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Spatial patterning of water quality in Biscayne Bay, Florida as a function of land use and water management

Valentina G. Caccia, Joseph N. Boyer *

Southeast Environmental Research Center, Florida International University, University Park, OE 148, Miami, FL 33199, USA

Abstract

An objective classification analysis was performed on a water quality data set from 25 sites collected monthly during 1994–2003. The water quality parameters measured included: TN, TON, DIN, NH_4^+, NO_3^-, NO_2^-, TP, SRP, TN:TP ratio, TOC, DO, CHL A, turbidity, salinity and temperature. Based on this spatial analysis, Biscayne Bay was divided into five zones having similar water quality characteristics. A robust nutrient gradient, driven mostly by dissolved inorganic nitrogen, from alongshore to offshore in the main Bay, was a large determinant in the spatial clustering. Two of these zones (Alongshore and Inshore) were heavily influenced by freshwater input from four canals which drain the South Dade agricultural area, Black Point Landfill, and sewage treatment plant. The North Bay zone, with high turbidity, phytoplankton biomass, total phosphorus, and low DO, was affected by runoff from five canals, the Munisport Landfill, and the urban landscape. The South Bay zone, an embayment surrounded by mangrove wetlands with little urban development, was high in dissolved organic constituents but low in inorganic nutrients. The Main Bay was the area most influenced by water exchange with the Atlantic Ocean and showed the lowest nutrient concentrations. The water quality in Biscayne Bay is therefore highly dependent of the land use and influence from the watershed.

Keywords: Biscayne Bay; Water quality; Nutrients; Estuary; Seasonal variation

1. Introduction

Biscayne Bay is a rectangular shaped, shallow, carbonate estuary, covering an area of approximately 700 km^2. The average depth is approximately 1.8 m with a maximum depth of 4 m, except in dredge areas where depths are reported to exceed 12 m (Roessler et al., 1975). It is located along the southeast coast of Florida, adjacent to the Miami metropolitan area (Fig. 1). As such, it is an important part of the recreational, social, economic, and cultural life of South Florida.

Biscayne Bay has a great ecological importance, supporting an enormous variety of wildlife. It is an excellent habitat for a wide variety of fish, invertebrates, dolphins, manatees, American crocodiles, bald eagles, and many wading birds. The majority of the Bay includes the waters of Biscayne National Park. In 1978, the State of Florida designated Biscayne Bay as an Outstanding Florida Water in recognition of an area worthy of special protection due to its natural attributes, and as such it receives the highest level of protection from degradation. Nevertheless, some parts of the Bay have been significantly affected by past development. Miami began to grow at the beginning of the 20th century, and Biscayne Bay became the site of one of its most important population centers. The Bay has experienced considerable environmental changes due to a century of extensive regional population growth that accelerated coastal and watershed development. Documented changes include periods of hypersalinity, algal blooms, seagrass die-offs, loss of some fish species, localized pollution problems, among others (SFWMD, 1995). These changes have been attributed to extensive urbanization (filling and dredging), agricultural activities and changes in water management practices.

* Corresponding author. Tel.: +1 305 348 4076; fax: +1 305 348 4096.
E-mail address: boyerj@fiu.edu (J.N. Boyer).

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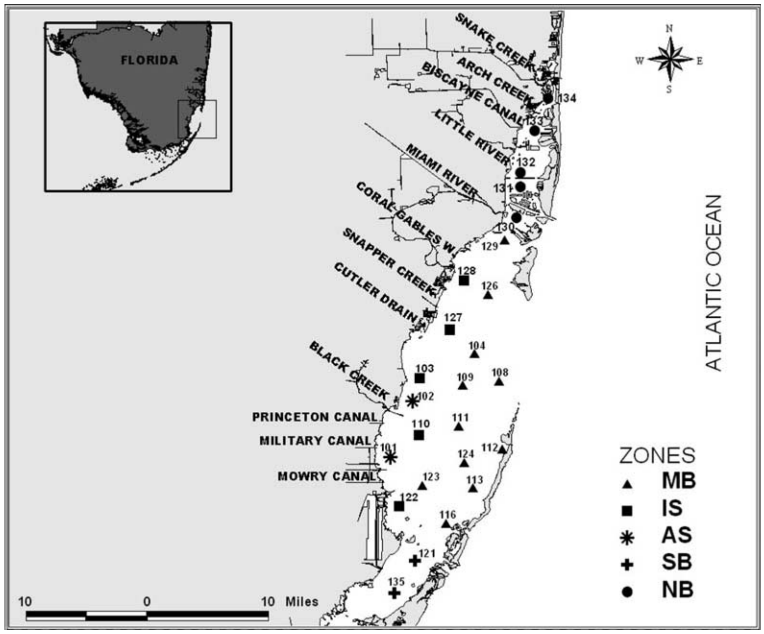

Fig. 1. Map of Biscayne Bay showing cluster assignment (zones) of individual sampling stations and major freshwater canal inputs.

Historically, Biscayne Bay has been divided into three regions separated by both natural and man-made structures. The North Bay extends from Dumfoundling Bay to Rickenbacker causeway; the Central Bay extends from Rickenbacker causeway to Featherbed Bank; and the South Bay extends from Featherbed Bank to Card Sound (Corcoran et al., 1984). The North Bay is heavily urbanized, 40% has been dredged or filled and the entire shoreline is almost completely seawalled (DERM, 1981). This area incorporates industrial complexes, the port of Miami, and the Miami River. The North Bay region suffers from habitat losses, reduced water transparency, toxicant loads such as heavy metals and hydrocarbons, excessive nutrient loading, and sewage pollution and it is in need of restoration rather than preservation (SFWMD, 1995). Turbidity has been identified as a major problem. Most of the original wetlands and a large portion of the original benthic communities were destroyed by dredging and filling activities (Wanless, 1976; Wanless et al., 1984; Harlem, 1979).

Central Bay is characterized as a transition zone from the heavily urbanized north and the lesser developed area to the south. Biscayne National Park boundaries begin in this part of the Bay. Central Bay suffers from influences of the Miami River and urbanization in the watershed of Key Biscayne, Coconut Grove, and Coral Gables. The major apparent impacts to water quality in this area come from localized problems at marinas. The concentrations of vessels in this area has resulted in impacts such as sewage pollution, solid wastes, fuel and oil pollution, metal accumulation, and propeller scouring in adjacent seagrass beds.

South Bay is relatively undeveloped, although several canals draining landfills, urban, and agricultural areas empty into it. This part of the Bay has vast seagrass beds, healthy marine and estuarine communities, and a relatively intact mangrove shoreline. Agricultural land use in Biscayne Bay watershed is concentrated in southern Dade County and in the 1980s these agricultural areas produced 50% of the nation's winter vegetables, covering about 80,000 acres (Howie, 1986). The problems that have been identified in this region include: leachate pollution from the Black Point Landfill, nutrient enrichments from the agricultural runoff; highly polluted sediments (metals, PAHs, PCBs) in Military Canal which serves the Homestead Air Force Base, and unnatural quantities and timing of freshwater releases from canals.

In this paper, we present a comprehensive, long-term study (10 years) of water quality conditions in Biscayne Bay waters. Our principal goals are to: (1) characterize the distribution and concentrations of nitrogen and phosphorus parameters, total organic carbon, chlorophyll *a*, dissolved oxygen, turbidity, temperature and salinity over an annual cycle and (2) address their seasonal patterns, (3) identify the sources of these parameters, and (4) determine the links among them as well as the factors that are affecting their concentrations.

