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Benthic Oxygen and Nutrient Fluxes in Tampa Bay: A Final Report to the Tampa Bay Estuary Program, Florida Department of Environmental Protection, and U.S. Environmental Protection Agency Gulf of Mexico Program

FINAL REPORT

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BENTHIC OXYGEN AND NUTRIENT FLUXES IN TAMPA BAY: A FINAL REPORT TO THE TAMPA BAY ESTUARY PROGRAM, FLORIDA, DEPARTMENT OF ENVIRONMENTAL PROTECTION, AND U. S. ENVIRONMENTAL PROTECTION AGENCY GULF OF MEXICO PROGRAM

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Introduction: This project measured rates of nutrient fluxes between Tampa Bay sediments and the overlying water column. This information has been lacking from previous nitrogen budgets for Tampa Bay, potentially hampering their accuracy and effectiveness. At the beginning of this study and in previous nitrogen budgets for Tampa Bay, sediment fluxes were assumed to provide approximately 25% to 30% of "new" nitrogen entering the water column. Our measurements demonstrate that the actual role of sediments in the nitrogen cycle of Tampa Bay is more complex than we anticipated. Nutrient fluxes measured at eight sites in Tampa Bay indicate that sediments in different Bay segments can serve as sources or sinks for nitrogen as well as temporary storage pools. Furthermore, the role of sediments within a Bay segment can vary seasonally. Refined nitrogen budgets for Tampa Bay can now include sediment processes in the continued development of nitrogen loading targets to support habitat restoration.

Background and Rationale: More than 80% of the seagrass habitat present in Tampa Bay in the late 1800's has been lost, primarily as the result of water quality degradation (Lewis et al., 1985). Seagrasses are extremely sensitive to declines in water quality because they are shaded by phytoplankton in the water column and by epiphytic algae which proliferate when nutrients- nitrogen and phosphorus- in the water column are high (Tomasko and Lapointe, 1991; Dixon and Leverone, 1995). Phosphorus concentrations in Tampa Bay are naturally high because several rivers drain the Bone Valley phosphorite deposits in eastern Hillsborough and Polk Counties (Fanning and Bell, 1985). For this reason, Tampa Bay is nitrogen-limited, and efforts are being made to improve Tampa Bay water quality by limiting nitrogen inputs to the Bay (Johansson, 1991; Janicki and Wade, 1996).

Water quality in Tampa Bay reached its nadir in the mid-1970's when almost 10,000 tons of nitrogen entered the Bay from various sources- a number five times greater than historical estimates (Zarbock et al., 1994). Nitrogen loading to Tampa Bay dropped to less than 4000 tons/year in the 1985-1991 period, primarily as the result of declines in point-source loading and fugitive emissions. However, resource managers are concerned by future nitrogen loading rates which might rise to nearly 6000 tons per year in 2010, in response to increases in nonpoint-source and atmospheric nitrogen loading. If we hope to maintain and restore seagrass habitats and their fisheries resources in Tampa Bay, we need to control nitrogen inputs to the estuary.

Efforts to manage nitrogen levels in Tampa Bay, in turn, depend on accurate estimates of nitrogen inputs, exports, and internal transformations for the Bay. However, existing nitrogen budgets for Tampa Bay have not included estimates of the rate of nitrogen exchange between sediments and the water column because those processes have not been measured in Tampa Bay. This omission is serious because Tampa Bay is a relatively shallow and well-mixed estuary, so exchanges between the water column and bottom sediments are potentially very large and might affect the entire water column (Fanning and Bell, 1985). In other estuaries, nitrogen is recycled between water column and sediments, effectively amplifying the effect of external nitrogen loads on estuarine water quality (Cowan et al., 1996; Fisher et al., 1982; Nixon 1981, Twilley et al., 1999). Other studies have shown that the sediment processes of denitrification and burial can enhance water quality by exporting or sequestering nitrogen from the water column (Seitzinger, 1987, 1988).

Methods- We collected four replicate cores from each of eight sites in Tampa Bay in fall 2002 as well as winter, spring, summer, and fall 2003. We incubated cores in the dark in plexiglas core sleeves with approximately one liter of water overlying each core. We stirred and sampled the overlying water periodically over 48 hours and analyzed filtered supernatant samples for ammonia, nitrate/nitrite, total dissolved nitrogen, phosphate, total dissolved phosphorus and silicate. Dissolved organic nitrogen and dissolved organic phosphorus were estimated by difference.

Site Selection: Within four regions of Tampa Bay (Old Tampa Bay, Hillsborough Bay, Middle Tampa Bay, and Lower Tampa Bay) we selected one site with fine-grained sediment and one site with coarse sediment. To locate coarse and fine sediment in each Bay region, we used sediment texture (sand, silt-clay) data collected by Hillsborough County Environmental Protection Commission. The data (in an Excel spreadsheet) were provided to us by Steve Grabe of HCEPC. We transferred the data to Arcview (Figure 1) and created contour maps of sediment texture using Spatial Analyst. From the contour map, we extracted the latitude and longitude of four to five sites in each Bay region which were likely to have either coarse or fine-grained sediment.

Several sites in each bay region were visited, and the eight sites selected were chosen using two primary criteria. The first criterion was sediment texture because, in this pilot study, we want to constrain the highest and lowest rates of benthic metabolism and nutrient flux for each bay region. Previous studies, ours and those of other authors, have shown that fine-grained sediments typically have high microbial respiration rates and high nutrient flux rates. We verified sediment texture at each site using a Petit Ponar benthic grab. The scarcity of fine-grained sediment in Lower Tampa Bay forced us to sample in Little Bayou, an embayment on the west side of Lower Tampa Bay. The second criterion was to find coarse and fine-grained sites within each region which were close enough together to have similar salinity regimes. The eight sites selected are shown below in Figure 2.

Collection and Incubation of Core Samples: During each sampling interval (fall 2002 and winter, spring, summer and fall 2003), cores from Old Tampa Bay and Hillsborough Bay sites were sampled on one date and Middle Tampa Bay and Lower Tampa Bay sites were sampled a week later. On each sampling date, divers collected four cores at each site, for a total of sixteen cores.

