Hydrobiologia (2006) 569:23–36
J.C. Trexler, E.E. Gaiser & D.L. Childers (eds), Interaction of Hydrology and Nutrients in Controlling Ecosystem Function in Oligotrophic Coastal Environments of South Florida
DOI 10.1007/s10750-006-0120-5

# Coastal groundwater discharge – an additional source of phosphorus for the oligotrophic wetlands of the Everglades

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*Key words:* coastal groundwater discharge, Everglades, phosphorus

## Abstract

In this manuscript we define a new term we call coastal groundwater discharge (CGD), which is related to submarine groundwater discharge (SGD), but occurs when seawater intrudes inland to force brackish groundwater to discharge to the coastal wetlands. A hydrologic and geochemical investigation of both the groundwater and surface water in the southern Everglades was conducted to investigate the occurrence of CGD associated with seawater intrusion. During the wet season, the surface water chemistry remained fresh. Enhanced chloride, sodium, and calcium concentrations, indicative of brackish groundwater discharge, were observed in the surface water during the dry season. Brackish groundwaters of the southern Everglades contain 1–2.3 $\mu$M concentrations of total phosphorus (TP). These concentrations exceed the expected values predicted by conservative mixing of local fresh groundwater and intruding seawater, which both have TP < 1 $\mu$M. The additional source of TP may be from seawater sediments or from the aquifer matrix as a result of water–rock interactions (such as carbonate mineral dissolution and ion exchange reactions) induced by mixing fresh groundwater with intruding seawater. We hypothesize that CGD maybe an additional source of phosphorus (a limiting nutrient) to the coastal wetlands of the southern Everglades.

## Introduction

All coastal aquifers with a hydraulic connection to the sea are susceptible to seawater intrusion (Bear et al., 1999). The interface between freshwater and seawater in coastal aquifers was first identified by Du Commun (1828), half a century earlier than the more widely cited Ghyben–Herzberg principle (Ghyben, 1888; Herzberg, 1901). A systematic study of seawater intrusion in the 1950s in south Florida formed a set of benchmark papers on the subject (Cooper, 1959; Kohout, 1960, 1964). The most significant finding of these studies was the recognition that the freshwater–seawater interface was not sharp as described by the Ghyben–Herzberg principle, but formed a zone of mixed water composition termed by many in the field as a 'mixing zone' (Fig. 1a; Back et al., 1986; Price & Herman, 1991). Brackish water in this mixing zone is circulated along with the freshwater to the sea (Cooper, 1959). If the groundwater discharge occurs beneath overlying marine or estuarine waters it is termed submarine groundwater discharge (SGD; Younger, 1996; Fig. 1a). However, the position and extent of the mixing zone and the flux of its associated brackish

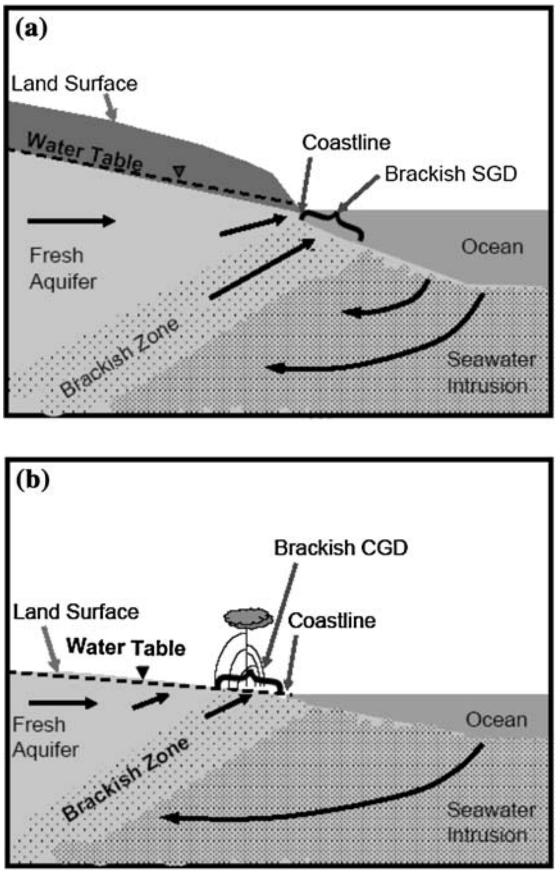

*Figure 1.* (a) Submarine groundwater discharge (SGD) and (b) coastal groundwater discharge (CGD).

groundwater discharge is governed by many factors such as rainfall, groundwater withdrawals, irrigation and evapotranspiration on the freshwater side, with tides, waves, and changes in sea level on the seawater side (Kohout, 1960; Bear et al., 1999). Along many of the worlds developed coastlines, the combined effects of increased groundwater withdrawals and sealevel rise results in enhanced seawater intrusion into the freshwater coastal aquifers (Konikow & Reilly, 1999), thereby shifting the discharge of brackish groundwater inland (Fig. 1b). We wish to define a new term, coastal groundwater discharge (CGD) to describe the discharge of brackish to saline groundwater to coastal areas including coastal wetlands and streams (Fig. 1b).

The discharge of this brackish groundwater can have a significant impact on the ecology of dominantly freshwater coastal wetlands and streams. CGD has the potential to alter the salinity of wetland soils and surface waters, to be a source of water, and to deliver dissolved constituents like nutrients and dissolved toxins. Such discharge also can be an important determinant of the productivity of coastal systems, as they are often nutrient limited and groundwater tends to be enriched in nitrogen and phosphorus compared to oligotrophic surface waters.

The potential for brackish groundwater discharge to the surface water of the Everglades as evidenced by a comparison of groundwater and surface water levels was presented earlier (Price et al., 2003). The objective of this paper is to provide geochemical evidence of the discharge of brackish groundwater to the overlying surface water of the coastal Everglades. Furthermore, this paper demonstrates that the brackish groundwater contains elevated concentrations of phosphorus. Phosphorus limits primary producer biomass, animal biomass, the structure of the primary producer community, the structure of the microbial community and the structure of animal community of the coastal Everglades (Armitage et al., 2005, 2006; Gil et al., 2006). We propose that the enhanced productivity of the freshwater–marine ecotone of the coastal Everglades as compared to either freshwater or marine end-members may be fueled by the P delivered by CGD.

