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Marine Pollution Bulletin 54 (2007) 994–1008
MARINE POLLUTION BULLETIN
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A nutrient loading budget for Biscayne Bay, Florida

Valentina G. Caccia, Joseph N. Boyer *

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

Abstract

The water quality in Biscayne Bay has been significantly affected by past and continuing coastal and watershed development. The nutrient concentrations in the Bay have been dramatically changed by the conversion of natural creeks and sheet flow freshwater inputs to rapid and episodic canal inputs from the large and rapidly expanding Miami metropolitan area. This study is an evaluation of nutrient loadings to Biscayne Bay for 1994–2002 from canal, atmospheric, and groundwater sources. Dissolved inorganic nitrogen (DIN, as nitrate, nitrite, and ammonium) and total phosphorus (TP) loadings by the canals were influenced by their geographic locations relative to discharge amount, watershed land use, stormwater runoff, and proximity to landfills. Annual budgets showed that canals contributed the bulk of N loading to the bay as 1687.2 metric ton N yr^{-1} (88% total load). Direct atmospheric DIN load for Biscayne Bay was only 231.7 ton N yr^{-1}, based on surface area. Of the canal DIN load, nitrate+nitrite (NO_x^-) loading (1294.5 ton N yr^{-1}) made up a much greater proportion than that of ammonium (NH_4^+, 392.6 ton N yr^{-1}). In the urbanized north and central Bay, canal DIN load was evenly split between NO_x^- and NH_4^+. However, in the south, 95% of the DIN load was in the form of NO_x^-, reflecting the more agricultural land use. Contrary to N, canals contributed the only 66% of P load to the bay (27.5 ton P yr^{-1}). Atmospheric TP load was 14 ton P yr^{-1}. In the north, canal P load dominated the budget while in the south, atmospheric load was almost double canal load. Groundwater inputs, estimated only for the south Bay, represented an important source of N and P in this zone. Groundwater input of N (141 ton N yr^{-1}) was about equal to atmospheric load, while P load (5.9 ton P yr^{-1}) was about equal to canal load.

Keywords: Biscayne Bay; Nutrients; Nutrient loading; Estuary; Atmospheric; Land use

1. Introduction

During the past century, human activities have had a tremendous impact on the global cycling of nutrients in coastal systems. The export of P to the oceans has increased threefold compared to pre-industrial and pre-agricultural levels while the export of N has increased even more dramatically (Caraco, 1995). In many estuaries, anthropogenic sources of N and P now exceed natural inputs of these elements. Population growth and the accompanying increase in per capita resource use has significantly changed the N and P cycle on local, regional, and global scales. Fertilizer production has increased tremendously, from 3 Tg N yr^{-1} in 1950 to 80 Tg N yr^{-1} in 2000 (Galloway, 1998). Over the period 1950–1997, the amount of N emitted into the atmosphere from fossil fuel production increased from 8 to 30 Tg N. In the 1950s to 1960s, N mobilization by fossil fuel combustion was more important than the production of commercial fertilizer. However, in the 1990s, the total amount of N fixed by human activities was about 150 Tg N, of which 80% was due to food production (fertilizer) and 20% was due to energy production (Valigura, 2001).

One of the most rapidly growing sources of N loading is atmospheric deposition. In North America, coastal atmospheric N deposition ranged from 400 to over 1000 mg N m^{-2} yr^{-1}, while in the highly urbanized, industrialized, and intensively farmed regions of Western Europe deposition commonly exceeds 1000 mg N m^{-2} yr^{-1} (Prospero et al., 1996; Holland et al., 1999). It has been estimated that ~1 – >40% of new N inputs into coastal

* Corresponding author. Tel.: +1 305 3484076; fax: +1 305 3484096.
E-mail address: boyerj@fiu.edu (J.N. Boyer).

0025-326X/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2007.02.009

waters are now of atmospheric origin, for example: 10–60% for the Mediterranean Sea (Martin et al., 1989), 40–70% for the North Pacific Ocean (Prospero and Savoie, 1989), 38% in the New York Bight (Hinga et al., 1991), 26% for Sarasota Bay (Sarasota Bay NEP, 1996), and 28% for Tampa Bay (Tampa Bay NEP, 1996).

The relative contribution of atmospheric deposition of N to total external N loading of an estuary depends on land use, watershed area, airshed size, and hydrological and morphological characteristics of receiving waters (Paerl et al., 2001). Concurrently, increases in nutrient inputs have also been linked to increases in population density within coastal watersheds, high rates of fertilizer applications, conversion of forest and prairies to agricultural land, sewage inputs and atmospheric deposition (Turner and Rabalais, 1991; Prado-Fiedler, 1990; Paerl, 1995). Globally, coastal watersheds receive 103 Tg yr^{-1} of N from the combination of synthetic fertilizer (73.6 Tg yr^{-1}), atmospheric deposition (22.5 Tg yr^{-1}), and human sewage (9.1 Tg yr^{-1}). Approximately 20% of the dissolved inorganic nitrogen (DIN) exported by world rivers to the coastal zone (21 Tg N yr^{-1}) is attributed to atmospheric deposition (Seitzinger and Kroeze, 1998), underscoring the importance of this type of deposition to coastal N loading and eutrophication.

Biscayne Bay, a shallow estuary adjacent to the Miami metropolitan area (Fig. 1), has been significantly affected due to a century of extensive regional population growth that accelerated coastal and watershed development (Harlem, 1979; Alleman et al., 1995). Miami began to grow at the beginning of the twentieth century, and Biscayne Bay became the site of one of the most important population centers in Florida. Large changes in the Bay (nutrient enrichment, hypersalinity, algal blooms, seagrass die-offs, toxic pollution (metals, PAHs, PCBs), among others) have resulted from land use changes and the conversion of creeks and sheet flow freshwater inputs to managed canal inputs in the watershed. Water quality of Biscayne Bay has been significantly affected by changes in the quantity, quality, timing, and distribution of freshwater releases from canals, which drain agricultural and urban areas.

This study is a continuation of our previous research on water quality in Biscayne Bay (Caccia and Boyer, 2005), and is a response to the EPA National Strategy for the development of Regional Nutrient Criteria for expanding efforts to reduce nutrient enrichment of US waters. Two states already have plans in place, while the other 48 states are working on developing numeric nutrient criteria for adoption in 2010. Many States including Florida are currently developing specific nutrient criteria for streams, lakes, rivers and canals, estuaries, and coastal zones. Therefore, we hope that the information from this study will prove to be valuable in future restoration and management of Biscayne Bay.

Our previous research focused on characterizing the spatial distribution of the water quality parameters and their seasonal trends in the Bay. We observed that water quality in the Bay is highly dependent of the land use and influences from the watershed, and we also suggested some possible sources. In this study we want to corroborate the influences from the watershed and the sources of nutrients to existing water quality conditions of the Bay, by quantifying the nutrient loading from canals, atmosphere, and groundwater to Biscayne Bay. We also assess the areas of the Bay most affected by these inputs, using historical subdivisions (Corcoran et al., 1984) based on three regions separated by both natural and man-made structures: North, Central and South Bay (Fig. 1).

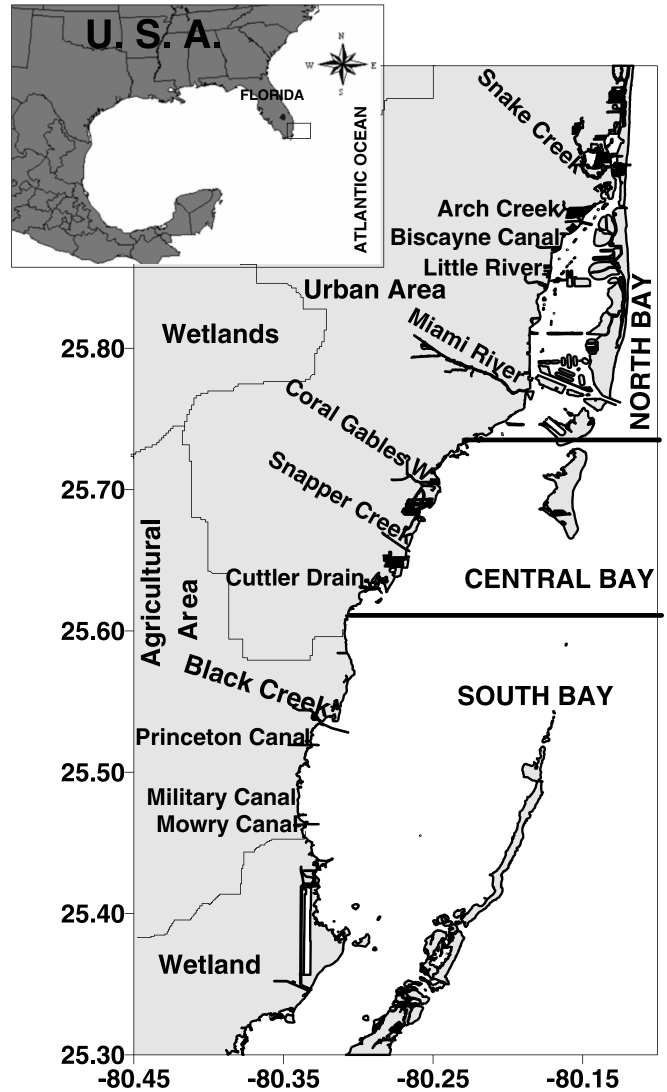

Fig. 1. Map of Biscayne Bay showing location of canals and corresponding land use.

