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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

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 to 2.3 μM 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 μM. 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 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 (P). 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; Armitage et al., this issue; Gil et al., this issue). We propose that the enhanced productivity of the freshwater-marine ecotone of the coastal Everglades as compared to either freshwater or marine end-members maybe 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 (5×10^{-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 m 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, 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 yr^{-1}, and estimated hydraulic conductivity between 1.5 and 4.5 million m yr^{-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. Futhermore, 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

Geochemical Investigation

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 to 4 wells with finished depths ranging from 2 to 60 m within the SAS and were completed by either the USGS (Fish and Stewart, 1991; Fitterman, 1999) or the National Park Service. Most of the wells completed by the USGS contained and some wells completed just for this investigation by the National Park Service consisted of PVC pipe that was 2.5 to 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 cm to 15 cm diameter metal surface casing that was between 1 to 2 meters 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 4^0C 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 9 surface water samples 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 to 5 days of sample collection. A total of 23 water samples were analyzed for TP (Table 1).

Water Chemistry

Specific conductance measured in all of the water samples varied from 100 and 36,900 μS 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 during three 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). Goundwater 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 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 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, while calcium concentrations of some surface waters collected at E146, EP8A, and RB-1 are enriched in calcium compared to the seawater dilution line (Fig. 8). Sodium concentrations in the surface waters and groundwaters plotted along the seawater mixing line, 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.

Ambient surface water concentrations of TP in the fresh waters of the Everglades were extremely low and ranged from 0.16 to 0.45 μM (Table 1). Concentrations of TP in the groundwaters were consistently higher than the surface water at 0.5 to 2.3 μM. 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 on 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 groundwater zone varying between 6 to 25 km wide. The landward extent of seawater intrusion extends the farthest inland in Shark Slough (25 to 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 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 to 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. 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 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). Salinity increases in the surface waters of the C-111 canal and southern marshes during the end of the dry seasons in 1997 and 1999 (Fig. 4) are most likely in response to lowered water levels. In 1997, the groundwater salinity in wells EP8A increased markedly from near 1 to above 10, and remained high throughout 1998 and into 1999. This increase in groundwater salinity followed a spike in the surface water salinity occurring at the end of the dry season in 1997 and is most likely in response to lowered water levels during that time. The subsequent year long increase in groundwater salinity of the C-111 basin suggests that landward advancement of seawater intrusion within the SAS is slow compared to that observed in the surface water. 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 to 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 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. That these sites are approximately 6 to 25 km inland of the coastline and coincident with the position of the seawater intrusion in the shallow portion of the SAS (Fig. 3) suggests that brackish groundwater is the source of the seawater signature.

Elevated concentrations of calcium in the surface waters also suggest a brackish groundwater source as opposed to surface seawater from Florida Bay or the Gulf of Mexico moving inland in response to the lowering of water levels (Fig. 8). 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 a seawater dilution line produced from mixing of fresh Everglades waters and surface seawater. 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.

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

Phosphorus

Ambient surface water TP concentrations in the fresh waters of the Everglades range from 0.15 to 0.45 μM (Table 1). Median TP concentrations in marine surface waters of northeastern Florida Bay and the Gulf of Mexico are 0.25 μM and 0.58 μM, respectively (Boyer et al., 1999). Concentrations of TP in the groundwater underlying the coastal wetlands of the Everglades range from 0.5 to 2.3 μM and are consistently 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 μM (Table 1). Conservative mixing of fresh groundwater having TP concentrations of less than 1 μM with surface seawater from Florida Bay and/or the Gulf of Mexico also having TP concentrations of less than 1 μM can not produce the 1 to 2.3 μM 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. 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 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 is observed in receiving surface waters. This seasonality in groundwater discharge was observed by others (Top et al., 2001; Sutula 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/yr during the dry season, but during the wet season the groundwater was recharged between 25 to 35 cm/yr, resulting in a mean annual discharge of 8 cm/yr (Sutula et al., 2001). This groundwater discharge value is similar to the rate of 2 to 12 cm/yr estimated for groundwater recharge in the upland regions of ENP (Price & Swart, In press).

Assuming an average TP value in the CGD of 1.5 μM, a CGD of 8 cm/yr results in a discharge flux of 0.12 mM P $m^{-2}yr^{-1}$. This value is twice as high as earlier estimates of groundwater input of 0.06 mM P $m^{-2}yr^{-1}$ 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/yr) to Florida Bay. This amount of P, however, is considerably less than the estimated 14 metric tons/yr of P delivered to the 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 (<0.5μM) 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.

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References:

Armitage, A. R., T. A. Frankovich & J. W. Fourqurean, This issue. Variable responses within epiphytic and benthic microalgal communities to nutrient enrichment. Hydrobiologia.

Armitage, A. R., T. A. Frankovich, K. L. J. Heck & J. W. Fourqurean, 2005. Experimental nutrient enrichment causes complex changes in seagrass, microalgae, and macroalgae community structure in Florida Bay. Estuaries, 28:422-434.

Back, W., B. B. Hanshaw, J. S. Herman & J. N. Van Driel, 1986. Differential dissolution of a Pleistocene reef in the ground-water mixing zone of coastal Yucatan, Mexico. Geology, 14:137-140.

Bear, J., A. H.-D. Cheng, S. Sorek, D. Ouazar & I. Herrera, 1999. Fresh Water-Salt Water Interface in Coastal Aquifers: Concepts, Methods, and Practices. Dordrecht, The Netherlands: Kluwer.