## Site description

The Everglades occupies most of the south Florida peninsula and discharges into Florida Bay and the Gulf of Mexico (Fig. 2). The topography across the Everglades is extremely flat, and contributes to an exceptionally low hydraulic gradient ($5\times10^{-5}$) and poorly defined watershed boundaries. The Surficial Aquifer System (SAS) in south Florida consists of Miocene to Holocene age siliclastic and carbonate sediments and varies in thickness from 50 to 82 m (Fish & Stewart, 1991; Reese & Cunningham, 2000). The Biscayne Aquifer forms the top of the SAS and is the principal water supply for human development in South Florida. Its thickness increases across the study site in a southeasterly direction from a feather edge in northwestern Shark Slough to over 65 m thick along the southeastern coastline (Fish & Stewart,

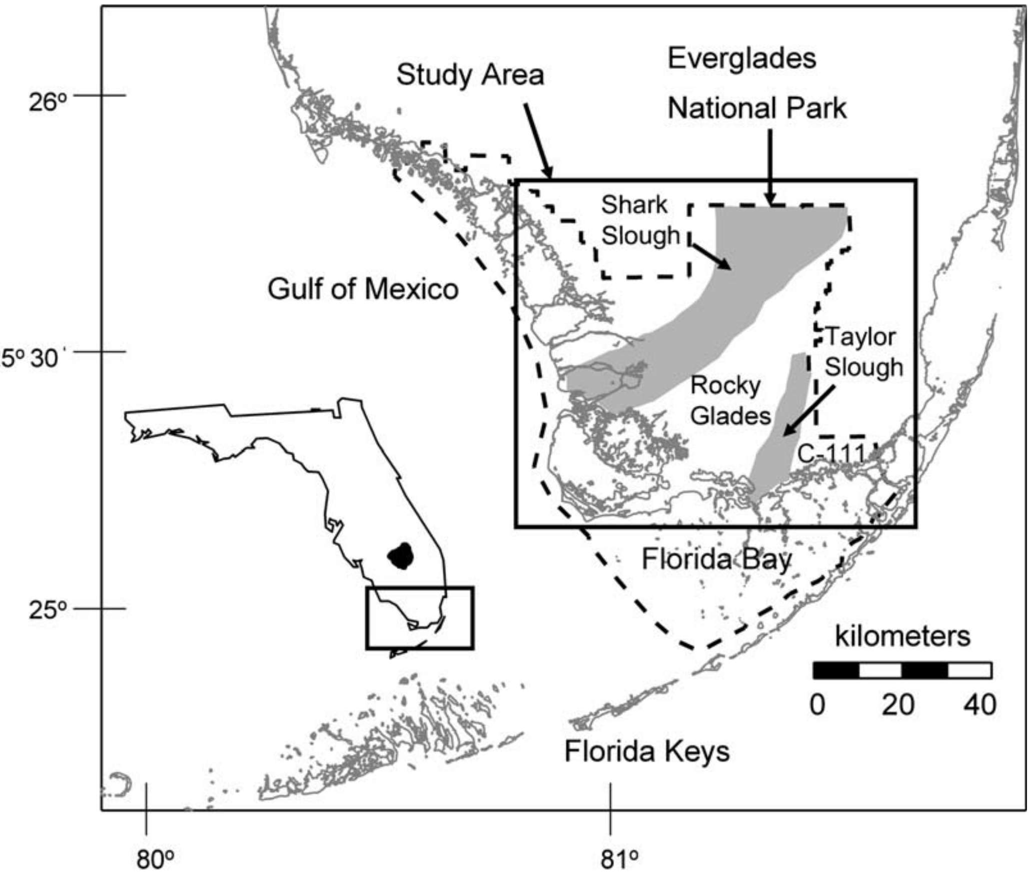

*Figure 2.* Map of south Florida and study area.

1991). The Biscayne Aquifer is one of the most productive karst aquifers in the world with measured transmissivities in excess of 30 million $m^2$ $year^{-1}$, and estimated hydraulic conductivity between 1.5 and 4.5 million m $year^{-1}$ (Fish & Stewart, 1991).

On average the Royal Palm Ranger station located in the Everglades receives 140 cm of rain a year (30-year average from 1971 to 2000) with most occurring in the summer months from mid-May through mid-October (Southeast Regional Climate Center, *sercc@dnr.state.sc.us* ). Despite the high hydraulic conductivity of the Biscayne Aquifer and the high rainfall rate in south Florida, there is significant intrusion of seawater into the SAS along its coastline, particularly along the southern Everglades. The low topographic relief of the region contributes to its susceptibility to seawater intrusion, particularly in response to sea level rise. Furthermore, most of the water which once flowed naturally from Lake Okeechobee in central Florida southward through ENP and into Florida Bay and the Gulf of Mexico, has been diverted away from ENP via a complex system of canals, levees, and water control structures (Light & Dineen, 1994). Seawater intrusion into the Biscayne Aquifer along the southern Florida Peninsula was first documented in 1940 by Parker et al. (1955). The onset of seawater intrusion was attributed to lowering of groundwater levels in the Biscayne Aquifer as a result of construction of an extensive system of canals in the 1920s and 1930s designed to drain surface water from Lake Okeechobee and the Everglades to the ocean. Construction of additional canals combined with periodic drought conditions resulted in increasing the extent of seawater intrusion in the Biscayne Aquifer from 1904 to 1990 (Parker et al., 1955; Klein & Waller, 1985; Sonenshein & Koszalka, 1996). No significant increase in seawater intrusion occurred in the area between 1990 and 1995 (Sonenshein, 1997). An aerial resistivity survey of shallow groundwater conditions confirmed that seawater intrusion into the Biscayne Aquifer occurs along the entire southern and western coastlines of the southern Everglades (Fitterman et al., 1999).

