Chapter 5

Nutrient Dynamics

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Introduction

Question 2*—What is the relative importance of the influx of external nutrients and of internal nutrient cycling in determining the nutrient budget of Florida Bay? What mechanisms control the sources and sinks of the bay's nutrients?*

Ecological changes within Florida Bay, including *Thalassia testudinum* mass mortality and algal blooms, which have been evident during the past two decades, have commonly been attributed to many of the same human activities that have changed the Everglades. The diversion of freshwater to the Atlantic coast by canals has increased the salinity of the bay. Freshwater discharges from canals to the Atlantic Ocean were roughly four times larger than discharges to sloughs that flowed toward Florida Bay during the 1980s. Additionally, anthropogenic nutrient inputs from the Florida Keys, Gulf of Mexico, the atmosphere, and the Everglades may have increased. Inputs from the gulf may include phosphorus, which is transported by longshore currents from the central Florida coast, and nitrogen (N), which originates in the Everglades and flows into the gulf through Shark River Slough.

The main informational needs relative to nutrient cycles in Florida Bay is an understanding of the factors that triggered and maintain the mass mortality of seagrasses and the episodic phytoplankton blooms. Also critical is sufficient understanding to enable us to assess the effects of various environmental management strategies being considered for bay restoration. In particular, we need to accurately predict the sensitivity of the bay's nutrient cycles to changing freshwater flow into the bay and to the resultant change in the bay's salinity regime. For much of the bay, any factor that increases phosphorus (P) availability either by increasing input or decreasing removal is likely to exacerbate the current problems of the bay. Recent evidence also indicates that algal blooms in the central and western bay are sometimes stimulated by nitrogen (N) enrichment. Thus we need a thorough understanding of the bay's nutrient cycles. Questions that the current monitoring and research program must address in order to meet these needs follow.

The water column in Florida Bay is generally oligotrophic, and phytoplankton biomass has historically been quite low throughout the system. Although phytoplankton in Florida Bay are generally phosphorous limited (Fourqurean *et al.*, 1993; Phlips and Badylak, 1996; Lavrentyev *et al.*, 1998), other resources (*e.g.*, light, nitrogen, silicon) may also be important in controlling plankton biomass in some areas of the bay (Lavrentyev *et al.*, 1998). Dissolved inorganic phosphorous (DIP) concentrations are near detection limits (20 nmol), but concentrations of dissolved inorganic nitrogen (DIN) can be relatively high (median value 3.3 µmol, but concentrations >10 µmol are not uncommon) and dominated by ammonium (Fourqurean *et al.*, 1993; Boyer *et al.*, 1997; as summarized in Fourqurean and Robblee [1999]).

A spatial analysis of data from the monitoring program conducted by Boyer *et al.* (1997) resulted in the delineation of three groups of stations (eastern, central, and western) that have robust similarities in water quality (Figure 5.1). We deem these spatially contiguous groups of stations to be the result of similar hydrodynamic forcing and processing of materials; hence, we call them "zones of similar influence." The eastern bay zone acts most like a 'conventional' estuary in that it has a quasi-longitudinal salinity gradient caused by the mixing of freshwater runoff with seawater. In contrast, the central bay zone is a hydrographically isolated area with low and infrequent terrestrial freshwater input, a long water residence time, and high evapora-

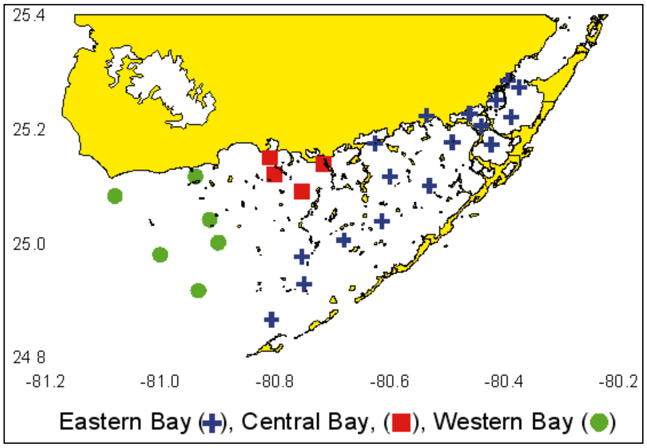

Figure 5.1 *Zones of similar water quality in Florida Bay.*

tive potential. The western bay zone is the most influenced by the Gulf of Mexico tides and is also isolated from direct overland freshwater sources.

Summary of Knowledge

Research on nutrient dynamics in Florida Bay focuses on the exchange of nutrients with adjacent regions ("external" dynamics), the cycling of nutrients within Florida Bay ("internal" dynamics), and the influence of these processes on ecosystem structure and function, *i.e.,* on spatial and temporal variation (Table 5.1). A continuing program of monitoring and research, including computer modeling, addresses the question of how human activity is affecting the nutrient dynamics of Florida Bay and how future restoration actions will alter these dynamics.

- What do we know about status and trends in water quality over space and time?
  - Objective analysis shows that there are three zones (eastern, central, and western) in the bay that exhibit significant differences in water-quality characteristics due to nutrient inputs, tidal advection, and water residence time.
  - In general, DIP concentrations increase and DIN decreases from east to west, resulting in a shift from P limitation to N limitation.
  - Central bay waters have high ammonium concentrations, which may indicate a bottleneck in the process of nitrification.
  - Temporal trends over a 13-year period of record show bay-wide declines in total phosphorus (TP), total nitrogen (TN), and chlorophyll *a* and an overall increase in turbidity (cloudiness of the water).
- What do we know about sources and amounts of external nutrient loading to Florida Bay?
  - Terrestrial nutrient loading fluctuates with freshwater flow, but flow-weighted concentrations decrease with increasing flow.
  - Phosphorus loading from the Everglades is a small proportion of the Florida Bay nutrient budget. Most phosphorus (P) appears to be derived from the Gulf of Mexico.
  - Nitrogen output from the southern Everglades (including Shark River Slough) is a significant proportion of the Florida Bay nutrient budget (similar in magnitude to atmospheric loading). Most nitrogen flowing from the wetlands is in the form of dissolved organic compounds. Studies on the bioavailability of dissolved organic nitrogen (DON) are currently underway.
  - The atmospheric input of nutrients is large, and most atmospheric nitrogen is inorganic.
  - Knowledge of the bay's nutrient budget is coarse over time and space (annual averaging for entire bay). Large uncertainty exists regarding the magnitude of nutrient exchange at the Gulf of Mexico boundary and regarding saline groundwater sources.
  - There is a measurable effect of water management on the quantity and distribution of water and nutrients through the length of the Taylor Slough–C-111 basin system, influencing inputs to Florida Bay.
  - A serious disconnect exists between upland/canal loading estimates and actual input to the bay because of unmeasured nutrient processing in the intervening wetland/mangrove areas.
- What do we know about internal nutrient-cycling processes?
  - Benthic denitrification is higher than expected based on denitrification: N-loading relationships in other estuaries.
  - The balance of N_2 fixation and denitrification in the bay is highly variable, but there appears to be a net loss of N in the overall system.
  - Sediment regeneration of ammonium under dark conditions is low relative to benthic dissolved oxygen demand.
  - Sediment regeneration of ammonium decreases with increases in sediment chlorophyll *a* concentration, indicating that the microphytobenthos is important in regulating water column N concentrations.
  - There is very little, if any, P flux out of the sediments, with the exception of the western bay-shelf area.
  - High rates of organic carbon (C) and N fluxes occur, both into and out of sediments over diel cycles (particularly in the central and western bay).
  - Phosphorus sorption-desorption varies strongly as

Table 5.1 *Research topics defined by Question 2 (cells in the matrix) and key references to the associated research.*

Research Topics	Spatial Variation	Temporal Variation
Water-Quality Patterns and Trends	Fourqurean *et al.*, 1993; Boyer *et al.*, 1997; Burd and Jackson 2002	Boyer *et al.*, 1999; Burd and Jackson, 2002
Overall Nutrient Budget	Boyer and Jones, 1999; Rudnick *et al.*, 1999; Cerco *et al.*, 2000	Boyer and Jones, 1999; Rudnick *et al.*, 1999; Cerco *et al.*, 2000
External Nutrient Loading		
Terrestrial Inputs		
Everglades	Walker, 1998; Rudnick *et al.*, 1999	Walker, 1998; Rudnick *et al.*, 1999
Mangroves	Childers *et al.*, 1999a,b; Davis *et al.*, 2001; Sutula *et al.*, 2001, 2003	Childers *et al.*, 1999a,b; Davis *et al.*, 2001a,b; Cable *et al.*, 2001; Sutula *et al.*, 2001, 2003
Keys	Kruczynski and McManus, 2002	
Atmospheric Inputs	Nuttle *et al.*, 2000	
Groundwater Inputs	Shinn *et al.*, 1994; Corbett *et al.*, 1999, 2000a,b; Price and Swart 2001	
Gulf of Mexico	Rudnick *et al.*, 1999	
Atlantic Ocean	Szmant and Forrester, 1996	
Internal Nutrient Cycling		
N_2 Fixation	Cornwell, 2001; Owens and Cornwell, 2001	
Benthic Flux	Rudnick, 1999; Carlson and Yarbro, 1999; Yarbro and Carlson, 1999; Chambers *et al.*, 2001; Yarbro and Carlson, unpublished	
Nitrification/Denitrification	Kemp and Cornwell, 2001	Kemp and Cornwell, 2001
Microbial Loop	Cotner *et al.*, 2000; Boyer *et al.*, 2006	Boyer *et al.*, 2006
DOM Remineralization	Boyer *et al.*, 2006	Boyer *et al.*, 2006
Seagrass Effects on Water Quality	Madden and McDonald, 2006; Madden *et al.*, 2003; McDonald *et al.*, 2003; Gras *et al.*, 2003; Nielson *et al.*, 2006	Madden and McDonald, 2006; Madden *et al.*, 2003; McDonald *et al.*, 2003; Gras *et al.*, 2003; Nielson *et al.*, 2006
Higher-Trophic-Level Effects on Water Quality		
Water Quality Modeling	Cerco *et al.*, 2000	

a function of temperature and salinity.

- The decreasing bayward gradient in iron content of sediments has implications in P availability, sulfide toxicity, and primary production in the benthos.
- The seagrass community is a major sink for nutrients from either the water column or sediment pore waters in the bay.

Patterns and Trends in Water Quality

A network of water-quality monitoring stations was established in 1989 (and funded by SFWMD in 1991) to investigate both spatial patterns and temporal trends in water quality in an effort to elucidate mechanisms behind the recent ecological change. One of the primary

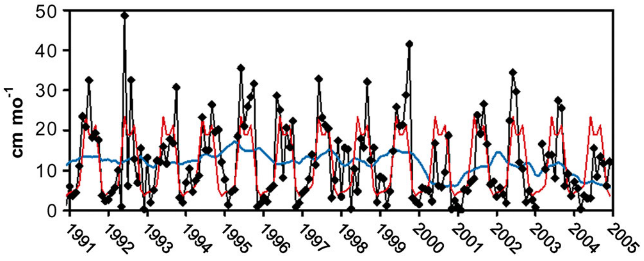

Figure 5.2 *Monthly average rainfall in the Florida Bay area, 1991–2005.*

purposes for conducting long-term monitoring projects is to be able to detect trends in the measured variables over time. These programs are usually initiated as a response to public perception (and possibly some scientific data) that 'the river-bay-prairie-forest-etc. is dying.' In the case of Florida Bay, during 1987, the impetus was the combination of a seagrass die-off, increased phytoplankton abundance, sponge mortality, and a perceived decline in fisheries.

