Evaluating the reliability of continuous resistivity profiling to detect submarine groundwater discharge in a shallow marine environment: Sarasota Bay, Florida

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Evaluating the Reliability of Continuous Resistivity Profiling to Detect Submarine Groundwater Discharge in a Shallow Marine Environment: Sarasota Bay, Florida

by

Arnell Harrison

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science Department of Geology College of Arts and Sciences University of South Florida

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Evaluating the Reliability of Continuous Resistivity Profiling to Detect Submarine Groundwater Discharge in a Shallow Marine Environment: Sarasota Bay, Florida

Arnell Harrison

ABSTRACT

Submarine groundwater discharge (SGD) can be an important pathway for nutrients entering coastal systems. However SGD flow paths can be difficult to identify and flow volumes difficult to quantify. This study assesses whether geophysical techniques are potentially cost effective methods for detecting the presence or lack of SGD within an estuary environment found in Sarasota Bay, Florida. In this area, a rapid increase in urbanization has led to increased nitrogen loading into the bay, with some 10% of this loading attributed to SGD. Discharging groundwater is expected to be fresher and hence higher resistivity, than “background” surface waters. Thus resistivity surveys sensitive to seafloor conductivities may be useful for identifying zones of SGD. However, terrain resistivities are influenced by matrix geology as well as pore water resistivity. In this study we compare the results of marine resistivity surveys against both geochemical measures of SGD (radon tracers) and seismic profiles indicative of subsurface structure to better determine the relative impacts of geology and SGD on marine resistivity measurements in Sarasota Bay.
On both regional (kilometers to tens of kilometers) and local scales (hundreds of meters) the relationship between marine resistivity and tracer-based SGD estimates does not follow the expected pattern of higher resistivities associated with higher SGD flux. Seafloor resistivities instead appear primarily influenced by stratigraphy, particularly the presence of a clay layer at ~10-15 m depth in the southern part of the bay. In the southern bay, resistivities decrease at the depths associated with the clay layer. On the local (hundreds of meters) scale, lateral variations in resistivities derived from inversions of resistivity data were not found to be reproducible; nearly-coincident lines collected 30 minutes apart in time show different local signatures. This apparent local lateral variability in the resistivity profiles is inferred to be a result of inversion of noisy streaming resistivity data.
1. Introduction

(Valiela and D’Elia 1990; Moore 1996; Horn 2002; Burnett 1999, 2001a; Burnett et al. 2003 and Swarzenski 2004;) have shown that in some cases, the direct discharge of groundwater into the coastal zone is an important pathway for nutrient and contaminant transport from land to sea. Until fairly recently, investigations of submarine groundwater discharge (SGD) have been accomplished using methods that tend to be labor intensive and time consuming.

For example, prior to the development of equipment such as the RAD 7 (Burnett et al. 2003), which is used for continuous radon (Rn) sampling, radon and methane sampling and processing was a very labor intensive process. Another method that is commonly used in SGD investigations is the deployment of seepage meters, usually large metal drums that have been cut and placed on the seafloor, with a plastic baggie attached to them to collect water discharging upwards across the seafloor. This method can be problematic for many reasons which include 1) surface water motion may drive flow into the meter, 2) only a few can be deployed at a time, 3) they assess seepage over a small spatial zone, and 4) they must be left out for long periods of time (hours to days).

New techniques for observing and quantifying SGD in faster, more cost effective manners are desirable for better understanding the patterns of SGD.
Geophysical techniques may offer the possibility of rapid reconnaissance for SGD. Marine-based continuous resistivity profiling (CRP) is one method that can be used for rapid data acquisition on a variety of scales ranging from meters to kilometers. This method works on the premise that discharging groundwater is fresher than overlying surface waters and therefore sites of concentrated SGD will exhibit higher subseafloor resistivities.

The principal complication in using this method to potentially detect zones of fresher groundwater is that variations in ground resistivity reflect not only pore water variations but also differences in sediment porosity and type (i.e. clays are good conductors and hence show lower resistivity but can have high porosities).

