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

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**Coastal Groundwater Discharge -  
an additional source of phosphorus for the oligotrophic wetlands of the Everglades**

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Key Words

Coastal groundwater discharge, phosphorus, Everglades

1 **Abstract**

2           In this manuscript we define a new term we call Coastal Groundwater Discharge (CGD),  
3 which is related to submarine groundwater discharge (SGD), but occurs when seawater intrudes  
4 inland to force brackish groundwater to discharge to the coastal wetlands. A hydrologic and  
5 geochemical investigation of both the groundwater and surface water in the southern Everglades  
6 was conducted to investigate the occurrence of CGD associated with seawater intrusion. During  
7 the wet season , the surface water chemistry remained fresh. Enhanced chloride, sodium, and  
8 calcium concentrations, indicative of brackish groundwater discharge, were observed in the  
9 surface water during the dry season. Brackish groundwaters of the southern Everglades contain  
10 1 to 2.3  $\mu\text{M}$  concentrations of total phosphorus (TP). These concentrations exceed the expected  
11 values predicted by conservative mixing of local fresh groundwater and intruding seawater,  
12 which both have  $\text{TP} < 1 \mu\text{M}$ . The additional source of TP may be from seawater sediments or  
13 from the aquifer matrix as a result of water-rock interactions (such as carbonate mineral  
14 dissolution and ion exchange reactions) induced by mixing fresh groundwater with intruding  
15 seawater. We hypothesize that CGD maybe an additional source of phosphorus (a limiting  
16 nutrient) to the coastal wetlands of the southern Everglades.

17

## 1 **Introduction**

2 All coastal aquifers with a hydraulic connection to the sea are susceptible to seawater  
3 intrusion (Bear et al., 1999). The interface between freshwater and seawater in coastal aquifers  
4 was first identified by (Du Commun, 1828), half a century earlier than the more widely cited  
5 Ghyben-Herzberg principle (Ghyben, 1888; Herzberg, 1901). A systematic study of seawater  
6 intrusion in the 1950s in south Florida formed a set of benchmark papers on the subject (Cooper,  
7 1959; Kohout, 1960; 1964). The most significant finding of these studies was the recognition  
8 that the freshwater-seawater interface was not sharp as described by the Ghyben-Herzberg  
9 principle, but formed a zone of mixed water composition termed by many in the field as a  
10 ‘mixing zone’ (Fig. 1a; Back et al., 1986; Price & Herman, 1991). Brackish water in this mixing  
11 zone is circulated along with the freshwater to the sea (Cooper, 1959). If the groundwater  
12 discharge occurs beneath overlying marine or estuarine waters it is termed submarine  
13 groundwater discharge (SGD; Younger, 1996; Fig 1a). However, the position and extent of the  
14 mixing zone and the flux of its associated brackish groundwater discharge is governed by many  
15 factors such as rainfall, groundwater withdrawals, irrigation and evapotranspiration on the  
16 freshwater side, with tides, waves, and changes in sea level on the seawater side (Kohout, 1960;  
17 Bear et al., 1999). Along many of the worlds developed coastlines, the combined effects of  
18 increased groundwater withdrawals and sealevel rise results in enhanced seawater intrusion into  
19 the freshwater coastal aquifers (Konikow & Reilly, 1999), thereby shifting the discharge of  
20 brackish groundwater inland (Fig. 1b). We wish to define a new term, coastal groundwater  
21 discharge (CGD) to describe the discharge of brackish to saline groundwater to coastal areas  
22 including coastal wetlands and streams (Fig. 1b).

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

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

19

## 20 **Site Description**

21           The Everglades occupies most of the south Florida peninsula and discharges into Florida  
22 Bay and the Gulf of Mexico (Fig. 2). The topography across the Everglades is extremely flat,  
23 and contributes to an exceptionally low hydraulic gradient ( $5 \times 10^{-5}$ ) and poorly defined

1 watershed boundaries. The Surficial Aquifer System (SAS) in south Florida consists of Miocene  
2 to Holocene age siliclastic and carbonate sediments and varies in thickness from 50 m to 82 m  
3 (Fish & Stewart, 1991; Reese & Cunningham, 2000). The Biscayne Aquifer forms the top of the  
4 SAS and is the principal water supply for human development in South Florida. Its thickness  
5 increases across the study site in a southeasterly direction from a feather edge in northwestern  
6 Shark Slough to over 65 m thick along the southeastern coastline (Fish & Stewart, 1991). The  
7 Biscayne Aquifer is one of the most productive karst aquifers in the world with measured  
8 transmissivities in excess of 30 million  $\text{m}^2 \text{yr}^{-1}$ , and estimated hydraulic conductivity between 1.5  
9 and 4.5 million  $\text{m} \text{yr}^{-1}$  (Fish & Stewart, 1991).

10 On average the Royal Palm Ranger station located in the Everglades receives 140 cm of  
11 rain a year (30-year average from 1971 to 2000) with most occurring in the summer months from  
12 mid-May through mid-October (Southeast Regional Climate Center, *sercc@dnr.state.sc.us* ).  
13 Despite the high hydraulic conductivity of the Biscayne Aquifer and the high rainfall rate in  
14 south Florida, there is significant intrusion of seawater into the SAS along its coastline,  
15 particularly along the southern Everglades. The low topographic relief of the region contributes  
16 to its susceptibility to seawater intrusion, particularly in response to sea level rise. Furthermore,  
17 most of the water which once flowed naturally from Lake Okeechobee in central Florida  
18 southward through ENP and into Florida Bay and the Gulf of Mexico, has been diverted away  
19 from ENP via a complex system of canals, levees, and water control structures (Light & Dineen,  
20 1994). Seawater intrusion into the Biscayne Aquifer along the southern Florida Peninsula was  
21 first documented in 1940 by Parker et al.(1955). The onset of seawater intrusion was attributed  
22 to lowering of groundwater levels in the Biscayne Aquifer as a result of construction of an  
23 extensive system of canals in the 1920s and 1930s designed to drain surface water from Lake

1 Okeechobee and the Everglades to the ocean. Construction of additional canals combined with  
2 periodic drought conditions resulted in increasing the extent of seawater intrusion in the  
3 Biscayne Aquifer from 1904 to 1990 (Parker et al., 1955; Klein & Waller, 1985; Sonenshein &  
4 Koszalka, 1996). No significant increase in seawater intrusion occurred in the area between  
5 1990 and 1995 (Sonenshein, 1997). An aerial resistivity survey of shallow groundwater  
6 conditions confirmed that seawater intrusion into the Biscayne Aquifer occurs along the entire  
7 southern and western coastlines of the southern Everglades (Fitterman et al., 1999).

