Working Title: Trends and variability in chlorophyll a in a back-barrier lagoonal estuary in the southeastern United States

Effective management of coastal ecosystems to sustain current status or to mitigate impacts requires information on how these systems have changed over time. This is especially true to differentiate between anthropogenic impacts and natural variability within these systems. Estuaries, the natural buffer zone between rivers and ocean, are often some of the most vulnerable ecosystems as their watersheds are much larger than their area. The problem of nutrient enrichment and pollution in coastal environments is growing worldwide, particularly as populations increase in these watersheds and more of the upland habitats are developed for residential, urban, or industrial complexes (Freeman et al. 2019; Kyzar et al. 2021).

**Nutrient enrichment alters coastal ecosystems often first with increases in algal production and biomass (CITATION?)** and the response of these systems is quite variable over space and time (Cloern and Jassby 2010). Anthropogenic impacts are not the only the primary drivers in these systems as climate also plays a large role in long-term conditions. In the Chesapeake Bay, precipitation and tropical cyclone activity results in variable phytoplankton production coupled with underlying increases in chlorophyll *a* (a common proxy for phytoplankton biomass) due to eutrophication (Harding et al. 2016). In the Indian River Lagoon and St. Lucie estuaries, variability in phytoplankton blooms have been attributed to cyclical patterns (e.g. El Niño/La Niña periods) and tropical cyclone events, typically as these events bring large amounts of precipitation (Phlips et al. 2020; Phlips et al. 2021). There are also systems, like the San Francisco estuary which, though nutrient-enriched, do not experience water quality impacts common to other enriched systems (like frequent phytoplankton blooms or low dissolved oxygen) attributed to a variety of variables such as strong tidal flushing and heavy phytoplankton grazing pressure from bivalves (Jassby 2008; Cloern and Jassby 2010; Cloern 2019). Additionally, the issue of nutrient pollution is not isolated to developed watersheds as even watersheds with low levels of development have been found to exhibit high levels of nutrient and chlorophyll *a* concentrations, such as the tidal creeks in the Ashepoo-Combahee-Edisto Basin in South Carolina (CJ et al. 2015). Therefore the use of observational information from long-term research and monitoring programs provides the most valuable information for place-based and adaptive strategies in the management of coastal ecosystems.

The System-Wide Monitoring Program (SWMP) of the National Estuarine Research Reserve System (NERRS) is an established long-term monitoring program that has been a cornerstone of the NERRS since its inception in 1995. The SWMP utilizes standardized equipment and protocols to collect high-frequency and continuous water quality and meteorological data in a variety of estuarine environments across the United States and Puerto Rico. Due to the standardization of the program, and its well-developed and documented data management protocols for quality assurance and quality control, it serves as an excellent resource for helping to identify trends, patterns, and scales of variability in phytoplankton dynamics as well as their potential drivers within estuarine environments (System 2022).

One of thirty NERRS nationwide, three of which exist in Florida, the Guana Tolomato Matanzas National Estuarine Research Reserve (GTMNERR) has collected long-term data on water quality and meteorological conditions in the Guana-Tolomato-Matanzas (GTM) estuary since 2002. The GTM is a bar-built estuary with enclosed lagoons “rivers” (the Guana, Tolomato, and Matanzas) that trifurcate at the St. Augustine Inlet. The St. Augustine Inlet is one of two inlets in this system and it is stabilized with a jetty and maintained by the US Army Corps of Engineers to a depth of 5-m and the other, the Matanzas Inlet, is one of Florida’s few remaining unstructured inlets on the Atlantic Coast (Dean and O’Brien 1987). Overall, the GTM estuary is a well-mixed and well-flushed estuary with an absence of a freshwater river and a short residence time of approximately 12.6 days (Phlips et al. 2004; Sheng et al. 2008; Gray et al. 2021).

The last study to have performed any trend or status of the GTM estuary was performed almost 20 years ago in 2004 using monitoring data collected by the St. Johns River Water Management District (Winkler and Ceric 2004). Their assessment encompassed a suite of water quality indicators which included chlorophyll *a*. At that time, the Northern Coastal Basin, which includes the GTM estuary, was found to have some of the best water quality out of all the basins in the District; however, many of the sites, though deemed of good water quality, provided insufficient data (did not have at least 10 years of data) or had insignificant results for trend tests (Winkler and Ceric 2004).