Marine resistivity surveys were conducted in Sarasota Bay and compared with radon and seismic data. Comparison of the resistivity and Rn data collected around the same time period does not show simple correlations, suggesting that porosity and sediment/rock type strongly influence the resistivity signal in Sarasota Bay. Direct information on seafloor porosity and lithology would have required drilling into limestone and was beyond the scope of this project. However, indirect information on local geology was available through examination of seismic records collected in Sarasota Bay by the University of South Florida's (USFSP) Marine Science department in July 1996.

In this thesis we examine the relationships between resistivity, Rn, and geology at two scales: 1) a regional scale using both radon concentration-derived SGD estimates that encompass the entire bay, including Sarasota Bay in the north and Little Sarasota Bay to the south and regional geological data, and 2) a
local scale (hundreds of meters) at predetermined, site specific locations where nearby resistivity and seismic data were available.

Regional Geology and Hydrogeology

Study Area

Located just south of Tampa Bay in southwest Florida, Sarasota Bay is an enclosed lagoon that is bounded to the west by shallow barrier islands and to the east by the mainland (Figure 1).

The bay is approximately 400 km$^2$ and the watershed for the bay encompasses about 730 km$^2$. The bay is relatively shallow with an average depth of approximately 2-3 m and a maximum depth of 3-4 m. The tidal range for the bay is roughly 0.5 m (SBNEP, 2001). It is hydrologically connected to the Gulf of Mexico by several small passes (Longboat Pass, New Pass and Big Sarasota Pass) that subdivide the barrier island chain. Salinity in the bay is brackish to saline and is highly dependent on local rainfall and flushing within the bay. Sarasota Bay

Figure 1. Location map showing study area.
receives a majority of its freshwater input from several small tidal bayous and creeks which attain most of their input from storm water runoff, rainfall and groundwater seepage (Dillon, 2003). When present, groundwater seepage directly into the bay can be attributed to both artesian flow of deeper groundwater from underlying aquifers and to the re-circulated seawater moving across the sediment/surface water interface (Torres, 2001).

Regional Geology

In the vicinity of the bay, surface and near-surface sediments consist of quartz sand, consolidated and unconsolidated shell beds, clays, limestone and dolomites. These unconsolidated carbonates and siliclastic sediments represent a thin veneer (a few centimeters to four meters thick) overlying an irregular base of Miocene limestone bedrock (Hine, 2003) (Figure 2).
The Miocene bedrock has been classified by Scott (1988) as the Hawthorn Group, a unit consisting of the Arcadia and Peace River formations. The Peace River formation (PRF), unlike the Arcadia, is not contiguous throughout the study area. The Arcadia formation consists of, in ascending order, (1) Nocatee Member (2) Tampa Member and (3) Undifferentiated Arcadia Formation. It can be classified as a white to tan colored quartz sandy limestone with a carbonate mud matrix. The Peace River formation, which is found in the southern portion of the bay, consists of sediments described as the “Upper Hawthorn Clastics”, which are distinguishable as yellowish-gray to light olive green interbedded phosphatic sands, clayey sands, clays and dolomite stringers (Campbell, 1985). The Avon Park formation, Ocala limestone and Suwannee limestone (ascending order) all reside underneath the previously mentioned Hawthorn Group.

The southern portion of the bay differs geologically from its northern counterpart because of the presence of the Peace River formation clay layers that form a semi-confining unit between the undifferentiated deposits and the Arcadia limestone. Core samples taken from ROMP well TR 6-1 located on Siesta Key (Figure 3) show that the top of the Arcadia lies ~25.3 m below land surface, beneath surficial deposits and tens to hundreds of meters of the clays associated with the PRF. In contrast, ROMP well TR 7-1, located in northern Sarasota Bay (Figure 3) produced core samples that show the Arcadia formation approximately 9.10 meters below land surface and a very thin layer of unconsolidated sediments with no significant clay layers present.
Figure 3. ROMP wells and Formation factor location map.
In other areas in the northern bay, such as near New College (Figure 18), an even thinner sediment cover exists or is not present and the limestone outcrops at the seafloor or land surface.

**Hydrogeology**

The Sarasota area is underlain by Tertiary and Quaternary aged sediments and sedimentary rocks that constitute the Surficial, Intermediate and Upper Floridan Aquifer Systems. Each aquifer contains one or more water producing zones separated by less permeable units (Knochenmus and Bowman, 1998).