Period of Study

Climactic changes occurring over the data-collection period of record had major effects on the health of the bay. Precipitation rebounded from the drought during the late 1980s and has been greater than the long-term average (9.2 cm mo^{-1}) for 9 of the past 12 years (Figure 5.2). Early in the record, salinity and total phosphorus (TP) concentrations declined baywide, while turbidity increased dramatically. The salinity decline in eastern and central Florida Bay was dramatic early on but has since stabilized into a regular seasonal cycle (Figure 5.3). Some of the decrease in the eastern bay could be accounted for by increased freshwater flows from the Everglades, but declines in other areas point to the climactic effect of increased rainfall during this period. The central bay continues to experience hypersaline conditions (greater than 35 practical salinity units [psu]) during the summer, but the extent and duration of the events are much smaller.

Chlorophyll *a* concentrations (CHLA), a proxy for phytoplankton biomass, were particularly dynamic and spatially heterogeneous (Figure 5.4). The eastern bay generally has the lowest CHLA, and the central bay has the highest. In the eastern bay, which makes up roughly half of the surface area of Florida Bay, CHLA have declined by 0.9 μg l^{-1} or 63%. Most of this decline occurred over a few months in the spring-summer of 1994 and has remained relatively stable. The isolated central bay zone underwent a fivefold increase in CHLA from 1989 to 1994, and then rapidly declined to previous levels by 1996. In western Florida Bay, there was a significant increase in CHLA, but median concentrations remained modest (2 μg l^{-1}) by most estuarine standards. There were significant blooms in the central and western bay immediately following Hurricane Georges (November 1998), but it was Hurricane Irene's large rainfall input (October 1999) that induced a large bloom throughout the bay. It is important to note that these changes in CHLA (and turbidity) happened years after the poorly understood seagrass die-off in 1987. It is possible that the death and decomposition of large amounts of seagrass biomass might partially explain some of the changes in water quality of Florida Bay, but the connections are temporally disjunct and the processes are indirect and not well understood.

As mentioned previously, TP concentrations have declined baywide over the 12-year study period (Figure 5.5). As with salinity, most of these declines occurred during the early part of the study. Unlike most other estuaries, increased terrestrial runoff may have been partially responsible for the decrease in TP concentrations in the eastern bay because the TP concentrations of the runoff were at or below ambient levels in the bay. The elevated TP in the central bay was mostly due to high evaporation. It is important to understand that almost all the phosphorus measured as TP is in the form of organic matter, which is less accessible to plants and algae than inorganic phosphate.

The DIN pool is made up of three components: ammonium (NH_4^+), nitrate (NO_3^-), and nitrate (NO_2^-). The western bay is lowest in DIN; phytoplankton in this region may be limited by N availability on a regular basis (Figure 5.6). DIN in the eastern bay is a little higher and is mostly in the form of NO_3^-, and highest levels are found in the central bay as NH_4^+.

Turbidities in the central and western bay have increased tremendously since 1991 (Figure 5.7). Turbidity in the eastern bay increased twofold from 1991 to 1993, whereas those in the central and western bays increased by factors of 20 and 4, respectively. Generally, the eastern bay has the clearest water, which is due to a combination of factors such as high seagrass cover, more protected basins, low tidal energy, and shallow sediments. We are unsure what caused it, but the loss of seagrass coverage may have destabilized the bottom so that it is more easily disturbed by winds.

An extensive set of contour maps of water-quality parameters for Florida Bay is available at http://serc.fiu.edu/wqmnetwork/.

Recent Conditions

Most water-quality variables during 2001 generally followed typical annual trends, with one prominent exception. All regions of the bay experienced a pro-

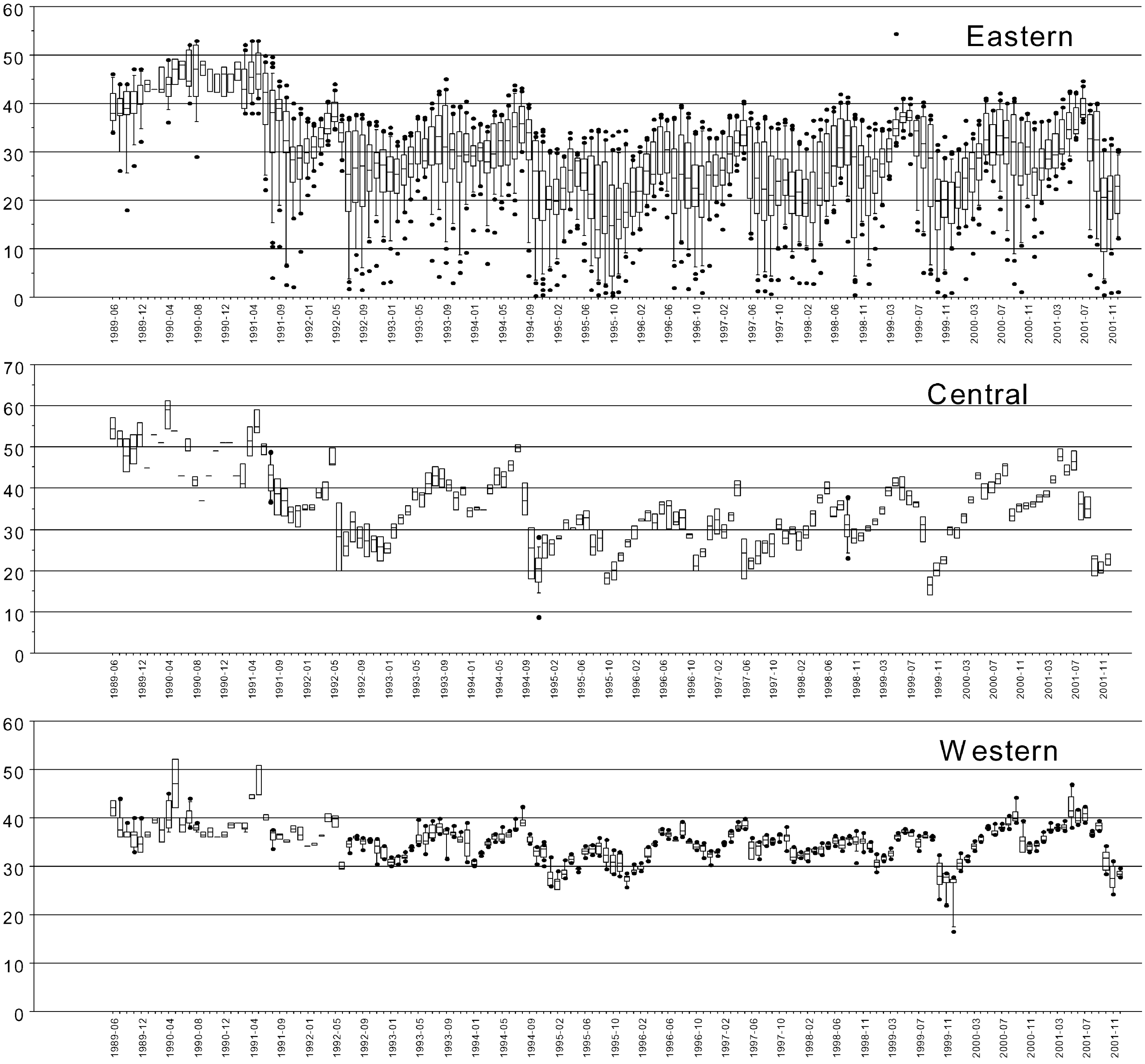

Figure 5.3 *Monthly median salinity in the three Florida Bay zones.*

longed period of hypersalinity during the summer months. Most of this was due to the previous dry year, which set up the system for this occurrence. The annual pattern in CHLA was unremarkable—no blooms reported. Total phosphorus values declined from very high levels in the fall of 2000 to normal levels in 2001. The western bay showed elevated DIN during the early part of 2001 but was not excessive compared with other years. Turbidity continued to fluctuate above post-1993 levels. Note that the high turbidities observed in the western bay during the winter also correlated with elevated TP.

NOAA/AOML also has a water-quality monitoring program in Florida Bay. Its primary purpose is to measure physical aspects of the system (see Question 1), but there is also a nutrient component to the sampling. An example of this is the analysis of phosphorus (Figure 5.8) using long-path-length liquid waveguide technology from Zhang and Chi (2002).

Exogenous Sources of Nutrients

A budget of Florida Bay's exogenous nutrient sources, which was estimated for the 2001 Florida Bay Confer-