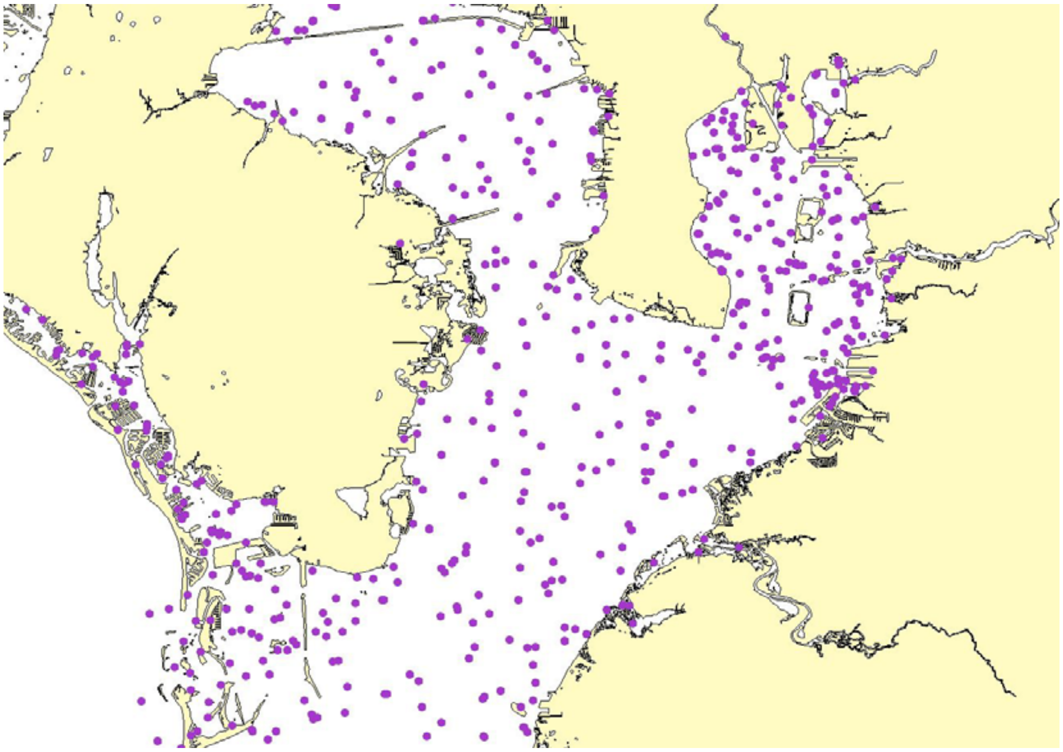

Figure 1: Location of HCEPC sediment sampling sites

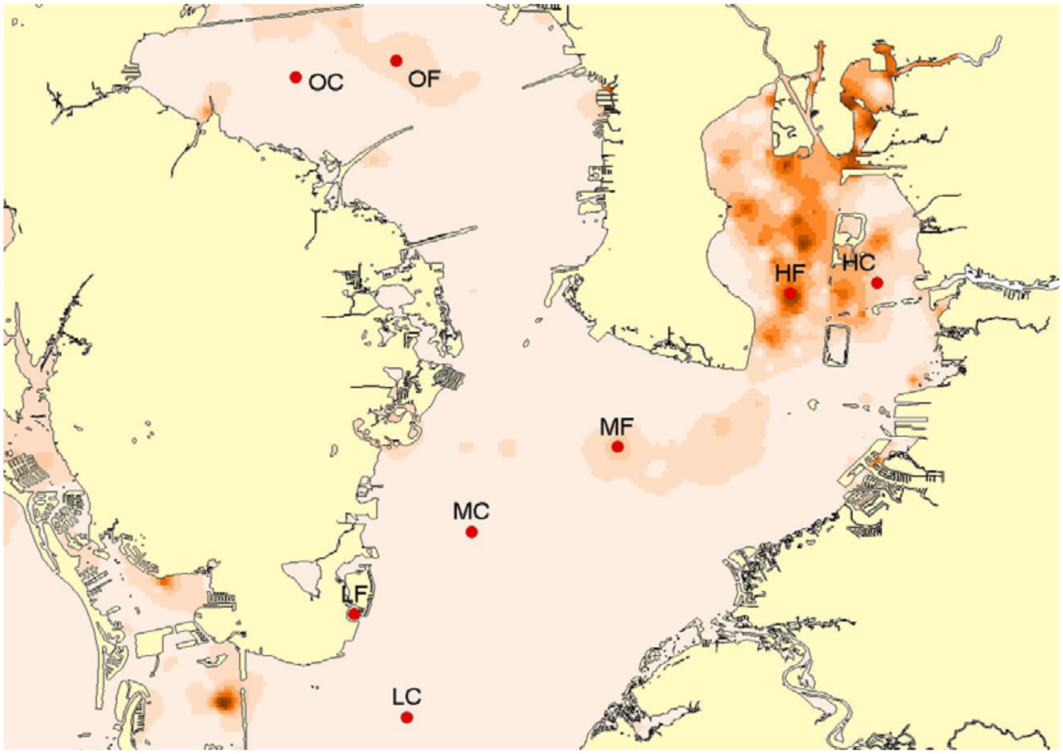

Figure 2. Eight sites selected for benthic flux measurements in this study. The first letter of each site code refers to bay region, while the second letter refers to sediment texture (C=coarse; F=fine).

To collect a core, divers inserted a Plexiglas core sleeve into the sediment to a pre-determined depth. Visibility was often so poor that divers literally could not see their hands in front of their faces. In those cases, rubber bands on the outside of core sleeves served as a tactile reference for core insertion. The core was capped with an undisturbed column of water in the sleeve. The core sleeve was gently excavated, and a custom-made, dual O-ring, piston was inserted in the bottom of the core sleeve to seal the sediments in place and to prevent any disturbance of sediment or porewater nutrient profiles. The sealed core was gently transferred to the boat (see Figure 3 below) and transported to the lab at FWRI.

Figure 3: Jitka Hyniova collects a core at the LTB fine site.

In the laboratory, cores were transferred to two 20-gallon aquaria. The aquaria were filled with water from each bay region to prevent cores from heating or cooling during incubation. Incubations were carried out in a dark, temperature-regulated wet lab (see Figure 4, below).

After collection and transfer to the wet lab, cores were held overnight in the dark while being bubbled with air to prevent hypoxia. In the morning after collection, the supernatant water was gently siphoned off the cores and replaced with low-nutrient seawater adjusted to ambient salinity for each site. Nutrient fluxes were measured over the next 48 hours by periodically withdrawing supernatant from each core. Supernatant samples were filtered and frozen prior to analysis for dissolved silicate, ammonia, nitrate+nitrite, phosphate, total dissolved phosphorus, and total dissolved nitrogen.

Extrapolation of measured fluxes- Estimates of benthic nutrient supply (or uptake) for Bay segments were carried out in a series of steps. Supernatant water for each core was sampled every two hours on the first day of incubation, and filtered water samples were analyzed for silicate, phosphate, ammonia, nitrate+nitrite, total dissolved nitrogen and total dissolved phosphorus. Linear regression was then performed on nutrient concentration data to calculate flux rates, using only data from the first day of core incubation (see QA section below). Mean flux rates were calculated for each group of four replicate cores, and outliers were excluded.

Figure 4. Cores on wet lab bench. Photos taken after incubations.