The Surficial aquifer system comprises Pliocene to Holocene-age, unconsolidated to poorly indurated, clastic sediments, and is defined as a permeable unit contiguous with the land surface (Southeastern Geological Society, 1986). The water-bearing capacity of the aquifer system is largely dependent on grain size, sorting, and saturated thickness of sediments. There is a relationship between sediment type and hydraulic properties that can be seen in maps by Vacher et al. (1992) that show an increase in hydraulic conductivities from north to south (Torres, 2001) (Figure 4).
Recharge to this aquifer is provided by rainfall and by upward leakance from the Intermediate aquifer system in areas where there is a reversal in the regional head gradient.

The Intermediate aquifer system is Oligocene to Miocene in age and consists of all rock units that lie between the overlying aquifer system and the underlying Upper Floridan aquifer. It generally coincides with the previously mentioned stratigraphic unit designated as the Hawthorn Group which consists of interbedded clastic sediments and carbonate rocks. The Intermediate aquifer
system averages approximately 120 m in thickness and contains an upper and lower confining unit as well as three water producing zones (Torres, 2001). The clays associated with the PRF are found in the Intermediate aquifer system with the top of the unit separating the Intermediate from the overlying Surficial aquifer system. There is no natural recharge from the overlying aquifer system because of the upward head gradient that exists between all the aquifers. In certain areas; however, specifically those dominated by agricultural activities, changes to the natural potentiometric surface have caused reversals within the head gradients thereby inducing recharge to the underlying aquifers (Knochenmus and Bowman, 1998).

Manatee County, for instance, is an agricultural region that is highly dependant on constant groundwater withdrawals from the underlying aquifers for both irrigation and domestic purposes especially during the dry season, which runs from December thru May. Over-pumping of these aquifers has caused a depression in the potentiometric surface and other adverse affects (SWFWMD, 1988). This change has in effect caused a change in the regional flow gradient and reversed the head gradient between the aquifers (the coast in the vicinity of the Manatee and northern Sarasota County line now acts as both a discharge and recharge area), which may have allowed for seepage of saline waters from the bay into the underlying aquifers. As previously stated, these reversals in head gradients occur mainly in the northern part of the bay, which has more agricultural areas, but head reversals have also been seen in the south in the vicinity of large well fields and pumping stations used for public supply.
Finally, the Upper Floridan aquifer system consists of carbonate rocks primarily of Tertiary (Paleocene to Oligocene) age that are approximately 910 m thick. Recharge to this aquifer is by lateral flow from adjacent areas, whereas discharge is upward into the Intermediate aquifer system in the form of diffuse leakage or along perpendicular flow zones and fractures (Knochenmus and Bowman, 1998).
Previous Marine Resistivity and Electromagnetic Studies

Using electrical resistivity techniques to study seafloor terrain resistivity is such a new method that there is a limited quantity of literature on the topic. Two studies that have used electrical resistivity with the aim of identifying zones of submarine groundwater discharge are those by Manheim et al. (2004) and Krantz et al. (2004).

Manheim et al. (2004) used streaming resistivity along with other adjunct methods (core and pore water samples) to detect fresh ground water located in the subsurface below coastal bays of the Delmarva Peninsula, which consists of both fine-grained surficial sediments and permeable sands.

Manheim et al. (2004) showed fresh water lenses that extend from a few hundred meters to more than 2 km from shore. Hypersaline brines were also detected in the subsurface at shallow (<20 m) as well as deeper (>300 m) depths. Their work showed that streamer resistivity systems can be effective tools for locating fresh and/or brackish waters in specific types of coastal environments. This technique can provide continuous regional/local scale profiling and allow for faster (~30 times) data collection than comparable land based studies (Manheim et al., 2004).

