_4^{3-}, nitrite + nitrate, NH_4^+ and chlorophyll-a) and physical parameters (e.g., salinity, DO and turbidity) using temporal alignment, trend consistency and changepoint co-occurrence. The analyses revealed associations such as increasing phosphate aligning with land cover changes, decreasing nitrogen species with declining atmospheric deposition and DO declines with storm surge intensification. The findings were organized by driver category and their explanatory strength (see Deliverables 3 in Year 2).

4.4.2. Key findings

The analyses and results showed a significant shift towards phosphorus-driven eutrophication, characterized by increasing phosphate and declining nitrogen concentrations, alongside rising water temperatures and decreasing DO, indicating potential impacts of climate change and variability. Reduced freshwater inflows, evidenced by precipitation and streamflow patterns, significantly altered salinity and nutrient delivery. While storm surges and tidal fluctuations influenced sediment resuspension and land cover change contributed to increased runoff, the dominant trends suggested that the Apalachicola Bay system is increasingly controlled by phosphorus availability and warming conditions. The paradoxical increases in the freshwater input, despite the evidence of droughts (Rabby et al. 2024), pointed out the importance of further investigations to clarify hydrologic dynamics.

This project showed the vulnerability of the Apalachicola Bay to multiple stressors, including altered nutrient loading, climate, hydrodynamic and hydrology. The observed trends in the water quality parameters and their drivers provided insights for mitigating factors responsible for water pollution, thereby protecting the health of Apalachicola water and ecosystem. The key findings included:

1) Nutrient shifts: The bay system had a transition towards phosphorus-driven eutrophication, driven by declining nitrogen inputs and internal phosphorus recycling.
2) Climatic influences: Warming temperatures and decreasing DO reflect climate change/variability and altered stratification.
3) Hydrologic modifications: Reduced freshwater inflows impacted salinity, nutrient delivery and sediment transport.
4) Episodic events: Storm surges and tidal fluctuations influenced sediment resuspension and saltwater intrusion.
5) Land cover impacts: Cumulative effects of increased impervious surfaces on runoff and nutrient loads.

4.5. Task 4 in Year 2: Impacts of hydroclimatic extremes on water quality

4.5.1. Summary of work performed

Grantee characterized hydroclimatic extremes and evaluated their impact of on water quality trends in the Apalachicola Bay. Using meteorological, hydrologic, hydrodynamic and water quality data, we identified and characterized hydroclimatic extreme events—extreme heat, storm surges, high river flows and heavy precipitation. The events were statistically defined using percentile thresholds. The characteristics (e.g., intensity and duration) of each extreme event were derived. Overlaying these extreme events with the trends of the water quality parameters revealed potential linkages. Details can be seen in Deliverables 4 in Year 2.

4.5.2. Key findings

The analyses showed that hydroclimatic extremes—such as extreme heat, storm surges, high flows and intense rainfall—often occurred in close succession or simultaneously, resulting in compounding effects that hindered the clear attribution of water quality changes to any single driver. While extreme heat was expected to elevate water temperatures, our results revealed a more nuanced pattern: mean and median water temperatures increased in inner and semi-enclosed bay stations, but maximum temperatures at the mid-bay station Dry Bar declined after 2010, likely reflecting enhanced flushing or mixing during co-occurring events. The frequent overlap of extreme heat with storm surges and rainfall obscured the ability to isolate temperature's standalone influence. DO levels declined markedly during extreme heat years, particularly in shallow, inner-bay sites like Dry Bar, likely due to thermal stratification and elevated microbial respiration.

Chlorophyll-a levels increased persistently across the system, with an intensification of this trend between 2009 and 2011. This was a post-drought period, which was coinciding with heavy precipitation and substantial number of high flow events that accelerated post-drought riverine phosphorus delivery, an important driver of algal growth. High storm surges since 2012 disrupted increasing salinity trends and caused vertical decoupling in turbidity dynamics, while also altering nitrogen cycling through sediment resuspension and mixing.

High flows played a dual role, buffering drought stress and shaping nutrient transport, although their influence was sometimes offset by coinciding storm surges. Phosphate trends reflected strong influence from drought regimes, increasing during low-flow periods and being flushed downstream during recovery phases. Ammonium and nitrite + nitrate diverged in their drought responses, with ammonium trending downward under prolonged drought, while nitrite + nitrate stabilized due to internal cycling and reduced export. Lastly, pH declines around 2003–2006 likely resulted from the compound effects of extreme rainfall, high flow and organic matter influx.

These findings emphasized that estuarine water quality in the Apalachicola Bay is governed not only by individual extremes alone, but by their cumulative, interactive and temporally cascading effects. Future research should address this and provide a more comprehensive understanding of the impacts of these hydroclimatic extreme events on water quality in the Apalachicola Bay.