8

## 9 **Methods**

### 10 ***Geochemical Investigation***

11 Data presented in this paper was compiled from two investigations, one conducted  
12 between 1997 and 1999, and the other conducted during the summer of 2003. Between 1997 and  
13 1999, a total of 45 groundwater wells (Fig. 3) were sampled on an approximately monthly basis.  
14 These wells were organized into clusters of 1 to 4 wells with finished depths ranging from 2 to  
15 60 m within the SAS and were completed by either the USGS (Fish and Stewart, 1991;  
16 Fitterman, 1999) or the National Park Service. Most of the wells completed by the USGS  
17 contained and some wells completed just for this investigation by the National Park Service  
18 consisted of PVC pipe that was 2.5 to 5.0 cm in diameter with the bottom 2 m or less screened  
19 for water collection. To prevent the exchange of surface water into the groundwater well, the  
20 annulus surrounding the PVC pipe was sealed at the land surface with a bentonite/cement  
21 mixture, and then the PVC pipe was capped. Pre-existing wells completed by the National Park  
22 Service contained a 7 cm to 15 cm diameter metal surface casing that was between 1 to 2 meters

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

3 Prior to sampling, all wells were purged of at least three well volumes. Surface water  
4 was collected at 23 sites in conjunction with the groundwater wells or from the canals that border  
5 ENP (Fig. 3). Both groundwater and surface water samples were filtered in the field and stored  
6 at 4<sup>0</sup>C until analyzed. Bottles collected for cations were acidified to a pH of less than 2. The  
7 pH, specific conductance and/or salinity, and temperature were recorded at the time of sample  
8 collection using an Orion pH, and S/C/T meter, respectively. Major cations (calcium,  
9 magnesium, sodium and potassium) and anions (chloride and sulfate) were determined by ion  
10 chromatography on a Dionex 120. Total alkalinity was determined by acid titration according to  
11 the Gram method. A total of 1685 water samples were analyzed. A detailed description of the  
12 methods for this investigation can be found in Price (2001).

13 During the summer of 2003, 14 of the groundwater wells and 9 surface water samples  
14 were sampled across the seawater-freshwater mixing zone in the southern Everglades for TP  
15 (Table 1). To reduce the exposure of anoxic groundwater to oxygen during sampling,  
16 groundwater samples were collected directly into acid-washed, evacuated blood collection tubes  
17 that were first flushed with nitrogen gas. Samples were processed for TP using colorimetry  
18 following dry-oxidation/acid hydrolysis methods (Solorzano & Sharp, 1980) within 1 to 5 days  
19 of sample collection. A total of 23 water samples were analyzed for TP (Table 1).

20

## 21 ***Water Chemistry***

22 Specific conductance measured in all of the water samples varied from 100 and 36,900  
23  $\mu\text{S cm}^{-1}$  while salinity varied from 0 to 27.4 psu, with both specific conductance and salinity



1 increasing towards the coastline. During most times of the year, surface water salinities in  
2 southern Taylor Slough and the C-111 basin were below 1 psu , but increased above a value of 1  
3 during three times during the study period, in March and April 1997, in July 1998, and again in  
4 April and May 1999 (Fig. 4). Surface water salinity was most variable in the southern reaches of  
5 Shark Slough, particularly at Tarpon Bay and Canepatch (Fig. 4). For most groundwater wells,  
6 there was no discernable trend in salinity between 1997 and 1999 (Fig. 5). Goundwater salinity  
7 in the C-111 basin well EP8A was the most variable (Fig. 5).

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

18 The mean concentrations of the cations and anions in the water samples were plotted  
19 against their percent seawater composition (assuming chloride to be conservative) and compared  
20 to a seawater mixing line. Calcium was enriched relative to the seawater dilution line in all  
21 groundwaters containing greater than 5% seawater (Fig. 7). Surface waters collected from  
22 Canepatch and Tarpon Bay fall along the seawater dilution line, while calcium concentrations of  
23 some surface waters collected at E146, EP8A, and RB-1 are enriched in calcium compared to the

1 seawater dilution line (Fig. 8). Sodium concentrations in the surface waters and groundwaters  
2 plotted along the seawater mixing line, indicating that sodium behaved conservatively upon  
3 mixing with seawater. Potassium concentrations in most groundwaters plotted below the  
4 seawater mixing line indicating that potassium is not conservative in the groundwater upon  
5 mixing with seawater. Magnesium concentrations in both surface waters and groundwaters plot  
6 along the seawater mixing line with a few groundwaters falling below the line. Similarly, sulfate  
7 in most of the groundwaters and surface waters fell along the seawater mixing line, but sulfate  
8 concentrations in a few groundwaters were lower than expected with seawater mixing indicating  
9 sulfate is not conserved.

10 Ambient surface water concentrations of TP in the fresh waters of the Everglades were  
11 extremely low and ranged from 0.16 to 0.45  $\mu\text{M}$  (Table 1). Concentrations of TP in the  
12 groundwaters were consistently higher than the surface water at 0.5 to 2.3  $\mu\text{M}$ . There was a  
13 direct relationship between TP with salinity in the groundwater (Fig. 9).

14

## 15 **Discussion**

### 16 ***Seawater Intrusion***

17 High concentrations of sodium and chloride along with salinity measurements in some  
18 groundwater wells confirm the presence of seawater intrusion into the SAS along the coastline of  
19 ENP (Fig. 3.). The 5 psu salinity contour line depicted on Fig. 3 is coincident with the position  
20 of the seawater intrusion as determined by aerial resistivity (Fitterman et al., 1999). Contrary to  
21 the aerial resistivity results that suggest a relatively sharp seawater intrusion front boundary  
22 (Fitterman et al., 1999), the salinity of the groundwater wells measured in this study suggest a  
23 wide brackish groundwater zone varying between 6 to 25 km wide. The landward extent of

1 seawater intrusion extends the farthest inland in Shark Slough (25 to 28 km ) most likely due to  
2 tidal action in the Gulf of Mexico. The Gulf of Mexico experiences a mixed semi-diurnal tide  
3 with a maximum tidal range of 2.28 m at the mouth of the Shark River. Tidal forces aid in the  
4 dispersion of salts along the interface of a seawater intrusion (Moore, 1999).

