Investigation of Coastal Hydrogeology Utilizing Geophysical and Geochemical Tools along the Broward County Coast, Florida

By Christopher D. Reich, Peter W. Swarzenski, W. Jason Greenwood, and Dana S. Wiese

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Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Flow rate	
meter per day (m/d)	3.281	foot per day (ft/d)
kilometer per hour (km/h)	0.6214	mile per hour (mi/h)
	Radioactivity	
becquerel per liter (Bq/L)	27.027	picocurie per liter (pCi/L)
	Hydraulic conductivity	
meter per day (m/d)	3.281	foot per day (ft/d)
	Hydraulic gradient	
meter per kilometer (m/km)	5.27983	foot per mile (ft/mi)
	Transmissivity*	
meter squared per day (m^2/d)	10.76	foot squared per day (ft^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Acronyms and Abbreviations

Symbol or Abbreviation	Definition	Symbol or Abbreviation	Definition
<	Less than	m	Meters
>	Greater than	cm	Centimeters
~	Approximately	ka	1,000 years before present
SGD	Submarine Groundwater Discharge	m^2/d	Square meters per day
CRP	Continuous Resistivity Profile	Fm	Formation
CHIRP	Compressed High-Intensity Radar Pulse	mg/L	Milligrams per liter
DC	Direct-current (voltage)	L/min	Liters per minute
mbsl	Meters below sea floor	kph	Kilometers per hour
km	Kilometers	mS/cm	milliSiemens per centimeter
kHz	kiloHertz	dpm/L	Disintegrations per minute per liter

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Abstract

Geophysical (CHIRP, boomer, and continuous direct-current resistivity) and geochemical tracer studies (continuous and time-series ^{222}radon) were conducted along the Broward County coast from Port Everglades to Hillsboro Inlet, Florida. Simultaneous seismic, direct-current resistivity, and radon surveys in the coastal waters provided information to characterize the geologic framework and identify potential groundwater-discharge sites. Time-series radon at the Nova Southeastern University National Coral Reef Institute (NSU/NCRI) seawall indicated a very strong tidally modulated discharge of ground water with ^{222}Rn activities ranging from 4 to 10 disintegrations per minute per liter depending on tidal stage. CHIRP seismic data provided very detailed bottom profiles (i.e., bathymetry); however, acoustic penetration was poor and resulted in no observed subsurface geologic structure. Boomer data, on the other hand, showed features that are indicative of karst, antecedent topography (buried reefs), and sand-filled troughs. Continuous resistivity profiling (CRP) data showed slight variability in the subsurface along the coast. Subtle changes in subsurface resistivity between nearshore (higher values) and offshore (lower values) profiles may indicate either a freshening of subsurface water nearshore or a change in sediment porosity or lithology. Further lithologic and hydrologic controls from sediment or rock cores or well data are needed to constrain the variability in CRP data.

Introduction

Coastal environments are subjected to increased stressors in south and southeast Florida (Renken and others, 2005; McPherson and Halley, 1996). Reef environments along the Broward County coast (Figure 1) are considered high-latitude reef systems because they occur north of 25°N (Moyer and others, 2003). As a result of their high-latitude location, these reefs may incur additional stresses such as greater surface-water-temperature variability, increased sedimentation from land, and enhanced nutrient influx. An unseen and often overlooked phenomenon that occurs along coastal margins is submarine groundwater discharge (SGD). SGD is defined as the phenomenon that forces ground water to flow from beneath the seafloor into the overlying ocean regardless of its composition—whether fresh, recirculated seawater, or a combination of both (Kohout, 1964; Burnett and others, 2003). In southeast Florida, SGD is likely to account for 6-10% of the total water influx to coastal waters (Langevin, 2003). During the dry season, SGD can account for a greater quantity of water influx than surface drainage. Along the Florida coast, SGD is often associated with tidal pumping. The results of tidal pumping are intense along coastlines such as in the Florida Keys, where a hydraulic head has been established between bay and ocean, but tidal-pumping forces typically decrease exponentially as the distance increases offshore (Shinn and others, 1994; Reich and others, 2002).

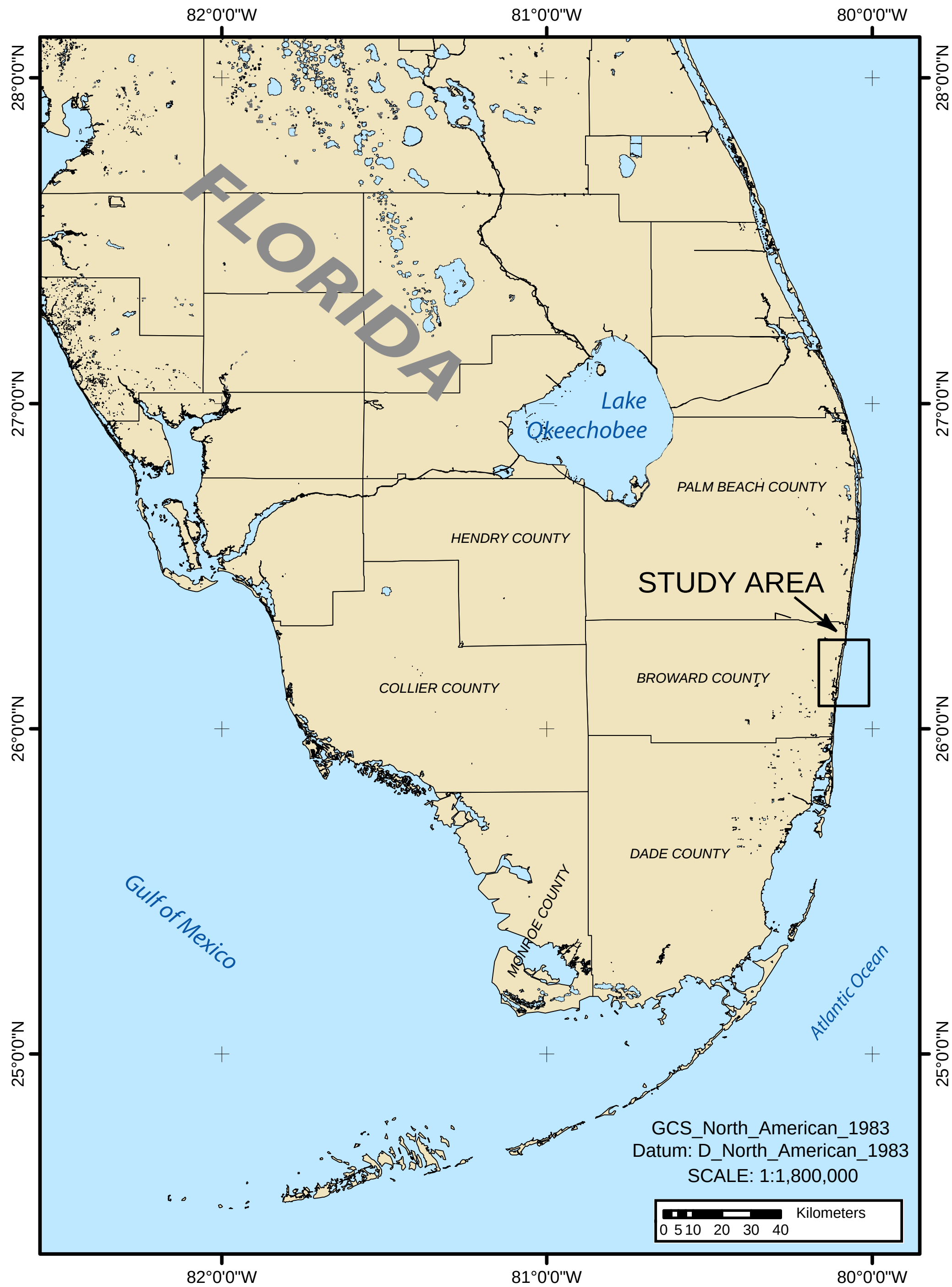

Figure 1. Location map of the study area in Broward County, Florida.

Defining zones of SGD can be a daunting task due to the diffuse nature of the phenomenon. Existing geophysical and geochemical techniques are finding new applications in mapping, quantifying, and constraining coastal hydrogeologic processes. Geophysical tools such as high-resolution seismic and direct-current (DC) resistivity are useful for investigating the geologic framework and composition, respectively (Hoefel and Evans, 2001; Manheim and others, 2002; Mota and Santos, 2006; Day-Lewis and others, 2006; Greenwood and others, 2006; Swarzenski and others, 2007a). South Florida consists of karst limestone that is hydraulically very conductive and allows ground water to flow rapidly down gradient toward the coast. Conducting seismic surveys can identify collapse or solution-type features that may serve as conduits for such groundwater movement. These conduits may act as point sources for discharge or as entry points for seawater encroachment (Fish, 1987; Esteves and Finkl, 1999; Dausman and Langevin, 2005). Continuous surface-water ^{222}Rn surveys of the nearshore coastal systems have been used to identify ‘hotspots’ of SGD because ^{222}Rn, an inert gas, is formed and found in higher quantities in the subsurface and is advected into the overlying surface water. Rn-222 is an ideal natural tracer to the extent that it does not build up in seawater but rather evades into the atmosphere (Burnett and others, 2001; Swarzenski and others, 2007b). Combining geophysical and geochemical techniques such as ^{222}Rn surveys allows for an enhanced view of the coastal hydrogeologic framework.

Statement of Problem

Onshore, urban expansion and canals have impacted both groundwater quality and groundwater flow to the coast. Studies off the coast of Broward County indicate that offshore ecological changes are occurring. The causes may arise from multiple sources, such as the presence of offshore sewage outfalls (e.g., Hollywood and Hillsboro Inlet), ~67,000 septic tanks, and Class I sewage-injection wells used to dispose of tertiary treated wastewater (Waller and others, 1987; Bradner and others, 2004; Koopman and others, 2006; Maliva and others, 2007). Designing appropriate wastewater-treatment and disposal practices for a coastal community can be challenging, and educating residents on proper application of pesticides and fertilizers is essential for protecting water resources. Port Everglades wastewater-treatment plant, for example, injects 211,080 cubic meters per day (m^3/d) of secondary treated wastewater through four 61-cm-diameter disposal wells into the Boulder Zone (~900 m below land surface) (*http://broward.org*). McNeill (2000) showed that improper installation of these deep injection wells in Miami-Dade led to the migration of injected fluids into the surficial aquifer system. Proper design and installation of deep injection wells is critical for protection against upward leakage and contamination of potable and coastal-water resources. Movement of these sources of contaminants to the coastal-shelf environment via groundwater transport through vertical fault systems may equal surface runoff, but research to address this issue has been insufficient (McNeill, 2000).

Offshore areas of Broward County have experienced changes in benthic biota that are most likely the result of an increase in anthropogenic-nutrient influx (eutrophication) (Moyer and others, 2003; Lapointe and others, 2005). Eutrophication of nearshore marine waters has been linked to degradation of benthic communities, harmful algal blooms (HABS), and human health risks (Bokuniewicz, 1980; Hallock & Schlager, 1986; Valiela and D’Elia, 1990; Griffin and others, 1999; Lipp and others, 2001; Lapointe and others, 1990; Lapointe and others, 2004; Paul and others, 1997). Pristine meadows of scleractinian (*Acropora cervicornis*, *Montastrea cavernosa*) and alcyonacian (*Eunicea* spp. and *Erythropodium caribaeorum*) corals and other subtropical hardbottom communities have recently been stressed and out competed by blankets of macroalga (*Codium* and *Dictyota* spp., Moyer and others, 2003; Lapointe and others, 2005). Offshore algal-bloom events have raised concerns over the mechanisms that cause their occurrence in these reef communities (Figure 2). The hydrogeologic control of groundwater flow to the coastal zone along southeast Florida is not well understood. Kohout (1964; 1966) and Kohout and Kolpinski (1967) described the seepage face along the coastal zone and its role in benthic-biota diversity in Biscayne Bay (Figure 3) and recount anecdotal information from the early 1900s about the occurrence of offshore freshwater springs. Dausman and Langevin (2005) provide results from field data and a groundwater-flow model showing that the dynamic freshwater/seawater interface is located ~5 km inshore of Port Everglades and ~2.5 km inshore of Hillsboro Inlet (Figure 2). These data indicate that the hydraulic gradient is not great enough to allow SGD to occur any significant distance from the coast. However, Finkl and Krupa (2003) and Finkl and Charlier (2003) have hypothesized that permeable beds within the Biscayne Aquifer are capable of transporting nutrient-laden ground water offshore, thus allowing seepage into the overlying water column along the middle reef.