5. Data collection and evaluation

We utilized a set of water quality parameters (Table 2) and drivers (Table 3) spanning from 2001 to 2022. The water quality parameters included nutrients such as phosphate (PO_4^{3-}), nitrite + nitrate ($NO_2^- + NO_3^-$), ammonium (NH_4^+), TN and chlorophyll-a, as well as physical-chemical parameters including water temperature, DO, salinity, turbidity and pH. All data were collected on a monthly basis from monitoring stations managed by the ANERR. In addition, we analyzed a series of drivers, including precipitation, streamflow, air temperature, storm surge, tide levels, wind speed, atmospheric deposition and land cover changes, which were obtained from various sources such as NOAA, USGS and NADP. These datasets were used to assess long- and mid-term trends, identify potential changepoints and examine the interactions between drivers and observed water quality trends.

Table 3. Summary of water quality parameters analyzed, including monitoring period, sampling frequency and measurement units. All data were collected monthly from the ANERR stations between 2001 and 2022.

Parameter	**Unit**	**Period**	**Sampling frequency**
Phosphate	mg/L	2002-2022	Monthly
Nitrite + Nitrate	mg/L	2002-2022	Monthly
Ammonium	mg/L	2002-2022	Monthly
Chlorophyll-a	ug/L	2002-2022	Monthly
pH	-	2002-2006	30 minutes-interval
Salinity	ppt	2002-2006	30 minutes-interval
Water temperature	℃	2002-2006	30 minutes-interval
Turbidity	NTU	2002-2006	30 minutes-interval
Dissolved oxygen	mg/L	2002-2006	30 minutes-interval
pH	-	2007-2022	15 minutes-interval
Salinity	ppt	2007-2022	15 minutes-interval
Water temperature	℃	2007-2022	15 minutes-interval
Turbidity	NTU	2007-2022	15 minutes-interval

Parameter	Unit	Period	Sampling frequency
Dissolved oxygen	mg/L	2007-2022	15 minutes-interval

6. Methods

This section summarizes the methods used to compile, process and analyze the data of water quality parameters and their drivers for all tasks

6.1. Task 1: Data compilation and integration

Long-term monthly monitoring data from ANERR, including nutrients (e.g., PO_4^{3-}, NH_4^+ and nitrite + nitrate) and physical parameters (e.g., temperature, salinity and DO) at each station were collected and documented in a unified dataset (see Table 3). Driver data were compiled from authoritative and publicly available sources (see Table 4). All data were harmonized into a unified format, with timestamps standardized and values aligned to monthly intervals. This approach ensured full compatibility with monthly water quality observations. Metadata were prepared to document source, units and any quality flags.

6.2. Task 2: Trend analyses of environmental drivers

6.2.1. Long-term trends: Mann-Kendall test

The Mann-Kendall test was selected due to its robustness for detecting monotonic trends in non-normally distributed and incomplete environmental time series. It does not require assumptions about data distribution or linearity, making it highly suitable for hydroclimatic and land-based drivers. Analyses were conducted on:

- Annual statistics of mean, median and max
- Seasonal: Grantee divided each year into dry (November–April) and wet (May–October) seasons

Grantee assumed that a minimum of 10 years of data was required to ensure statistical validity.

6.2.2. Mid-term trends: Rolling window approach

To detect mid-term variations, rolling 10-year windows were used. This method improves temporal resolution while preserving trend directionality. It allows identification of trend reversals and non-stationarity, which are common in coastal systems affected by land use and climate pressures.

6.2.3. Changepoint detection

The changepoint analysis (using the changepoint R package) identifies statistically significant shifts in the mean of a time series. It is particularly effective for revealing abrupt changes that may correspond to events such as policy interventions, droughts, or hurricanes. The method was applied to yearly series of water quality and driver metrics with at least 5 years of data.

6.3. Task 3: Joint analyses of the trend of the water quality parameters and their drivers

To explore potential causality, trends in environmental drivers were compared to those in water quality parameters through:

- Temporal alignment of trend direction and changepoints;
- Cross-matrix analysis, scoring co-occurrences and explanatory consistency;

- Visual overlays, supporting pattern recognition and correlation assessment.

This approach was selected because of its feasibility with available data (monthly time step), its ability to compare different data types and its interpretability in a management context. It allowed identification of plausible driver-constituent relationships without requiring complex modeling or extensive assumptions.

All analyses mentioned above were performed in R, using reproducible and well-documented workflows built with dplyr, lubridate, ggplot2, readxl, openxlsx, kendall and changepoint. Scripts were modularized for reusability and version-controlled to ensure traceability.