The estuary is within the ecotone of salt marsh and mangrove habitats with diverse habitats such as intertidal oyster reefs, tidal creeks, mud flats, and open water (Williams et al. 2014; Bacopoulos et al. 2019). The GTM estuary hosts exceptionally intact and robust populations of eastern oysters (*Crassostrea virginica*) that filter ~60% of the estuary’s volume within a single residence time (Gray et al. 2021). It is likely these filtration services coupled with the short residence times keep phytoplankton biomass low (Dix et al. 2013; Hart et al. 2015).

Given the lack of recent information regarding the status of water quality or nutrients within this system, the access of a robust water quality time series, and the continued increase in coastal population density pressure in the region (Kyzar et al. 2021), this study uses the established long-term continuous monitoring framework of the NERRS SWMP to establish trends, patterns, and scales in variability of chlorophyll *a* for a 20-year time period (2003-2022) while providing some potential drivers of that variation.

# Methods

## Study Area

The SWMP of the GTM Research Reserve operates and maintains four water quality stations equipped with YSI EXO2 sondes, deployed within one meter of the bottom, that record environmental parameters (e.g. temperature, salinity) every 15-minutes. It is at these stations in which monthly water samples are collected during an ebb tide for chlorophyll *a* and a suite of other parameters such as nitrogens, phosphorus, bacteria, and total suspended solids.

Established in 2002, the station locations were selected to represent the influence of watersheds with varying degrees of urban development and reflect a diversity of physical processes (e.g., tidal exchange, freshwater input) and climatic conditions. Pine Island (PI) is located off of channel marker 25 in the Tolomato River surrounded by silviculture-dominated uplands in the northern portion of the GTM estuary. The Guana River runs parallel to the Tolomato on the seaward side, with the two lagoons joining 11.3-km north of the St. Augustine Inlet, approximately X-km south of the PI station. The Tolomato River Basin converges with the Matanzas River and Salt Run from the south before flowing into the Atlantic Ocean at the St. Augustine Inlet.

San Sebastian (SS) is located at the confluence of the San Sebastian and Matanzas Rivers. The San Sebastian River drains an urbanized watershed in the western portion of St. Augustine. The Matanzas River estuary is approximately 32 km in length and extends 13 km south of the Matanzas Inlet. The tidal node within the Matanzas is located around the CR-206 bridge with waters flowing northward of the bridge and southward of the bridge at outgoing tides. Fort Matanzas (FM) is located at Channel Marker 75 approximately 4-km north of the Matanzas Inlet.

Pellicer Creek is located in the southern part of the Matanzas River Basin, serves as a border between St. Johns and Flagler counties, and is surrounded by public conservation lands. Pellicer Creek is a tidal creek and is the primary source of natural freshwater drainage into the Matanzas River. SJRWMD collects in the mouth of Pellicer Creek near Marineland, Florida. The Pellicer Creek water quality station (PC) is at the end of a recreational dock in Faver-Dykes State Park located within the Pellicer Creek Aquatic Preserve.

## Field and Laboratory Procedures

All chlorophyll *a* data were “grab” samples except for Pellicer Creek in which some missing data values were filled in with data collected at similar time frames using an automated water sampler. This diel sampling is also performed by the SWMP on the same tidal stage at the Pellicer Creek station. All samples were collected monthly, in duplicate, from as close to sonde depth as possible (no deeper than 3 meters in the deeper sites). Samples were filtered in the field whenever feasible; otherwise, they were placed on ice in the dark and filtered immediately upon returning to the laboratory. All chlorophyll *a* samples were performed using Standard Methods (SM10200H). All duplicate values were averaged into a monthly value at all sites. Temperature (°C) and salinity (practical salinity units, psu) data from each site was averaged to each month. Data was removed that failed to meet quality standards for all parameters. For the SWMP, values below the nominal base minimum detection limit of 0.55 (µg\L) were replaced with this nominal base to standardize across the dataset.

## Climate Data

Continuous meteorological data is also collected by the GTMNERR SWMP at the Pellicer Creek weather station, approximately 4 km southeast of the Pellicer Creek water quality station, at the mouth of Pellicer Creek in Princess Place Preserve in Flagler County. Rainfall (mm) data were totalled for each month and year after removing data that failed to meet quality standards. Information on El Niño/Southern Oscillation (ENSO) was downloaded from the National Oceanic and Atmospheric Administration’s Pacific Coast Laboratory (https://psl.noaa.gov/enso/mei/). The Multivariate ENSO Index (MEI) is based on multiple variables that are used to describe conditions in the tropical Pacific during ENSO events. This index is computed for 12 bimonthly rolling windows per year. This rolling window was summed to the following month (representing preceding and existing conditions) and was used to examine climate patterns during this study period.