2. Methods

2.1. Site discription

Biscayne Bay is a subtropical, lagoonal estuary located in Miami-Dade and Monroe Counties, on the southeastern coast of Florida (Fig. 1). Biscayne Bay extends approximately 55 miles in a southwesterly direction from Dumfoundling Bay in the north to Barnes Sound in the south. The bay varies from 1 to 10 miles in width and is divided into three major regions: north, central and south. Depths are generally in the range of 0.5–3.0 m with an overall surface area of 700 km^2. Most of Biscayne Bay is bounded by the city of Miami, a sprawing urban region with a population approaching 2 million people. The juxtaposition of such a sensitive resource next to the most densely populated area of the state distinguishes Biscayne Bay from other Florida estuaries.

Major development of the area began in the early 1900s with the construction of artificial navigation inlets. As a result, circulation and salinity patterns in the Bay were altered due to the enhanced exchange of water between the Bay and the Atlantic Ocean. Construction of the major canals through the Everglades and channelization of natural tributaries and transverse glades that carried fresh water to Biscayne Bay lowered the regional and coastal water table, decreased groundwater flow to the bay, and reduced the surface water sheetflow to the bay. This severely reduced the nearshore salinity gradient, which had provided critical estuarine habitat for estuarine species. In addition, delivery of fresh water into the bay changed to being a pulsed, point-source discharge, causing damaging, rapid salinity fluctuations near canal mouths. The unnatural timing, the increased quantity, and the point source nature of these canal discharges disrupt and prevent establishment of viable biological communities. As a result, managers are planning to re-establish estuarine habitat through the Biscayne Bay Coastal Wetlands subcomponent of the Comprehensive Everglades Restoration Project (see http://www.evergladesplan.org/).

For the purposes of this report, the northern portion of Biscayne Bay (about 10% of the total bay area) is defined as that portion of the bay that extends from the Broward/Miami-Dade County line south to the Rickenbacker Causeway. Major tributaries to North Bay include Snake Creek, Arch Creek, Biscayne Canal, Little River, and Miami River. The Miami River is the largest river flowing to Biscayne Bay, and suffers from a history of contamination with industrial runoff and untreated sewage effluent. Stormwater runoff from urbanized uplands has been identified as a source of contamination in discharges from Snake Creek, Arch Creek, Biscayne Canal, Little River, and of course the Miami River.

The central region of Biscayne Bay, the 17 mile section south of Rickenbacker Causeway to Featherbed Banks and Black Point, represents a transition zone between the North and South Bays and includes the Coral Gables Waterway, Snapper Creek and Cutler Drain canals. Tidal exchange with the Atlantic Ocean occurs through a wide series of shoals called the Safety Valve and directly through Bear Cut. Water from Coral Gables Waterway and Snapper Creek is primarily residential stormwater. The portion of central Biscayne Bay that is included in Biscayne National Park generally has the best water quality. Seagrasses and their associated communities along with small areas of soft corals and sponges are prominent in this area.

Southern Biscayne Bay includes the area south of Featherbed Banks through Card and Barnes Sounds. Almost all of this area is incorporated into Biscayne National Park. Southern Biscayne Bay benthic communities include lush seagrass beds, large areas of hard bottom, some soft and hard corals, and other marine life. Ocean exchange occurs though Angelfish, Broad and Ceasar's Creeks. The main canals draining into this area are Black Creek, Princeton, Military, and Mowry canals. Black Creek drains the South Dade Landfill, and the Old South Dade Dump, as well as the Miami/Dade Sewage Treatment Facility. Military and Mowry Canals drain the former Homestead Air Force Base and the South Dade agricultural lands, respectively.

2.2. Canal freshwater flows

The names and locations of the canals entering Biscayne Bay along with their corresponding land use are shown in Fig. 1. Daily freshwater flow in $ft^3\,s^{-1}$ (CFS) at individual canal flow structures were measured by the South Florida Water Management District (SFWMD) and retrieved from their DB-HYDRO database (www.sfwmd.gov/org/ema/dbhydro/). Daily flows were converted to $ft^3\,d^{-1}$ and summed for the month ($ft^3\,mo^{-1}$) and for the year ($ft^3\,yr^{-1}$). Total monthly flows were back calculated to CFS reported as the monthly mean. Annual flows were back calculated to CFS reported as the annual mean. The period of record for this analysis was from January 1994 to December 2002.

2.3. Canal nutrient loads

Canal nutrient data, consisting of monthly grab samples, were gleaned from a database supplied by Miami-Dade Department of Environmental Resource Management (DERM). Water samples were analyzed for $NO_3^- + NO_2^- (NO_x^-)$, ammonium (NH_4^+) and total phosphorus (TP), using EPA methods: 353.2, 350.1 and 365.1, respectively. Dissolved inorganic nitrogen (DIN) was calculated as the sum of $NO_x^- + NH_4^+$. All nutrient concentrations were reported in mg L^{-1} as N or P. Missing nutrient data were rare, but when this occurred we used the mean nutrient concentration for all years in that specific canal for that month. The year 1997 was excluded from our analysis because of the lack of nutrient data for the entire year.

Monthly nutrient loads for each canal were calculated using the following formula using NH_4^+ as an example.

$$\text{Monthly } NH_4^+ \text{ load } (\text{kg mo}^{-1}) = \text{monthly mean flow (CFS)} * 7.438 \times 10^7\ \text{L mo}^{-1}\ \text{CFS}^{-1} * [NH_4^+]$$

Monthly loading estimates ($kg\,mo^{-1}$) were summed to get annual loads in metric tons of N or P per year ($ton\,yr^{-1}$). Some canals or creeks (Arch Creek, Coral

Gables W., Cutler Drain) had negative freshwater flow some months. For these cases, we considered monthly loading to be zero.

2.4. Atmospheric loads

Atmospheric wet deposition of NO_3^- and NH_4^+ in Biscayne Bay (kg N ha^{-1} yr^{-1}) was estimated using monthly data (1994–2002) from the National Atmospheric Deposition Program (NADP, http://nadp.sws.uiuc.edu). This data were collected from one station located in Everglades National Park (FL11, 25.39 Latitude North and −80.68 Longitude West) as it was the nearest site to Biscayne Bay. Precipitation data were obtained from the same source (NADP). Atmospheric TP loading was calculated using the mean wet deposition rate from 1978–1996 of 20 mg P m^{-2} yr^{-1} (0.2 kg P ha^{-1} yr^{-1}; Fitz and Sklar, 1999). Annual deposition average of each parameter was multiplied by estuary surface area (700 km^2 or 70,000 ha) to get annual loads in metric tons per year (ton yr^{-1}).

2.5. Groundwater loads

Data for groundwater flows and nutrient loads were kindly provided by Danielle Mir-Gonzalez as part of her thesis work (unpublished). Groundwater input was measured using seepage meters placed at four sites along four transects of four sites from 50–300 m offshore in South Biscayne Bay. Transects were distributed between Black Point and Turkey Point (Fig. 1). Nutrient concentrations in the groundwater were measured bimonthly during 2003 and loads calculated as g m^{-2} day^{-1}. Annual nearshore loads (out to 300 m) were calculated by extrapolating both along and between transects and reported in ton yr^{-1}.

2.6. Ocean exchange

According to Wang et al. (2003), the bulk of exchange between Biscayne Bay and the Atlantic Ocean occurs through the Safety Valve. Other exchanges at Haulover Cut in the North and Snake and Angelfish Creeks in the South are not significant to the budget. As concentrations of N and P in Biscayne Bay are equal to or greater than ocean levels (Caccia and Boyer, 2005), we expected Biscayne Bay to consistently export both N and P to the ocean. This being the case, we expected that tidal exchange between the two water masses would result in there being no net input of N or P from the ocean, only export. This model is not concerned with sinks in the nutrient budget, only external loads. Therefore, as the ocean is only a sink, we did not include it in the analysis.

3. Results

3.1. Canal freshwater flows

From 1994 to 2002, annual freshwater inputs from canals varied from 1608 to 2551 CFS (4.5–72.2 m^3 s^{-1}), averaging 2086 CFS (59.1 m^3 s^{-1}) over the study period (Table 1). The Miami River presented the highest average flow at 535.5 CFS, and Arch Creek showed the lowest average flow of 1.5 CFS. Arch Creek presented negative flows in 1998 and 2000, meaning that there were no contributions of freshwater to the Bay during those years, and its lowest positive flow occurred in 2001 (0.2 CFS). Cutler Drain also exhibited negative flow in 1995. In both canals, the negative flow was too small (−1.6 CFS) to be significant.