6.4. Task 4: Impacts of hydroclimatic extremes on water quality

6.4.1. Extreme event classification

Events were defined using percentile thresholds (e.g., 95th for extreme heat and 99th for surge/rainfall based on the literature review, e.g., Perkins and Alexander, 2013; Smith et al., 2013; Hausfather et al., 2013; Lau and Nath, 2012; Asadieh & Krakauer, 2017; Schär et al., 2016) to maintain consistency across different drivers and ensure applicability to historical distributions. This method is commonly used in climate impact assessments and allows quantification of rare but ecologically significant conditions.

6.4.2. Overlay and impact evaluation

A temporal overlay method was used to examine the coincidence of extreme events with inflection points in water quality trends. Compound conditions (e.g., simultaneous high heat and low flow) were also identified to assess their joint effects. This method was chosen for its transparency, ease of communication and its ability to highlight high-risk periods without requiring complex multivariate models. The analyses mentioned in this section were performed in Python.

7. Results and discussion

7.1. Temporal trends in the water quality parameters

Analysis of water quality data from 2001 to 2022 revealed distinct temporal trends across multiple constituents in the Apalachicola Bay system. Phosphate concentrations showed a persistent and spatially consistent increase, particularly in western and southern bay stations, while nitrite + nitrate and ammonium exhibited declining trends over the same period. Chlorophyll-a concentrations rose steadily, with intensified trends between 2009 and 2013, coinciding with post-drought recovery and elevated nutrient delivery. DO declined markedly in inner-bay sites, especially after 2010, indicating increased risk of hypoxia potentially linked to elevated water temperatures and microbial respiration. Salinity and turbidity both showed positive trends beginning in the mid-2010s, suggesting reduced freshwater inflow and enhanced physical disturbance, possibly from storm events. These constituent-specific trends provide a critical baseline for understanding both chronic and event-driven changes in the bay's water quality.

7.2. Temporal changes in the water quality drivers

Long-term analyses of environmental drivers from 2001 to 2022 revealed statistically significant changes in multiple variables upstream and within the Apalachicola Bay watershed. Notably, annual and seasonal streamflow patterns exhibited downward trends and multiple changepoints, particularly post-2017, consistent with increasing drought frequency and upstream water management pressures. These findings aligned with observations by Apalachicola Riverkeeper (2023) that highlighted the persistent low flows, exacerbated by upstream water management, have led to more frequent and severe low flow periods in the Apalachicola River.

Atmospheric nitrate and phosphate deposition declined in the wet season, likely reflecting broader reductions in regional nitrogen emissions. Land cover change assessments indicated persistent increases in impervious surface area and urban development (particularly after 2011) accompanied by corresponding declines in forest and wetland cover. These transitions were most evident in western upland watersheds, contributing to altered runoff regimes and potential changes in nutrient delivery pathways. Storm surge height and frequency also increased, as indicated by rising annual maxima and seasonal extremes, suggesting enhanced coastal vulnerability linked to sea level rise and storm activity.

7.3. Drivers of water quality changes

7.3.1. Influences of atmospheric deposition

Atmospheric deposition of nitrate (NO_3^-) and ammonium (NH_4^+) significantly declined, while phosphate (PO_4^{3-}) deposition increased (with episodic fluctuations) over time. This aligned with the observed decrease in estuarine nitrite + nitrate and ammonium (NH_4^+) concentrations, suggesting that reduced atmospheric nitrogen inputs may contribute to the shifting nutrient limitation in the estuary, leading to phosphorus dominance in supporting algal growth, which is depicted in the sustained increase in chlorophyll-a level in the bay. This increase, combined with internal phosphorus recycling from sediments, can be a major driver of rising chlorophyll-a levels. TN showed decreasing trends in deposition, with periodic fluctuations, reinforcing the downward nitrogen trend in estuarine waters, possibly leading to greater nitrogen limitation for phytoplankton and influencing species composition in the bay.