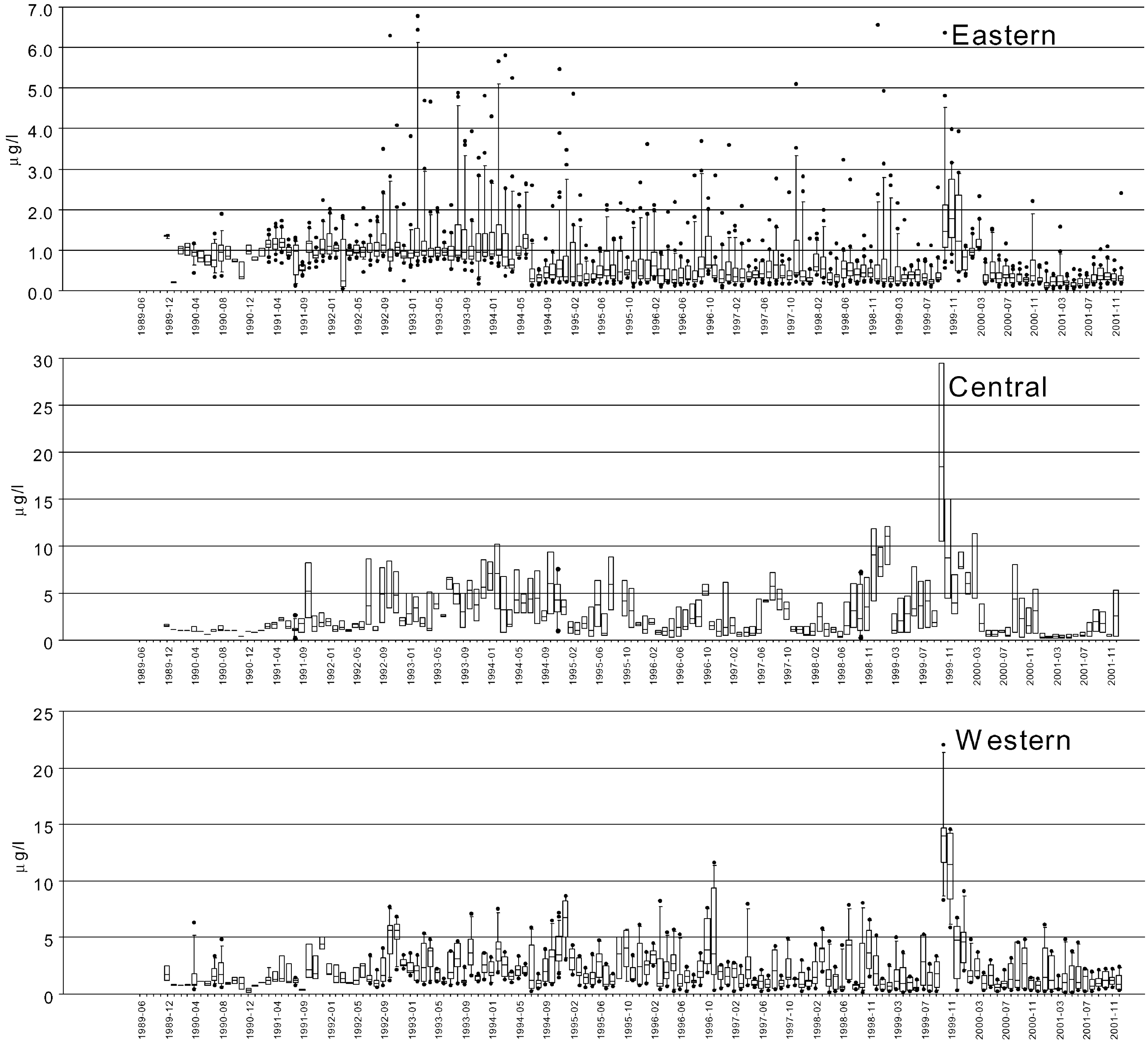

Figure 5.4 *Monthly median chlorophyll* a *in the three Florida Bay zones.*

ence, included inputs from the Everglades, wastewater and storm water from the Florida Keys, saline groundwater, the Gulf of Mexico, the Atlantic Ocean, and the atmosphere. Results from this exercise, with revision of the estimated saline groundwater source, are presented in Figures 5.9–5.11.

Nutrient Inputs from the Everglades: Taylor Slough–C-111 and Shark River

Nutrient outputs from the Everglades in this budget have been estimated from inputs to Everglades National Park wetlands from canals as reported by Rudnick *et al.* (1999). This approach can only be considered a rough estimate because of nutrient-processing during transport through the southern Everglades. However, these estimates are more likely to be correct than estimates of most other components of the bay's nutrient budget. The accuracy of estimates for the southeastern Everglades nutrient outputs is indicated by results of Sutula *et al.* (2003). This study found that TN and TP inputs from the mouths of mangrove creeks into Florida Bay in 1997 were similar to estimated inputs to the wetland that year (TN loads differed by 7%, and TP loads differed by one metric ton per year).

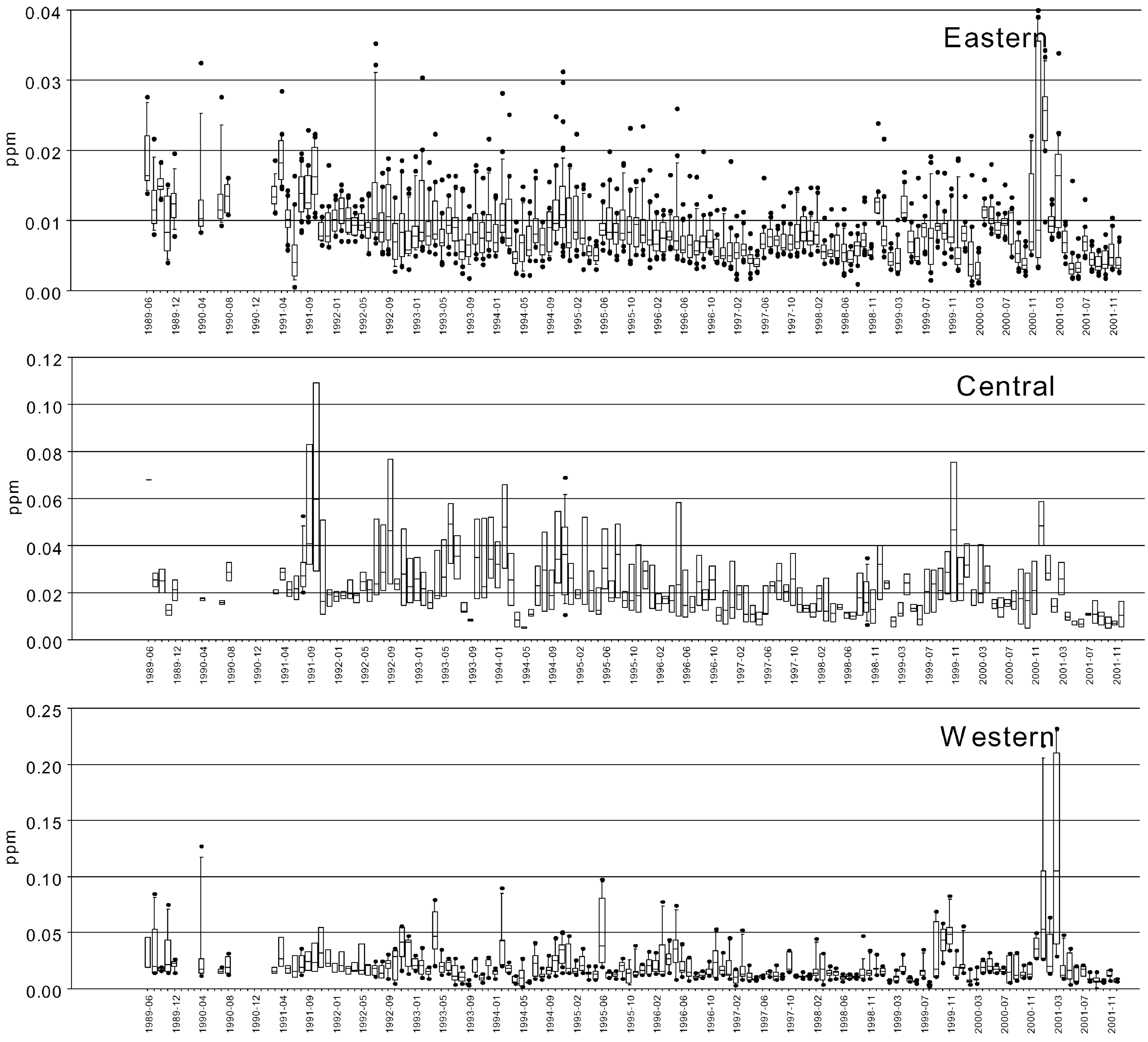

Figure 5.5 *Monthly median total phosphorus in the three Florida Bay zones.*

Studies of nutrient export from Taylor River, Trout Creek, and McCormick Creek (Sutula *et al.*, 2003; Davis *et al.*, 2003) have provided insights into the relationship between patterns of freshwater discharge and those of nutrient dynamics and output into Florida Bay. Nutrient outputs have been found to increase with increasing water discharge. As observed for inflows to Everglades National Park wetlands from canals, this increase is not linear; flow-weighted mean nutrient concentrations decrease with increasing discharge (Rudnick *et al.*, 1999; Figure 5.12). Output of phosphorus to Florida Bay is mostly as dissolved organic phosphorus, but it is very low in magnitude. During the dry season, both suspended solids and phosphorus are imported into the mangrove ecotone from the northeastern region of the bay. Output of nitrogen is also largely as dissolved organic nitrogen, but this quantity is high, resulting in a very high TN:TP ratio in creek outputs (molar ratio average near 200).

During the next year, RECOVER (the monitoring and assessment program of the Comprehensive Everglades Restoration Plan [CERP]) will expand the network of creek discharge and nutrient-sampling stations to include new sites along Florida Bay's coastline and the western Everglades rivers. A total of eight paired (upstream-downstream) stations are planned, includ-

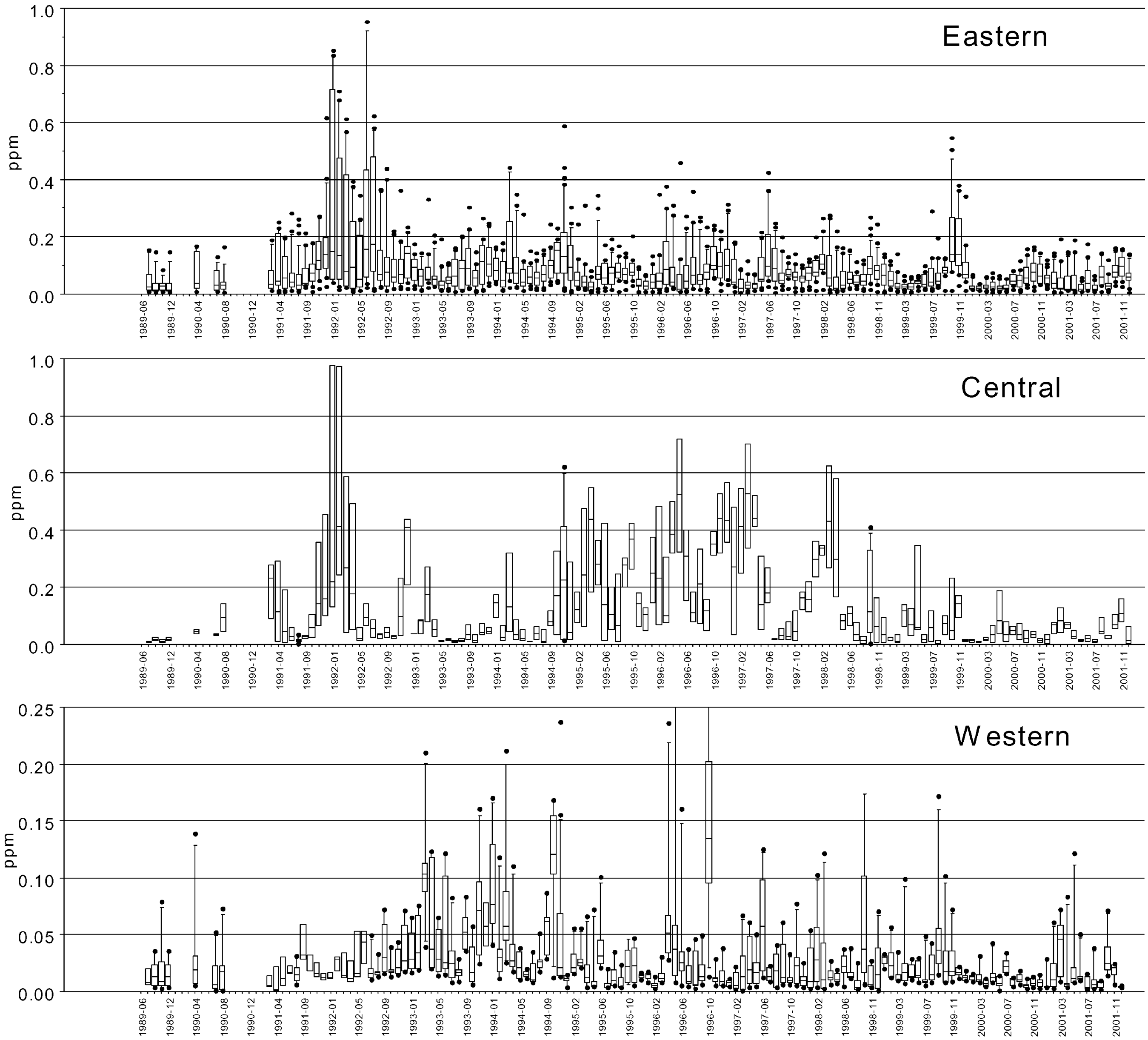

Figure 5.6 *Monthly median dissolved inorganic nitrogen in the three Florida Bay zones.*

ing four creeks entering Florida Bay and four rivers entering the Gulf of Mexico. It should also be noted that the Florida Coastal Everglades Long Term Ecological Research (LTER) is providing information on nutrient processing in the southern Everglades and mangrove zone, with particular emphasis on the formation, transport, and decomposition of dissolved organic matter.

