Water quality in coastal systems in the Suwannee River Water Management District

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Executive summary

Florida's coastal waters are vulnerable to eutrophication, an increase in organic matter. Increased production of organic matter typically occurs in response to higher nutrient loads, which often are created by a larger human population and more intense land use. Impacts from eutrophication have included phytoplankton blooms; lowered oxygen levels; damage to habitats; and loss of scallops, shrimps, blue crabs, myriad fishes, and other ecologically and economically important animals. In recognition of such concerns, broad-scale sampling of water quality began in 1997 (Project COAST). This report summarizes key results for systems in the Suwannee River Water Management District.

Concentrations of total nitrogen, total phosphorus, and chlorophyll represent three valuable indicators of eutrophication. Evidence of this value was provided by positive relationships between chlorophyll concentrations, a proxy for organic matter in phytoplankton, and concentrations of total nitrogen and total phosphorus across a wide range of values.

Increased rainfall, particularly during the 1998 El Niño event, generated increased concentrations of total nitrogen, total phosphorus, and chlorophyll, along with decreased water clarity across all systems. However, the systems recovered in 6–8 months.

In an attempt to reduce noise that can obscure trends, this event was excluded, and data from 1999 through the available periods of record were analyzed to identify groups of months and stations with similar characteristics. Relative to other months, May, June, July, and August were characterized by warmer water temperatures, more rainfall per month, higher light attenuation, and longer days. In addition, water temperatures were lower and daylengths were shorter in January, February, November, and December. Riverine stations, those that were landward of the marsh areas at the mouths of the rivers, were analyzed separately. For estuarine stations in each system, a series of analyses revealed spatial patterns in salinities and concentrations of total nitrogen, total phosphorus, and chlorophyll that varied with distance and direction from the mouth of the adjacent river. In combination, these results guided pooling of data from stations within systems before analyses of trends.

Trends, or correlations with time for the relevant periods of record, indicated that concentrations of total nitrogen, total phosphorus, and chlorophyll increased in the Steinhatchee, Suwannee, and Waccasassa systems, with the most consistent increases recorded in the Suwannee system. Data for the Aucilla, Econfina, and Fenholloway systems covered only twelve months spanning 2013 and 2014. In these systems, concentrations of total nitrogen, total phosphorus, and chlorophyll tended to decrease through time, which likely was related to a decrease in rainfall after the first three months of sampling.

Overall, sampling raised some concerns about nutrients from the rivers affecting the coastal waters. Management of these increases and the resulting threat of eutrophication has been initiated through the total maximum daily load process, and these efforts will benefit from additional analyses and data that enhance insights into spatial and temporal changes and trends. For example, an understanding of spatial coherence can foster optimal allocation of sampling effort in programs designed to evaluate and adapt management actions. In some cases, the desired level of understanding will require investment in collection of data that complement the existing baseline. Ultimately, long-term baseline data combined with targeted diagnostic studies can guide the design of monitoring that continually evaluates and adapts management actions to ensure healthy coastal systems that deliver value to stakeholders in the Suwannee River Water Management District.

INTRODUCTION

Nutrient concentrations in coastal waters can increase due to agricultural practices and urban development within the relevant watersheds (Jones et al. 1997, Frazer et al. 2006). When loads in these systems exceed internal rates of assimilation or transformation, the rivers discharge surplus nutrients, especially nitrate, into the Gulf of Mexico (Frazer et al. 1998, 2001, 2006). This anthropogenic nutrient enrichment can fuel increased algal production resulting in an accumulation of organic matter, or eutrophication.

In most nearshore waters, detrimental effects follow nutrient enrichment and eutrophication (Duarte 1995, Valiela et al. 1997). Seagrass beds are particularly vulnerable to such effects. Damage to seagrasses raises broader concerns about the overall health and ecological integrity of Florida's estuarine and nearshore systems (Frazer and Hale 2001, Mattson et al. 2007). For example, seagrass beds rank among the world's top three most valuable habitats, and they provide refuge and a habitat for foraging to scallops, shrimps, blue crabs, myriad fishes, manatees, and sea turtles (Killam et al. 1992, Costanza et al. 1997).

Seagrasses and other plants require nutrients, especially nitrogen and phosphorus, to support their growth. However, nutrient enrichment often results in damage to seagrasses. For example, seagrasses die if phytoplankton, epiphytic microalgae and/or benthic macroalgae shade them too much. These fast-growing algae generally take up nutrients more efficiently, especially when concentrations in the water column become enriched, and they need less light (Williams and Ruckelhaus 1993, Duarte 1995). In fact, studies from around the world indicate that increased nutrient loading to estuarine systems fosters replacement of seagrasses with blooms of fast-growing macroalgae and phytoplankton (Duarte 1995, Valiela et al. 1997, Waycott et al. 2008). Moreover, available information suggests that damaged seagrass beds require years to centuries to recover (Duarte 1995).

Historically, Florida's coastal systems, including Apalachee Bay, Tampa Bay, and Florida Bay, suffered substantial losses of seagrass, with declines often attributed to changes driven by increased nutrient loads (Hale et al. 2004, Handley et al. 2007). Along Florida's Gulf coast, Hale et al. (2004) reported 1–4 m shoreward shifts in the depth distribution of turtle grass (*Thalassia testudinum*) and shoal grass (*Halodule wrightii*), as well as areas of seagrass loss near the mouths of rivers. They suggested that increased nutrient loading to coastal rivers could underlie these changes. If such a link is valid, then reducing nutrient loads could promote recovery of seagrasses as it has in Tampa Bay (http://www.tbep.org/).

The potential negative consequences from increased nutrient delivery to estuarine and coastal waters led to broad-scale sampling of water quality that began in 1997 (Project COAST). Continuing surveys are critical if managers of water resources plan to i) differentiate natural variation in water quality from persistent declines that arise from human activities and threaten to degrade coastal systems; ii) identify targets for diagnostic studies that optimize management actions; and iii) guide responses to unforeseen circumstances, document the success of management, and demonstrate accountability to stakeholders. Consistent with these objectives, we provide answers to two key questions:

i) Did concentrations of total nitrogen, total phosphorus, and chlorophyll provide valuable insights into the relationship between increasing nutrient loads and eutrophication?

ii) Did monthly sampling detect trends that are of concern?