## Methods

Data presented in this paper was compiled from two investigations, one conducted between 1997 and 1999, and the other conducted during the summer of 2003. Between 1997 and 1999, a total of 45 groundwater wells (Fig. 3) were sampled on an approximately monthly basis. These wells were organized into clusters of 1–4 wells with finished depths ranging from 2 to 60 m within the SAS and were completed by either the USGS (Fish & Stewart, 1991; Fitterman et al., 1999) or the National Park Service. Most of the wells completed by the USGS and some wells completed just for this investigation by the National Park Service consisted of PVC pipe that was 2.5–5.0 cm in diameter with the bottom 2 m or less screened for water collection. To prevent the exchange of surface water into the groundwater well, the annulus surrounding the PVC pipe was sealed at the land surface with a bentonite/cement mixture, and then the PVC pipe was capped. Pre-existing wells completed by the National Park Service contained a 7–15 cm diameter metal surface casing that was

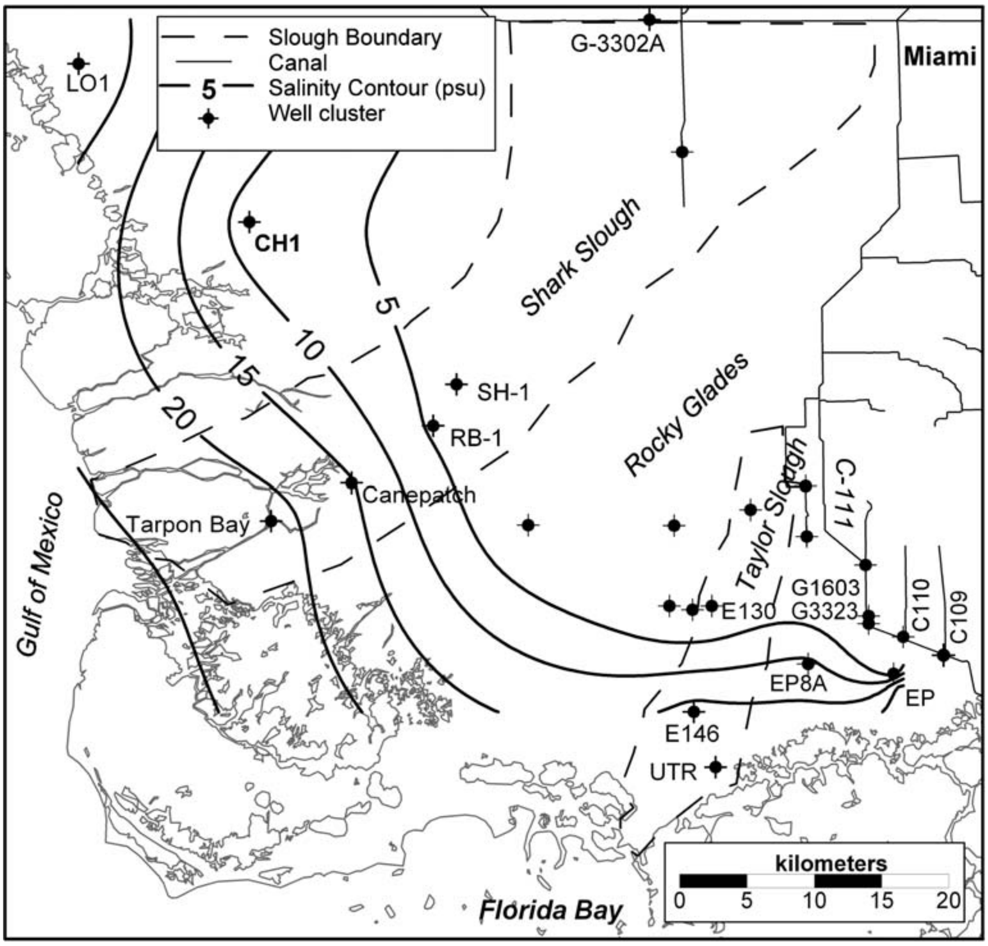

*Figure 3.* Extent of seawater intrusion into the shallow portion (< 28 m) of the SAS. Contours represent salinity with a 5 psu contour interval. Circles with crosses represent a cluster of one to four groundwater wells completed in the SAS.

between 1 and 2 m long, with the remainder of the well left as an open borehole. More detailed description of the wells and their locations can be found in Price (2001).

Prior to sampling, all wells were purged of at least three well volumes. Surface water was collected at 23 sites in conjunction with the groundwater wells or from the canals that border ENP (Fig. 3). Both groundwater and surface water samples were filtered in the field and stored at 4 °C until analyzed. Bottles collected for cations were acidified to a pH of less than 2. The pH, specific conductance and/or salinity, and temperature were recorded at the time of sample collection using an Orion pH, and S/C/T meter, respectively. Major cations (calcium, magnesium, sodium and potassium) and anions (chloride and sulfate) were determined by ion chromatography on a Dionex 120. Total alkalinity was determined by acid titration according to the Gram method. A total of 1685 water samples were analyzed. A detailed description of the methods for this investigation can be found in Price (2001).

During the summer of 2003, 14 of the groundwater wells and nine surface water sites were sampled across the seawater–freshwater mixing zone in the southern Everglades for TP (Table 1). To reduce the exposure of anoxic groundwater to oxygen during sampling, groundwater samples were collected directly into acid-washed, evacuated blood collection tubes that were first flushed with nitrogen gas. Samples were processed for TP using colorimetery following dry-oxidation/acid hydrolysis methods (Solorzano & Sharp, 1980) within 1–5 days of sample collection. A total of 23 water samples were analyzed for TP (Table 1).

*Table 1.* Summary of phosphorus concentrations in groundwater and surface water

| Site name | Sampling date | Depth (m) | Temperature (°C) | pH | Salinity (psu) | Total P ($\mu$M) |
|---|---|---|---|---|---|---|
| *(SW = Surface water)* | | | | | | |
| SH-1 SW | 20-Jun-03 | | 31.1 | 7.35 | 0.0 | 0.31 |
| LO1 SW | 18-Jul-03 | | 30.6 | 7.53 | 0.0 | 0.21 |
| CH1 SW | 18-Jul-03 | | 35.5 | 7.38 | 0.0 | 0.45 |
| Upper Taylor River SW | 12-Aug-03 | | 30.2 | 7.46 | 0.2 | 0.27 |
| E-146 SW | 15-Aug-03 | | 28.3 | 7.32 | 0.0 | 0.21 |
| RB-1 SW | 19-Aug-03 | | 28.4 | 7.00 | 0.0 | 0.33 |
| Canepatch SW | 19-Aug-03 | | 29.3 | 7.02 | 0.0 | 0.16 |
| Tarpon Bay SW | 19-Aug-03 | | 30.6 | 7.30 | 0.6 | 0.22 |
| E-130 SW | 25-Nov-03 | | 24.9 | 7.30 | 0.0 | 0.15 |
| *(GW = Groundwater)* | | | | | | |
| SH-1 GW | 20-Jun-03 | 2.5 | 25.9 | 6.37 | 0.06 | 0.88 |
| G-3302A | 1-Aug-03 | 4.3 | 26.5 | 7.06 | 0.0 | 0.75 |
| E-130 Shallow | 25-Nov-03 | 3 | 26.2 | 7.01 | 0.0 | 0.12 |
| E-130 Deep | 25-Nov-03 | 15.2 | 25.9 | 6.96 | 0.0 | 0.22 |
| CH1 GW | 18-Jul-03 | 2.5 | 26.6 | 6.81 | 29.9 | 2.34 |
| UTR Deep GW | 12-Aug-03 | 6.7 | 27.4 | 6.54 | 28.1 | 1.45 |
| UTR Shallow GW | 12-Aug-03 | 0.6 | 28.7 | 6.54 | 27.5 | 2.12 |
| E-146 Shallow GW | 15-Aug-03 | 4.6 | 26.2 | 6.65 | 10.6 | 0.5 |
| E-146 Deep GW | 15-Aug-03 | 7.6 | 25.9 | 6.68 | 12.6 | 0.63 |
| E-146–27 GW | 15-Aug-03 | 8.4 | 25.8 | 6.58 | 16.3 | 0.75 |
| RB-1 GW | 19-Aug-03 | 6.7 | 25.1 | 6.67 | 3.4 | 0.37 |
| Canepatch GW | 19-Aug-03 | 15.5 | 25.4 | 6.84 | 15.2 | 1.9 |
| Tarpon BAY GW | 19-Aug-03 | 19.8 | 26.1 | 6.8 | 20.8 | 2.25 |
| LO1 GW | 18-Jul-03 | 3 | 27.7 | 6.57 | 7.6 | 0.97 |

