Measuring Chemical Loadings through Inlets: Hillsboro and Boca Raton Inlets (Florida, USA)

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***Abstract*—We describe a cost-effective methodology for obtaining loadings for the environmentally significant chemical species (silicate, nitrate, nitrite, ammonium, and orthophosphate) through coastal inlets (Hillsboro and Boca Raton, Florida, USA). Loading were computed from field measurements obtained during an 18-month period, including four ebb tide intensive sampling efforts and biweekly water grab samples.**

Keywords—land-based sources of pollution; inlets; coral health

I. INTRODUCTION

Land-based pollution is widely implicated in the worldwide decline of coral diversity and density [1]. These sources may be characterized as point sources (wastewater outfalls, inlets), non-point sources (groundwater discharge, urban runoff), and atmospheric deposition [2]. Understanding the relative contributions of pollutants from these sources has become an important topic in coastal management.

The southeast coast of Florida contains three intermittent reef tracts [3,4]. Major point sources of pollution include five wastewater treatment plant (WWTP) outfalls and six inlets [5]. These inlets have been implicated as pollution sources impacting the reefs in this area [6,7]. Management of the coastal waters with respect to land-based sources of pollution requires appropriate estimates of the loading of nutrients through these inlets [8]. However, determination of nutrient loadings may be challenging because of highly variable factors such as rainfall, water management actions, and groundwater flow. We have developed an approach for estimating the loadings through two inlets in southeast Florida using data collected 3-May-2012 through 5-Dec-2013.

II. METHODS

The Hillsboro Inlet (26.2578°N, 80.0808°W) and Boca Raton Inlet (26.3359°N, 80.0704°W) are improved natural inlets on the southeast coast of Florida connected by the Intracoastal Waterway (ICWW). The ICWW receives water from a complex network of canals, the levels of which are maintained for groundwater control (e.g., to prevent salt water intrusion) as well as flood control [9].

A. Water Grab Samples

Water grab samples were obtained at locations near the inlets as shown in Fig. 1 from 3-May-2012 through 9-Nov-2013. Sampling sites for grab sampling were chosen near the exit to the ocean. Samples were collected approximately every two weeks. Sample collection was timed so that the samples were collected near the middle of the ebb tide flow. These samples were characterized immediately with a hand-held probe instrument (YSI Pro-Plus, YSI, Yellow Springs, Ohio) for salinity, dissolved oxygen, and pH. Aliquots were returned to the laboratory for analysis of nutrients (nitrate, nitrite, phosphate, silicate) as described in [5].

B. Intensive Ebb Tide Sampling Efforts

A series of four intensive sampling efforts was conducted at each inlet using a small boat. During these efforts, each of which spanned a complete ebb tide, multiple measurements of the volume transport through the inlet were made and samples of water were collected hourly. The water samples were analyzed in the same manner as the grab samples previously described. To measure the volume transport through the inlet, the boat was equipped with a downward-looking, 1200 kHz Rio-Grande acoustic Doppler current profiler (ADCP) (Teledyne-RD Instruments, Poway, CA). A transect line was chosen for the vessel to follow (Fig. 1). This transect line was selected for practical and safe vessel operations so that the entire flow exiting the inlet would also flow across this section.

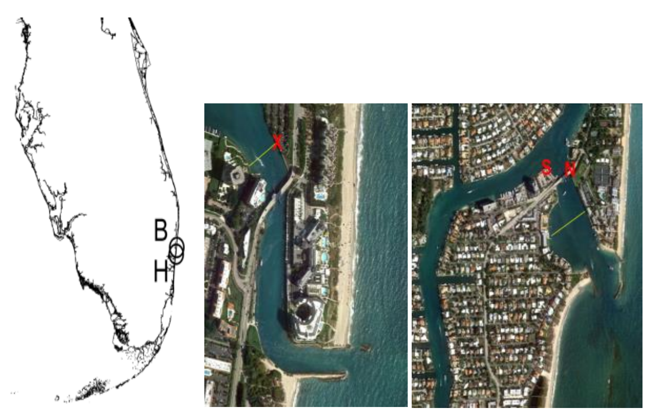

Fig. 1. Florida map showing location of Boca Raton Inlet “B” and Hillsboro Inlet (“H”), left; map of Hillsboro Inlet (right) with grab sample location for Hillsboro Inlet denoted “N” and “S”; map of Boca Raton Inlet (center) with grab sampling location denoted by the X. Dotted lines denote approximate track of the research ship *Cable* during sampling intensives.