The data reported here are the results of Phase I of the four-phase strategic plan. A four-phase strategic plan was proposed by the USGS, titled: “Framework geology and effects of groundwater seepage on benthic ecology in coastal-marine shelf environments: Broward County, Florida.” Phase I involved geophysical and geochemical surveys to identify potential zones of increased SGD. The results of the geophysical and geochemical surveys are included as Appendices and are described, interpreted, and evaluated in the body of the report. Based on results of Phase I, Phase II work would entail core drilling and installation of permanent monitoring wells along transects where enhanced SGD was detected. Phases III and IV would involve sampling water from the monitoring wells and surface waters to assess parameters such as nutrients, trace elements, microbiological indicators, and various isotopes for age dating and source tracking.

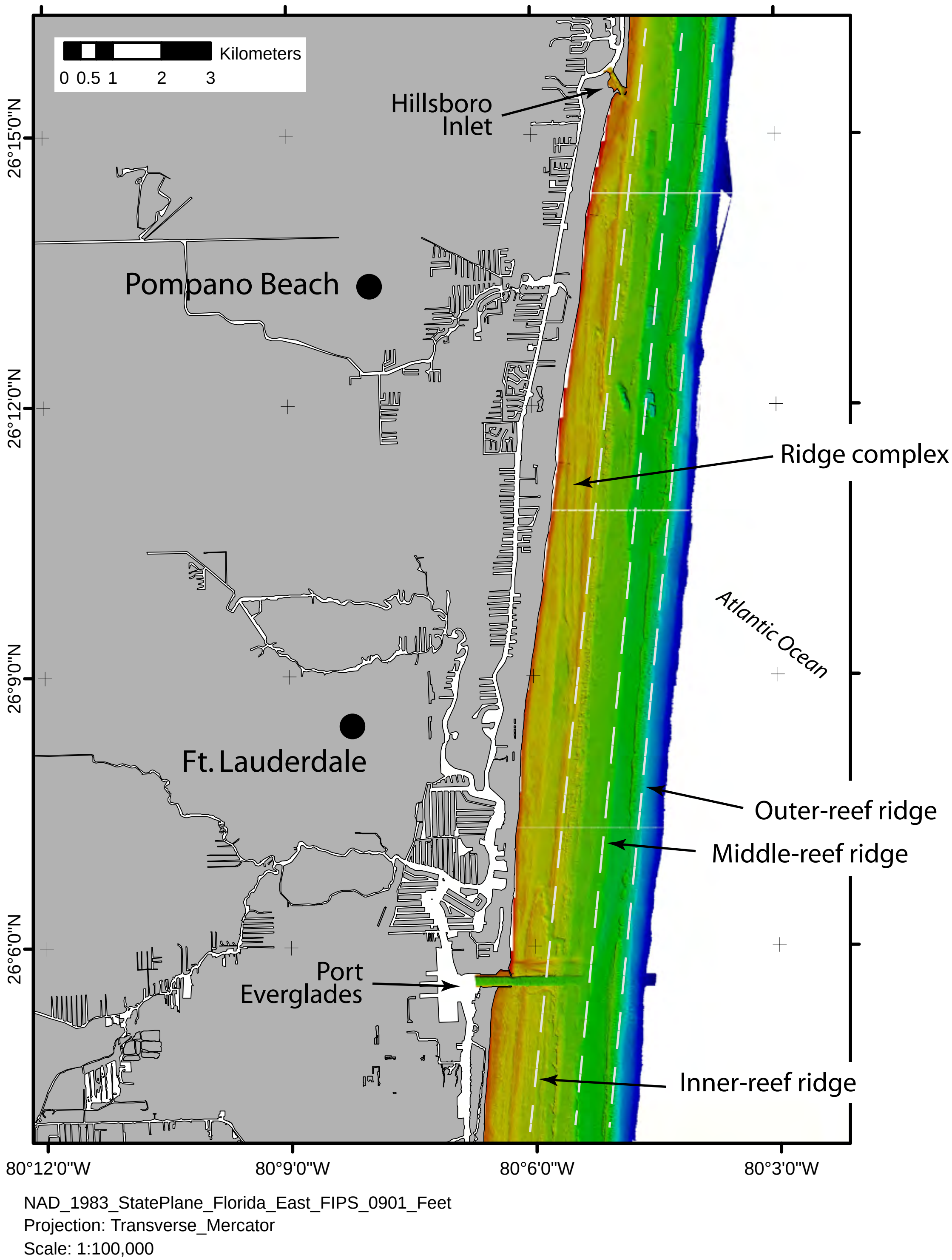

Figure 2. Study area with location of offshore reef features. Reef ridges occur along the dashed lines that are placed over the high-resolution laser depth surveys (LADS) dataset.

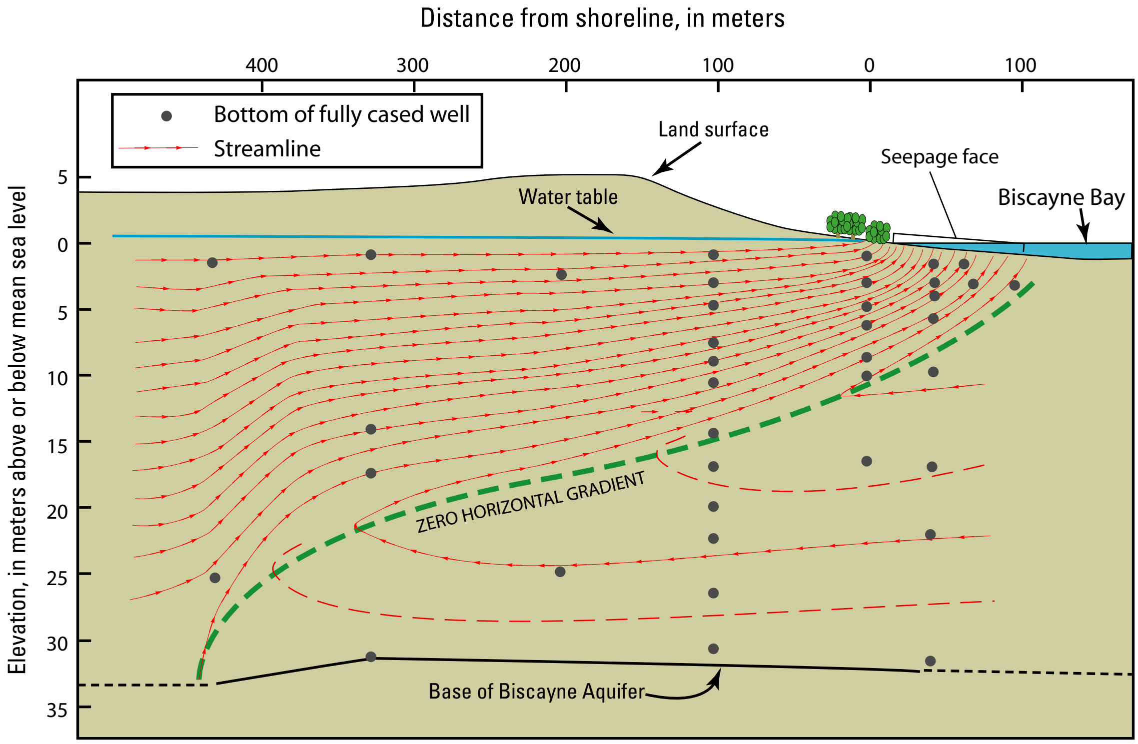

Figure 3. Cross-section of a typical freshwater/seawater interface in south Florida. Freshwater from the Biscayne aquifer flows toward the coast under a hydraulic gradient and discharges along the coast at the same time saline (marine) water encroaches on the aquifer at depth. Modified from Kohout (1964).

Purpose and Scope

The purpose of this report is to provide initial indications of potential zones of increased SGD using geophysical and geochemical surveys conducted from offshore Broward County extending from Port Everglades northward to Hillsboro Inlet. The co-utilization of seismic, CRP, and radon allows for enhanced characterization of hydrogeologic processes. Increased permeability/porosity in the underlying limestone bedrock would increase hydraulic exchange of ground and surface waters either through tidal pumping or onshore-offshore hydraulic gradients. Increased porosity/permeability in the limestone can be detected in both seismic and CRP, and where there is localized SGD, radon will invariably detect and capture an increase in ^{222}Rn activity.

Approach

The region between Port Everglades and Hillsboro Inlet and from just off the beach to 1.5 km offshore was surveyed using five techniques.

1. High-resolution (CHIRP and boomer) seismic profiles recorded sub-bottom geologic horizons to depths of 40 mbsl (meters below sea level).

2. Continuous resistivity profiling (CRP) with streaming dipole-dipole electrical resistivity acquired sub-bottom bulk-resistivity measurements to depths of 25 mbsl.

3. Continuous ^{222}Rn surveys of surface waters were conducted to map zones of enhanced groundwater discharge.

4. ^{224}Ra/^{223}Ra isotope ratios were obtained for potential identification of recently advected groundwater.

5. Stationary radon time-series equipment was set up at the seawall of NOVA Southeastern University National Coral Reef Institute to measure rates of groundwater discharge.

Description of Study Area

Broward County is located in southeast Florida and includes the metropolitan cities of Hollywood, Fort Lauderdale, and Pompano Beach (Figures 1 & 2). Eastern Broward County has ~40 km of coastline that supports various watersport activities, such as SCUBA diving, boating, and fishing. Port Everglades is home to the third busiest cruise port in the world (*http://www.broward.org*). The marine shelf off Broward County, Florida, is the narrowest in Florida at less than 3-4 km wide and supports a unique coral reef ecosystem accessible from the beach (Banks and others, 2007). The area west of the population centers is predominately uninhabited and contains a hydrological regime of freshwater marshes, tree islands, and sawgrass prairies within the Florida Everglades system (*http://www.evergladesplan.org*). Central and western Broward County are under the jurisdiction of the South Florida Water Management District (SFWMD) and have been partitioned into Water Conservation Areas (WCA) by a system of levees and canals (Figure 4). SFWMD has broken the WCA into three units, of which WCA 2 and WCA 3 partially or wholly fall within Broward County. These conservation areas allow regulation of groundwater levels and provide flood protection for coastal residents (Beaven, 1979). Portions of the surficial watershed ultimately drain east through a series of canals into the Atlantic Ocean, via the Hillsboro and Port Everglades inlets (Figure 2) and south through the Everglades (Figure 4).

Population

The current population density in Broward County is approximately 520 individuals per km^2. The total population has grown over the last 45 years from 333,946 in 1960 to ~1.7 million in 2005 and is projected to increase to ~2.3 million by 2030 (*http://www.censusscope.org*; *http://www.broward.org*). Conversely, Broward County population-modeling projections predict that the annual growth rate will continue to drop from ~3% in 2000 to less than 1% in 2030. Broward County is the second most populated county in the southeast—ahead of Palm Beach County (1.3 M) and behind Miami-Dade County (2.2 M). Combined, 3.8 M people live in the three counties (Renken and others, 2005).

Geologic Setting

Three shore-parallel reef ridges occur on the narrow, shallow shelf off Broward County (Figure 2). Each ridge (referred to as inner, middle, and outer) extends from Palm Beach County in the north to Miami-Dade County in the south. Further south, the ridges are believed to merge with the Florida Keys coral reef tract (Banks and others, 2007; Toscano and Macintyre, 2003), though adequate studies needed to confirm this idea have not been conducted. A ridge complex (Figure 2) also exists between the shore and the inner reef that is composed of a mixture of Pleistocene coquina (Anastasia Formation) and Holocene deposits (Lighty and others, 1978; Banks and others, 2007). The ridge complex is not continuous and is expressed at the surface from approximately Hillsboro Inlet southward to northern Miami-Dade County (Banks and others, 2007). The geomorphology of these ridges, based on core samples and high-resolution bathymetry laser depth surveys (LADS), indicates that they developed as paleo-beach and dune structures that provided a substrate for coral recruitment. Coastal dunes containing plant roots and land snails are known to underlie the first reef line (inner-reef ridge) offshore from north Miami-Dade County (Perkins, 1977; Shinn and others, 1977). Similar drowned beach ridges and dune features with coral caps have been described in 70 to 100 m of water at Pulley Ridge north of the Dry Tortugas (Jarrett and others, 2005).