## Results

Specific conductance measured in all of the water samples varied from 100 and 36,900 $\mu$S cm$^{-1}$ while salinity varied from 0 to 27.4 psu, with both specific conductance and salinity increasing towards the coastline. During most times of the year, surface water salinities in southern Taylor Slough and the C-111 basin were below 1 psu, but increased above a value of 1–3 times during the study period, in March and April 1997, in July 1998, and again in April and May 1999 (Fig. 4). Surface water salinity was most variable in the southern reaches of Shark Slough, particularly at Tarpon Bay and Canepatch (Fig. 4). For most groundwater wells, there was no discernable trend in salinity between 1997 and 1999 (Fig. 5). Groundwater salinity in the C-111 basin well EP8A was the most variable (Fig. 5).

A Piper diagram provided geochemical evidence of brackish groundwater discharge to the surface water (Fig. 6). Surface water of the Everglades is most often characterized as a calcium-bicarbonate type water, typical for water in contact with limestone. The underlying groundwater, at site EP8A located within the mixing zone in the C-111 basin had an average salinity of 13.7 psu at a depth of 7.6 m and was dominated by sodium and chloride ions (Fig. 6). During four sampling events in the dry-season, surface water at EP8A had elevated concentrations of sodium and chloride relative to the other ions and these samples plot along a mixing line between the freshwater and the underlying brackish groundwater. Enhanced sodium and chloride signatures were also observed in the surface waters at sites EP in the C-111 basin, E146 in Taylor Slough at RB-1 in Shark Slough during the dry-season.

The mean concentrations of the cations and anions in the water samples were plotted against their percent seawater composition (assuming chloride to be conservative) and compared to a seawater mixing line. Calcium was enriched relative to the seawater dilution line in all groundwaters containing greater than 5% seawater (Fig. 7). Surface waters collected from Canepatch and Tarpon Bay fall along the seawater dilution line. Sodium concentrations in the surface waters and groundwaters plotted along the seawater mixing line (not shown), indicating that sodium behaved conservatively upon mixing with seawater. Potassium concentrations in most groundwaters plotted below the seawater mixing line indicating that potassium is not conservative in the groundwater upon mixing with seawater. Magnesium concentrations in both surface waters and groundwaters plot along the seawater mixing line with a few groundwaters falling below the line. Similarly, sulfate in most of the groundwaters and surface waters fell along the seawater mixing line, but sulfate concentrations in a few groundwaters were lower than expected with seawater mixing indicating sulfate is not conserved.

A trilinear mixing diagram of calcium to chloride using the surface water of EP8A, the groundwater at EP8A and surface seawater as end-members is included as Figure 8. The lines drawn between the three end-members represent conservative mixing lines. Most of the surface waters samples from EP8A cluster around the surface water end-member. One of the samples (May 1999) plots on the mixing line between the surface water and seawater end-members. Three samples plot near the line between the surface water and groundwater (April 1997; July 1998; and March 1999).

Ambient surface water concentrations of TP in the fresh waters of the Everglades were extremely low and ranged from 0.16 to 0.45 $\mu$M (Table 1). often of TP in the groundwaters were often higher than the surface water at 0.1–2.3 $\mu$M. There was a direct relationship between TP with salinity in the groundwater (Fig. 9).

## Discussion

### *Seawater intrusion*

High concentrations of sodium and chloride along with salinity measurements in some groundwater wells confirm the presence of seawater intrusion into the SAS along the coastline of ENP (Fig. 3.). The 5 psu salinity contour line depicted in Fig. 3 is coincident with the position of the seawater intrusion as determined by aerial resistivity (Fitterman et al., 1999). Contrary to the aerial resistivity results that suggest a relatively sharp seawater intrusion front boundary (Fitterman et al., 1999), the salinity of the groundwater wells measured in this study suggest a wide brackish