CHARACTERISTICS OF THE SYSTEMS

Along the coast in the Suwannee River Water Management District, sixty fixed stations were sampled near the mouths of six rivers with differing catchments and hydrology (Figure 1). The stations characterized the downstream riverine reaches and nearshore estuarine waters of the Aucilla, Econfina, Fenholloway, Steinhatchee, Suwannee, and Waccasassa rivers.

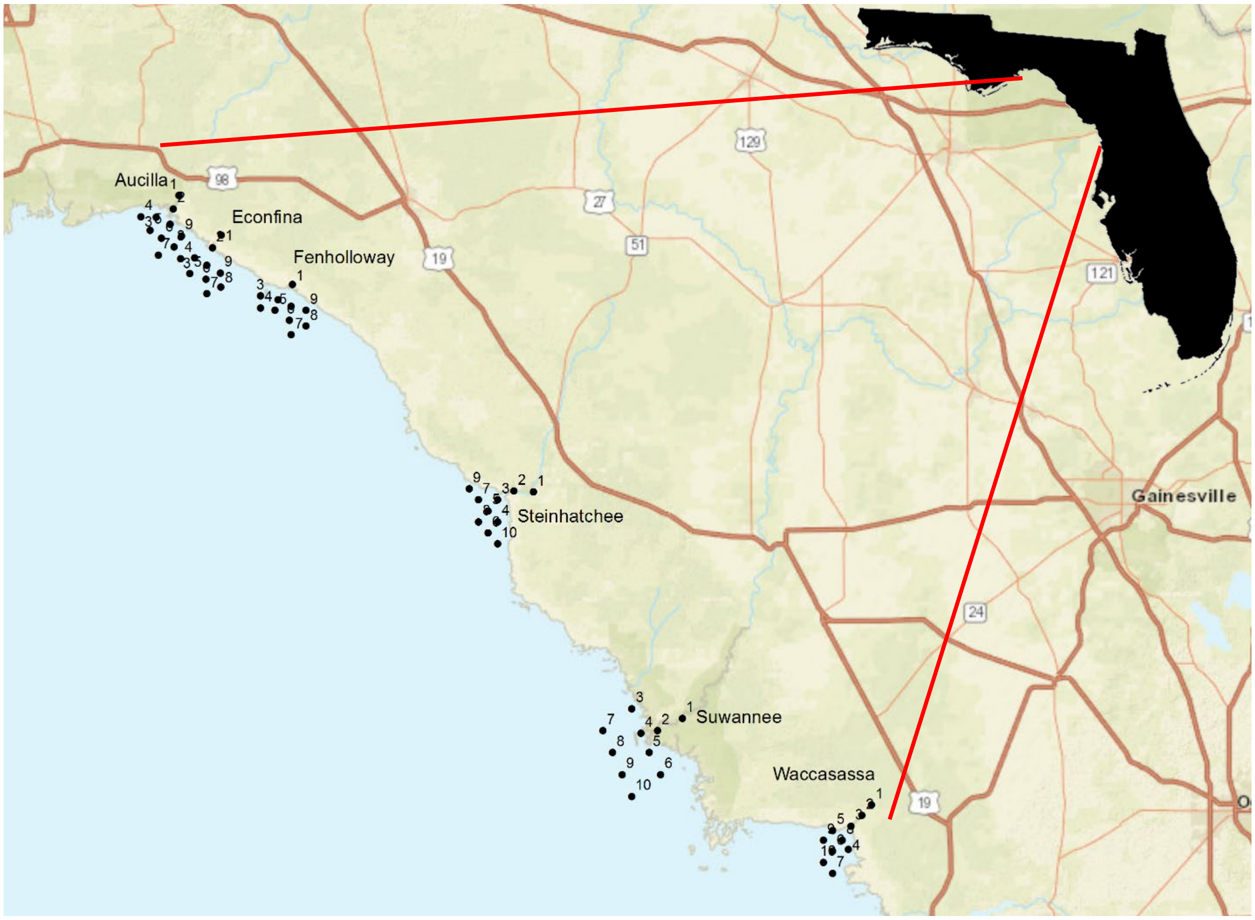

Figure 1. Study area and sampling stations. black dots = sampling stations

Aucilla River

The Aucilla River flows south for approximately 89 miles from artesian springs in southern Georgia to the Gulf of Mexico. This basin contains marshes and lakes in north Florida, karst limestone east of Tallahassee, and sinks. This blackwater river disappears below the Cody Scarp before rising again at Nutall Rise, the only known major spring on the river. The Wacissa River is a spring-fed tributary that flows approximately 12 miles through a broad cypress swamp and breaks into numerous braided channels that join the Aucilla. Twelve major springs feed the Wacissa River as it flows through the Aucilla Wildlife Management Area. In combination, the Aucilla and Wacissa drain 731 square miles.

Econfina River

Beginning in the San Pedro Bay swamp in Madison County, Florida, the Econfina River flows for approximately 40 miles through Taylor County before discharging into the Gulf of Mexico. This blackwater river has several small springs and flows that feed it as it traverses swampy lowlands. The basin covers approximately 239 square miles.

Fenholloway River

The Fenholloway River also originates in the San Pedro Bay swamp, and it drains approximately 392 square miles. This blackwater river receives freshwater input from springs as it flows for 36 miles in Taylor County, Florida. In the past, a paper mill discharged about 40 million gallons per day of treated wastewater at a point about 24.6 miles upstream of the river's mouth, which represented up to 90 percent of the flow at this location (Sousa et al. 2002). By 2021, the facility had upgraded its treatment of wastewater and moved the point of discharge to 1.5 miles upstream of the mouth of the river.

Steinhatchee River

The blackwater Steinhatchee River originates in Mallory Swamp to the south of the Town of Mayo in Lafayette County, and it flows approximately 35 miles before discharging into the Gulf of Mexico. The river drains approximately 586 square miles, and there are two priority springs that contribute to its discharge, Steinhatchee Rise and TAY76992.

Suwannee River

The Suwannee River basin covers approximately 9,950 square miles, with approximately 4,250 square miles (43%) in Florida and 5,700 square miles (57%) in Georgia. The Suwannee River originates in the Okefenokee Swamp in southeastern Georgia, and two of its tributaries, the Alapaha and Withlacoochee rivers, also originate in Georgia. Another tributary in Florida, the Santa Fe River flows for approximately 75 miles before joining the Suwannee River.