The middle- and outer-reef ridges at 10-m and 15-m water depths, respectively, are composed of Holocene corals (Lighty and others, 1978). Similar framework was found in the inner reef (~8-m water depth) after ship groundings exposed massive head corals (Banks and others, 1998). The Holocene middle reef off Broward County is approximately 3.2 m thick (Banks and others, 2007). Similar observations were made farther south in a trench that was cut through the middle reef off Key Biscayne for a sewer-pipe outfall, where approximately 2.5 m of Holocene coral buildup overlie quartz sand (Shinn and others, 1977). Using ^{14}C, Lighty (1977) dated *Acropora palmata* from the Hillsboro sewer trench that cut through the outermost reef in Broward County and showed that the reef accumulated between 9 and 7 ka. This former fringing reef was drowned by a rapidly rising sea during the early Holocene (Lighty and others, 1978). The depth of the Hillsboro sewer trench did not reach the base of the reef cap, but a similar outer reef, seaward of Fowey Reef, was core-drilled to its base (Shinn and others, 1991). These reefs are known as outlier reefs in the Florida Keys (Lidz and others, 1991). These observations support the concept that linear beach dunes provided antecedent topography for reef initiation during rising Holocene sea level, both off Broward County and likely farther south off the Florida Keys (Lidz and others, 1991).

The geologic framework onshore is an extension of lithologies found in the offshore environment and has been thoroughly described by Parker and others (1955), Enos and Perkins (1977), Causaras (1984), Fish (1987), Esteves and Finkl (1999), and Multer and others (2002). The Anastasia Formation and Pamlico Sand (Pleistocene) units are the backbone of the coastal ridge in Broward County, upon which the Fort Thompson and Miami Limestone (Pleistocene) interfingers (Parker and others, 1955; Causaras, 1984; Causaras, 1986; Fish, 1987; Esteves and Finkl, 1999).

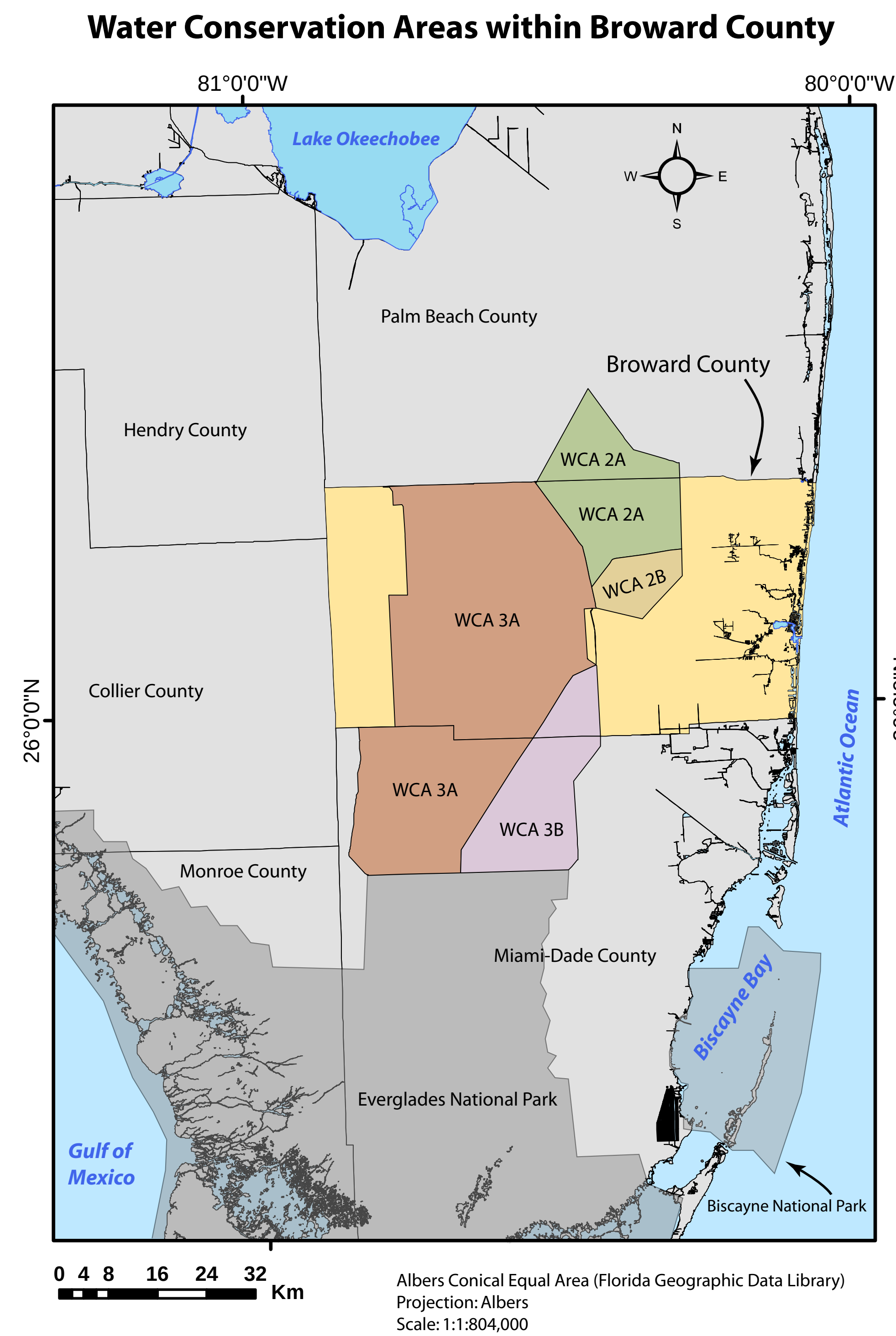

Figure 4. Hydrography map of Broward County and surrounding areas. Division of Water Conservation Area (WCA) lands and the Everglades are shown to depict the extent to which the watershed is subdivided in order to control surface-water elevations and flows to the surrounding areas.

Hydrogeology

The Biscayne aquifer (Figure 5), the sole source for drinking water in south Florida (Parker and others, 1955; Fish, 1987; Renken and others, 2005), courses through limestones of the Ft. Thompson and Anastasia Formations. The Biscayne aquifer is one of the world's most productive aquifers, with localized transmissivity values of >27,000 m^2/d (Parker and others, 1955; Fish, 1987; Fish and Stewart, 1990). Average transmissivity for Broward County is 12,000 m^2/d (Fish, 1987; Dausman and Langevin, 2005). The base of the Biscayne aquifer is deepest at ~70 m below sea level, along the coastline of Broward County (Fish, 1987; Causaras, 1984; Causaras, 1986). The aquifer pinches out to the west and thins to the south and southwest. Beneath the Biscayne aquifer, thick sequences of impermeable sandstones and limestones of the Hawthorn Group (Tamiami Formation) separate water in the deeper, confined Upper Floridan aquifer from the unconfined Biscayne aquifer (Beaven, 1979; Causaras, 1984; Causaras, 1986; Fish, 1987). This confinement is crucial to prevent contamination of the Biscayne aquifer because the Upper Floridan aquifer contains water high in chlorides (1,000 to 3,000 mg/L; Reese and Alvarez-Zarikian, 2006).

The Biscayne aquifer is susceptible to saltwater intrusion due to several stresses: development of the drainage canal system in the early 1900s that lowered water-table elevation; withdrawal of water for drinking and industrial uses; and increased evaporation or decreased precipitation (Dausman and Langevin, 2005; Renken and others, 2005). As a result of a higher water table in the northeastern quadrant of Broward County, the freshwater/seawater interface there is located closer to the coastline than it is in central and southeastern Broward County (Figure 6).

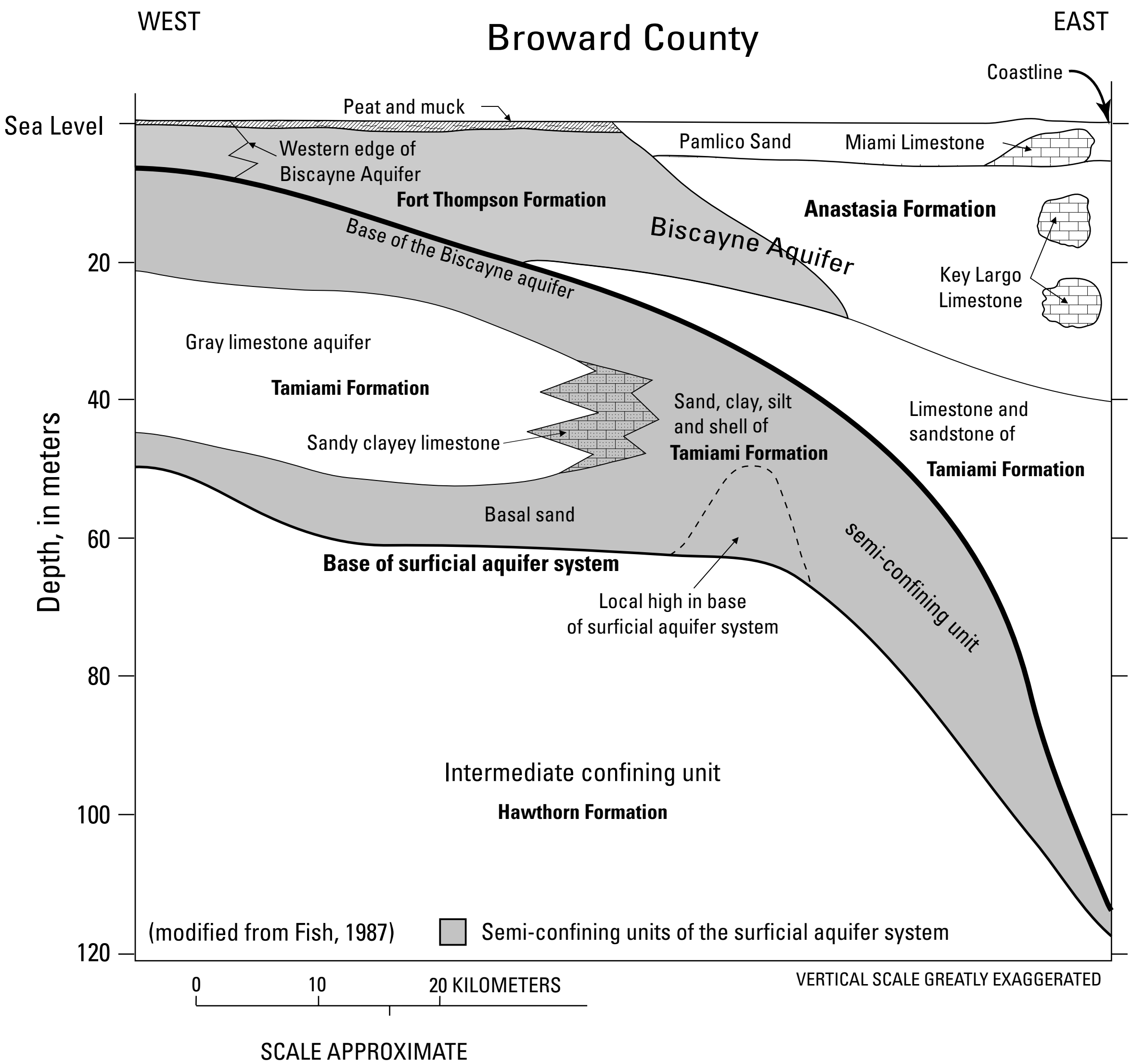

Figure 5. Generalized section showing lithostratigraphy and aquifers in Broward County. Shaded portions of the cross-section represent semi-confining units within the Biscayne aquifer. Modified from Fish (1987).

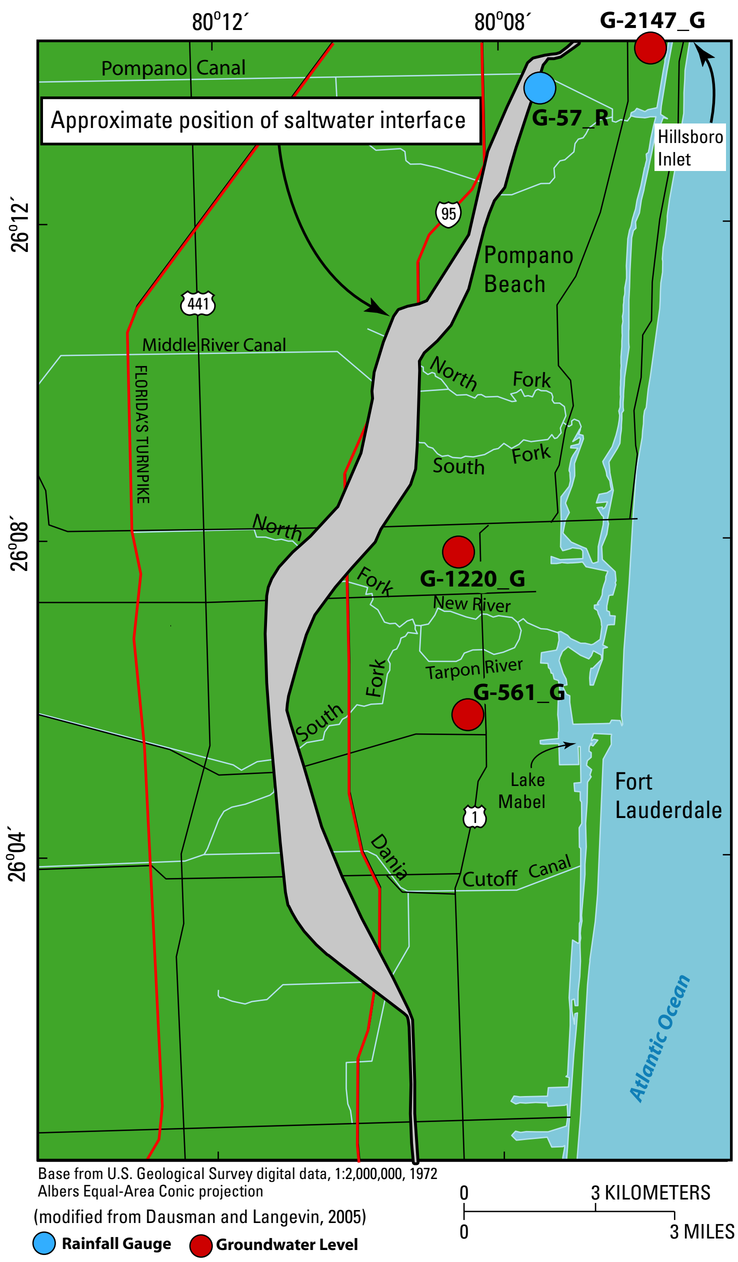

Figure 6. Map of eastern Broward County shows approximate location of the freshwater/seawater interface for the study area. Rainfall-gauge and groundwater-well locations, depicted by blue and red dots, respectively, identify sites of data in Figure 7. Modified from Dausman and Langevin, 2005.