Boyer, J. N., J. W. Fourqurean & R. D. Jones, 1999. Seasonal and long-term trends in the water quality of Florida Bay (1890-1997). Estuaries, 22:417-430.

Chambers, R. M., J. W. Fourqurean, S. A. Macko & R. Hoppenot, 2001. Biogeochemical effects of iorn availability on primary producers in a shallow carbonate environment. Limnology and Oceanography, 46:1278-1286.

CHEN, R. & R. R. Twilley, 1999. Patterns of Mangrove Forest Structure and Soil Nutrient Dynamics Along the Shark River Estuary, Florida. Estuaries 22:955-970.

Cooper, H. H. J., 1959. A Hypothesis Concerning the Dynamic Balance of Fresh Water and Salt Water in a Coastal Aquifer. Journal of Geophysical Research, 64:461-467.

Davis, S. M., 1994. Phosphorus inputs and vegetation sensitivity in the Everglades. In Davis, S. M. & J. C. Odgen (eds), Everglades: The ecosystem and its restoration. St. Lucie Press, Boca Rotan: 357-378.

De Kanel, J. & J. W. Morse, 1978. The chemistry of orthophosphate uptake from seawater onto calcite and aragonite. Geochimica et Cosmochimica Acta, 42:1335-1340.

Du Commun, J., 1828. On the causes of fresh water springs, fountains, etc. American Journal of Science, 14:174-176

Fish, J. E. & M. Stewart. 1991. Hydrogeology of the surficial aquifer system, Dade County, Florida.: USGS Water-Resources Investigations Report 90-4108.

Fitterman, D. V., M. Deszcz-Pan & C. E. Stoddard. 1999. Results of Time-Domain Electromagnetic Soundings in Everglades National Park, Florida.. Denver: USGS Open-File Report 99-426.

Fourqurean, J. W., G. V. N. Powell & J. C. Zieman, 1992. Relationships bewteen porewater nutrients and seagrasses in a subtropical carbonate environment. Marine Biology, 114:57-65.

Fourqurean, J. W. & M. B. Robblee, 1999. Florida Bay: A History of Recent Ecological Changes. Estuaries, 22:345-357.

Gaiser, E. E., L. J. Scinto, J. H. Richards, K. Jayachandran, D. L. Childers, J. C. Trexler & R. D. Jones, 2004. Phosphorous in periphyton mats provides the best metric for detecting low-level P enrichment in an oligotrophic wetland. Water Research, 38:507-516.

Ghyben, B., W., 1888. Nota in verband met de vorrgenomen putboring nabij Amsterdam: Tijdschrift van Let Koninklijk Institute van Ingeneiurs, The Hague:8-22.

Gil, M., A. R. Armitage & J. W. Fourqurean, This issue. Nutrients alter epifaunal density and species composition in a subtropical seagrass bed. Hydrobiologia.

Herzberg, B., 1901. Die Wasserverzorgung einiger Nordseebaden. J. Gasbelechntung und Wasserversorgung, 44:815-819.

Hittle, C., E. Patino & M. Zucker. 2001. Freshwater Flow from Estuarine Creeks into Northeastern Florida Bay, USGS Water Resources Investigations Report 01-4164.

Klein, H. & B. G. Waller. 1985. Synopsis of saltwater intrusion in Dade County, Florida, through 1984. USGS Water-Resources Investigations Report 85-410.

Kohout, F. A., 1960. Cyclic Flow of Salt Water in the Biscayne Aquifer of Southeastern Florida. Journal of Geophysical Research, 65:2133-2141.

Kohout, F. A. 1964. Flow of freshwater and saltwater in the Biscayne aquifer of the Miami area, Florida.: USGS Water-Supply Paper 1613-C, C12-C32.

Konikow, L. F. & T. E. Reilly, 1999. Seawater intrusion in the United States. In Bear, J., Cheng, Soerk, Ouazar & Herrera (eds), Seawater intrusion in coastal aquifers: Concepts, methods, and practices. Kluwar Academic Publishers, Dordrecht, The Netherlands: 463-506.

Light, S. S. & J. W. Dineen, 1994. Water control in the Everglades: A historical perspective. In Davis, S. M. & J. C. Odgen (eds), Everglades: The ecosystem and its restoration. St. Lucie Press, Delray Beach, FL: 47-84.

Millero, F., F. Huang, X. Zhu, X. Liu & J.-Z. Zhang, 2001. Adsorption and Desorption of Phosphate on Calcite and Aragonite in Seawater. Aquatic Geochemistry, 7:33-56.

Moore, W. S., 1999. The subterranean estuary: a reaction zone of ground water and sea water. Marine Chemistry, 65:111-125.

Noe, G. B., L. J. Scinto, J. Taylor, D. L. Childers & R. D. Jones, 2003. Phosphorous cycling and partitioning in an oligotrophic Everglades wetland ecosystem: a radiostope tracing study. Freshwater Biology, 48:1993-2008.

Parker, G. G., G. E. Gerguson, S. K. Love & others. 1955. Water resources of Southeastern Florida with special reference to geology and groundwater of the Miami areas. pp. 965: USGS Water-Supply Paper 1255.

Price, R. M. 2001. Geochemical determinations of groundwater flow in Everglades National Park. In: *Marine Geology and Geophysics*, pp. 307. Miami: University of Miami.

