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Nutrient Mass Flux between Florida Bay and the Florida Keys National Marine Sanctuary

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Abstract There is a net discharge of water and nutrients through Long Key Channel from Florida Bay to the Florida Keys National Marine Sanctuary (FKNMS). There has been speculation that this water and its constituents may be contributing to the loss of coral cover on the Florida Keys Reef tract over the past few decades, as well as speculation that changes in freshwater flow in the upstream Everglades ecosystem associated with the Comprehensive Everglades Restoration Plan may exacerbate this phenomenon. The results of this study indicate that although there is a net export of approximately 3,850 (±404) ton N year^{-1} and 63 (±7) ton P year^{-1}, the concentrations of these nutrients flowing out of Florida Bay are the same as those flowing in. This implies that no significant nutrient enrichment is occurring in the waters of the FKNMS in the vicinity of Long Key Channel. Because of the effect of restricted southwestward water flow through Florida Bay by shallow banks and small islands, the volume of relatively high-nutrient water from central and eastern portions of the bay exiting through the channel is small compared to the average tidal exchange. Nutrient loading of relatively enriched bay waters is mediated by tidal exchange and mixing with more ambient concentrations of the western Florida Bay and Hawk Channel. System-wide budgets indicate that the contribution of Florida Bay waters to the inorganic nitrogen pool of the Keys coral reef is small relative to offshore inputs.

Keywords Florida Bay · Florida Keys · Nutrients · Nutrient loading · Volume transport · Nitrogen · Phosphorus

Introduction

Nutrient loading to coastal ecosystems has resulted in profound shifts in system structure and function in a variety of environments (Nixon 1995; Vitousek et al. 1997). These altered states generally have decreased ecosystem function in terms of nutrient cycling and provision of habitat. This is especially true for the coral reef areas of the Florida Keys. Many reports blame anthropogenic nutrient loading for the decline in coral biomass and health (Gardner et al. 2003). One hypothesis is that nutrient export from Florida Bay through the tidal passes of the Florida Keys is delivering extraneous nutrient loads to the Florida Keys reef tract, resulting in dramatic declines in coral biomass and health (Porter et al. 1999, 2002). Although these shifts have undoubtedly occurred over the last few decades, little evidence has been provided to identify Florida Bay waters as the culprit (Lapointe and Clark 1992).

South Florida's marine ecosystem is highly connected by regional circulation patterns that fluctuate over seasonal cycles according to wind forcing (Lee et al. 2002). Throughout the year, shelf waters, including discharge from the Everglades, are directed southeastward along the

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southwest Florida coast and enter Florida Bay through the central and northern parts of the open western boundary. Water leaves the bay through the southern part of the western boundary and especially through tidal channels in the Middle Keys, where it may then be advected toward the reef tract (Fig. 1).

The islands of the Florida Keys extend southwest from Miami and mainland Florida in a shallow arc that terminates at Key West. The archipelago serves as a perforated boundary between two distinct, nationally protected ecosystems: Florida Bay (as part of Everglades National Park) and the Florida Keys National Marine Sanctuary (FKNMS). Florida Bay estuary is a dynamic region of exchange for three distinct hydrological systems of South Florida: the freshwater Everglades to the north, the Southwest Florida Shelf and the Gulf of Mexico to the west, and the coastal Atlantic and Florida Keys reef tract to the south and east (Fig. 1). Changes in the hydrologic regime and water quality parameters of source waters may have direct or indirect effects on the ecologically sensitive downstream systems of Florida Bay and the reef tract (Lapointe and Barile 2004).

Rapid development of both the mainland and island communities of South Florida has drastically altered natural water transport processes of the area through the construction of canals, levees, water control structures, and wastewater management practices. As the Everglades are entering an era of ecosystem rehabilitation as part of the Comprehensive Everglades Restoration Plan, close attention must be paid to the downstream effects of restoration efforts with special attention of water flow, quality, and nutrient loading.

Nutrient exchange between Florida Bay and its adjacent ecosystems varies as a function of flow and concentration. Resultant concentrations in the bay are a factor of input from upstream systems of the Everglades and the Gulf of Mexico, atmospheric and groundwater inputs, wastewater and storm water delivery from the developed islands of the Florida Keys, and the biogeochemical transformations occurring within the bay itself. Flows to and from adjacent systems are driven by geomorphology, tidal forcing, wind stress, and the influence of regional mesoscale behavior of the Loop and Florida Currents (Lee et al. 2002). The tidal passes of the Keys island chain serve as a connection between waters from Florida Bay, the Southwest Florida Shelf, and the Gulf of Mexico with the waters of the Atlantic coastal environment. Previous studies of the physical processes of South Florida have revealed persistent