North Bay receives freshwater from five canals (Snake Creek, Arch Creek, Biscayne Canal, Little River and Miami River), South Bay receives freshwater from four canals (Black Creek, Princeton, Military and Mowry canals) and Central Bay has influence from three canals (Coral Gables Waterway, Snapper Creek and Cutler Drain). The North Bay showed the greatest average of freshwater flow (1238 CFS) for all the studied years, followed by the South Bay (599 CFS) and the Central Bay (249 CFS). The Miami River, Snake Creek and Little River delivered 52.6% of the total freshwater contributions into Biscayne Bay. The lowest freshwater flow contribution into the Bay was from Arch Creek (0.1%), while sometimes exhibited negative flows.

Table 1
Annual mean freshwater flow (CFS) at each canal discharge in Biscayne Bay

Year	Snake Creek	Arch Creek	Biscayne Canal	Little River	Miami River	Coral Gables	Snapper Creek	Cutler Drain	Black Creek	Princeton Canal	Military Canal	Mowry Canal	Total flow
1994	409.1	4.0	161.1	166.8	463.4	11.2	229.1	22.3	253.8	129.5	30.4	240.9	2121.6
1995	362.4	3.4	161.5	213.1	570.3	29.7	345.9	−1.5	346.0	162.4	22.9	334.5	2550.7
1996	257.6	1.1	90.8	176.5	469.0	3.1	135.7	18.7	163.1	90.1	14.3	188.3	1608.2
1998	375.4	−1.6	100.2	242.6	621.1	15.0	172.6	100.4	227.5	95.5	14.9	204.1	2167.7
1999	342.3	2.9	154.1	249.0	679.2	29.5	235.1	83.5	210.7	136.4	19.1	225.2	2366.8
2000	311.0	−1.6	145.9	202.0	515.2	15.0	89.4	54.5	125.4	128.1	16.9	206.4	1808.3
2001	343.2	0.2	154.2	255.2	392.5	4.7	140.0	47.2	158.3	133.0	34.1	203.7	1866.4
2002	323.1	3.4	142.9	270.2	573.4	4.3	163.4	46.2	260.6	146.8	34.9	231.1	2200.3
Mean	340.5	1.5	138.9	221.9	535.5	14.1	188.9	46.4	218.2	127.7	23.4	229.3	2086.2
Percent of total	16.3	0.1	6.7	10.6	25.7	0.7	9.1	2.2	10.5	6.1	1.1	11.0	

3.2. Canal nutrient loads

3.2.1. Nitrogen

NO_x^- was the most abundant form of DIN present in the canals (Table 2). Annual NO_x^- loading from Mowry (502.14 ton yr^{-1}) and Princeton (455.45 ton yr^{-1}) canals, situated in the South Bay, accounted for 74% of the total NO_x^- load to the Bay (Fig. 2). The proportional contribution of NO_x^- loading from each canal did not change significantly during the period of record. The Miami River (86.79 ton yr^{-1}), Snake Creek (72.36 ton yr^{-1}) and Little River (49.97 ton yr^{-1}) located in the North Bay accounted for another 16% of the total load. Black Creek has a similar NO_x^- loading (48.16 ton yr^{-1}) as Little River. Arch Creek exhibited the lowest NO_x^- load (0.36 ton yr^{-1}) and in some years was negligible due to negative freshwater flow. Coral Gables W. (4.82 ton yr^{-1}) and Cutler Drain (8.92 ton yr^{-1}) both located in the Central Bay also produced low NO_x^- loadings to the Bay.

Table 2
Annual canal loads of NO_x^-, NH_4^+, DIN, TP (ton yr^{-1}) and DIN:TP (molar) to Biscayne Bay

Year	Total canal load (ton yr^{-1})				
	NO_x^-	NH_4^+	DIN	TP	DIN:TP
1994	1290.2	474.1	1764.3	22.4	174.4
1995	1670.8	514.6	2185.4	27.4	176.6
1996	967.7	285.7	1253.5	15.0	185.2
1997					
1998	1136.7	382.2	1519.0	26.1	128.9
1999	1353.6	444.2	1797.8	26.0	153.2
2000	1177.9	270.8	1448.8	38.6	83.1
2001	1308.0	393.4	1701.5	27.9	135.2
2002	1451.3	376.0	1827.2	36.3	111.5
Mean	1294.5	392.6	1687.2	27.5	143.5
North Bay	235	312	547	18.6	65.1
Central Bay	39	28	67	3.4	43.6
South Bay	1021	52	1073	5.4	440.0

Unlike the South Bay, NH_4^+ was the major form of DIN loading to the North Bay (Table 2). The Miami River (145.1 ton yr^{-1}), Little River (93.7 ton yr^{-1}) and Snake Creek (52.8 ton yr^{-1}) contributed 74% of the total NH_4^+ load to the Bay (Fig. 3). The relative proportion of annual NH_4^+ loading from each canal varied little over time. The lowest NH_4^+ average loadings were found in Arch Creek (0.8 ton yr^{-1}) and Military Canal (1.08 ton yr^{-1}). Arch Creek, Military Canal, Mowry Canal, Princeton Canal, Cutler Drain and Coral Gables Waterway showed lower range (<10 ton yr^{-1}). The highest DIN loading occurred in 1995 (2185 ton yr^{-1}) while 1996 (1253 ton yr^{-1}) was the lowest (Table 2).

3.2.2. Phosphorus

The Miami River (8.37 ton yr^{-1}), Little River (5.1 ton yr^{-1}) and Snake Creek (3.03 ton yr^{-1}) canals located in the North Bay showed the highest annual TP loadings (Fig. 4). These three inputs accounted for 60% of the total TP load to the Bay. Black Point (2.27 ton yr^{-1}) in the South Bay contributed another 8%. The lowest TP

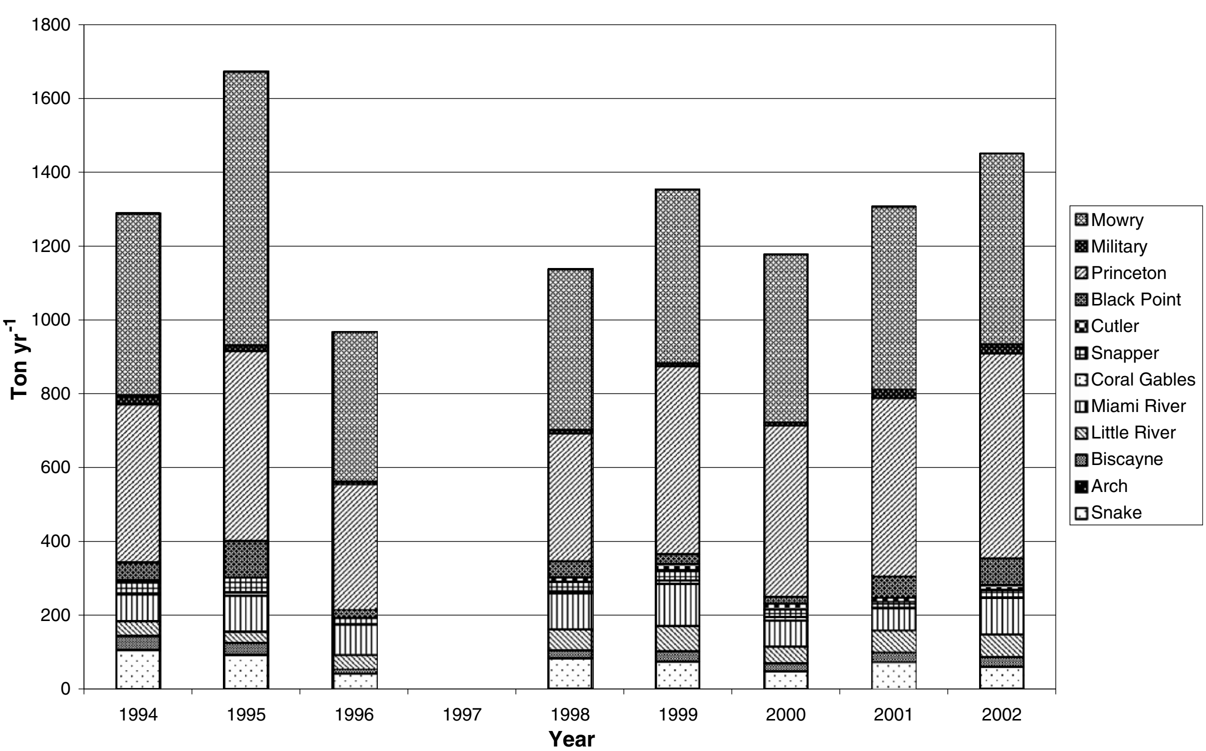

Fig. 2. Contribution of individual canals to annual NO_x^- loading (ton yr^{-1}) to Biscayne Bay over the 9-year period of record.