Price, R. M. & J. S. Herman, 1991. Geochemical investigation of salt-water intrusion into a coastal carbonate aquifer; Mallorca, Spain. GSA Bulletin, 103:1270-1279.

Price, R. M. & P. K. Swart, In press. Geochemical indications of groundwater recharge into the Surficial Aquifer System: Everglades National Park. GSA Bulletin Special Publication "Karst Geomorphology, Hydrology, & Geochemistry-A Tribute Volume to Derek C. Ford and William B. White".

Price, R. M., Z. Top, J. D. Happell & P. K. Swart, 2003. Use of tritium and helium to define groundwater flow conditions in Everglades National Park. Water Resources Research, 39:1267.

Reese, R. S. & K. J. Cunningham. 2000. Hydrogeology of the Gray Limestone Aquifer in Southern Florida. pp. 1-78: USGS Water-Resources Investigation Report 99-4213.

Rudnick, D., Z. Chen, D. L. Childers, J. N. Boyer & T. D. I. Fontaine, 1999. Phosphorus and Nitrogen Inputs to Florida Bay: The Importance of the Everglades Watershed. Estuaries, 22:398-416.

Sivan, O., Y. Yechieli, B. Herut & B. Lazar, 2005. Geochemical evolution and timescale of seawater intrusion into the coastal aquifer of Isreal. Geochimica et Cosmochimica Acta, 69:579-592.

Solorzano, L. & J. H. Sharp, 1980. Determination of total dissolved phosphorus and particulate phosphorus in natural waters. Limnology and Oceanography, 25:754-758.

Sonenshein, R. S. 1997. Delineation and extent of saltwater intrusion in the Biscayne Aquifer, Eastern Dade County, Florida. USGS Water-Resour. Invest. Report 96-4285.

Sonenshein, R. S. & E. J. Koszalka. 1996. Trends in water-table altitude (1984-93) and saltwater intrusion (1974-93) in the Biscayne aquifer, Dade County, Florida. pp. 2 sheets: USGS Open-File Report 95-705.

Sutula, M., J. W. Day, J. Cable & D. Rudnick, 2001. Hydrological and nutrient budgets of freshwater and estuarine wetlands of Talyor Slough in Southern Everglades, Florida (U.S.A.). Biogeochemistry, 56:287-213.

Top, Z., L. E. Brand, R. D. Corbett, W. Burnett & J. P. Chanton, 2001. Helium and Radon as Tracers of Groundwater Input Into Florida Bay. Journal of Coastal Research, 17:859-868.

Younger, P. L., 1996. Submarine groundwater discharge. Nature, 382:121-122.

Zhou, M. & Y. Li, 2001. Phosphorus-Sorption characteristics of calcareous soils and limestone from the southern Everglades and Adjacent Farmlands. Soil Scienctists Society of American Journal, 65:1404-1412.

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

Site Name (SW=Surface water)	Sampling Date	Depth (m)	Temp. (^{o}C)	pH	Salinity (psu)	Total P (uM)
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

List of Figures

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.

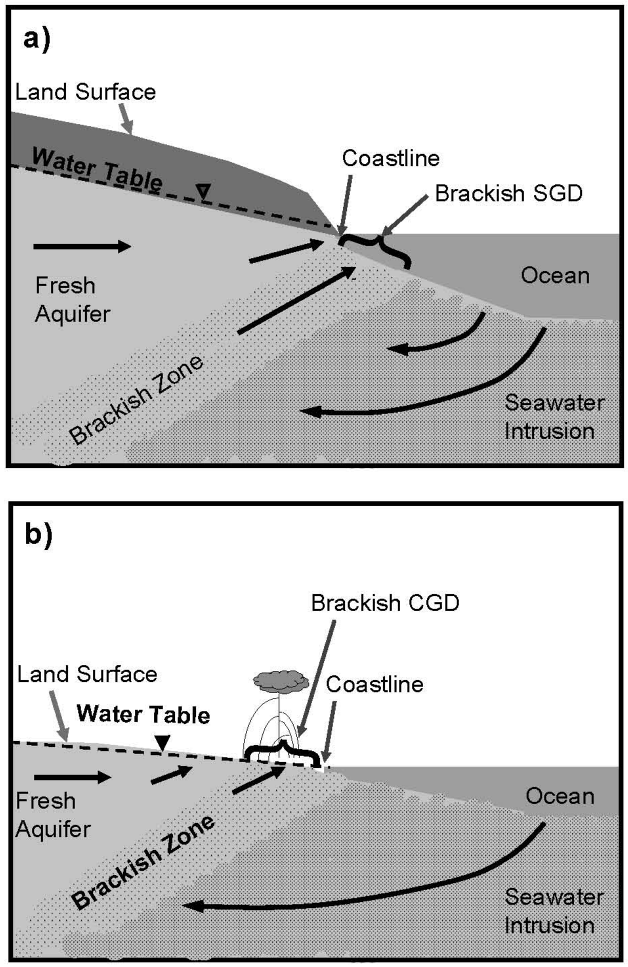
Figure 5. Salinity of groundwater in wells a) along the C-111 canal; b) in Taylor Slough and the C-111 basin; and c) in Shark Slough. Legend refers to the well name as shown on Fig. 3 and well depth in parenthesis.

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 Ca^{2+}-HCO_3^- type water. Groundwater (square) is dominated by Na^+ and 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.