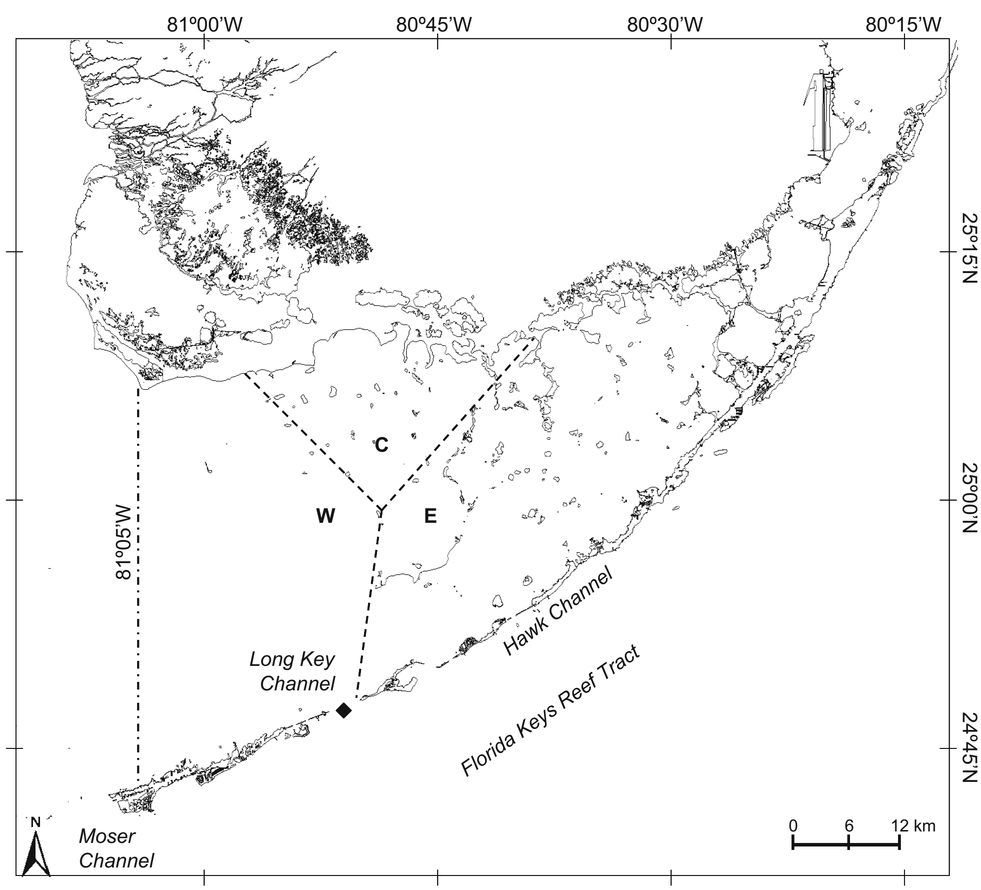


Fig. 1 Map of Florida Bay and the Florida Keys depicting Long Key Channel study area. The bay is divided into three zones: west, central, and east, based on multivariate analysis of water quality characteristics and driving forces after Boyer et al. (1997). Station 244 of the Water Quality Monitoring Network is represented as a *diamond* in the Long Key Channel area

residual transport through the passes of the Middle Keys toward the Atlantic (Lee and Smith 2002; Smith and Lee 2003).

Although large-scale nutrient budgets for total nitrogen (TN) and total phosphorus (TP) for Florida Bay have been proposed (Rudnick et al. 1999; Cerco et al. 2000; Boyer and Keller 2007), nutrient mass exchange through the Keys' tidal passes has never been measured directly. The best estimates were based upon nutrient concentration data with monthly or quarterly intervals applied to hourly flow measurements (Boyer and Keller 2007), and the resulting budgets are largely unbalanced and have admitted uncertainties in the material flux estimates to and from the estuary. These prior attempts at estimating nutrient transport across the boundaries of Florida Bay vary in both magnitude and direction of net mass flux.

The purpose of this study was to directly quantify the exchange of water and nutrients through one of the largest pass in the Keys, Long Key Channel, using long-term, high-resolution, mass flow measurements combined with periodic tidal-scale observations of nutrient concentrations. The resulting loads are compared to published values of other regional nutrient fluxes and used to revise the present state of knowledge of nutrient dynamics of the Florida Bay and Florida Keys marine ecosystems.

Materials and Methods

Study Location

Long Key Channel is located on the southwest end of Long Key and connects the waters of western Florida Bay to Hawk Channel. Previous hydrological studies of the area (Smith 1998; Smith and Lee 2003) have shown transport rates for Long Key Channel to be 250–400 $m^3\ s^{-1}$, representing the most significant conduit for water transport in the Keys island chain other than Moser Channel of the Seven Mile Bridge. Moser Channel lies west of the 81°05′ W meridian, the operational western boundary of Florida Bay, and is beyond the scope of this study.

The monitoring station for this study was established approximately mid-channel, bay side of the Long Key Viaduct Bridge at 24°47.857′N and 80°52.225′W, which corresponded with previous Long Key Channel studies (Smith 1998). Long Key Channel is approximately 3767 m across, has an average depth of 2.85 m, and is oriented along a roughly 160/340° heading. The channel bottom is composed of limestone hardbottom spotted with solution holes, soft corals, a few sponges, and scattered small hard corals. A few shallow banks are present in the channel giving the bottom varying topography. The tidal signal of Long Key Channel is complex because of the influence of mixed semidiurnal tides of the eastern Gulf of Mexico interacting out of phase with the semidiurnal tides of the southern Atlantic (Fig. 2). Transport through the channels is further complicated by the influence of local wind forcing (Smith 2002).

Instrumentation

Three instruments were positioned on site, deployed, and serviced at varying intervals. A SonTek Argonaut acoustic Doppler current meter was deployed for three extended time periods: April 9 to July 16, 2003, August 27, 2003 to May 28, 2004, and July 17 to November 18, 2004. For each sampling period, current velocity (cm s^{-1}) was measured and averaged for a period of 120 s every hour, along with measurements of pressure and temperature. A total of 11,721 current meter data points were directly measured for the study. Also deployed at the station was a YSI 6600 EDS environmental sensor. This instrument obtained a measure of temperature (°C), salinity (psu), depth (m), dissolved oxygen (mg l^{-1}), pH, and turbidity (NTU) every 15 min of

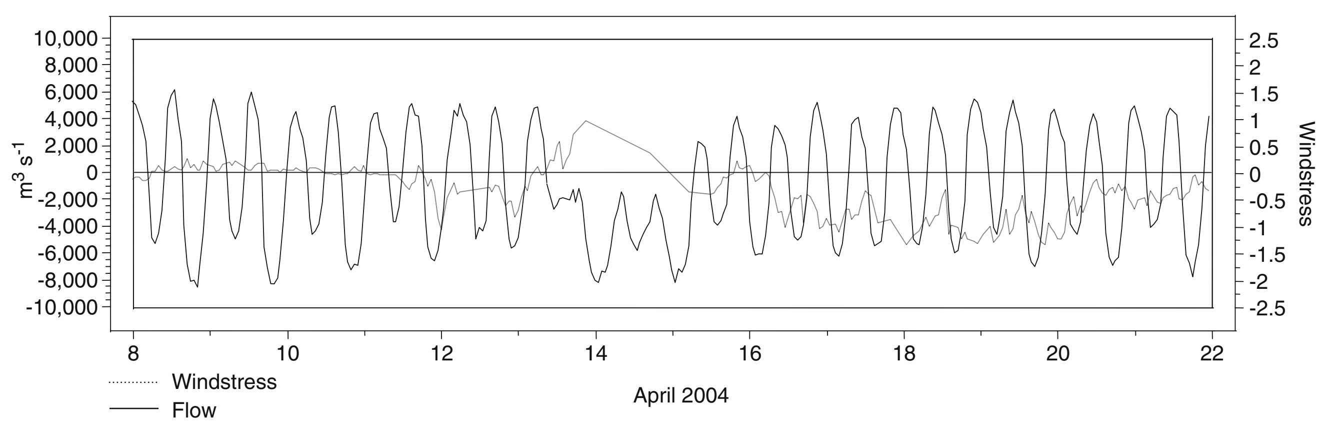


Fig. 2 Flow pattern and wind stress from a 2-week period in April 2004 displaying persistent net outflow (*solid line*) in response to elevated wind stress at the 071 heading (*broken line*)

