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Shifting N and P limitation along a north-south gradient of mangrove estuaries in South Florida

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Abstract

A multivariate statistical analysis was applied to a 10 year, multiparameter data set in an effort to describe the spatial dependence and inherent variation of water quality patterns in the mangrove estuaries of Ten Thousand Islands – Whitewater Bay area. Principal component analysis (PCA) of 16 water quality parameters collected monthly resulted in five groupings, which explained 72.5% of the variance of the original variables. The "Organic" component (PC_I) was composed of alkaline phosphatase activity, total organic nitrogen, and total organic carbon; the "Dissolved Inorganic N" component (PC_{II}) contained NO_3^-, NO_2^-, and NH_4^+; the "Phytoplankton" component (PC_{III}) was made up of total phosphorus, chlorophyll *a*, and turbidity; dissolved oxygen and temperature were inversely related (PC_{IV}); and salinity and soluble reactive phosphorus made up PC_V. A cluster analysis of the mean and SD of PC scores resulted in the spatial aggregation of the 47 fixed stations into six classes having similar water quality, which we defined as: Mangrove Rivers, Whitewater Bay, Gulf Islands, Coot Bay, Blackwater River, and Inland Waterway. Marked differences in physical, chemical, and biological characteristics among classes were illustrated by this technique. Comparison of medians and variability of parameters among classes allowed large scale generalizations as to underlying differences in water quality in these regions. A strong south to north gradient in estuaries from high N - low P to low N - high P was ascribed to marked differences in landuse, freshwater input, geomorphology, and sedimentary geology along this tract. The ecological significance of this gradient discussed along with potential effects of future restoration plans.

Introduction

The mangrove estuaries of the Ten Thousand Islands – Whitewater Bay complex (TTI-WWB), located on the SW coast of the Florida peninsula are geomorphologically diverse and have diffuse, and for some, undefined watersheds (Fig. 1). This makes it difficult to study nutrient biogeochemistry using standard schemes of estuarine ecology, i.e., mixing diagrams. Exact sources of freshwater and nutrients are almost impossible to quantify owing to the nonpoint source nature of runoff from the Everglades and Big Cypress Basin.

Most temperate estuaries are N limited (Vitousek & Howarth, 1991) while the upstream freshwater reaches tend to be phosphorus limited (Smith, 1990). In the Everglades, both the freshwater wetlands and the saline estuaries are P limited (Fourqurean et al., 1993; Boyer et al., 1999; Noe et al., 2001). This has led Childers et al. (2006) to call the Shark River an "upside-down estuary", where the coastal Gulf of Mexico, rather than the watershed, is the source of phosphorus (Chen & Twilley, 1999). Therefore, estuaries along the Everglades west coast are unique in their oligotrophic nature and marine supply of the limiting nutrients.

The water quality of these estuaries is of great concern two main reasons. First, the coastal Everglades ecosystem is oligotrophic (as

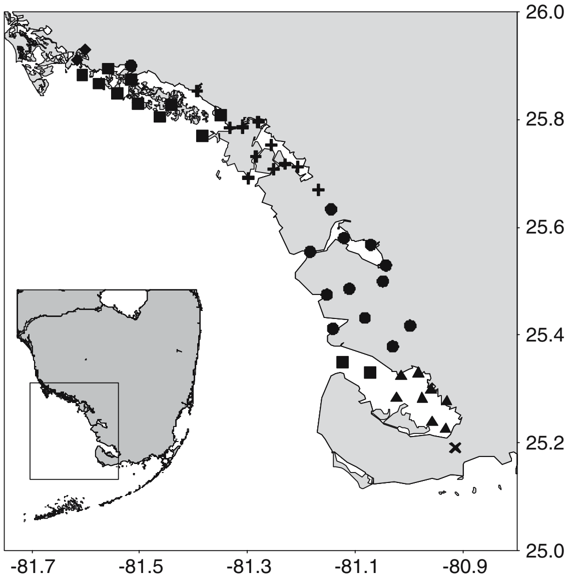

Figure 1. Map of sampling stations in Ten Thousand Islands – Whitewater Bay complex showing distinct water quality zones as a result of cluster analysis of mean and SD of five principal component scores. The zones are: Blackwater River (◆), Gulf Islands (■), Inland Waterway (+), Mangrove Rivers (●), Whitewater Bay (▲), and Coot Bay (×)

to P) which makes it extremely sensitive to anthropogenic stressors. Structural and functional responses of the Everglades to human perturbations are rapid and often quite dramatic. Second, the Everglades ecosystem is the focus of the largest watershed restoration effort ever implemented, the Comprehensive Everglades Restoration Plan (CERP, see http://www.evergladesplan.org/). The goal of this $8 billion, 50-year project is to deliver the right amount of water, of the right quality, to the right places, and at the right time to restore the health of the Everglades and adjacent estuarine and coastal ecosystems. In anticipation of this plan, a water quality-monitoring program was initiated in 1992 to gather baseline data for status and trend analysis (Boyer, 2005).