2. Methods

2.1. Field sampling

A total of 25 stations were sampled monthly across Biscayne Bay from January 1994 to December 2003 (Fig. 1). Surface seawater samples were collected and analyzed using standard methodology outlined in the SERC Quality Assurance Plan with prior approval from Florida Department of Environmental Protection (FDEP) and South Florida Water Management District (SFWMD). Salinity (practical salinity scale), temperature (°C) and dissolved oxygen (DO, mg l^{-1}) were measured in situ, 10 cm below the surface and 10 cm above the bottom using a combination sonde (Hydrolab 140). Sondes were calibrated prior to and after sampling to ensure accuracy. Due to the shallow, well mixed nature of the Bay, surface and bottom data were very similar; therefore we used only surface data in this paper. DO saturation (DO_{sat} as %) was calculated using the equations of Garcia and Gordon (1992).

Duplicate, unfiltered water samples were collected from 10 cm below the surface using sample rinsed 150 ml 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* (CHL A) analysis, were placed in 1.8 ml plastic centrifuge tubes to which 1.5 ml of 90% acetone was added (Strickland and Parsons, 1972). They were then capped and put into a dark bottle on ice for transport.

2.2. Laboratory analyses

Unfiltered water samples were analyzed for total nitrogen (TN), total phosphorus (TP), total organic carbon (TOC), alkaline phosphatase activity (APA), and turbidity. 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 and Jones, 1998). The method detection limit (MDL) for TN was 0.05 mg l^{-1}. TP was determined using a dry ashing, acid hydrolysis technique (Solorzano and Sharp, 1980) with a MDL of 0.0006 mg l^{-1}. 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 (MDL = 0.06 mg l^{-1}). The APA assay measures the activity of alkaline phosphatase, an enzyme used by bacteria to mineralize phosphate from organic compounds (Hashimoto et al., 1985). This assay was performed by adding a known concentration of an organic phosphate compound (*o*-methylfluorescein phosphate) to an unfiltered water sample. Alkaline phosphatase in the water sample cleaved the phosphate, leaving *o*-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 nitrate + nitrite (NO_X^-), nitrite (NO_2^-), ammonium (NH_4^+), and soluble reactive phosphorus (SRP), on a four channel autoanalyzer (Alpkem model RFA 300) by flow injection analysis. The nutrient analysis followed the procedure suggested by Alpkem Corporation and modified for optimum conditions in our laboratory. NO_X^- was determined by the quantitative reduction of nitrate (NO_3^-) to NO_2^- using an activated Cd column. NO_2^- was quantified as azo dye formed by the reaction of NO_2^- with sulfanilamide and subsequent coupling with N-1 naphthylethylenediamine. The MDL for NO_x^- and NO_2^- was 0.0014 and 0.0003 mg l^{-1}, respectively. NH_4^+ was quantified by its reaction with alkaline phenol and hypochlorite to form indophenol with Na nitroferricyanide intensification. The MDL for NH_4^+ was 0.0036 mg l^{-1}. SRP was determined by the reaction with molybdenum (IV) and antimony (III) in an acid medium with ascorbic acid reduction. The MDL for SRP was 0.0016 mg l^{-1}.

Filters for CHL A 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) and compared to a standard curve of pure CHLA (Sigma). All analyses were completed within 28 days after collection.

Some parameters were not measured directly, but were calculated by difference. NO_3^- was calculated as $NO_X^- - NO_2^-$. Dissolved inorganic nitrogen (DIN) was calculated as the sum of $NO_X^- + NH_4^+$. Total organic nitrogen (TON) was defined as TN − DIN. Concentrations for all of these water quality parameters are reported in units of milligrams C, N, or P per liter (mg l^{-1}, or ppm) because these are the units used by FDEP and EPA to establish numerical standards. All N:P ratios discussed were calculated on a molar basis.

2.3. Canal flows

Data of freshwater flows at different canals of Biscayne Bay were derived from South Florida Water Management District database. They are reported as monthly means from 1994 to 2003 in cubic feet per second (CFS). We processed these data to obtain the 10 year mean and seasonal means, as South Florida exhibits a markedly seasonal rainfall pattern. The greatest precipitation occurs in the summer, from June to October and was defined as the wet season. The lowest precipitation occurs in the winter, from November to May and was considered as the dry season.

2.4. Statistical analyses

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, principal component analysis (PCA) was used to extract composite variables (principal components) from the original data (Overland and 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 fewer groups, which could then be analyzed in more detail. Because this procedure required a complete dataset for all stations, only data from 1994 to 2003 were used for the analysis.

Once stations were classified, statistical analysis of the water quality among zones was possible (see box-and-whiskers plots, Figs. 4, 6, 8 and 10). 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. Outliers were suppressed to reduce figure compression. 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 $P < 0.05$.

3. Results

3.1. Overall water quality

Large ranges in most measured variables were the norm owing to the wide spatial and temporal sampling plan (Table 1). Medians are reported as the nonparametric statistic of comparison due to the skewed nature of most water quality data (Christian et al., 1991). On average, the region was warm and slightly hyposaline, with a median temperature of 26.5 °C and salinity of 33.5. The median DO was 6.3 mg l^{-1}, or ~92% saturation. Dissolved inorganic N (DIN) concentrations were a small fraction (7.7%) of the TN pool with TON making up the bulk. NH_4^+ and NO_3^- made up 58% and 37% of the DIN pool, respectively. SRP concentrations were very low (median 0.001 mg l^{-1}) and comprised only 12% of the TP pool. CHLA concentrations were low overall, 0.28 μg l^{-1}, but ranged up to 9.2 μg l^{-1}. Ratios of total N to P suggested a overall N limitation of the water column (median TN:TP was 91) However, since most TON is relatively refractory (Boyer et al., 2003), a more realistic ratio of DIN:TP (7.8) showed the system tending toward N limitation.

A comparison of wet vs. dry season water quality showed that all variables but turbidity were significantly affected by the seasonal forcing. Salinity and DO were lower in the wet season while the other parameters are significantly higher ($P < 0.05$).

3.2. Spatial analysis based on water quality

PCA identified four composite variables (hereafter called PC_I, PC_{II}, etc.) that passed the rule N for significance at $P < 0.05$ (Overland and Preisendorfer, 1982). The factor loadings, as correlations between the original variables and the principal components (Table 2), indicated four separate modes of variation in the data. PC_I was composed of NO_3^-, NO_2^-, and NH_4^+, which were inversely related to salinity and was called the "inorganic nitrogen" component. What this told us was that higher concentrations of DIN occurred in lower salinity waters. Both increased precipitation and high canal inputs during the wet season may be important in driving this relationship. PC_{II} showed that DO was negatively correlated with temperature, a relationship based on the physical basis of gas solubility and one which is routinely observed in South Florida estuaries (Boyer et al., 1997). PC_{III} had high factor loadings for TON, APA, and TOC and was therefore des-

Table 1
Summary statistics for all observations for 1994–2003 broken out by season

Variable	Overall			Wet season			Dry season		
	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median
NO_3^-	0.000	1.082	0.007	0.000	1.082	0.013	0.000	0.458	0.005
NO_2^-	0.000	0.060	0.001	0.000	0.060	0.002	0.000	0.032	0.001
NH_4^+	0.000	0.228	0.011	0.000	0.228	0.016	0.000	0.112	0.009
TON	0.000	1.288	0.227	0.000	0.877	0.250	0.020	1.288	0.215
TP	0.000	0.049	0.006	0.001	0.049	0.006	0.000	0.038	0.005
SRP	0.000	0.021	0.001	0.000	0.021	0.001	0.000	0.005	0.001
APA	0.01	3.21	0.13	0.02	2.11	0.17	0.01	3.21	0.11
CHL A	0.00	9.18	0.28	0.04	9.18	0.30	0.00	4.52	0.26
TOC	0.459	11.982	3.261	1.090	11.982	3.614	0.459	9.330	3.052
Salinity	6.21	42.30	33.50	6.21	38.60	32.34	12.80	42.30	33.90
Temperature	10.20	33.30	26.50	22.90	33.30	29.50	10.20	31.00	23.30
DO	2.80	11.60	6.34	2.80	11.30	5.70	3.72	11.60	6.72
Turbidity	0.00	22.35	0.69	0.00	22.35	0.66	0.00	19.00	0.70
DO_{sat}	42.1	161.0	92.0	42.1	156.6	85.5	47.2	161.0	94.9
TN:TP	2.6	1092.7	91.5	5.4	809.2	97.4	2.6	1092.7	88.4
DIN:TP	0.2	575.4	7.8	0.2	575.4	10.7	0.2	258.6	6.3

All concentrations are given in mg l^{-1}, except CHL A given in μg l^{-1}.