Flux rates, expressed in millimoles oxygen, nitrogen, phosphorus, or silica per square meter per day (see Appendix A tables), were multiplied by the area of fine-grained and coarse sediment present in each Bay segment. Sediment texture was determined from the HCEPC sediment dataset noted earlier, and bottom area for each sediment type was calculated using ArcGIS 8.3. HCEPC water temperature data were also used to translate seasonal flux measurements into annual estimates. The annual estimates, in turn, were compared to external nitrogen and phosphorus loads calculated by Poe et al. (2005). Complete spreadsheets outlining calculations are included in the Appendix.

Precautions for quality control and data analysis- At every step in the sampling, core incubation, and data analysis, precautions were taken to ensure data quality:

1. Cores were collected by divers using methods to minimize disturbance of the sediment-water interface and the isolated column of sediment. Double O-ring pistons were inserted into the bottom of each core sleeve to minimize leakage. Core sleeves were completely filled with site water and capped to avoid disturbance during transport to the lab.

2. In the lab, core sleeves were aerated continuously in the dark overnight to "reset" the status of benthic microalgae. Phytoplankton and benthic microalgae have

demonstrated the capacity to fix nitrogen and phosphorus for up to 12 hours in the dark. Site water was replaced with low nutrient seawater adjusted to the salinity of each site. In our calculations of nutrient flux rates, we ignore the potential effect of a concentration gradient decreased by elevated water column nutrient concentrations. Replacing site water with filtered seawater also eliminated any potential influence of phytoplankon on core flux estimates.

3. Estimates of nutrient fluxes in each core were based solely on fluxes measured during the first day of incubation. Although incubations were carried out for almost 72 hours, concerns about longer incubation times were expressed at the Tampa Bay Basis 4 Symposium. Fred Holland, in particular, was concerned that, based on sediment-water exchange measurements in the Patuxent Estuary, artifacts increased with increasing duration of incubation. Artifacts that might affect flux estimates include development of microalgal or bacterial mats, decomposition of infauna killed by coring or by subsequent hypoxia.

4. Core incubations and sampling were carried out in total darkness, so cores were examined and photographed at the end of the incubation period to identify incubation artifacts. Data were not used from cores which demonstrated leakage around piston O-rings or contained dead infauna.

Results and Discussion: Differences in sediment texture and redox state among sites were striking. For example, Figure 5 (below) illustrates visible redox discontinuities in the Middle Tampa Bay coarse sediment core and the Lower Tampa Bay coarse

Figure 5: Fine and coarse texture sediment cores from Middle Tampa Bay and Lower Tampa Bay

sediment core. Fine grained sediment cores from Middle Tampa Bay and Lower Tampa Bay are uniformly anoxic. Fine sediment cores from Hillsborough Bay had the highest silt-clay content, followed by Old Tampa Bay, Middle Tampa Bay, and Lower Tampa Bay.

Bioturbation and irrigation of cores by infauna also might have had significant impacts on measured fluxes depending on the number, size, and activity of animals (Figure 6). Old Tampa Bay and Hillsborough Bay cores typically had brachiopod bivalves and small polychaetes in them. Many sites have numerous brittle stars, and the LTB coarse site has lots of sand dollars. With the exception of sand dollars, we allowed organisms to remain in the cores because it is too disruptive to remove them.

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Figure 6. Effects of burrowing organisms on sediment cores. Core on left contains a large brittle star with its disk approximately 5 cm below the sediment surface and its arms stretched upward through the sediment into the overlying water. Core on right contains numerous small polychaetes which irrigate the sediment during incubations.

Transformations among nitrogen species occurred during core incubations as shown in Figure 7. Core incubations remove phytoplankton from the overlying water, and they eliminate external sources and sinks. However, Tampa Bay sediments (and all estuarine sediments) contain a mixture of dissolved organic nitrogen (DON) as well as inorganic nitrogen species such as ammonium (NH4), nitrate (NO3), and nitrite (NO2). Because Tampa Bay sediments are generally anaerobic, porewater nitrate and nitrite concentrations are frequently very low, and DON and ammonium comprise most of the nitrogen dissolved in sediment porewaters.

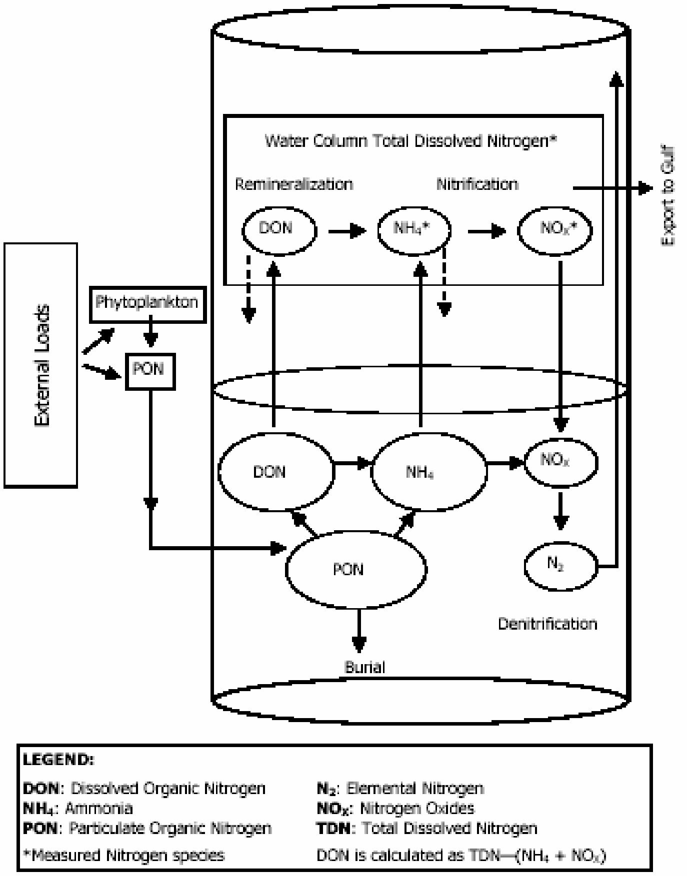


Figure 7. A conceptual model of nitrogen cycling and transformation in Tampa Bay, Florida. Drawing by Lindsay Cross.

As DON and ammonium move from the sediment to the overlying water, bacteria on the sediment surface or in the overlying water can convert DON to ammonium or vice versa. In the process of nitrification, ammonium is oxidized to nitrite and nitrate. Anaerobic sediment bacteria can use nitrate as a terminal electron receptor for respiration, causing nitrate concentrations to decline in the overlying water. This process, denitrification, converts nitrate to nitrogen gas which then diffuses out of the sediment and overlying water. Because DON and ammonium concentrations are generally much higher in sediments than in overlying water, flux of these two nitrogen species from the overlying water to the sediments is generally negligible.

Because nitrogen can be transformed in a number of different ways, the movement of total dissolved nitrogen is the most important parameter describing the nitrogen “processing” capability of sediments from different regions of Tampa Bay. The behavior of individual nitrogen species in core incubations represents the potential magnitude of fluxes and dominant microbial pathways. Potential losses from the system as the result of denitrification are particularly interesting, because they reduce the “fuel” for phytoplankton blooms.