## Data analysis

All statistical analyses and data visualizations were carried out using R v4.3.0 (R Core Team 2023). Generalized additive models on log10-transformed chlorophyll *a* data were performed for each station using the wqtrends package with terms *s*(“cont\_year”), day of the year converted into a continuous numeric variable to represent annual effect, and the upper limit of the basis complexity (*k*) was set to 12 times the number of years for the input data (12 \* 20 = 240) (M. Beck et al. 2022; M. W. Beck et al. 2022). Diagnostic information of the model fit and procedure were checked using the mgcv package (Wood 2011). These models computed a smooth temporal pattern in the raw data with an uncertainty of the smoother. The model results were then used to calculate seasonal metrics, trends, and plot results. The predicted values from the model results were also used to fill in data, by creating monthly averages, for missing months at each of the stations (CITE SUPPLEMENTAL MISSING DATA INFORMATION HERE) to complete the time series for decomposition to further investigate patterns and scales of variability using methods from (Cloern and Jassby 2010).

Seasonality was determined not only through decomposition, but also by measuring changes in phases of annual chlorophyll *a* cycles using wql package (Jassby and Cloern 2022). As an indicator of peak annual biomass, phenoPhase() was used to calculate the fulcrum or “center of gravity” as the date each year in months when the cumulative chlorophyll *a* reached half the total annual cumulative chlorophyll *a* (Greve et al. 2005; Cloern et al. 2023). These fulcrums were then used to determine the time frame of annual peak chlorophyll *a* which was used to further test for trends in seasonal changes over time using meta-analysis with wqtrends.

# References

Bacopoulos, P., A. S. Tritinger, and N. G. Dix. 2019. Sea-Level Rise Impact on Salt Marsh Sustainability and Migration for a Subtropical Estuary: GTMNERR (Guana Tolomato Matanzas National Estuarine Research Reserve). *Environmental Modeling & Assessment* 24: 163–184. <https://doi.org/10.1007/s10666-018-9622-6>.

Beck, M. W., P. De Valpine, R. Murphy, I. Wren, A. Chelsky, M. Foley, and D. B. Senn. 2022. Multi-scale trend analysis of water quality using error propagation of generalized additive models. *Science of The Total Environment* 802: 149927. <https://doi.org/10.1016/j.scitotenv.2021.149927>.

Beck, M., P. de Valpine, R. Murphy, I. Wren, A. Chelsky, M. Foley, and D. Senn. 2022. Wqtrends: Assess water quality trends with generalized additive models.

CJ, K., B. DC, B. LM, F. J, and G. DI. 2015. A spatial assessment of baseline nutrient and water quality values in the ashepoo–combahee–edisto (ACE) basin, south carolina, USA. *Marine Pollution Bulletin* 99: 332–337. <https://doi.org/10.1016/j.marpolbul.2015.07.035>.

Cloern, J. E. 2019. Patterns, pace, and processes of water-quality variability in a long-studied estuary. *Limnology and Oceanography* 64. <https://doi.org/10.1002/lno.10958>.

Cloern, J. E., and A. D. Jassby. 2010. Patterns and Scales of Phytoplankton Variability in EstuarineCoastal Ecosystems. *Estuaries and Coasts* 33: 230–241. <https://doi.org/10.1007/s12237-009-9195-3>.

Cloern, J. E., T. S. Schraga, E. Nejad, and T. Eddy. 2023. Phytoplankton as indicators of global warming? *Limnology and Oceanography Letters*: lol2.10354. <https://doi.org/10.1002/lol2.10354>.

Dean, R. G., and M. P. O’Brien. 1987. [*Florida’s east coast inlets: Shoreline effects and recommeded action*](http://hdl.handle.net/1834/18098). University of Florida.

Dix, N., E. Phlips, and P. Suscy. 2013. Factors Controlling Phytoplankton Biomass in a Subtropical Coastal Lagoon: Relative Scales of Influence. *Estuaries and Coasts* 36: 981–996. <https://doi.org/10.1007/s12237-013-9613-4>.

Freeman, L. A., D. R. Corbett, A. M. Fitzgerald, D. A. Lemley, A. Quigg, and C. N. Steppe. 2019. Impacts of Urbanization and Development on Estuarine Ecosystems and Water Quality. *Estuaries and Coasts* 42: 1821–1838. <https://doi.org/10.1007/s12237-019-00597-z>.