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

Variable	Principal component			
	PC_I	PC_{II}	PC_{III}	PC_{IV}
NO_2^-	**0.851**	−0.020	−0.018	−0.011
NO_3^-	**0.877**	0.062	0.045	0.066
NH_4^+	**0.800**	0.215	−0.130	0.014
Salinity	**−0.699**	0.199	−0.330	−0.059
Temperature	0.095	**0.828**	0.194	−0.032
DO	−0.001	**−0.833**	0.205	−0.032
APA	−0.002	−0.014	**0.689**	0.182
TOC	0.338	0.102	**0.657**	−0.014
TON	−0.002	−0.043	**0.734**	−0.061
TP	0.027	0.249	0.071	**0.585**
SRP	−0.022	0.165	0.242	**0.496**
CHL A	0.072	−0.144	0.023	**0.696**
Turbidity	−0.012	−0.265	−0.225	**0.510**
% Variance	27.0	12.9	10.9	9.9

For clarity, loadings with a magnitude > 0.50 are shown in boldface type. The cumulative variance explained was 60.7%.

ignated as the "organic" component. As in Florida Bay (Boyer et al., 1997), APA was not inversely related to SRP concentration as expected, but was related to the dissolved organic matter (DOM) pool. We believe that this may be due to C substrate limitation of bacteria in these systems (unpublished results). TP, SRP, CHLA, and turbidity were highly correlated with the "phytoplankton" PC_{IV} component. This grouping inferred that there was a strong coupling between phytoplankton biomass and *P* availability. It also suggested that some of the CHLA in the water column may have come from sediment resuspension. These four principal components accounted for 60.7% of the total variance of the original variables.

We ran PCA separately on wet and dry season data to see if there was a seasonal effect on the relationships. Dry season PCA memberships were identical to those of the complete data set. The wet season PCA was slightly different in that TP and SRP separated from CHLA and turbidity was put into a distinct category. This implied that during the wet season, phytoplankton biomass was not as tightly coupled with P concentration as it was in the dry season. The differences were small, so we continued to use the combined dataset for cluster analysis.

The *k*-means cluster analysis delineated five groups of stations which had robust similarities in water quality. Based on this analysis, we divided Biscayne Bay in five spatial zones of similar influence (Fig. 1). The Along Shore zone (AS) was composed of two stations closest to the shore located in the south Bay; an area strongly influenced by several canals (Black Creek, Princeton, Military and Mowry Canals). The Inshore zone (IS) was made up of five stations farther from the coast located in the central and south part of the Bay. The Main Bay zone (MB) was composed of 11 stations situated mostly in the central and south part of the Bay; these are the farthest stations from the coast. The North Bay zone (NB) contained five stations located north of the Rickenbacker Causeway. This is a very narrow part of the Bay behind the barrier island of Miami Beach. The NB zone is heavily influenced by inputs from Snake Creek, Arch Creek, Biscayne Canal, Little River, and the Miami River as well as Miami proper and the Port of Miami. The last zone delimited, South Bay (SB), was comprised of two stations located in Card Sound in the southern part of the Bay. This semi-enclosed area is surrounded by mangrove wetlands with little urban development.

3.3. Freshwater flow in the canals

Freshwater flow data was provided by South Florida Water Management District (SFWMD) as a monthly mean for each canal. Table 3 shows the freshwater flow of each canal (CFS) processed as the 10 year annual mean and seasonal means (wet and dry). The Bay was divided in three main areas (North, Central and South) to determine which one received more freshwater inputs from the canals (Fig. 2). North Bay showed the greatest freshwater flow for the last 10 years, followed by the South Bay. The Central area had the lowest freshwater input. North Bay has the freshwater influence from five canals, South Bay receives freshwater from four canals and Central Bay has influence from three canals. The wet season (summer) exhibited the highest freshwater flow in all areas, around 2–3 times higher than in the dry season (winter). Larsen (1995) also found that during the dry season less freshwater

Table 3
The 10 year (1994–2003) annual mean, wet season, and dry season canal inputs (CFS) from the canals in the three zones of Biscayne Bay

	Canal input (CFS)		
	Annual mean	Wet season	Dry season
North Bay			
Snake Creek	335.8	537.3	191.9
Arch Creek	1.4	1.4	1.5
Biscayne Canal	132.5	224.2	66.9
Little River	220.0	306.6	158.2
Miami River Canals	530	535	526
Total	1219.7	1604.5	944.5
Central Bay			
Coral Gables Waterway	15.9	30.6	5.4
Snapper Creek	186.7	316.8	93.8
Cutler Drain	46.1	86.6	19.0
Total	248.7	434.0	118.2
South Bay			
Military Canal	21.9	36.0	11.8
Mowry Canal	231.5	354.9	143.3
Black Creek	223.4	357.1	127.9
Princeton Canal	126.3	187.8	82.4
Total	603.1	935.8	365.4
Grand mean	2071.5	2974.3	1428.1

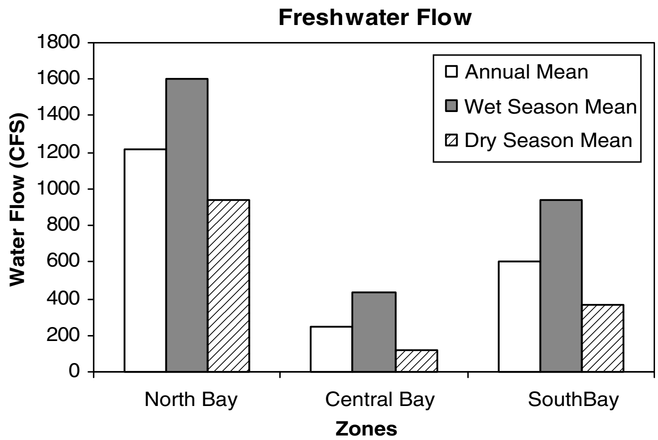

Fig. 2. Total freshwater flow from the canals in the three zones of Biscayne Bay.

reached Biscayne Bay because of the reduced terrestrial storage and lowered groundwater levels.

3.4. Salinity

Salinity showed a strong gradient increasing from the coast to the open Bay (AS > IS > MB) because it is influenced by the seasonal rainfall pattern and the freshwater runoff from the mainland. Fig. 3 shows the salinity distribution for September 2003 (wet season) and February 2002 (dry season) as an example for the two seasons. The increasing gradient from the coast to open Bay is clear in both months. Lower salinities were found in zones (AS, IS and NB) that received freshwater input from canals, and higher salinities were found in areas near to the open ocean (MB and SB). The grand medians ranged from 26.8 (AS) to 35.1 (MB). The seasonal behavior was different among zones. NB zone exhibited the largest seasonal change (3 units) between dry (33.2) and wet seasons (29.9) (Fig. 4). This zone also received the greatest freshwater input all year. Although AS and IS zones also received freshwater from some canals, they did not present significant seasonal differences, their salinity medians changed only 1 unit among seasons. The salinity values in MB and SB zones were not significantly different between seasons.

