

Point Source Nutrient Fluxes from an Urban Coast: the Boynton (Florida) Inlet

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Abstract

The Boynton Inlet (SE Florida, USA) is one of two tidal inlets connecting the Lake Worth Lagoon to the Atlantic Ocean. To quantitate the amount of anthropogenic materials reaching the South Florida coastal ocean and reef track, nutrient fluxes through the Boynton Inlet were measured during two 48-hour intensive studies conducted on June 4-6 and September 26-28, 2007. These studies combined analyses of water samples taken at regular intervals in the Boynton Inlet with acoustic Doppler current profiler (ADCP) measurements of the flow through the inlet. Data collected include concentrations of nutrients (silicate [Si], orthophosphate [PO₄], ammonium [NH₄], nitrate+nitrite [N+N]), isotope ratios of nitrogen, and physical parameters that included pH, salinity, total suspended solids (TSS), and turbidity. The study found a significant but highly variable flux of nutrients in the eight outgoing (ebb) tidal pulses sampled. Daily fluxes of nitrate+nitrite ranged from 16 to 565 kg N, silicate from 564 to 5197 kg Si, phosphate from 154 to 309 kg P, and ammonium from 34 to 354 kg N. These results are compared with other sources of nutrient inputs into the coastal environment. Inlets are a significant source of offshore nutrients.

Keywords: coastal ocean, Boynton Inlet, nutrients, nitrate, nitrite, ammonium, phosphate, silicate, nutrient flux

1. Introduction

The **near-shore ecosystems** off of SE Florida are vital to the economy of the population of 5.5 million (Bureau of Census, 2010), through commercial and sport fishing, boating, diving, and swimming generating \$2B in income and nearly 30,000 jobs annually (Johns et al., 2003). As elsewhere, these **ecosystems** are subject to multiple stressors including chemical and microbiological pollution discharges, loss of natural habitat, climate change, and overfishing (Enochs et al., 2015, Vega-Thurber et al., 2014, Gregg, 2013, Helmle et al., 2011, Rabalais, 2005, Holland & Pugh 2010). While management of these **ecosystems** is of recognized importance (State of Florida and NOAA Coral Reef Conservation Program, 2010), addressing land-based pollution into the coastal ocean is not well understood. Sources of these materials include surface water drainage, treated-wastewater outfalls, groundwater seepage, atmospheric deposition, and ocean upwelling processes (Collier et al., 2008).

Surface waters in southeast Florida are transported to the ocean by rivers and drainage canals, including the Atlantic Intracoastal Waterway (Heimlich et al., 2009). These **waters** may contain chemical fertilizers, pesticides, suspended solids and chromophoric organic materials, elevated nutrients, and contaminants from septic tanks and landfills (Marella, 1998; SFWMD, 2010; Trnka, undated, Puglise, & Kelty, 2007). In southeast Florida, **surface water** is transferred to the open ocean predominantly through a series of inlets: Norris Cut, Bear Cut, Government Cut, Haulover Inlet, Port Everglades Inlet, Hillsboro Inlet, Boca Raton Inlet, Boynton Inlet, and Palm Beach (North Lake Worth) Inlet.

The **Boynton Inlet** (a.k.a. the South Lake Worth Inlet, Inlet, 26°32'43"N, 80°2'33"W) is one of two inlets draining the Lake Worth Lagoon (LWL), Figure 1. The **inlet** was created in 1927 to improve tidal circulation and provide

flushing for the south end of LWL (CPE, 1998). Modifications were performed in 1953 and 1967 (ATM undated). Features of the inlet are shown in Figure 2. The **inlet** width varies from 30-38 m. The lagoon side of the **inlet** includes an enclosed channel (total length about 0.5 km) with barriers on both sides. Bird Island is located on the north side of the channel, and there is a break in the barrier on the south side of the channel which is an alternate path for flow into the inlet. The narrow width of the inlet causes the tidally-driven flow to be quite rapid. The **inlet** is crossed by the A1A highway bridge running nearly north/south above the center of the inlet. Because the flow at Boynton **Inlet** is principally driven by the local semidiurnal tide, there are two outflow/inflow cycles through the inlet each day. Between each pulse there is a short time interval (~10 minutes) of nearly zero flow.

The **LWL**, a component of the Atlantic Intracoastal Waterway (Crigger et al., 2005), is a barrier island lagoon ~33 km long, ~0.6 km wide, and 2-3 m deep, oriented approximately north-south, with an area of ~24.5 km² and a tidal range from 0.85 to 1.34 m (PBCDERM 1998) (Figure 1). The shallow depth is thought to preclude stratification of the water column (Rodrigo et al, 2001). Originally a freshwater lagoon, **the LWL** has been significantly altered by dredging, shoreline development, and the addition of canals and inlets. **It** is now saline with freshwater inflow from three canals (Earman River Canal [C-17], Palm Beach Canal [C-51], and Boynton Beach Canal [C-16]), which result in large fluctuations in salinity (LWLI 2013). All three feeder canals have been denoted as impaired waterways (NPDES 2009). Additional sources of water into the **LWL** include storm water from surrounding cities, two small wastewater plants, and non-point pollution sources such as septic tanks, polluted aquifers, and agricultural runoff (LWLI 2013). Based on hydrologic parameters, it has been found useful to divide up **the LWL** into three segments separated at ~26°43.13' and ~26°37.06'; the north segment is associated with the C-17, the mid segment with the C-51, and the south segment with the C-16 (FDEP, 2013; LWLI, 2013).