its deployment. This instrument was deployed intermittently for a total of 141 of the 213 days between February 17 and September 17, 2004. Data from the YSI was binned to the nearest hour for analysis, to a total of 3,385 data points.

The third instrument used for monitoring in the study was an underwater autosampler engineered specifically for this project. The sampler was capable of being programmed to collect discrete or composite samples at designated times or over specific time intervals. The pump-based device was mounted to the seafloor and programmed to collect and store water samples at various intervals, typically every 6 h, to observe tidal-scale variation in nutrient concentrations. Construction consisted of a polyvinyl chloride (PVC) base platform to which a peristaltic pump, control unit, and battery were mounted. The unit was covered by a PVC dome secured to a rubber gasket seat via several bail and lever clamps to maintain a dry operating environment. Bulkhead fittings allowed passage of pump tubing to the water column and exterior collection vessels. Water was sampled via a collection tube positioned above the autosampler in the water column. The collected water was stored in flexible sample bags (IV bags, Baxter Healthcare, Deerfield, IL) composed of multilayer polypropylene film fitted with tubulation and a one-way valve. The instrument was deployed at irregular intervals throughout the study period and collected a total of 173 individual water samples for the analysis of TN and TP concentrations.

Volume Transport

Calculations of water volume transport through the channel were obtained from current velocity measurements, depth, and channel calibration coefficients determined from previous studies (Smith 1998). The calibration coefficients were used to extrapolate velocity values from the single mid-channel sensor to the entire width of Long Key Channel. These constants varied slightly with inflow and outflow because of channel topography.

Current speed (m s^{-1}) was multiplied by an empirically derived correction factor of 0.9856 to account for the seafloor boundary layer not detected by the acoustic current meter (Smith personal observation). This value was multiplied by the instantaneous channel depth (m) for the speed of a vertically integrated slice of the water column in m^2 s^{-1}. This was then multiplied by the channel calibration coefficients of 2,790.8 m for inflows and 2,917.0 m for outflows to obtain whole-channel water transport in m^3 s^{-1}. The resulting volume of flow was the integrated total channel transport used to calculate nutrient loading in further calculations. The cross-channel calibration constants differ for inflows and outflows because of complex bank morphology and bottom topography resulting in slightly different effective channel areas on flood and ebb flows.

Long Key Channel lies at a general heading of 160/340°. All water movements along a heading between 70 and 250° were considered exports from the bay and were assigned negative flux values. All other headings, from 250 to 70°, were taken to be imports to the bay and were assigned positive flux values.

Nutrient Concentrations

Samples were collected from the underwater autosampler and stored in a cooler at ambient temperature until return to the laboratory. The water from the samples was transferred from the autosampler bags to sample-rinsed high-density polyethylene (HDPE) bottles and refrigerated at 4°C before nutrient analysis by the Southeast Environmental Research Center (SERC) Nutrient Analysis Laboratory for concentrations of TN and TP. Additional nutrient data were obtained from a cross-channel survey of five sites parallel to the Long Key Viaduct. The sites were equally spaced across the channel and were used to detect spatial variability of water masses passing through the channel at any given time. The midpoint of this cross-channel survey was directly above the benthic-mounted instrument site where the autosampler collects water from the water column. If nutrient concentrations from each of the five cross-channel sites were found to be statistically equivalent, then our single mid-channel sampler collection could be used as a representative sample of all waters passing through the channel. This cross-channel survey was conducted on most visits to the site for instrument maintenance, with a total of 16 collections between September 2003 and January 2005. The cross-channel samplings consisted of a SeaBird CTD cast and grab samples of surface waters for analysis of total nutrients (TN, TP, total organic carbon [TOC]), as well as dissolved constituents: dissolved organic carbon (DOC), nitrate+nitrite (NO_x^-), nitrite (NO_2^-), ammonium (NH_4^+), soluble reactive phosphorus (SRP), and chlorophyll *a* (chl *a*).

All nutrient analyses were conducted using standard methodology under National Environmental Laboratory Accreditation Conference certification. Sample water was submitted unfiltered for TOC, TN, and TP analyses in sample rinsed 120-ml HDPE bottles. TOC was measured by direct injection onto hot platinum catalyst in a Shimadzu TOC-5000 after first acidifying to pH<2 and purging with CO_2-free air. TN was measured using an ANTEK 7000N Nitrogen Analyzer using O_2 as carrier gas (Frankovich and Jones 1998). TP was determined using a dry-ashing, acid hydrolysis technique (Solórzano and Sharp 1980). DOC was measured in the same way as TOC, only the water was filtered through a Whatman GF/

F immediately after sampling. Water for dissolved nutrient analyses, including NO_x^-, NO_2^-, NH_4^+, and SRP, was filtered by hand through a sample-rinsed 25-mm GF/F filter into acetone-washed and sample-rinsed 60-ml HDPE bottles. Samples were analyzed in duplicate by flow injection analysis (Alpkem model RFA 300). The filters from the dissolved constituents were placed in 2-ml plastic centrifuge tubes with 90% acetone for chl *a* analysis. These tubes were kept at −20°C for a minimum of 4 days to complete extraction before being analyzed using a Gilford Fluoro IV Spectrophotometer (excitation=435 nm, emission=667 nm) as compared to a standard curve of pure chl *a* (Sigma). Three N parameters were not measured directly but rather calculated by difference. Nitrate (NO_3^-) was calculated as $NO_x^- - NO_2^-$, dissolved inorganic nitrogen (DIN) is calculated as $NO_x^- + NH_4^+$, and total organic nitrogen was defined as TN–DIN. Concentrations (μM) from various samplings were all binned to the nearest hour to coordinate with current meter and environmental sensor time series.