3.5. Temperature

Temperature in the Bay showed a markedly seasonal pattern, but did not vary among zones (Fig. 4). The grand medians ranged from 26.9 °C at AS to 26.1 °C at NB. Temperatures were lower in the dry season (winter) and higher in the wet season (summer). The difference between seasons was around 6 °C, i.e. difference at AS was 29.8 °C (wet season) vs. 23.5 °C (dry season). The maximum value during the 10 year period was 32.9 °C and the minimum 10.2 °C, both found at AS.

3.6. Nitrogen parameters

A strong gradient in N from the coast to the open Bay (AS > IS > MB) was observed at all times. However, the effect is more dramatic during the wet season when the fresh water input from canals is higher. Fig. 5 shows DIN distribution for September 2003 (wet season) and February 2002

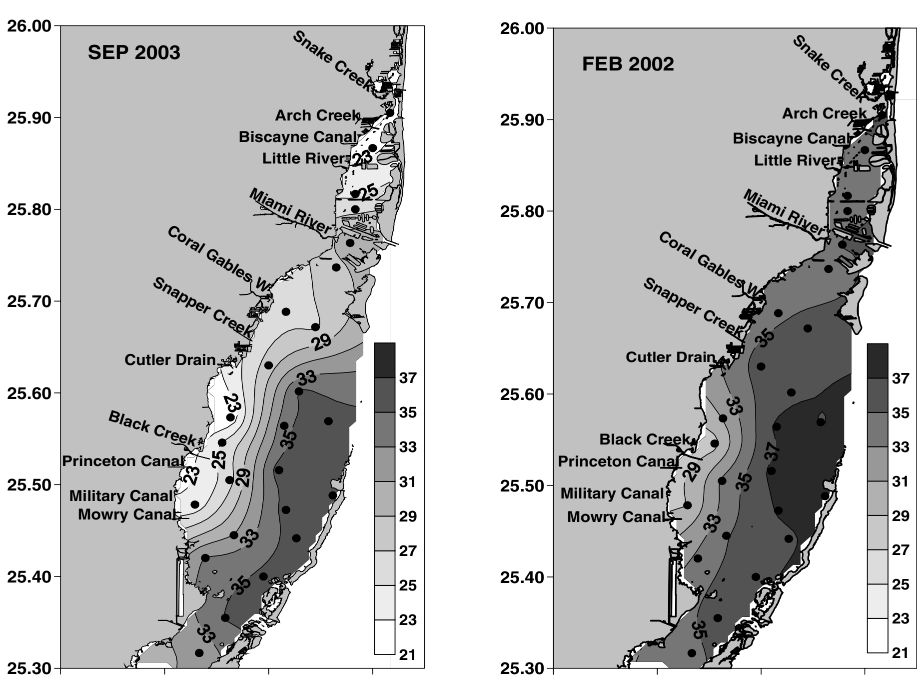

Fig. 3. The distribution of salinity in September 2003 (wet season) and February 2002 (dry season).

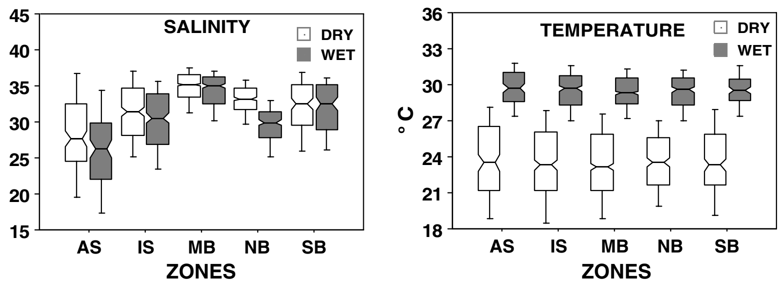

Fig. 4. The wet and dry season medians for salinity and temperature (surface) at different zones of Biscayne Bay.

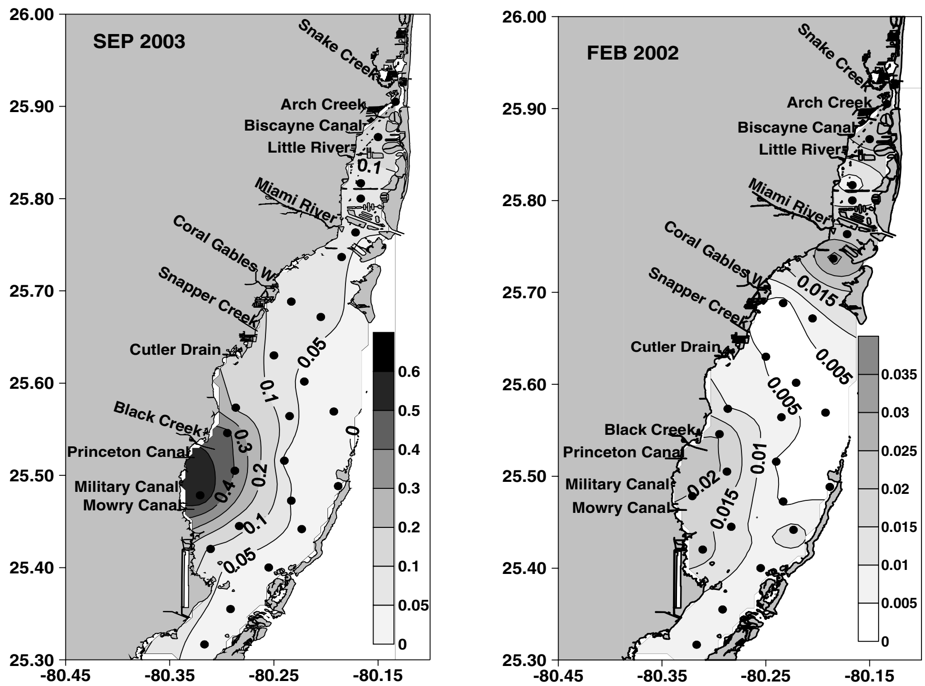

Fig. 5. The distribution of DIN [mg l^{-1}] in September 2003 (wet season) and February 2002 (dry season).

(dry season) as an example of this effect. Also, it is notable that the difference in concentrations was much higher in wet season than dry season. The grand median concentrations for TN ranged from 0.478 mg l^{-1} at AS to 0.221 mg l^{-1} at MB. The Along Shore zone (AS) exhibited the highest concentrations of both organic and inorganic N in both wet and dry seasons, while the MB zone presented the lowest values (Fig. 6). Most of the N in the Bay was found in the organic form (TON). The grand medians for TON ranged from 0.347 mg l^{-1} at AS to 0.199 mg l^{-1} at MB, while the DIN grand medians were from 0.064 mg l^{-1} at AS to 0.016 mg l^{-1} at MB. NO_3^- presented higher concentrations than NO_2^- and NH_4^+, and showed the most pronounced gradient among zones (1 order of magnitude). NH_4^+ varied the least (maximum 2 times). The grand medians were: NO_3^- 0.042 mg l^{-1} (AS) and 0.004 mg l^{-1} (MB), NO_2^- 0.004 mg l^{-1} (AS) and 0.001 mg l^{-1} (MB), and NH_4^+ varied between 0.016 mg l^{-1} (AS) to 0.009 mg l^{-1} (MB). NH_4^+ was also high at NB (0.014 mg l^{-1}) and the same concentration was found at IS and SB (0.012 mg l^{-1}). NB, IS and SB had similar NH_4^+ concentrations, however, for NO_3^-, NB > SB and for TON, SB>NB. This reflected the differences in sources of N along the coast; NB is a much more narrow area surrounded by urban development (higher inorganic N) while SB is an isolated embayment fringed by coastal wetlands (higher organic N).