Ground Water

The input of nutrients to Florida Bay via ground water remains highly uncertain. No new estimates of groundwater flux have been made since the 2001 conference. At that time, it was evident that subsurface freshwater inputs are negligible. Ground water beneath Florida Bay and its mangrove ecotone along the Everglades coast is saline (Reich *et al.,* 2002; Price, 2001; C. Reich and E. Shinn, personal communication). Thus, fresh ground water beneath the Everglades that flows toward Florida Bay appears to rise toward the surface, over denser saline water, to the north of the bay boundary (Price, 2001).

In contrast to fresh ground water, significant advection of saline ground water into the bay may occur from beneath the bay itself. Based on groundwater-tracer (radon, methane) concentrations, Corbett *et al.*

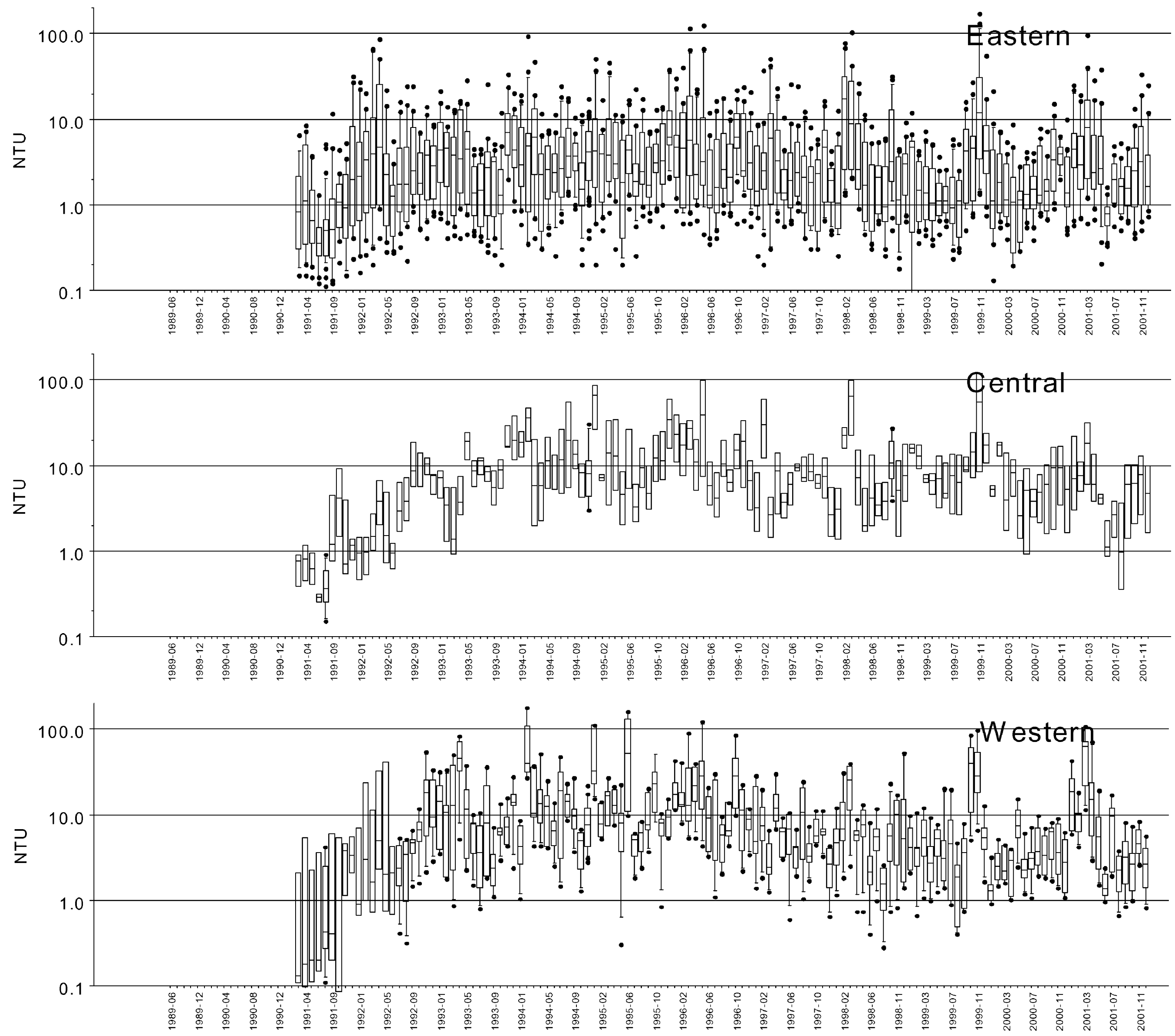

Figure 5.7 *Monthly median turbidity in the three Florida Bay zones.*

(1999, 2000a) have estimated a bay-wide vertical groundwater flow of about 1 cm/d or higher (Top *et al.*, 2001). The nutrient budget presented at the 2001 Florida Bay Conference used this value along with nutrient concentrations of 0.1 µmol TP, 1 µmol DIN, and 10 µmol TN. These concentrations are typical of wells at pristine sites in the Florida Keys (E. Shinn, personal communication). However, C. Reich and E. Shinn (personal communication) now report that these concentrations are considerably lower than those found in wells throughout Florida Bay. Over a four-year period, concentrations averaged approximately 1.5 µmol TP, 80 µmol TN, and 44 µmol NH_4. Still assuming a 1-cm/d groundwater flow, these higher concentrations would result in a groundwater nutrient input of 38 MT/y for TP, 8,800 MT/y for TN, and 5,000 MT/y for DIN. Compared to nutrient inputs from the Everglades, these estimated groundwater inputs are about 10 times higher for TP, about 6 times higher for TN, and more than 100 times higher for DIN. Some caution may be advised before applying these well-water concentrations because they may be affected by biogeochemical processes such as adsorption or denitrification prior to discharge, thus lowering their input into surface waters.

However, if this groundwater-input estimate of DIN is accurate, it would represent about 75% of all in-

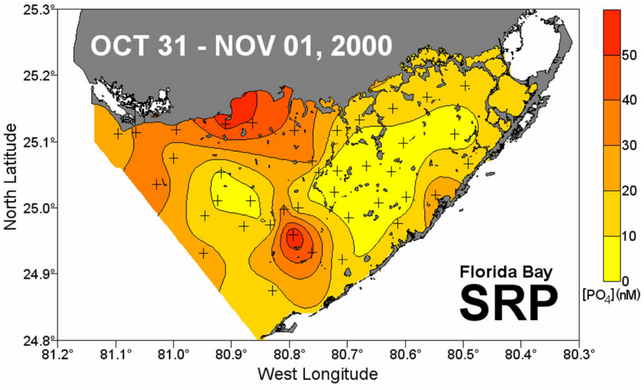

Figure 5.8 *Water column phosphate concentration in Florida Bay.*

organic nitrogen inputs to the bay. Furthermore, at such a high concentration, this inorganic nitrogen would be readily available for algal and submerged aquatic vegetation (SAV) productivity (in contrast to the low-concentration input from the Gulf of Mexico). It should be noted that this estimated groundwater DIN input is equivalent to 18 µmol m^{-2} h^{-1}, or roughly half of the median nocturnal nutrient flux across the sediment–water interface, as measured along the northern Florida Bay coast. It is also roughly equal to the median nocturnal benthic input found in the interior bay (P. Carlson, personal communication). The surprisingly high magnitude of the groundwater DIN input estimate, combined with the fact that ground water is usually hypersaline, is grounds for skepticism regarding the estimated 1 cm/d groundwater input as a rate that occurs commonly throughout the bay. This does not, however, preclude the possibility that large inputs of ground water occur at some locations in the bay, particularly near the Keys (see below).

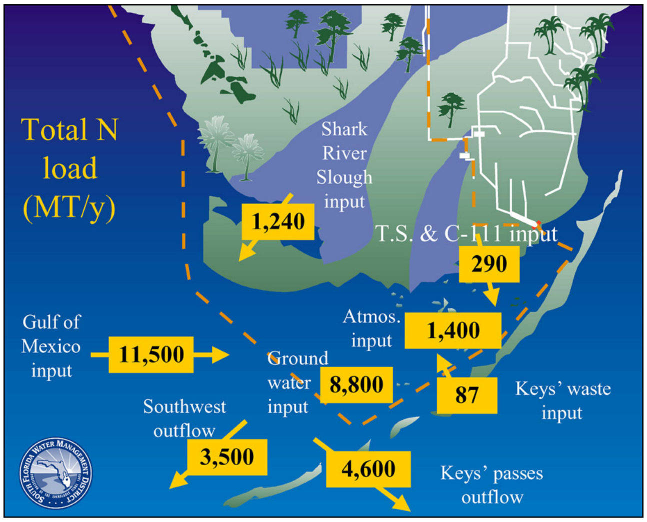

Figure 5.10 *Estimates of the annual exchange of TN at Florida Bay's boundaries. Everglades estimates are annual median inputs to wetlands from canals (since 1979 for Shark Slough and since 1984 for Taylor Slough and the C-111 basin). Note that flow-weighted mean TN concentrations have been consistently decreasing since 1985 in both systems and that medians provided here may be higher than those of recent years.*

An additional source of uncertainty in groundwater input is the depth from which the ground water is advected. For example, advective flow through surficial sediments can be caused by current-induced gradients over topographic expressions such as sand ripples (Huettel and Gust, 1992). Presumably, flow over