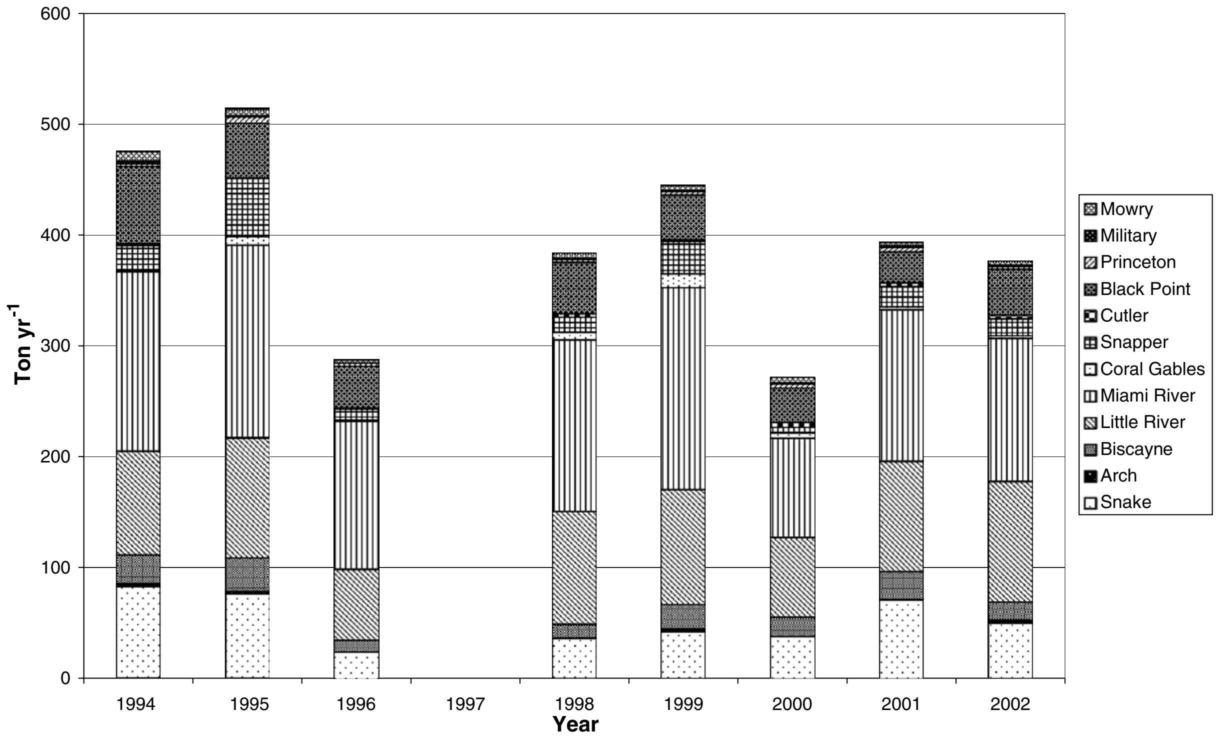

Fig. 3. Contribution of individual canals to annual NH_4^+ loading (ton yr^{-1}) to Biscayne Bay over the 9-year period of record.

loads were delivered by Arch Creek (0.11 ton yr^{-1}), Military Canal (0.19 ton yr^{-1}) and Cutler Drain (0.36 ton yr^{-1}). Highest TP loading occurred in both 2000 (38.6 ton yr^{-1}) and 2002 (36.3 ton yr^{-1}), while 1996 (15 ton yr^{-1}) and 1994 (22.4 ton yr^{-1}) were lowest (Table 2).

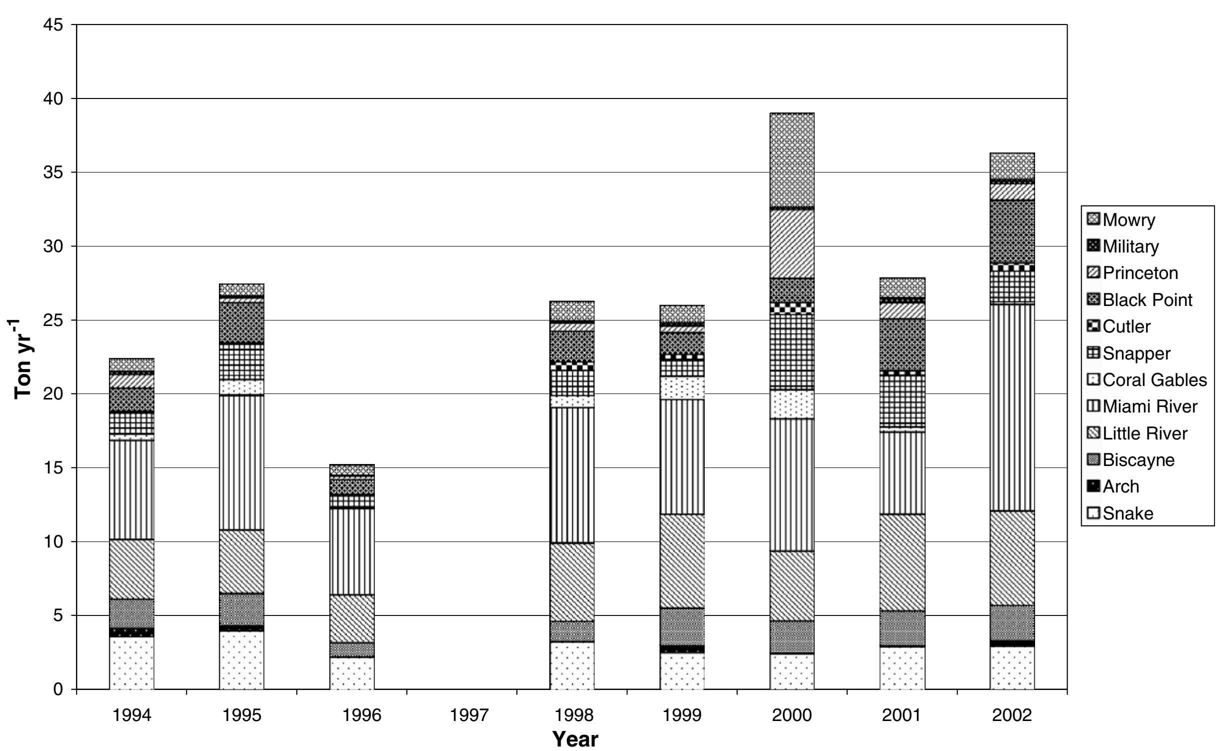

Fig. 4. Contribution of individual canals to annual TP loading (ton yr^{-1}) to Biscayne Bay over the 9-year period of record.

Table 3
Atmospheric deposition (kg N ha^{-1}) in the Everglades National Park Research Center from the National Atmospheric Deposition Program (NADP)

Year	NH_4^+	NO_3^-	DIN
1994	1.73	2.23	3.97
1995	1.45	1.98	3.42
1996	0.95	1.48	2.43
1997	1.43	2.31	3.74
1998	2.18	1.94	4.12
1999	1.13	1.72	2.84
2000	1.02	1.73	2.75
2001	1.23	1.96	3.19
2002	1.39	1.93	3.32
Mean	1.39	1.92	3.31

3.3. Atmospheric loads

3.3.1. Nitrogen

Both NO_3^- and NH_4^+ contributed relatively equal to the inorganic N input from direct precipitation to the Bay (Table 3). NO_3^- input ranged from 1.48 to 2.18 kg ha^{-1} yr^{-1}, averaging 1.92 kg ha^{-1} yr^{-1} (58% of total). On average, the atmospheric NH_4^+ input was 1.39 kg ha^{-1} yr^{-1}. The highest atmospheric N input was observed in 1998 (4.12 kg N ha^{-1} yr^{-1}) and the lowest in 1996 (2.43 kg N ha^{-1} yr^{-1}).

3.3.2. Phosphorus

TP inputs were calculated using a 0.2 kg P ha^{-1} yr^{-1} as a mean wet deposition rate obtained by Fitz and Sklar (1999). This resulted in a total of 14 ton yr^{-1} of direct deposition to Biscayne Bay (700 km^2). By dividing the Bay into sections we calculated that North Bay (140 km^2) received 2.8 ton yr^{-1}, Central Bay (155 km^2) 3.1 ton yr^{-1}, and South Bay (405 km^2) 8.1 ton yr^{-1}.

3.4. Groundwater loads

Groundwater nutrient loading estimates were the most incomplete (portion of South Bay only) and are used here only for comparative purposes. Groundwater DIN inputs to South Biscayne Bay between Black Point and Turkey Point was 141 ton yr^{-1}. Of that, 109 ton yr^{-1} was in the form of NH_4^+. TP load from groundwater was estimated to be 5.9 ton yr^{-1}.