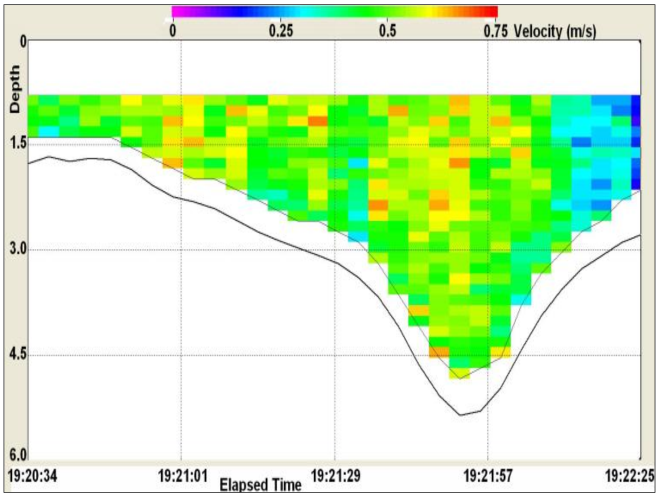

Fig. 2. Magnitude of current velocity at the Boca Raton Inlet on a transect conducted on March 1, 2003. Horizontal axis is elapsed time. The black line denotes the inlet depth as the ship transected southwest to northeast along the transect line shown in Fig. 1.

During each transect, the ADCP measured the horizontal and vertical water velocities through nearly the entire water column at ~1 m spacing. Channel bathymetry across the transect line was also measured by the ADCP (Fig. 2). Constraints on vessel operations prevented the entire transect line to be directly measured by the ADCP. User inputs to the survey software (Win River II, Teledyne-RD Instruments, Poway, CA) allowed for the water column velocities and the channel bathymetry not directly measured by the ADCP along the transect line to be estimated.

Using the measured and estimated data, the survey software then calculated the volume transported through the inlet during that transect. This is expressed as Q (m^3/s) [10]. During the ebb tide, multiple transects (typically 70-120) were made. Q values measured at each inlet, during these transects, are shown in Fig. 3. These measurements of Q were later integrated over the period of the ebb tide to determine the tidal prism (TP).

C. *Estimated Tidal Prism Time Series*

To estimate a time series of the ebb tidal prisms for each that occurred during the duration of the water sampling effort, we regressed each of the ebb tidal prisms measured at an inlet against the corresponding tidal range for that ebb tide (defined as the tidal height at the start of an ebb tide minus the tidal height at the end of that ebb tide). The tidal height information was gathered from published tidal data [11]. These regressions are shown in Fig. 4. These expressions were then used to estimate each ebb tidal prism occurring during the study period for both inlets.

D. *Nutrient Concentration Time Series*

A time series of nutrient data was constructed from the nutrient data collected via the grab samples and from that collected during the sampling intensives (for the intensive samples, the mean of the nutrient values measured during that ebb tide was used). This time series was then linearly