Waccasassa River

The Waccasassa River begins in the southern end of the Waccasassa Flats, a broad complex of swamps and pine flatwoods in central Gilchrist County. The river flows for approximately 29 miles. Initially, it comprises multiple channels, swamps, and areas of sheet flow before becoming a named river in extreme southern Gilchrist County. The river becomes a wide, tidal floodplain before emptying into Waccasassa Bay, a broad, shallow estuary. Major tributaries include Cow Creek, Tenmile Creek, Wekiva River, and McGee Branch, with Wekiva Springs and Levy Blue Springs being important sources of baseflow. The Waccasassa River drains about 820 square miles.

Field methods and chemical analyses

All sampling was conducted during daylight hours, generally between 1000 and 1500 hours. At each location, a surface water sample for nutrient analysis was collected in a 250-ml, acid-cleaned Nalgene bottle that was rinsed with ambient surface water. Water samples were stored frozen and subsequently analyzed for total nitrogen (TN) and total phosphorus (TP). Total phosphorus concentrations (µg L^{-1}) were determined using the procedures of Murphy and Riley (1962) with a persulfate digestion (Menzel and Corwin 1965). Total nitrogen concentrations (µg L^{-1}) were determined by oxidizing water samples with persulfate and measuring nitrate-nitrogen concentrations with second-derivative spectroscopy (Bachmann and Canfield 1996). Analyses were performed by the water chemistry laboratory of the Fisheries and Aquatic Sciences Program in the University of Florida/Institute of Food and Agricultural Sciences.

A second surface water sample for chlorophyll analysis was collected at each station and filtered through a 47-mm Gelman type A/E glass fiber filter. The filtered material was placed over silica gel desiccant and stored frozen prior to chlorophyll analysis. Chlorophyll concentrations (µg L^{-1}) were determined spectrophotometrically (Method 10200 H; American Public Health Association 1989) following pigment extraction with ethanol (Sartory and Grobbelaar 1984). The filtrate was refrigerated and analyzed for color (platinum-cobalt units, pcu) with a spectrophotometer (American Public Health Association 1989).

Field measurements included surface water temperature, salinity, and dissolved oxygen that were recorded as part of each sampling event with either a YSI model 85 or Y600QS meter. Temperature measurements were recorded to the nearest 0.1°C, salinity to the nearest 0.1 ppt and dissolved oxygen to the nearest 0.1 mg L^{-1}. In addition, water clarity was measured with a 20-cm diameter Secchi disc, with the Secchi depth at each station recorded to the nearest 0.1 m. Furthermore, two quantum light sensors (Li-Cor Instruments Inc.) were used with a data logger to simultaneously collect surface and downwelling light intensity (µmole photons s^{-1} m^{-2} of photosynthetically available radiation, i.e., PAR). Light attenuation (k_d, m^{-1}) was calculated as:

$$k_d = [\ln(I_0/I_z)]/z$$

where I_0 is incident irradiance at the surface and I_z is light intensity at a depth of z meters (Kirk 1994). When feasible, light readings were recorded at three different depths (all $\geq$ 0.5 m) and an average k_d calculated for use in subsequent analyses. Light attenuation coefficients were not adjusted for cloud cover or sun angle.

Value of key parameters

Patterns in forcing factors and water quality will vary among stations according to their spatial relationships to the mouths and discharge plumes of the six rivers. In recognition of such differences, stations landward of the coastal marshes, termed riverine stations, were analyzed separately from estuarine stations. Initially, the focus will be on the estuarine stations.

Eutrophication can manifest as increased organic matter in different forms, but in many coastal systems, eutrophication initially involves increased biomass of phytoplankton. Thus, concentrations of chlorophyll, proxies for phytoplankton biomass, represent valuable indicators. Across all estuarine stations over the period of record, $\log_{10}$-transformed chlorophyll concentrations were correlated with $\log_{10}$-transformed concentrations of total phosphorus and total nitrogen (Figure 2). In combination, these relationships support a focus on trends in these three parameters for the coastal waters.

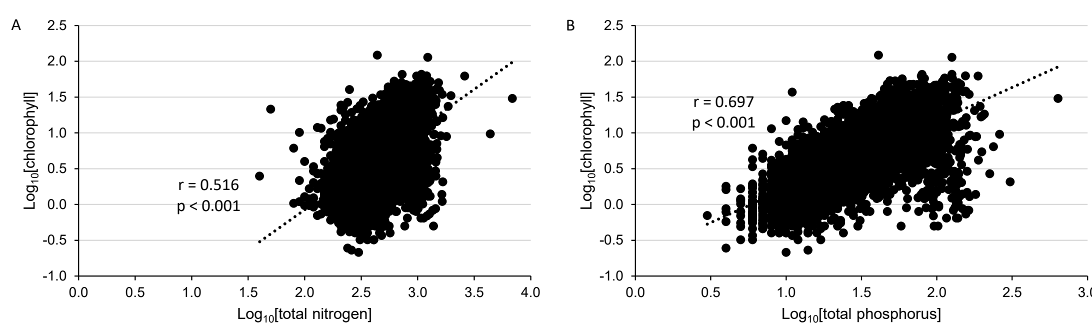

Figure 2. Relationship between $\log_{10}$-transformed concentrations of chlorophyll and (A) concentrations of total phosphorus and (B) concentrations of total nitrogen from all estuarine systems.

DETECTING TRENDS

Eutrophication can generate non-linear responses characterized by thresholds, with undesirable consequences occurring rapidly once a threshold is crossed (Duarte 1995). The onset and pace of a progression to eutrophication can be influenced by a variety of factors, including residence time or rate of dilution in the system of interest, competition for nutrients among primary producers, and grazing. Nevertheless, increasing concentrations of total nitrogen or total phosphorus, or "hypernutrification," typically represent the "earliest" warnings of eutrophication. In addition, increased chlorophyll concentrations would provide evidence of further progression toward eutrophy. Thus, sampling that can detect trends in concentrations of total nitrogen, total phosphorus, and chlorophyll represents a valuable tool for managers of coastal systems.