Precipitation

Broward County is situated in a subtropical environment at the southeastern tip of the Florida peninsula. The rainy season begins in May and runs through October, during which time the area receives approximately 70-80% of the annual precipitation (McPherson and Halley, 1996). Average annual precipitation for Broward County is 163 cm (64 inches), of which less than 30% is available for aquifer recharge. During 2006, the year this study took place, the annual cumulative precipitation was 102 cm (40 in) (SFWMD site G57_R, Pompano Beach; Figure 7). This quantity is below the normal yearly average precipitation for the area and undoubtedly had an impact on recharge of the Biscayne aquifer and on the movement of ground water to the coast. Even during years with 'normal' precipitation, high evapotranspiration (ET) rates drive moisture back into the atmosphere (German, 2000). On average, ET can equate to 114 cm (45 in) of water loss to the atmosphere each year (German, 2000).

Methods of Investigation

Radon

Time-series ^{222}Rn measurement in the surface water is one geochemical tool that has been proven effective in identifying and quantifying groundwater discharge along coastal environments (Corbett and others, 2000; Burnett and Dulaiova, 2006; Swarzenski and others, 2004; Swarzenski

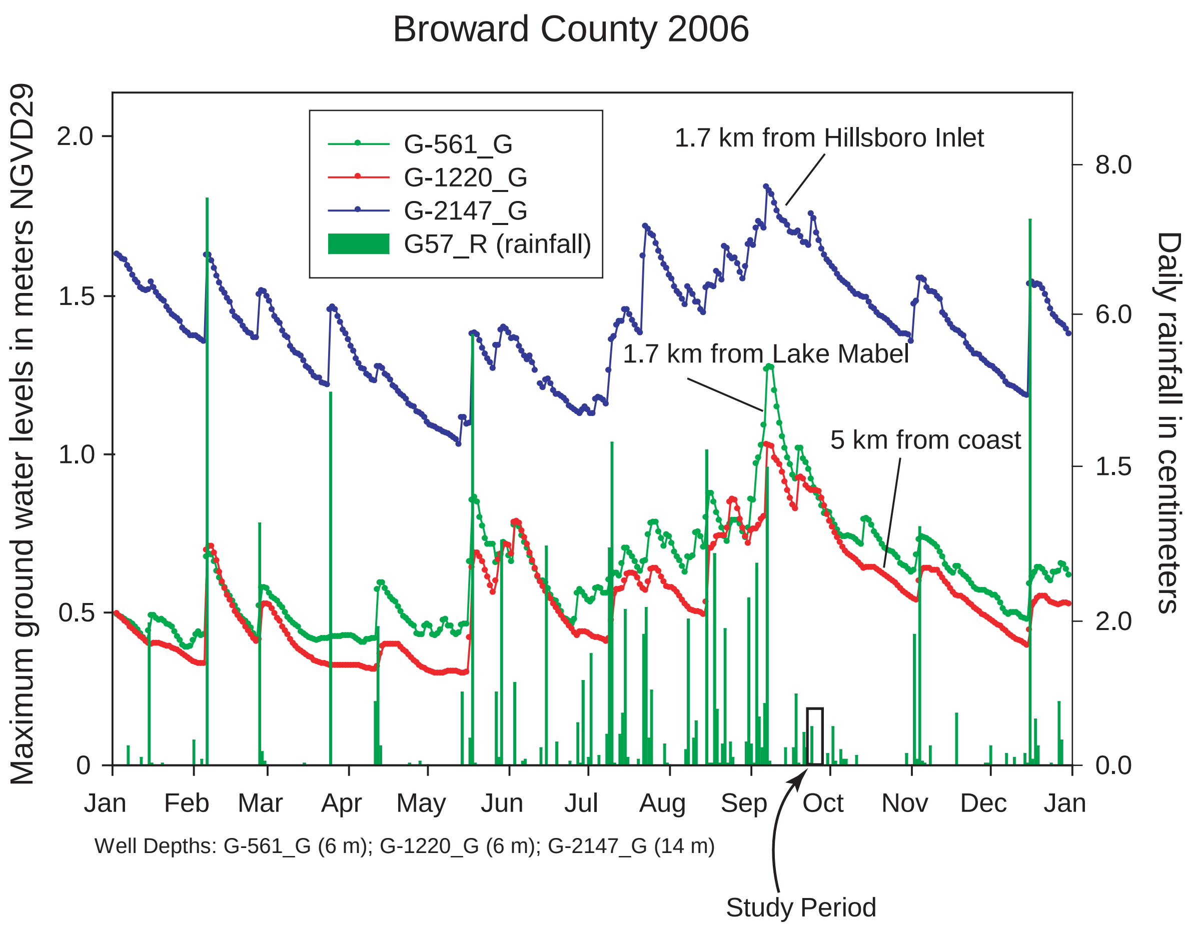

Figure 7. Plot depicts rainfall (G57_R) and variability in water levels between north and south extents of the study area. The northern well (G-2147_G) has higher groundwater levels than the southern wells (G-561_G and G-1220_G).

and others, 2007b). A ^{222}Rn time-series site was established on the Lake Mabel side of the NSU/NCRI facility (Figure 8). A single, commercially available radon monitor (RAD7: Durridge Inc., Co.) was set up in a waterproof box and was programmed to collect surface-water radon data at 30-minute intervals. A 12VDC-powered pump, placed on the seafloor near the seawall, ran continuously over the 3-day field study. The pump circulated water at a rate of 1.5 to 2 L/min into a water-air exchanger. The water flowed out of the exchanger and back into the surface water. The RAD7 is connected to the top of the water/air exchanger through small-diameter tubing. Its internal air pump sucks air out of the water/air exchanger, through a humidity-controlling unit, and into the solid-state alpha detector whereby radioactive particles decay and are counted. The air is returned to the water/air exchanger. Since the system is a closed loop, the in-growth (buildup) of radon within the exchanger usually takes about 30 minutes. In addition to measuring surface-water radon, a second RAD7 monitor was set up to measure background air radon. These values were used in the calculation of radon in water concentrations.

In addition to the RAD7 monitor at the time-series site, a YSI 650QS multi-probe unit measuring temperature, salinity, dissolved oxygen, ph/oxygen-reduction potential, and pressure and a Solinst measuring water level, temperature, and specific conductance (LTC) were placed on the seafloor near the pump intake. A Solinst barologger measuring barometric pressure was installed on the outside of the waterproof box housing the RAD7 monitor. The barologger data were used to correct water-level information collected by the LTC unit.

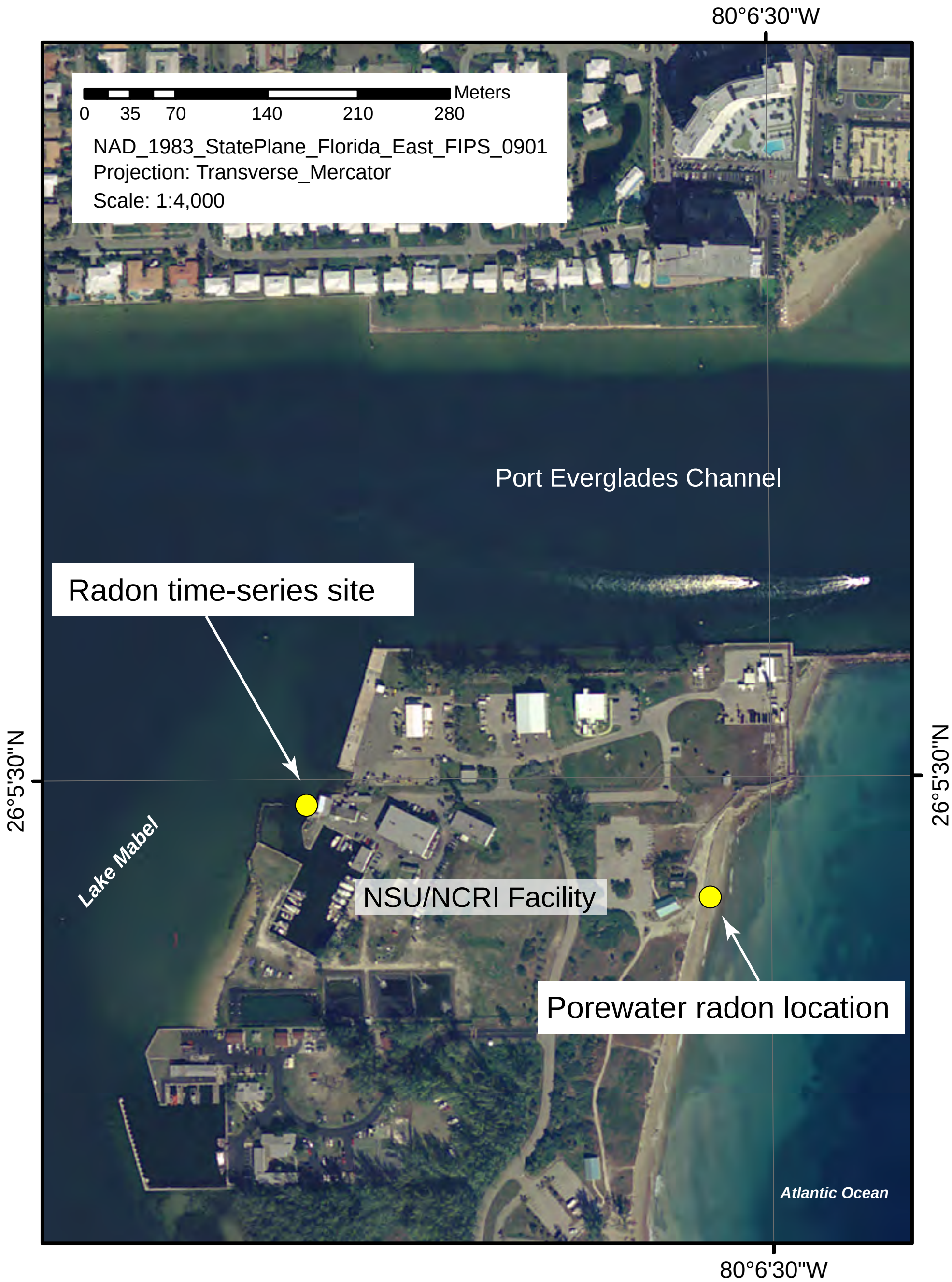

Figure 8. Aerial photo shows the National Coral Reef Institute (NCRI) facility and locations of the time-series radon experiment and porewater sampling near the Port Everglades channel.

Continuous Resistivity Profiles

Continuous resistivity profiling (CRP) is a geophysical method used to map subsurface features that differ in electrical resistance (i.e., resistivity). Resistivity can vary widely in natural systems and can be influenced by a multitude of physical parameters such as temperature, specific conductivity (salinity) of pore fluids, lithology, and porosity. CRP measures bulk resistivity that can lead to ambiguities in interpreting the data. Only through field investigations (ground-truthing) can a correct interpretation be resolved. *A priori* knowledge of the geology and hydrology of an area and calibration by towing the CRP streamer over established underwater monitoring wells are beneficial in interpreting resistivity profiles.