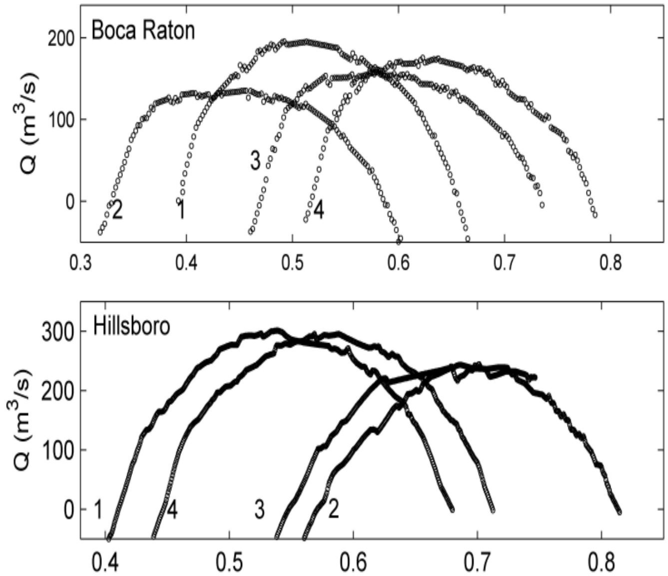

Fig. 3. Q measurements during sampling efforts at the Boca Raton Inlet (upper panel) and Hillsboro Inlet (lower panel). For Boca Raton, these were conducted on 15-Oct-2012, 25-Jan-2013, 1-Mar-2013, and 26-Jun-2013 (denoted 1-4). At Hillsboro, they were conducted on 21-Aug-2013, 26-Aug-2013, 10-Sep-2013, and 5-Dec-2013 (denoted 1-4).

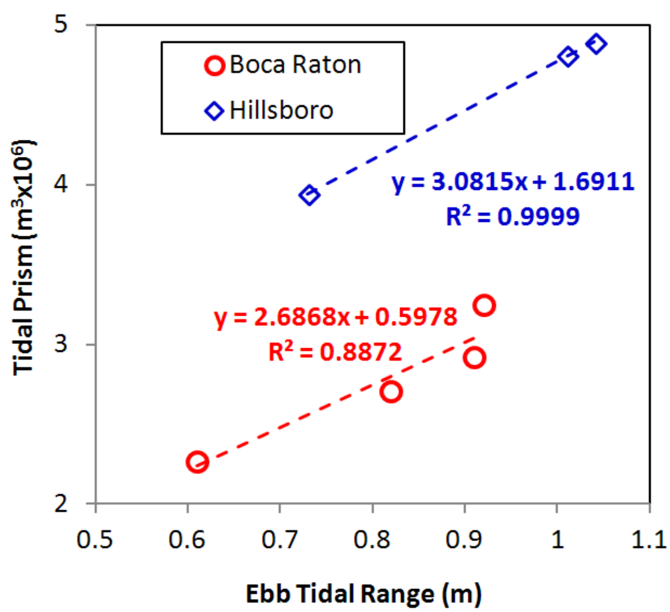

Fig. 4. Tidal prism measurements (vertical axis) versus predicted ebb tide range (horizontal axis) for the Boca Raton Inlet (red circles) and the Hillsboro Inlet (blue diamonds). Statistical parameters are given in the insets.

interpolated to the times of the ebb tides occurring during the duration of the experiment (Fig. 5). An estimate of the nutrient loading to the coastal ocean from the inlets was then made for each ebb tide during the study period by multiplying the interpolated nutrient concentration by the estimated tidal prism. In this manner we were able to construct a time series of nutrient loadings for the study period.