4. Discussion

Nutrient loading to Biscayne Bay was budgeted using only three compartments: canal freshwater inputs, atmospheric wet precipitation, and groundwater. Other internal sources and sinks, such as N_2 fixation, denitrification, and burial were not included, mostly because very little is known about any of these processes in Biscayne Bay. Capone and Taylor (1980) measured N_2 fixation associated with Thalassia sp. roots and found that "annual rates of N_2 fixation were 10–50 kg N ha^{-1}, taking into account seasonal variations and activities to a depth of 20 cm." If we assume that these rates apply all seagrass areas (~40% coverage), we might expect N_2 fixation to add 280–1400 ton N yr^{-1}. However, it generally accepted that acetylene reduction rates seriously overestimate N_2 fixation estimates and we would, therefore, need to revise these estimates down.

Also not included in the budget was the exchange at the ocean boundary; the reason being that the tidal inputs were of low nutrient concentration and probably overwhelmed by tidal output concentrations. The major point of the study was to determine the relative contributions of the different nutrient sources in an effort to propose future management strategies and predict their effectiveness in reducing such loads.

4.1. Canal freshwater flows

Annual variability in flows was a result of both climate and management activities. Although SFWMD has the ability to modify water delivery schedules, much of the interannual variability was due to climactic conditions. Annual precipitation accounted for only half of the variability in annual flow (Fig. 5). Highest precipitation occurred during El Niño-Southern Oscillation (ENSO) years: 1994–1995, 1997–1998, and 2002. Flows were not so highly correlated with ENSO because of another climatic factor – hurricanes. Although 1999 was a La Niña year (typically dry), the passage of Hurricane Irene dropped 25–65 cm of rain during its passage in August. Summer water management strategy is to routinely open the canal gates to draw down the water table in preparation to hurricane season. These large releases may have significant impacts on nearshore salinity and nutrient concentrations (Caccia and Boyer, 2005).

Monthly precipitation for the region (Fig. 6a) is temporally decoupled from monthly flows (Fig. 6b). Wet season rainfall occurs in May but canal flows held back until June. Conversely, precipitation drops off rapidly by November

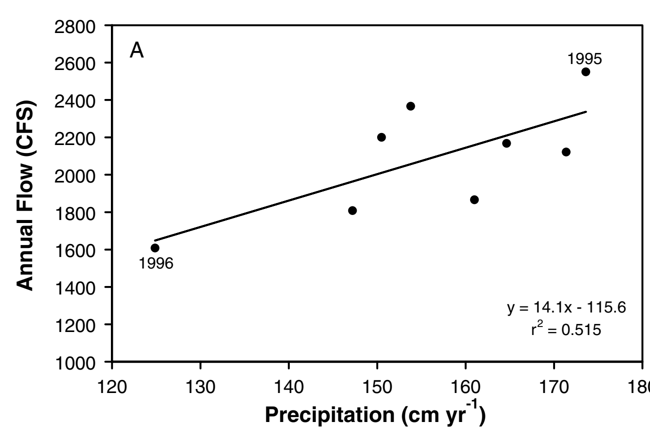

Fig. 5. Regression of annual precipitation (cm yr^{-1}) with annual average canal flow (CFS).

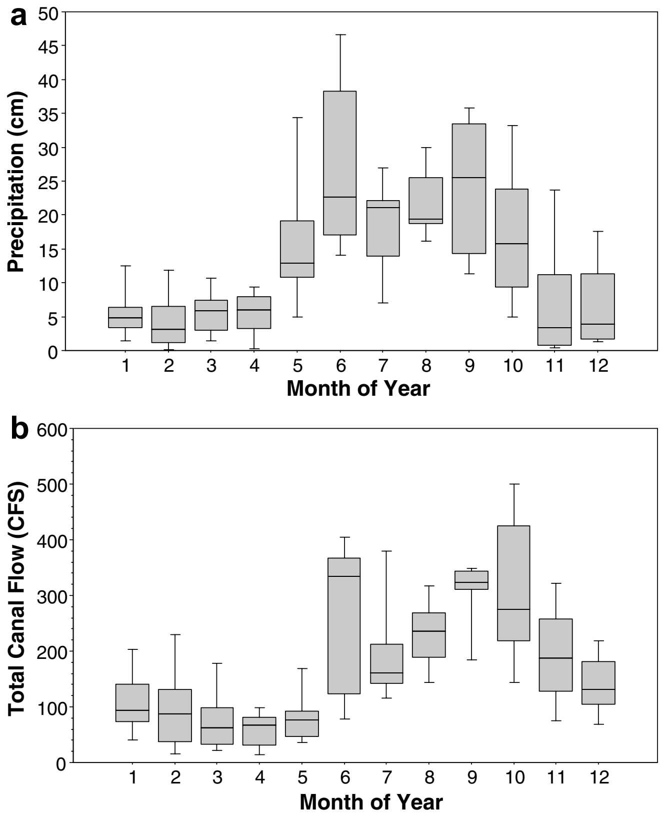

Fig. 6. Monthly precipitation (cm) for region during 1994–2002 (a) and mean monthly canal flows (CFS) into Biscayne Bay (b).

but flows remain elevated through December and even into January. The net effect is a management strategy, which allows for early spring build up of hypersaline conditions with the extension of freshwater inputs long into the dry season.

4.2. Canal nutrient loads

Mean DIN loading over the 9-year period was 1687 ton yr^{-1} (Table 2). Overall, canal loading of NO_x^- was triple that of NH_4^+. This relationship was relatively consistent across the years of the study and is due in part to the sources of freshwater as the canals drain both urban and agricultural areas where NO_3^- is prevalent. There is also a significant lag between input to the canal system and export to the Bay which may allow for significant nitrification to occur (Graves et al., 2004).

TP load was much lower, averaging 27.5 ton yr^{-1}. This resulted in an average DIN:TP ratio of 143.5. Relating DIN to TP is not normally done as it may not be assumed that all the TP is bioavailable. However, comparison of these variables allows us to show the great potential for P limitation within this ecosystem, even with overestimated P availability. It is clear from this analysis that South Bay is potentially more P (440) limited than the Central or North (43.6 and 65.1, respectively).

4.2.1. Temporal trends

Highest DIN loading occurred in 1995 (2185 ton yr^{-1}), while 1996 was the lowest (1253 ton yr^{-1}). These extremes corresponded to the wettest (El Niño) and driest years in the period of record (Fig. 5). No consistent trend in DIN load was observed during the period of record. Doering and Chamberlain (2004) in their study in Caloosahatchee Estuary (Florida) also found the highest TN load in 1995 ($\sim$5800 ton yr^{-1}) and one of the lowest loads occurred in 1996 ($\sim$1500 ton yr^{-1}). Annual DIN loading was strongly dependent of the freshwater flow (Fig. 7). Over 77% of the variability in DIN load was explained by flow, tying load, to a certain extent, to climatic conditions.

Although the overall DIN load and the freshwater flow are correlated, this relationship does not hold for all canals. For example, Princeton and Mowry canals do not represent the highest freshwater flow; however, they had the highest the NO_x^- loadings, meaning they have the highest flow-weighted mean concentrations. These canals drain the agricultural area of Dade County where fertilizer use is prevalent. The relative portions of the different forms of N vary widely based on proximity of sources to receptors, receiving waters, and atmospheric transformations as well as on land surface and transfer through the watershed via surface runoff (Paerl, 1997). In the case of NH_4^+ loading, the major contributors were the Miami River, Little River, and Snake Creek, that also showed the highest freshwater flow. This means that the form of DIN may be influenced by the urban land use around the canals.

Contrary to DIN, TP load was not significantly related to flow, implying that factors other than precipitation-driven input from the watershed were responsible for differences in loading among years. Obviously, there must be other factors, potentially related to management activity, which account for the variability in TP loading. The fractionated nature of the watershed and large potential for variations in flow distribution across the watershed (canalization) increases the variability of TP concentrations and weakens the load/flow relationship.

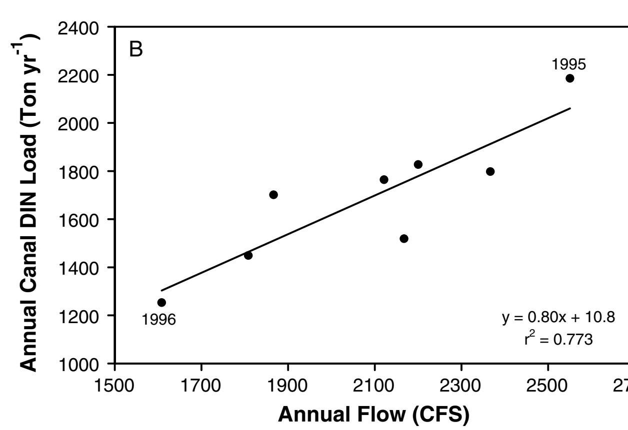

Fig. 7. Regression of annual average canal flow (CFS) vs. annual DIN loading (ton yr^{-1}).