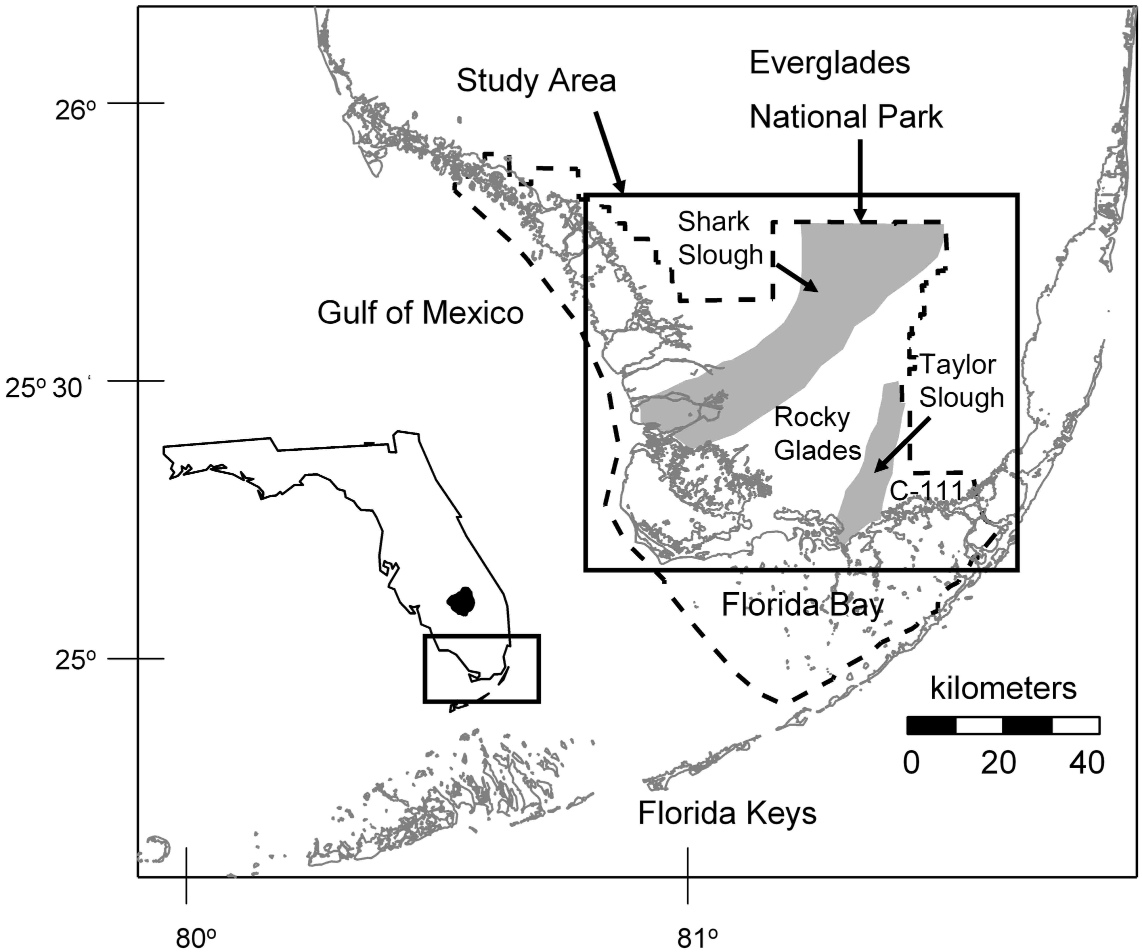
Figure 7. Mean calcium (mM) in groundwaters (open circles) and surface waters (solid diamonds) relative to a seawater mixing line. Error bars represent ± one standard error.