Nutrient Flux

The primary objective of this study was to calculate the flux of N and P between Florida Bay and the inner shelf on the Atlantic side of the Keys (locally referred to as Hawk Channel). This mass transport was derived from measurements of water flow and nutrient concentration using the formula:

$$f_i = q_i \times c_i \tag{1}$$

where *f*, *q*, and *c* are instantaneous flux, flow, and concentration values, respectively. For instantaneous nutrient flux calculations, concentrations of TN and TP were converted from μM to kg N or P m^{-3}. These values were multiplied by the instantaneous water volume transport at that time ($m^3\ s^{-1}$) to find nutrient flux in kg s^{-1}. These observed estimates of instantaneous mass transport of N and P are the basis for extrapolation of nutrient-loading estimates for larger time scales.

The study generated far more data points for water volume transport through the channel than nutrient concentrations associated with those water masses. To estimate nutrient flux values for points in time where flow was known but concentration data were missing, Beale's Ratio Estimator (BRE) was used (Cohn 1995; Richards 1998). In this approach, the mean instantaneous mass flux estimate was calculated from flow and observed nutrient concentrations. This value was adjusted by a flow ratio obtained by dividing the mean flow of all observed values during the study period by the mean flow of points in time associated with observed nutrient concentrations. This estimate calculation also incorporates a bias correction factor that is designed to compensate for the effects of correlation between discharge and flux. The formula for the BRE is:

$$\hat{F} = \overline{Q} \times \frac{\overline{f}}{\overline{q}} \times \left(\frac{1 + \frac{\mathrm{cov}_{fq}}{n \times \overline{f} \times \overline{q}}}{1 + \frac{\mathrm{var}_q}{n \times \overline{q}^2}} \right) \tag{2}$$

where for any given time period: $\hat{F}$=estimated flux, $\overline{Q}$= mean flow for all observed points, $\overline{f}$=mean flux for points with observed nutrient concentrations, $\overline{q}$=mean flow for points with observed nutrient concentrations, and var and cov represent the variance and covariance of the flow and flux terms. The BRE is an adaptation of a commonly used flux estimation technique of flow-weighted mean concentration (FWMC). This value represents the amount of a nutrient in a volume of water but takes into consideration possible concentration or dilution effects from high or low flow values. For any given period of time, the formula for calculating FWMC is:

$$\mathrm{FWMC} = \frac{\sum_{i=1}^{n} (c_i \times q_i)}{\sum_{i=1}^{n} q_i} \tag{3}$$

FWMC is calculated as concentration (*c*) times flow (*q*), i.e., nutrient load (kg) divided by volume flow (*q* as m^3). This value is generally scaled down to more traditional units for nutrient concentrations of micromolars. Whereas the BRE method is effectively flow weighted by incorporating the load over flow term, FWMC is not designed to estimate missing values, only to provide a relative concentration for a given time period. For the purposes of this study, the BRE approach was slightly modified by using the median nutrient flux instead of the mean, with the above formula (Eq. 2) adjusted accordingly. The calculated estimates of median N and P load were applied to each time step of missing concentration values. The summation of these fluxes gave the net load for the total time period in question.

Results

Volume Transport

In the course of this investigation, more than 488 days of hourly current velocity, bottom pressure, and temperature data were collected between April 9, 2003 and November 18, 2004. When taken as a whole, the mean long-term net transport of water was out of Florida Bay at −384 (±39) $m^3\ s^{-1}$ (negative values represent exports from the bay; standard error of the mean is in parentheses). Short periods of net inflow driven by wind forcing were observed but generally persisted for only a few days (Fig. 2). Peak observed flows were 7,894 $m^3\ s^{-1}$ into the bay and

−9,799 $m^3 s^{-1}$ out toward the Atlantic. Mean volume transport varied significantly between inflows and outflows, with respective values of 3,455 (±19) and −4,231 (±27) $m^3 s^{-1}$. Median current speed was 39.02 cm s^{-1}, while the maximum observed speed was 99.57 cm s^{-1}. Depth at the sampling location varied with tide and spanned a range from 3.03 to 4.08 m, with the median value of 3.55 m.

Seasonal variability was present in the volume transport data with respect to magnitude of mean flow. Although South Florida truly only has two seasons (wet and dry), four seasons were used for this study to better group variability in wind speed and direction. The seasons were defined as 3-month intervals, beginning with March for spring, June for summer, September for fall, and December for winter. Because of bias of unequal numbers of data points among seasons, the long-term net transport value may not represent an annual period because of the overemphasis on the spring and fall flow conditions, during which more observations were made. To account for this seasonal sampling bias and to acquire a representative annual mean flow estimate, a random subset of the data was generated using 2,000 hourly samples per season. Two thousand hourly samplings equal 83.33 days of a 91-day quarter or about 91% of all flows and should be representative. This unbiased subset of data from 2003 to 2004 generated a mean long-term net transport of −447 (±47) $m^3 s^{-1}$. This value is greater than but on the order of previously reported values for Long Key Channel of −250 and −400 $m^3 s^{-1}$ (Smith 1998; Smith and Lee 2003).

Long-term net flows displayed strong seasonal patterns. Winter periods exhibited the strongest outflow with a mean of −737 $m^3 s^{-1}$, while summer mean flows were small, −253 $m^3 s^{-1}$, out of the bay (Table 1). This discrepancy is likely due to prevailing seasonal wind patterns driving cross-key sea level slope differences. The passage of winter cold fronts increased the frequency of winds from the west and northwest, which caused a sea level setup in Florida Bay relative to the Atlantic (Lee and Smith 2002).