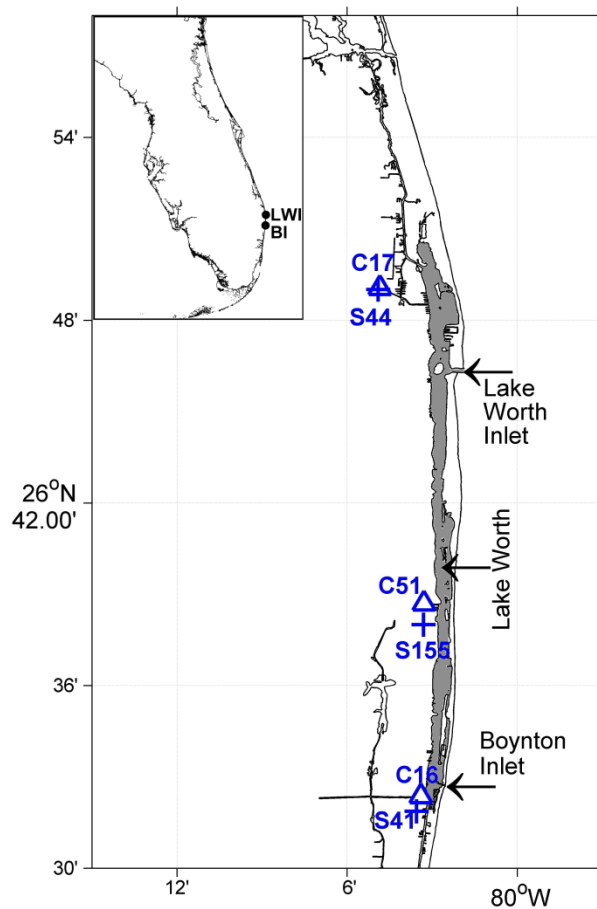


Figure 1. View of the southeast Florida coast with arrows showing the location of the Boynton Inlet, Lake Worth Inlet, and Lake Worth. Triangle symbols denote location of the three significant feeder canals at their monitoring sites (C17, C51 and C16); “+” symbols denote location of three rain measurement sites (S44, S156, and S41). Inset shows outline of Florida with black dots denoting location of Lake Worth inlet (LWI) and Boynton Inlet (BI), with Lake Worth in between

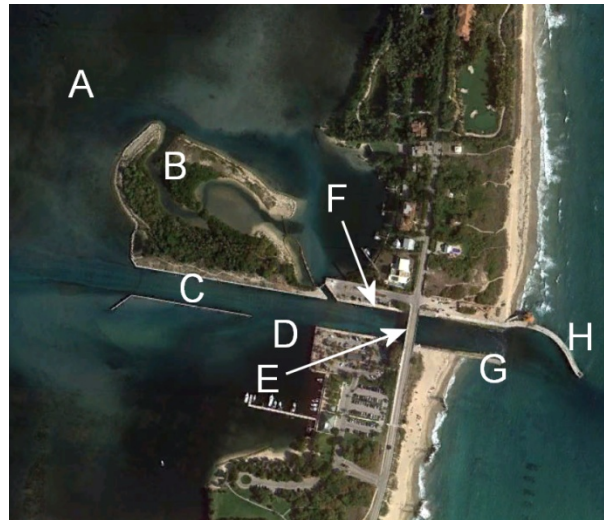


Figure 2. Lower panel: Florida map showing location of the Boynton Inlet (left inset), and details of the inlet (right) as follows: the Lake Worth lagoon (A), Bird Island (B) the inlet channel (C), sand trap (D), south jetty (G) and north jetty (H). Sampling took place from the south side of the inlet from the State Road A1A Bridge (E) or from the south bank near the bridge. The side-looking ADCP was placed on the north side of the inlet (F)