For this study, a Supersting R8/IP unit (Advanced Geosciences, Inc.) and a 100-m-long cable with a 10-m electrode spacing were used to collect an electrical-resistivity image to a depth of approximately 25 m. The Supersting R8/IP injects a current of up to 2 amps and power of 200 watts. The unit is self-contained and can be run either off one 12V battery (100W) or two 12V batteries (200W). In CRP mode, the Supersting unit can simultaneously measure eight channels while injecting a current at a rate of 1 to 3 seconds.

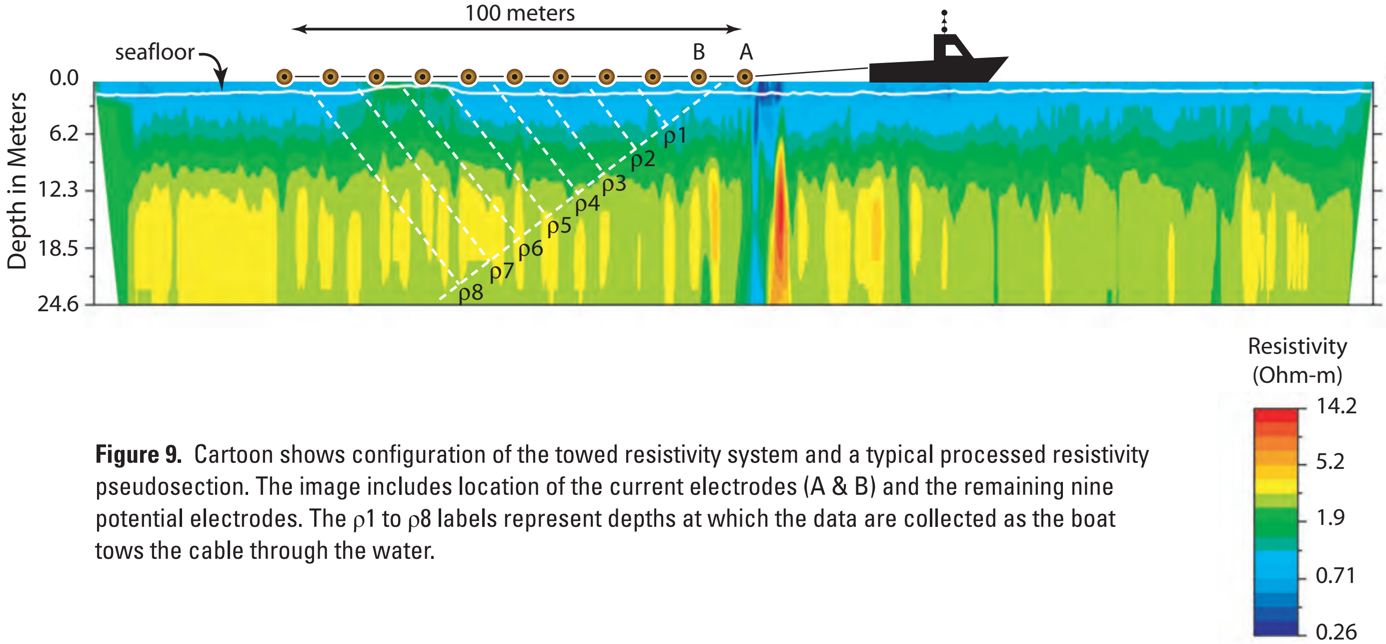

Figure 9. Cartoon shows configuration of the towed resistivity system and a typical processed resistivity pseudosection. The image includes location of the current electrodes (A & B) and the remaining nine potential electrodes. The ρ1 to ρ8 labels represent depths at which the data are collected as the boat tows the cable through the water.

The Supersting can store more than 79,000 measurements in volatile memory, which allows about 16 continuous hours of CRP data collection. The 11-electrode cable was set up in a streaming dipole-dipole array (Figure 9). The first two electrodes produced the current (current electrodes) and the remaining nine measured the resulting voltage potential (potential electrodes). The boat towed the cable, suspended by pool floats, along the surface of the water and an apparent resistivity profile with eight simultaneous measurement points, each at a different apparent depth (0 to 25 m), was constructed. A profile from the sea surface to ~25 m was collected; therefore, the 110-m-long cable typically used in shallow (<10 m) water was used to image the subsurface. Towing the cable at a speed of about 5 km per hour (kph) can yield about 40-50 line-kilometers per day.

Processing CRP data was accomplished by using AGI Earth Imager 2D software (Advanced Geosciences, Inc.). Earth Imager 2D uses a finite-element forward-modeling method with the smooth-model L2-normalized inversion and an average apparent-resistivity starting model. The program does not use reciprocal errors in CRP mode due to the fact that the electrodes cannot be stacked or reversed rapidly enough before they have moved while being towed. CRP-saltwater program default parameters were used for all inversions. Minimum and maximum resistivity values were set at 0.1 and 1000 ohm-m, respectively. Since file size and number of shot points can be quite large in continuous mode, EarthImager 2D uses a divide-and-conquer strategy to break the long lines into manageable, overlapping shorter segments and then processes each shorter segment individually. The final step in the processing stitches the short segments together to form the pseudosection. Additional information such as surface-water resistivity can be input into the inversion process to fix the water column. Although we collected surface-water conductivity (resistivity^{-1}) and temperature, we did not fix the surface-water column in the CRP profiles (Appendix A). Day-Lewis and others (2006) have shown that entering an incorrect surface-water resistivity can lead to large errors in interpreted resistivity profiles. The goodness of fit of the model was determined by the lowest model root means-squared error (RMS%). The lowest RMS% was achieved by allowing the water column to be processed during the inversion process.

Seismic

This study utilized two different seismic instruments: CHIRP and boomer. The CHIRP (Compressed High-Intensity Radar Pulse) system produces a signal of continuously varying frequency that creates a high-resolution (<8 cm) but fairly shallow penetrating (<20 m), sub-bottom profile. We used an EdgeTech SB-424 sub-bottom profiler with a sample frequency range of 4 to 24 kHz, shot rate of 0.250 s, and record length of ~50 ms (Flocks and others, 2001; Kindinger and others, 1997). Shot spacing was approximately 0.193 - 0.257 m at boat speeds of ~5 kph. The towfish is a combination sound source and receiver and was towed approximately 1-2 m beneath the boat. The acoustic energy produced by the CHIRP and boomer systems reflects at density boundaries such as the seafloor and other lithologic boundaries beneath the seafloor. The reflected energy is detected by a receiver and recorded on a PC-based seismic-acquisition system. Data were geo-referenced by streaming time and position from a WAAS DGPS Furuno GP1650DF navigational receiver to a laptop computer running HyperTerminal.

The single-channel boomer system used was a C-System LVB sled and Benthos 1210 10-channel hydrophone streamer (Flocks and others, 2001). Unlike the CHIRP system, the boomer sled and streamer are towed on the surface. The boomer creates a shot of acoustic energy (104 Joules per shot and sampling rate of 24 kHz) by charging capacitors to a high voltage and discharging through a transducer (boomer plate) in the water. Reflected energy was received by a Benthos 1210 hydrophone streamer and recorded by Delph Seismic FSSB acquisition software. The streamer contains 10 hydrophones evenly spaced every 0.5 m. The streamer was positioned approximately 9 m behind the research vessel and laterally separated from the boomer sled by about 4 m. The 4-m-separation is depicted in the seismic profiles as the first arrival signal and labeled as the "1st return" in Appendix B.

The unprocessed seismic data were stored in SEG-Y (Society of Exploration Geophysicists) format (Barry and others, 1975). All seismic data collected for this work, including metadata, unprocessed data, maps, and filtered and gained (a relative increase in signal amplitude has been applied) digital images of the seismic profiles, can be found in Harrison and others (2007).

Results and Discussion

Geochemical Data

Radon-222 was collected in offshore surveys, simultaneous with geophysical data collection, and at a fixed site located on the seawall of the National Coral Reef Institute near the Port Everglades Channel. Radon-222 is used to identify zones of enhanced SGD and to quantify groundwater discharge to coastal waters. This section only discusses the time-series ^{222}Rn, because offshore ^{222}Rn data were unusable due to instrument problems.

Time-Series Radon

Results from the ^{222}Rn time-series measurements show a very strong tidally modulated signal. This is seen in other field studies (Swarzenski and others, 2007a) where tides control the bi-directional flow of ground water into and out of a coastal aquifer (also called tidal pumping), and this field site is no exception. Rn-222 activity is greatest during low tide when hydraulic gradients between the water table and sea level are steepest, resulting in a slow yield from aquifer storage (Figure 10). The yield is represented by an average lag of ~2 hours between low tide and peak radon concentration. Radon decreases after peak high tide when surface water recharges the pores of the coastal aquifer, resulting in a 2-hour lag behind peak high tide and low radon activity. The variability in tidal range over 3 days influences groundwater discharge represented by the radon activity observed in surface water. Radon activities were greatest following the lower low tide and ranged from 11.2 dpm/L (9/26/06 06:51) to 12.0 dpm/L (9/27/06 07:51), compared to the mid-low tides, where radon activity ranged from 8.1 dpm/L (9/26/06 19:51) to 6.8 dpm/L (9/27/06 21:21) (Figure 10). A scatter plot of tide level versus ^{222}Rn activity shows a negative correlation such that as tide floods, the radon activity decreases. This reaction can also be seen in the time-series plot of radon and tide, whereby higher water levels either during low tide or high tide respond by having lower radon activities.

In addition to increased ^{222}Rn during low tide, a strong freshening of the surface waters occured (Figure 11), signifying that there is groundwater discharge of lower specific-conductance (i.e., salinity) waters from land. The specific conductance decreased from a high of 50.7 milliSiemens/centimeter (mS/cm) during a high tide to about 36.4 mS/cm during low tide. No major rivers discharge into the Lake Mabel (Port Everglades) basin to cause fluctuations in surface-water specific conductance. The fluctuation in specific conductance observed at the time-series site therefore must be a result of groundwater discharge of brackish water during low tide.

Radium

Because of their intrinsic geochemical properties, the two short-lived radium (^{223}Ra 11.3 d half-life and ^{224}Ra 3.66 d half-life) isotopes are useful tracers of the saline component of submarine groundwater discharge. Their isotopic ratio (^{223}Ra/^{224}Ra) should reflect the same source (ground water) and a variable decay rate that can provide some measure of distance traveled or time elapsed (^{224}Ra decays at a faster rate relative to ^{223}Ra).

A known volume of MnO_2-impregnated fiber was towed behind the survey boat northward along the coastline for a known distance/time (Figure 12), and subsequently processed and counted using RADDEC detectors. Although an activity per volume could not be determined using this technique, isotope ratios were obtained at the start and for four segments along the coast. In the four segments, the ^{223}Ra/^{224}Ra isotope ratio varied from 5.0 to 13. Typically, the larger the isotope ratio, the 'older' the water mass is (i.e., longer time since advected across the sediment/water interface).