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

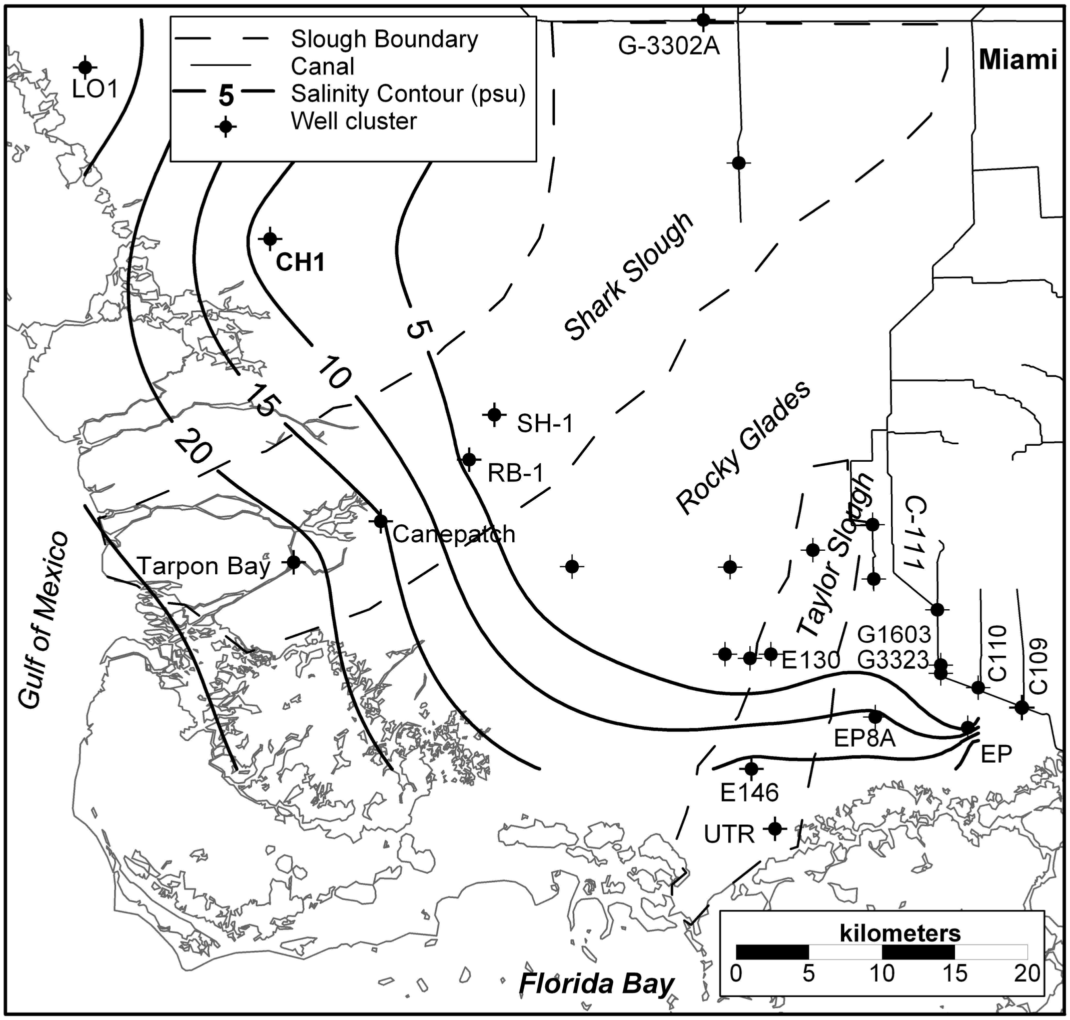
Figure 9. Total phosphorus (μM) in groundwater samples (solid circles) increase linearly with salinity, and are higher than the mean TP of surface waters of the Everglades (open square), eastern Florida Bay (open cross), and the Gulf of Mexico (solid triangle).