5         Seawater intrusion in the C-111 basin was found to extend 6 to 10 km landward from the  
6 coastline, approximately coincident with the placement of the C-111 canal. Variations in  
7 shallow groundwater salinity in wells located south of the C-111 canal indicate that the extent of  
8 seawater intrusion in this area can vary on a monthly to seasonally basis. Tidal forces in  
9 northeast Florida Bay are weak due to a dampening of the Gulf of Mexico tides by the many  
10 shallow mud banks across Florida Bay. However, passing storm fronts and changes in wind  
11 direction can result in changes in water levels up to 30 cm (Fourqurean & Robblee, 1999). Low  
12 water levels caused by dry season conditions and southerly winds can drive seawater from  
13 Florida Bay into the southern creeks of the C-111 Basin (Hittle et al., 2001). Salinity increases  
14 in the surface waters of the C-111 canal and southern marshes during the end of the dry seasons  
15 in 1997 and 1999 (Fig. 4) are most likely in response to lowered water levels. In 1997, the  
16 groundwater salinity in wells EP8A increased markedly from near 1 to above 10, and remained  
17 high throughout 1998 and into 1999. This increase in groundwater salinity followed a spike in  
18 the surface water salinity occurring at the end of the dry season in 1997 and is most likely in  
19 response to lowered water levels during that time. The subsequent year long increase in  
20 groundwater salinity of the C-111 basin suggests that landward advancement of seawater  
21 intrusion within the SAS is slow compared to that observed in the surface water. The drops in  
22 salinity of the groundwater in EP8A in May and July 1999 may signify a slight seaward retreat  
23 of the seawater intrusion in the SAS within the C-111 basin. The landward extent of seawater

1 intrusion in Taylor Slough is about 10 to 14 km inland (Fig. 3), intermediate between that of the  
2 C-111 basin and Shark Slough. The salinity of groundwater in the E-146 wells did not vary  
3 markedly throughout the study period (Fig. 5), suggesting that the position of the seawater  
4 intrusion front in Taylor Slough may be more stable than observed in the C-111 basin.

5  
6 ***Evidence of CGD***  
7

8         During times of low water levels, the surface water at EP8A (as well as at E146 and RB-  
9 1) exhibited a brackish signature (Fig. 6). There are two potential sources for the observed  
10 seawater mixture at these surface water sites: 1) surface seawater from Florida Bay or the Gulf of  
11 Mexico moving inland with the lowering of water levels, or 2) the discharge of brackish  
12 groundwater. That these sites are approximately 6 to 25 km inland of the coastline and  
13 coincident with the position of the seawater intrusion in the shallow portion of the SAS (Fig. 3)  
14 suggests that brackish groundwater is the source of the seawater signature.

15         Elevated concentrations of calcium in the surface waters also suggest a brackish  
16 groundwater source as opposed to surface seawater from Florida Bay or the Gulf of Mexico  
17 moving inland in response to the lowering of water levels (Fig. 8). If surface seawater flowing  
18 inland from the marine bays was the source of the brackish signatures in the surface waters, then  
19 the surface water concentrations of calcium would fall along a seawater dilution line produced  
20 from mixing of fresh Everglades waters and surface seawater. In fact, mean calcium  
21 concentrations of surface waters from Tarpon Bay and Canepatch fall along a seawater mixing  
22 line indicating that surface waters at these sites do receive surface seawater from the Gulf of  
23 Mexico (Fig. 7). This result is expected since surface water levels at these sites are tidally  
24 influenced.

1 Close inspection of calcium concentrations of individual surface water samples collected  
2 from the surface water at sites E146, EP8A, and RB-1 reveal elevated concentrations of calcium  
3 relative to the seawater dilution line in samples containing greater than 1 percent seawater (Fig.  
4 8). The elevated calcium concentrations in the surface waters is a result of mixing with the  
5 underlying brackish groundwater that also has elevated calcium levels as compared to seawater  
6 mixing. The excess calcium in the brackish groundwaters relative to the seawater mixing line is  
7 as high as 9 mM with an average of  $4.1 \pm 3.5$  mM. The excess calcium concentrations are most  
8 likely the result of dissolution of calcium carbonate minerals from the aquifer matrix.

9

#### 10 *Phosphorus*

11 Ambient surface water TP concentrations in the fresh waters of the Everglades range  
12 from 0.15 to 0.45  $\mu\text{M}$  (Table 1). Median TP concentrations in marine surface waters of  
13 northeastern Florida Bay and the Gulf of Mexico are 0.25  $\mu\text{M}$  and 0.58  $\mu\text{M}$ , respectively (Boyer  
14 et al., 1999). Concentrations of TP in the groundwater underlying the coastal wetlands of the  
15 Everglades range from 0.5 to 2.3  $\mu\text{M}$  and are consistently higher than either surface freshwater or  
16 surface seawater; TP also shows a direct relationship with salinity (Fig 9). Fresh groundwater  
17 TP concentrations tend to be less than 1  $\mu\text{M}$  (Table 1). Conservative mixing of fresh  
18 groundwater having TP concentrations of less than 1  $\mu\text{M}$  with surface seawater from Florida Bay  
19 and/or the Gulf of Mexico also having TP concentrations of less than 1  $\mu\text{M}$  can not produce the 1  
20 to 2.3  $\mu\text{M}$  concentrations of TP observed in the brackish groundwater. An additional source of  
21 phosphorus is needed.

22 Given that the seawater intrusion from Florida Bay must first pass through the underlying  
23 sediments before entering the aquifer, then the sediments could be a source of phosphorus for

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

19 Groundwater discharge in the southern Everglades appears to be seasonal, occurring  
20 dominantly during the dry season when excess sodium, chloride, and calcium is observed in  
21 receiving surface waters. This seasonality in groundwater discharge was observed by others  
22 (Top et al., 2001; Sutula et al., 2001) , and is due to higher surface water levels in both the  
23 Everglades and in Florida Bay in the summer wet season. The higher surface water levels result

1 in either reducing groundwater discharge to near zero or even reversing the direction so that the  
2 surface water recharges the groundwater. For instance, groundwater discharge in the regions of  
3 Taylor Slough and C-111 basin have been estimated at 48 cm/yr during the dry season, but  
4 during the wet season the groundwater was recharged between 25 to 35 cm/yr, resulting in a  
5 mean annual discharge of 8 cm/yr (Sutula et al., 2001). This groundwater discharge value is  
6 similar to the rate of 2 to 12 cm/yr estimated for groundwater recharge in the upland regions of  
7 ENP (Price & Swart, In press).

8         Assuming an average TP value in the CGD of 1.5  $\mu\text{M}$ , a CGD of 8 cm/yr results in a  
9 discharge flux of 0.12  $\text{mM P m}^{-2}\text{yr}^{-1}$ . This value is twice as high as earlier estimates of  
10 groundwater input of 0.06  $\text{mM P m}^{-2}\text{yr}^{-1}$  along Taylor Slough and the C-111 basin (Sutula et al.,  
11 2001), however, those estimates were made without groundwater P data. Assuming an extent of  
12 seawater intrusion of 10 km inland along 75 km length of coastline extending from the C-111  
13 basin to the western edge of Shark Slough, results in a CGD zone of 750  $\text{km}^2$ , and a flux of 2.8  
14 metric tons of P to the surface water annually. This amount of P is equivalent to the amount of  
15 phosphorus delivered by Taylor Slough (<2.6 metric tons/yr) to Florida Bay. This amount of P,  
16 however, is considerably less than the estimated 14 metric tons/yr of P delivered to the the 750  
17  $\text{km}^2$  coastal zone via atmospheric inputs (Rudnick et al., 1999).