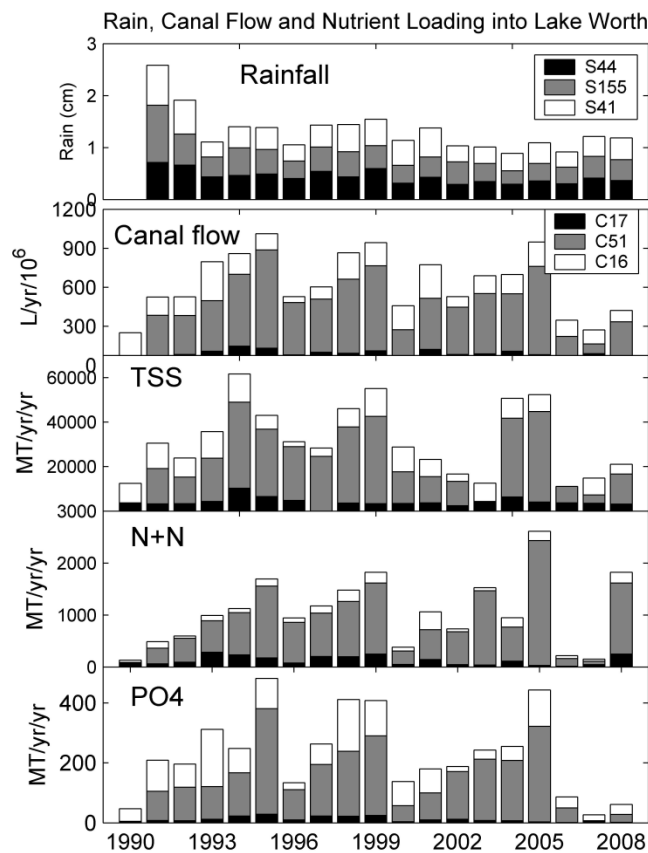


Figure 3. Panels from top to bottom: Average rainfall from three FDEP sites near canal sites (S44 [26°49'00.217", 80°04'54.142"] at C17, S155 [26°38'41.237", 80°03'18.141"] at C51, and S41[26°31'52.251", 80°03'33.142"] at C16) (FDEP DBHYDRO, <http://www.sfwmd.gov/dbhydroplsql>, accessed 12-Oct-2012); annual flow data for stated canals (FDEP DBHYDRO, <http://www.sfwmd.gov/dbhydroplsql>, accessed 9-Oct-2012); annual data for inflow nutrients, TSS, N+N, and PO₄ fluxes from the three major canals flowing into the Lake Worth Lagoon for the years 1990-2008, data are from SFWMD (2009)

Water quality measurements in the LWL of the three canals have been made by the Palm Beach County Department of Environmental Resources Management (ERM) and the South Florida Water Management District (SFWMD) (LWLI, 2013). These data are available through SFWMD's DBYHDRO website (www.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu) and are summarized in Figure 3 for 1990-2008. Note that the C16 canal is located closest to the Boynton Inlet (LWL southern segment) and would be expected to have the most impact on nutrient fluxes through the inlet (LWLI, 2013). Nutrient concentrations during the year of this study (2007) were among the lowest in Figure 3. These data have been recently reviewed (LWLI, 2013); overall concentration trends for sites in the southern segment of the LWL during 2007-2012 were unchanging or decreasing for salinity, chlorophyll-a, TN, TP, and clarity (Secchi disk depth), and decreasing for TSS (ideally, Secchi disk depth should be high, nutrient concentrations low).

Rainfall data (from DBYHDRO) from the same time period are also shown in Figure 3; these data are from inland sites near the canal flow measurement sites (Figure 1). The year of this study (2007) was an average rainfall year; the average of the three rainfall rates for 2007 (0.40 cm) was close to the average for all years in Figure 1 (0.43 cm). The total canal flow is not well correlated with total rainfall ($r^2=0.13$); however, canal flow is well correlated with the canal concentrations of N+N ($r^2=0.78$), TSS ($r^2=0.62$), and PO_4 ($r^2=0.87$).

In 2006, NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) entered into an agreement with the Utility Council of the Florida Water Environment Association as part of the Florida Area Coastal Environment (FACE) program. A part of the agreement was to quantitate the chemical and microbiological materials entering the coastal waters of southeast Florida at selected locations; inlets such as Boynton have been considered likely sources of materials to the coastal ocean (Collier et al., 2008). Our approach was 1) obtain a long-term measurement of the flow characteristics through the inlet via side-looking acoustic Doppler current profiler instrumentation, and 2) conduct two 48-hour chemical and biological intensive studies of the water flowing through the inlet. Each intensive would include four incoming (flood) and four outgoing (ebb) tidal pulses. The first 48-hour intensive was conducted on June 4-6, 2007, while the second sampling intensive was conducted on September 26-28, 2007.

2. Methods and Materials

2.1 Water Sampling

For the June 2007 intensive, sampling began at the center of the State Road A1A Bridge over the Boynton Inlet (Figure 2). Due to sampling instrument failure, however, the later samples were collected from the walkway south of the overpass. AOML collected a total of 50 water samples, FAU collected 62. Samples were obtained following a predetermined sampling schedule designed to sample four outgoing (ebb) and four incoming (flood) tides. Samples for nutrient analysis were taken every half hour from midnight (EDT) 3-June through midnight 4-June, plus five blanks (102 samples). These samples were analyzed at AOML according to the above-described procedures and at Florida Atlantic University (FAU) according to the procedures described in Bloetscher and Meeroff (2006).

For the September 2007 intensive, a sample was collected from the center of the bridge every hour on the incoming tide and every half hour on the outgoing tide. A sample was also collected at three locations along the bridge during the outgoing tide to measure variability in the nutrient concentrations across the channel. AOML collected a total of 84 samples; FAU collected 60. For this intensive, the sampling schedule was modified; samples were obtained every half hour on the outgoing tide and every hour on the incoming tide. Again, four outgoing and four incoming tidal flows were sampled. While the June 2007 intensive began on an ebb tide, the September 2007 intensive began on a flood tide.