This assertion is supported by the observed interannual variations in DIN:TP ratios of loads (Table 2). We used the DIN:TP ratio because the SFWMD did not measure TN. Although unconventional, the DIN:TP ratio gave us usable information on loading sources. However, unlike other ecosystems where NO_3^- is the main component in the TN pool (Dodds, 2006), only 8% of the TN pool in the bay was in the form of DIN (Caccia and Boyer, 2005). Regression analysis of 12 years of monthly surveys showed that DIN did not predict TN with any certainty ($r^2 = 0.36$). DIN:TP ratios tend to underestimate TN:TP by almost two orders of magnitude which leads to the conclusion that the bay is much more N limited than it really is. These data suggest that the general condition of consistent P limitation in the bay is some way driven by the unbalance DIN:TP stoichiometry of the nutrient load itself.

4.2.2. Spatial trends

South Bay received the largest amount of NO_x^- loading (1021 ton yr^{-1}) from the canals (Table 2 and Fig. 8). Principal NO_x^- sources were the South Dade agricultural basins, the Black Point Landfill, and possibly, the Sewage Treatment Plant (Fig. 1). In the 1980s these agricultural areas produced 50% of the nation's winter vegetables, covering about 80,000 acres (Howie, 1986). 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 (5.6–8.3 kg N ha^{-1} and 5.6–16 kg ha^{-1} of P_2O_5; DERM, 1978). Nitrate pollution is by far, the most conspicuous impact of agricultural impacts to water quality. Previously, we reported that the highest water column NO_3^- concentrations found in Biscayne Bay also occurred in the South Bay, specifically at those stations located near the Black Point, Princeton, and Mowry Canals (Caccia and Boyer, 2005). Therefore, these loading estimates confirm that the low salinity and elevated concentrations of DIN in the nearshore sites of South Bay are the direct result of canal inputs.

The highest loading contribution of NH_4^+ to the Bay (312 ton yr^{-1}) occurred in North Bay and came primarily from the Miami River (145 ton yr^{-1}). NH_4^+ loadings were highest in the North Bay because: (1) land use was predominately urban, (2) frequency of chronic sewage contamination, (3) low DO concentration of incoming waters, and (4) the presence of landfills – Munisport in the North and Black Point in the South (Fig. 1). The North Bay is heavily urbanized, 40% has been dredge or filled, and this area also incorporates industrial complexes, the port of Miami and Miami River. Sewage contamination has been a problem since early growth of the Miami urban area (DERM, 1981). Large volumes of raw sewage were discharged directly into Miami River and Little River from 1920 to 1955 (McNulty, 1970; Wanless, 1976), both have been identified as a conveyance of sewage contamination (McNulty, 1970). This hase since been remediated. Snake Creek also

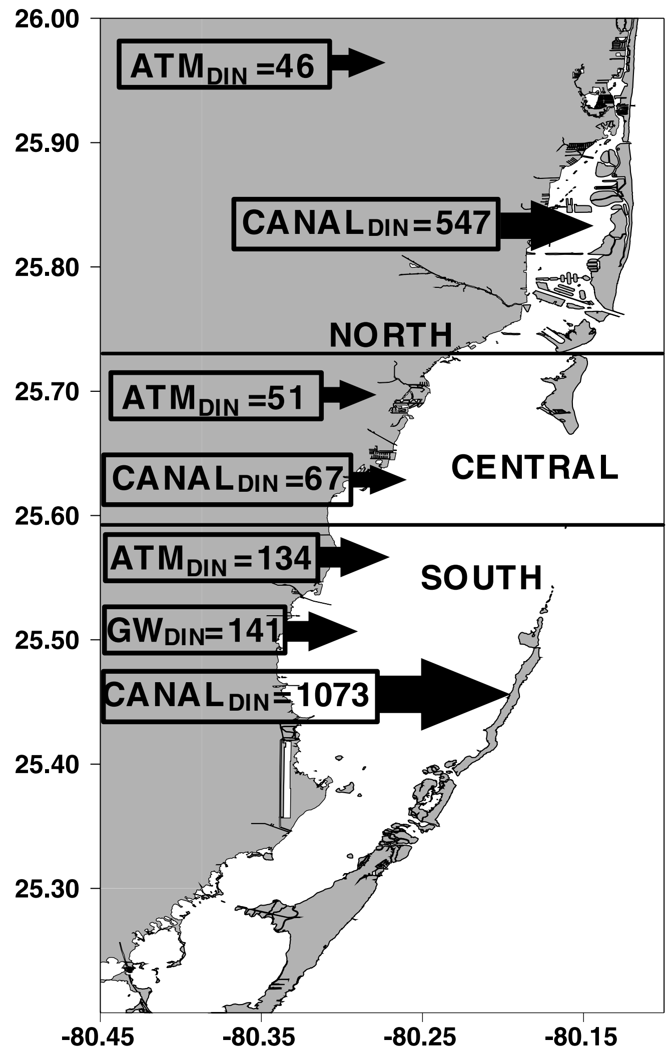

Fig. 8. Annual average DIN loading budget showing canal, atmospheric, and groundwater loads by region of the Bay (ton yr^{-1}).

carries freshwater flow from urban stormwater management systems. DO is chronically low (<4 mg L^{-1}) in some of the northern canals. Caccia and Boyer (2005) observed the lowest DO at stations located in the North Bay. The Dade county standard for unionized ammonia (NH_3) is exceeded frequently in several locations of this region (Alleman et al., 1995).

TP load was also the highest in the North Bay (Table 2 and Fig. 9), being in agreement with the results found in the update of the surface water improvement and management (SWIM) plan for Biscayne Bay (Alleman et al., 1995). This mostly a function of the high TP concentrations found in the canals entering North Bay. Caccia and Boyer (2005) also reported the highest water column TP concentrations in the North Bay. High TP concentrations are related to sewage discharge and the discharge of treatment plants and landfills (Munisport and Black Point). The accumulation of P in urban regions is mainly a surface problem (Forsberg, 1995), and there is an urgent need to improve

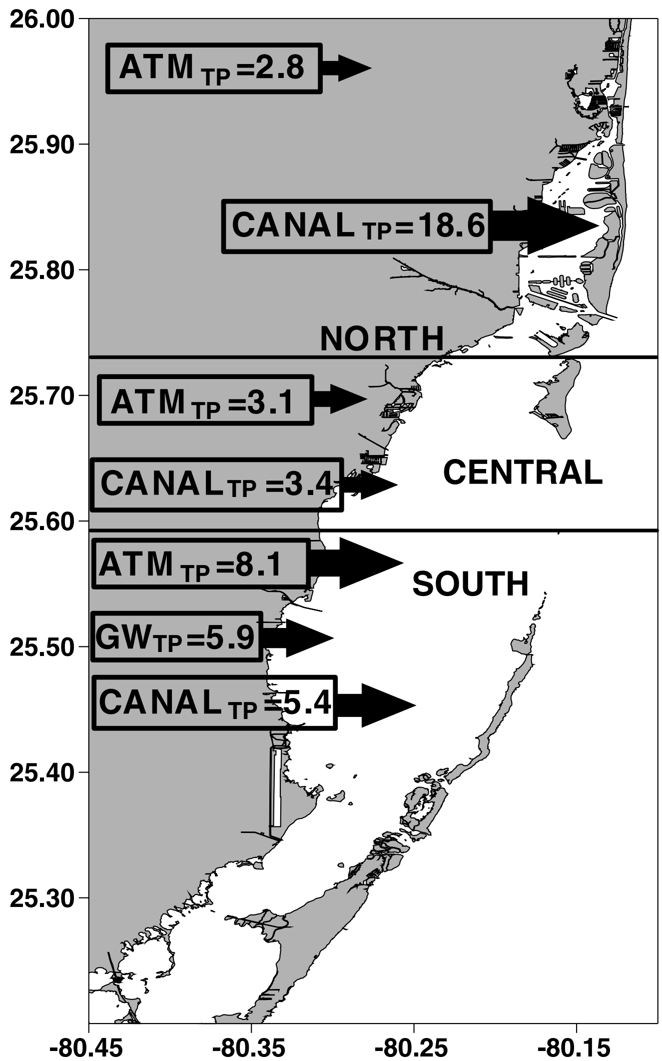

Fig. 9. Annual average TP loading budget showing canal, atmospheric, and groundwater loads by region of the Bay (ton yr^{-1}).

the recycling of nutrients via new methods for more specific recovery of P in municipal sewage treatment plants (Eggers et al., 1991). The leaching of P from landfills is something that we should not undervalue, because many types of food (butter, margarine, soups, sauces, cheese, jam, fish products, soft drinks) use phosphorus (ortho-, poly-, starch-phosphate and phosphoric acid) as food additives, increasing the concentration of P that may leach from the landfills. For example, sewage effluent from a treatment plant with dephosphatation (working effectively) contains <0.5 mg P L^{-1} while and the concentration of P found in soft drinks (cola) is 360 times greater (180 mg L^{-1}, Forsberg, 1995). Munisport Landfill has had a history of problems with stormwater runoff into the Bay (Fig. 1). This site was not an approved landfill and did not have a proper stormwater system or normal landfill lining precautions. Although this site has been inactive for years, it is suspected of impacting surrounding mangrove wetlands within Oleta River State Recreation Area located near to Snake Creek (Alleman et al., 1995).