We have previously found that water quality monitoring programs composed of many sampling stations are often difficult to interpret due to the ''can't see the forest for the trees'' problem (Boyer et al., 2000). For example, the X measured variables for the Y number of sites are typically individually analyzed, independently graphed, and separately summarized in tables to form a massive matrix of isolated data. This approach makes it difficult to see the larger, regional picture or to determine associations among sites. Translating this volume of data into useful information for managers is the crux of what Ward et al. (1986) called the DRIP syndrome (data-rich-but-information-poor). In order to gain a better understanding of the spatial and temporal patterns of water quality of the TTI-WWB complex we wanted to reduce the complicated data matrix into fewer elements.

Multivariate statistical techniques have been useful in reducing data into smaller sets of independent, synthetic variables, which capture much of the original variance. To understand the factors influencing nutrient biogeochemistry in SW Florida estuaries, it was important to be able to objectively group stations according to water quality (i.e., physical, chemical, and biological variables), not by anecdotal information. We previously performed such an objective analysis using principal component analysis (PCA) followed by k-means clustering to characterize the mesoscale variability of Florida Bay (Boyer et al., 1997) and found that stations having similar water quality were the result of a variety of driving forces, including oceanic and freshwater inputs/outputs, sinks, and internal cycling. In this paper, we applied this approach to a 10 year, monthly sampled, multi-parameter data set in an effort to describe the spatial dependence of water quality patterns in the TTI-WWB complex. This allowed us to objectively classify sites into groups with similar water quality for the period of record. The utility of this approach for further spatial and temporal analysis and new hypothesis development are discussed.

Materials and methods

Study area

The Ten Thousand Islands – Whitewater Bay area is located on the SW coast of the Florida peninsula between Cape Sable and Cape Romano (Fig. 1). Whitewater Bay is located on extreme southwest end of the Florida peninsula, enclosed within Cape Sable. It is a brackish water complex draining to the southwest Florida shelf region of the Gulf of

Mexico that exchanges water through several narrow, shallow passes. The watershed for Whitewater Bay is comprised of mangrove-lined streams and rivers originating from the Shark River Slough in the Everglades. Historical evidence indicates that Whitewater Bay was predominately freshwater exchanging water with the Gulf through several narrow, shallow passes (Van Arman, 1984). Under pre-managed conditions, freshwater flowed through Shark River Slough into Whitewater Bay and Shark River, and subsequently affected western Florida Bay via flow around Cape Sable (Fourqurean et al., 1993). The bottom of the embayments in this region is largely calcareous mud, with occasional seagrass beds (Scholl, 1963).

The southern portion of TTI is adjacent to the Everglades and composed of mangrove-lined streams and rivers originating from the Shark River Slough in the Everglades. It is a brackish complex that drains into the SW Florida Shelf region of the Gulf of Mexico (hereafter called Shelf). In this region there are > 60,000 ha of mangrove forest made up of tall trees (up to 25 m); mainly red (*Rhizophora mangle*), black (*Avicennia germinans*) and white (*Laguncularia racemosa*) mangroves (Smith et al., 1994). The mangrove forest is a continuous band that stretches about 15 km inland from the coast. Southern TTI lacks distinctive mangrove islands. This area is also distinctive in that it is marked by many interior bays which are connected to the main rivers by small channels. Northern TTI is adjacent to the Big Cypress Reserve and is composed on numerous mangrove islands, which overlay oyster bars and vermiform reefs. The benthos of this region is largely calcareous mud, with occasional seagrass beds. Oyster bars are common in this area.

Field and analytical methods

A total of 47 stations were originally established within the TTI-WWB complex so as to provide a broad regional characterization of the many rivers and bays in the region (Fig. 1). Stations in WWB were sampled monthly from Oct. 1992 to Aug. 2004; the period of record (POR) for TTI was Sept. 1994–Aug. 2004. Four days were required for each monthly sampling event. The three sites in Shark River also coincide with the Florida Coastal Everglades Long Term Ecological Research program (FCE-LTER). Stations there are equipped with water column autosamplers, recording water level and rain gauges, and temperature, and salinity.

Surface and bottom salinity (practical salinity scale) and temperature (°C) were measured using a combination salinity–conductivity–temperature probe (Orion model 140). Dissolved oxygen (DO, mg l^{-1}) was measured 10 cm below the surface using an oxygen electrode (Orion model 840) corrected for salinity and temperature. DO saturation (DO_{sat} as %) was calculated using the equations of Garcia & Gordon (1992).