Water sampling employed acid-cleaned, 15-L buckets to collect water samples from the bridge. A single bucket was lowered by rope from the center of the bridge and rinsed three times with sample water before the final sample was collected. The bucket of sample water was transferred into sample bottles and bags for subsequent analysis of nutrients (orthophosphate [PO_4], silicate [Si], nitrite [NO_2], nitrate [NO_3], ammonium [NH_4], total nitrogen [TN], total organic nitrogen [TON], total organic carbon [TOC]), TSS, and selected microbiological assays (not included in this report). After the first hour of the outgoing tide, three samples were collected at the three locations on the bridge (A, B, and C north to south) to assess nutrient variability across the channel; no significant differences ($p>0.05$) were found. A set of duplicate samples and a blank sample were also collected on the outgoing tide. Because of contamination issues, PO_4 measurements from the June 2007 intensive were not included in our analyses. Water samples were analyzed for nutrients according to established procedures described elsewhere (Carsey et al., 2011a, Bloetscher and Meeroff 2006).

In the field, water quality data (pH, conductivity, salinity, water temperature, and dissolved oxygen) were collected using a YSI 556 multi-parameter probe (YSI Inc., Yellow Springs, OH), calibrated daily according to the manufacturer's procedures (YSI, 2009). Additional observations included general weather conditions, ambient air temperature, tidal conditions, previous rainfall, approximate channel depth, and current direction and strength. Meteorological data was collected with a Kestrel K3000 hand-held weather station (Nielsen-Kellerman, Boothwyn, PA) and through visual observations.

2.2 Flow Measurements and Tidal Prism Calculation

Tidal prism values are typically either estimated, for example from inlet cross-sectional areas (Jarrett 1976), or directly measured (Table 1). We chose to directly measure ebb and flood tidal prisms for the two intensives. To measure the volume of water passing through the Boynton Inlet per unit time, a SonTek Argonaut 500-kHz side-looking ADCP was installed on February 20, 2007 on the north side of the inlet (pointed nearly due south) at a point chosen to best represent the mean channel velocity ("F" in Figure 2). The instrument made simultaneous measurements of the water level at the location of the instrument and of the flow velocity across the channel. Water level was measured using pressure and upward looking acoustical sensors located on the instrument. Water velocity was measured by averaging the Doppler velocity returned from 450 acoustical pings transmitted over a 7.5 minute interval at a 1-Hz rate; these data were recorded every 15 minutes. The acoustic measurement volume was programmed to encompass approximately the middle 50% of the channel width and was vertically located at the mid-water depth relative to the mean low water level.

Table 1. Boynton Inlet, Reported Ebb and Flood Tidal Prism and Maximum Flow

Reference	Ebb (m ³)	TP	Flood (m ³)	TP	Max Ebb Flow Velocity (cm/s)	Max Flood Flow Velocity (cm/s)
This report, Jun 07	3.16E+06		2.97E+06		145.7	148.8
This report, Sep 07	5.21E+06		3.64E+06		165.5	133.4
Stamates 2013 (13-month average)	3.45E+06		2.98E+06		201.1	184.6
Carr-Betts 1999 (estimated)	1.90E+06					
Marino 1986	3.10E+06					
CP&E: Lake Worth Inlet Management Plan 1998 (12 hr average)	1.61E+06				243.8	274.3
ATM SLWI Feasibility Report (9 day average)	4.00E+06		3.60E+06		310.9	

To correct for the particular characteristics of the Boynton Inlet and the instrument installation, a series of calibration exercises were conducted using a 1200-kHz down-looking Rio-Grande Doppler sonar (Teledyne RD, Poway CA). This instrument was repeatedly transected across the inlet during the tidal cycle (flood and ebb). During these transects, velocity data were gathered across the entire width of the inlet and throughout nearly the entire water column. Water velocity data from these calibration exercises enabled the correction of the velocity measurements made by the side-looking Doppler sonar to more closely represent the true mean channel velocity of the inlet (Ruhl and Simpson 2005). The measurement system and results are described in Stamates (2013).

The water level measurement, in conjunction with measurements of the channel geometry, provided an estimate of the cross sectional area of the channel during the measurement interval. The product of the channel cross sectional area estimate (m²) and the mean channel velocity (m s⁻¹) provided the average flux (m³ s⁻¹) of water passing through the channel during the measurement interval. The product of the average flux measurement and the time of the measurement interval (900 s) provided the estimated volume (m³) of water transported through the Boynton Inlet during the measurement interval. All the volume measurements made during a particular tidal phase, as determined by the sign of the velocity, were summed to measure the tidal prism for that tidal phase. Tidal prism and maximum flow velocities from this study and from previous studies are given in Table 1.

Figure 4 presents the ebb and flood tidal prism volumes for two intensives, flow rates of the principal canals feeding the LWL (C17, C51, and C16), winds from the Lake Worth Pier (NOAA/NDBC LKWF1), and rainfall rates from sites near the canal monitoring sites preceding and during the intensives. The ebb or flood tidal prism

can be affected by the strength of the northern directed wind component (Stamates 2013). Thus, on 2-June, a strong south wind was present (denoted as “An” in Figure 4). On that day, rainfall was heavy as was canal flow. The wind diminished the ebb prism, presumably forcing the water to exit through the Lake Worth Inlet. By 4-June, the winds had generally abated and the ebb and flood prisms were more typical. During the September intensive, winds were not strong and tidal flows were unaffected by wind. For these times in Figure 4, canal flow and rainfall were somewhat correlated ($r^2=0.69$ for June, $r^2=0.42$ for September); note how closely canal flow follows rainfall on 2-June (a primary function of the canal system is flood control, [SFWMD 2010]).