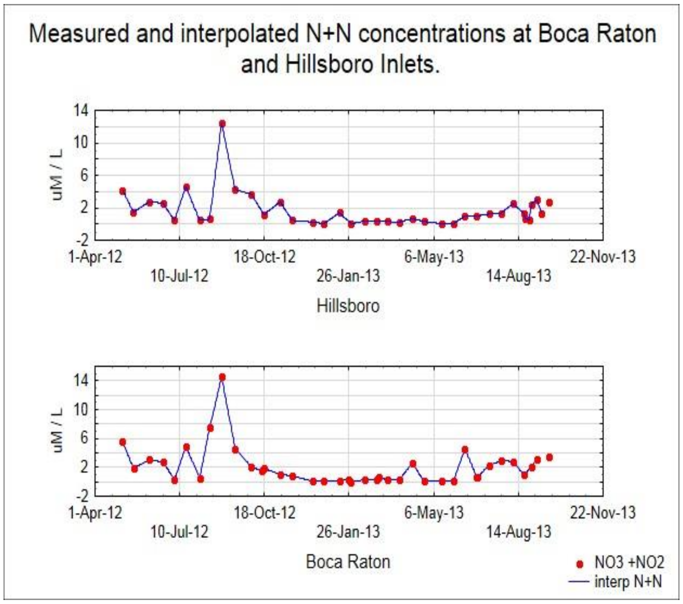

Fig. 5. Nitrate+nitite sample collected inside the Hillsboro and Boca Raton inlets and interpolation of these samples to the times of each ebb tide occurring within the data collection interval.

III. Results

Using the interpolated nutrient concentrations and the estimated tidal prism, we were able to estimate the total nutrient loading to the coastal ocean through the Hillsboro and Boca Raton inlets for each of the ebb tides that occurred during our study interval. From this data monthly averages were calculated and are presented in Table 1.

To investigate the relationship of the chemical fluxes to nearby rainfall and the concomitant canal flow, the latter data were obtained through the Florida Department of Environmental Protection's DBHYDRO website (http://www.sfwmd.gov/dbhydroplsql). We show rainfall and canal flow as reported from sites in the vicinity of the inlets in Fig. 6; as expected, loadings followed rainfall and canal flow closely.

IV. Discussion of Errors

In this section, we attempt to recognize the potential sources of errors inherent in this method and offer suggestions to minimize these in future efforts. While we do not have quantitative estimates of all the sources of error, we will attempt to qualitatively classify them.

The per tide loading estimates given in this paper are the product of two estimated time series, both of which may contains errors. The errors in the laboratory analysis of the water samples are low compared to other sources of errors present and may be considered negligible.

The nutrient time series is constructed by linearly interpolating samples taken bi-weekly. Should one of the bi-weekly samples have been taken at a moment when nutrient values were anomalously high or low compared to the mean for that period, the interpolated time series during this interval will be biased by this sample. This is most likely the largest source of error in these estimates. In future efforts, sampling more frequently would be desirable, especially during the rainy

TABLE I. Chemical loadings (kg/tide) of ebb tide flow through the Hillsboro and Boca Raton inlets by month.

Hillsboro	**Si**	**NO2**	**NO3**	**NH4**	**PO4**
Jan	201	39	35	41	14
Feb	415	18	15	31	10
Mar	590	16	14	22	11
Apr	2,219	7	19	61	22
May	3,201	32	44	118	36
Jun	5,586	66	64	117	33
Jul	5,004	36	71	152	39
Aug	7,000	42	142	260	78
Sep	11,460	76	186	324	103
Oct	3,022	126	99	40	46
Nov	2,438	71	63	33	29
Dec	333	16	14	48	19
Boca Raton					
Jan	114	11	9	31	9
Feb	171	8	7	34	6
Mar	644	13	20	22	19
Apr	1,407	6	29	53	38
May	1,625	29	55	67	66
Jun	2,268	38	53	68	45
Jul	3,119	24	64	93	66
Aug	4,471	33	126	180	106
Sep	4,959	46	161	234	123
Oct	1,117	43	42	19	40
Nov	500	30	26	20	22
Dec	200	10	8	31	13