7.3.2. Influences of precipitation, streamflow and air temperature

Annual precipitation trends showed no statistically significant trends before 2013 (i.e., high variability over time). After 2013, a downward trend was observed at the station closest to the bay (US1FLFR002), while another local station near Apalachicola Airport, showed an upward trend during the early years (2004–2011). This spatial inconsistency underscores the localized nature of precipitation in coastal settings. Major decreases in annual precipitation in January, March, June and October (varied station-wise) further corroborated the reduced local precipitation for the entire study period. However, more detailed examination revealed a decline in streamflow from 2001 to 2004, a rise from 2004 to around 2009, followed by another decline beginning after 2013. Notably, annual maximum streamflow values showed a decreasing trend from 2013 to 2018, despite the longer-term rolling average trend appeared upward. This apparent paradox reflects the influence of short-term variability and highlights the limitations of using aggregated trends alone to characterize hydrologic behavior. The temporal mismatch between local precipitation and streamflow patterns suggested that upstream watershed contributions may play a more dominant role in driving streamflow increases during the early years (2004–2011). In contrast, the streamflow decline beginning around 2015 aligns more clearly with observed reductions in local precipitation, particularly with significant seasonal declines in January, March, June and October (varied by station) over the full study period. While upstream precipitation was not directly analyzed, the divergence between local rainfall and streamflow trends supports the hypothesis that upstream runoff likely had a greater influence during earlier years. Irrespective of this detected trend in streamflow (annual average), a declining pattern in streamflow from 2001 to 2004 was observed. This confounding overall patterns in streamflow remain statistically inconsistent; decreasing for the initial few years (2001-2004) and then again decreasing for the later years (2015-2022) but making an aggregated trend upward (from 2001-2016). Past research, including Rabby et al. (2024) also showed that, from 2006 to 2017, multiple streamflow droughts occurred because of the declining streamflow patterns, which further corroborate the reduction in streamflow with episodic fluctuations. Reduced freshwater flow to the estuary may limit nitrogen delivery while allowing for greater phosphorus retention, favoring phosphorus-driven eutrophication.

Due to these episodic fluctuations in streamflow, resulted largely from the varying precipitation till 2013, phosphate level increased mostly within 2006-2016 through accumulation of runoff-driven phosphate and flushing (drought-influenced phosphorus flushing) into the stream and bay area. The elevated turbidity levels, mostly from 2002-2012, could stem from the same physical process, in which the surface runoff carried soil particles, including silt and clay, into estuary. While the immediate effect of lowering in the streamflow was observed in elevated turbidity level, elevation of phosphate in the bay water can be lagged due to reduced mixing-remixing dynamics driven by reduced streamflow. Salinity also increased, particularly from 2003 to 2012 (that included the drought period of 2006-2009), that directly suggested the reduction in freshwater inflow led to increased levels of salinity.

Increase in annual minimum air temperature in the early years of the study period (2002-2010) and seasonal increases (in February and June, respectively) throughout the entire period, further impacted the water quality trends. Warmer temperatures heightened biological activity, including algal growth, which may contribute to the observed chlorophyll-a increase. Additionally, the warmer temperatures promote higher rates of phosphorus release from sediments, further driving phosphate enrichment as observed in our data.

7.3.3. Influences of streamflow, storm surge & wind

Overall, the storm surge showed an increasing trend, particularly in recent years. Stronger storm surges can resuspend phosphorus-rich sediments, leading to temporary spikes in phosphate concentrations and stimulating algal blooms. The increased storm surge height in recent years can be further related to the lagged increase in phosphate levels after streamflow reduction. Storm surge may also enhance saltwater intrusion, altering salinity regimes, which can impact nutrient cycling and microbial processes that control nitrogen availability. The observed increase in salinity regimes was during 2003-2012, but the annual mean storm surge showed an increasing trend throughout the study period (2001-2021), while the maximum annual storm surge increased solely in recent years (2010-2019). This suggested that storm surge was not a significant reason in the salinity increase as their timing of their trends did not fully match. Although general increases in storm surge height did not align with the salinity trends, extreme storm surge events did contribute to short-term salinity spikes. These episodic surges, while not influencing long-term salinity trends, played a role in offsetting the expected salinity reductions following high-flow events (discussed in 7.4.2 & 7.4.3)

Trends of wind speed showed episodic variabilities in the average values, which decreased for initial few years (limiting water column remixing and redistribution of nutrient and salinity) and then increased for a short period (increasing remixing). This might also be related to the lagged increase in phosphate levels in water after the streamflow reduced and turbidity elevated. Further, the reduction in DO levels, largely between 2009 and 2013, is also related to this declining average wind speed for these years as reduced speeds lead to reduced water-air mixing. Wet season's 5-minute wind speed, however, increased throughout the years (episodic positive trends were also observed). Wind played an important role in the overall chemical dynamics in the bay water.

7.3.4. Influences of tidal fluctuations

Maximum astronomical tide levels were found to decline over the years, particularly till 2015-2016, which would typically introduce more oceanic water into the estuary. However, salinity increased, likely due to reduced freshwater inflow (and reduced flushing), allowing the existing saline water to become more concentrated rather than being diluted by river discharge, leading to salt retention and stratification. Further, due to the decline in tidal levels, scouring effects can contribute to the long-term increases in turbidity. Reductions in pH suggested that tidal level decline can also contribute to these as weak tides reduced the exchange between estuarine water and alkaline seawater.