Geophysical Data

Geophysical surveys were conducted from just south of the Port Everglades channel to Hillsboro Inlet. CRP and CHIRP lines were run simultaneously at a position closest to shore and on either side of the inner reef ridge. The resistivity results provide information regarding salinity, lithology, and porosity in the subsurface. High-resolution seismic profiling using the Boomer system were run shore-normal (perpendicular) and parallel to the coast from nearshore out to the middle reef ridge. The Boomer surveys provided information on subsurface geologic structures. The surveys were conducted shoreward of the middle-reef ridge because Finkl

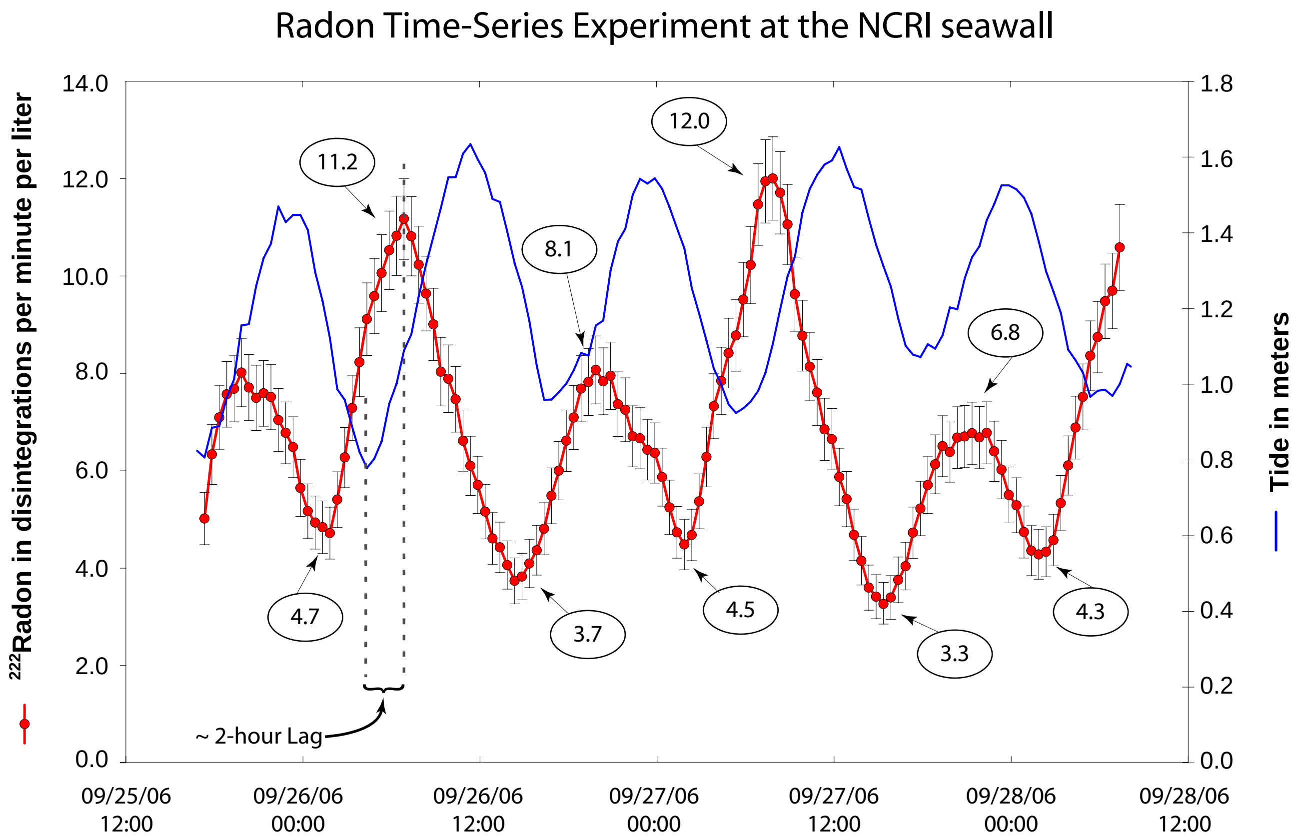

Figure 10. Plot of the time-series radon experiment along the NCRI seawall shows a normal tidal cycle (blue line) and varying ^{222}Rn activities (red line) corresponding to high or low tide. Values in circles represent max and min 222Rn activities at each tidal stage. Note that peak radon occurs ~ 2 hours after low tide.

and Charlier (2003) suggested that ground water is transported through a permeable unit that crops out between the inner- and middle-reef ridges. The geophysical survey tracklines were designed, as presented in this report, to focus on the inner- and middle-reef ridges where suggested freshwater is discharging. The seismic (Boomer) survey tracklines were run different than the CRP and CHIRP tracklines in order to image structural changes in ridge framework and to collect data to test the idea of permeable zones by Finkl and Charlier (2003).

Continuous Resistivity Profiling

Interpreting results from the CRP surveys requires knowledge of the geologic and hydrologic setting. Information regarding subsurface geology is generally limited at this study site. The occurrence of Pamlico Sand, localized oolitic facies of the Miami Limestone, and the Anastasia, Key Largo and Fort Thompson Formations are known from previous studies by Fish (1987), Causaras (1984, 1986), and Esteves and Finkl (1999). Banks and others (2007) core-drilled the inner reef and recovered ~3 m of Holocene (*Acropora palmata*) limestone unconformably overlying Anastasia rocks (*Diploria sp.*). Banks and others (2007) also collected sediment cores from the sand channels between the middle and outer reef ridges that showed up to 8 m of sand and reef rubble that have collected in the trough between the two ridges during the Holocene. This information can assist in the interpretation of the CRP as well as seismic data.

Approximately 60 km of CRP data were collected September 25-26, 2006. The CRP inversion-model profiles (Appendix A) have the same log-linear scale (0.10 to 20 ohm-m). CRP figures in Appendix A show the location of the inverted-resistivity section, a brief summary, and some typical resistivities for various water salinities and lithologies. The inverted-resistivity sections presented here represent bulk resistivities that can constitute a porewater salinity, porosity, or lithology change. If information on any of these parameters is known, a formation factor can be used to calculate true water salinity (Archie, 1942).

Interpretation of the CRP data shows subtle variability between the nearshore and offshore transects. It is unfortunate that the sea became rougher in the afternoon of the second day, resulting in numerous errors and unusable data; hence, CRP data, shown in this report, end at line 13 although the trackline

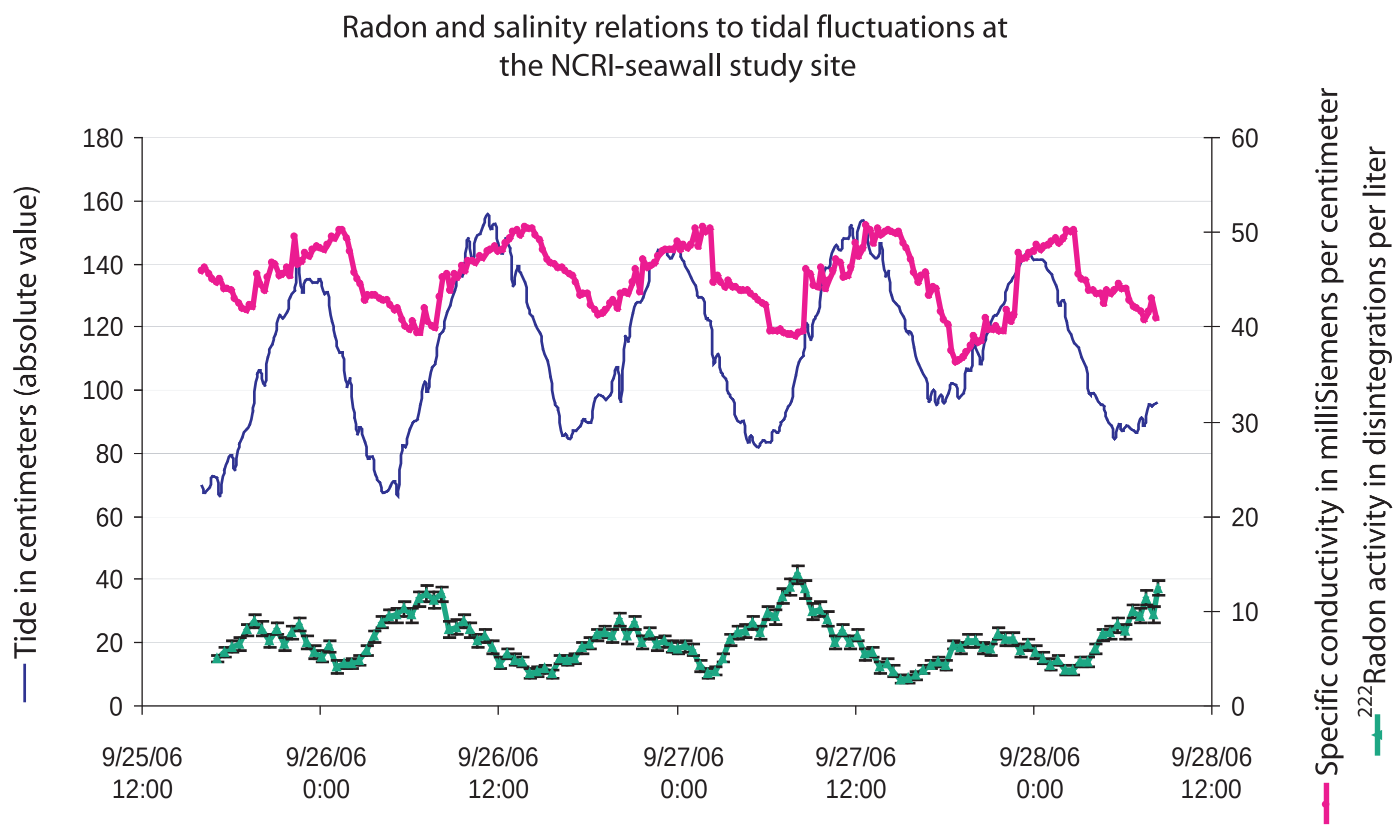

Figure 11. Time-series plot showing ^{222}Rn activities and specific conductivity in the nearshore surface water. Specific conductivity decreases and 222Rn increases during low tide, indicating presence of brackish-groundwater discharge from land. Peak ^{222}Rn and low specific conductivity occur ~2 hours after low tide.

continued north toward Hillsboro Inlet (Appendix A). All CRP lines presented in this paper were collected from the shore to the inner-reef ridge (~1 km). CRP line 4 shows a general trend of increasing resistivity in the subsurface from the middle-reef ridge to onshore. Localized resistivity values of ~5 ohm-m beneath the inner-reef ridge and shore may indicate a decrease in porosity or freshening of pore water. The other nine CRP lines shown in this report were run parallel to the coast between the shore and the inner-reef ridge and had very similar ranges in resistivity with values that ranged from 1 to 5 ohm-m. Despite a similar range in values between onshore and offshore, there appears to be a subtle trend in the occurrence of the higher resistivity values. There is a greater distribution of the 4 to 5 ohm-m resistivities (light-blue tones) in the nearshore profiles and a greater distribution of 1-2 ohm-m resistivities (light-green tones) in the offshore CRP profiles.

Care must be taken to differentiate between acquisition artifacts and subsurface features; for example, CRP line 5 shows two low-resistivity ‘bodies’ dipping into the subsurface (located at ~400 m and 1100 m). These low-resistivity ‘bodies’ look like seawater-filled solution holes; however, inspection of the measured apparent (raw) data indicates that there was a shift in the injected current (Figure 13), thereby creating an artifact in the inversion process. These anomalies have to be scrutinized to ascertain their validity. Similar artifacts occur in lines 7, 8, and 9. However, there are instances where there is no shift in the raw data, and the data may be indicative of real features, such as in lines 9 (~1600 m and 4000 m), 10 (~850 m), and 11 (between 628 and 739 m). Unfortunately, the CHIRP data that were collected simultaneously do not indicate any evidence of sand-filled solution features corresponding to these shallow-subsurface conductive bodies.

High-Resolution Seismic Profiling

Boomer surveys extended from just south of the Port Everglades inlet north to Hillsboro Inlet. These surveys were conducted to obtain geologic framework information by running track lines that traversed in a zigzag pattern, crossing topographic features (reef ridges) as well as sand flats in the troughs between reef ridges. Boomer data penetrated up to 30 mbsf and captured sub-bottom geologic features