18         Despite the high concentrations of TP in the brackish groundwaters, only low TP values  
19 (<0.5 $\mu\text{M}$ ) are detected in the overlying surface waters. These results suggest that the phosphorus  
20 transported with the CGD is either removed from the surface water column quickly by biotic  
21 processes (Gaiser et al., 2004) or is retained in the Everglades soils by sorption, particularly to  
22 calcium carbonate particles (De Kanel & Morse, 1978), clays (Zhou & Li, 2001) and iron-oxides  
23 (Chambers et al., 2001). Soils within the mangrove zone are indeed a sink for phosphorus as

1 indicated by higher concentrations of phosphorus measured in shallow sediments (2.5 cm) within  
2 the mangrove zone as opposed to freshwater upland sites (Chen & Twilley, 1999). The high  
3 concentrations of TP in the groundwater along with any sorbed to the soils is then available for  
4 plant root uptake by the coastal mangroves.

5         The Everglades and Florida Bay are oligotrophic systems and extremely sensitive to  
6 exogenous inputs of nutrients, particularly phosphorus (Fourqurean et al., 1992; Gaiser et al.,  
7 2004). Phosphorus inputs from canals that drain the surrounding agricultural landscape have  
8 been implicated as major drivers of biotic change of the Everglades ecosystem (Davis, 1994;  
9 Noe et al., 2003). Along the southern margin of the Florida peninsula, the freshwater,  
10 oligotrophic Everglades and the marine oligotrophic Florida Bay ecosystems are separated by an  
11 often lush mangrove forest. The highly productive mangrove forest separating the two nutrient-  
12 limited ecosystems seems to require a phosphorus source that is independent of the mixing of  
13 Everglades surface water and the marine waters of Florida Bay. We hypothesis that the high  
14 productivity of the mangrove forest along the coastal Everglades maybe supported by P  
15 delivered by CGD.

16



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7

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

<b>Site Name</b>	<b>Sampling</b>	<b>Depth</b>	<b>Temp.</b>		<b>Salinity</b>	<b>Total P</b>
<b>(SW=Surface water)</b>	<b>Date</b>	<b>(m)</b>	<b>(°C)</b>	<b>pH</b>	<b>(psu)</b>	<b>(uM)</b>
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
<b>(GW=Groundwater)</b>						
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

1 **List of Figures**

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

Figure 2. Map of south Florida and study area.

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.

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

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 on Fig. 3 and well depth in parenthesis.

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  $\text{Ca}^{2+}\text{-HCO}_3^-$  type water. Groundwater (square) is dominated by  $\text{Na}^+$  and  $\text{Cl}^-$  ions indicative of seawater intrusion. Surface waters had a brackish signature (gray triangles) during the months indicated in the legend. See Fig. 3 for site location.



1 Figure 7. Mean calcium (mM) in groundwaters (open circles) and surface waters (solid  
2 diamonds) relative to a seawater mixing line. Error bars represent  $\pm$  one standard error.

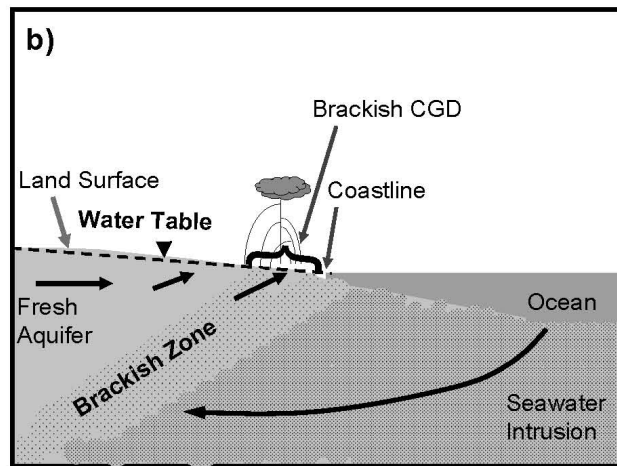
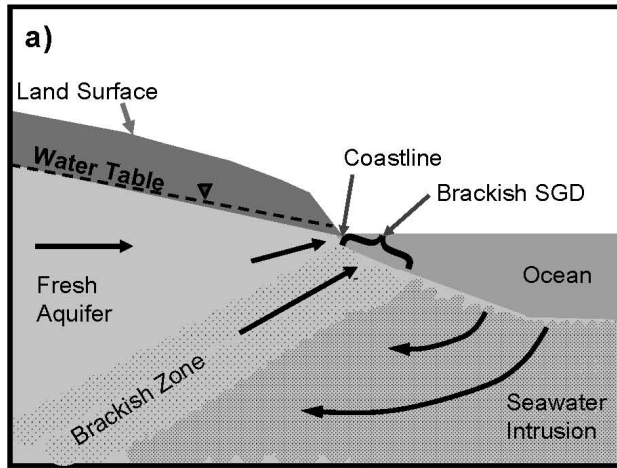
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4 Figure 8. Elevated calcium concentrations in Everglades surface waters relative to surface  
5 seawater mixing. Mean calcium (mM) in the groundwaters at sites EP8A (solid triangle),  
6 E146 (solid square), and RB-1 (solid circle) are elevated relative to the surface seawater  
7 mixing line. Error bars represent the range in values. Surface waters collected at these  
8 sites (open symbols) at certain times of the year also show elevated calcium  
9 concentrations relative to the surface seawater mixing line indicating TBGD to these  
10 sites.

11 Figure 9. Total phosphorus ( $\mu\text{M}$ ) in groundwater samples (solid circles) increase linearly with  
12 salinity, and are higher than the mean TP of surface waters of the Everglades (open  
13 square), eastern Florida Bay (open cross), and the Gulf of Mexico (solid triangle).