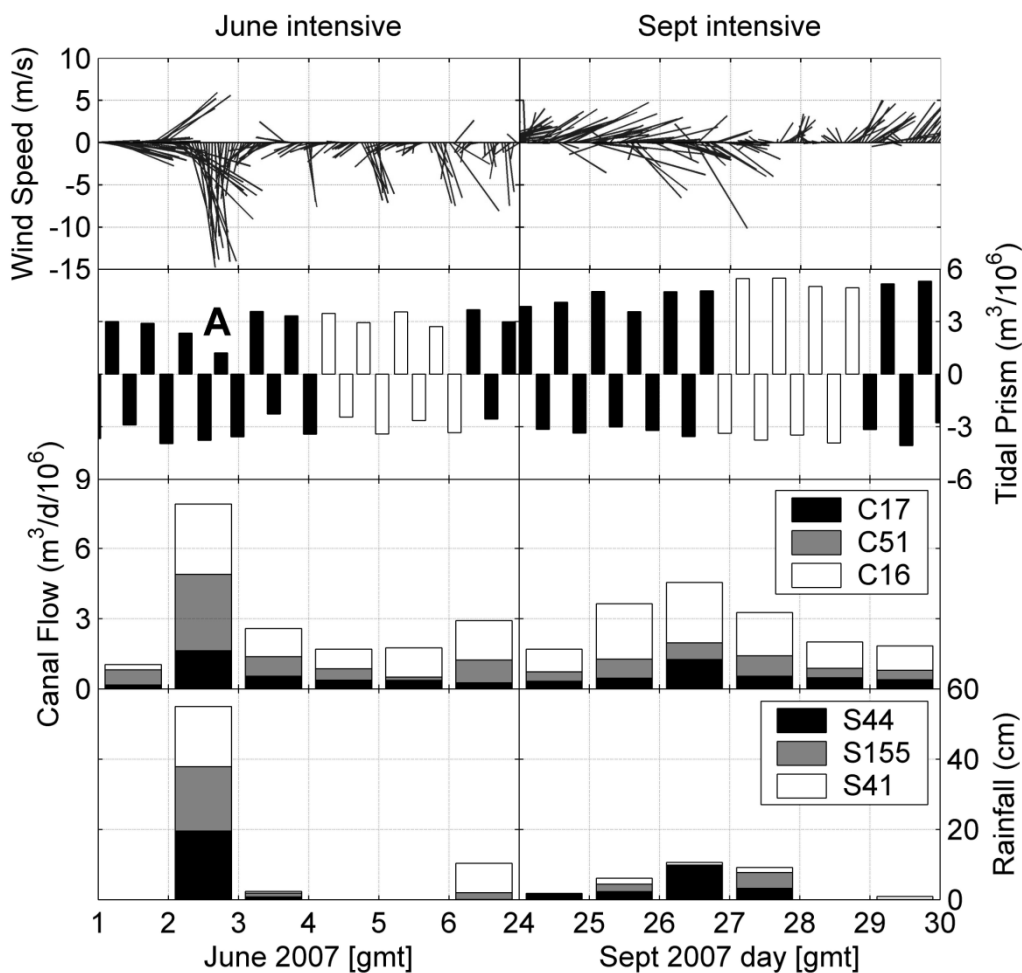


Figure 4. Meteorological and hydrodrological data during the June 2007 and September 2007 intensives. Topmost panels: wind arrows (meteorological format) from the LWKF1 buoy (<http://www.ndbc.noaa.gov/>). Second panels: ebb and flood flow volumes through the Boynton Inlet (this paper), ebb tides positive, with sampled tidal pulses shown in black. Minimum ebb flow event denoted by "A". Third panels: canal flow from canals C17, C51, C16. Bottom panels: rainfall at FDEP sites S155 (16583), S44 (16674), and S41 (16675). Flow and rain data are from the Florida Department of Environmental Protection (FDEP DBHYDRO, <http://www.sfwmd.gov/dbhydroplsqli>, accessed 11-August-2011)

Discrete water sample results and inlet flow rates versus sampling time from the June and September intensives are presented in Figures 5 and 6, and are summarized in Figure 7, in which averages from each ebb and flood tide are shown. Each flood tide brings in high salinity, low nutrient water; each ebb tide is characterized by the inverse. The expected pattern for concentration changes during ebb tide flow was increasing concentration of continentally-derived materials and decreasing salinity through the ebb tide, as water originating more distant from the inlet (thus more continentally impacted and less marine impacted) exits the inlet. We see this most

clearly with turbidity on the June 5 ebb tides ("An" in Figure 6). However, in many cases elevated nutrient concentrations (and lower salinities) were also observed at the start of the ebb flow, e.g., "B" in Figure 6. This feature suggests that flow characteristics from the Lake Worth Lagoon through the Boynton Inlet are different for different flow rates, and that nutrient concentrations in the lagoon may not be spatially homogeneous. Thus, we may speculate that as flow rates change during the course of the ebb tide, the flow characteristics of water moving towards the inlet changes, i.e. a wide, shallow flow including the sand trap area ("D" in Figure 2, lower panel) at low flow rates changes to primary flow within the channel ("C" in Figure 2) at higher flow rates, removing water with different chemical characteristics.