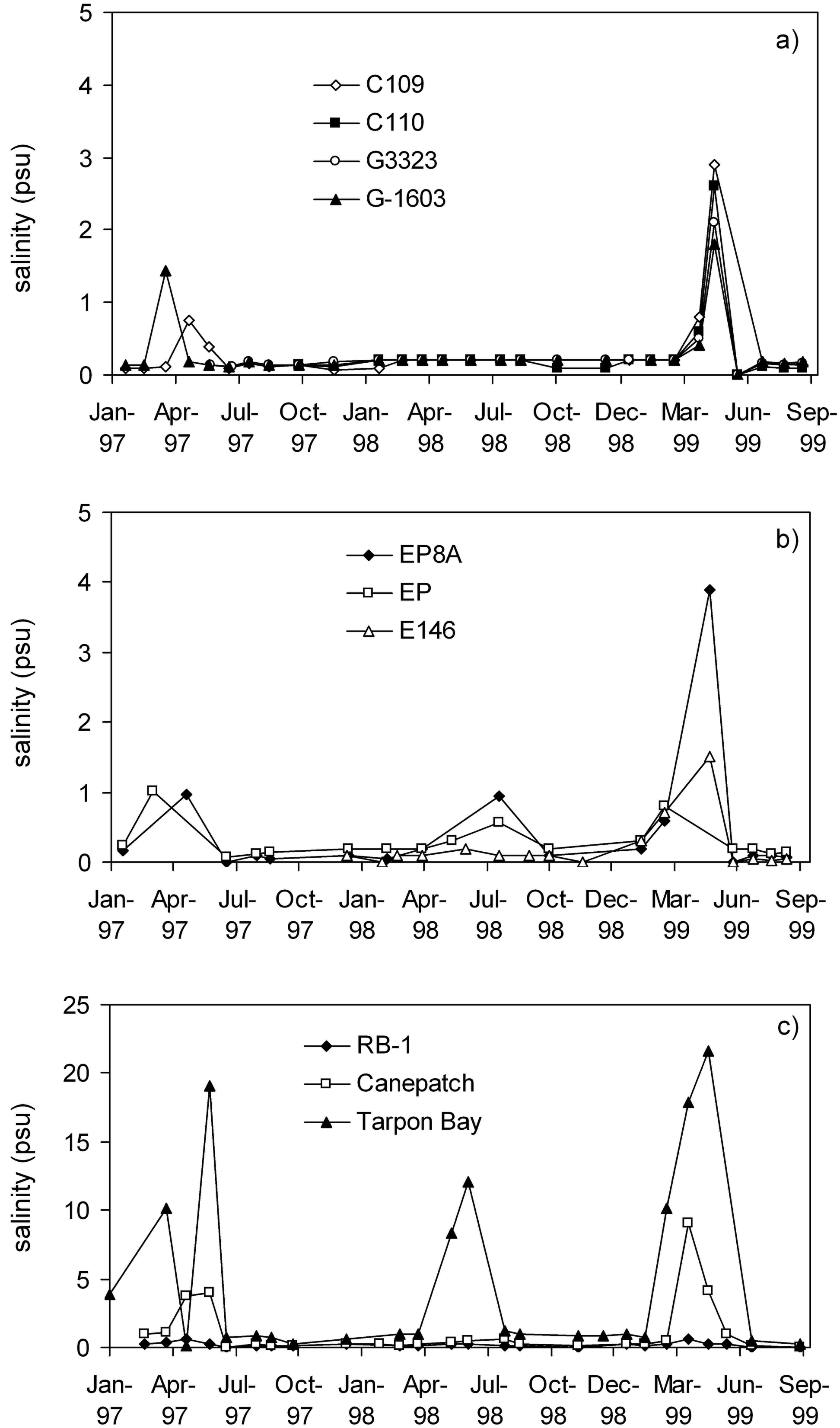
Price et al. Fig. 1



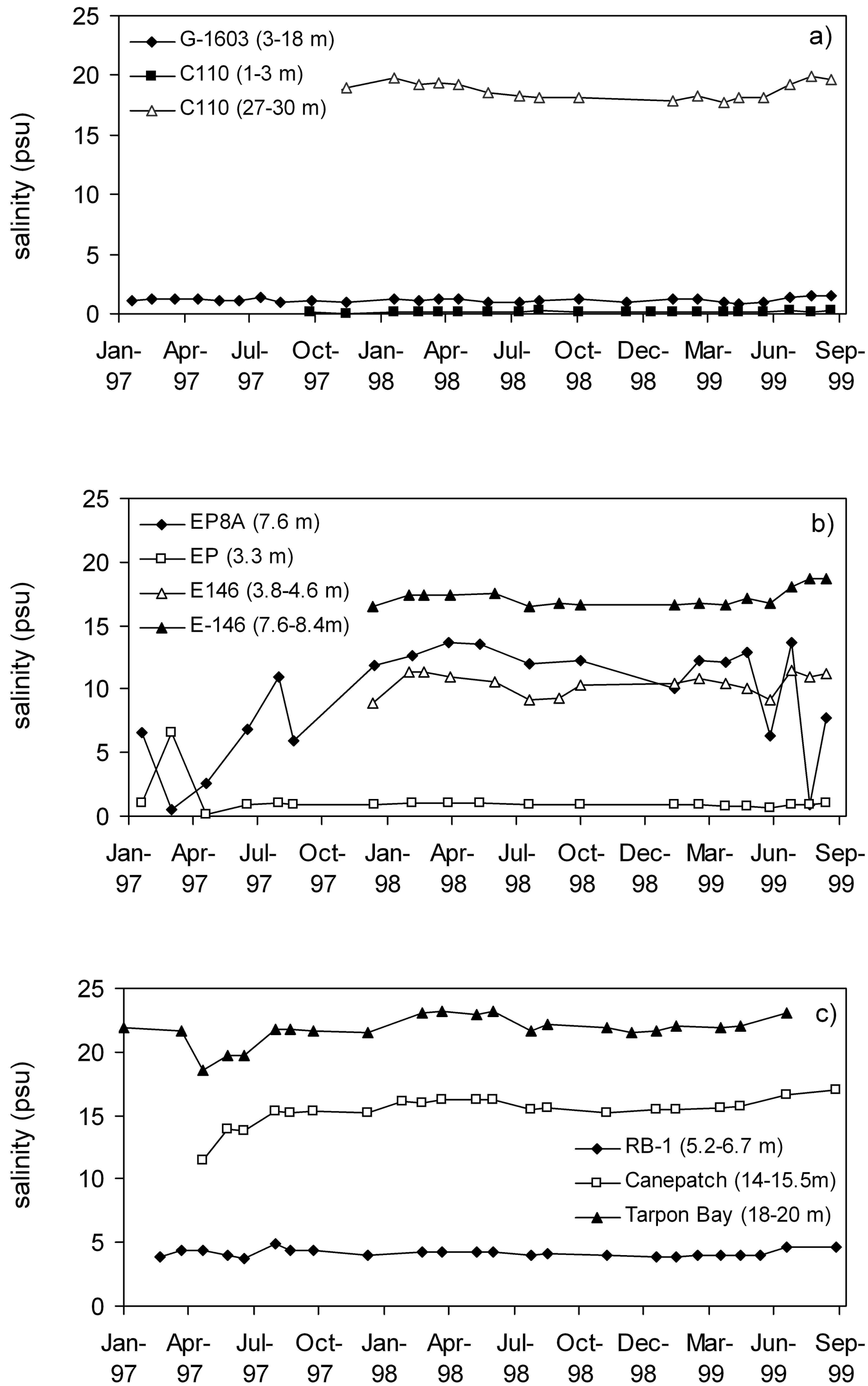
Price et al. Fig 2



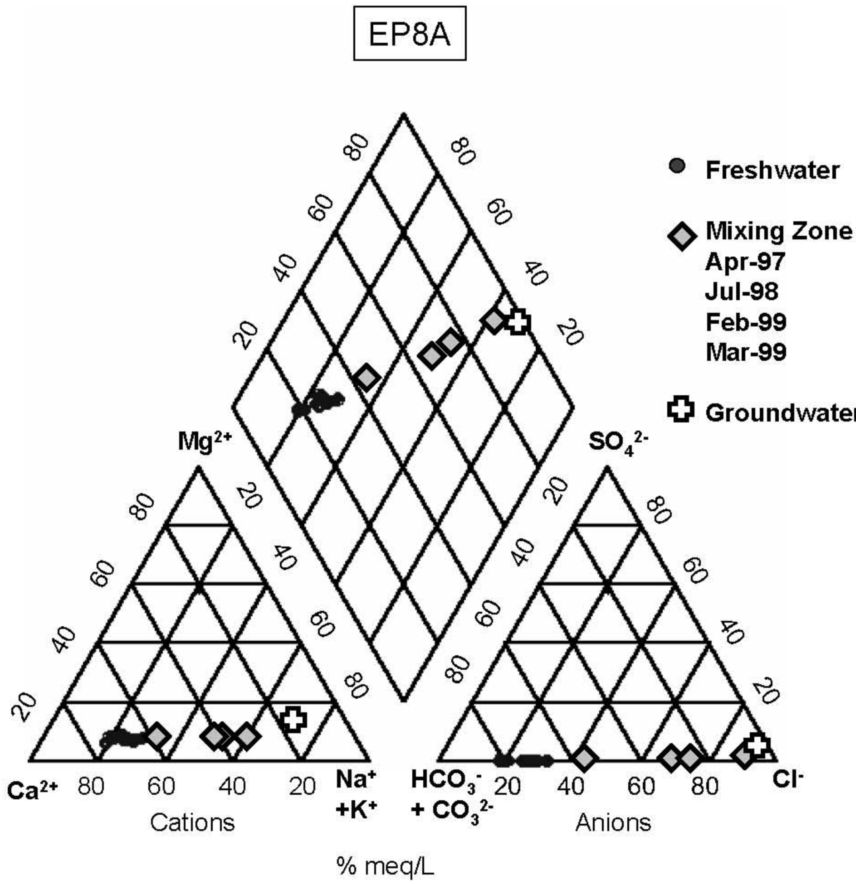
Price et al Fig. 3


a)
C109
C110
G3323
G-1603
salinity (psu)
0
1
2
3
4
5
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Dec-98
Mar-99
Jun-99
Sep-99
b)
EP8A
EP
E146
c)
RB-1
Canepatch
Tarpon Bay
10
15
20
25