Seasonal and Spatial Patterns of Sediment Nitrogen Fluxes- Fluxes of the three principal nitrogen species varied seasonally among Bay segments and between fine and coarse sediment sites within Bay segments (Table 1). Net ammonia fluxes were positive (moving from sediment to overlying water) for most sites and most seasons. However, uptake by benthic microorganisms or nitrification caused ammonia concentrations to decline in Lower Tampa Bay coarse sediment cores collected in May and August. Elsewhere, lowest positive fluxes were observed in February when temperatures were lowest. Highest release from the sediments was measured in coarse sediments from Hillsborough Bay in August. Releases of ammonia were also elevated from coarse and fine sediments in Old and Middle Tampa Bay regions In May.

The direction and magnitude of fluxes of the oxidized inorganic nitrogen species, nitrate and nitrite (NOX), varied seasonally and among sites. Moderate and positive NOX fluxes (increasing concentrations during core incubations) were observed in fine and coarse sediments of Hillsborough Bay for all seasons. Because Hillsborough Bay sediments are anaerobic, the observed increases in NOX species during core incubations probably resulted from nitrification of sediment ammonia at the sediment surface or in the overlying water. Old Tampa Bay sediments had mixed NOX fluxes, but Middle and Lower Tampa Bay sediments had small, negative NOX fluxes during most incubations, indicating denitrification occurred for much of the year. Small, positive fluxes (nitrification) occurred during November at Middle and Lower Tampa Bay sites.

Table 1: Seasonal and Spatial Variation in Measured Nitrogen Fluxes. Data are mol/ha/d.

		Hillsborough Bay		Old Tampa Bay		Middle Tampa Bay		Lower Tampa Bay	
		Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
Ammonia									
	Feb-03	1.94	5.53	7.78	3.27	7.89	0.20	8.42	0.47
	May-03	9.76	19.1	20.6	24.3	22.7	19.8	7.64	-2.48
	Aug-03	12.8	33.7	19.9	4.70	18.0	8.05	18.6	-1.27
	Nov-03	12.5	12.5	20.5	7.06	14.5	1.96	18.8	0.97
Nitrate+Nitrite									
	Feb-03	1.47	1.61	5.70	1.78	-0.59	-0.25	-0.25	0.09
	May-03	6.91	2.34	3.18	-0.81	-0.73	-1.39	0.16	-1.34
	Aug-03	5.54	1.01	-0.23	0.17	-0.60	-0.32	-1.09	-0.86
	Nov-03	4.63	1.64	-0.84	0.39	0.33	0.44	0.74	0.29
Dissolved Organic Nitrogen									
	Feb-03	11.9	8.00	9.27	5.26	9.39	-1.87	8.32	-0.23
	May-03	14.2	-19.7	-32.9	-18.2	15.0	24.2	8.44	-14.2
	Aug-03	-27.4	42.3	-39.2	-19.0	33.4	12.5	17.7	-20.9
	Nov-03	22.8	23.7	26.1	-13.6	31.8	7.57	41.8	-24.8
Total Nitrogen (by summation)									
	Feb-03	15.3	15.1	22.8	10.3	16.7	-1.92	16.5	0.34
	May-03	30.9	1.81	-9.20	5.30	37.0	42.6	16.2	-18.0
	Aug-03	-9.04	77.1	-19.5	-14.1	50.8	20.2	35.3	-23.0
	Nov-03	39.9	37.9	45.7	-6.10	46.6	9.97	61.3	-23.5

Dissolved organic nitrogen fluxes exhibited a complex spatial and temporal pattern, and their overall magnitude was slightly greater than to several times higher than ammonia fluxes. Negative DON fluxes occurred in the fine sediments of Hillsborough Bay in August and Old Tampa Bay in May and August. Negative DON fluxes occurred in Lower Tampa Bay coarse sediments in all seasons.

Net total nitrogen fluxes were positive for most sites and most seasons, but there were some exceptions. Lower Tampa Bay coarse sediments were negative (net sediment uptake or denitrification) in May, August, and November. Small positive fluxes occurred at Lower Tampa Bay coarse sites only in February. Net positive fluxes occurred for all sampling dates in coarse sediments of Hillsborough Bay, and in fine sediments of Middle and Lower Tampa Bay.

Comparison with other estuaries- Benthic fluxes of nutrients have been measured in a wide variety of estuaries in North America, and Twilley et al. (1999) summarized this information with an emphasis on fluxes in estuaries along the Gulf of Mexico. Ammonia releases from sediments from Ochlockonee Bay, Appalachicola Bay and Mobile Bay along the northern Gulf coast averaged from 4.5 to 15 mol ha^{-1} day^{-1}, close to the range of our measurements. The range of average fluxes reported for Chesapeake Bay, Narragansett Bay, the Patuxent estuary, and the Neuse River estuary (-8 to 121 mol ha^{-1} day^{-1}) is much greater than the range we observed in Tampa Bay (Twilley et al., 1999, this study). Average benthic fluxes of nitrate-nitrite in Ochlockonee Bay and Mobile Bay were greater than our measurements for Tampa Bay sediments and ranged from an uptake of -8.9 to release of 3.4 mol ha^{-1} day^{-1}(Twilley et al., 1999). DON fluxes, which are a large part of the total nitrogen exchange between Tampa Bay sediments and the water column, were not reported in Twilley et al. (1999).

Benthic fluxes of phosphorus and silicate- Fluxes of phosphate were highly variable throughout the study (Table 2) and ranged from uptake in Lower Tampa Bay coarse sediments during May, August, and November to large releases from coarse sediments in Hillsborough Bay during August and from fine sediments in Middle Tampa Bay in November. Phosphate was released from all Hillsborough Bay and Middle Tampa Bay cores, but showed a mixture of uptake and release in cores from Old Tampa Bay and Lower Tampa Bay.

Fluxes of total dissolved phosphorus (TDP--phosphate and dissolved organic phosphorus) were similar in magnitude to fluxes of phosphate but generally did not show as strong a seasonal variation as was observed for phosphate fluxes. TDP was released from all Hillsborough Bay cores. Other sites showed a mixture of uptake and release, and fluxes tended to be smaller in February when temperatures were lowest. In Lower Tampa Bay coarse sediments, TDP was removed from the water column in February, August, and November.

Silicate fluxes were much greater in magnitude than fluxes of any other measured nutrient, and were especially high in Hillsborough Bay. Except for coarse sediments from Lower Tampa Bay in May, silicate was released from all sediment cores. Overall, releases tended to be smaller in February, and to decrease seaward in the bay. Fluxes from coarse sediments in Lower Tampa Bay were an order of magnitude less than silicate fluxes observed elsewhere in the bay.