All nitrogen variables showed their highest concentration in wet season (summer) and their lowest in the dry season (winter) (Fig. 6). Overall, DIN presented larger seasonal changes than the TON. NO_3^- exhibited the largest seasonal change at AS of almost an order of magnitude between dry and wet seasons, 0.013 vs. 0.103 mg l^{-1}, respectively. NH_4^+ in AS also increased during the wet season (~3-fold), while differences in TON were much less.

3.7. Phosphorus parameters

Contrary to N, TP and SRP concentrations showed little difference with distance from land along the offshore gradient. TP concentrations in North Bay were significantly

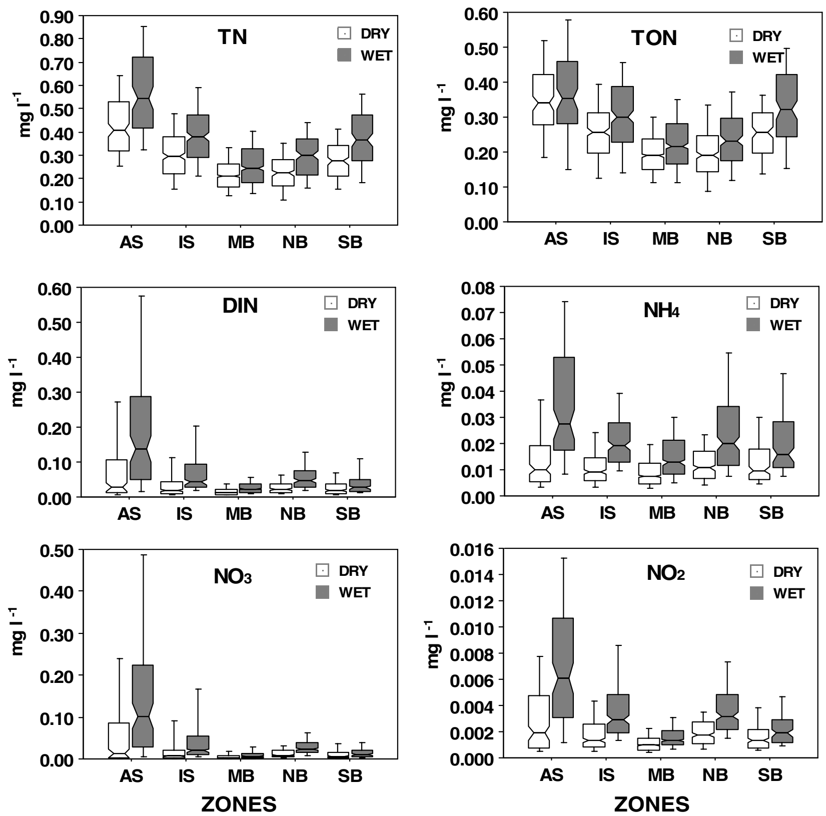

Fig. 6. The wet and dry season medians for nitrogen parameters at different zones of Biscayne Bay.

higher than other regions at all times of the year. Fig. 7 exhibits the distribution of TP in September 2003 as example of the wet season, showing high concentrations at NB and AS zones. The TP grand medians ranged from $0.009\ mg\ l^{-1}$ to $0.005\ mg\ l^{-1}$ (NB > AS > SB > IS > MB). However, SRP levels in NB were not different than those in the rest of the Bay. The highest SRP grand medians were found at AS ($0.001\ mg\ l^{-1}$) and the lowest at MB ($0.0005\ mg\ l^{-1}$) (AS > NB > IS > SB > MB). This means that the SRP concentration in NB was drawn down to similar bay wide levels, irrespective of TP concentration.

Seasonal differences in TP among zones were most pronounced in areas receiving freshwater input from canals, i.e. difference at AS and NB were much greater than those in MB and SB (Fig. 8). Higher concentrations of TP were found during the wet season. The seasonal medians for NB varied from $0.01\ mg\ l^{-1}$ (wet season) to $0.008\ mg\ l^{-1}$ (dry season), while for MB were $0.0052–0.0049\ mg\ l^{-1}$, for wet and dry season respectively. SRP also presented higher values during the wet season, but the seasonal medians were significantly different only for NB and MB zones. The wet season medians for SRP ranged from $0.0012\ mg\ l^{-1}$ (AS) to $0.0006\ mg\ l^{-1}$ at MB. Even though AS zone had the highest concentration for the wet season, but due to the variability of the data, the seasonal medians were not significantly different. The leaching from the landfill and sewage treatment plant (further discussed) may be the cause of this variability. The wet season median for NB

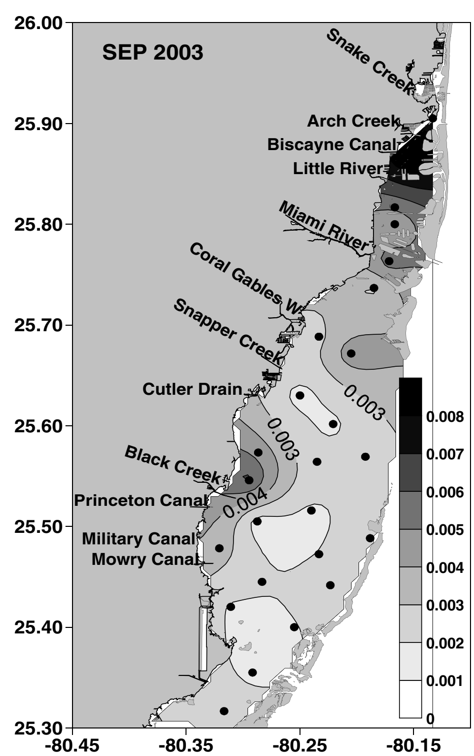

Fig. 7. The distribution of TP [$mg\ l^{-1}$] in September 2003 (wet season).

was also high ($0.0011\ mg\ l^{-1}$) compared with the dry season ($0.0007\ mg\ l^{-1}$), this showed a significant difference.

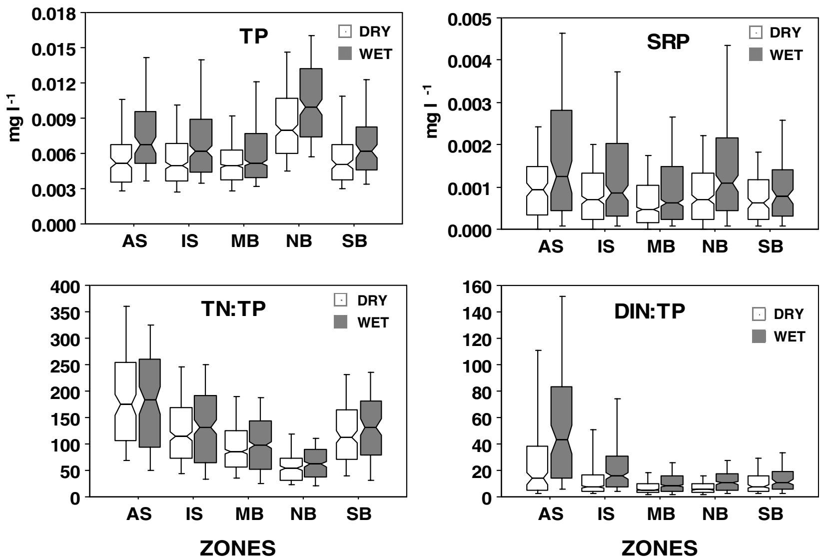

Fig. 8. The wet and dry season medians for phosphorus parameters (concentrations are given in [mg l^{-1}]), TN:TP and DIN:TP molar ratios , at different zones of Biscayne Bay.