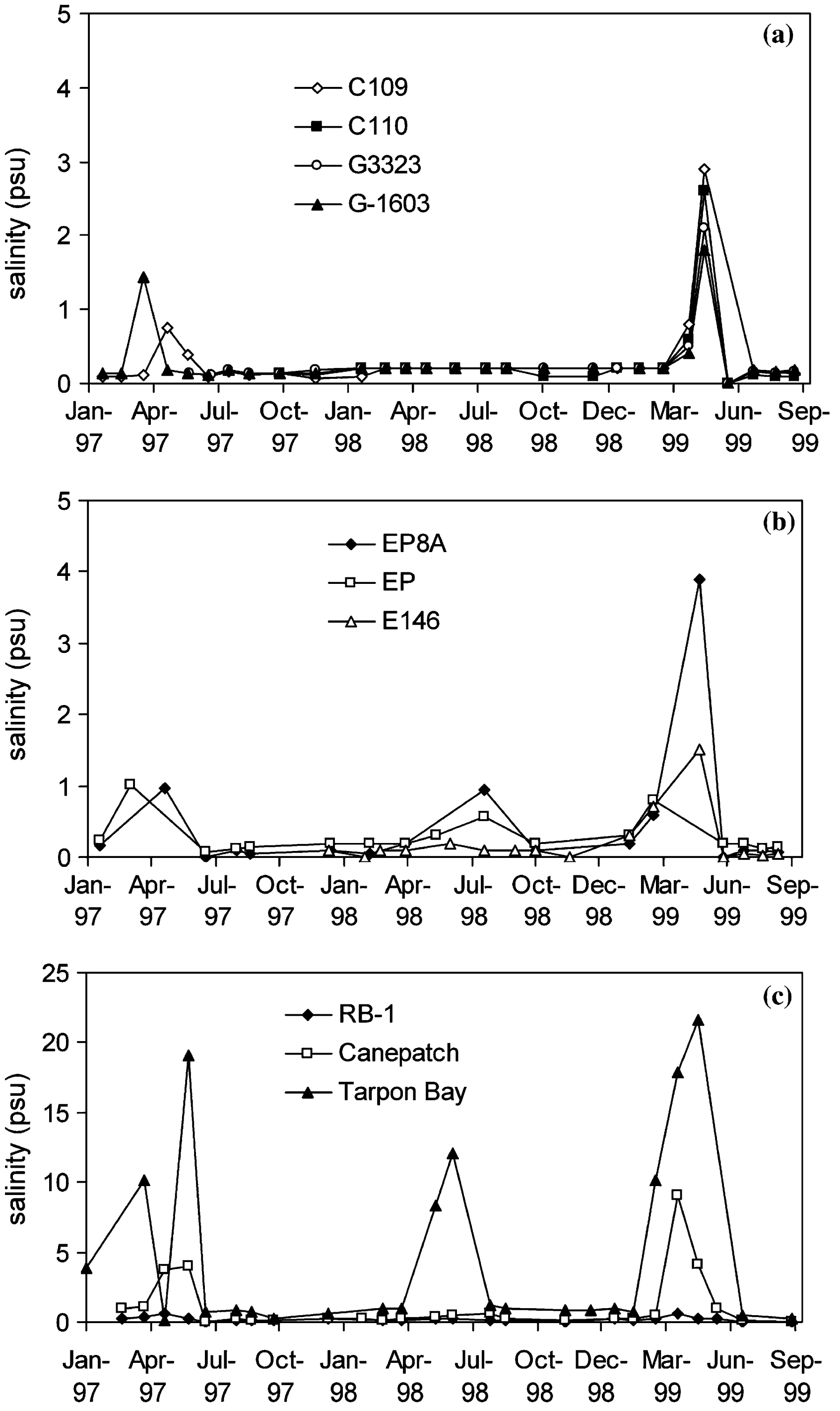

*Figure 4.* Salinity of surface water in (a) the C-111 canal; (b) Taylor Slough and C-111 basin; and (c) Shark Slough. See Figure 3 for station locations.

groundwater zone varying between 6 and 25 km wide. The landward extent of seawater intrusion extends the farthest inland in Shark Slough (25–28 km) most likely due to tidal action in the Gulf of Mexico. The Gulf of Mexico experiences a mixed semi-diurnal tide with a maximum tidal

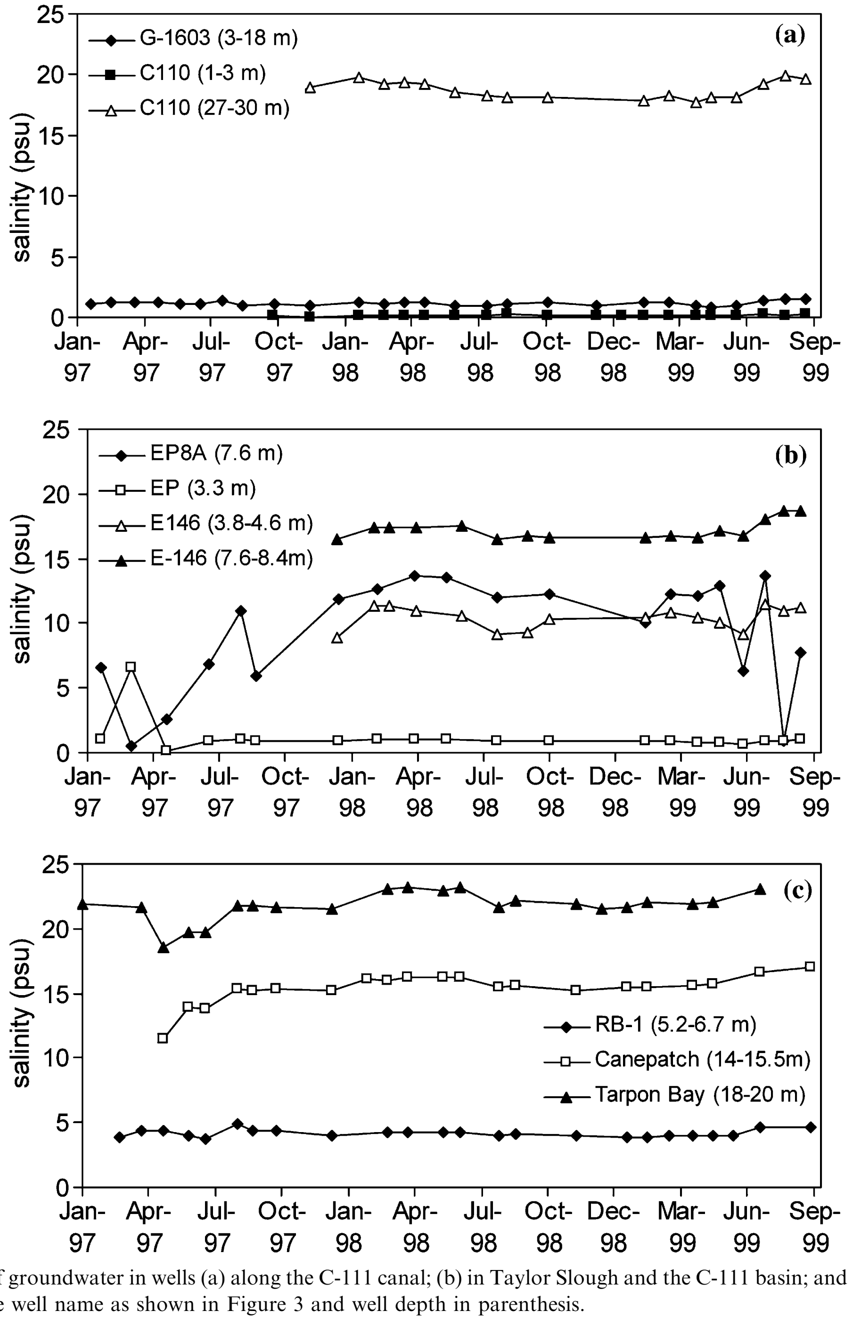

*Figure 5.* Salinity of groundwater in wells (a) along the C-111 canal; (b) in Taylor Slough and the C-111 basin; and (c) in Shark Slough. Legend refers to the well name as shown in Figure 3 and well depth in parenthesis.

range of 2.28 m at the mouth of the Shark River. Tidal forces aid in the dispersion of salts along the interface of a seawater intrusion (Moore, 1999).