Table 2: Seasonal and Spatial Variation in Measured Dissolved Phosphorus and Silicate Fluxes.

Data are mol/ha/day.

	Hillsborough Bay		Old Tampa Bay		Middle Tampa Bay		Lower Tampa Bay	
	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
Phosphate								
Feb-03	1.44	0.77	2.59	0.98	3.54	1.38	1.74	1.13
May-03	5.58	4.92	4.83	3.99	1.61	6.86	0.34	-0.05
Aug-03	10.70	21.65	-3.37	-2.22	18.75	4.43	3.69	-2.29
Nov-03	7.03	7.79	12.10	2.09	24.58	0.75	7.99	-1.16
Total Dissolved Phosphorus								
Feb-03	4.89	2.46	0.67	2.91	1.78	-0.54	2.22	-0.25
May-03	5.34	8.97	5.97	4.42	2.63	5.87	2.36	0.66
Aug-03	8.54	8.10	-0.99	-1.42	10.45	4.76	5.44	-1.74
Nov-03	8.17	6.93	6.63	1.62	21.59	0.22	6.25	-12.57
Silicate								
Feb-03	36.25	17.60	52.26	35.05	71.41	4.78	21.22	2.36
May-03	90.09	87.07	89.10	79.59	122.8	45.86	52.19	-4.35
Aug-03	104.5	125.8	66.79	44.59	91.39	91.58	60.31	6.60
Nov-03	73.64	37.20	68.27	16.78	45.60	16.92	63.24	0.16

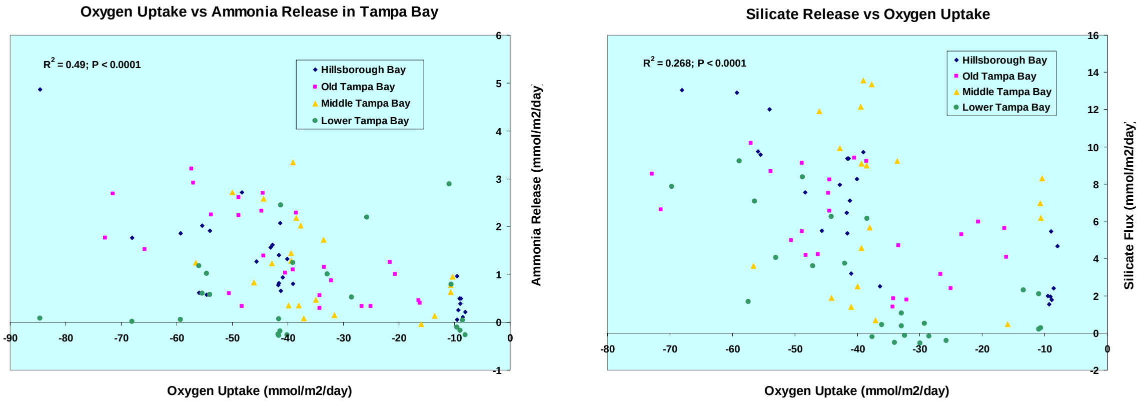
Oxygen uptake by sediments showed a strong seasonal variation with lowest uptake in winter (-8.8 to 25 mmol m^{-2} day^{-1}) and highest uptake (33 to 71 mmol m^{-2} day^{-1}) in spring or summer (Table 3). Highest oxygen uptake rates were measured in coarse Hillsborough Bay sediments and fine Old Tampa Bay sediments in August. Lowest rates overall were observed in cores from coarse sediments in Lower Tampa Bay.

Oxygen uptake was significantly and negatively correlated with ammonia and silicate fluxes (Figure 8) for all sites and seasons, but correlations of oxygen fluxes with nutrient fluxes were not significant for any other nutrient for all sites.

Table 3. Benthic Uptake of Dissolved Oxygen by Tampa Bay Sediments:

Sediment Type:		Hillsborough Bay		Old Tampa Bay		Middle Tampa Bay		Lower Tampa Bay	
		Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
Areal fluxes based on core incubations (mmol/m2/day):									
Feb-03	Mean	-8.77	-9.22	-18.71	-25.00	-10.57	-15.34	-12.13	-10.63
	Std. Dev.	0.65	0.30	2.81	1.69	0.18	1.54	1.25	0.32
May-03	Mean	-43.19	-44.20	-47.78	-51.08	-38.75	-49.19	-50.60	-31.82
	Std. Dev.	5.40	3.58	7.26	5.42	0.90	7.82	8.75	5.12
Aug-03	Mean	-55.00	-70.64	-70.01	-49.88	-37.15	-42.31	-43.02	-33.23
	Std. Dev.	0.86	12.85	3.79	3.50	3.09	4.02	5.71	2.96
Nov-03	Mean	-41.20	-41.53	-41.39	-34.92	-44.21	-38.17	-56.34	-35.37
	Std. Dev.	0.75	3.93	6.83	2.92	10.1	5.26	9.89	8.45

Figure 8. Scatter plot of oxygen uptake versus ammonia and silicate release in Tampa Bay sediments. Data includes all sites and dates.



Nitrogen Fluxes by Bay Segment- Seasonal flux data were extrapolated to annual fluxes for each site, and flux rates measured in coarse and fine sediments were multiplied by their respective Bay bottom areas for each Bay segment (Table 4). Total annual ammonia fluxes were positive in Hillsborough Bay, Old Tampa Bay and Middle Tampa Bay segments, but negative in Lower Tampa Bay. Annual nitrate/nitrite fluxes were positive for Hillsborough Bay and Old Tampa Bay and negative for Middle Tampa Bay and Lower Tampa Bay. DON fluxes were negative for Old Tampa Bay and Lower Tampa Bay but positive for the other two Bay segments. Sediments removed all nitrogen fractions in Lower Tampa Bay. For Tampa Bay as a whole, sediment releases of ammonia contributed the most nitrogen to estuarine waters; overall there was a small net release of NOX to the system, and a substantial net uptake of DON by the sediments. Overall, the sediments contributed about 2900 tons of nitrogen per year to Tampa Bay

Table 4. Total Annual Nitrogen Flux Estimates by Bay Segment.
Values are tons per year.

	Hillsborough Bay	Old Tampa Bay	Middle Tampa Bay	Lower Tampa Bay	Bay Total
Ammonia	786	1110	1290	-44.3	3140
NO3&NO2	133	92	-70	-58.9	96
DON	541	-1030	1730	-1580	-339
TDN	1460	172	2950	-1680	2900

Comparison of Benthic Fluxes with External Nitrogen Load Estimates- Poe et al (2005) found that annual external nitrogen loads to Tampa Bay varied as the result of variations in rainfall. To provide a context for our measured flux rates, we compared benthic nitrogen fluxes to external load estimates for 2000, a dry year, and 2003, a wet year. In a dry year, total benthic nitrogen flux is approximately 200% of external nitrogen loads for Hillsborough Bay, 40% for Old Tampa Bay, 590% for Middle Tampa Bay, and -780% for Lower Tampa Bay (indicating net uptake by the sediments), respectively (Table 5). In a wet year, the magnitude of benthic fluxes diminishes in comparison to external inputs. For Tampa Bay overall, benthic fluxes of nitrogen contribute 156% of external loads in a dry year and 55% of external loads in a wet year.