3.8. TN:TP and DIN:TP ratios

A gradient from the coast to the open Bay (AS > IS > MB) was observed for both ratios TN:TP and DIN:TP, although the lowest values of TN:TP were found at NB zone during both seasons. The grand median for the TN:TP ratio ranged from 177.9 (AS) to 56 (NB), and for DIN:TP were 21.2 at AS and 6.5 at MB. TN:TP ratio showed a significant difference between seasons only at two zones (IS and MB), while DIN:TP showed a significant seasonal difference for all zones (Fig. 8). The median DIN:TP ratios in the wet season were higher than for the dry season, especially in the AS zone which present the greatest seasonal difference, 43.3 vs. 14, respectively.

3.9. Chlorophyll a

The highest Chlorophyll *a* (CHLA) concentrations were found in the North Bay zone (NB), almost 3 times higher than anywhere else. Fig. 9 shows the distribution of CHLA for September 2003 as an example of this behavior. The grand medians ranged from 0.956 μg l^{-1} at NB to 0.226 μg l^{-1} at MB. In general, the CHLA monthly medians were higher in early spring (February and March) and fall (October and November). The CHLA seasonal medians for AS and IS were slightly higher in the wet season, but there were not significant differences at the rest of the zones (Fig. 10).

3.10. Total organic carbon

A strong decreasing gradient of TOC from the coast to the open Bay (AS > IS > MB) was observed at all times. NB and SB zone also presented high concentrations respect to MB zone. These high concentrations are influence by the loading of the canals located in these zones. The highest grand median of TOC was found at AS (4.67 mg l^{-1}) and the lowest at MB (2.75 mg l^{-1}). The medians of TOC for all zones during the wet season were significantly higher than those found for the dry season (Fig. 10). The AS zone showed the highest medians for both seasons (5.07 mg l^{-1} (wet) and 0.49 mg l^{-1} (dry)), and the MB zone had the

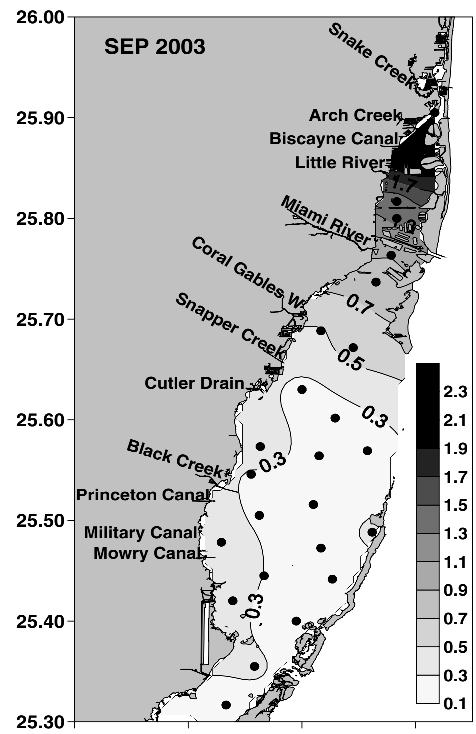

Fig. 9. The distribution of chlorophyll *a* [μg l^{-1}] in September 2003 (wet season).

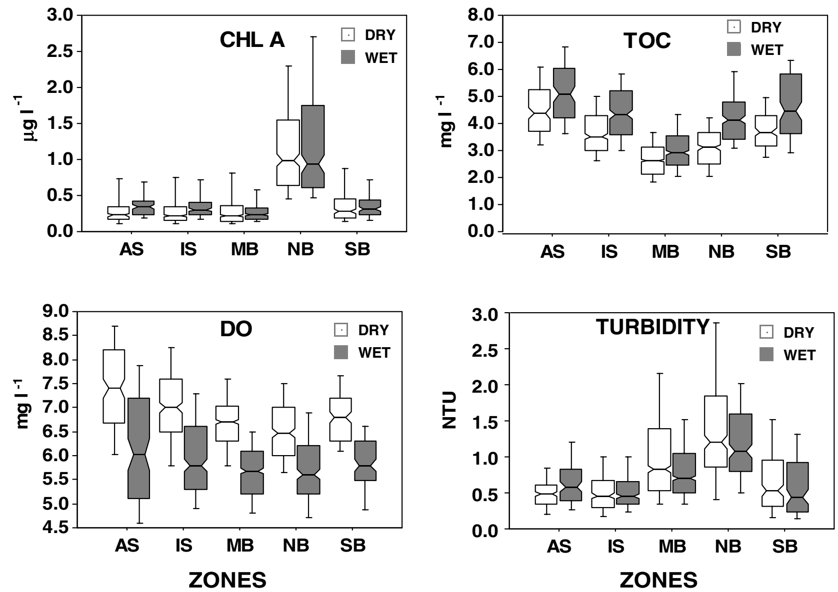

Fig. 10. The wet and dry season medians for CHL A [µg l^{-1}], TOC [mg l^{-1}], DO [mg l^{-1}] and turbidity (NTU) at different zones of Biscayne Bay.

lowest medians for the wet (2.92 mg l^{-1}) and the dry season (2.62 mg l^{-1}).

3.11. Dissolved oxygen

DO annual values showed little difference with distance from land along the AS–IS–MB gradient. DO grand medians were between 6.9 mg l^{-1} at AS and 6.2 mg l^{-1} at NB. The medians for the dry season were significantly higher than the wet season medians for all zones (Fig. 10), around 1 unit of difference. The AS zone exhibit the highest median in the dry season (7.4 mg l^{-1}), while the wet season median was 6 mg l^{-1}. NB zone always showed the lowest concentrations, 6.5 mg l^{-1} for the dry season and 5.6 mg l^{-1} for the wet season. The maximum value found for the 10-year period was 11.6 mg l^{-1} (AS) and the minimum was 2.8 mg l^{-1} (MB).

3.12. Turbidity

Turbidity was higher in the North Bay (NB) than anywhere else in the Bay (Fig. 10). The grand medians were ranged from 1.15 NTU to 0.46 NTU (NB > MB > AS = SB > IS). The seasonal pattern was different among zones, i.e. MB zone had higher turbidity in the dry season (0.84 NTU) than in wet season (0.7 NTU), while AS zone was significantly higher in the wet season (0.59 NTU) than in the dry season (0.49). The rest of the zones did not present any significant seasonality.

4. Discussion

The water quality in Biscayne Bay is highly dependent upon the land use and dependent influences from the watershed such as canals or tributaries, agricultural areas, urban areas, landfills, sewage plants, stormwater runoff, etc. Therefore, the spatial patterning of water quality conditions in the Bay is different among regions (North, Central and South) and zones (NB, MB, AS, IS and SB) due to these local watershed drivers. We observed a strong declining gradient from the coast to the open Bay (AS > IS > MB) for most nutrient variables. After discussing the sources of pollution in each region (Fig. 11), we will

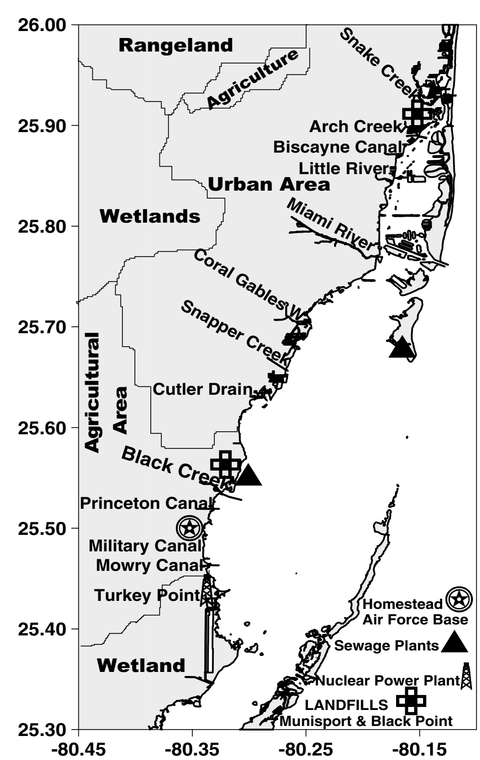

Fig. 11. Land use and sources of pollution in Biscayne Bay.

discuss the influence of the physical factors in the spatial distribution and finally we will discuss the seasonal trends.