Table 1 Annual and seasonal water quality and transport parameters measured for Long Key Channel from April 2003 to November 2004

Long Key Channel	Spring	Summer	Fall	Winter	Annual
Flow ($m^3 s^{-1}$)	−298	−253	−357	−737	−447
[TN] (μM)	13.30	14.67	23.60	13.73	18.15
TN flux (kg s^{-1})	0.503	−0.380	−0.125	−0.105	−0.123
[TP] (μM)	0.07	0.31	0.17	0.15	0.17
TP flux (kg s^{-1})	0.006	−0.014	−0.002	−0.004	−0.002
N/P	190	43	151	99	116
Depth (m)	3.01	3.03	3.06	3.17	3.03
Temperature (°C)	24.95	31.14	29.20	21.05	27.31
Salinity	38.23	38.27	37.46	36.09	38.04
Average wind speed (kts)	7.07	5.09	7.04	7.37	6.64
Average wind direction (°)	97	120	67	40	85

Wind data is from SMKF1 data buoy at Sombrero Key.

Nutrient Concentrations

Water samples collected by the underwater autosampler were analyzed only for TN and TP. Because of a time interval of up to a week or more between collection by the autosampler and sample preparation for nutrient analysis, dissolved nutrients could not be accurately determined with these samples. Surface grab samples from the autosampler site and four other cross-channel locations were analyzed for total and dissolved nutrient constituents as described above.

Water quality concentration data rarely achieve a normal distribution. Outliers typically appear in the upper range of concentrations, but low outliers are rarely observed or are obscured by minimum detection limits. For the purposes of concentration comparisons, median values were used in lieu of mean values because of the lack of normality in concentration distributions (Christian et al. 1991). Wilcoxon and Kruskal–Wallis tests (equivalent to analysis of variance in parametric analyses) were used to compare differences between two-level and multiple-level comparisons, respectively (Sokal and Rohlf 1995).

Total Nitrogen

Concentrations of TN ranged from 8.75 to 39.07 μM, excluding a single outlier at 55.66 μM. Mean TN value was 20.08 (±0.58) μM, while the median value was 18.15 μM. Seasonal variability that was present as fall median TN concentrations were elevated (23.60 μM) compared to winter, spring, and summer (13.73, 13.30, and 14.66 μM, respectively). There was no difference among the five cross-channel survey sites for all events (Kruskal–Wallis, p=0.91), indicating that the mid-channel sampling site was representative of TN concentrations in the entire channel. There were no differences in TN concentration detected between the mid-channel surface grab samples and the water column samples collected by the autosampler. No difference in median TN between inflowing and outflowing water masses was detected (Wilcoxon, p=0.41).

Total Phosphorus

Mean concentration of TP observed during this study was 0.20 (±0.01) μM, ranging from 0.07 to 0.82 μM with a median value of 0.17 μM. Summer TP concentrations were significantly higher than other seasons with a median value of 0.31 μM compared to fall, winter, and spring mean concentrations at 0.23, 0.15, and 0.07 μM, respectively. Median TP did not vary by inflow or outflow (Wilcoxon, p=0.37). The cross-channel survey revealed no significant differences between surface water TP concentrations (Kruskal–Wallis, p=0.74), indicating that the mid-channel site was representative of the entire channel.

Dissolved Inorganic Nutrients

Inorganic constituents of N and P comprised only a small fraction of the total pools. DIN values had a median concentration of 0.80 μM or about 4.4% of the TN pool. Of this inorganic component, NO_3^- was dominant with a median concentration of 0.44 μM, followed by NH_4^+ with a median of 0.27 μM, and NO_2^- at a median of 0.08 μM. Analysis of a long-term data set of nutrient concentrations in western Florida Bay (the SERC South Florida Water Quality Monitoring Program) calculated the inorganic constituent at about 6.1% of the TN pool, slightly higher but on order with the ratio found in this study. SRP had a median concentration of 0.03 μM, representing about 17% of the TP pool. This value is nearly equivalent to that of the long-term water quality data set of about 18%.

Nutrient Flux

Cross-key transport of TN and TP through Long Key Channel was estimated using measurements of water flow and nutrient concentration as described above. Observed instantaneous nutrient loading for TN and TP had median values of −0.123 and −0.002 kg s^{-1}, respectively. When these median loads were extrapolated to represent an entire year, the annual nutrient flux (in metric tons) was −3,880 ton N $year^{-1}$ and −66 ton P $year^{-1}$. These estimates were derived solely from directly measured values of flow and concentration and did not include loading values estimated by extrapolation. The directly measured concentration values were collected across the range of measured flow values with good representation of all flow magnitudes.

The BRE method was used to estimate loading values for points in time where only flow was measured. The method produced mean instantaneous loading values of −0.122 kg N and −0.002 kg P. When incorporated with the observed nutrient loading values, the annual estimated flux through Long Key Channel equaled −3,850 ton N $year^{-1}$ and −63 ton P $year^{-1}$ (Table 2). The similarity of BRE estimates to observed values of nutrient flux indicated that there was little relationship between flow and concentration in Long Key Channel. Although methods for assessing the precision or bias of empirically derived BRE values have not been published (Cohn 1995), information as to the uncertainty of these estimates may be gleaned from error in the flow term (see below).

Discussion

Volume Transport

The net outflow from Florida Bay through Long Key Channel described in this study was −447 m^3 s^{-1}. This value can be used along with estimates of Florida Bay water column volume and other transport processes to calculate a coarse estimate of water residence time in the system. Long Key Channel has been found to represent approximately 70% of all transport through the Keys archipelago (Smith and Lee 2003). There is also net export of water across the southern third of the western boundary of the bay (the 81°05′W meridian) with a long-term average transport of −300 m^3 s^{-1} (Smith 2002; Smith and Pitts 2002), resulting in a total surface water export of approximately −940 m^3 s^{-1}. Taking Florida Bay to have an average area of 2,200 km^2 and a mean depth of 1 m, the residence time of the bay system based on long-term net outflow calculations is on the order of 27 days. This value is for the entire bay system and assumes annual rates of evaporation and precipitation are equivalent. Local variations because of the complex geomorphology of this shallow estuary are certainly significant. Sections of central Florida Bay may be hydraulically isolated and endure highly restricted flow and mixing with other water masses. Water mass exchange in these basins will often be controlled by evaporation and precipitation rather than advective flux through the Florida Bay ecosystem. Our estimated residence time of 27 days is indicative of a given parcel of water in the bay as a whole, despite occurrences of drastically different values for some isolated regions.