7.3.5. Influences of land cover change

Impervious surfaces and developed land in both ACF and Apalachicola basins increased over time, although these land covers constitute only a small portion of the basin. Increased impervious surfaces reduced infiltration and increased surface runoff, altering the timing and magnitude of nutrient inputs. Additionally, the expansion of developed land contributed to increased sediment and pollutant transport from urban areas, potentially influencing phosphorus and chlorophyll-a levels. The observed increase in the phosphate and turbidity can be linked to the increased imperviousness, but the impact was likely minimal.

7.4. Influence of hydroclimatic extremes

Hydroclimatic extremes—including extreme heat, high rainfall, tropical cyclones and elevated storm surges—emerged as critical episodic drivers of water quality variability. Analysis of compound events indicated that years such as 2012, 2017 and 2020 experienced multiple coinciding stressors, which often aligned with changepoints in parameters such as chlorophyll-a, turbidity and DO. For instance, the post-2016 rise in turbidity at several stations followed a series of high-surge hurricane years (e.g., Hermine, Irma, Michael and Sally), pointing to enhanced sediment resuspension and coastal disruption. Extreme rainfall years were associated with temporary increases in nutrient concentrations and algal biomass, while extreme heat events coincided with DO minima, particularly during dry season months. The overlay of these extremes on long-term trends complicates attribution but underscores the importance of considering multi-driver interactions and the increasing role of climate variability in estuarine water quality dynamics.

7.4.1. Impacts of extreme heat

Extreme heat events influence the water temperature. However, due to frequent occurrences of events hindered understanding the exact dynamics. While water temperature (mean and median) in inner bay or the semi-enclosed East Bay throughout the water column (both in East Bay Surface and Bottom) showed increasing trends since 2009-2010, the maximum water temperature in a mid-bay station (Dry Bar) showed a decreasing trend since 2010.

In years such as 2012, 2017 and 2020, persistent extreme heat coincided with declines in DO, particularly at inner-bay stations. This may reflect reduced oxygen solubility and enhanced microbial respiration under warmer temperatures. For example, an inner-bay station-Dry Bar exhibited severe DO declines, potentially due to shallow water depths and limited flushing during extreme heat events, which intensified thermal stratification and microbial oxygen demand.

Frequent extreme heat events also might have contributed to the persistent increasing trends in chlorophyll-*a* concentrations and this thermal stress-driven phytoplankton growth have possibly contributed to the lowering of DO. Similar effects have been reported in other estuarine systems where warming amplifies eutrophication and hypoxia (Paerl & Huisman, 2008). However, as extreme heat often co-occurred with high rainfall or storm surge, the exact contribution of temperature alone remains difficult to isolate.

7.4.2. Impacts of storm surge and hurricanes

High surge events have been more frequent since 2012. We observed an increased salinity trends from 2003-2012 and no statistically significant trends afterwards, although episodic fluctuations and spikes were observed. Although extreme storm surge events did not significantly contribute to the increasing salinity trend observed between 2003 and 2012, they disrupted the salinity pattern during 2012–2022, resulting in the absence of a clear trend. Notably, the salinity spikes in 2005 and 2009—driven by extreme surges—helped counteract the salinity reductions that would typically be expected from high-flow conditions during those years. (described later in Section 7.4.3) that were expected to reduce the salinity, but this effect might be canceled out by a few sudden salinity spikes caused by extreme surge events during those years. Within the same timeline (2012-2022) when the surge events became more frequent, we observed that mean turbidity started decreasing in the bottom layer of water at East Bay Bottom station. This pattern suggested a vertical decoupling in turbidity behavior between the bottom and surface waters, likely driven by changes in storm-induced mixing, sediment dynamics and freshwater influence. It should be noted that the timeline also coincided with the occurrences of extreme rainfall in 2012 that likely compounded the influence.

In addition to the more widely recognized impacts of elevated storm surge, negative storm surge events may also influence estuarine water quality. These events can lead to temporary exposure of nearshore sediments, altering redox conditions and increasing the potential for sediment resuspension upon rewetting. This resuspension can mobilize legacy nutrients or contaminants and lead to spikes in turbidity and biological oxygen demand following water return. Furthermore, negative surge conditions may enhance salinity intrusion upstream by temporarily reducing estuarine water volume and stratification, particularly when followed by rapid return flow. However, in the Apalachicola Bay, the major storm surge events are aligned with hurricanes/tropical storms (see Fig. 2 and 3). It would be difficult to infer that the negative surge solely impacted the water quality parameters as it matched the timing of Hurricanes.