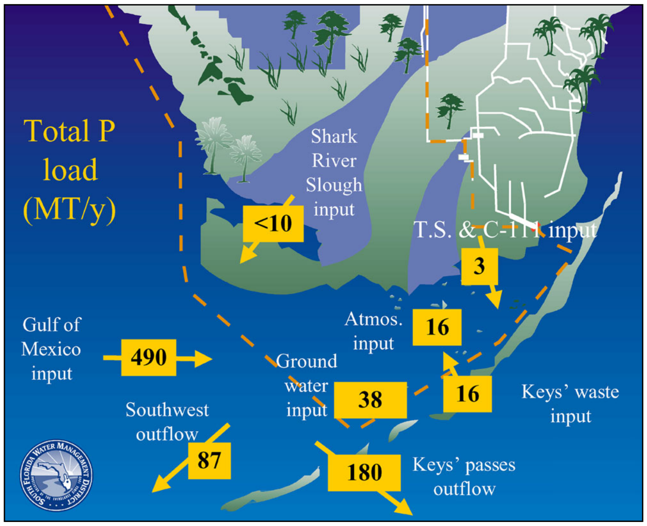

Figure 5.9 *Estimates of the annual exchange of total phosphorus at Florida Bay's boundaries. Everglades estimates are annual median inputs to wetlands from canals (since 1979 for Shark Slough and since 1984 for Taylor Slough and the C-111 basin).*

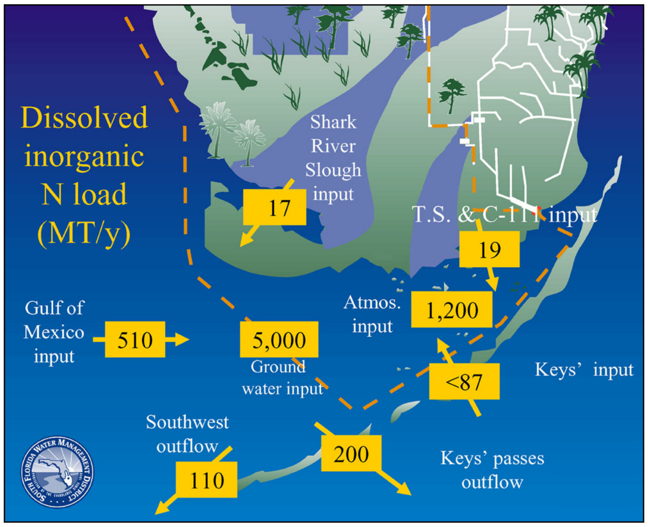

Figure 5.11 *Estimates of the annual exchange of inorganic nitrogen at Florida Bay's boundaries. Everglades estimates are annual median inputs to wetlands from canals (since 1979 for Shark Slough and since 1984 for Taylor Slough and the C-111 basin).*

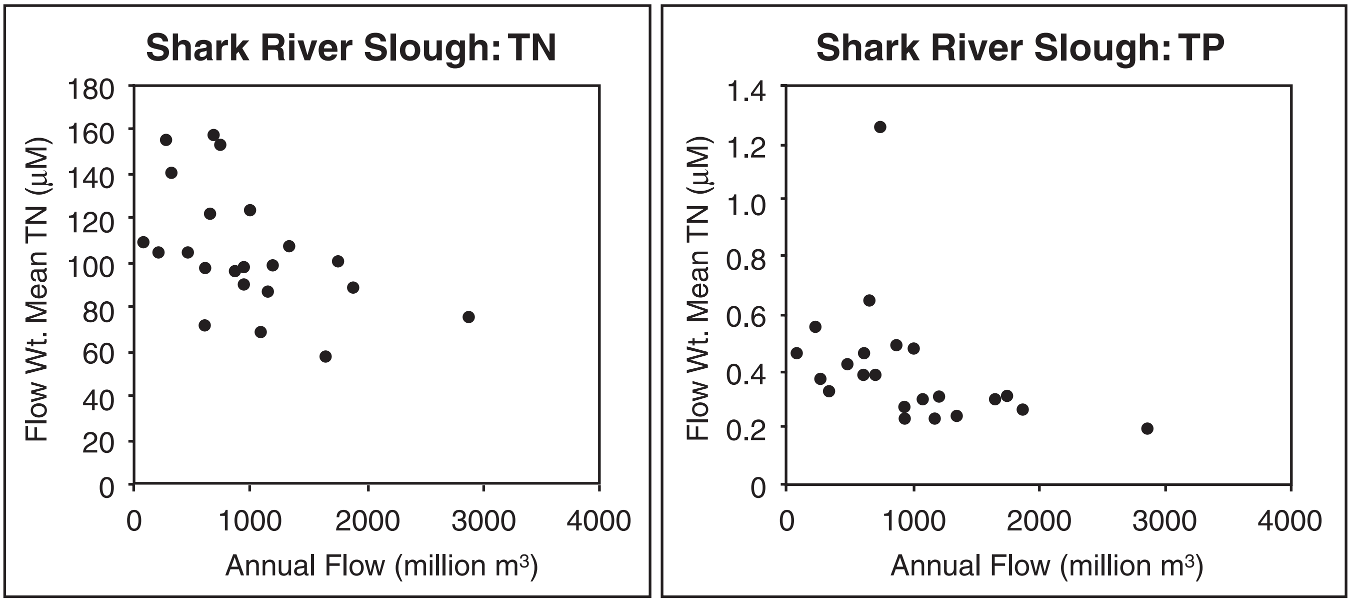

Figure 5.12 *Relationship between TN and TP concentrations (annual flow-weighted mean) in waters flowing into Shark River Slough and annual water discharge into the slough.*

banks, corals, or a host of other features could set up such shallow, subsurface flows. Flow through the seafloor caused by currents flowing over topography or waves may be responsible for the elevated tracer concentrations in the water column. The nutrient concentrations of these advected waters are probably lower than those sampled in wells and thus would lower the estimates of nutrient flux from groundwater flow.

An additional mechanism that can drive groundwater flow is the difference in tidal elevations across narrow reefs or barrier islands (Bokuniewicz and Pavlik, 1990; Reich *et al.,* 2002; Chanton *et al.,* 2003). Observations of seepage in the Upper Keys are consistent with this hypothesized mechanism (Chanton *et al.,* 2003). On an annual average basis, the water level in Florida Bay is several cm higher than the water level in the Atlantic (Reich *et al.,* 2002). However, the Atlantic has a daily tidal range of roughly half a meter, whereas daily water levels in Florida Bay are relatively constant. Therefore, during a high Atlantic tide, the ocean level is higher than the bay's water surface, creating a pressure differential pushing water from the Atlantic toward Florida Bay. In contrast, when the Atlantic tide is low, the situation is reversed, and there is a pressure differential pushing ground water from Florida Bay toward the Atlantic (Reich *et al.,* 2002).

The porous nature of the Key Largo Limestone that underlies the Upper Keys is consistent with this delivery of ground water to Florida Bay by this tidal-pumping mechanism. Studies employing viral and chemical tracers have documented horizontal and vertical transport rates of meters per day for water flow in the subsurface (Dillon *et al.,* 1999, 2000, 2003; Paul *et al.,* 1995, 1997, 2000; Lapointe *et al.,* 1990; Reich *et al.,* 2002). Hydraulic conductivity in the Key Largo Limestone ranges between 1,400 and 38,000 meters per day (Dillon *et al.,* 1999; Vacher *et al.,* 1992). Dillon *et al.* (1999) followed water-table height as a function of Atlantic tide in an onshore well on Key Largo. In this well, the groundwater table oscillated with Atlantic tide with only a 1.4-hour lag between Atlantic high tide and the highest water level in the well (Dillon *et al.,* 1999). There was only a 60% dampening of the tidal amplitude as the pressure wave moved through the carbonate rock. The extremely transmissive nature of the Keys aquifer system, in conjunction with the varying head differentials, promotes the interaction of subsurface waters with surface waters.

Ground waters in the shallow subsurface of the Keys contain dissolved nutrients from organic materials disseminated within the matrix (Sansone *et al.,* 1990) and are further contaminated from on-site sewage-disposal systems. Sewage in the Florida Keys is discharged into more than 600 disposal wells that penetrate the permeable Key Largo Limestone to depths of 10–30 m. Additionally there are an estimated 24,000 septic tanks and 5,000 cesspits on the islands (Kruczynski and McManus, 2002). Recent research has demonstrated a direct interaction between waste water delivered to the subsurface via injection wells and surface waters (Corbett *et al.,* 2000b; Dillon *et al.,* 1999, 2000, 2003). Natural tracers, including ^{15}N of seagrass tissue, have indicated that the greatest impact of groundwater discharge is along the shore of the Florida Bay side of the Upper Keys (Corbett *et al.*, 1999). Nutrient inputs from Keys ground water may be dominated by wastewater inputs and so are considered in the next section. The associated nutrient load to coastal waters would be substantial without significant subsurface biogeochemical alteration. This is particularly true with respect to phosphate delivery, which has been shown to be the limiting nutrient in eastern Florida Bay. Studies of the fate of nutrients injected into Class 5 wells in the Keys suggest phosphate removal with moderate nitrate attenuation (Corbett *et al.*, 2000b; Dillon *et al.*, 2003). Although it is understood that phosphate may be removed during transport, it is not clear whether this removal will be sustained. One question of particular importance is whether the phosphate may be released at some point to the phosphorus-limited waters surrounding the Keys, thus creating a significant water-quality problem for the marine environment. If phosphate uptake is ephemeral, then long-term transport of phosphorus to coastal waters may occur through the limestone aquifers. There is some evidence that the limestone surrounding Class 5 injection wells may saturate with phosphorus (Dillon *et al.*, 2003).

Atmospheric, Keys Waste Water, Keys Storm Water, and the Gulf of Mexico Nutrient Inputs

The remaining components of the Florida Bay nutrient budget (atmospheric, Keys wastewater and storm water, and the Gulf of Mexico) have not been revised since the 2001 conference. Atmospheric deposition is certainly an important nutrient source, particularly with regard to the relatively high input of inorganic nitrogen. The estimates in Figures 5.9–5.11 are derived from a study by T. Meyers in 1999 and 2000 on Long Key (T. Meyers, personal communication). Although bulk deposition of nitrogen can be estimated from a long-term National Atmospheric Deposition Program (NADP) site in Everglades National Park, few data are available to estimate dry deposition of nitrogen or phosphorus. Furthermore, phosphorus estimates in south Florida are often suspect because of the contamination of low ambient concentrations (Redfield, 2000). Estimates of the Florida Keys and Gulf of Mexico contributions are based on methods and data described in Rudnick *et al.* (1999). The Keys estimate entails far less uncertainty than the gulf estimate. It should be noted that the gulf contribution provided here (Figures 5.9–5.11) probably overestimates inputs to interior Florida Bay because the flow meters that produced the data used in the calculation were west of Florida Bay's mud banks. A large proportion of water flow measured by these flow meters never entered the bay. It should also be noted that a large discrepancy between the estimates of Rudnick *et al.* (1999) and Cerco *et al.* (2000) exists. The latter estimate was based on flow fields derived from a hydrodynamic model (Table 5.2).

Summary

The major source of TP and TN was the Gulf of Mexico (Figures 5.9, 5.10) and the major source of DIN was ground water (Figure 5.11). The smallest source of TP was Taylor Slough–C-111 (Figure 5.9). The smallest input of TN was from the Keys (Figure 5.10), whereas the smallest inputs of DIN were from Shark River and Taylor Sough–C-111 (Figure 5.11).