Middle Keys Flux Estimates

There was a net annual export of nutrients from Florida Bay to the FKNMS during this study period. This export was principally due to water transport, as flow accounted for about 90% of nutrient load. This net outflow of water was ultimately driven by higher sea level in Florida Bay relative to the Atlantic because of a complex interaction of tides, geomorphology, and wind stress. Given that this dominant flow term has an annual net mean of −447 (±47) m^3 s^{-1}, the standard error of the mean of the flow term is approximately 10.5% and provides a basis for calculating the uncertainty of annual flux estimates. Because little to no relationship between flow and concentration in Long Key Channel exists, we assume that the error of the flow term is representative of the error of the flux value. The uncertainty of N and P flux through Long Key Channel can be represented as −3,850 (±404) ton N $year^{-1}$ and −63 (±7) ton P $year^{-1}$.

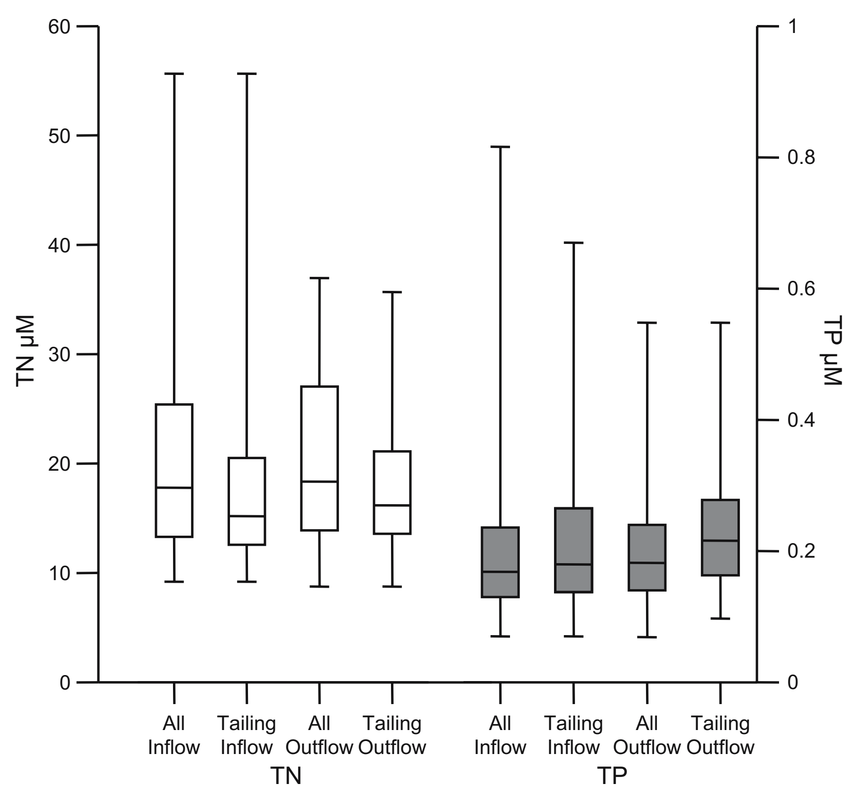
Table 2 Comparison of volume flow and mass transport budget estimates for Long Key Channel and the Middle Keys obtained in this and other recent studies

Study location	Source	Volume flow	TN concentration (μM)	TP concentration (μM)	TN load $year^{-1}$ (metric tons)	TP load $year^{-1}$ (metric tons)
Long Key Channel	This study	$-447\ m^3\ s^{-1}$ $-1.41\times10^{10}\ m^3\ year^{-1}$	18.15	0.17	−3,850	−63
All Middle Keys passes	This study	$-638\ m^3\ s^{-1}$ $-2.01\times10^{10}\ m^3\ year^{-1}$	18.15	0.17	−5,500	−90
All Keys passes	Rudnick et al. 1999	$-2.28\times10^{10}\ m^3\ year^{-1}$	–	–	−12,000	−180
All Keys passes	Cerco et al. 2000	$164\ m^3\ s^{-1}$ $5.18\times109\ m^3\ year^{-1}$	–	–	1,516	58
Reef tidal bores	Leichter et al. 2003	$1.08\times10^9\ m^3\ bore^{-1}$	4.00 NO_3^-	0.30	$-5,190\ NO_3^-$	−861
Keys WW + SW	Kruczynski and McManus 2002	–	9.14 to 49.46	0.032 to 1.74	−499	−163

Numbers from the reef tidal bores are from offshore transport to the FKNMS, while Keys wastewater (*WW*) and stormwater (*SW*) data are for all developed islands of the Keys chain. Note that reef tidal bore nitrogen input is reported as nitrate, not total nitrogen.

Nutrient concentration values varied seasonally, but no significant difference was detected in the concentrations of inflowing or outflowing waters. This implies that the water masses surrounding this region are well mixed and have a long residence time relative to tidal periodicity. Water ebbing out of Florida Bay may be highly conserved from that which flooded in from Hawk Channel on an earlier tidal cycle. To address this issue further, TN and TP concentrations were compared for the end-of-flood and end-of-ebb periods, which should contain the greatest proportion of new water from their respective sources. These tailing periods were arbitrarily defined from the point when a slackening tide decreased to a velocity of 20 cm s^{-1} or less. No significant differences in tailing water TN or TP were detected (Wilcoxon, p=0.24 and 0.14, respectively; Fig. 3). Although the waters of central and eastern Florida

Fig. 3 Box and whisker plots of total nitrogen (*TN*) and total phosphorus (*TP*) concentrations in inflowing and outflowing waters, as well as in tailing waters, those at the end of a slacking flood or ebb tide