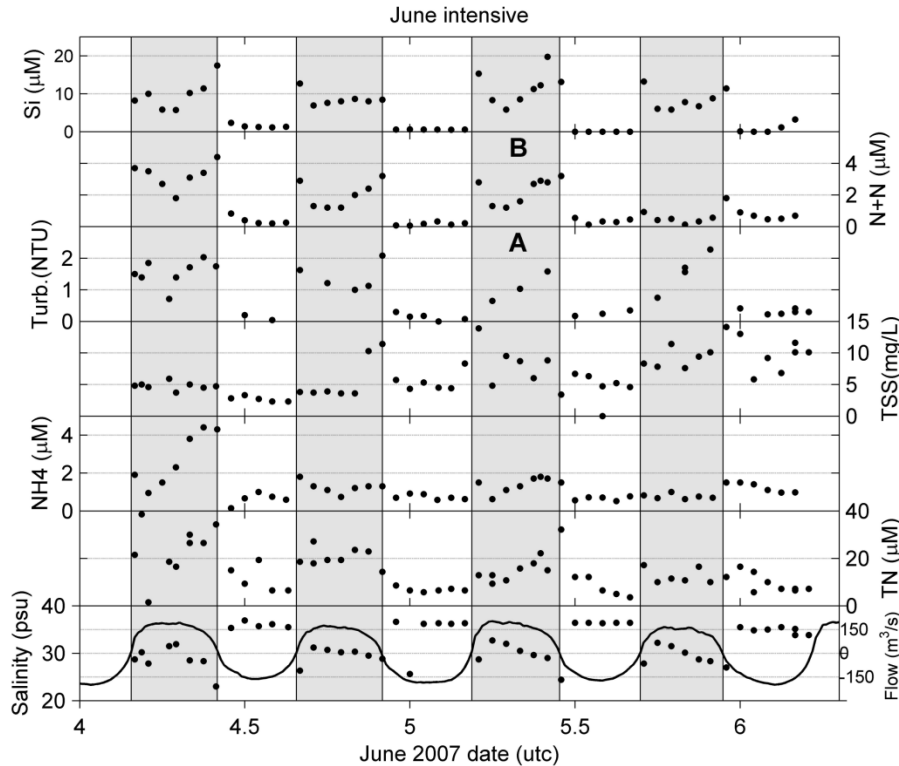


Figure 5. Concentration data for salinity, TN, NH_4 , TSS, turbidity, N+N, and Si from the June 2007 intensive vs time (UTC). The solid line in the bottom panel represents the flow through the Boynton Inlet (right-hand axis), with positive values being seaward (ebb tide) flow. Ebb tide flow times are denoted by a grey background. Notations "A" and "B" refer to patterns of concentration changes during ebb tides

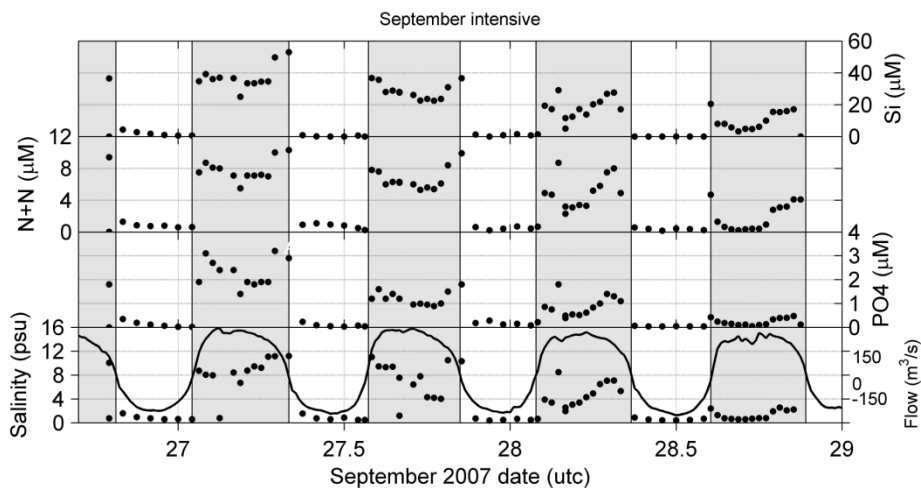


Figure 6. Concentrations of Si, N+N, PO_4 , and NH_4 from samples obtained during the September 2007 intensive. Format is similar to Figure 5