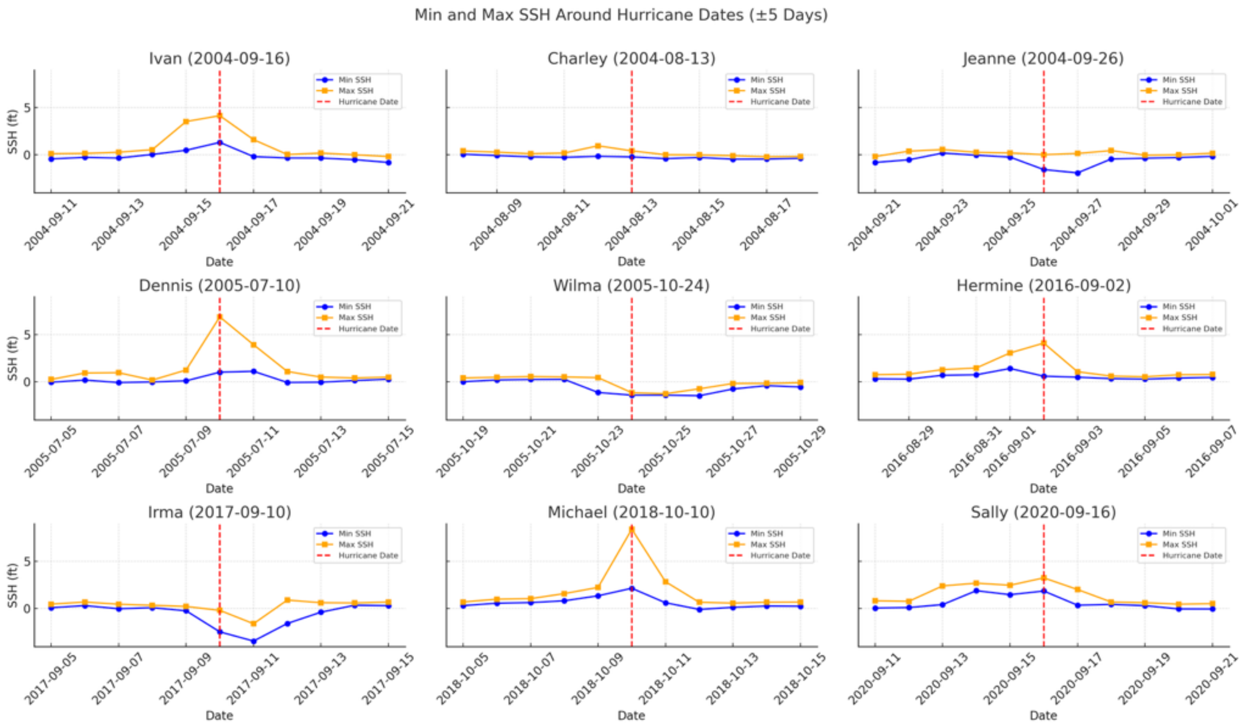

Fig. 2. Daily minimum and maximum storm surge height (SSH) within ±5 days of ten hurricane events: Ivan (2004), Charley (2004), Jeanne (2004), Dennis (2005), Wilma (2005), Hermine (2016), Irma (2017), Michael (2018) and Sally (2020). Orange and blue lines represent the daily maximum and minimum SSH, respectively, while the red dashed line marks the hurricane landfall date. Most hurricanes were associated with sharp SSH peaks, especially Ivan, Dennis and Michael, indicating significant storm surge effects.