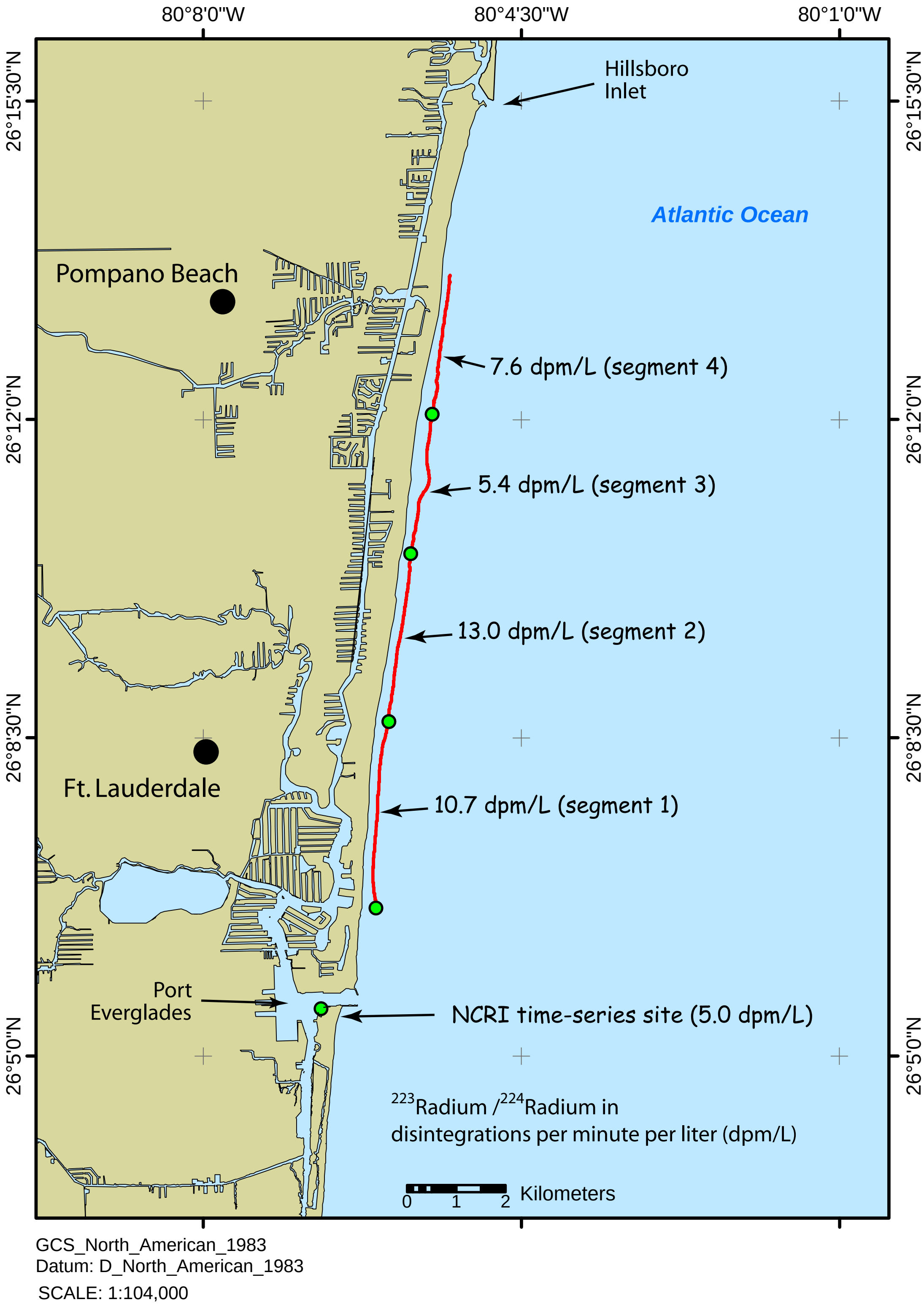

Figure 12. ^{223}Radium/^{224}Radium ratios along four segments of the shoreline show that variability occurs from south to north and that the $^{223/224}$Ra is low at the NCRI time-series site.

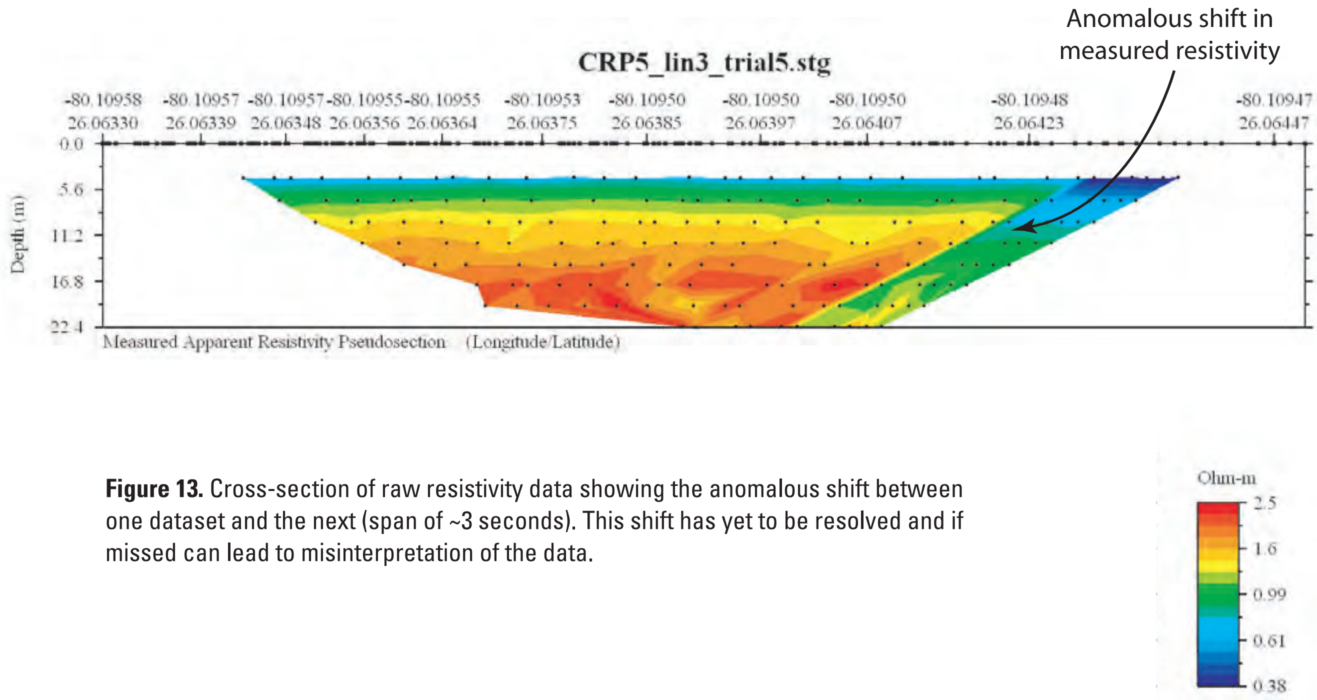

Figure 13. Cross-section of raw resistivity data showing the anomalous shift between one dataset and the next (span of ~3 seconds). This shift has yet to be resolved and if missed can lead to misinterpretation of the data.

(Appendix B). Due to time constraints, tie lines (crossing seismic profiles) were limited and therefore geologic-framework fence diagrams could not be constructed. Nonetheless, the seismic profiles depict a multitude of varying geologic structures. Some of the most notable geologic features are sediment-filled troughs (lines 19, 20), reef-crest topography and scarps (line 1, 2, 11, 13, 15), antecedent topography or buried reefs (lines 2, 19, 20), and karst features (lines 6, 7, 8, 10, 12, 14). Surface features such as wave-cut cliffs and scarps between the inner and middle reefs and spur-and-groove features along the outer reef, detailed in Banks and others (2007), are visible in the boomer data (line 20). Other features on the Boomer profiles, and common to most seismic surveys, are multiples of the seafloor (hereafter referred to as multiples). Multiples are an acoustic anomaly that are caused by the bouncing of the acoustical energy from the seafloor back to the sea surface multiple times. It is typically easy to discern multiples because they are spaced at a vertically uniform distance from each other: simply the distance from the sea surface to the seafloor.

Intermediate reef ridges, visible in the LADS data (Figure 2) as sporadically protruding structures from the seafloor between the middle and outer reefs, were detected in the boomer data (line 20). Line 20 shows a very well-defined buried reef that does not protrude from the sand-filled trough; however, an area between lines 19 and 20 shows that the intermediate reef protrudes from the seafloor and is visible as a topographic feature on the LADS dataset. Other boomer lines did not traverse the area except for line 19, which may show antecedent topography but is not as clearly defined as in line 20.

Paleo-karst features are of utmost interest in this study because they provide potential pathways for transporting ground water from onshore to offshore as well as increasing connectivity between ground water and surface water. Areas landward of the inner reef-and-ridge complex had the highest occurrence of hummocky buried topography. These are interpreted as karst surfaces. Boomer line 8 shows a structure that can be interpreted as either an incised (paleo-channel) or solution-collapse feature. The edges of the feature sag, but the reflectors remain in the horizontal position. This suggests that the feature was initiated by dissolution of the limestone and subsequent collapse. An irregular (hummocky) reflector to the south of the collapse feature may indicate karst enhancement. Closer to shore, along line 14, a reflection pattern occurs that does not resemble a collapse feature but rather is interpreted as a paleo-river channel. Banks and others (2007) described other surface-expressed paleo-river channels along the Broward County coastline that traverse the ridge complex, inner reef, and potentially the gaps in the outer reef.

CHIRP results show very little sub-bottom penetration and structural framework. At best, the data show a very detailed description of the seafloor topography. All illustrations in Appendix C include the CHIRP seismic profile, location map of the co-located profile, and scale. It is conceivable that the poor penetration was a result of towing the fish under the boat or that the characteristics of the siliciclastic/carbonate material did not allow for penetration at the high-frequency range of the instrument. Banks and others (2007) collected CHIRP (EdgeTech 512) data and obtained penetration showing Pleistocene/Holocene contacts where sand-filled troughs overlie Pleistocene bedrock.

Summary and Conclusions

Understanding the hydrogeology of a coastal system is a complicated process. Geologic framework is locally highly variable and can have a profound impact on the flow of ground water, either toward the coast or encroachment shoreward. The complex geology is further exacerbated by continued human alteration of drainage and groundwater systems. For this reason, creating hydrogeologic maps of a coastal system is crucial and can only be accomplished by utilizing multiple geophysical and geochemical techniques such as those presented in this paper. Regardless of some of the ambiguities that still remain, time-series radon data do indicate that ground water is discharging along the coast. The discharge of ground water (brackish salinity and high radon) at low tide is a positive indicator of SGD driven by tidal pumping. Unfortunately, offshore radon was not useful in determining regions of enhanced discharge. However, the fact that the saltwater interface is located 2-5 km inland and the hydraulic head is small (annual average <0.30 cm) along the coast indicates that if ground water is discharging to the coast, it is diffuse, with rates too low to be detected by our techniques.

High-resolution seismic profiles are important for interpreting the framework and potential pathways of groundwater flow but do not provide hydrogeologic information. Combining DC resistivity surveys with seismic data is a basis for constraining coastal hydrogeology. We show in this paper that subsurface features are heterogeneous, geologically and hydrogeologically. Subtle changes in subsurface direct-current resistivity from higher onshore to lower offshore indicate either a slight freshening of water nearshore or a change to geologic material with lower interstitial porosity. The next logistical step needed to ascertain these differences is to core-drill certain areas where we have CRP and seismic data along a transect from nearshore to offshore and examine the variability in lithostratigraphy and porewater salinity.

Ecological change is occurring along Broward County and the southeast Florida coast in general. These changes are most likely the result of eutrophication; but the source, whether SGD, deep-water upwelling events, atmospheric deposition, or overland discharge, remains uncertain. This study has provided evidence that the hydrogeology is complex and does change from nearshore to offshore, but further investigation into the hydrogeologic composition is warranted.

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References Cited

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics, *Petroleum Transactions American Institute of Mining, Metallurgical, and Petroleum Engineers*, 146, p. 54–62.

Banks, K.W., R.E. Dodge, L. Fisher, D. Stout, and W. Jaap, 1998, Florida coral reef damage from a nuclear submarine grounding and proposed restoration, In: Proceedings of the 1st International Coastal Science Symposium, Palm Beach, FL, p. 64-71.

Banks, K.W., B.M. Riegl, E.A. Shinn, W.E. Piller, and R.E. Dodge, 2007, Geomorphology of the southeast Florida continental reef tract (Miami-Dade, Broward, and Palm Beach Counties, USA), *Coral Reefs*, 26(3), p. 617-633.

Barry, R.M., D.A. Cavers, and C.W. Kneale, 1975, Recommended standards for digital tape formats, *Geophysics*, 40(2), p. 344-352.

Beaven, T.R., 1979, Hydrologic Conditions in Broward County, Florida, 1976, U.S. Geological Survey Open-File Report 79-1258, 102p.

Bokuniewicz, H., 1980, Groundwater seepage into Great South Bay, New York, *Estuarine, Coastal Marine Science*, 10, p. 437-444.

Bradner, A., B.F. McPherson, R.L. Miller, G. Kish, and B. Bernard, 2004, Quality of Ground Water in the Biscayne Aquifer in Miami-Dade, Broward, and Palm Beach Counties, Florida, 1996-1998, with Emphasis on Contaminants, U.S. Geological Survey Open-File Report 2004-1438, 25p.

Burnett, W.C., H. Bokuniewicz, M. Huettel, W.S. Moore, and M. Taniguchi, 2003, Groundwater and pore water inputs to the coastal zone, *Biogeochemistry*, 66, p. 3-33.

Burnett, W.C., and H. Dulaiova, 2006, Radon as a tracer of submarine groundwater discharge into a boat basin in Donnalucata, Sicily, *Continental Shelf Research*, 26,p. 862-873.

Burnett, W.C., G. Kim, and D. Lane-Smith, 2001, A continuous monitor for assessment of ^{222}Rn in the coastal ocean, *Journal of Radioanalytical Nuclear Chemistry*, 249, p. 167-172.

Causaras, C.R., 1984, Geology of the Surficial Aquifer System: Broward County, Florida, U.S. Geological Survey Water-Resources Investigations Report 84-4068, 167p.

Causaras, C.R., 1986, Geology of the Surficial Aquifer System: Dade County, Florida, U.S. Geological Survey Water-Resources Investigations Report 86-4126, 240p.

Corbett, D.R., L. Kump, K. Dillon, W. Burnett, and J. Chanton, 2000, Fate of wastewater-borne nutrients under low discharge conditions in the subsurface of the Florida Keys, USA, *Marine Chemistry*, 69, 99-115.