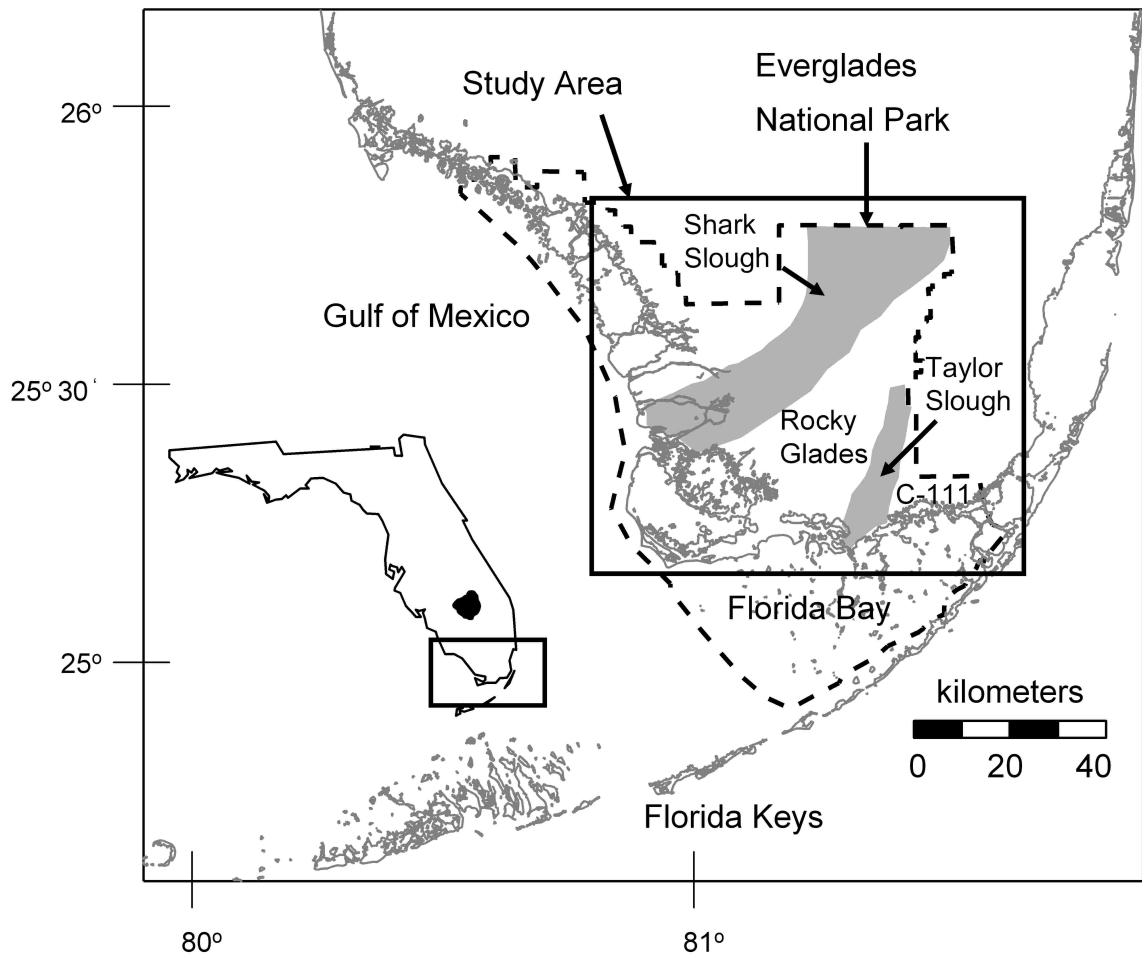
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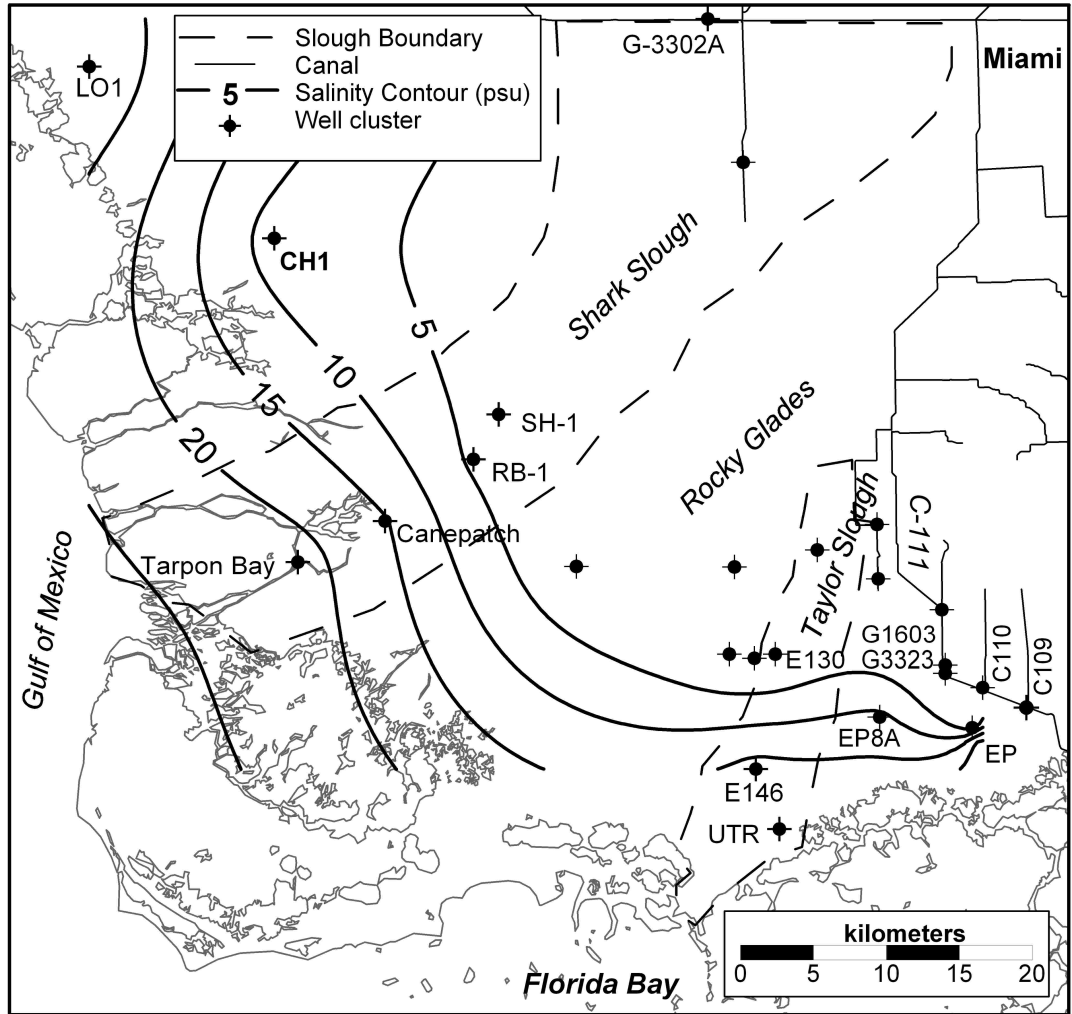