Duplicate, unfiltered water samples were collected from 10 cm below the surface-using sample rinsed 150 ml high density polyethylene (HDPE) bottles and kept at ambient temperature in the dark during transport. Duplicate water samples for dissolved nutrient analysis were collected using sample rinsed 150 ml syringes. These samples were filtered by hand through 25 mm GF/F glass fiber filters into sample rinsed 60 ml HDPE bottles, which were capped and immediately placed on ice in the dark for transport. The wet filters, used for chlorophyll *a* (CHLA) analysis, were placed in 1.8 ml plastic centrifuge tubes to which 1.5 ml of 90% acetone was added (Strickland & Parsons, 1972). They were then capped and put into a dark bottle on ice for transport.

Unfiltered water samples were analyzed for total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), alkaline phosphatase activity (APA), and turbidity. TOC was measured by direct injection onto hot platinum catalyst in a Shimadzu TOC-5000 after first acidifying to pH < 2 and purging with CO_2−free air. TN was measured using an ANTEK 7000N Nitrogen Analyzer using O_2 as carrier gas instead of argon to promote complete recovery of the nitrogen in the water samples (Frankovich & Jones, 1998). TP was determined using a dry ashing, acid hydrolysis technique (Solorzano & Sharp, 1980). The APA assay measured the amount of enzymatic activity present in the sample (Hashimoto et al., 1985). The assay was performed by adding a known concentration of an organic phosphate compound (methylfluorescein phosphate) to an unfiltered water sample. Alkaline phosphatase in the water sample cleaved the phosphate, leaving methylfluorescein, a highly fluorescent compound. The fluorescence of initial and 2 h incubations were measured using a Gilford Fluoro IV Spectrofluorometer (excitation = 430 nm, emission = 507 nm) and subtracted to give APA (μM h^{-1}). Turbidity was measured using an HF Scientific model DRT-15C turbidimeter and reported in NTU.

Filtrates were analyzed for soluble reactive phosphorus (SRP), nitrate + nitrite (NO_x), nitrite (NO_2^-), and ammonium (NH_4^+) on a four channel autoanalyzer (Alpkem model RFA 300). Filters for CHLA content (μg l^{-1}) were allowed to extract for a minimum of 2 days at −20 °C before analysis. Extracts were analyzed using a Gilford Fluoro IV Spectrofluorometer (excitation = 435 nm, emission = 667 nm). All analyses were completed within 28 days after collection.

Some parameters were not measured directly, but were calculated by difference. Nitrate (NO_3^-) was calculated as $NO_x^- - NO_2^-$. Dissolved inorganic nitrogen (DIN) was calculated as NO_x + NH_4^+. Total organic nitrogen (TON) was defined as TN−DIN. All concentrations are reported in μM unless noted. All N:P ratios calculated and discussed in this paper are on a molar basis.

Statistical analysis

In order to assess the underlying patterns in the distribution of the measured parameters, we followed the objective analysis procedure of Boyer et al. (1997). Briefly, PCA was used to extract composite variables (principal components) from the original data (Overland & Preisendorfer, 1982). Data were standardized (Z-scores) prior to analysis to reduce artifacts of magnitude. The PCA solution was rotated (using VARIMAX) in order to facilitate the interpretation of the principal components and the factor scores saved for each data record. Both the mean and SD of the factor scores for each station over the POR were then used as independent variables in a cluster analysis (k-means algorithm) in order to aggregate stations into zones of similar water quality. The purpose of this analysis was to collapse the number of stations into a few groups, which could then be analyzed in more detail. Because this procedure required a complete dataset for all stations, data prior to 1994 were excluded from the analysis leaving a 10-year POR. In addition, $Si(OH)_4$ was excluded from the analysis because it was only sampled quarterly.

Once stations were classified, statistical analysis of the water quality among zones was possible (see box-and-whiskers plots, Figs. 2–5). The center horizontal line of the box is the median of the data, the top and bottom of the box are the 25th and 75th percentiles (quartiles), and the ends of the whiskers are the 5th and 95th percentiles. The notch in the box is the 95% confidence interval of the median. When notches between boxes do not overlap, the medians are considered significantly different. The box-and-whisker plot is a powerful statistic as it shows the median, range, distribution of the data as well as serving as a graphical, nonparametric ANOVA. In addition, differences in parameters among classes were quantified using the Kruskall–Wallace test with significance set at $p < 0.05$.