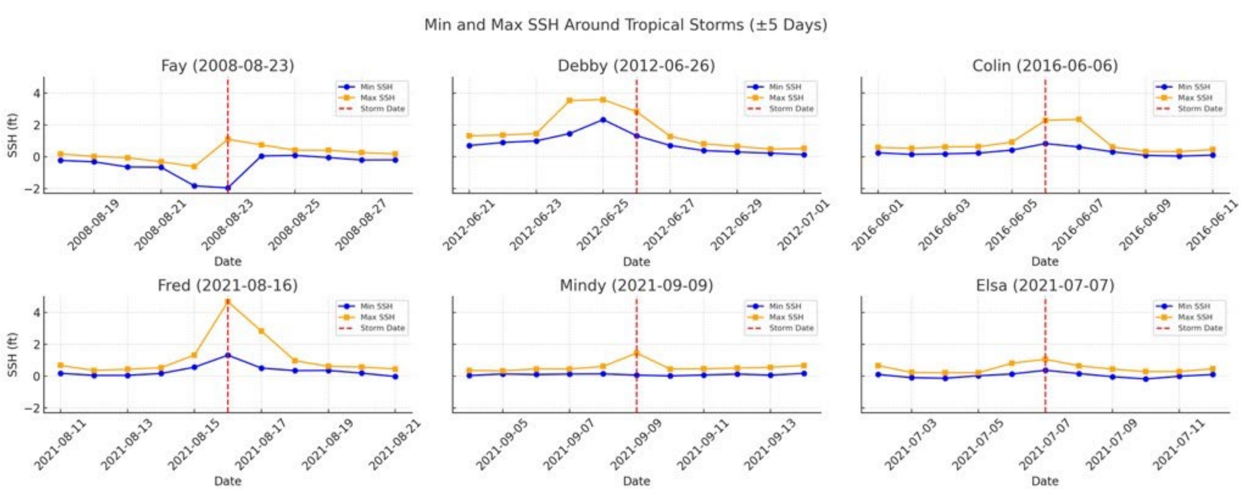

Fig. 3. Daily minimum and maximum storm surge height (SSH) within ±5 days of six tropical storms affecting the region: Fay (2008), Debby (2012), Colin (2016), Fred (2021), Mindy (2021) and Elsa (2021). Blue and orange lines represent the daily minimum and maximum SSH, respectively, while the red dashed line indicates the storm date. Notable peaks in SSH are observed on or immediately surrounding the storm events, with particularly strong surges during Fay and Fred.

The shift in turbidity (median and max) trend from significant positive trends to insignificance in surface-layer waters (at both East Bay Surface and Dry Bar stations) around 2011–2012 further suggests a disturbance-induced regime shift, wherein sediment inputs and water column stratification began interacting differently, disrupting previously consistent increasing trends. Although not certain in this case, sediment resuspension can trigger short-term acidification and oxygen stress (Bianucci et al., 2018) and stratification breakdown. Along with the consistent decreasing trends observed prior to 2011, we noted non-monotonic shifts in nitrite + nitrate trends—including mean, median and maximum values—across multiple stations during 2011–2014. This temporal shift coincided with the onset of more frequent high storm surges post-2012, suggesting that enhanced vertical mixing and sediment resuspension, that disturbed turbidity trends, also began altering nitrogen dynamics. Storm surge-induced mixing likely disrupted vertical stratification and mobilized sediment-bound nitrogen from the benthos, leading to episodic increases in water-column nitrate hindering significant trend detection.

7.4.3. Impacts of high flows

Extreme high flow events were observed largely in 2003, 2005, 2009, 2016 and 2019 along with some other years experiencing isolated high flow events. It should be noted that the Lower Apalachicola River experienced streamflow droughts in the following periods: 2006-2009, 2011-2013 and in 2017 (Rabby et al., 2024). Because of these streamflow droughts, the high flow events often worked as the flow reduction-stress buffering process. Additionally, the high flow events, particularly in 2005 and 2009, coincided with some extreme storm surge events. Although the high flow is expected to reduce the salinity, due to the storm surges possibly counteracted with episodic salinity spikes (although the surge-driven salinity spikes disturbed the salinity trend within 2012-2022, which is discussed in 7.4.2), whereas increasing salinity trends were observed from 2003 to 2012. Although extreme storm surge events didn't have considerable contribution to the increasing salinity trends (within 2003-2012) rather disturbed the salinity pattern resulting in no significant trend (within 2012-2022), the salinity spikes in 2005 and 2009 driven by extreme surges help counteracting the high-flow driven expected salinity reduction.

Phosphate started showing significant increasing trends in 2006, highlighting low flow regimes (or streamflow droughts) are more responsible for the phosphate levels elevation than the high flow events. However, high flow plays an important role in shaping the influence pathway such as during the initiation-peaking phases of streamflow droughts, phosphates accumulates in the bottom sediment in the upstream river and during the drought recovering and post-drought phases they started being diluted within the water column and carried away, largely with the high flow events (Rabby et. al., 2024).

Ammonium and nitrite + nitrate showed decreasing patterns throughout the period. However, interestingly within the timeline of two consecutive streamflow droughts (2006-2009 and 2008-2013), ammonium shifted from insignificant trends to significant negative trends, while nitrite + nitrate shifted from significant negative to insignificant trends. This divergence in trend behavior for ammonium and nitrite + nitrate points to differential biogeochemical responses of nitrogen species to prolonged low-flow conditions. We posit that, during prolonged droughts, ammonium became more efficiently removed or transformed within the estuary, driving a shift toward significant depletion. In contrast, after an initial decline, nitrite + nitrate reached a new balance under drought, with internal sources and reduced flushing maintaining steady levels, leading to the loss of significant trend.

We also observed that the pH started showing significant decreasing trends around that timeline (2003-2006), which may be reflective of high organic loads from upstream with the high flows during those extreme events. However, the high flow events during those years also coincided with the extreme rainfall events and it is hypothesized that the compound influences of extreme rainfall and high flow events increased acidification and decreasing pH. However, this trend may also reflect increased organic matter input, soil-derived acidity, or enhanced microbial respiration, all of which can lower pH during and after large runoff events.