Internal Nutrient Cycling

Benthic Nutrient Fluxes

In situ benthic metabolism and nutrient regeneration were measured seasonally for 3 years (1997 through 2000) at five sites near the northern Florida Bay coast (Rudnick *et al.*, 2001) and for 1.5 years (1997–1998) at six bay sites away from the northern coast (Carlson and Yarbro, 1999). Additional flux measurements have been made more recently in sediment cores (Cornwell and Owens, 2003). The most notable results of these studies have been that phosphorus fluxes are very low (typically not significantly different from zero) and that inorganic nitrogen fluxes from sediment to water are surprisingly low. Sediments consistently removed nitrates and nitrites from the water column under dark and light conditions. Compared to rates of sedimentary oxygen uptake in the dark, rates of ammonium release have been found to be very low. Median O:N (oxygen:nitrogen) molar ratios in dark chambers at northern coastal sites greatly exceeded that expected from the mineralization of algal or seagrass detritus, ranging from 51 to 124 (O uptake:N release) (Rudnick *et al.*, 2001). Given the high organic matter concentrations of central Florida Bay, the finding of consistently low ($<50\ \mu\text{mol m}^{-2}\ \text{h}^{-1}$) ammonium fluxes from Rankin Lake sediments (Carlson and Yarbro, 1999; Kemp and Cornwell, 2001) is surprising.

Studies by Cornwell *et al.* (2000) and Kemp and Cornwell (2001) provide insights of mechanisms that explain the observed low rates of ammonium regeneration. They found that ammonium fluxes were negatively correlated with benthic chlorophyll *a* concentrations (Figure 5.13), perhaps because benthic algae stimulate coupled nitrification-denitrification.

Table 5.2 *Comparing Florida Bay nutrient budgets (positive into system) (from Cerco* et al., *2000).*

	Rudnick *et al.*		**Model Dry Season**		**Model Wet Season**	
System	**Total P (kg/day)**	**Total N (kg/day)**	**Total P (kg/day)**	**Total N (kg/day)**	**Total P (kg/day)**	**Total N (kg/day)**
Everglades	7.1	685	3.0	679	9.1	1,753
Atmosphere	104.1	1,945	127.0	2,393	127.0	2,393
Keys Loads	115.1	466	54.9	238	54.9	238
Western Boundary	1,112.3	21,918	192.7	3,105	-589.6	–6,217
Keys Passes	–493.2	–32,877	101.8	2,068	158.4	4,154
Net	**845.5**	**–7,863**	**479.4**	**8,483**	**–240.2**	**2,321**

These studies found that net N_2 fluxes were typically from sediment to water (dentrification exceeding nitrogen fixation). Denitrification rates (dark N_2 fluxes) at six sites averaged 127 ± 87 μmol m^{-2} h^{-1} in August and 65 ± 82 μmol m^{-2} h^{-1} in March. These fluxes greatly exceeded ammonium fluxes. Further support for the inference that low inorganic nitrogen regeneration is attributable to coupled nitrification-denitrification was provided by *in situ* hypoxia experiments (Rudnick *et al.*, 2001). Dissolved oxygen and nutrients were followed in a time series over 28 hours in dark benthic chambers. When dissolved oxygen in the water column dropped below 0.2 mg/L, ammonium fluxes increased five fold.

Yarbro and Carlson (unpublished) measured benthic fluxes of filterable reactive phosphorus (FRP), NH_4^+, silicate, TP, TN, dissolved organic phosphorus (DOP), and DON in seagrass beds in the eastern bay (Sunset Cove and Swash keys), central bay (Rankin Lake and Calusa Key), and western bay (Johnson and Rabbit Key basins). FRP fluxes ranged from uptakes of 3 μmol m^{-2} h^{-1} in Johnson Key Basin in the western bay to releases of 1–2 μmol m^{-2} h^{-1} in the eastern bay. Dissolved organic phosphorus (DOP) fluxes (2–4 μmol m^{-2} h^{-1}) were considerably higher than FRP fluxes and were more often released from the benthos, especially at central and western bay sites. These small fluxes are in sharp contrast to the large phosphorus pool in surficial sediments (1–12 μmol gDW^{-1}).

Additionally, the sharp increase in sediment phosphorus from east to west in the bay was not reflected in benthic fluxes. Keeping in mind that these fluxes represent net flux to or from the seagrass community, we estimate that ammonium and the sum of FRP and DOP fluxes can meet 20%–50% of the phytoplankton demand in the eastern and western regions of Florida Bay but only 5%–10% of the phytoplankton demand in the highly productive, *Synechococcus*-dominated north-central bay.

Internal Nutrient Cycling: Carbonate-Phosphorus-Iron Relations

A study by Chambers *et al.* (2001) documented the spatial variation in sediment phosphorus, iron, and sulfur. Total sediment phosphorus decreases on a west-east gradient across Florida Bay, similar to the pattern in which surface-water quality decreases. Mineral sulfides and extractable iron in Florida Bay sediments decrease on a north-south gradient. Most inorganic phosphorus in the sediment is associated with abundant calcium carbonate minerals and not with reactive iron oxides that occur in very low concentrations. Iron availability limits mineral sulfide formation, but dissolved sulfide concentrations in Florida Bay sediments are high. Experimental addition of reactive iron to seagrass plots in Florida Bay stimulated phosphorus retention in the sediment and buffered plants from toxic sulfide accumulation. Phosphorus availability to seagrass still appears to limit production in carbonate sediments more than sulfide toxicity. Generation of inorganic phosphorus in seagrass sediments may occur directly via mineralization of organic matter and indirectly via concomitant carbonate mineral dissolution (Ku *et al.*, 1999).

Role of Sediment Resuspension in Phosphorus Cycling

Phosphorus is retained on the surface of calcium carbonate sediments (Zhang and Fischer, 2001). Within a few minutes of sediment resuspension, phosphate that is weakly bound to particle surfaces is released to the water column, where it may be used by phytoplankton. Coprecipitation of calcium phosphate with calcium carbonate may scavenge dissolved phosphate out of the water column.

Total sedimentary phosphorus (TSP) was fractionated into five chemically defined pools (Zhang and

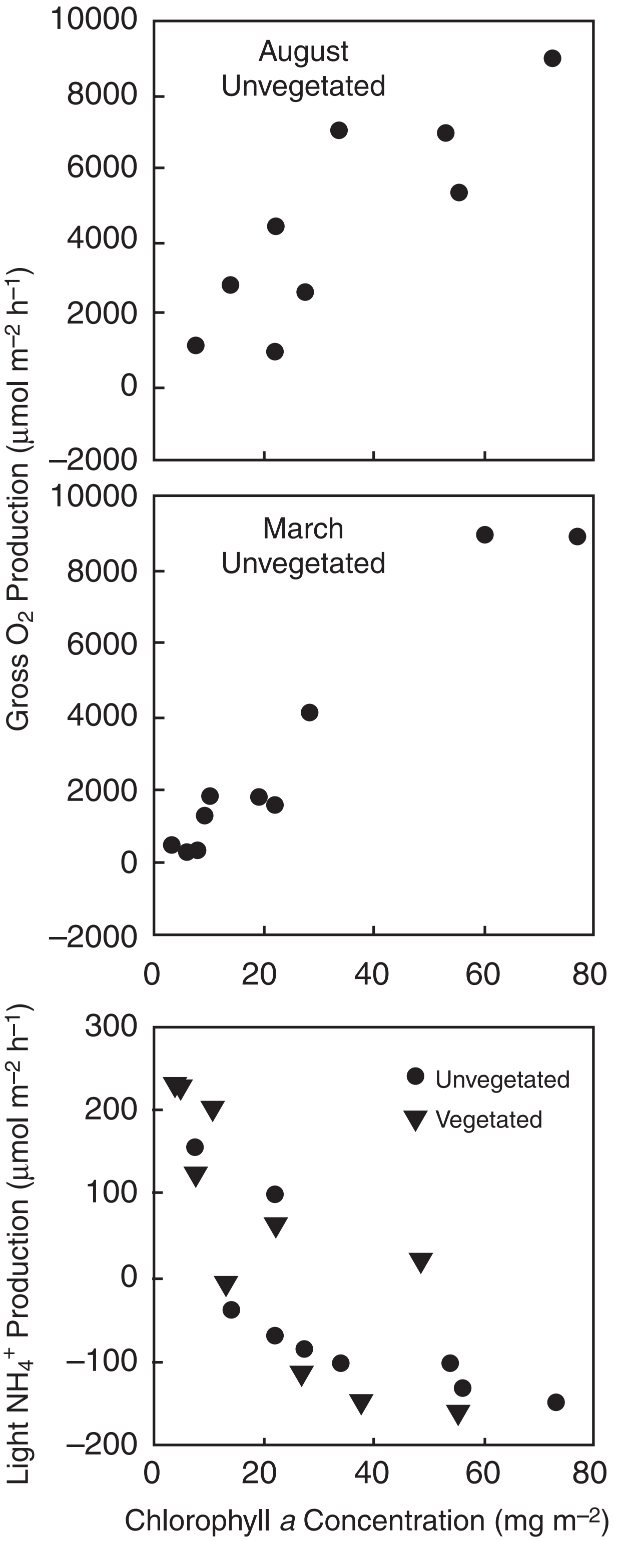

Figure 5.13 *Results from denitrification study conducted by Cornwell (2001). This figure indicates the importance of benthic microalgae in the nitrogen cycle. Ammonium uptake from the water column is associated with high chlorophyll concentrations.*

Fischer, 2001): (1) adsorbed (readily exchangeable) inorganic and organic phosphorus, (2) Fe-bound inorganic phosphorus, (3) autogenic apatite calcium carbonate-bound inorganic and organic phosphorus, (4) detrital apatite phosphorus, and (5) refractory organic phosphorus. This study observed a strong gradient of decreasing TSP from the west (14.6 µmol g^{-1}) to the east (1.2 µmol g^{-1}) across central Florida Bay (Zhang *et al.*, 2004).

Among the five pools, autogenic apatite calcium carbonate-bound phosphorus accounted for the largest fraction of phosphorus (45% of TSP; Zhang *et al.*, 2004); inorganic phosphorus dominated this pool (70%–90%). The refractory organic phosphorus (24% of TSP) and iron-bound inorganic phosphorus (19% of TSP) were the second largest pools. Adsorbed phosphorus accounted for 8% of TSP (60% organic phosphorus), and detrital apatite phosphorus composed the smallest fraction (5% of TSP). Overall, organic phosphorus accounted for 38% of TSP.

Nutrient Flux at the Sediment-Water Interface

Yarbro and Carlson (1999) measured silicate fluxes that ranged from –337 µmol m^{-2} h^{-1} at Rankin Lake, (September 1997) to 766 µmol m^{-2} h^{-1} (August 1998). Ammonium fluxes ranged from –8.3 µmol m^{-2} h^{-1} at Rankin Lake (November 1998) to 156 µmol m^{-2} h^{-1} at Sunset Cove in November 1998. Total dissolved nitrogen fluxes were highly variable between sites and sampling dates, ranging from –340 µmol m^{-2} h^{-1} at Rabbit Key Basin in August 1998 to 193 µmol m^{-2} h^{-1} at Sunset Cove in November 1998. Dissolved organic nitrogen (DON) also varied between sites and sampling dates, ranging from 5.7 µmol m^{-2} h^{-1} at Swash (May 1998) to 250 µmol m^{-2} h^{-1} at Rabbit Key Basin (August 1998). Net DON flux was always from the sediment to the water column.