Dausman, A., and C.D. Langevin, 2005, Movement of the Saltwater Interface in the Surficial Aquifer System in Response to Hydrologic Stresses and Water-Management Practices, Broward County, Florida, U.S. Geological Survey Scientific Investigations Report 2004-5256, 73p.

Day-Lewis, F.D., E.A. White, C.D. Johnson, and J.W. Land Jr., 2006, Continuous resistivity profiling to delineate submarine groundwater discharge—examples and limitations, *The Leading Edge*, p. 724-728.

Enos, P., and R. Perkins, 1977, Quaternary sedimentation in South Florida, *Geological Society of America Memoir 147*, 198p.

Esteves, L.S., and C.W. Finkl, Jr., 1999, Late Cenozoic depositions paleoenvironments of southeast Florida interpreted from core logs, *Revista Brasileira de Geociencias*, 29(2), p. 129-134.

Finkl, C.W., and R.H. Charlier, 2003, Sustainability of subtropical coastal zones in southeastern Florida: challenges for urbanized coastal environments threatened by development, pollution, water supply, and storm hazards, *Journal of Coastal Research*, 19(4), p. 934-943.

Finkl, C.W., and S.L. Krupa, 2003, Environmental impacts of coastal-plain activities on sandy beach systems: hazards, perception and mitigation, *Journal of Coastal Research*, SI 35 (Proceedings of the Brazilian Symposium on Sandy Beaches: Morphodynamics, Ecology, Uses, Hazards and Management), p. 132-150.

Fish, J.E., 1987, Hydrogeology, Aquifer Characteristics, and Ground-Water Flow of the Surficial Aquifer System, Broward County, Florida. U.S. Geological Survey Water-Resources Investigations Report 87-4034, 87p.

Fish, J.E., and M. Stewart, 1990, Hydrogeology of the Surficial Aquifer System, Dade County, Florida, U.S. Geological Survey Water-Resources Investigations Report 90-4108, 56p.

Flocks J., J. Kindinger, J. Davis, and P. Swarzenski, 2001, Geophysical investigations of upward migrating saline water from the lower to upper Floridan Aquifer, central Indian River region, Florida, U.S. Geological Survey Water-Resources Investigations Report 01-4011, p. 135-140.

German, E.R., 2000, Regional Evaluation of Evapotranspiration in the Everglades, U.S. Geological Survey Water-Resources Investigations Report 00-4217, 55p.

Greenwood, W.J., S.E. Kruse, and P.W. Swarzenski, 2006, Extending electromagnetic methods to pore water salinities, *Groundwater*, 44(2), p. 292-299.

Griffin D.W., C.J. Gibson, III, E.K. Lipp, K. Riley, J.H. Paul, and J.B. Rose, 1999, Detection of viral pathogens by reverse transcriptase PCR and of microbial indicators by standard methods in the canals of the Florida Keys, *Applied and Environmental Microbiology*, 65, p. 4118-4125.

Hallock, P., and W. Schlager, 1986, Nutrient excess and the demise of coral reefs and carbonate platforms, *Palaios*, 1(4), p. 389-398.

Harrison, A.S., S.V. Dadisman, C.D. Reich, D.S. Wiese, J.W. Greenwood, and P.W. Swarzenski, 2007, Archive of digital boomer and CHIRP seismic reflection data collected during USGS cruise 06FSH03 offshore of Ft. Lauderdale, FL, September 2006, U.S. Geological Survey Data Series 308 (DVD).

Hoefel, F.G., and R.L. Evans, 2001, Impact of low salinity porewater on seafloor electromagnetic data: a means of detecting submarine groundwater discharge? *Estuarine, Coastal and Shelf Science,* 52, p. 179-189.

Jarrett, B.D., A.C. Hine, R.B. Halley, D.F. Naar, S.D. Locker, A.C. Neumann, D. Twichell, C. Hu, B.T. Donahue, W.C. Jaap, D. Palandro, and K. Ciembronowicz, 2005, Strange bedfellows—a deep-water hermatypic coral reef superimposed on a drowned barrier island; southern Pulley Ridge, SW Florida platform margin, *Marine Geology*, 214(4), p. 295-307.

Kindinger, J.L., J.B. Davis, and J.G. Flocks, 1997, Seismic Stratigraphy of the Central Indian River Region, U.S. Geological Survey Open-File Report 97-723, 1p.

Kohout, F.A., 1964, The flow of freshwater and saltwater in the Biscayne Aquifer of the Miami area, FL, In: Seawater in the Coastal Aquifer, U.S. Geological Survey Water-Supply Paper 1613-C, p. 12-32.

Kohout, F.A., 1966, Submarine springs, In: Fairbridge, R.W. (ed.), *The Encyclopedia of Oceanography,* New York: Reinhold, p. 878-883.

Kohout, F.A., and M.C. Kolpinski, 1967, Biological zonation related to groundwater discharge along the shore of Biscayne Bay, Miami, Florida, In: Lauff, G.H., (ed.), *Estuaries*, Washington DC: American Association for the Advancement of Science, p. 488-499.

Koopman, B., J.P. Heaney, F.Y. Cakir, M. Rembold, P. Indeglia, and G. Kini, 2006, Ocean Outfall Study, Final Report to the Florida Department of Environmental Protection, April 18, 2006, 241p.

Langevin, C.D., 2003, Simulation of submarine ground water discharge to a marine estuary: Biscayne Bay, Florida, *Groundwater*, 41(6), p. 758-771.

Lapointe, B.E., P.J. Barile, M.M. Littler, and D.S. Littler, 2005, Macroalgal blooms on southeast Florida coral reefs: II. Cross-shelf discrimination of nitrogen sources indicates widespread assimilation of sewage nitrogen, *Harmful Algae*, 4(6), p. 1106-1122.

Lapointe, B.E., P.J. Barile, and W.R. Matzie, 2004, Anthropogenic nutrient enrichment of seagrass and coral reef communities in the lower Florida Keys: discrimination of local versus regional nitrogen sources, *Journal of Experimental Marine Biology and Ecology*, 308, p. 23-58.

Lapointe, B.E., J.D. O'Connell, and G.S. Garrett, 1990, Nutrient couplings between on-site waste disposal systems, groundwater, and nearshore surface waters of the Florida Keys, *Biogeochemistry*, 10, p. 289-307.

Lidz, B.H., A.C. Hine, E.A. Shinn, and J.L. Kindinger, 1991, Multiple outlier-reef tracts along the South Florida bank margin: Outlier reefs, a new windward margin model, *Geology*, 19, p. 115-118.

Lighty, R.G., 1977, Relic shelf edge Holocene coral reef: S.E. coast of Florida, In: Proceedings of the 3rd International Coral Reef Symposium, Miami, Florida, 2, Geology, p. 215-221.

Lighty, R.G., I.G. Macintyre, and R. Stuckenrath, 1978, Submerged early Holocene barrier reef, southeast Florida shelf, *Nature*, 276, p. 59-60.

Lipp, E.K., S.R. Farrah, and J.B. Rose, 2001, Assessment and impact of microbial fecal contamination and human enteric pathogens in a coastal community, *Marine Pollution Bulletin*, 42, p. 286-293.

Maliva, R.G., W. Guo, and T. Missimer, 2007, Vertical migration of municipal wastewater in deep injection well systems in south Florida, USA, *Hydrogeology Journal*, 15, p. 1387-1396.

Manheim, F.T., D.E. Krantz, D.S. Snyder, and B. Sturgis, 2002, Streamer resistivity surveys in Delmarva coastal bays, Proceedings of the Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP), paper 13GSL5, 17p.

McNeill, D., 2000, A review of upward migration of effluent related to subsurface injection at Miami-Dade water and sewer south district plant, Final report to Sierra Club, Miami Geological Society, 31p.

McPherson, B.F. and R.B. Halley, 1996, The South Florida Environment: A Region Under Stress, U.S. Geological Survey Circular 1134, 67p.

Mota, R., and F. Moneiro Dos Santos, 2006, 2-D sections of porosity and water saturation percent from combined resistivity and seismic surveys for hydrogeology studies, *The Leading Edge*, p. 735-737.

Moyer, R.P., B. Riegl, K. Banks, and R.E. Dodge, 2003, Spatial patterns and ecology of benthic communities on a high-latitude south Florida (Broward County, USA) reef system, *Coral Reefs*, 22, p. 447-464.

Multer, H.G., E. Gischer, J. Lundberg, R. Simmons, and E. Shinn, 2002, Key Largo Limestone revisited: Pleistocene shelf-edge facies, Florida Keys, USA, *Facies*, 46, p. 229-272.

Parker, G.G., G.E. Ferguson, and S.K. Love, 1955, Water Resources of Southeastern Florida: with Special Reference to the Geology and Groundwater of the Miami Area, U.S. Geological Survey Water-Supply Paper 1255, 965p.

Paul, J.H., J.B. Rose, S.C. Jiang, X. Zhou, P. Cochran, C. Kellogg, J.B. Kang, D. Griffin, S. Farrah, and J. Lukasik, 1997, Evidence for groundwater and surface marine water contamination by waste disposal wells in the Florida Keys, *Water Research*, 31(6), p. 1448-1454.

Perkins, R.D., 1977, Depositional framework of Pleistocene rocks in south Florida, In: Quaternary Sedimentation in South Florida, Part II, Enos, P., and R.D. Perkins (eds.), *Geological Society of America Memoir 147*, Boulder, CO., p. 131-198.

Reese, R.S., and C.A. Alavarez-Zarikian, 2006, Hydrogeology and Aquifer Storage and Recovery Performance in the Upper Floridan Aquifer, Southern Florida, U.S. Geological Survey Scientific Investigations Report 2006-5239, 80p.

Reich C.D., E.A. Shinn, T.D. Hickey, and A.B. Tihansky, 2002, Tidal and meteorological influences on shallow marine groundwater flow in the upper Florida Keys, In: *The Everglades, Florida Bay, and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook*, Porter, J.W., and K.G. Porter (eds), Boca Raton, FL, p. 659-676.

Renken, R.A., J. Dixon, J. Koehmstedt, A.C. Lietz, S. Ishman, R.L. Marella, P. Telis, J. Rogers, and S. Memberg, 2005, Impact of Anthropogenic Development on Coastal Ground-Water Hydrology in Southeastern Florida, 1900-2000, U.S. Geological Survey Circular 1275, 77 p.

Shinn, E.A., J.H. Hudson, and R.B. Halley, 1977, Topographic control and accumulation rate of some Holocene coral reefs--South Florida and Dry Tortugas, In: Proceedings of the 3rd International Coral Reef Symposium, Miami, Florida, 2, Geology, p. 1-8.

Shinn, E.A., B.H. Lidz, and A.C. Hine, 1991, Coastal evolution and sea-level history: Florida Keys, In: Coastal Depositional Systems in the Gulf of Mexico, Quaternary Framework and Environmental Issues: Gulf Coast Section/SEPM Foundation 12th Annual Research Conference, Program with Extended and Illustrated Abstracts, p. 237-239.

Shinn, E.A., R.S. Reese, and C.D. Reich, 1994, Fate and Pathways of Injection-Well Effluent in the Florida Keys, U.S. Geological Survey Open-File Report 94-276, 116 pp.

Swarzenski, P.W., W. Burnett, C. Reich, H. Dulaiova, R. Peterson, and J. Meunier, 2004, Novel geophysical and geochemical techniques used to study submarine groundwater discharge in Biscayne Bay, Florida, U.S. Geological Survey Fact Sheet 2004-3117, 4p.

Swarzenski, P.W., C.D. Reich, K. Kroeger, and M. Baskaran, 2007b, Radium and radon isotopes as natural tracers of submarine groundwater discharge in Tampa Bay, *Marine Chemistry*, 104, p. 69-84.

Swarzenski, P.W., F.W. Simonds, A.J. Paulson, S. Kruse, and C.D. Reich, 2007a, Geochemical and geophysical examination of submarine groundwater discharge and associated nutrient loading estimates into Lynch Cove, Hood Canal, WA, *Environmental Science & Technology*, 41(20), p. 7022-7029.

Toscano, M.A., and I.G. Macintyre, 2003, Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from *Acropora palmata* framework and intertidal mangrove peat, *Coral Reefs*, 22, p. 257-270.

Waller, B.G., B. Howie, and C. Causaras, 1987, Effluent Migration from Septic Tank Systems in Two Different Lithologies, Broward County, Florida, U.S. Geological Survey Water-Resources Investigations Report 87-4075, 28p.

Valiela I., and C. D'Elia, 1990, Groundwater inputs to coastal waters, *Biogeochemistry*, Special Volume, 10(3), 158p.