1 Price Fig. 4



Price et a. Fig. 5



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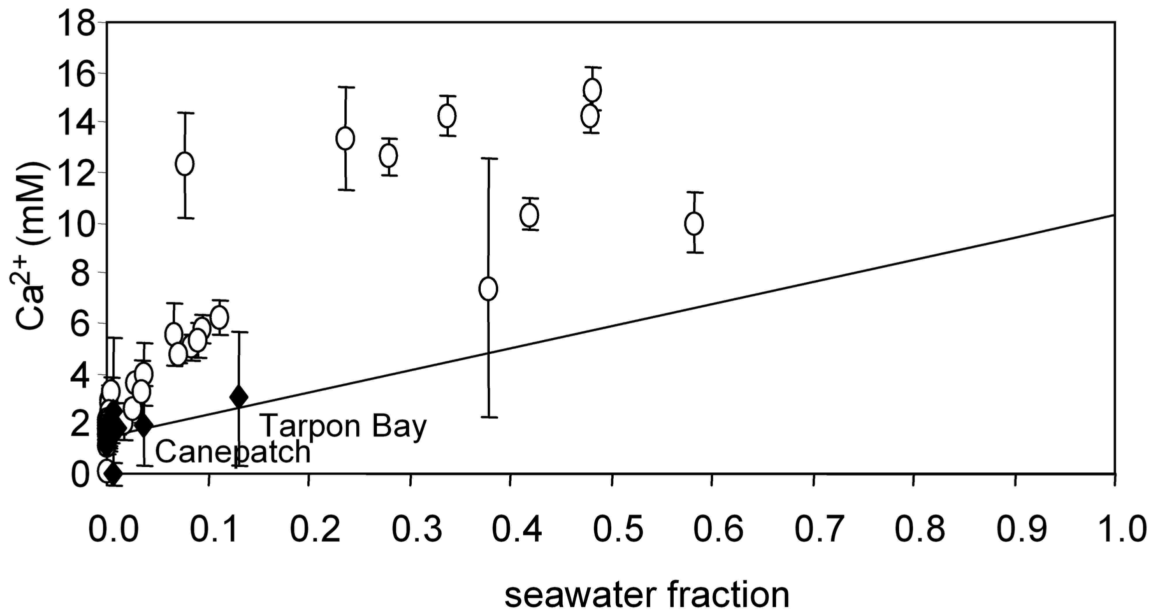
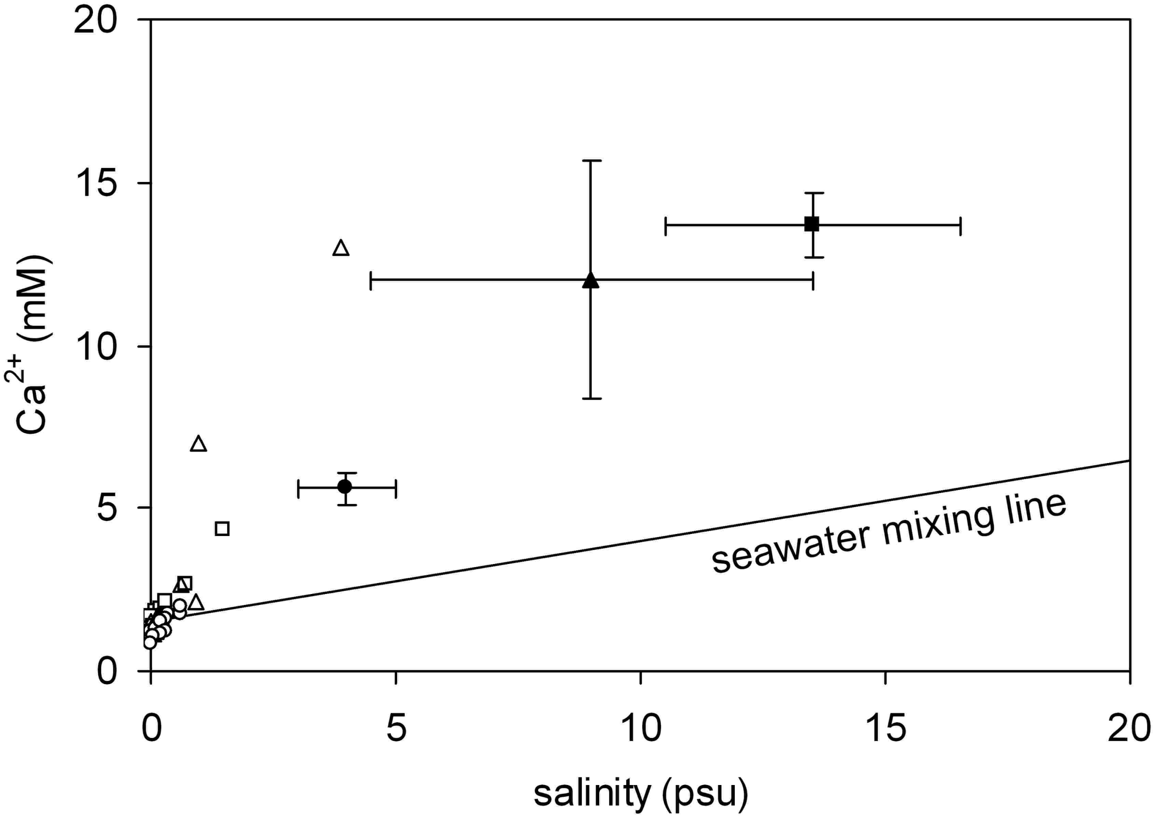
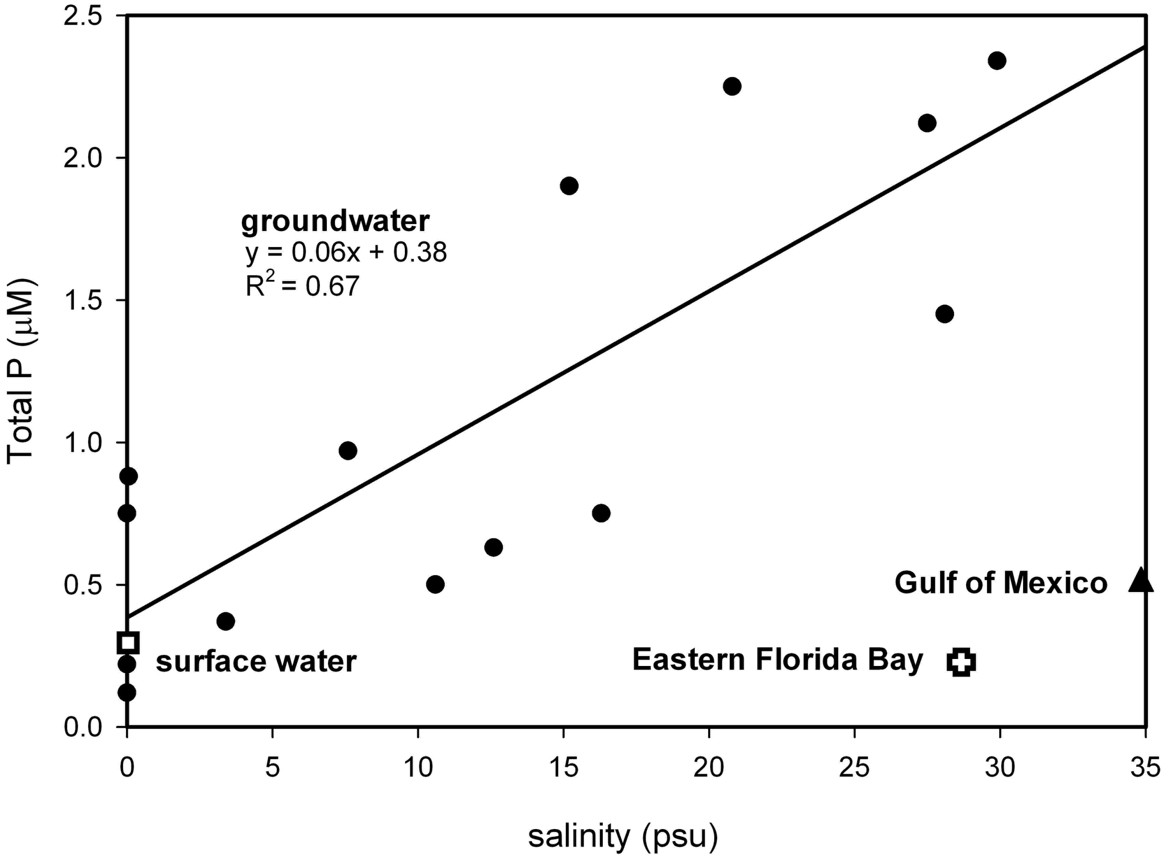


Price et al. Fig. 7



Price et al. Fig. 8



Price et al. Fig. 9.