Because filterable reactive phosphorus (FRP) concentrations generally were very low, flux estimates were highly variable (Yarbro and Carlson, 1999). Total dissolved phosphorus and FRP fluxes ranged from net uptakes of –6.23 to –0.02 µmol m^{-2} h^{-1} and sediment releases of 0.02 to 11.57 µmol m^{-2} h^{-1}. Most fluxes were less than 1 µmol m^{-2} h^{-1}.

Seagrass Modeling

An ecological model of the Florida Bay seagrass community, funded by USGS through the Critical Ecosystems Initiative, was conceived as a means of enhancing the ability of managers to improve health of the Florida Bay ecosystem, seagrass habitat in particular (Madden *et al.,* 2003, McDonald and Madden, 2003; Figures 5.14, 5.15). This model is a dynamic, mechanistic simulation of seagrasses, emphasizing nutrient cycling and nutrient demand related to seagrasses. It is being used as a tool for determining the causes of seagrass mortality due to environmental stress and to calculate nutrient-sink characteristics of the seagrass community.

In scenario analyses, this model was used to test the effects of individual and simultaneous multiple stressors, at levels measured to occur *in situ* on primary productivity. Application of multiple stressors involving elevated nutrients, salinities, and elevated sulfide concentrations produced dramatic results in the *Thalassia* growth profile. Biomass declined continuously from the point of application of simultaneous stressors in January throughout the growing season as *Thalassia* rapidly died off. Examination of processes underlying this model behavior revealed that photosynthesis, though operational, was impaired and functioning at such a low level that the net daily production was negative throughout the growing season.

Interaction of the above- and below-ground compartments played a strong role in the trajectory of the seasonal biomass curve in the model. Exchanges of organic carbon and nutrients between leaf and root compartments are seasonally variable and critical for survival of submerged plants. The modeled plants can mobilize below-ground resources to supplement carbon input to the above-ground compartment should autotrophic assimilation become deficient. The amount of carbon in the root/rhizome material available for growth supplementation can control the outcome of plants subjected to stress conditions. Therefore, the status of the below-ground compartment can determine the survival of the entire plant. Conversely, when conditions are unfavorable to growth and below-ground resources are depleted, the existence of above-ground plant material can mask a plant community in fragile condition. We believe that this model's conceptualization is realistic and is likely close to the physiological and community reactions that occur in the real system, emphasizing the importance of thresholds and nonlinear reactions, which can be tracked and revealed by model analysis.

A series of model runs were made to determine nutrient demand under a range of C:N ratios (15–36) and C:P (400–1800) ratios typical of the bay. On an annual basis, P supplied to sediment pore waters via organic remineralization and rock dissolution each averaged about 1–1.5 mg P m^{-2} d^{-1}, whereas P exported from the Everglades averaged 0.05 mg P d^{-1} to overlying waters in Little Madeira Bay (Rudnick *et al.,* 1999). Depending on tissue ratios of nutrients applied to the model, these rates supply from >1,000% to only 30% of P demand by *Thalassia.* Significantly, the C:P ratio estimated by inverse modeling required to use 100% of the available sediment P regenerated daily (2.3 mg^{-2} d^{-1}) is 500:1, which approaches the average C:P ratio of 800:1 that has been measured empirically in Little Madeira Bay and northeastern Florida Bay.

Influence of Florida Bay Water Quality on the Reef Tract

Nutrient Export Through Keys Passes

The rate of outflow was estimated by Lee and Smith (2002) from measurements made in Channel 5 and Channel 2 near Long Key in 1997 and 1998. The long-term mean was 370 m^3/s (11.7 × 109 m^3/y). The estimated exports (MT/y) were TP = 180; TN = 4,600; DIN = 200 (Figures 5.9–5.11). Nutrient concentrations were measured as part of FIU's monitoring (Jones and Boyer, 2002), and the flux calculation assumed median concentrations.

Based on these estimates, Florida Bay is a sink for approximately half of the inputs of TP and TN and more than 80% of the inputs of DIN. Additional export of N and P from Florida Bay may occur in the form of drift seagrasses and algae but no quantitative estimates have been made of these exports.

Water-Quality Modeling

The water-quality model (Cerco *et al.,* 2000) linked modules including water-column eutrophication, seagrass dynamics, sediment diagenesis, solids and nutrient resuspensions, and benthic algal production. To our knowledge, this is a first for Florida Bay. In fact, we know of few systems that currently have a model application to rival the current effort in Florida Bay. However, the model requires substantial upgrading to fully represent processes in the bay.

Nutrient loads from various sources to the bay and surrounding waters were calculated for the model study. Estimates indicated that the atmosphere is the largest loading source to the bay. Runoff from the mainland is the smallest source of phosphorus and second smallest source of nitrogen. Paradoxically, runoff appears to be the most intensely studied loading source. There are large degrees of uncertainty as to what the greatest loads are. Attention should be devoted to accurately quantifying atmospheric and phosphorus loads from the Keys.

No *in situ* measures of nitrogen fixation were available to us. Rates associated with seagrass beds, measured in other systems, were adapted for the model.

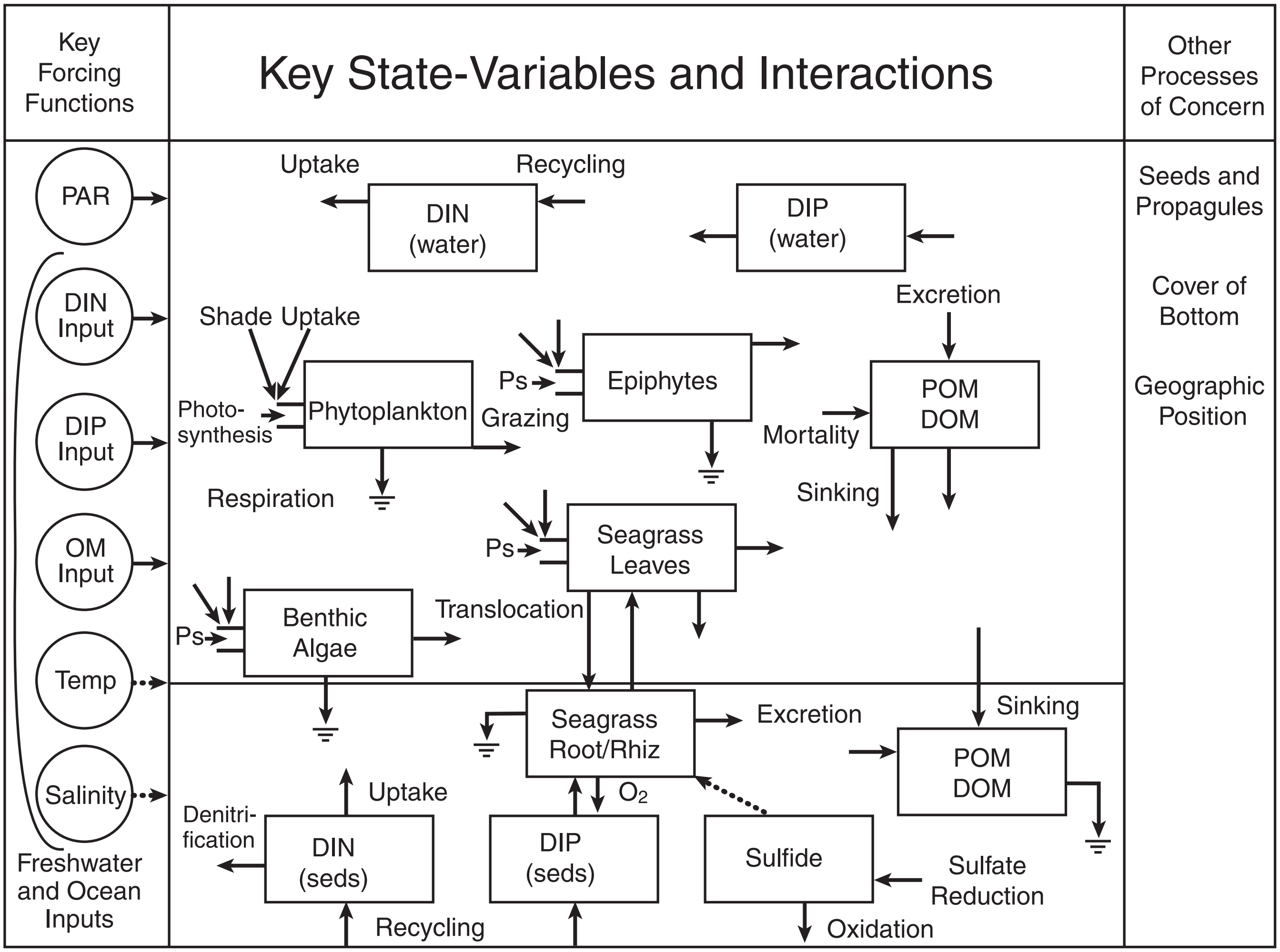

Figure 5.14 *Ecosystem process model of south Florida estuarine systems. Conceptual diagram of Florida Bay seagrass model emphasizing major nutrient cycles. (Madden* et al.*, 2003).*

Estimated nitrogen fixation associated with seagrass leaves equals the estimated atmospheric nitrogen load. The sum of nitrogen fixed in the leaves and roots makes nitrogen fixation the largest single source to the system. Measures of nitrogen fixation are currently being conducted and these measures should be swiftly incorporated into the model and into system nutrient budgets.

Measures of denitrification within benthic sediments were also unavailable. Rates of denitrification were calculated by the sediment diagenesis model, with values adapted from Chesapeake Bay. Calculated denitrification roughly equals total nitrogen fixation. Denitrification rates should be measured and used to verify the computations provided by the model.

The model underestimates the amount of nitrogen in both the sediments and water column. Sensitivity analysis indicates that the shortfall is unlikely to originate from the loading estimates. Either a source of nitrogen has been omitted or the estimated loads are greatly in error. Potential sources of omission or error include groundwater, nitrogen fixation, and denitrification.

The model does not indicate that material does not concentrate in the central basins. This behavior may be attributed to several factors. First, the underlying hydrodynamic calculations may not concentrate material. Second, the linkage method may introduce errors in the computed hydrodynamic field. Third, the water-quality grid and numerics may introduce artificial dispersion. Dye-tracer tests indicated that the water-quality model qualitatively tracks transport in the hydrodynamic model in Florida Bay. (Transport is not equivalent on the western shelf because of artificial dispersion and boundary-condition specification.) The tracer tests led us to the conclusion that the underlying hydrodynamics prevent computation of hypersalinity and concurrent concentration of nitrogen and other materials.