Results

Medians and ranges of data

Medians are reported as the nonparametric statistic of central tendency due to the skewed nature of most water chemistry data (*see* Christian et al., 1991). Large ranges in most measured variables were the norm owing to the wide spatial and temporal sampling plan (Table 1). Overall, the region was warm and brackish, with a median temperature of 26.9 °C and a median salinity of 16.2. The median DO was 5.8 mg l^{-1}, or ~81% of saturation. DIN concentrations were a small fraction of the TN pool (4.8%) with TON making up the bulk. NH_4^+ was the dominant DIN species in almost all of the samples (57% of DIN). SRP concentrations were very low (0.09 μM) and comprised only ~10% of the TP pool (0.81 μM). Median CHLA concentrations were low overall (2.9 μg l^{-1}) but showed a wide range across the area (0.11–45.1 μg l^{-1}). There was a wide range in TOC as well (38.2–5334 μM) with the median being 947 μM. The median TN:TP ratio of 61 suggested a strong P limitation of the water column, but ranged from 10–157 over the POR.

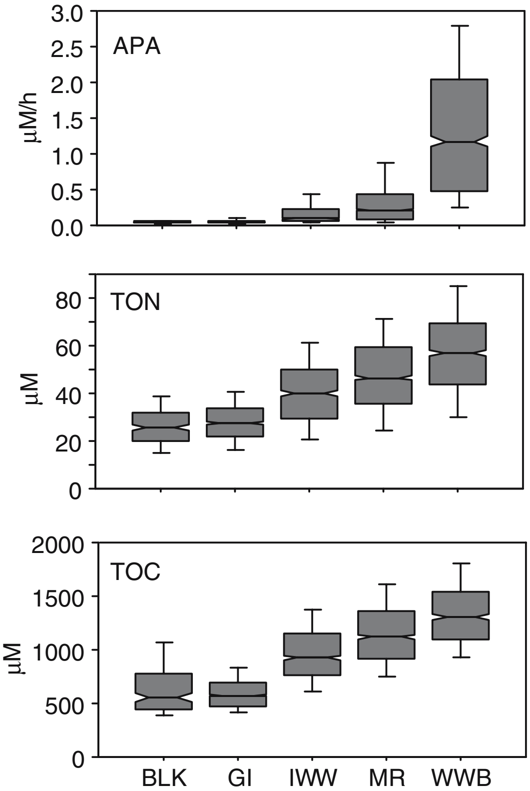

Figure 2. Box-and-whisker plots of PC_I factors: alkaline phosphatase activity (APA; $\mu M\ h^{-1}$), total organic nitrogen (TON; μM), and total organic carbon (TOC; μM) where BLK = Blackwater River, GI = Gulf Islands, IWW = Inland Waterway, MR = Mangrove Rivers, and WWB = Whitewater Bay. The center horizontal line in the box is the median, the top and bottom of the box are the 25th and 75th percentiles (quartiles), and the ends of the whiskers are the 5th and 95th percentiles. The notch is the 95% confidence interval of the median. When notches between boxes do not overlap, the medians are significantly different. Outliers have not been included so as to increase resolution of plot.

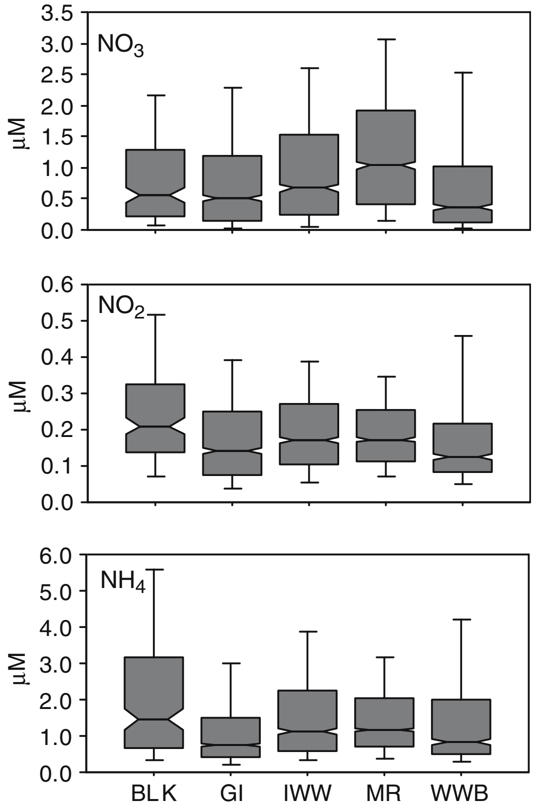

Figure 3. Box-and whisker plots of PC_{II} factors: NO_3^- (μM), NO_2^- (μM), and NH_4^+ (μM) by zone.