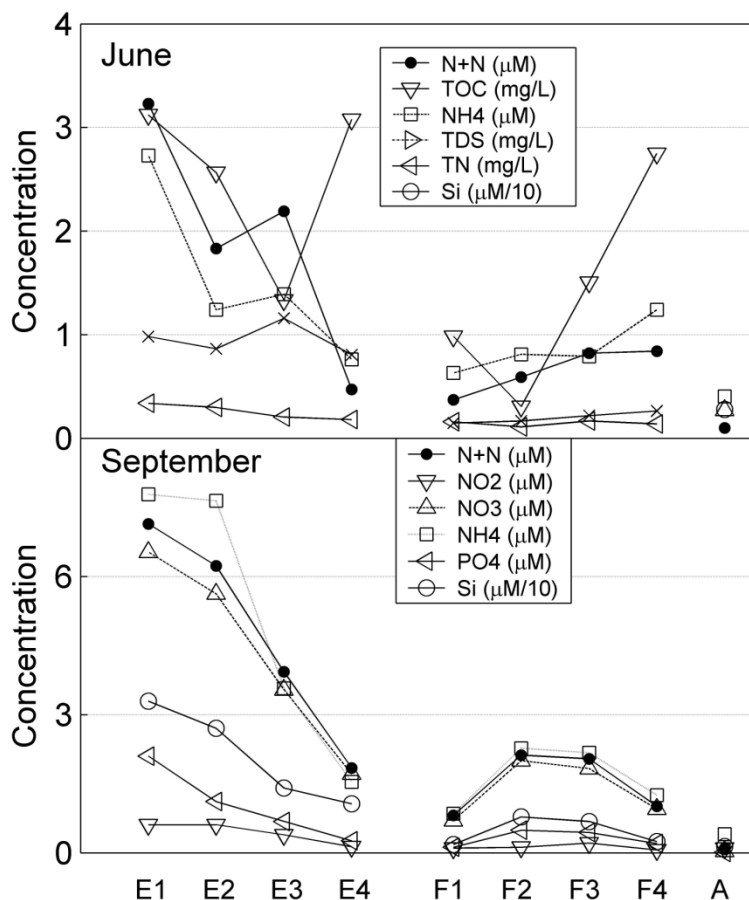


Figure 7. Upper panel: Concentrations of N+N (μM), TOC (mg/L), NH₄ (μM), TSS (mg/L), TDS (mg/L), TN (mg/L-N), and Si (μM), averaged over each tidal pulse, for the June 2007 intensive. The x-axis labels denote the ebb tide (E1, E2, ...) or flood tide (F1, F2, ...) pulse. Symbols at "A" denote concentrations of N+N, NH₄, TSS, and Si found in nearshore samples away from point sources. Lower panel: Concentrations of N+N (μM), NO₂ (μM), NO₃ (μM), NH₄ (μM), PO₄ (μM) and Si (μM), averaged over each tidal pulse for the September 2007 intensive. Symbols at "A" denote concentrations of N+N, NO₂, NO₃, NH₄, PO₄, and Si (/10) found in nearshore samples away from point sources (see text)

The flux of material exiting the Boynton Inlet was then calculated as the product of the concentration and flow data summed over the tidal flow. Beginning with the inlet flow data, concentrations were linearly interpolated onto the flow measurement bin times of 15 minute duration to cover the ebb or flow period. Extrapolation of nutrient data for a few 15-minute bins to complete the beginning of the first tidal pulse and to complete the last tidal pulse were performed (this correction added <2% to the fluxes). These approximations enabled the flux estimates to extend over all eight tidal pulses for both intensives. These data are shown in Figure 8. It is noted that the fluxes in the outgoing pulses varied substantially; e.g. N+N ranged from 16 to 565 kg. The similarity of the concentrations (Figures 7) and the fluxes (Figure 8) is evident; what was noted about the trends in concentrations applies equally to the trends in fluxes. Notably, the ebb tide fluxes may be equal to or even less than the flood tide fluxes, e.g. the fourth ebb and flood pulses in June. Not all relevant analytes were measured in both intensives; for example, TN was only measured during the June 2007 intensive. This was critical because inorganic nitrate (N+N, Figure 5) was only a small portion (4-19%) of the TN in June (Figure 6). Similarly, TSS and TOC were found to have substantial concentrations in June, as did TDP and DOP in September.