Lietz (1999) made the first attempt to estimate nutrient loads to Biscayne Bay by measuring nutrient concentrations (including organic N) and freshwater discharges at each canal for 1996 and 1997. He observed the maximum concentration of NO_x^- at Princeton Canal, and the maximum NH_4^+ and TP at Arch Creek, being in agreement with our results. Although there were some variations (due to short period of study and analytical problems) both studies arrived at similar conclusions: "median concentrations of NO_x^- were higher in agricultural areas (South Bay), while NH_4^+ and TP were higher in urban areas (North and Central Bay)".

4.3. Atmospheric loads

The highest N atmospheric input was observed in 1998 (4.12 kg N ha^{-1} yr^{-1}) and the lowest in 1996 (2.43 kg N ha^{-1} yr^{-1}) (Table 3). Coincidently, in 1996 was also observed the lowest DIN canals loading. In Biscayne Bay as well as other Florida estuaries, the NO_3^- contribution was also higher than NH_4^+, and the DIN loads for Biscayne Bay were similar than those reported for Meyers et al. (2001) in various estuaries of Florida (Table 4). In general, Florida has a low atmospheric input of DIN in comparison with estuaries located in the northeast coast of United States, such as Chesapeake Bay and Delaware Bay (Meyers et al., 2001).

Given that Biscayne Bay has a surface area of 70 000 ha and the average of wet atmospheric deposition is 3.31 kg N ha^{-1}, then the annual atmospheric input for the Bay is 231.7 ton N yr^{-1}. This value represents 12% of the total DIN input to Biscayne Bay (Fig. 8). South Bay had the highest atmospheric DIN load due to its large surface area. Castro et al. (2003) found that the average percent of N from atmospheric input for six estuaries from the southeast coast of United States (South Carolina, Georgia, and Florida) was 29%. The lowest atmospheric input (8%) was found in the Indian River, FL (East Coast). In the same study, four estuaries of the West coast of Florida ranged from 7% to 23% of the N atmospheric input (Castro

Table 4
Atmospheric loads of NO_3^-, NH_4^+, and DIN (kg N ha^{-1} yr^{-1}) in some US estuaries

ESTUARY	NO_3^-	NH_4^+	DIN
Biscayne Bay, FL	1.92	1.39	3.31
Indian River, FL[a]	1.96	1.05	3.01
Charlotte Harbor, FL[a]	2.15	1.24	3.39
Tampa Bay, FL[a]	1.85	1.08	2.93
Chesapeake Bay, MD-VA[a]	4.03	2.3	6.33
Delaware Bay, DE[a]	4.12	1.99	6.11
Hudson River, NY[a]	3.89	1.87	5.76
Narragansett Bay, MA[a]	3.3	1.46	4.76

[a] From Meyers et al. (2001).

et al., 2003). Therefore, Biscayne Bay is in the expected range of atmospheric input of N found for Florida.

Atmospheric deposition is a significant and growing source of biologically available N (NO_x^-, NH_4^+ and dissolved organic N (DON)) entering nitrogen-limited estuarine and coastal waters (Paerl et al., 2001). Several studies argue that long range atmospheric transport of N from sources located in the mid-continental regions is a significant source of N deposition to surface waters on the East coast of the United States. The processes by which these atmospheric depositions of N sources are generated and enter coastal waters are changing both temporally and spatially. For example, recent urbanization in Southwest Florida: Tampa, St. Petersburg and Sarasota, has been accompanied by rapidly increasing N emissions from power plants and automobiles. In Tampa Bay and Sarasota region, oxidized N deposition associated with these activities accounts for approximately 30% of the new N input into adjacent near shore waters (Greening et al., 1997). Sources and sinks of N pollutants operate on spatially explicit scales; all of which are essential for understanding how changing human activities and land-use affect water quality.

Atmospheric TP loading was significantly lower than DIN due to the low concentrations of P in rainwater. Data on atmospheric TP were difficult to obtain, especially for the period of record of our study. Although the atmospheric deposition of P is an issue in Florida, few studies have been done and most of them were only for a very short period. The results of the revised studies presented much variability: Hendry et al. (1981) found TP input (wet + dry) to South Florida between 30 and 40 mg m^{-2} yr^{-1} (1-year study); Ahn and James (1999) reported a mean and standard deviation of P load 33 ± 40 mg m^{-2} yr^{-1}, respectively, at one station in the Everglades (1992–1996); Grimshaw and Dolske (2002) found the mean rate of wet atmospheric P deposition across Florida was 25 ± 5 μg P m^{-2} wk^{-1} (1992–1993); Graham and Duce (1979) suggested a continent-wide average of 30 mg m^{-2} yr^{-1}. We selected the mean wet deposition rate obtained by Fitz and Sklar (1999) of 20 mg P m^{-2} yr^{-1} (1978–1996) because it had the longest period of record and it represented a medium value of all revised studies. In external panel report to the Florida Department of Environmental Protection "Overview and Evaluation of Everglades Nutrient Threshold Research" (1996–1997) found a large range of previous estimates of TP in rainfall in South Florida 13–96 mg P m^{-2} yr^{-1}. The differences in sampling method and locations have resulted in a conflicting literature concerning regionally representative concentrations of P in Florida rainfall (Grimshaw and Dolske, 2002).

Hendry et al. (1981) found spatial and temporal variability in the atmospheric deposition of nutrients across Florida, also found that P bulk depositions rates were highest in agricultural areas (due to smoke and ash from burning of sugar cane foliage), moderate in urban areas, and lowest in coastal and non-agricultural rural areas. Grimshaw and Dolske (2002) found no significant variation among six stations located across all Florida, where the average rates of P deposition ranged from 20 to 31.5 μg P m^{-2} wk^{-1}. One of their stations was located at the Everglades National Park (the nearest station to Biscayne Bay), and although the P deposition was in the middle of the range (26.5 μg P m^{-2} wk^{-1}), the volume-weighted mean P concentration was the highest in this station (1.7 μg P L^{-1}). Although it was not possible to identify the sources of P, they concluded that their regionally rate of wet atmospheric P deposition to the Florida Peninsula agreed closely with a calculated estimate of wet atmospheric P deposition to Miami from Saharan dust.

On an area basis, South Bay received the highest TP atmospheric input (8.1 ton yr^{-1}) representing 42% of the total TP load. This was greater than the canal (28%) and groundwater (30%) loads (Fig. 9). North Bay showed the lowest TP load (2.8 ton yr^{-1}), and in perspective, the TP input from canal sources (87%) was much higher than the atmospheric input (13%). In Central Bay, the atmospheric and canal TP loads were similar in proportion. Although the area of the region leads our results, according with Hendry et al. (1981) findings agricultural areas had greater TP loads than urban areas, being the case of South Bay that is mainly an agricultural area.

4.4. Groundwater

DIN load from groundwater source accounted for about 10% of the total loading in South Bay (Fig. 8), while TP load from groundwater was almost equal than canal loading (30%) (Fig. 9). We believe that groundwater represents an important unregulated and poorly gauged source of TP to the South Bay. The probable sources of DIN and TP inputs to South Bay are infiltration from inland agricultural activities, leaching from the Black Point Landfill, and leakage from a treatment plant where treated wastewater is injected into the non-potable aquifer. Agricultural land use in the Biscayne Bay watershed is concentrated in southern Dade County, and is located above the highly porous Biscayne Aquifer. Many studies have found high NO_3^- concentrations in the South Dade groundwater around the area of intensive agricultural activity (Britt, 1994; Church et al., 1980; DERM, 1978). A large source of NH_4^+ contamination in South Bay is associated with Black Point 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 and the levels of NH_4^+ in the sediments were an order of magnitude higher than in the water column. Landfills create a high potential for stormwater to impact surrounding water bodies. The high water table and the high transmissivity of the Florida aquifer mean that stormwater can easily mix with groundwater and move compounds effectively into surface waters (Alleman et al., 1995). From a model estimations (1989–1998) groundwater discharge was 151.2

CFS, which represented ~10% of the surface freshwater discharge for the same period, and during dry season groundwater can exceed the surface freshwater discharge (Langevin, 2003). We hope that future studies focused on measuring groundwater flows and loads will eventually provide more information as to this important nutrient source.

4.5. Nutrient loading comparisons with other estuaries

In an overview study of N and P budgets of the North Atlantic Ocean including fourteen regions in North America, South America, Europe and Africa, the largest N fluxes (per area basis >1000 kg N km^{-2} yr^{-1}) were found in the highly disturbed watersheds around the North Sea (NW Europe) and NE coast of the USA (Howarth et al., 1996). The North Sea showed the most perturbed situation with a largely open N cycle. They also found that in US coast the NE region had more individuals per km^2 and higher water discharge per area than the SE region, as well as TN and TP export in rivers were decreasing from the North to the South Atlantic coast of the USA. The N and P inputs to the North Atlantic Ocean from terrestrial sources were higher at the NE coast of the USA (TN = 0.51 Tg yr^{-1}; TP = 0.067 Tg yr^{-1}) than those from the SE coast (TN = 0.24 Tg yr^{-1}; TP = 0.011 Tg yr^{-1}), with fertilizer accounting for roughly two-thirds of the total N inputs (Howarth et al., 1996).