Ammonia fluxes range from a net uptake of 20% of external loads in Lower Tampa Bay to releases that were 280% of external nitrogen loads to Tampa Bay segments in a dry year. Acknowledging that there are errors associated both with external load estimates and those introduced by extrapolating core flux measurements, these flux estimates still suggest that sediments produce, store, and recycle considerable amounts of nitrogen in Tampa Bay (see Figure 7 above). Large differences in the magnitude and direction of fluxes among the four regions of Tampa Bay also indicate that nitrogen processing as well as loading vary significantly as a function of bay location. The upper bay is a source of remineralized inorganic nitrogen (ammonia and NOX) while the lower bay removes inorganic nitrogen from the water column. Cycling of DON is much more complex with Old Tampa Bay and Lower Tampa Bay sediments removing DON and Hillsborough Bay and Middle Tampa Bay sediments releasing DON to the water column.

Negative fluxes of nitrate/nitrite and DON also indicate that sediments and associated microorganisms have the capacity to transform significant amounts of nitrogen in Tampa Bay. For example, DON processing by contact with sediments can account for up to 1030 tons of nitrogen in Old Tampa Bay each year, a number very similar to the positive ammonia flux measured for this Bay segment.

How significant are benthic nitrogen fluxes to the Tampa Bay nitrogen budget? Our answer at this point is that benthic processing is very important. However, the assessment is more qualitative than quantitative, and our research indicates that several processes should be investigated further. For example, our flux estimates are based on diffusive fluxes. Mass flux driven by tidal pumping of porewaters or by groundwater discharge might increase flux estimates.

We have also measured large, positive fluxes of ammonia in Old Tampa Bay, Hillsborough Bay, and Middle Tampa Bay. Additional research should determine whether the ammonia is “new” nitrogen entering the system from runoff or atmospheric deposition.

Large, positive fluxes of dissolved organic nitrogen out of the sediments are also worthy of additional study because we don’t know how labile DON is in Tampa Bay. If it is easily broken down to ammonia, it can be a significant source of nitrogen for phytoplankton.

Finally, large, negative fluxes of nitrogen into sediments of Lower Tampa Bay indicate this Bay region can remove large amounts of nitrogen from the water column. The fate of this nitrogen- denitrification or uptake by benthic algae- should be determined.

To better quantify the role of sediment/water exchange processes, we still need to answer the following questions:

1. What is the storage capacity and turnover time of nitrogen in Tampa Bay sediments? How old is the nitrogen fluxing from sediments? Days, weeks, months, or years?
2. What is the ultimate source of nitrogen in Tampa Bay sediments? Do sediments add new nitrogen to the system or recycle external nitrogen loads?

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Appendix : Estimates of Benthic Nutrient Fluxes

Table A-1: Benthic Ammonia Flux Estimates

		Hillsborough Bay		Old Tampa Bay		Middle Tampa Bay		Lower Tampa Bay	
Sediment Type:		Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
Areal fluxes based on core incubations (mmol/m2/day):									
Feb-03	Mean	0.194	0.553	0.778	0.327	0.789	0.020	0.842	0.047
	Std. Dev.	0.150	0.297	0.419	0.012	0.162	0.101	0.299	0.033
May-03	Mean	0.976	1.91	2.06	2.43	2.27	1.98	0.764	-0.248
	Std. Dev.	0.431	0.707	1.02	0.330	0.972	1.04	0.340	0.046
Aug-03	Mean	1.28	3.37	1.99	0.470	1.80	0.805	1.86	-0.127
	Std. Dev.	0.791	1.80	0.614	0.192	0.346	0.440	0.890	0.130
Nov-03	Mean	1.25	1.25	2.05	0.706	1.45	0.196	1.88	0.097
	Std. Dev.	0.605	0.311	0.798	0.349	1.06	0.142	0.604	0.046
Area (ha):		3160	7374	4013	16054	3099	27892	493	24165
AMMONIA FLUXES (MOL/HA/DAY)									
Feb-03		1.94	5.53	7.78	3.27	7.89	0.202	8.42	0.475
May-03		9.76	19.14	20.56	24.30	22.66	19.82	7.64	-2.48
Aug-03		12.79	33.73	19.91	4.70	18.00	8.05	18.62	-1.27
Nov-03		12.49	12.55	20.46	7.06	14.46	1.96	18.76	0.973
Days	FLUXES (mol/subsegment/season)								
121	Winter	743100	4934000	3780000	6349000	2957000	682500	502200	1389000
91	Spring	2806000	12840000	7508000	35500000	6390000	50290000	342700	-5460000
92	Summer	3719000	22880000	7349000	6939000	5133000	20660000	844700	-2815000
62	Fall	2447000	5736000	5091000	7028000	2778000	3391000	573500	1458000
	FLUXES (mt/subsegment/season)								
	Winter	10.40	69.08	52.92	88.89	41.40	9.56	7.03	19.45
	Spring	39.28	180.0	105.1	497.0	89.46	704.1	4.80	-76.44
	Summer	52.07	320.3	102.9	97.15	71.86	289.2	11.83	-39.41
	Fall	34.26	80.30	71.27	98.39	38.89	47.47	8.03	20.41
	ANNUAL FLUX BY SEDIMENT TYPE (mt/subsegment/yr):								
		136.0	649.7	332.2	781.4	241.6	1050	31.68	-75.99
	ANNUAL FLUX BY BAY SEGMENT (mt/segment/yr):								
		786		1114		1292		-44.3	
	TOTAL ANNUAL FLUX FOR THE WHOLE BAY (mt/yr):								
		3147							