Statistical analyses

PCA identified five composite variables (hereafter called PC_I, PC_{II}, etc.) that passed the rule N for significance at $p < 0.05$ (Overland & Preisendorfer, 1982). The factor loadings, as correlations between the original variables and the principal components (Table 2), indicate five separate modes of variation in the data. PC_I had high factor loadings for APA, TON, and TOC and was therefore designated as the "Organic" component. PC_{II} was composed of NO_2^-, NH_4^+, and NO_3^- and was called the "DIN" component. TP, CHLA, and turbidity were highly correlated in the "Phytoplankton" PC_{III} component. PC_{IV} included negatively correlated temperature and DO concentration. Finally, salinity and SRP were included in PC_V. These five principal components accounted for 72.5% of the total variance of the original variables.

The k-means clustering algorithm used the mean and SD of the five factor scores of each station to objectively classified the 47 sampling sites into six groups having robust correspondence in water quality (Fig. 2). The first cluster was composed of 13 stations in and around the Shark, Harney, Broad, and Lostmans Rivers and is called the "Mangrove River" group (MR). This cluster also included a site at the mouth of the Faka Union Canal in northern TTI. The second cluster was made up of the 8 stations enclosed within Whitewater Bay proper (the "Whitewater Bay" group, WB). Twelve stations situated mostly in the coastal islands of TTI-WWB formed the "Gulf Island" zone (GI).

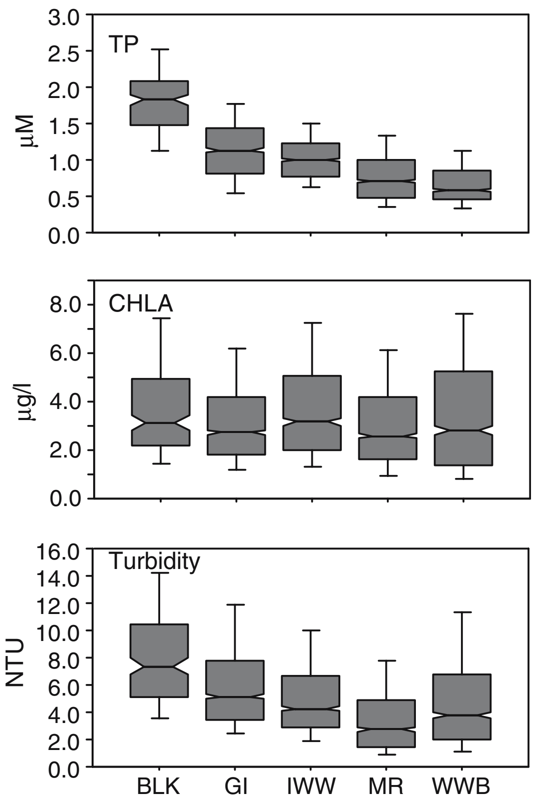

Figure 4. Box-and-whisker plots of PC_{III} factors: total phosphorus (TP; μM), chlorophyll *a* (CHLA; μg l^{-1}), and turbidity (NTU) by zone.

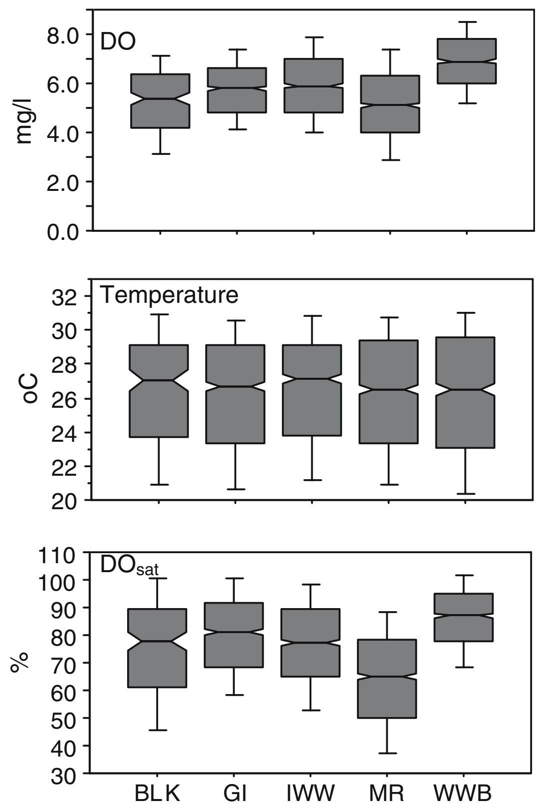

Figure 5. Box-and-whisker plots of PC_{IV} factors: dissolved oxygen (DO; mg l^{-1}), and temperature (°C) as well as DO saturation (DO_{sat}; %) by zone.

Water quality characteristics at the Coot Bay site were sufficiently different so as to be a cluster of its own. Coot Bay is a small, almost completely enclosed bay that once was connected to Florida Bay by the Buttonwood canal dug through the mangroves in 1957 (Tabb et al., 1962). In 1982 the canal was plugged at the Florida Bay end, which effectively isolated it once again from both Whitewater Bay and Florida Bay. Because of its small area and isolated outlier status, Coot Bay will not be included in further discussions. The next cluster contained the northernmost two stations in the Blackwater River estuary (BLK). Finally, the "Inland Waterway" (IWW) class included 11 stations distributed throughout the inside passage as well as the Chatham River and a station off Everglades City.