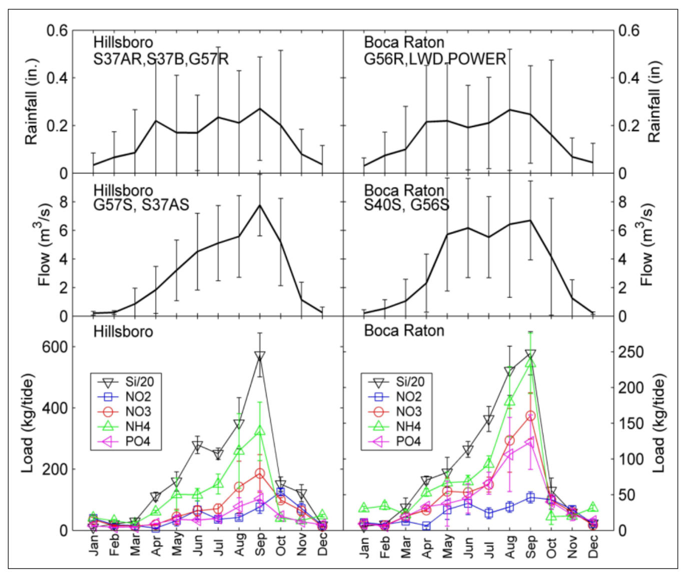

Fig. 6. Upper panels: monthly average rainfall from rain stations associated with the Hillsboro Inlet (left) and Boca Raton Inlet (right). Middle panels: monthly averaged canal flow through canals associated with the Hillsboro Inlet (left) and Boca Raton Inlet (right). Bottom panels: estimated loadings (Kg/ebb tide) of five nutrients through the Hillsboro Inlet (left) and the Boca Raton Inlet (right), averaged over months. Silicate (Si) concentrations have been divided by 20 for ease of presentation. Vertical bars in all panels denote one standard deviation of the results for that month (±½σ).

season when concentrations are changing rapidly. Financially constraints in this effort dictated the bi-weekly sampling scheme used.

Estimating the flux rate (Q) using a small boat is a challenging procedure, especially in this effort as both of these inlets are irregularly shaped. This necessitated choosing a transect line which was practical and safe to navigate. Skilled boatmanship allowed the ADCP instrument to be transected accurately during the majority of the attempts. The large number of transects that were made during the ebb tide intensive efforts minimized the possibility of an individual transect significantly biasing the tidal prism estimate. The small portion of the transect line cross section that is not directly measured by the ADCP is estimated by the survey software. The software includes a number of post-processing options that allow the user to optimize this approximation and minimize the errors associated with it. Having only a limited number of tidal prism estimates to include in the regression calculation with the tidal heights is a source of error; however, the regression statistics suggest that these errors are not large.

The estimation of a tidal prism time series using tidal ranges which are generated from astronomical tidal constituents does not capture the contributions to the tidal prism attributable to rainfall and/or canal water releases. This type of error will bias the data low on days when rainwater or canal flow is contributing to the tidal prism. As an example, it was observed that on October 15, 2012, significant rain had fallen recently, and the water levels appeared high. The tidal prism was measured at $3.25*10^6$ m^3. The estimated tidal prism from the subsequent regression calculation was $3.15 *10^6$ m^3. In this example the calculated tidal prism is 3% lower than the measured tidal prism.

V. Conclusions

We have described a method of estimating the nutrient loading to the coastal ocean through tidal inlets. By utilizing shore-based sampling, the expense associated with vessel operations is reduced. By interpolation of nutrient concentration data and the estimation of tidal prisms from published tidal data, reasonable estimates of tidal loadings through a tidal inlet may be made at significant savings compared to continuous measurement techniques. The resulting chemical loading data will be of critical importance in understanding the impact of continental material into the coastal ocean and should be incorporated into coastal modelling and watershed management efforts.

We have applied this procedure at two important southeast Florida inlets, resulting in the first time series estimates of chemical loadings through those inlets into the coastal ocean. As can be seen from Fig. 5, the largest loadings occur concurrently with maxima in the rainfall and the flow through canal control structures. In this region, seasonal rainfall directly contributes to nutrient enhancement of inland waters via surface runoff. In a less direct manner, rainfall modulates the flow through the water management system. When it is deemed necessary to reduce inland canal levels, control structures are operated and, in some instances, a large volume of inland water (generally with elevated nutrient concentrations compared to the coastal ocean [12]) is released into the ICWW and subsequently reaches the coastal ocean through the inlets. During the dry season, the intracoastal water salinities rise, approaching that of the coastal water. During this time, nutrient concentrations and hence, tidal loadings, are low when compared to the rainy season.

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