Table A-2: Nitrate+Nitrite Fluxes from Tampa Bay Sediments

			Hillsborough Bay		Old Tampa Bay		Middle Tampa Bay		Lower Tampa Bay	
Sediment Type:			Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
	Areal fluxes based on core incubations (mmol/m2/day):									
	Feb-03	Mean	0.147	0.161	0.570	0.178	-0.059	-0.025	-0.025	0.009
		Std. Dev.	0.058	0.115	0.130	0.108	0.022	0.019	0.047	0.039
	May-03	Mean	0.691	0.234	0.318	-0.081	-0.073	-0.139	0.016	-0.134
		Std. Dev.	0.641	0.071	0.151	0.046	0.011	0.034	0.027	0.076
	Aug-03	Mean	0.554	0.101	-0.023	0.017	-0.060	-0.032	-0.109	-0.086
		Std. Dev.	0.237	0.099	0.048	0.006	0.048	0.053	0.028	0.041
	Nov-03	Mean	0.463	0.164	-0.084	0.039	0.033	0.044	0.074	0.029
		Std. Dev.	0.034	0.016	0.051	0.023	0.019	0.015	0.016	0.024
Area (ha):			3160	7374	4013	16054	3099	27892	493	24165
	NOX FLUXES (mol/ha/day)									
	Feb-03		1.47	1.61	5.70	1.78	-0.59	-0.25	-0.25	0.09
	May-03		6.91	2.34	3.18	-0.81	-0.73	-1.39	0.16	-1.34
	Aug-03		5.54	1.01	-0.23	0.17	-0.60	-0.32	-1.09	-0.86
	Nov-03		4.63	1.64	-0.84	0.39	0.33	0.44	0.74	0.29
Days	FLUXES (mol/subsegment/season)									
121	Winter		563700	1435000	2766000	3453000	-222200	-833300	-14730	257800
91	Spring		1987000	1569000	1162000	-1185000	-206900	-3536000	6962	-2955000
92	Summer		1610000	685900	-85940	257000	-170900	-832700	-49270	-1913000
62	Fall		906600	748200	-208300	388500	63700	756300	22570	436800
	FLUXES (mt/subsegment/season)									
	Winter		7.89	20.09	38.72	48.34	-3.11	-11.67	-0.21	3.61
	Spring		27.82	21.97	16.27	-16.59	-2.90	-49.50	0.10	-41.37
	Summer		22.54	9.60	-1.20	3.60	-2.39	-11.66	-0.69	-26.78
	Fall		12.69	10.47	-2.92	5.44	0.89	10.59	0.32	6.12
	ANNUAL FLUX BY SEDIMENT TYPE (mt/subsegment/yr):									
			70.94	62.13	50.87	40.79	-7.51	-62.24	-0.48	-58.43
	ANNUAL FLUX BY BAY SEGMENT (mt/segment/yr)									
			133		92		-70		-58.9	
	TOTAL ANNUAL FLUX FOR THE WHOLE BAY (mt/yr):									
			96							

Table A-3. Dissolved Organic Nitrogen Flux Estimates for Tampa Bay Sediments.

		Hillsborough Bay		Old Tampa Bay		Middle Tampa Bay		Lower Tampa Bay	
Sediment Type:		Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
	Areal fluxes based on core incubations (mmol/m2/day):								
Feb-03	Mean	1.19	0.800	0.927	0.526	0.939	-0.187	0.832	-0.023
	Std. Dev.	0.369	0.202	0.118	0.088	0.151	0.683	0.222	0.052
May-03	Mean	1.42	-1.97	-3.29	-1.82	1.50	2.42	0.844	-1.42
	Std. Dev.	0.076	0.026	0.707	1.15	1.20	2.13	0.137	0.141
Aug-03	Mean	-2.74	4.23	-3.92	-1.90	3.34	1.25	1.77	-2.09
	Std. Dev.	1.08	0.639	0.914	0.335	1.81	0.485	0.889	0.755
Nov-03	Mean	2.28	2.37	2.61	-1.36	3.18	0.757	4.18	-2.48
	Std. Dev.	0.018	1.12	0.648	0.568	1.63	0.148	2.09	0.677
Area (ha):		3160	7374	4013	16054	3099	27892	493	24165
	DON FLUXES (mol/ha/day)								
	Feb-03	11.87	8.00	9.27	5.26	9.39	-1.87	8.32	-0.226
	May-03	14.22	-19.67	-32.94	-18.19	15.05	24.17	8.44	-14.21
	Aug-03	-27.37	42.33	-39.17	-19.01	33.36	12.50	17.75	-20.91
	Nov-03	22.76	23.74	26.10	-13.55	31.81	7.57	41.76	-24.76
Days	FLUXES (mol/subsegment/season)								
121	Winter	4537000	7142000	4503000	10210000	3520000	-6317000	496100	-660000
91	Spring	4089000	-13200000	-12030000	-26570000	4243000	61340000	378800	-31260000
92	Summer	-7957000	28720000	-14460000	-28080000	9512000	32090000	805000	-46480000
62	Fall	4458000	10850000	6494000	-13490000	6112000	13090000	1277000	-37090000
	FLUXES (mt/subsegment/season)								
	Winter	63.52	99.99	63.04	142.9	49.28	-88.44	6.95	-9.24
	Spring	57.25	-184.8	-168.4	-372.0	59.40	858.8	5.30	-437.6
	Summer	-111.4	402.1	-202.4	-393.1	133.2	449.3	11.27	-650.7
	Fall	62.41	151.9	90.92	-188.9	85.57	183.3	17.88	-519.3
	ANNUAL FLUX BY SEDIMENT TYPE (mt/subsegment/yr):								
		71.78	469.2	-216.9	-811.0	327.4	1403	41.40	-1617
	ANNUAL FLUX BY BAY SEGMENT (mt/segment/yr):								
		541		-1028		1730		-1575	
	TOTAL ANNUAL FLUX FOR THE WHOLE BAY (mt/yr):								
		-332							

Table A-4 Phosphate Flux Estimates for Tampa Bay Sediments.

			Hillsborough Bay		Old Tampa Bay		Middle Tampa Bay		Lower Tampa Bay	
Sediment Type:			Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
	Areal fluxes based on core incubations (mmol/m2/day):									
	Feb-03	Mean	0.144	0.077	0.259	0.098	0.354	0.138	0.174	0.113
		Std. Dev.	0.091	0.059	0.094	0.028	0.218		0.024	0.104
	May-03	Mean	0.558	0.492	0.483	0.399	0.161	0.686	0.034	-0.005
		Std. Dev.	0.421	0.411	0.265	0.165	0.077	0.424	0.012	0.218
	Aug-03	Mean	1.07	2.17	-0.337	-0.222	1.88	0.443	0.369	-0.229
		Std. Dev.	0.163	1.07	0.172	0.121	1.63	0.437	0.042	0.084
	Nov-03	Mean	0.703	0.779	1.21	0.209	2.46	0.075	0.799	-0.116
		Std. Dev.	0.410	0.468	0.637	0.184	0.624	0.253	0.455	0.025
Area (ha):			3160	7374	4013	16054	3099	27892	493	24165
	PO4 FLUXES (mol/ha/day)									
	Feb-03		1.44	0.77	2.59	0.98	3.54	1.38	1.74	1.13
	May-03		5.58	4.92	4.83	3.99	1.61	6.86	0.34	-0.05
	Aug-03		10.70	21.65	-3.37	-2.22	18.75	4.43	3.69	-2.29
	Nov-03		7.03	7.79	12.10	2.09	24.58	0.75	7.99	-1.16
Days	FLUXES (mol/subsegment/season)									
121	Winter		551600	689200	1556000	1912000	1329000	4666000	104100	3300000
91	Spring		1605000	3301000	1765000	5833000	454900	17400000	15190	-100800
92	Summer		3110000	14690000	-1243000	-3282000	5347000	11360000	167400	-5089000
62	Fall		1376000	3564000	3011000	2083000	4723000	1293000	244400	-1744000
	FLUXES (mt/subsegment/season)									
	Winter		7.72	9.65	21.78	26.77	18.61	65.32	1.46	46.20
	Spring		22.47	46.21	24.71	81.66	6.37	243.6	0.21	-1.41
	Summer		43.54	205.7	-17.40	-45.95	74.86	159.0	2.34	-71.25
	Fall		19.26	49.90	42.15	29.16	66.12	18.10	3.42	-24.42
	ANNUAL FLUX BY SEDIMENT TYPE (mt/subsegment/yr):									
			93.00	311.4	71.25	91.64	166.0	486.1	7.44	-50.87
	ANNUAL FLUX BY BAY SEGMENT (mt/segment/yr)									
			404		163		652		-43.4	
	TOTAL ANNUAL FLUX FOR THE WHOLE BAY (mt/yr):									
			1176							