7.4.4. Impacts of heavy rainfall

Extreme rainfall events (analyzed from local rainfall data) occurred throughout the study period, except for 2007-2008 and 2014-2015. In 2003 and 2005, extreme rainfall coincided with the start of pH decreasing trends. The shifting trends of turbidity (from positive to negative) in the bottom water was influenced by the extreme rainfall events around 2012. However, the coincidence of high flow events confounded understanding of the exact role of extreme rainfall.

Although chlorophyll-a was increasing consistently throughout the entire period across the water quality monitoring stations, changes in their trend strength were observed between 2009 and 2011 that coincided a substantial number of rainfall events occurred within this period. Notably, this period was in between two streamflow drought events. The post drought phases are responsible for increased riverine phosphate loads into the Apalachicola Bay (Rabby et al., 2024). The extreme rainfall within the study area can further contribute to carrying excess phosphate loads from the land adjacent to the estuary via direct runoff. We posit that the shift in the trend strength in the chlorophyll-a within 2009-2011 was largely triggered by the excess phosphate load, to which extreme rainfalls contributed substantially.

7.4.5. Impacts of El Niño and La Niña

Broader climate patterns, El Niño and La Niña phases of the El Niño–Southern Oscillation (ENSO), likely influence hydroclimatic variability and associated water quality responses in the Apalachicola Bay. The classification of El Niño and La Niña years in this analysis is based on the Oceanic Niño Index (ONI), which represents the 3-month running mean of sea surface temperature (SST) anomalies in the Niño 3.4 region (5°N–5°S, 120°–170°W). An ONI value of ≥ +0.5 °C for five consecutive overlapping seasons qualifies as an El Niño event, while a value of ≤ –0.5 °C indicates a La Niña event. The ENSO phases listed in follow NOAA's official ONI dataset (NOAA, 2025), which categorizes each year based on the duration and magnitude of SST anomalies in the central tropical Pacific.

El Niño years (e.g., 2009 and 2015) are generally associated with reduced streamflow and less flushing in the region, which coincides with higher salinity and limited nutrient input. However, El Niño can also bring cooler, wetter winters to Florida, potentially increasing storm activity and freshwater inflow, which may enhance nutrient delivery and storm surge exposure depending on the phase strength and timing. In contrast, La Niña years (e.g., 2010, 2011 and 2020) often bring more rainfall and higher flows, resulting in increased turbidity, nutrient delivery and freshwater intrusion. For example, 2020, a La Niña year, was marked by high streamflow, active storm events and widespread water quality shifts, including elevated nutrient concentrations and reduced DO.

8. Limitations and recommendations

The first limitation was data availability, even though Apalachicola Bay system is relatively data rich compared to many bay-estuarine systems. The data limitation varied by water quality parameter and station, with some time series containing gaps or limited years of coverage, particularly in the earlier years of the study period. This constrained inclusion in trend and changepoint analyses and may introduce spatial bias. Second, all analyses were conducted using monthly or annual aggregations, which, while appropriate for long-term patterns, limit the resolution needed to capture short-term dynamics such as storm pulses or diel DO fluctuations. Third, while trend alignment and changepoint co-occurrence were used to infer potential relationships between drivers and water quality responses informed by Grantee's knowledge on the underlying mechanisms, these methods do not necessarily establish causality and may be influenced by unmeasured confounding factors. Finally, the classification of hydroclimatic extremes relied on percentile thresholds that do not fully capture the spatial variability, antecedent conditions or cumulative effects of these events on the bay system. Future research should address these limitations through applying more extensive and higher resolution data as well as more complex analysis methods.

To enhance future analyses and monitoring efforts, methodological improvements may be considered. Incorporating higher-frequency data collection—such as daily (or sub-daily) measurements of chlorophyll-a and nutrient concentrations—at selected inner-bay stations would significantly improve our ability to resolve short-term variability associated with storm events or seasonal extremes. While DO and salinity are already measured at 15-minute intervals at several stations, event-triggered sampling for nutrients and chlorophyll-a following major rainfall or storm surge could capture transient peaks that current monthly sampling may overlook. Collecting water quality data at additional locations would enhance the spatial coverage and provide insights about the spatial pattern and dependency of various locations across the Apalachicola Bay system. Future statistical analyses might benefit from modeling approaches (e.g., generalized additive models) that explore potential nonlinear relationships between water quality responses to various drivers. Additionally, satellite products (e.g., Sentinal-2, MODIS, PACE and Landsat) can be used to supplement *in-situ* chlorophyll-a and turbidity records during the periods with data gaps. The observations can enhance the temporal resolution of water quality data too. Not only for the water quality parameters, but satellite observations can be also used for the same purpose on the drivers.

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