Gray, M. W., D. Pinton, A. Canestrelli, N. Dix, P. Marcum, D. Kimbro, and R. Grizzle. 2021. Beyond Residence Time: Quantifying Factors that Drive the Spatially Explicit Filtration Services of an Abundant Native Oyster Population. *Estuaries and Coasts* 45: 1343–1360. <https://doi.org/10.1007/s12237-021-01017-x>.

Greve, W., S. Prinage, H. Zidowitz, J. Nast, and F. Reiners. 2005. [On the phenology of north sea ichthyoplankton](https://doi.org/10.1016/j.icesjms.2005.03.011). *ICES Journal of Marine Science* 62: 1216–1223.

Harding, L. W., C. L. Gallegos, E. S. Perry, W. D. Miller, J. E. Adolf, M. E. Mallonee, and H. W. Paerl. 2016. Long-Term Trends of Nutrients and Phytoplankton in Chesapeake Bay. *Estuaries and Coasts* 39: 664–681. <https://doi.org/10.1007/s12237-015-0023-7>.

Hart, J. A., E. J. Phlips, S. Badylak, N. Dix, K. Petrinec, A. L. Mathews, W. Green, and A. Srifa. 2015. Phytoplankton biomass and composition in a well-flushed, sub-tropical estuary: The contrasting effects of hydrology, nutrient loads and allochthonous influences. *Marine Environmental Research* 112: 9–20. <https://doi.org/10.1016/j.marenvres.2015.08.010>.

Jassby, A. D. 2008. Phytoplankton in the Upper San Francisco Estuary: Recent Biomass Trends, Their Causes, and Their Trophic Significance. *San Francisco Estuary and Watershed Science* 6. <https://doi.org/10.15447/sfews.2008v6iss1art2>.

Jassby, A. D., and J. E. Cloern. 2022. [Wq: Exploring water quality monitoring data](https://CRAN.R-project.org/package=wq).

Kyzar, T., I. Safak, J. Cebrian, M. W. Clark, N. Dix, K. Dietz, R. K. Gittman, et al. 2021. Challenges and opportunities for sustaining coastal wetlands and oyster reefs in the southeastern United States. *Journal of Environmental Management* 296: 113178. <https://doi.org/10.1016/j.jenvman.2021.113178>.

Phlips, E. J., S. Badylak, N. G. Nelson, L. M. Hall, C. A. Jacoby, M. A. Lasi, J. C. Lockwood, and J. D. Miller. 2021. [Cyclical patterns and a regime shift in the character of phytoplankton blooms in a restricted sub-tropical lagoon, indian river lagoon, florida, united states](https://www.frontiersin.org/articles/10.3389/fmars.2021.730934). *Frontiers in Marine Science* 8.

Phlips, E. J., S. Badylak, N. G. Nelson, and K. E. Havens. 2020. Hurricanes, El Niño and harmful algal blooms in two sub-tropical Florida estuaries: Direct and indirect impacts. *Scientific Reports* 10: 1910. <https://doi.org/10.1038/s41598-020-58771-4>.

Phlips, E. J., N. Love, S. Badylak, P. Hansen, J. Lockwood, C. V. John, and R. Gleeson. 2004. A Comparison of Water Quality and Hydrodynamic Characteristics of the Guana Tolomato Matanzas National Estuarine Research Reserve and the Indian River Lagoon of Florida\*\*. *Journal of Coastal Research* 10045: 93–109. <https://doi.org/10.2112/SI45-093.1>.

R Core Team. 2023. [*R: A language and environment for statistical computing*](https://www.R-project.org/). Vienna, Austria: R Foundation for Statistical Computing.

Sheng, Y. P., B. Tutak, J. R. Davis, and V. Paramygin. 2008. Circulation and Flushing in the Lagoonal System of the Guana Tolomato Matanzas National Estuarine Research Reserve (GTMNERR), Florida. *Journal of Coastal Research* 10055: 9–25. <https://doi.org/10.2112/SI55-002.1>.

System, N. N. E. R. R. 2022. *System-wide monitoring program data management manual* (version Version 6.7). Centralized Data Management Office.

Williams, A. A., S. F. Eastman, W. E. Eash-Loucks, M. E. Kimball, M. L. Lehmann, and J. D. Parker. 2014. Record Northernmost Endemic Mangroves on the United States Atlantic Coast with a Note on Latitudinal Migration. *Southeastern Naturalist* 13: 56–63. <https://doi.org/10.1656/058.013.0104>.

Winkler, S., and A. Ceric. 2004. *Status and trends in water quality at selected sites in the st. Johns river water management district*. Palatka, Florida.

Wood, S. N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models 73: 3–36.