4.1. South Bay

The Along Shore (AS) zone composed of the two stations closest to the shore of the South Bay is the area most degraded in terms of water quality. Ten of the fifteen measured parameters showed their highest concentrations in this zone. For the last 10 years, the highest medians of all nitrogen parameters (TN, TON, DIN, NH_4^+, NO_3^- and NO_2^-), SRP, TOC, DO and TN:TP ratio were found in AS. Even though South Bay is less urbanized than the North and Central Bay, the principal sources of N and P are located there. These are: the South Dade agricultural basins, the Black Point Landfill and Sewage Treatment Plant, all drained by Goulds Canal, Black Creek Canal, Princeton Canal, Military Canal and Mowry Canal. Apparently, the trends of high nutrient concentrations in the canals of South Bay have not changed since 1979, because a previous data analysis from 1979 to 1992 (SFWMD, 1995), found that combined NO_3^- and NO_2^- median concentrations were highest in Princeton Canal (3.6 mg l^{-1}), Mowry Canal (1.9 mg l^{-1}), and Goulds Canal (1.3 mg l^{-1}). Highest NH_4^+ concentrations were found in Goulds Canal (0.96 mg l^{-1}). These concentrations are much higher than the ones we found in the Bay near of these canals. Most of all N was found in the organic form (TON) mostly because naturally-occurring organic N from decaying plant remains and cultural organic N from septic tanks and sewage treatment plant effluents are slowly converted to NH_4^+ state by biological degradation.

Agricultural land use in the Biscayne Bay watershed is concentrated in southern Dade County (Fig. 11), and is located on top of the highly porous Biscayne Aquifer. This agricultural land drains through the canals located at the south of Biscayne Bay (Table 3 and Fig. 2). Most of Dade county crops are grown on Rockland soils (oolitic limestone) characterized by low organic content, rapid internal drainage, alkaline pH, and low nutrient content. The lack of sufficient nutrients requires frequent and intensive fertilization (30–45 Lbs $acre^{-1}$ of N and 30–90 Lbs $acre^{-1}$ of P) (DERM, 1978). NO_3^- pollution is by far, the most conspicuous impact of agricultural impacts to water quality. Many authors have found high NO_3^- concentrations in the South Dade groundwater in the area of intensive agricultural activity (Britt, 1994; Church et al., 1980; DERM, 1978). Mowry and Princeton Canals located at the South Bay have had the highest NO_3^- concentrations (3–15 mg l^{-1}) especially at the growing season (March to August) due to the intensive use of fertilizers (DERM, 1978; Scheidt and Flora, 1983).

Landfills create a high potential for stormwater to impact to surrounding water bodies. The study area contains two major landfills: Munisport in the North Bay and Black Point in the South Bay (Fig. 11). Both are located directly on the Biscayne Bay watershed and have been well documented to affect surface waters (SFWMD, 1995). Extensive contamination of wetlands surrounding both landfills demonstrates the impact of this type of land use on surface waters. The high water table and the high transmissivity of the aquifer mean that stormwater can easily mix with ground water and move compounds effectively into surface waters. Munisport has had a history of problems with stormwater runoff into the Bay. This site was not an approved landfill and did not have a proper stormwater system or normal landfill lining precautions. Although the site has been inactive for years, the impacts still have not adequately documented. Records show the site accepted domestic garbage, yard refuse, construction debris, and hospital waste. This site is suspected of impacting surrounding mangrove wetlands within Oleta River State Recreation Area in the North Bay (SFWMD, 1995).

The Black Point landfill is active, and as it continues to enlarge, will pose an even greater threat to the Bay. A large source of NH_4^+ contamination in South Bay is associated with this landfill. Meeder and Boyer (2001) found elevated concentrations of nutrients (especially NH_4^+) and very low DO in the canals adjacent to Black Point landfill (Black Point, Cutler, Goulds, Military and Mowry Canals). The median value of unionized ammonia (NH_3) was 122 ppb which may be toxic to some marine fish. Levels of NH_4^+ in the sediments were an order of magnitude higher than in the water column. They also found a strong correlation between elevated NH_4^+ concentrations and decreased abundance of *Thalassia testudinum* (seagrass) and increased in filamentous algal cover.

Homestead Air Force Base (Fig. 11) has a record of extensive contamination. This site has some of the worst organic contamination of any site within the watershed (SFWMD, 1995). It has contaminated areas that are in the process of being designated for characterization and clean up. Contamination on this base results from fuel containment failures and organic chemical and pesticide storage and usage. DERM has also documented serious heavy metal pollution in the sediments of Military Canal which drains the Base.

4.2. North Bay

The water quality in North Bay is also heavily degraded. Sewage contamination has been a problem in the Bay since early growth of the Miami urban area. Large volumes of raw sewage were discharged directly into canals and Miami River from 1920 to 1955 (McNulty, 1970; Wanless, 1976; Wanless et al., 1984). Our results showed the highest medians of TP, turbidity and CHLA, and the lowest DO in the North Bay Zone (NB). Also, it was the zone that occupied the second place after AS of high concentrations of DIN (NH_4^+, NO_3^- and NO_2^-) and SRP. The North Bay zone has freshwater influence of five canals and it had the highest freshwater flow into the Bay (Table 3 and Fig. 2) for the last 10 years. Snake Creek carries freshwater flow from urban stormwater management systems. The Little River and Miami River have been identified as a conveyance of sewage contamination to North Bay (McNulty, 1970).

North Bay also suffers from absence of natural habitat, because it was one of the first areas to be modified by extensive dredge and fill practices which created many islands for the residential use since the early 1900s. Vast areas of wetlands were filled for development and some of the methods utilized to fill these wetlands have created long-term pollution problems. Phosphorus, aromatic hydrocarbons, and trace metal concentrations tend to be much higher in the tributaries of North Bay as compared to Central or South Bay. DO is chronically low (<4 ppm) in most of the canals. The Dade county standard for NH_4^+ is exceeded frequently in several locations. Violations of state water quality standards for fecal coliform bacteria occur chronically in several tributaries. Stormwater runoff from Munisport landfill and the urban landscape continue to degrade this area of the Bay (SFWMD, 1995).

Historically, Biscayne Bay was a clear, shallow coastal estuary (Wanless, 1976), but Harlem (1979) found an increase in turbidity from 1925 to 1976, as determined from aerial photographs of the Bay during the period. Today, turbidity is a major problem in the northern Biscayne Bay; our results showed almost the double of turbidity at NB than anywhere else and it has been a continued cause of water quality degradation. Unstabilized shorelines were created when spoil was deposited from the construction and maintenance of navigational channels and filling of the Bay to create land. Five primary sources of turbidity have been identified in North Bay as follows: (a) the scouring of unstabilized shorelines by wave action; (b) transport of fine sediments into the Bay through inlets from ocean beach renourishment projects; (c) deep holes and dredged areas that become repositories for sediment fines and high organic content mud; (d) stormwater runoff; and (e) boat propellers stirring up the bottom.