Table A-5 Total Dissolved Phosphorus Flux Estimates for Tampa Bay Sediments.

			Hillsborough Bay		Old Tampa Bay		Middle Tampa Bay		Lower Tampa Bay	
Sediment Type:			Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
	Areal fluxes based on core incubations (mmol/m2/day):									
	Feb-03	Mean	0.489	0.246	0.067	0.291	0.178	-0.054	0.222	-0.025
		Std. Dev.	0.089	0.112	0.017	0.041	0.085	0.024	0.059	0.120
	May-03	Mean	0.534	0.897	0.597	0.442	0.263	0.587	0.236	0.066
		Std. Dev.	0.243	0.409	0.287	0.192	0.189	0.261	0.043	0.236
	Aug-03	Mean	0.854	0.810	-0.099	-0.142	1.04	0.476	0.544	-0.174
		Std. Dev.	0.129	0.432	0.523	0.043	0.488	0.433	0.127	0.092
	Nov-03	Mean	0.817	0.693	0.663	0.162	2.16	0.022	0.625	-1.26
		Std. Dev.	0.435	0.426	0.082	0.144	0.535	0.311	0.090	0.407
Area (ha)			3160	7374	4013	16054	3099	27892	493	24165
	TDP FLUXES (mol/ha/day)									
	Feb-03		4.89	2.46	0.67	2.91	1.78	-0.54	2.22	-0.25
	May-03		5.34	8.97	5.97	4.42	2.63	5.87	2.36	0.66
	Aug-03		8.54	8.10	-0.99	-1.42	10.45	4.76	5.44	-1.74
	Nov-03		8.17	6.93	6.63	1.62	21.59	0.22	6.25	-12.57
Days	FLUXES (mol/subsegment/season)									
121	Winter		1870000	2199000	324300	5659000	666600	-1809000	132300	-742500
91	Spring		1535000	6018000	2179000	6462000	742000	14910000	106000	1450000
92	Summer		2484000	5497000	-364600	-2094000	2979000	12210000	246800	-3866000
62	Fall		1600000	3170000	1650000	1615000	4147000	378200	191000	-18830000
	FLUXES (mt/subsegment/season)									
	Winter		26.18	30.79	4.54	79.23	9.33	-25.33	1.85	-10.40
	Spring		21.49	84.25	30.51	90.47	10.39	208.7	1.48	20.30
	Summer		34.78	76.96	-5.10	-29.32	41.71	170.9	3.46	-54.12
	Fall		22.40	44.38	23.10	22.61	58.06	5.29	2.67	-263.6
	ANNUAL FLUX BY SEDIMENT TYPE (mt/subsegment/yr):									
			104.8	236.4	53.04	163.0	119.5	359.6	9.47	-307.8
	ANNUAL FLUX BY BAY SEGMENT (mt/segment/yr)									
			341		216		479		-298.4	
	TOTAL ANNUAL FLUX FOR THE WHOLE BAY (mt/yr):									
			738							

Table A-6. Silicate Flux Estimates for Tampa Bay Sediments.

			Hillsborough Bay		Old Tampa Bay		Middle Tampa Bay		Lower Tampa Bay	
Sediment Type:			Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
	Areal fluxes based on core incubations (mmol/m2/day):									
	Feb-03	Mean	3.62	1.76	5.23	3.50	7.14	0.478	2.12	0.236
		Std. Dev.	1.70	0.211	1.01	1.24	1.08		0.157	0.030
	May-03	Mean	9.01	8.71	8.91	7.96	12.28	4.59	5.22	-0.435
		Std. Dev.	1.66	1.13	0.609	2.00	1.60	3.80	3.27	0.151
	Aug-03	Mean	10.45	12.58	6.68	4.46	9.14	9.16	6.03	0.660
		Std. Dev.	1.37	0.712	1.85	0.433	0.115	3.19	2.38	0.337
	Nov-03	Mean	7.36	3.72	6.83	1.68	4.56	1.69	6.32	0.016
		Std. Dev.	1.81	1.56	2.28	0.244		0.941	2.02	0.310
Area (ha):			3160	7374	4013	16054	3099	27892	493	24165
	SIO4 FLUXES (mol/ha/day)									
	Feb-03		36.25	17.60	52.26	35.05	71.41	4.78	21.22	2.36
	May-03		90.09	87.07	89.10	79.59	122.8	45.86	52.19	-4.35
	Aug-03		104.5	125.8	66.79	44.59	91.39	91.58	60.31	6.60
	Nov-03		73.64	37.20	68.27	16.78	45.60	16.92	63.24	0.16
Days	FLUXES (10^6 mol/subsegment/season)									
121	Winter		13.86	15.71	25.38	68.08	26.78	16.14	1.266	6.889
91	Spring		25.91	58.43	32.54	116.3	34.63	116.4	2.342	-9.571
92	Summer		30.39	85.33	24.66	65.85	26.06	235	2.735	14.67
62	Fall		14.43	17.01	16.98	16.7	8.761	29.26	1.933	0.2396
	FLUXES (mt/subsegment/season)									
	Winter		194.0	219.9	355.3	953.1	374.9	226.0	17.72	96.45
	Spring		362.7	818.0	455.6	1628	484.8	1630	32.79	-134.0
	Summer		425.5	1195	345.2	921.9	364.8	3290	38.29	205.4
	Fall		202.0	238.1	237.7	233.8	122.7	409.6	27.06	3.35
	ANNUAL FLUX BY SEDIMENT TYPE (mt/subsegment/yr):									
			1184	2471	1394	3737	1347	5555	115.9	171.2
	ANNUAL FLUX BY BAY SEGMENT (mt/segment/yr)									
			3655		5131		6902		287.1	
	TOTAL ANNUAL FLUX FOR THE WHOLE BAY (mt/yr):									
			15970							