In order to identify trends accurately and effectively, long-term sampling should detect short-term changes in water quality, which have been termed events or pulse perturbations (Glasby and Underwood 1996). Extreme events can create medium-term to long-term consequences that obscure trends (e.g., the 2011 phytoplankton bloom in the Indian River Lagoon and subsequent loss of thousands of acres of seagrass that persisted through 2013; Jacoby unpublished data). Across all stations in all systems, mean concentrations of total nitrogen, total phosphorus, and chlorophyll increased in response to an El Niño event in 1998 (Figure 3A–C). These changes decreased water clarity as shown by a reduction in the proportion of times a Secchi disc remained visible throughout the water column (Figure 3D). The systems recovered, with "typical" values recorded after 6–8 months. If an event of this magnitude is included in analyses to detect trends, it can overshadow subtler, yet important, changes because subsequent values will appear less extreme. Therefore, further analyses focused on data collected during and after 1999. In particular, these results illustrated how natural variation can confound identification of anthropogenic impacts, and they pointed to the value of sustained sampling.

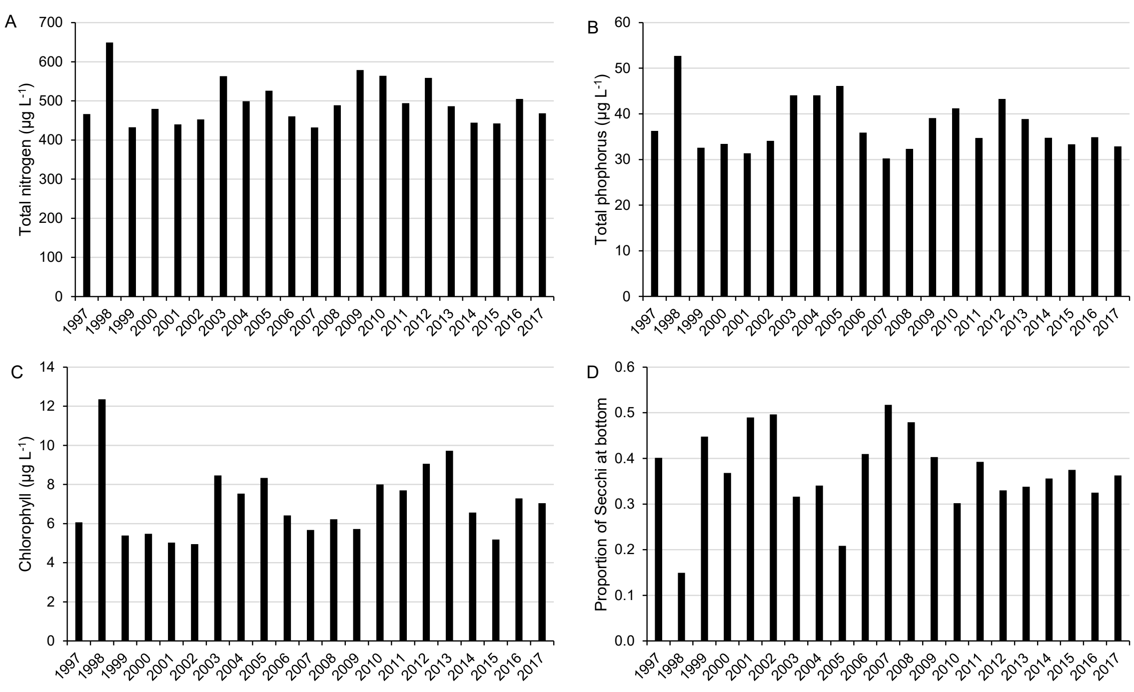

Figure 3. Annual mean (A) total nitrogen concentrations, (B) total phosphorus concentrations, (C) chlorophyll concentrations and (D) proportion of sampling events where the Secchi disk was visible at the bottom based on monthly samples across the six estuarine systems.

Events represent one type of impact on coastal systems, but long-term trends also affect the health of these systems. Even with major events excluded, trends can be difficult to detect given the spatiotemporal variation or “noise” exhibited by water quality parameters, including concentrations of total nitrogen, total phosphorus, and chlorophyll. For example, data from the most northern and southern stations, Steinhatchee station 8 and Waccasassa station 10, indicated that concentrations of total nitrogen spanned a similar range at both stations, concentrations of total phosphorus and chlorophyll spanned wider ranges in the south, and all parameters were characterized by substantial variability within and among years (Figure 4). Trends will be detected more reliably if data can be parsed in a way that maximizes coherence in time and space.