Water quality characteristics among zones

The "Organic" component (PC_I), composed of APA, TON, and TOC, explained 16.3% of the variance in the original data set (Table 2). The similarity in spatial trend of these 3 parameters among zones is striking (Fig. 2). It is interesting to note the decreasing gradient in these variables with northward direction. It is clear that APA as well as TON and TOC concentrations were highest in Whitewater Bay > Mangrove River > Inland Waterway > Gulf Islands and Blackwater River. These differences among zone were all statistically significant from each other ($p < 0.05$).

The water quality parameters composing the "DIN" component (PC_{II}) included NO_3^-, NO_2^-, and NH_4^+ and explained 16.1% of the total variance (Table 2). Small but significant differences in DIN species among zones were observed (Fig. 3). NO_2^- concentrations were highest in the Blackwater River and Mangrove Rivers (0.22 and 0.20 μM), lowest in Whitewater Bay (0.14 μM) although it had the greatest range (0.01–5.33 μM), with the other zone being intermediate. Median

Table 1. Summary statistics for all measured parameters, 1994–2004

Variable	Median	Min	Max.	*n*
Salinity	16.2	0	42.8	6299
Temperature (°C)	26.9	12.3	38.4	6280
DO (mg l^{-1})	5.8	0.3	24.4	6279
NO_3^- (μM)	0.66	0.01	19.17	6302
NO_2^- (μM)	0.16	0.005	9.94	6302
NH_4^+ (μM)	1.06	0.01	74.68	6302
TON (μM)	36.85	1.51	213.47	6299
TP (μM)	0.81	0.005	4.02	6287
SRP (μM)	0.086	0.001	2.138	6291
APA (μM h^{-1})	0.14	0.03	8.305	6259
CHLA (μg l^{-1})	2.93	0.11	45.11	6300
TOC (μM)	946.9	38.2	5334.0	6281
$Si(OH)_4$ (μM)	59.25	0.10	228.57	1668
Turbidity (NTU)	3.97	0.06	107.81	6299

NH_4^+ concentrations in the Blackwater River and Mangrove Rivers (1.48 and 1.35 μM) were significantly higher than for all other zone. For NO_3^-, the Mangrove Rivers were significantly higher than the other zones (1.19 μM), although Whitewater Bay had the greatest range (0.0–19.7 μM).

TP, CHLA, and turbidity were the three elements which made up the "Phytoplankton" component (PC_{III}) and explained 15.0% of the variance (Table 2). The spatial gradient of the "Phytoplankton" group (Fig. 4), being low in south – high in north, was opposite that of the "Organic" group (Fig. 2). Median TP in the Blackwater River (1.91 μM) was significantly greater than any other zone while the Mangrove Rivers (0.80 μM) and Whitewater Bay (0.62 μM) were the lowest. CHLA concentrations in the Inland Waterway (3.66 μg l^{-1}) and Blackwater River (3.18 μg l^{-1}) were significantly higher than the other zones. Turbidity followed the same pattern as TP, being highest in Blackwater River (9.45 NTU), intermediate in the Gulf Islands (6.68 NTU) and Inland Waterway (5.70 NTU), and lowest in the south in Whitewater Bay (4.45 NTU) and Mangrove Rivers (3.15 NTU).

DO concentrations in Whitewater Bay (6.8 mg l^{-1}) were significantly higher than the other zone (Fig. 5) with the Mangrove Rivers exhibiting the lowest (5.1 mg l^{-1}). Median water temperatures were not significantly different among zones. DO saturation (DO_{sat}; %) followed a slightly different trend than DO (mg l^{-1}), mostly

Table 2. Results of principal component analysis are shown as factor loadings (correlations between the raw variables and the principal components) for the first five principal components after VARIMAX rotation. For clarity, loadings with a magnitude > 0.50 are shown in boldface

Variable	Principal Component				
	PC_I	PC_{II}	PC_{III}	PC_{IV}	PC_V
APA	**0.81**	−0.05	0.12	−0.31	0.12
TON	**0.79**	−0.01	0.02	0.17	−0.34
TOC	**0.70**	0.18	−0.05	0.17	−0.32
NO_2^-	0.06	**0.87**	−0.01	−0.08	0.07
NH_4^+	0.11	**0.77**	−0.01	0.02	0.07
NO_3^-	−0.13	**0.77**	0.01	−0.02	−0.21
TP	−0.17	0.08	**0.84**	0.29	0.12
CHLA	0.19	−0.12	**0.78**	−0.13	−0.18
Turbidity	0.06	0.01	**0.69**	−0.27	0.20
DO	0.16	−0.05	0.09	**−0.89**	0.03
Temperature	0.25	−0.17	−0.01	**0.78**	0.21
Salinity	−0.20	−0.10	0.01	0.07	**0.88**
SRP	−0.35	0.23	0.37	0.22	**0.55**
% Total Variation	16.3	16.1	15.0	13.7	11.4

Cumulative variance explained = 72.5%.

as a function of salinity. DO_{sat} in the Mangrove Rivers (63.1%) was significantly lower than in the Inland Waterway (76.0%), which in turn was lower than the other zone (80–86%).