Seawater intrusion in the C-111 basin was found to extend 6–10 km landward from the coastline, approximately coincident with the placement of the C-111 canal. Variations in shallow groundwater salinity in wells located south of the C-111 canal indicate that the extent of seawater intrusion in this area can vary on a monthly to seasonally basis (Fig. 4). Tidal forces in northeast Florida Bay are weak due to a dampening of the Gulf of Mexico tides by the many shallow mud banks across Florida Bay. However, passing storm

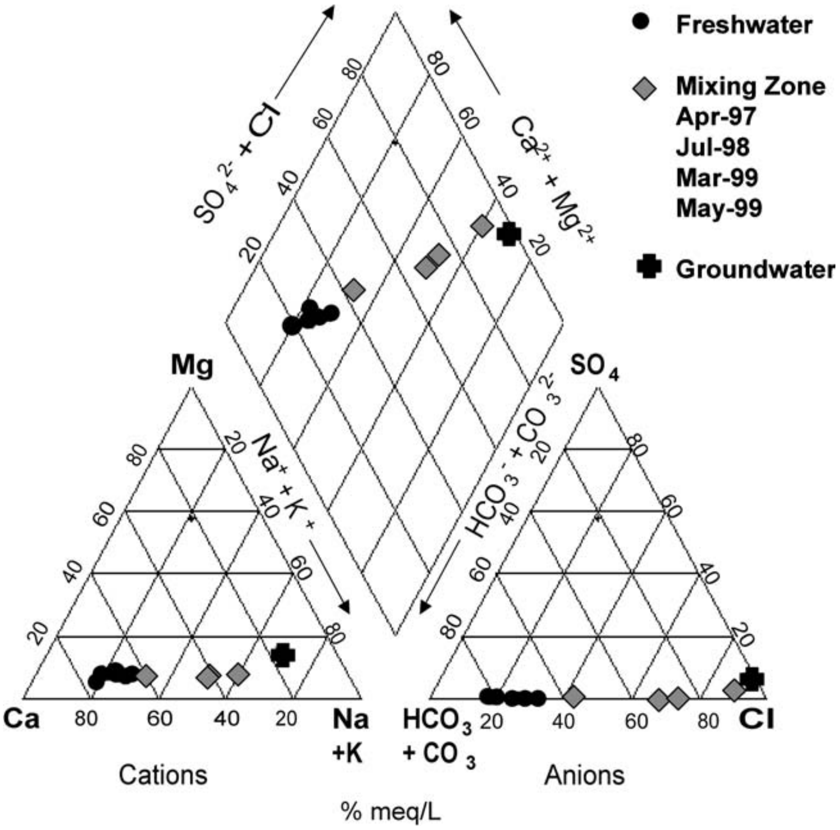

*Figure 6*. Piper diagram depicting major ion chemistry at EP8A in the southern Everglades. During most of the sampling events, surface waters (black dots) were a $Ca^{2+}$–$HCO_3^-$ type water. Groundwater (black cross) is dominated by $Na^+$ and $Cl^-$ ions indicative of seawater intrusion. Surface waters had a brackish signature (gray diamonds) during the months indicated in the legend. See Figure 3 for site location.

fronts and changes in wind direction can result in changes in water levels up to 30 cm (Fourqurean & Robblee, 1999). Low water levels caused by dry season conditions and southerly winds can drive seawater from Florida Bay into the southern creeks of the C-111 Basin (Hittle et al., 2001). Such a condition is most likely responsible for the high increase in salinity observed in the surface water in the C-111 basin in May 1999 (Fig. 4).

In 1997, the groundwater salinity in well EP8A increased markedly from near 1 to above 10, and remained high throughout 1998 and into 1999. The drops in salinity of the groundwater in EP8A in May and July 1999 may signify a slight seaward retreat of the seawater intrusion in the SAS within the C-111 basin. The landward extent of seawater intrusion in Taylor Slough is about 10–14 km inland (Fig. 3), intermediate between that of the C-111 basin and Shark Slough. The salinity of groundwater in the E-146 wells did not vary markedly throughout the study period (Fig. 5), suggesting that the position of the seawater intrusion front in Taylor Slough may be more stable than observed in the C-111 basin.

### *Evidence of CGD*

During times of low water levels, the surface water at EP8A (as well as at sites EP, E146, and RB-1) exhibited a brackish signature (Fig. 6). There are two potential sources for the observed seawater mixture at these surface water sites: (1) surface seawater from Florida Bay or the Gulf of Mexico moving inland with the lowering of water levels, or (2) the discharge of brackish groundwater. Evaporation of the surface water would increase the concentrations of each of the ions collectively and

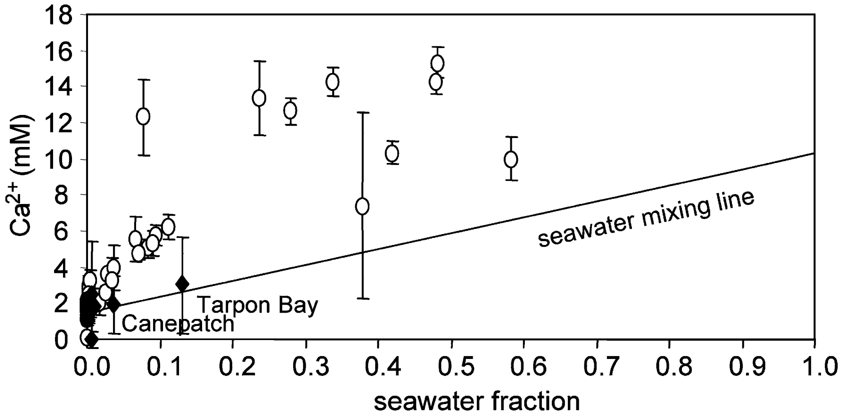

*Figure 7.* Mean calcium concentrations in groundwaters (open circles) tend to be elevated above the seawater mixing line, while mean calcium concentrations in some of the surface waters (solid diamonds) fall on the seawater mixing line. Error bars represent ± one standard error.