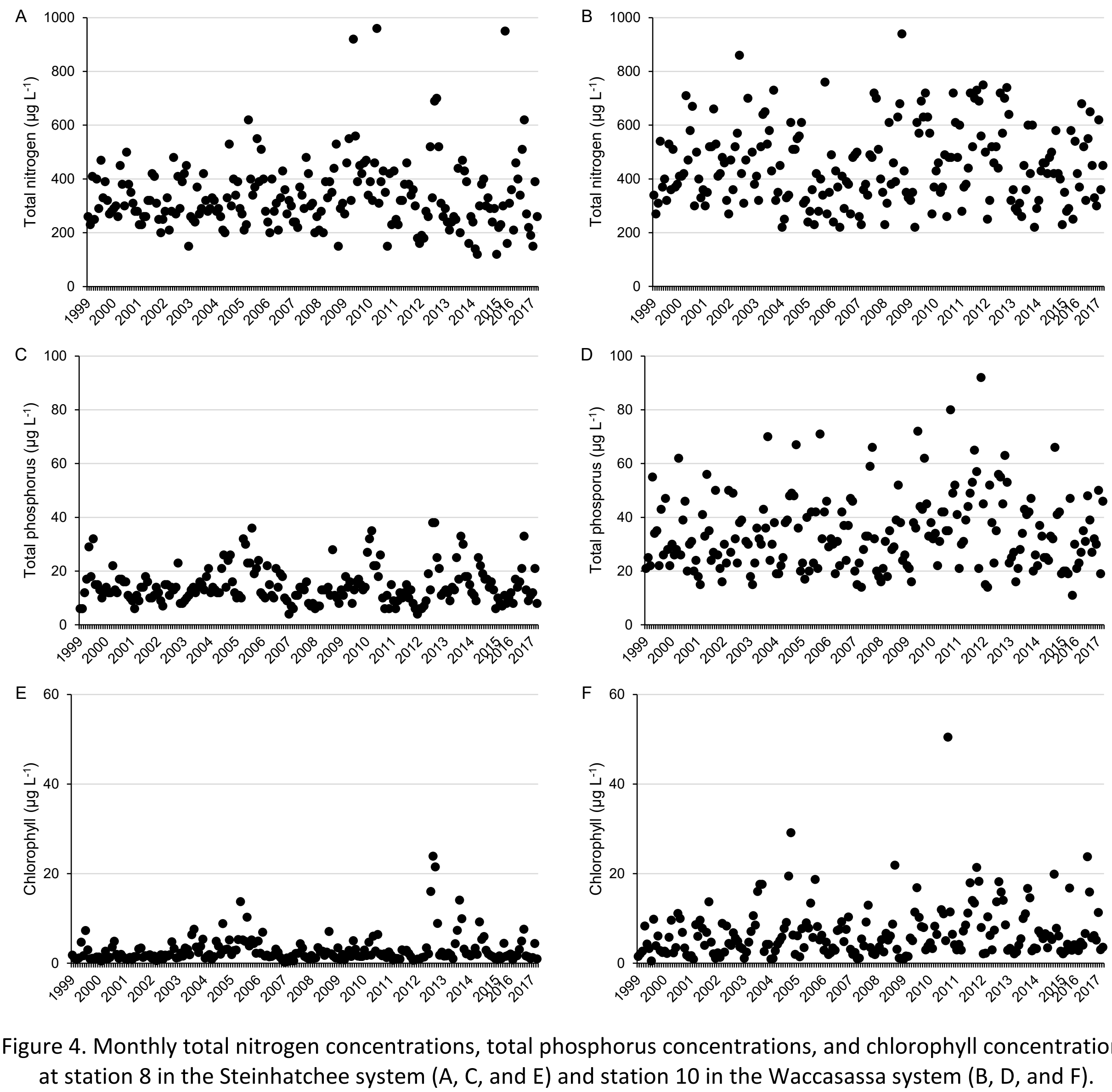

Figure 4. Monthly total nitrogen concentrations, total phosphorus concentrations, and chlorophyll concentrations at station 8 in the Steinhatchee system (A, C, and E) and station 10 in the Waccasassa system (B, D, and F).

Some of the variation will be due to temporal variation in regional forcing factors. For example, rainfall can drive nutrient loading, and water temperature or availability of light can affect productivity of phytoplankton. Light availability is a function of daylength, which affects the overall quantity of light available at the water’s surface, and light attenuation due to the combined effects of color, phytoplankton biomass, and suspended solids, which is assessed through light attenuation coefficients (k_d; Kirk 1994). Non-metric multidimensional scaling assessed the consistency of these influences across months from 1999 to 2017. The ordination was based on i) the mean monthly rainfall in the six basins, ii) mean monthly hours of daylight, iii) mean monthly k_d-values calculated across all stations, and iv) monthly mean water temperatures calculated across all stations. All data were range-standardized [(value – minimum value)/range] prior to analysis.

The results yielded a pattern to guide analyses of trends (Figure 5). The months of June, July, August, and September were the most similar (grouped closest together in the ordination), with generally higher water temperatures, higher monthly rainfall, and longer days (Table 1). Daylengths were shorter, water temperatures were lower, and light attenuation coefficients were generally lower in January, February, November, and December (Table 1). The remaining months, March, April, May, and October, were characterized by transitional values for the parameters of interest (Table 1). Parsing data into these periods prior to evaluating trends in concentrations of total nitrogen, total phosphorus, and chlorophyll will reduce variation or "noise" created by broad-scale drivers that influence the supply and utilization of nutrients. Reducing such noise will improve the likelihood of detecting early warnings of increased nutrient supply and eutrophication.

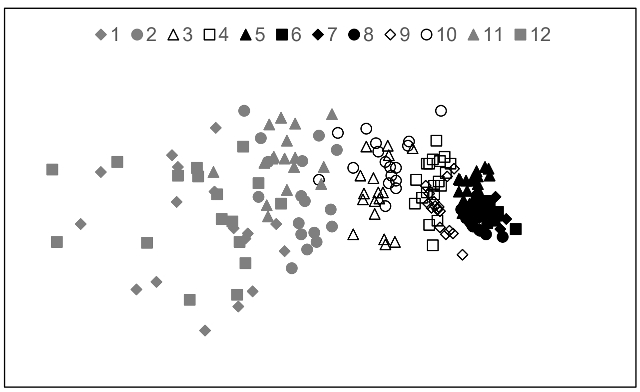

Figure 5. Ordination based on environmental data. gray symbols = January, February, November, and December; white symbols = March, April, May, and October; black symbols = June, July, August, and September

Table 1. Mean values for Temperature = monthly water temperatures (°C) calculated across all stations, Rainfall = monthly rainfall (mm) in the six basins, Daylength = monthly daylength (h), k_d = monthly light attenuation coefficients (m^{-1}) calculated across all stations.

Month	Temperature	Rainfall	Daylength	k_d
1	13.80	94.90	10.55	1.30
2	15.93	93.82	11.15	1.56
3	19.58	101.96	11.93	1.75
4	22.57	83.66	12.78	1.82
5	26.09	79.12	13.50	1.61
6	29.27	192.99	13.85	1.51
7	29.92	180.74	13.70	1.75
8	30.22	204.71	13.08	2.05
9	27.84	148.63	12.27	2.17
10	23.46	56.72	11.42	1.76
11	18.34	54.50	10.72	1.48
12	14.90	83.32	10.37	1.30

For estuarine stations, conditions affecting the production of phytoplankton will differ according to factors such as exposure to freshwater inputs and the residence time of water. Salinity represents a conservative marker of exposure to riverine inputs. In addition, concentrations of nutrients and chlorophyll can vary independently of riverine influences due to other inputs (e.g., submarine groundwater seeps) and differences in biological and biogeochemical processing. Therefore, coherence among estuarine stations within each system was assessed with multivariate ordinations based on monthly salinities and concentrations of nutrients and chlorophyll for the relevant period of record.

Ordinations of range-standardized data for estuarine stations within each system yielded suitable representations in two dimensions as indicated by stress values (Figure 6). Plots highlighted stations that had coherent temporal patterns in salinity and concentrations of nutrients and chlorophyll that were used in analyses of trends (Figure 6, Table 2). The actual locations of stations were considered when choosing groups in the ordinations (Figure 1). The resulting spatial patterns were used to reduce noise when correlating concentrations of nutrients and chlorophyll with time.