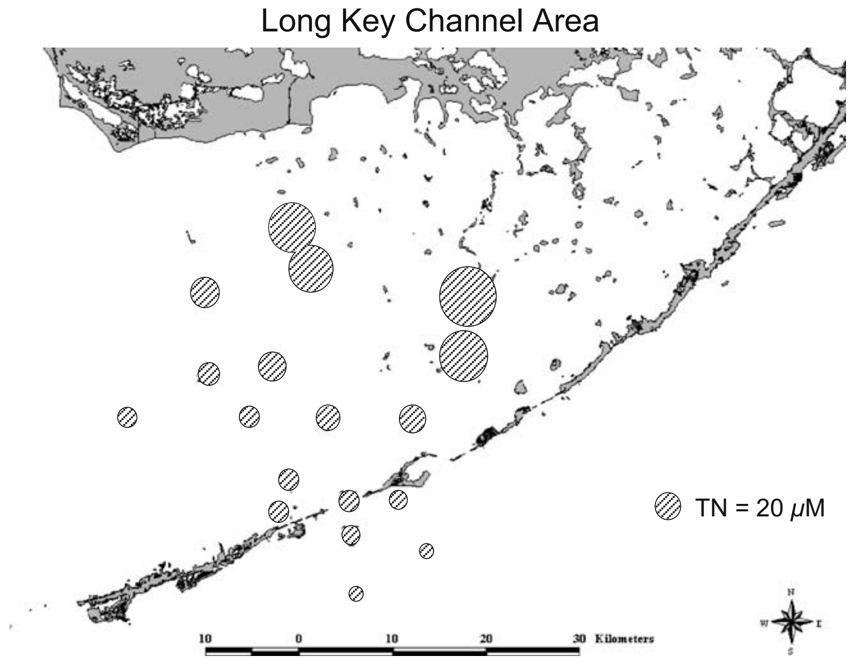


Fig. 4 Map of Florida Bay depicting relative median total nitrogen (*TN*) concentrations in the area of Long Key Channel in 2003–2004. Note the higher values in central bay relative to those of western Florida Bay and Hawk Channel on the Atlantic side of the Keys island chain

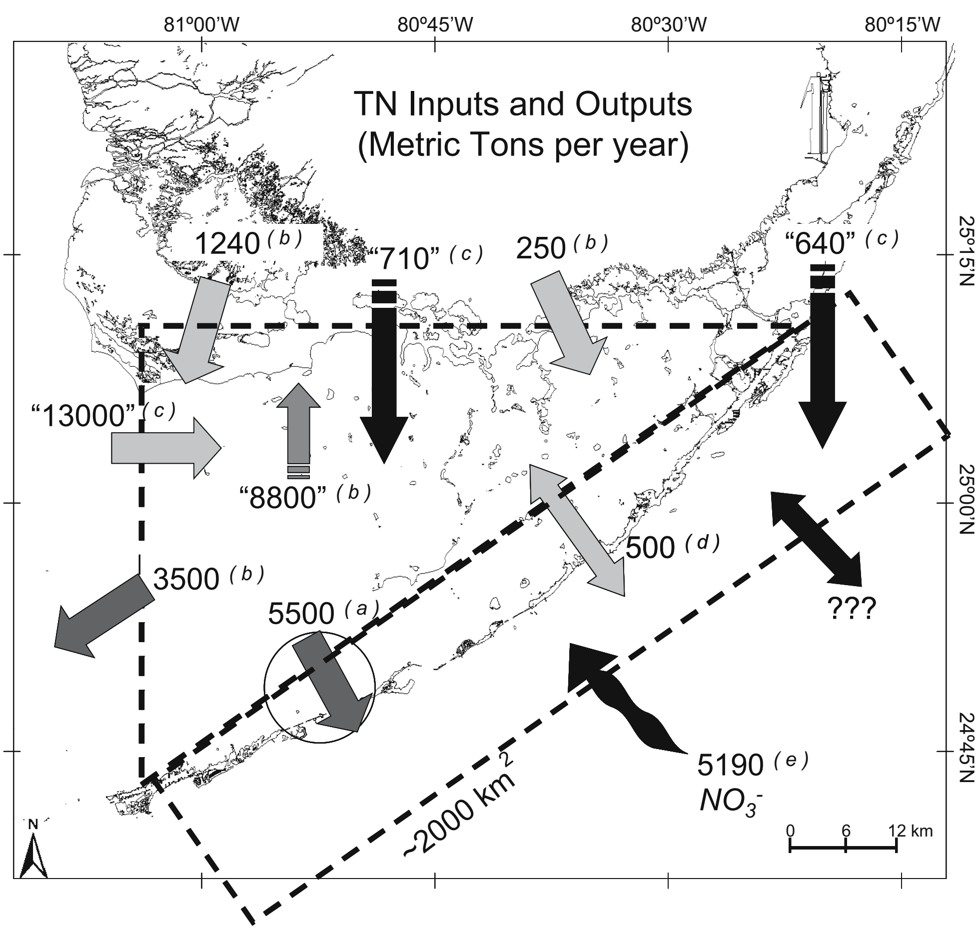


Fig. 5 Total nitrogen (*TN*) inputs and outputs for Florida Bay and the northern portion of the Florida Keys National Marine Sanctuary. Values of questionable accuracy are in quotes. Flux data are derived from the following sources and references therein: *a* This study, *b* Boyer and Keller (2007), *c* Rudnick et al. (1999), *d* Kruczynski and McManus (2002), *e* Leichter et al. (2003)