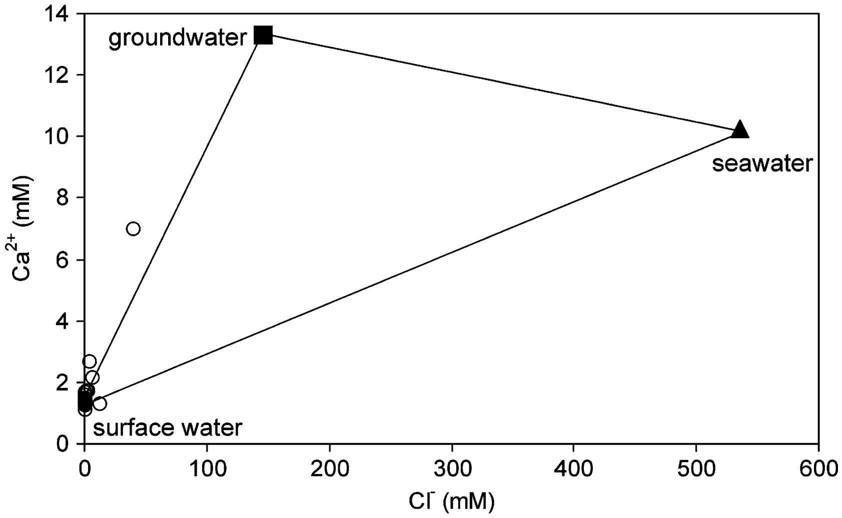

*Figure 8.* Calcium vs. chloride mixing diagram between surface water (open circles), groundwater (solid square) and seawater (solid triangle) as end-members.

not cause a change in the position of the water sample on the Piper Diagram (Fig. 6). An enhancement in sodium and chloride relative to the other ions is responsible for the shift of the surface water samples towards the brackish groundwater (Fig. 6).

Brackish groundwater discharge can be distinguished from a surface seawater source by enhanced concentrations of calcium (Fig. 7). Three of the surface water samples collected at EP8A contain elevated concentrations of calcium and plot either on or to the left of the mixing line between the fresh surface water end-member and the underlying brackish groundwater (Fig. 8). These samples were collected at EP8A during the months of April 1997, July 1998, and March 1999, and represent times when brackish groundwater was discharging to the surface water. At these times the salinity of the surface water at EP8A measured near 1 psu (Fig. 4). The groundwater obtained at EP8A was from a depth of 7.6 m and had an average salinity greater than 13 psu. Groundwater is expected to increase in salinity with depth in a the region of seawater intrusion, therefore, the salinity of the groundwater at the sediment/water interface is expected to be lower than that measured in well

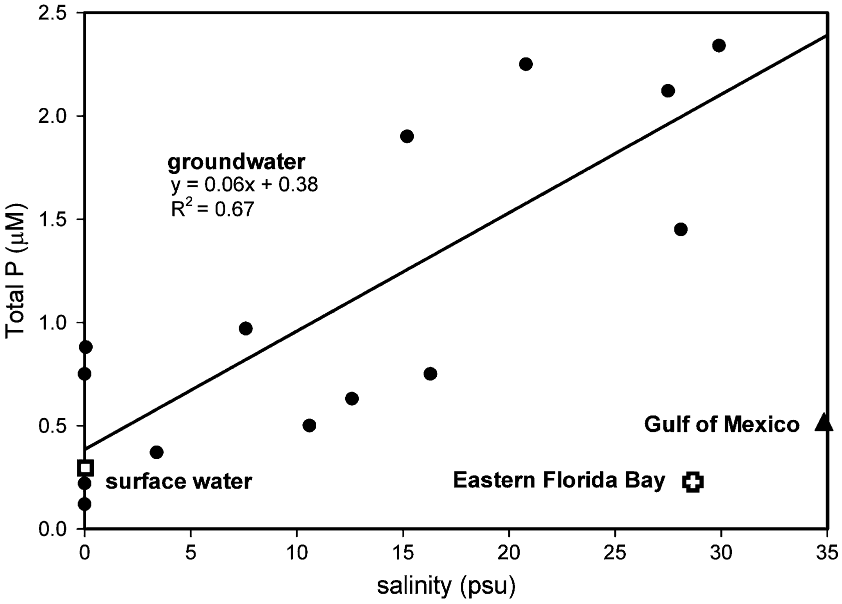

*Figure 9.* Total phosphorus in groundwater samples (solid circles) increase linearly with salinity, and are higher than the mean TP of surface waters of the Everglades (open square), eastern Florida Bay (open cross), and the Gulf of Mexico (solid triangle).

EP8A, however, additional shallower wells would be needed in the region to confirm this.

Also interesting is that two of the surface water samples plot to the left of the conservative mixing line between the surface water and groundwater end-members. The result indicates that calcium is not conserved during mixing but that an additional source of calcium is introduced as a result of the mixing. This additional source is most likely dissolution of the calcium carbonate sediments in response to the groundwater discharge. The brackish groundwater collected at all sites contained dissolved concentrations of hydrogen sulfide and iron as evident from odors and red staining of wells and sample bottles, both suggestive of reducing conditions. The mixing of reducing groundwater with surface water would cause a drop in pH allowing for dissolution of the calcium carbonate sediments (Stumm & Morgan, 1996). The average pH of the brackish groundwater at EP8A was 6.8 while that of the surface water was 7.5. At times of brackish groundwater discharge, the pH of the surface water was near 7.0 and measured 6.8 in July 1998.

If surface seawater flowing inland from the marine bays was the source of the brackish signatures in the surface waters, then the surface water concentrations of calcium would fall along the seawater mixing line (Figs. 7 and 8). In fact, mean calcium concentrations of surface waters from Tarpon Bay and Canepatch fall along a seawater mixing line indicating that surface waters at these sites do receive surface seawater from the Gulf of Mexico (Fig. 7). This result is expected since surface water levels at these sites are tidally influenced. In addition, the surface water sample collected at EP8A in May 1999, had a high salinity of 4 psu (Fig. 4), and plots on the mixing line between the fresh water and seawater end-members (Fig. 8). Surface seawater moving inland from Florida Bay is most likely responsible for the high salinity observed at EP8A in May 1999. Note that evidence of enhanced calcium concentrations in the surface water at times of low water levels were also observed at sites EP in the C-111 basin, E146 in Taylor Slough, and RB-1 in Shark Slough, but are not shown due to space limitations in this manuscript.