In Table 5 is presented a nutrient loading comparison with several estuaries along the East coast of the USA. TN and TP data in this table include all measured sources (atmospheric, rivers, canals, and sewage). Unfortunately, we could not find data of DIN, TN and TP for all estuaries presented. Total nitrogen loads are the sum of inorganic and organic N (which was not routinely measured in Biscayne Bay). Lietz (1999) found that 70% of the TN in the canals was in the organic form, while Caccia and Boyer (2005) reported that 90% of the TN in Biscayne Bay was in the organic form. Assuming that 70% of TN is organic N and a DIN loading of 24 kg N ha^{-1} yr^{-1}, then the TN load from canals would be 80 kg N ha^{-1} yr^{-1}. Adding DIN from atmospheric deposition (3.31 kg N ha^{-1} yr^{-1}) and groundwater (only to South Bay, 3.48 kg N ha^{-1} yr^{-1}) without considering the TON of these sources because the proportions are not known, the overall TN load to the Bay would be 86.8 kg N ha^{-1} yr^{-1}. The total TP for the Bay was 47.4 ton yr^{-1} and dividing it for the area was 0.68 kg P $^{-1}$ yr^{-1}. Biscayne Bay loads were in the middle range for TN and the low range for TP (Table 5). Estuaries from the NE coast showed higher TN and TP loads per area that the estuaries from the SE coast and Florida, with an exception of Ochlockonee Bay, FL. Boston Harbor, MA and Ochlockonee Bay, FL had the highest TN values per hectare, but their short residence times (<1/2 month) allow them to export more than 85% of TN. In contrast, the Chesapeake Bay had less TN input per hectare but longer residence time (~9 months) and exported only 25% of TN (Nixon et al., 1996). Therefore, Chesapeake and Potomac estuaries retained more N (60–70%) than Boston and Ochlockonee estuaries (~15%) (Nixon et al., 1996). The annual TN and TP budgets for the estuaries in the North Atlantic revealed that the net fractional transport of these nutrients through estuaries to the continental shelf was inversely related to the log mean residence time of water in the system (Nixon et al., 1996).

Biscayne Bay is very different from other major estuaries of the South Atlantic coast of North America in its geology, geomorphology, and hydrology. These differences are reflected in its nutrient loading aspects and water quality status (Caccia and Boyer, 2005). Because this present study is based mostly on DIN data from canal and river measurements, DIN data in Table 5 only included data from these two sources. DIN per area basis in Savannah River and Cape Fear River (>300 kg ha^{-1} yr^{-1}) was more than the double of all Florida estuaries (~140 kg ha^{-1} yr^{-1}) and at least one order of magnitude higher than the DIN of Biscayne Bay (24 kg ha^{-1} yr^{-1}). It should be noticed that Savannah and Cape Fear estuaries are seven times smaller than Biscayne Bay. The greatest DIN inputs per tons were found for Apalachicola Bay, Savannah River and Cape Fear River. Their freshwater flows are two to three times greater than those of Biscayne Bay. NH_4^+ loading was higher for Cape Fear (700 ton yr^{-1}) than in North Biscayne Bay (312 ton yr^{-1}), and the NO_x^- loading were higher for Savannah (3500 ton yr^{-1}) than those found in the South Biscayne Bay (1021 ton yr^{-1}). Dame et al. (2000) found the highest concentrations of NO_x^- and NH_4^+ in Cape Fear. Interestingly, these concentrations were lower than those found in some of the canals entering Biscayne Bay. Median NH_4^+ concentration in the northern canals of Biscayne Bay (0.3 mg L^{-1}), was twice than that of the Cape Fear (0.15 mg L^{-1}), while median NO_x^- concentrations in the South Bay canals (1.9 mg L^{-1}) was triple of the Cape Fear (0.65 mg L^{-1}).

The majority of the Florida estuaries included in this study are on the west coast of Florida, except St. Lucie and Biscayne Bay, and their watersheds were dominated by agricultural N sources. Ochlockonee Bay showed the highest DIN loadings per area basis and Tampa Bay had the lowest. Biscayne Bay was in the middle range of Florida estuaries. The total DIN loading from canals in the Bay represented 88% (agriculture + sewage) and DIN atmospheric inputs accounted for 12%. We should point out that depending of the region and land use, the percentages were different (Fig. 6). In North Bay 92% of the DIN input (primarily NH_4^+ from sewage) came from canals while only 8% was from atmospheric sources, and in South Bay 80% was DIN load (primarily NO_x^- from agriculture) from canals while DIN loads from atmospheric and groundwater sources accounted for about 10% each, of the total load.

Caraco (1995) found a direct relationship between population development, fertilizer applications, and riverine N and P fluxes. Florida has the highest average growth rate (45%) compared with Georgia and the Carolinas (15%)

Table 5
Nutrient loading comparisons with other US estuaries along the Atlantic coast

	Area (km^2)	Depth (m)	DIN (ton N yr^{-1})	TN (ton N yr^{-1})	DIN (kg ha^{-1} yr^{-1})	TN (kg ha^{-1} yr^{-1})	TP (kg ha^{-1} yr^{-1})
Florida estuaries							
Entire Biscayne Bay[a]	700	2.4	1687	6076	24.1	86.8	0.68
North Biscayne Bay (5 canals)[a]	140		547	243	39	17.4	1.53
Central Biscayne Bay (3 canals)[a]	155		67	298	4.3	19.2	0.42
South Biscayne Bay (4 canals)[a]	405		1073	2034	26.5	50.2	0.48
Apalachicola Bay[b]	554		7422		134.0		
Caloosahatchee C-43[c]	62		470	2400	75.8	387	
St. Lucie Estuary (C44, C23, C24)[b]	16.6		216		130.1		
Ochlockonee Bay[d]	24	1	403	2014	167.9	839.3	
Charlotte Harbor[f]	699			2724		39	
Tampa Bay[f]	940		780	3451	8.7	36.7	
Southeast USA							
Cape Fear River (NC)[g]	100	3.4	3700		370		
Savannah River (SC, GA)[g]	121	4.6	4000		330.6		
Edisto River (SC)[g]	203	4	600		29.5		
St. Marys River (GA)[g]	64	6.1	180		28		
Northeast USA							
Pleasant Bay (MA)[h]	27.5		67		24.4		
Little Narragansett Bay (RI)[i]	9.6		100.8	446	105	465	45.2
Providence Estuary (RI)[j]	~80		1862	4144	235.7	518	56.5
Narragansett Bay (RI)[d]	328	8.3		9000		274.4	35.6
Boston Harbor (MA)[d]	108	5.8		13752		1273.3	204.4
Potomac Estuary (MD-VA)[e]	1210	5.9		35489		293.3	13.6
Chesapeake Bay (MD-VA)[e]	11542	6		151546		131.3	12.7
Delaware Bay (DE)[d]	1989	9.7		52907		266	49
Greenwich Bay (RI)[k]						88.8	20.8

Empty space: data not available.
[a] Present study.
[b] Graves et al. (2004).
[c] Graves et al. (2004) (DIN) and Doering and Chamberlain, 2004) (TN).
[d] Nixon et al. (1996).
[e] Nixon et al. (1996) and Boynton et al. (1995).
[f] Stanley (2001).
[g] Dame et al. (2000).
[h] Carmichael et al. (2004).
[i] Fulweiler and Nixon (2005).
[j] Nixon et al. (2005).
[k] Granger et al. (2000).

(Dame et al., 2000). In Florida, coastal counties occupy 57% of the land, but contain 78% of the population (Montague and Odum, 1997). With a human population growth rate of 600 individuals per day, Florida is already exhibiting environmental stress in many areas. At this rate of human population growth, it is projected that Florida will lose the ability to sustain its estuarine environments within the next 20 years (Montague and Odum, 1997. Between agriculture, high human population density, growth rate, urbanization, and in general the habitat destruction, Miami and Biscayne Bay presents the scenario of potential environmental collapse. We hope that the information presented in this study will help in improving the management strategies to reduce the nutrient loadings in Biscayne Bay.

Acknowledgments

We thank Stephen Blair and Susan Kemp (Miami-Dade Department of Environmental Resource Management) for supplying nutrient data from the canals, Richard Alleman (SFWMD) for kindly providing us the canal freshwater flow data, and Joseph Prospero (RSMAS, UM) for his appreciable help with the atmospheric data and calculus. We also thank Jack Meeder and Danielle Mir for furnishing us with groundwater flow and nutrient data, respectively. The manuscript was much improved by comments of an anonymous reviewer. We acknowledge Biscayne National Park (PMIS Project #94291) and South Florida Water Management District (C-15397) for continued funding. This is contribution #346 of the Southeast Environmental Research Center at Florida International University.

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