Interpretation of results from the water-quality

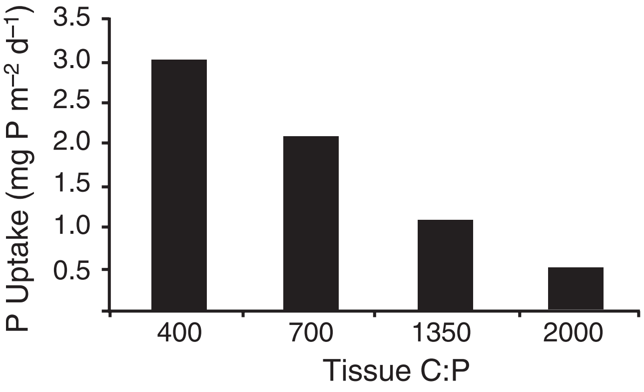

Figure 5.15 *Theoretical phosphorus demand by* Thalassia *in mg per m^2 per day as calculated by the seagrass model to satisfy seagrass primary productivity rates in northeast Florida Bay.*

model was severely compromised by the lack of a verified hydrodynamic model operable on the same time scale as the water-quality model.

Successful simulation of a ten-year sequence of water quality was virtually impossible without corresponding hydrodynamics. The highest priority should be given to applying a detailed, volume-conservative hydrodynamic model to the bay and adjoining waters. The model should simulate at least a ten-year period and provide good agreement to salinities observed within that period.

The major uncertainty in the system's nutrient budget is transport across the western boundary and through the Keys passes. This transport cannot be observed on a long-term basis. Computation via a model is the only alternative for long-term budget estimates. High priority should be given to estimating flow across system boundaries once a verified hydrodynamic model is available.

Sensitivity analysis indicated that model computations are very sensitive to the biological activity at the sediment–water interface. In the present model, this activity is represented by the benthic algal component, and as formulated, the model cannot represent all observed fluxes, especially those of dissolved organic matter. Attention should be devoted to quantifying sediment–water fluxes, to investigating the nature of the benthic community, and to process-based modeling of this community.

A great number of observations have been collected in the bay since this study commenced, and considerably more is known about the bay than was known a few years ago. Once suitable hydrodynamics are available, the water-quality model should be reapplied on a ten-year time scale and validated with the latest observations of conditions and processes in the bay. Concurrent with the reapplication, first-order improvements (*e.g.,* division of dissolved organic matter into labile and refractory components) can be incorporated into the water-quality model.

As part of the Florida Bay and Florida Keys Feasibility Study of the CERP, a new attempt is currently being made to develop, calibrate, validate, and apply a Florida Bay water-quality model.

Current and Ongoing Research

Unresolved Questions

Past informational needs relative to nutrient cycling in Florida Bay have been coupled to understanding the factors that triggered the mass mortality of seagrass and what initiated and maintained the phytoplankton blooms. Current needs have become more focused around assessing the effects of various environmental management strategies being considered for bay restoration. In particular, we need to accurately predict the sensitivity of the bay's nutrient cycles to changing freshwater flow to the bay and the resultant change in the bay's salinity regime. For much of the bay, any factor that increases phosphorus availability, either by increasing sources or decreasing removal, is likely to exacerbate the current problems of the bay. Recent evidence also indicates that algal blooms in the central and western bay are also stimulated by nitrogen enrichment. Thus we need a thorough understanding of the bay's nutrient cycles, particularly with regard to the fate and effects of dissolved organic nitrogen inputs from the Everglades. Understanding the mechanisms that have triggered and are sustaining algal blooms in the bay is fundamental to restoration decision-making. This understanding entails quantifying the nutrient demands of these algae and how these nutrients are supplied. Questions that the future program should address in order to meet these needs are as follows:

- What are the sources of nutrients that sustain algal blooms?

  Understanding the mechanisms that have triggered and are sustaining algal blooms in the bay is fundamental to restoration decision-making. This understanding entails quantifying the nutrient demands of these algae and how these nutrients are supplied.

- How will changing freshwater flow directly and indirectly alter the supply and availability of nutrients in the bay? What effect does changing salinity have on nutrient availability in the bay?
  - How will the quality and quantity of nutrient out-

  puts from the Everglades change with restoration?
  - What is the fate and effect of dissolved organic matter from the Everglades and how will this change with restoration?
  - What effect does changing salinity have on nutrient cycling and availability in the bay?

With increased freshwater flow expected from restoration of the Everglades and Florida Bay, nutrient loading from the Everglades watershed will also probably increase. For nitrogen, most of this loading will be in the form of dissolved organic compounds. The sources, fate, and effects of DON from the Everglades watershed are unknown, and predictions of how changing freshwater flow will influence these DON dynamics are highly uncertain. Measurements of the composition and bioavailability of Everglades DON to Florida Bay's microbial communities (pelagic, epiphytic, and benthic) are essential in order to assess the functional relationship of Florida Bay and its watershed. Although the magnitude of this expected increase is unknown, this direct input may be less important than the indirect effect of an altered salinity regime caused by increased freshwater influx. Altered salinity can affect internal nutrient cycling by (1) altering community structure (such as changing seagrass-species dominance, thus changing nutrient storage and cycling), and (2) modifying specific processes, such as phosphorus surface reactions and sulfate reduction. A change in freshwater flow and salinity could also alter nutrient processing in the mangrove zone and thus alter nutrient exchange along the bay's northern boundary, the Gulf of Mexico boundary with the Everglades, and near mangrove islands in the bay.

The factors that influence the loading of nutrients into Florida Bay and the availability of nutrients within the bay are not well understood. In particular, we need to understand the effect that potential environmental-management actions, such as increasing freshwater flow and decreasing salinity, will have on the bay's nutrient transformations and fluxes. Information on suspended sediment particles and on factors that may influence the mobilization and immobilization of phosphorus in carbonate sediments is critical. Results of past experiments (Zhang *et al.*, 1999) need to be evaluated in the context of the development of a water-quality model to assess the sufficiency of current data for estimating salinity effects.

Given the unusually high ammonium concentrations of the bay and the potential for nitrogen limitation in the western bay, experiments on factors that may influence key nitrogen transformations, such as nitrification and denitrification, are also needed. Experiments that explore how nutrient cycling is altered by changes in seagrass community structure and physiological condition (particularly below-ground nutrient changes) are also important but have yet to be done.

- What effect does a change in seagrass community structure have on nutrient availability in the bay? Has seagrass mortality only increased nutrient availability by releasing nutrients from this detrital source or has seagrass mortality also caused other less direct changes, such as a decrease in the capacity of the sediments to sequester nutrients?

The lag of several years between the onset of seagrass mass mortality and the occurrence of algal blooms in the bay argues against the hypothesis that only nutrients released from dead seagrass tissue fuel the blooms. However, the increase in nutrients from this detrital source, combined with a net decreased uptake capacity associated with seagrass mortality, may explain the bloom's temporal patterns. Thus, we need estimates of net benthic nutrient uptake or release rates over a range of seagrass growth rates, mortality rates, and detrital decomposition rates for different seagrass species. The accuracy of such estimates may depend largely upon understanding sedimentary nutrient transformations, including how seagrass roots affect nutrient mobility and how such processes change with seagrass mortality. Seagrass mortality may have indirectly affected nutrient cycles in the bay. For example, sediment resuspension increases with decreasing seagrass density, and phosphorus associated with this suspended sediment may be available to phytoplankton. Finally, changing seagrass cover also influences the biomass and activity of benthic algal mats. This change in microbial mats in turn affects nitrogen availability by altering patterns of nitrification, denitrification, and nitrogen fixation. Measurements of the quantitative relationships of these processes within the algal and SAV community structures are needed.

Given the shallow depth and restricted circulation of Florida Bay, internal cycling and transformations of nutrients probably have a strong influence on the structure and productivity of bay communities. These nutrient pathways and transformations have not been well studied. Essential measurements include nutrient uptake by primary producers (especially seagrass and phytoplankton), the exchange of nutrients between the sediments and the water column, the diagenesis of nutrients within the sediments (especially phosphorus–carbonate reactions and nitrogen transformations), and microbial and inorganic reactions within the water column (such as nitrification and phosphorus sorption to and removal from suspended sediment).

- How do we deal with the spatial heterogeneity of internal nutrient cycling in the bay?

There is no unified field theory for ecology—process rates from one area may not be applicable to another. What other factors are important in driving these processes?

- What is the quantitative role of microphytobenthos in nutrient cycling and how is this likely to change with Everglades restoration?

The microphytobenthos has been shown to be influential in regulating benthic flux rates. Fluxes in the form of drift seagrasses and algae have not been determined.

- To what extent is atmospheric deposition of nutrients contributing to ecological changes in Florida Bay? What is temporal variability (including long-term trend) of this nutrient source?

Atmospheric inputs have been shown to be a significant component of external nutrient loading, especially of nitrogen. There are no estimates of long-term trends in atmospheric nutrient-loading at present.

- Is ground water an important nutrient source in Florida Bay? If so, what is the spatial and temporal pattern of this input?

Given the high nutrient content of the groundwater beneath most of the bay, any groundwater flux approaching recently published rates (about 1 cm d^{-1}) would result in a very high nutrient flux. The accuracy of these estimates should be checked—sites with significant upward groundwater advection should be identified; if found, nutrient concentrations at these sites should be measured.

Summary of Ongoing Research

- Continued monitoring of ambient water quality in Florida Bay.
- Continued monitoring of freshwater inflows and loads with expansion of network along Florida Bay and southwest Florida gulf coast beginning.
- Continued monitoring of coastal circulation and biological and chemical parameters, with interpretation of transport and exchange of south Florida coastal waters.
- Expanded research into nutrient cycling in wetland/mangrove areas and seagrasses/epiphytes.
- Study of carbonate system–phosphorus–iron relations.
- Characterization of chemical structure of organic carbon and nitrogen from wetland/mangrove areas.
- Assessment of microbial bioavailability of organic carbon and nitrogen from wetland/mangrove areas.
- Expanded measurements of benthic nitrogen fixation, nitrification, and denitrification rates.
- Measurements of phytoplankton nitrogen uptake rates.
- Quantification of microbial loop parameters: heterotrophic bacterial numbers, bacterial production, nanoflagellate/protist grazing rates, and phytoplankton primary production.
- Effects of variability in regional climate, freshwater inputs, disturbance, and perturbations on the coastal Everglades ecosystem.
- Development of nitrogen and phosphorus mass-balance models and measurements of nutrient cycling rates in Florida Bay.
- Assessment and monitoring of dissolved nitrogen in Florida Bay.
- Measurement of nutrient fluxes through Florida Keys passes.
- Monitoring of salinity and estimates of fluxes of water and total nitrogen and phosphorus across the southern Everglades mangrove zone.
- Development of an integrated hydrodynamic and water-quality model to evaluate relationships with freshwater flow and oceanic/gulf hydrodynamics and exchange is in a planning phase.
- Seagrass uptake kinetics of phosphorus.
- Influence of dissolved organic matter on seagrass, epiphyte, and phytoplankton productivity.
- Seagrass survival and productivity under single and multiple stresses.
- Dynamic simulation model analysis of spatial patterns of seagrass productivity, community structure, and nutrient demand.

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