### *Phosphorus*

Ambient surface water TP concentrations in the fresh waters of the Everglades range from 0.15 to 0.45 $\mu$M (Table 1). Median TP concentrations in marine surface waters of northeastern Florida Bay and the Gulf of Mexico are 0.25 and 0.58 $\mu$M, respectively (Boyer et al., 1999). Concentrations of TP in the groundwater underlying the coastal wetlands of the Everglades range from 0.1 to 2.3 $\mu$M and are often higher than either surface freshwater or surface seawater; TP also shows a direct relationship with salinity (Fig. 9). Fresh groundwater TP concentrations tend to be less than 1 $\mu$ M (Table 1). Conservative mixing of fresh groundwater having TP concentrations of less than 1 $\mu$M with surface seawater from Florida Bay and/or the Gulf of Mexico also having TP concentrations of less than 1 $\mu$M cannot produce the 1–2.3 $\mu$M concentrations of TP observed in the brackish groundwater. An additional source of phosphorus is needed.

Given that the seawater intrusion from Florida Bay must first pass through the underlying sediments before entering the aquifer, then the sediments could be a source of phosphorus for saline groundwaters. Phosphorus concentrations in the sediment porewaters in the region are orders of magnitude higher than the concentrations of phosphorus in the overlying surface waters because of the remineralization of organic matter in the sediments and the trapping of inorganic phosphorus by sorption on calcium carbonate particles (Fourqurean et al., 1992). The solid aquifer matrix can also be a source of phosphorus. Phosphorous may exist either as phosphorus minerals (such as apatite) within the aquifer material, or may be adsorbed onto the particle surfaces. Areas of seawater intrusion are known geochemically active regions particularly in carbonate aquifers, where carbonate mineral dissolution (Back et al., 1986) and ion exchange (Sivan et al., 2005) are important. Both of these processes can lead to a release of phosphorus from the aquifer matrix to the groundwater. The excess calcium concentrations observed in the brackish groundwaters (Fig. 7) indicates that carbonate mineral dissolution is occurring within the saltwater intrusion zone of the southern Everglades. Millero et al. (2001) have determined that phosphate adsorption onto carbonate minerals decreases as salinity increases from 0 to 45 psu and attributed their results to the presence of sulfate and bicarbonate ions. These anions may be competing with the phosphate ion for exchange sites and may explain the nonconservative nature of sulfate upon mixing fresh groundwater and surface seawater. The linear increase in TP concentration with salinity in the brackish groundwaters suggests phosphorus may be desorbed from the aquifer materials with the intruding seawater (Fig. 8).

Groundwater discharge in the southern Everglades appears to be seasonal, occurring dominantly during the dry season when excess sodium, chloride, and calcium are observed in receiving surface waters. This seasonality in groundwater discharge was observed by others (Sutula et al., 2001; Top et al., 2001), and is due to higher surface water levels in both the Everglades and in Florida Bay in the summer wet season. The higher surface water levels result in either reducing groundwater discharge to near zero or even reversing the direction so that the surface water recharges the groundwater. For instance, groundwater discharge in the regions of Taylor Slough and C-111 basin have been estimated at 48 cm/year during the dry season, but during the wet season the groundwater was recharged between 25 and 35 cm/year, resulting in a mean annual discharge of 8 cm/year (Sutula et al., 2001). This groundwater discharge value is similar to the rate of 2–12 cm/year estimated for groundwater recharge in the upland regions of ENP (Price & Swart, 2006).

Assuming an average TP value in the CGD of 1.5 $\mu$M, a CGD of 8 cm/year results in a discharge flux of 0.12 mM P $m^{-2}$ $year^{-1}$. This value is twice as high as earlier estimates of groundwater input of 0.06 mM P $m^{-2}$ $year^{-1}$ along Taylor Slough and the C-111 basin (Sutula et al., 2001), however, those estimates were made without groundwater P data. Assuming an extent of seawater intrusion of 10 km inland along 75 km length of coastline extending from the C-111 basin to the western edge of Shark Slough, results in a CGD zone of 750 $km^2$, and a flux of 2.8 metric tons of P to the surface water annually. This amount of P is equivalent to the amount of phosphorus delivered by Taylor Slough ($<$2.6 metric tons/year) to Florida Bay. This amount of P, however, is considerably less than the estimated 14 metric tons/year of P delivered to the 750 $km^2$ coastal zone via atmospheric inputs (Rudnick et al., 1999).

Despite the high concentrations of TP in the brackish groundwaters, only low TP values ($<0.5$ $\mu$M) are detected in the overlying surface waters. These results suggest that the phosphorus transported with the CGD is either removed from the surface water column quickly by biotic processes (Gaiser et al., 2004) or is retained in the Everglades soils by sorption, particularly to calcium carbonate particles (De Kanel & Morse, 1978), clays (Zhou & Li, 2001) and iron-oxides (Chambers et al., 2001). Soils within the mangrove zone are indeed a sink for phosphorus as indicated by higher concentrations of phosphorus measured in shallow sediments (2.5 cm) within the mangrove zone as opposed to freshwater upland sites (Chen & Twilley, 1999). The high concentrations of TP in the groundwater along with any sorbed to the soils is then available for plant root uptake by the coastal mangroves.

The Everglades and Florida Bay are oligotrophic systems and extremely sensitive to exogenous inputs of nutrients, particularly phosphorus (Fourqurean et al., 1992; Gaiser et al., 2004). Phosphorus inputs from canals that drain the surrounding agricultural landscape have been implicated as major drivers of biotic change of the Everglades ecosystem (Davis, 1994; Noe et al., 2003). Along the southern margin of the Florida peninsula, the freshwater, oligotrophic Everglades and the marine oligotrophic Florida Bay ecosystems are separated by an often lush mangrove forest. The highly productive mangrove forest separating the two nutrient-limited ecosystems seems to require a phosphorus source that is independent of the mixing of Everglades surface water and the marine waters of Florida Bay. We hypothesis that the high productivity of the mangrove forest along the coastal Everglades maybe supported by P delivered by CGD.

## Acknowledgements

We thank Tiffany McKelvey, Gordon Anderson, Mark Stewart, and Gustavo Rubio for their help in the field, and the FIU seagrass lab for their help in the laboratory. This project was made possible with contributions from the FIU Foundation and was supported by the Florida Coastal Everglades LTER program funded by the US National Science Foundation (DEB-9910514) and the NSF REU program. This is contribution number #283 of the Southeast Environmental Research Center at FIU.

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