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2 Price et al. Fig. 1



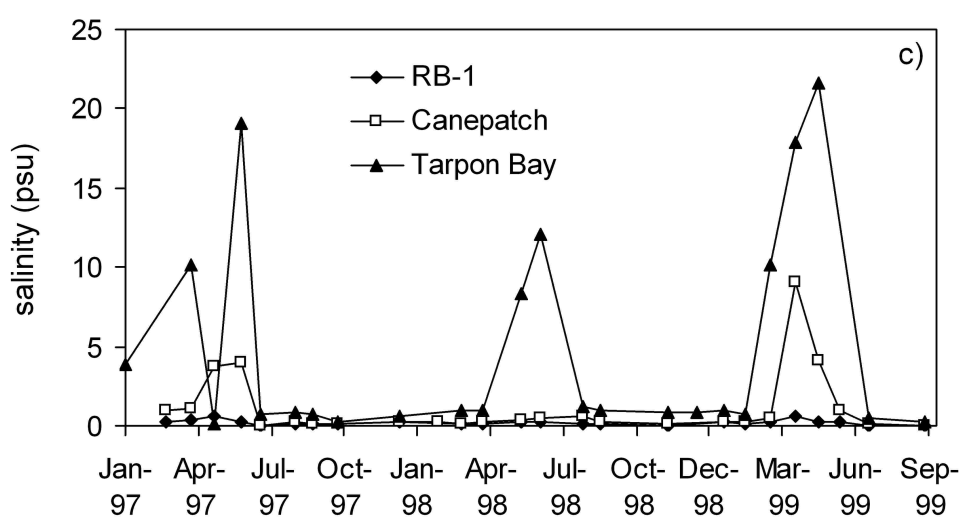
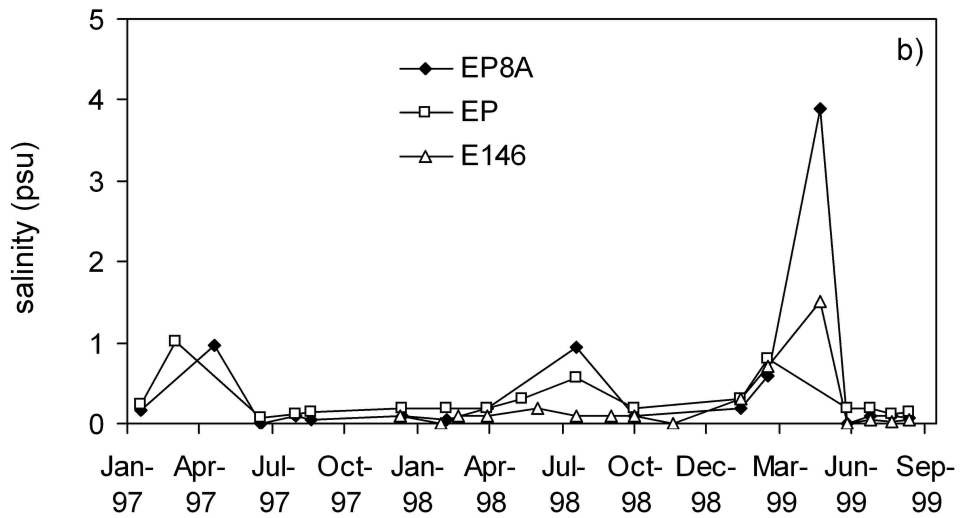
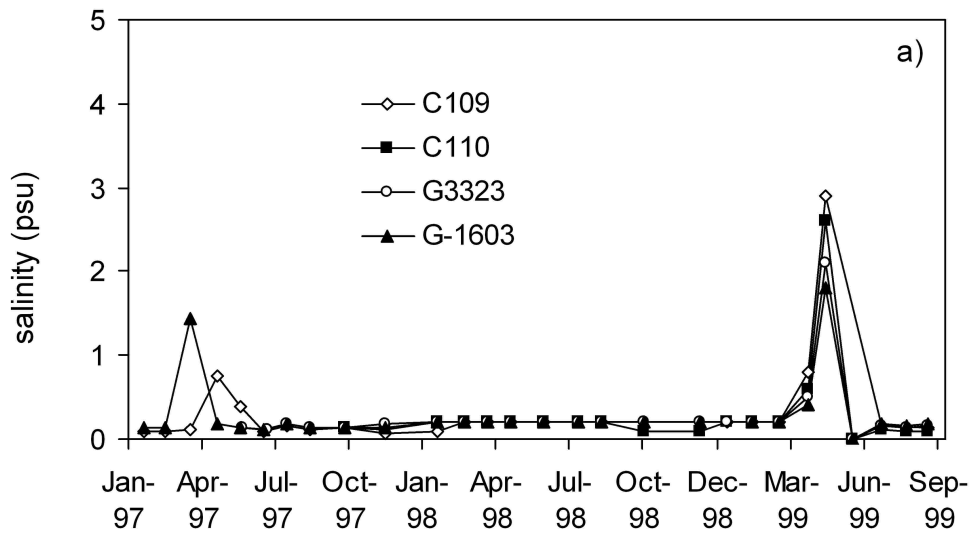
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Price et al. Fig 2

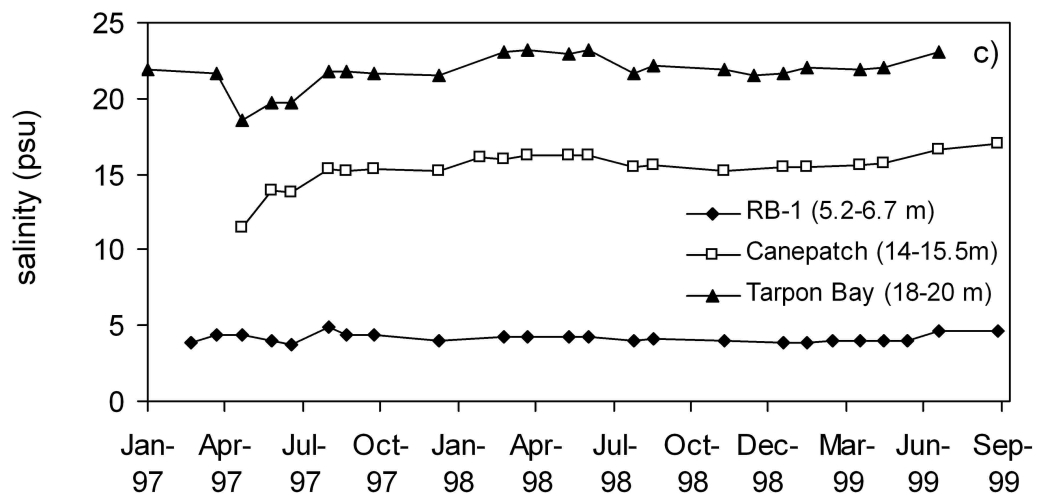
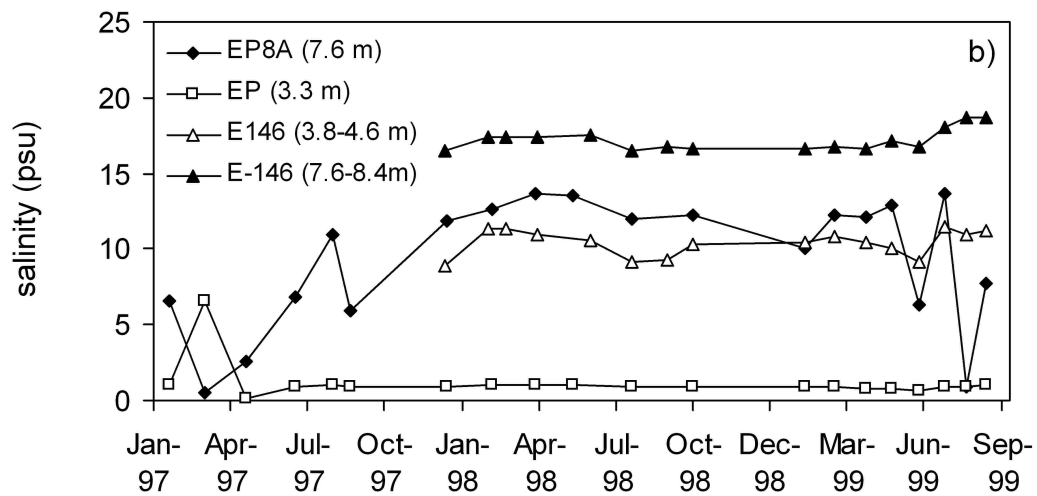
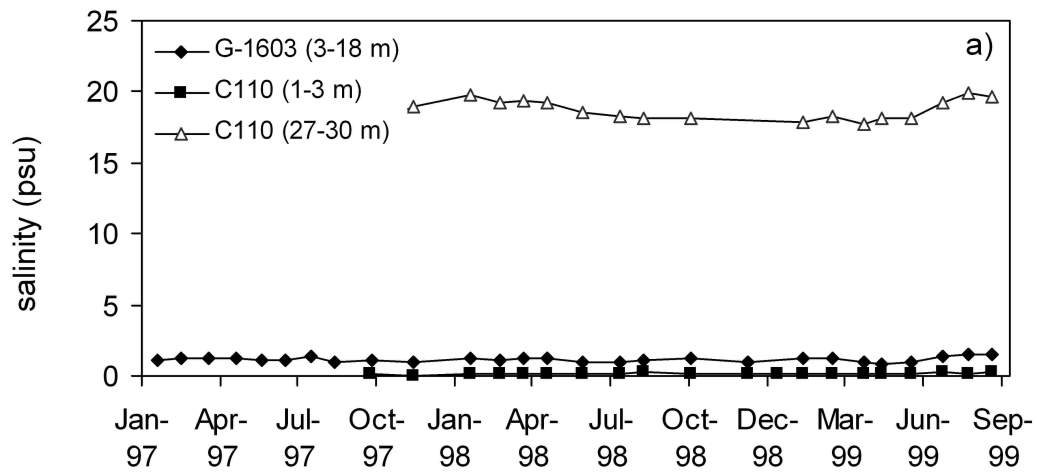