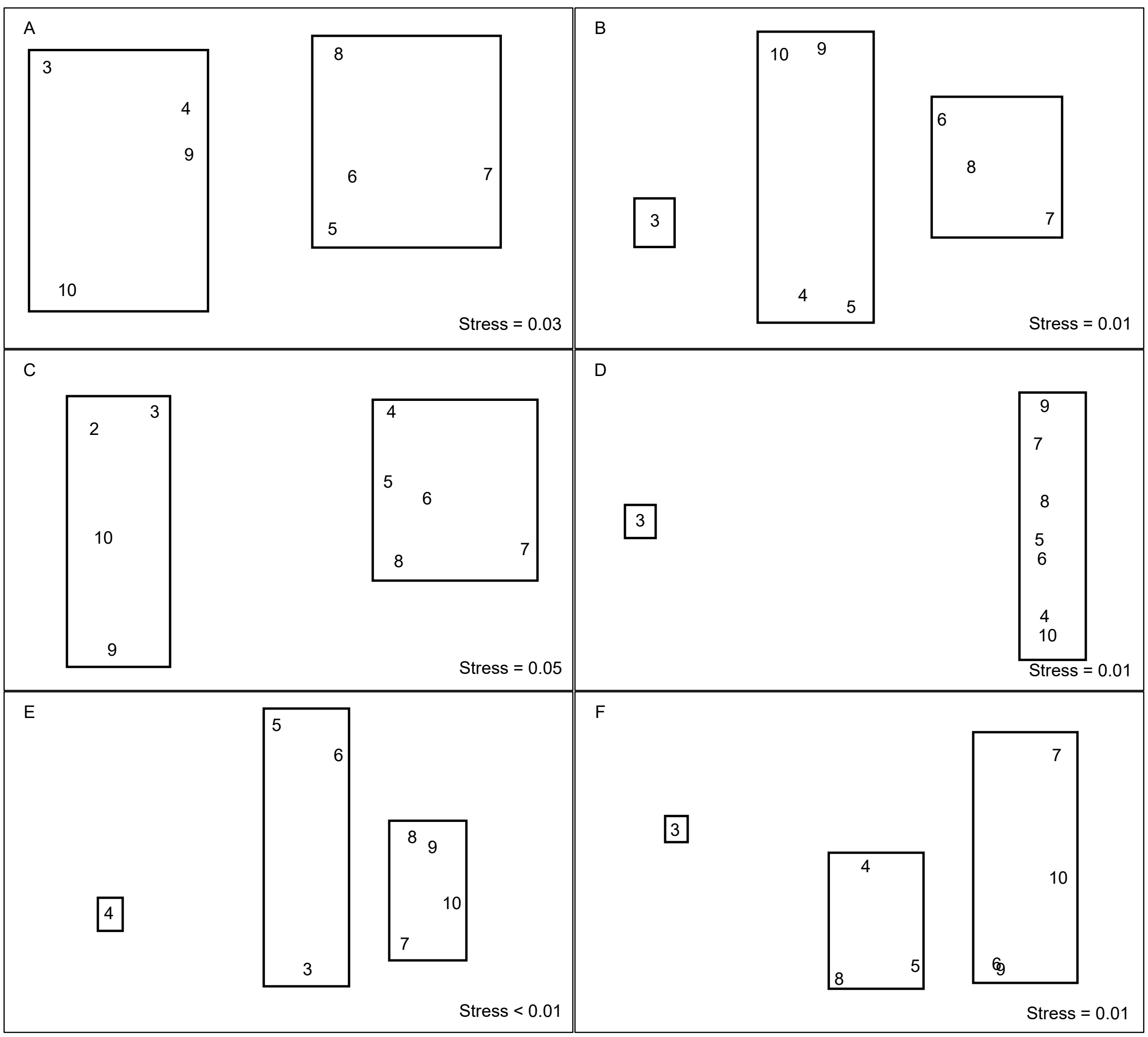

Figure 6. Ordinations for (A) the Aucilla system, (B) the Econfina system, (C) the Fenholloway system, (D) the Steinhatchee system, (E) the Suwannee system, and (F) the Waccasassa system based on salinity and concentrations of total nitrogen, total phosphorus, and chlorophyll.

Table 2. Groups of stations used in correlations.

Group	Aucilla	Econfina	Fenholloway	Steinhatchee	Suwannee	Waccasassa
River	1, 2	1, 2	1	1, 2	1, 2	1, 2
1	3, 4, 9, 10	3	2, 3, 9, 10	3	3, 5, 6	3
2	5, 6, 7, 8	4, 5, 9, 10	4, 5, 6, 7, 8	4, 5, 6, 7, 8, 9, 10	4	4, 5, 8
3		6, 7, 8			7, 8, 9, 10	6, 7, 9, 10

Correlations identified trends in concentrations of total nitrogen, total phosphorus, and chlorophyll across months between January 1999 and October 2017 for riverine and estuarine stations in the six coastal systems. Months were grouped into three classes: i) warm, wet: June, July, August, and September; ii) cool, dry: January, February, November, and December; and iii) transitional: March, April, May, and October. Within these temporal classes, correlations evaluated trends in data from 21 spatial classes comprising individual or groups of stations (Table 2). This approach yielded 189 correlations, with 58 being statistically significant ($p \leq 0.05$). Of these correlations, 30 indicated significant increases and 28 indicated significant decreases through time (Table 3). Overall, the correlations yielded three valuable insights.

Firstly, ~57% of the significant positive correlations related to increasing concentrations of total nitrogen, total phosphorus, or chlorophyll were noted for the Suwannee system (Table 3). Approximately 53% of these correlations indicated increasing concentrations of total nitrogen, and a further 23% indicated increasing concentrations of total phosphorus (e.g., Figure 7). These correlations explained 2% to 18% of the variation in the data.

Secondly, ~86% of the significant negative correlations related to decreasing concentrations occurred in the Aucilla, Econfina, and Fenholloway systems, which had twelve-month periods of record (Table 3). These trends were likely driven by higher rainfall in the first three months of sampling (June 2013 = 235 mm, July 2013 = 358 mm, and August 2013 = 248 mm versus 130 mm average for the other nine months).