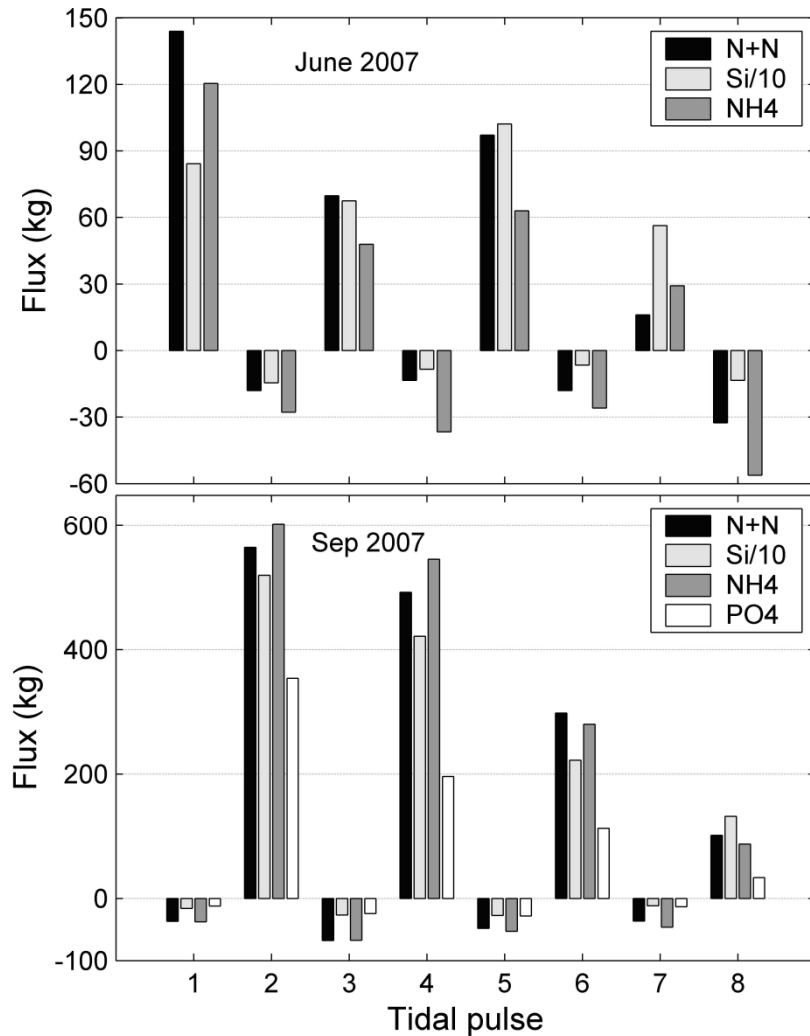


Figure 8. Flux of nutrients for the two 48-hour intensive sampling periods: June 2007 (upper panel) and September 2007 (lower panel). Format is similar to Figure 5, with noted concentrations reduced by 10 for plot readability

Figure 7 presents an overview of the sequence of ebb and flood tide concentrations. It was expected that the flood tide concentrations (aside from salinities) would be consistently lower than those of ebb tide concentrations. It was found, however, that both flood and ebb concentrations varied widely. For both intensives, ebb tide concentrations decreased across the entire intensive, with the final ebb tide concentrations comparable to the previous flood tide concentrations. This suggests that the rainfall events prior to each intensive (Figure 4) brought a nutrient loading from nearby or upstream sources, filled the Lake Worth Lagoon, and required several days to wash through the Boynton Inlet.

While the data from this work was limited to the two intensives, an estimate of the annual flux through the Boynton Inlet can be made. We reexamine the year-to-year variance. While a long-term record of concentrations or flow at the Boynton Inlet is not available, we have referred previously (Figure 3) to the 19-year record for site C17S44 (C17 canal) and C51S155 (C51 canal) for Jan-1990 to 2009 (Taylor Engineering 2009). If we take the 19-year data set as representative of the 'normal', an annual flux derived from the data in this report would be too low. If the average N+N flux from the intensives data is computed as an annual average (assuming the same flux for a year), it would be equivalent to ~115 MT. This compares to an average N+N flux from the three canal sources for 2007 of 148 MT. The average N+N flux for the 19 years is 978 MT, or about 6.6 times as much. This implies that we should multiply the net fluxes listed in Figure 7 by that number to account for the evidently low amount of material exiting the Inlet on the particular days chosen for the experiment, when compared to the 19-year average.

3. Comparison of Nutrient Sources

The flux of several important nutrients to the coastal ocean via the Boynton Inlet has been presented. We may compare these results to another known point source of anthropogenic nutrients, viz., treated-wastewater ocean outfalls. Published data from the Florida Department of Environmental Protection (FDEP 2006) lists a number of nutrient concentrations (as the average of monthly averages for a 14-month period in 2003-2004) from six outfalls operational at that time. Some of these analytes were also measured in the Boynton Inlet intensive experiment and are listed in Table 2 (TN was not measured during the September 2007 intensive). These data indicate that the Boynton Inlet provided a flux of nutrients to the coastal ocean comparable to and sometimes exceeding that of the nearby ocean outfalls.

Table 2. Comparison of daily mass flux from three ocean outfalls in the region and the Boynton Inlet.

Source	NH ₄ kgN/d	N+N kgN/d	TN kgN/d	TSS kg/d
Boynton-Delray	571.3	200.2	913.2	439.5
Boca Raton	425.3	133.7	684.5	243.0
Hollywood	1779.3	179.4	2482.1	2541.9
Boynton Inlet (Sept)	655.0	633.5	n/a	n/a
Boynton Inlet (June)	56.9	122.3	616.3	6566.4

4. Conclusions

A variety of chemical and physical measurements were obtained during two 48-hour sampling intensives conducted in 2007, including chemical and oceanographic information to help understand the processes that affect Florida's coastal environment and coral reef habitats. The nutrient flux from the Boynton Inlet was found to be substantial, and quite variable, and comparable to, and at times exceeding that of nearby treated-wastewater plant ocean outfalls. Elevated concentrations seen in the inlet were not observed a few kilometers away from the inlet. The data also suggest that excess rain and canal flow leads to elevated nutrient concentrations in the Boynton Inlet that are rapidly washed into the coastal ocean.

These results suggest that the Boynton Inlet is an important but not a dominant contributor to the nutrient loading of the coastal ocean. A rigorous determination of the relevant nutrient budgets would require that these kinds of flux assessments be made with other point and non-point sources such as the remaining inlets, atmospheric deposition, ocean upwelling, ship discharges, and groundwater discharge. Considering the range of variance in the fluxes reported herein, these results demonstrate the need for more data-intensive flux measurement programs to be initiated which could better account for the large number of variables that contribute to inlet fluxes. This is particularly recommendable where there is an urgent need to determine the impacts of land-based pollutant sources, to control anthropogenic water discharges, and guide the operation and development of water and sewer infrastructure.

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