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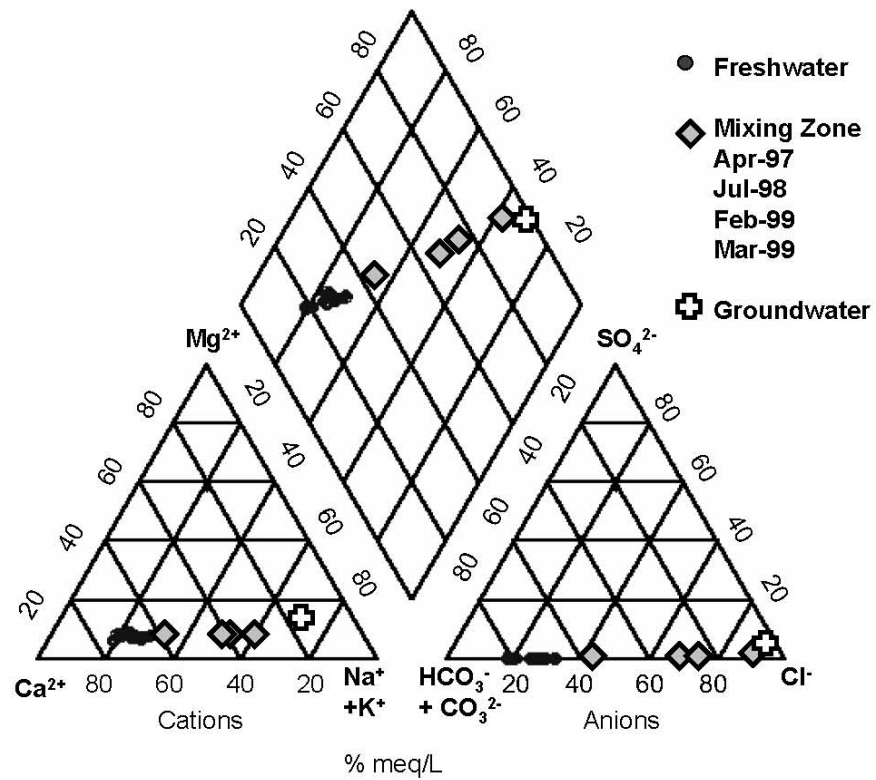
Price et al Fig. 3