Thirdly, only nine of the significant positive correlations related to concentrations of chlorophyll (Table 3). All of these correlations were from the Steinhatchee, Suwannee, or Waccasassa systems.

Table 3. Correlations with time. Auc = Aucilla; Eco = Econfina; Fen = Fenholloway; Stein = Steinhatchee; Suw = Suwannee; Wac = Waccasassa; W = May, June, July, and August; C = January, February, November, and December; T = March, April, September, and October; TN = concentration of total nitrogen; TP = concentration of total phosphorus; Chl = concentration of chlorophyll; italics = p-values; red = significant positive correlation or increasing concentrations; green = significant negative correlation or decreasing concentrations

System	Stations	TN			TP			Chl		
		W	C	T	W	C	T	W	C	T
Auc	1,2	-0.322	0.823	0.096	0.149	-0.181	-0.922	0.056	-0.617	-0.623
		0.436	*0.012*	*0.821*	*0.725*	*0.667*	*0.001*	*0.895*	*0.103*	*0.099*
	3,4,9,10	0.189	0.260	0.495	0.146	0.229	-0.825	-0.268	-0.729	-0.625
		0.484	*0.330*	*0.051*	*0.590*	*0.393*	*<0.001*	*0.316*	*0.001*	*0.010*
	5,6,7,8	0.170	-0.265	0.017	-0.086	-0.056	-0.934	-0.191	-0.673	-0.730
		0.528	*0.322*	*0.951*	*0.752*	*0.838*	*<0.001*	*0.479*	*0.004*	*0.001*
Eco	1,2	-0.452	0.740	0.043	0.087	-0.533	-0.937	-0.059	-0.646	-0.543
		0.261	*0.036*	*0.920*	*0.838*	*0.174*	*0.001*	*0.890*	*0.084*	*0.164*
	3	0.263	-0.832	-0.034	0.187	-0.897	-0.984	-0.115	-0.941	-0.837
		0.737	*0.168*	*0.966*	*0.813*	*0.103*	*0.016*	*0.885*	*0.059*	*0.163*
	4,5,9,10	0.038	-0.847	-0.364	-0.038	-0.890	-0.872	-0.226	-0.850	-0.838
		0.890	*<0.001*	*0.166*	*0.890*	*<0.001*	*<0.001*	*0.400*	*<0.001*	*<0.001*
	6,7,8	-0.011	-0.590	-0.834	-0.132	0.019	-0.840	-0.261	-0.673	-0.772
		0.972	*0.044*	*0.001*	*0.683*	*0.953*	*0.001*	*0.412*	*0.017*	*0.003*
Fen	1	0.898	-0.417	0.050	0.298	-0.955	-0.350	0.474	-0.921	-0.906
		0.102	*0.583*	*0.950*	*0.702*	*0.045*	*0.650*	*0.526*	*0.079*	*0.094*
	2,3,9,10	0.098	-0.185	-0.317	-0.083	-0.113	-0.643	-0.038	-0.711	-0.717
		0.717	*0.492*	*0.231*	*0.760*	*0.678*	*0.007*	*0.889*	*0.002*	*0.002*
	4,5,6,7,8	-0.127	0.084	-0.127	-0.435	0.082	-0.435	-0.678	-0.348	-0.678
		0.592	*0.726*	*0.592*	*0.055*	*0.732*	*0.055*	*0.001*	*0.133*	*0.001*
Stein	1,2	0.147	-0.121	0.056	0.236	0.040	0.197	-0.084	0.090	-0.084
		0.071	*0.141*	*0.486*	*0.003*	*0.624*	*0.014*	*0.305*	*0.273*	*0.303*
	3	0.033	0.114	0.060	0.160	0.118	0.000	-0.018	0.183	0.107
		0.783	*0.351*	*0.621*	*0.187*	*0.335*	*0.998*	*0.885*	*0.132*	*0.374*
	4,5,6,7,8,9	0.095	-0.139	0.027	0.103	-0.054	0.049	0.183	-0.068	0.214
		0.035	*0.003*	*0.558*	*0.022*	*0.247*	*0.286*	*<0.001*	*0.149*	*<0.001*
Suw	1,2	0.426	0.290	0.333	0.246	-0.064	0.030	0.092	0.329	-0.015
		<0.001	*<0.001*	*<0.001*	*0.002*	*0.442*	*0.719*	*0.263*	*<0.001*	*0.858*
	3,5,6	0.140	0.104	0.156	0.149	0.018	0.028	-0.051	0.297	-0.004
		0.043	*0.136*	*0.024*	*0.031*	*0.802*	*0.692*	*0.467*	*<0.001*	*0.952*
	4	0.404	0.323	0.239	0.134	0.138	0.033	0.112	0.027	-0.147
		0.001	*0.007*	*0.046*	*0.274*	*0.259*	*0.788*	*0.360*	*0.826*	*0.225*
	7,8,9,10	0.281	0.110	0.119	0.260	0.134	0.078	0.117	0.156	0.166
		<0.001	*0.070*	*0.053*	*<0.001*	*0.027*	*0.204*	*0.051*	*0.010*	*0.006*
Wac	1,2	0.063	0.120	-0.021	-0.169	-0.115	-0.159	-0.045	-0.039	0.028
		0.444	*0.142*	*0.795*	*0.038*	*0.159*	*0.051*	*0.586*	*0.637*	*0.735*
	3	-0.012	-0.017	-0.208	-0.170	-0.262	-0.161	0.047	-0.066	0.163
		0.919	*0.888*	*0.084*	*0.164*	*0.028*	*0.184*	*0.700*	*0.587*	*0.179*
	4,5,8	0.090	0.155	-0.056	0.024	0.144	0.003	0.041	0.272	0.146
		0.197	*0.024*	*0.417*	*0.730*	*0.037*	*0.967*	*0.560*	*<0.001*	*0.035*
	6,7,9,10	0.019	0.140	-0.024	-0.026	0.199	-0.043	0.011	0.316	0.088
		0.758	*0.019*	*0.692*	*0.662*	*0.001*	*0.474*	*0.854*	*<0.001*	*0.141*