There were large variations in salinity among the zone and almost all zones were significantly different from each other (Fig. 6). Salinity was highest in Blackwater River (31.7) > Gulf Islands (27.2) > Inland Waterway and Whitewater Bay (10.8 and 10.2) > Mangrove Rivers (3.7). Both the Inland Waterway and Mangrove Rivers had large ranges in salinity (0.0–37.9) as a function of their more estuarine nature. SRP concentrations were low in most of the zones (~0.07 μM) except for the Gulf Islands which was higher (0.30 μM) and the Blackwater River, which was 10 times higher than the other zones (0.73 μM). This northwards increasing gradient in SRP mirrored the TP gradient (Fig. 4).

The median TN:TP ratio of the TTI–WWB complex decreased significantly in a northerly direction along the coast (Fig. 6). Blackwater River had the lowest TN:TP (17.3), increasing to 105 in Whitewater Bay. This gradient in TN:TP ratio was reinforced by both an increase in TON concentration (Fig. 2) as well as the decrease in TP (Fig. 4).

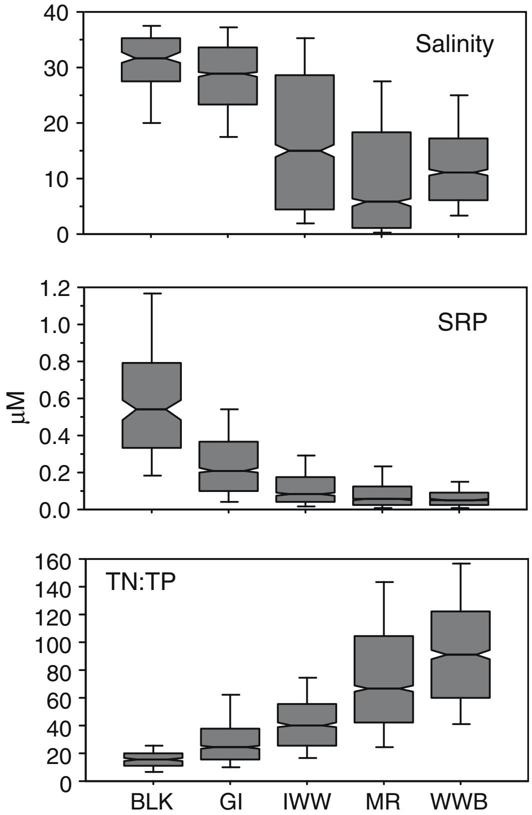

Figure 6. Box-and-whisker plots of PC_V factors: salinity, and soluble reactive phosphorus (SRP; μM). Also includes plot of molar TN:TP ratio by zone.

Discussion

The fundamental goal of monitoring is to provide information, not data. Many past and present monitoring programs are flawed by what Ward et al. (1986) called the "DRIP syndrome" (as being data rich, but information poor). This happens when the act of collecting data becomes an end to itself. One of the purposes of any monitoring program should be to use the data gained by routine sampling to extend our understanding of the system by developing new hypotheses as to the underlying driving processes. This requires analysis, information processing, and reporting of results in a readily usable form, e.g., visualization (Boyer et al., 2000). Significant inference into the behavior of Ten Thousand Islands – Whitewater Bay can be made from the observed magnitude and distribution of water quality parameters when taking this approach.

The process of using PCA in combination with multivariate cluster analysis has been shown to be a useful method of aggregating spatially distributed stations into geographical zones possessing similar water quality characteristics (Boyer et al., 1997; Caccia & Boyer, 2005). Using this approach, the TTI-WWB complex was classified into six distinct zones: Blackwater River, Gulf Islands, Inland Waterway, Mangrove Rivers, Whitewater Bay, and Coot Bay. Marked differences in physical, chemical, and biological characteristics among zones were illustrated by this technique, most strikingly the inverse north-south gradients between N and P. We believe these nutrient gradients are the result of changes in coastal geomorphology and watershed characteristics over this gradient.