In the update of the surface water improvement and management (SWIM) plan for Biscayne Bay (SFWMD, 1995), the highest concentrations for TP (0.003–0.181 $mg\,l^{-1}$) and CHLA (0.2–1.55 $\mu g\,l^{-1}$) were found at the canals and the stations of northern Biscayne Bay, which is in agreement with our findings. They also observed the highest turbidity and the lowest DO at stations located in the North Bay. We observed that the medians (1994–2003) of TP in NB were almost two times higher; CHLA was three times higher than anywhere else. The high turbidity and high TP in NB is most probably the result of the canals and river runoff and from resuspension of the bottom fine sediments due to the lack of benthic communities in this area.

Wanless (1969) identified eleven bottom types in Biscayne Bay and found that the barren mud bottom with high organic content was predominantly in the North Bay. This type of sediment contains less calcium carbonate than the sediments at the South Bay, and therefore binds less P. Phosphorus is a limiting factor in the central and southern part of the Bay, probably as a result of phosphate being absorbed onto the limestone. Since TP is more available in the water column in the North Bay, CHLA tends to be higher in these waters. Brand (1988) found phytoplankton abundance in the water column to be five times higher in the North Bay than in the Central and South Bay. He also observed large blooms of phytoplankton near the canal mouths and that phytoplankton biomass levels were inversely related to salinity as a result of freshwater runoff. The levels of CHLA that Brand (1988) found in the South Bay (0.2 $\mu g\,l^{-1}$) and in the North Bay (8.6 $\mu g\,l^{-1}$) are very similar to present conditions.

4.3. Central Bay

The Central Bay is characterized as a transition zone from the heavily urbanized North and the nearly pristine South. The majority of the stations grouped as Main Bay Zone (MB) are located in the central and southern part of the Bay. The tributaries or canals that discharge into the Central Bay include the Coral Gables Waterway, Snapper Creek, and Cutler Drain (Fig. 1). These canals presented the lowest freshwater flow for the last 10 years compared with the canals in North and South Bay (Table 3). Our results showed that the lowest concentrations of almost all measured parameters (TN, TON, DIN, NH_4^+, NO_3^-, NO_2^-, TP, SRP, TOC and CHLA) except salinity (highest) were found in MB zone. These stations are less influenced by the canals because the distance from the coast and the low freshwater flow of these canals. Also, MB zone has more water exchanged with the Atlantic Ocean than the rest of the zones. Because the majority of the stations in this zone are the nearest to the open ocean waters, the circulation and water exchange are higher, and water residence time is lower compared with the other zones. These physical factors (explained below) help in the dilution of the water quality variables.

4.4. Physical factors

Besides of the pollution sources discussed above, circulation, flushing, currents, tides and residence time play an important role in the distribution and concentration of nutrients and other parameters in Biscayne Bay. The heterogeneous flow in this shallow estuary results from geomorphology, presence of multiple inlets, and tide phase lag from North to South. Harmonic analysis of water levels indicated that the tidal regime in Biscayne Bay was characterized by decreasing tidal range from North to South (Wang et al., 2003). The average flows are 0.018 $m\,s^{-1}$ and 0.012 $m\,s^{-1}$ toward the South Gables and Turkey Point respectively. The Central Bay has more water exchanged between the Bay and Atlantic (East to West) which drives the lower concentrations at MB, while in the South Bay near to Black Creek, the water flow tends to go south toward Card Sound (Wang et al., 2003), influencing the higher concentrations in AS, IS and SB. Circulation and flushing in Card Sound is restricted since the embayments are impounded by barrier islands. The tidal range is small (22 cm) and the residence time is 2.3 months. This is the result of diversion of historical freshwater flows and artificial impoundments created for bridges and roads (Lee, 1975). All these physical variables have a large influence in the high nutrient concentrations found at SB zone. Computed residence times varied widely from several months in the more enclosed Barnes Sound, to one month in the western parts of South Biscayne Bay, and to near zero in the vicinity of the ocean inlets (Wang et al., 2003).

4.5. Seasonal trends

The seasonal patterns of the measured parameters were modulated by freshwater management practices (freshwater flow of canals), precipitation, evaporation, temperature, and winds. Annual evaporation in the Bay was fairly steady from 1965 to 1995 showing a seasonal variation due to the dependency on wind, temperature, and humidity (Wang et al., 2003). The average annual evaporation rate for the 31 yr period (1965–1995) was 1.66 ± 0.11 m yr^{-1}, with evaporation being highest in summer (wet season) due to higher temperatures. The surface seawater temperature had 6 °C of difference between winter median (~23 °C) and summer median (~29 °C) (Fig. 4). DO in the Bay was lowest in summer because high temperatures reduce oxygen solubility in the water column, and also because respiration rates are higher in this season. The turbidity was higher in winter than in summer (wet season) probably due to wind influence. Winds regimes around the Bay exhibited two typical seasonal patterns: a winter period (dry season) with prevailing stronger winds from the NW, but frequently interrupted by clockwise rotating winds associated with cold front passages; and a summer period with weaker wind speeds, but generally also from the NW (Wang et al., 2003). Salinity was higher in the winter (dry season) in all zones, except at MB (that did not show any seasonality) because it is a well mixed zone exchanging waters with the Atlantic. AS, IS and NB zones has a greater freshwater influence from the canals, and in summer (wet season) these canals discharged 2–3 times more water than in winter (dry season) (Table 3 and Fig. 2). These freshwater flows also influenced greatly in the higher concentrations of all nitrogen and phosphorus parameters, TN:TP, TOC and CHL A (at AS, IS and SB) found for summer (wet season). The mixing of the waters is also low in summer due to the low wind speeds. The water management practices in the canals are strongly depended on the rainfall pattern. The freshwater inputs from canals increase in the wet season, reflecting the high concentrations found for this season.

5. Conclusions

The spatial distribution of water quality in Biscayne Bay is related to terrestrial inputs drained by the canals and the land use. PCA showed an inverse relationship between DIN and salinity. The stations nearest to coast (AS) were more affected by the nutrient loading sources than the ones farthest from the coast (MB). The area most degraded in terms of water quality was the Along Shore zone (AS) showing the highest concentration of TN, TON, DIN, NH_4^+, NO_3^-, NO_2^-, SRP, TOC, DO and TN:TP ratio. AS zone has a freshwater input from four canals (Black Creek, Princeton, Military, and Mowry Canals) which carry nutrients and contaminants from the South Dade agricultural basins, the Black Point landfill, Black Point sewage treatment plant, and the Homestead Air Force Base. The North Bay zone (NB) is also heavily degraded because is the nearest to the Miami urban area and has the greatest freshwater input. This zone showed the highest turbidity, CHLA, TP and the lowest DO. The runoff of five canals, stormwater runoff, the Port of Miami, Munisport landfill and the urban landscape continue to degrade this zone. The healthier or least degraded zone in Biscayne Bay was the Main Bay zone (MB). The stations of this zone are the farthest to the coast and they are located in the central and southern part of the Bay. This zone showed the lowest concentrations of all measured parameters, except salinity. MB zone has more water exchange with the Atlantic Ocean than the rest of the zones. The highest concentrations of all nitrogen and phosphorus parameters, TN:TP ratio, TOC, CHLA (AS, IS), and temperature were observed in the wet season (summer). The highest turbidity, salinity and DO were found in the dry season (winter).

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