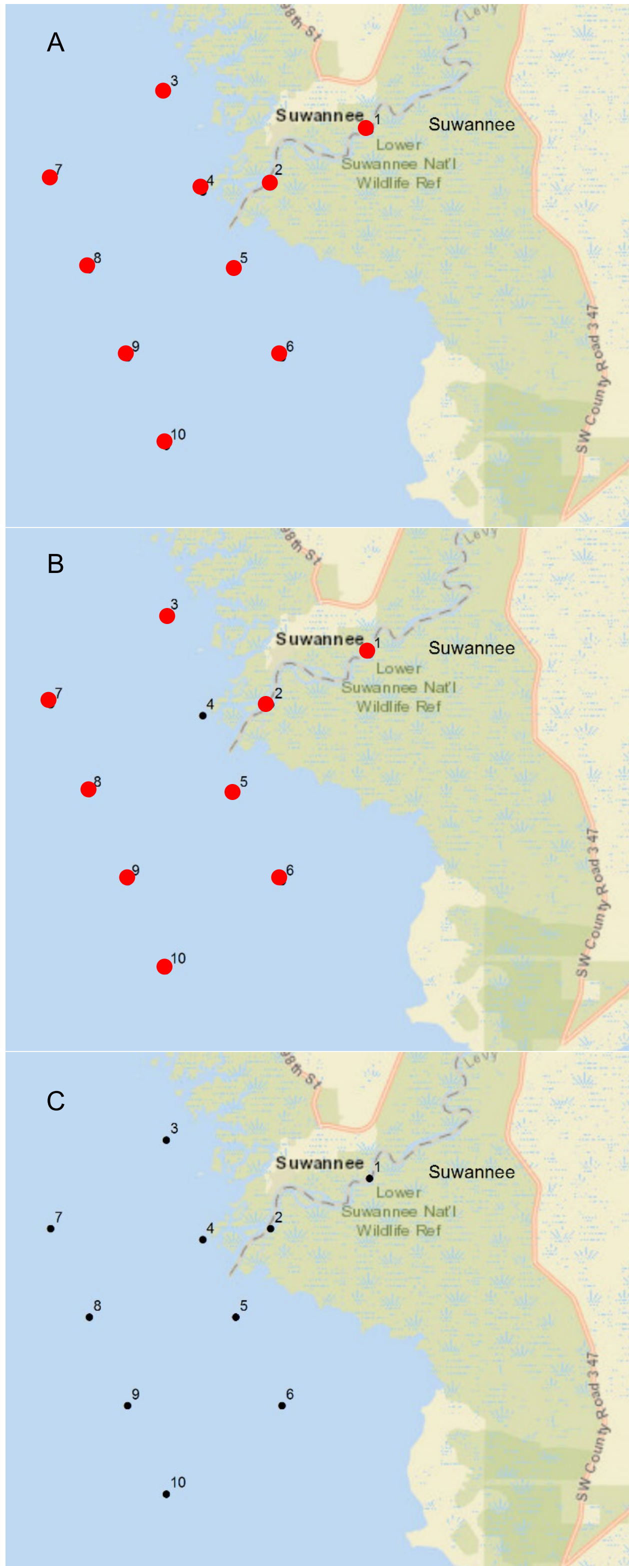

Figure 7. Stations (black dots) and significant positive correlations (red dots) for concentrations of (A) total nitrogen, (B) total phosphorus, and (C) chlorophyll in the Suwannee system during warm, wet periods.

Concluding remarks

The results in this report bear on issues related to sustainable management of Gulf coast waters in the Suwannee River Water Management District. Three parameters yield valuable information on eutrophication, with increasing concentrations of total nitrogen and total phosphorus linked to increasing concentrations of chlorophyll. In addition, the aftermath of an El Niño event highlighted how increased chlorophyll concentrations negatively affect light penetration, as measured with a Secchi disk. Prolonged decreases in light penetration can exceed the physiological tolerances of seagrasses and lead to their loss and a variety of undesirable consequences (Choice et al. 2014). Efforts to differentiate trends from short-term changes and variations in water quality benefited from evaluating i) temporal patterns in rainfall, light availability, and water temperature and ii) the extent of spatial coherence among sampling stations. Spatial coherence yielded "replication" that improved detection of trends.

In terms of trends, the Suwannee River system yielded the strongest evidence of increasing concentrations of total nitrogen, total phosphorus, and chlorophyll. Such trends are being addressed through the total maximum daily load process, with relevant basin management action plans adopted in 2018 (Florida Department of Environmental Protection 2018a, b). Coastal receiving waters act as the ultimate arbiter of successful management of eutrophication, which justifies further sampling.

Insights generated by elucidating spatial and temporal coherence also will contribute to the design of effective and efficient monitoring that can document the success of management and guide responses to unforeseen circumstances. Identifying, differentiating, and sourcing the effects of long-term, anthropogenic loading and short-term responses to climate and weather will require a combination of high-frequency sampling at characteristic stations and less frequent sampling across an array of stations over decades (Enfield et al. 2001, Sutton and Hodson 2005). Interestingly, analyses based on data from every other month yielded four less significant positive correlations for the Suwannee system. Overall, sampling monthly and sampling every other month differed in the number of potential false negatives (not detecting a trend or Type II errors) and false positives (incorrectly identifying a trend or Type I errors). Along with elucidating the causes and effects of increasing or decreasing trends in nutrient and chlorophyll concentrations, evaluating the import of these differences represents a key next step.

Information in the scientific literature combined with this report reinforces managers' concerns regarding increasing nutrient concentrations and eutrophication in systems found in the Suwannee River Water Management District. For example, if high chlorophyll concentrations become persistent and extensive, the resultant shading can cause loss of seagrasses and their associated fauna (Duarte 1991). In fact, seagrasses represent a valuable habitat that integrates the effects of water quality over time; therefore, data on seagrass distribution and abundance would complement sampling of water quality parameters. The absence of such data can compromise both inferences about the effects of deteriorating water quality at the ecosystem level and the design of effective management responses.

This report informs water resource managers of emerging patterns and potentially important issues that can affect decisions about ongoing sampling and auxiliary diagnostic work designed to evaluate, adapt and demonstrate accountability for existing and planned management actions. Clearly, there is a need for an improved quantitative understanding of nutrient loads in coastal waters and sustained monitoring of water quality in a program that is robust enough to detect events and trends that indicate the success or failure of management actions.

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