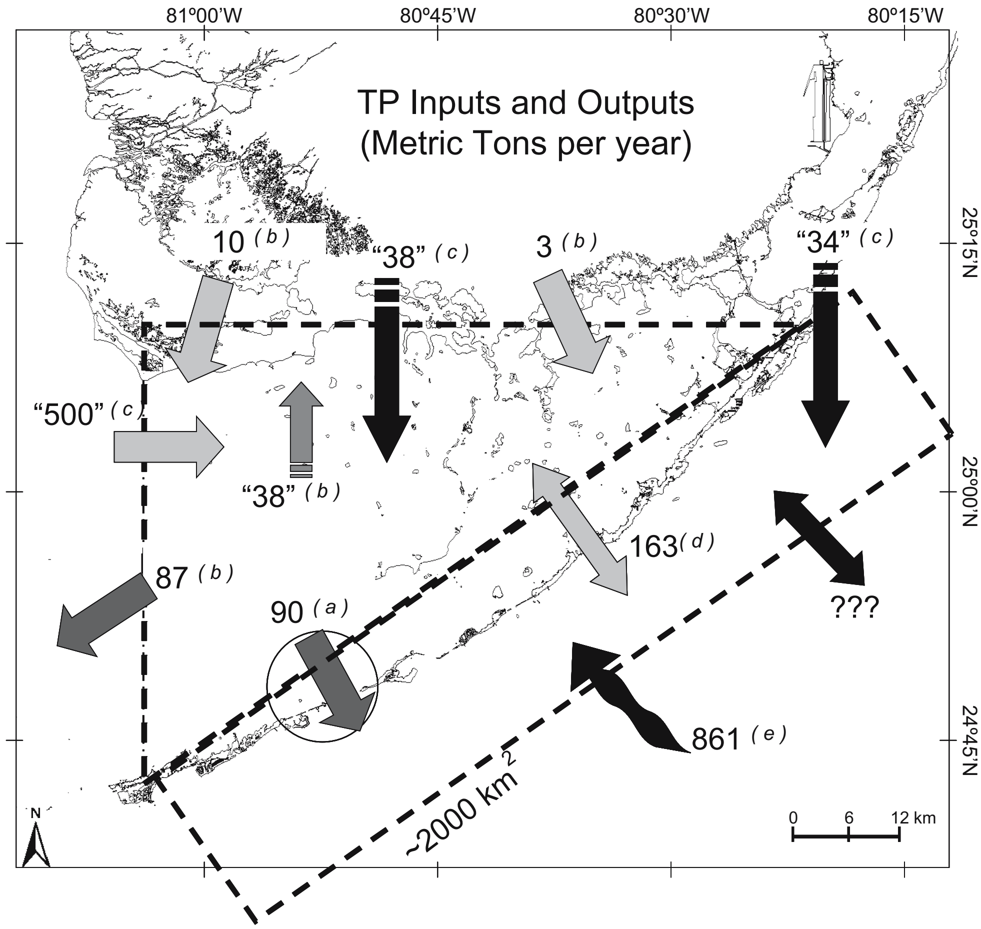


Fig. 6 Total phosphorus (*TP*) inputs and outputs for Florida Bay and the northern portion of the Florida Keys National Marine Sanctuary. Values of questionable accuracy are *in quotes*. Flux data are derived from the following sources and references therein: *a* This study, *b* Boyer and Keller (2007), *c* Rudnick et al. (1999), *d* Kruczynski and McManus (2002), *e* Leichter et al. (2003)

Bay generally display elevated TN concentrations relative to western Florida Bay and the waters of the Middle Keys (Boyer et al. 1997), there is no indication of this relatively enriched water mass leaving the system through Long Key Channel (Fig. 4). Water flow from central and eastern portions of the bay are likely restricted by the presence of mud banks, seagrass beds, and mangrove islands, resulting in a relatively low contribution of nutrient-enriched waters to the average outflowing volume of Long Key Channel.

Taking Long Key Channel to represent 70% of Middle Keys outflows (Smith and Lee 2003), the results can be extrapolated to estimate net flux through all Middle Keys passes, such as Channel 5 and Channel 2, northeast of Long Key. Using N- and P-loading estimates generated by the BRE method, the annual net flux from Florida Bay through the Middle Keys was −5,500 ton N year^{-1} and −90 ton P year^{-1}. Because studies have found that the passes of the Upper Keys show relatively little net transport (Lee and Smith 2002) and that passes west of Long Key Channel are outside the bounds of Florida Bay, our Middle Keys estimates may be taken as the total mass flux of surface flows between Florida Bay and the Atlantic. Results from this study are between the values of previous estimates of −12,000 ton N year^{-1} and −180 ton P year^{-1} (Rudnick et al. 1999) and 1,516 ton N year^{-1} and 58 ton P year^{-1} (Cerco et al. 2000) and are compared in Table 2. Discrepancies between past estimates and those presented here are likely due to their individual method of calculation. Rudnick et al. (1999) calculated annual load from transport values estimated using the difference between measured inflows and outflows for the western boundary of Florida Bay, assuming the residual inflows were exiting through the Keys. No direct measurements of volume transport were used in their calculation. Cerco et al. (2000) based annual Keys channel nutrient flux on a larger regional model of hydrological processes, resulting in an annual net influx of N and P. This estimate has largely been contradicted by repeated studies indicating persistent net outflow of water through the Middle Keys passes. The study presented here is the first to use a high-resolution measure of water transport and nutrient concentrations to derive an annual nutrient flux between the systems of Florida Bay and the waters of the Keys reef environment.

Comparison with Existing Water Quality Data

The South Florida Water Quality Monitoring Network collects water quality data at a location just ocean side of Long Key Channel on a quarterly basis (Boyer 2005). The site (station 244) is located at 24°47.600′N, 80°51.800′W, approximately 0.86 km east–southeast of the present study's sampling location. The median TN and TP concentrations from 2003 and 2004 for this station were 17.05 and 0.11 μM, slightly lower that those estimated using finer-scale nutrient collections from this study. When the quarterly values are used with the flow data from the present study to estimate annual nutrient flux through Long Key Channel, a result of −3,367 ton N year^{-1} and −46 ton P year^{-1} is obtained. These values are lower than but on order with the values calculated using finer-scale nutrient concentration collections estimated here (−3,850 ton N year^{-1} and −63 ton P year^{-1}). It appears that in the case of Long Key Channel, nutrient mass flux can be estimated to some degree using quarterly nutrient collections if accurate annual flow data is known. This finding suggests that a nutrient loading model may be possible for this system.

Nutrient Budget

The results generated by this study allow expansion of the current state of knowledge of South Florida nutrient budgets. The TN budget details the significance of the various inputs and outputs to the bay and reef ecosystems (Fig. 5). The dominant inputs to the bay system appear to be flux across the north portion of the open western boundary and groundwater inputs, although both of these estimates are of questionable accuracy. The Middle Keys passes are a significant outflow from the bay, but inputs of deep, cool, nutrient rich waters to the FKNMS via offshore tidal bores (Leichter and Miller 1999; Leichter et al. 2003; Table 2) contribute far greater amounts of biologically available inorganic N directly to the reef system. The TP budget (Fig. 6) also shows the importance of P fluxes across the open western boundary of Florida Bay and the input from tidal bores to the Keys reef ecosystem. It should be noted that both of these budgets are unbalanced, include estimates of varying quality, and require further investigation into the status of ecosystem development within the systems to fully understand the complex nutrient dynamics therein.

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