Whitewater Bay is a shallow, semi-enclosed body of water with a relatively long residence time (months) which receives diffusive freshwater input from the Everglades marsh and mangrove fringe. Its location at the edge of the P-limited Everglades and its long water residence time explain the presence of very low P concentrations, while the high evaporation rate would tend to concentrate salt and dissolved organic matter (DOM). Since the source of freshwater is similar, it is the long water residence time which affects water quality enough to separate Whitewater Bay from the Mangrove Rivers stations.

The mangrove forests are widest in the south (15 km) but grade to only 4 km wide in the northern TTI; this being a function of elevation, sediment type, and watershed. Estuaries in the Mangrove Rivers cluster are directly influenced by the Shark Slough of the Everglades and therefore have a huge watershed relative to their volume. The terrestrial freshwater inputs to the southern mangroves are orders of magnitude greater than for northern TTI. As such, concentrations of P in incoming waters are very low while DOM inputs are high (Boyer, 2005; Childers et al., 2006). The output of TON and TOC in the southern estuaries is clearly enhanced by the production of organic matter in the mangrove forest (Twilley, 1985; Boto & Wellington, 1988). An interesting anomaly in the cluster is the inclusion of the Faka Union Canal sampling site in the northern TTI (Fig. 1). The reason for this is that the Faka Union Canal drains the Southern Golden Gate Estates, a failed development which built 813 miles of roads and 138 miles of canals during the 1960s to drain the swamps of Collier County in SW Florida. Wet season over-drainage through the Faka Union Canal has resulted in a decline in salinity of 8–12 in Faka Union Bay and has significantly affected fish, oyster, and seagrass communities (Browder et al., 1989; SFWMD, 1994). Because of its unusual hydrology and large watershed, the Faka Union Canal site is more similar to the Mangrove River sites than other sites in northern TTI.

The Inner Waterway is an intermediate zone in all respects; having extensive channelization but lower freshwater input than the Mangrove Rivers to the south. In addition, the exchange with the Gulf of Mexico is diminished because of its small inlets attenuating tidal mixing as well. For these reasons, it falls between the hydrological and nutrient extremes of estuaries south and north. Most of the IW is part of Everglades National Park's Wilderness Waterway, a 99 mile (159 km) backcountry canoeing route that runs along the western edge of Everglades National Park from Flamingo to Everglades City.

The Gulf Island zone has very low freshwater input due to the poorly drained watershed of the Big Cypress Basin. Instead of mangrove river channels there are many mangrove islands set in lower tidal energy environment situated behind the Cape Romano Shoals in the Gulf of Mexico. Water quality here is dominated by that of the Shelf, although small freshwater inputs from land are regular features. A current restoration project consisting of the construction of 87 additional culverts at 30 separate sites under Tamiami Trail will increase watershed connectivity to the estuaries (http://www.evergladesplan.org/pm/projects/docs _30_sgge.cfm). I expect that salinity and therefore, nutrient regimes will change with increased terrestrial flows.

Finally there is the Blackwater River cluster with highest salinity and P. The Blackwater River is about 8 miles long; the flow varies seasonally in accordance with rainfall. There is much agriculture (tomatoes, etc.) in the Blackwater River watershed, which may contribute significant amounts of P to the system via drainage ditches (Ronald L. Miller pers. comm.). This area is also being rapidly developed as low density residences and golf courses. For these reasons, the Blackwater river has been designated as a FDEP 319 h Priority Water Body (http://www.dep.state.fl.us/water/nonpoint/docs/319 h/priority.pdf).

Another important factor in influencing the water quality of the region is the geological setting. Sediments in the southern region are composed of carbonates but change to siliceous quartz sand around Cape Romano (Gleason, 1984). The process of biogenic carbonate formation acts to scavenge P from the water column (Bosence, 1989). Therefore, we would expect the more northern estuaries to be less P limited than in the south.

The hydrology of the region is undergoing large-scale modifications, which will affect almost all of the northern TTI (SFWMD, 1994). It is difficult to predict the extent of the potential management signal from hydrological modifications beforehand. In response, a feasibility study was funded to provide such predictions using performance targets to constrain the restoration efforts (http://www.evergladesplan.org/pm/studies/swfl.cfm). Only time will tell if the Comprehensive Everglades Restoration Program is successful in doing so. To that end, it is vital to continue the monitoring of the region in an effort to provide feedback in water quality trends before, during, and after the restoration is completed.

I believe that this simple, objective approach to spatial analysis of fixed-station monitoring datasets will aid scientists and managers in the interpretation of factors which underlie the observed patterns in water quality. This large-scale view has provided an enhanced understanding of how the Florida Coastal Everglades LTER fits into the overall north to south estuaries gradient of shifting N to P limitation. I also expect that this approach will be useful in focusing attention on specific spatial areas of concern and in generating new ideas for hypothesis driven research.

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