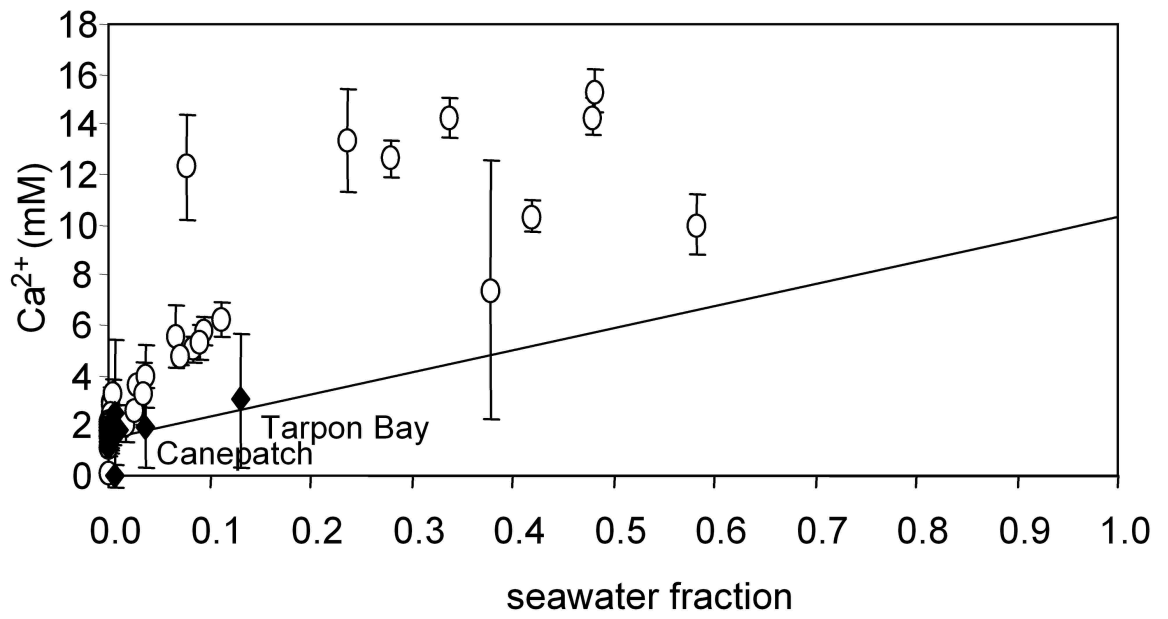
EP8A



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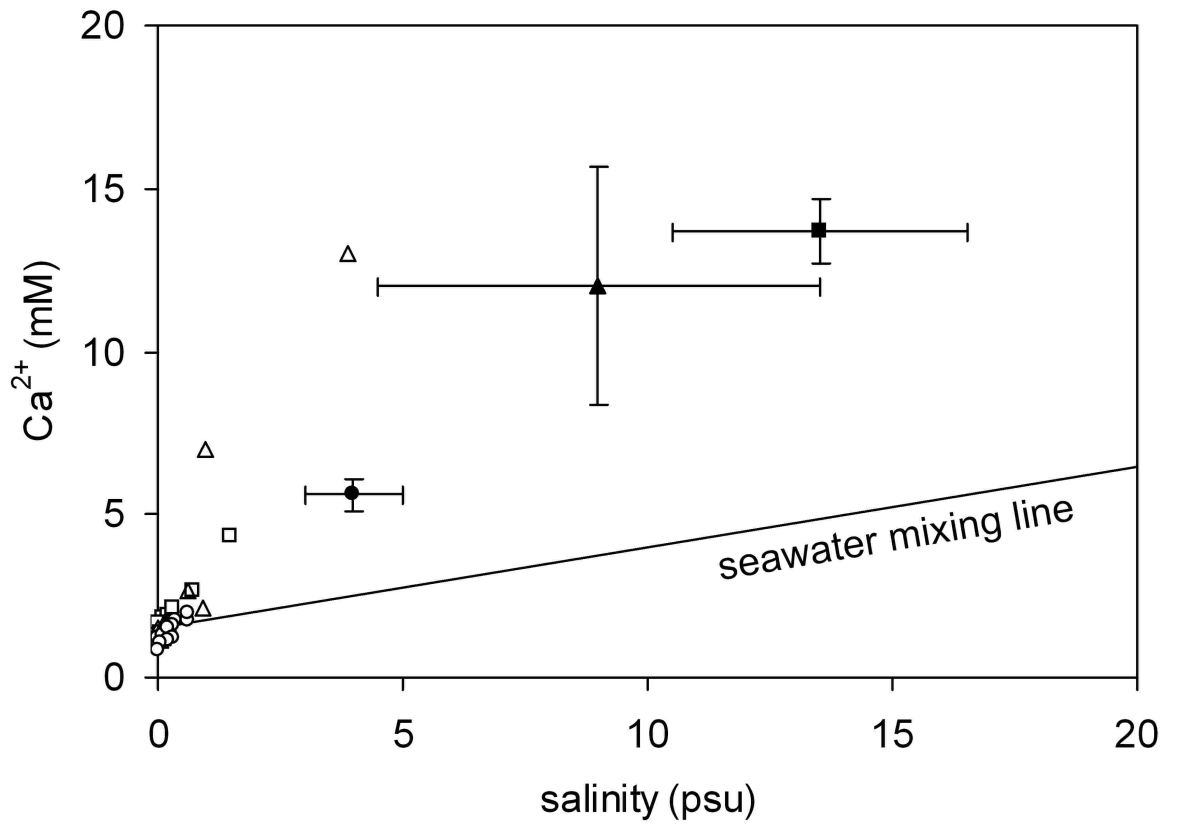
Price et al. Fig. 6





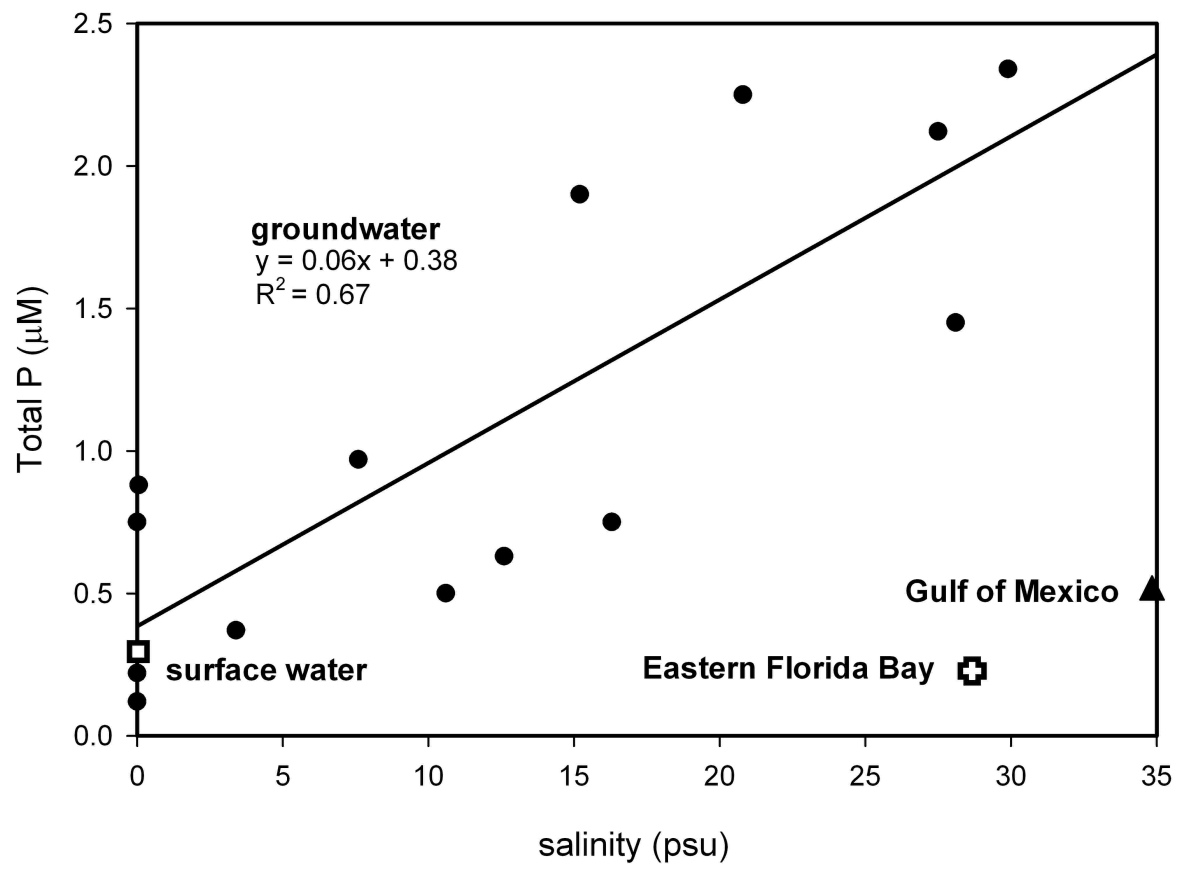
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Price et al. Fig. 7



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Price et al. Fig. 8



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Price et al. Fig. 9.