Krantz et al. (2004) used electrical resistivity in conjunction with drilling and geochemical methods to establish the hydrogeologic setting and groundwater flow beneath Indian River Bay, Delaware, an area that is primarily composed of organic-rich silts. In this study, the resistivity profiles helped show
submarine groundwater discharge, complex ground water flow patterns, and
various modes of mixing occurring in the underlying aquifer systems. In
particularly, the shore parallel resistivity profiles showed alternating subsurface
zones of high and low resistivity, which were interpreted as saline water from the
estuary moving down into the aquifer. Shore perpendicular profiles showed fresh
water coming from the land margin and flowing beneath the bay to discharge
near the center of the bay. Their combined methods provided results that
illustrated the flow of fresh ground water that produced plumes 20 m thick and
400 to 600 m wide that may extend 1 km or more from the shore beneath the
estuary. These plumes underlie small incised valleys which were filled with 1 to
2 m of silt and peat that act as a semi-confining layer to restrict the downward
flow of salt water from the estuary (Krantz et al., 2004).
2. Methods

To evaluate the utility of geophysical methods for detecting SGD, these methods were compared to geochemical tracers on both a larger regional scale (kilometers to tens of kilometers) and a small local scale (tens to hundreds of meters). For the regional scale surveys radon advection rates were measured and converted to SGD rates and then compared to continuous resistivity profiles collected throughout the entire bay. For the local scale surveys, coincident marine based resistivity and seismic profiles were compared.

Resistivity Methods

Marine resistivity follows the same basic principles of land based resistivity surveys with only a few variations. We note for reference that resistivity is the inverse of conductivity, and that terrain resistivity is the resistivity of the volume of material sampled by the instrument. Thus the terrain resistivity below the seafloor is the resistivity of the combined matrix plus porewaters, while above the seafloor the terrain resistivity is just the surface water resistivity, or 1/surface water conductivity.

For a single measurement of terrain resistivity, four electrodes are positioned at a given distance from each other. A constant direct current is introduced between the two (current/source) electrodes and the resulting potential difference is measured between the other two (potential) electrodes.
The measured potential difference is a function of the terrain resistivity and the electrode geometry.

Certain electrode geometries are utilized for ease of data collection and interpretation (See Figure 5). The geometry (also known as an “array”) used in this study was the dipole-dipole.

![Dipole-dipole resistivity array](image)

**Figure 5. Dipole-dipole array diagram.**

The dipole-dipole array has both current and potential electrode pairs oriented in a straight line with the potential electrode pair offset from the current electrode pair. For simplicity, the spacing between electrodes in each of the potential and current electrode pairs is set equal; this setup is sometimes referred to as “axial dipole”. The spacing between the current and potential electrode pairs is then varied. When the two pairs are closely spaced, the instrument is sensitive to the shallow subsurface; as the offset between the electrode pairs is increased, the depth of sensitivity increases. By sampling a range of offsets, terrain resistivities structure can be measured as a function of depth. The only constraint of using the dipole-dipole setup is that it requires
more power than other geometries to accommodate large offsets between the current and potential electrode pairs.

The potential differences measured at the potential electrode pair for the various geometries must be combined and inverted for a best-fitting terrain resistivity model. The final best-fitting model will depend on a number of parameters that control the inversion procedure. Because marine resistivity data sets are so large, inversions must be run separately on subsets of the profiles.

**Marine Resistivity**

Our resistivity surveys were adapted for marine deployment using streamer resistivity techniques which had been previously tested in other coastal bay environments (Manheim, 2004). Resistivity data for regional comparisons with radon data were collected by the Florida Geological Survey (FGS), in June 2002, and the U.S. Geological Survey (USGS), in May 2003 and February 2004 using the Zonge Streaming Resistivity/IP system of Zonge Engineering and Research Organization, Inc. and the AGI SuperSting of Advanced Geosciences, Inc., respectively (because the USGS data were collected around the same time as the radon data that data set was used for comparison instead of the FGS data, however, the FGS data can be found in the appendix). Both systems continually record and store data using a multi-channel resistivity receiver as well as collect position coordinates from a GPS receiver. The 100-m streaming resistivity cables used in both systems contain a current electrode pair and nine potential electrodes set up to be used in the dipole-dipole array with a 10 m
spacing. The streamers are towed across the water’s surface at a speed of ~3-5 knots.

Operating in continuous mode, the system injects current in the first two electrodes and then measures eight voltage potentials in the trailing electrode pairs (Figure 6).

Figure 6. Marine resistivity setup schematic.

Streaming resistivity data were collected once every few seconds. Measurement intervals were determined by the user and depth of penetration was equal to approximately 0.20-0.33 the length of the electrode array. Post-processing of the resistivity data involved several inverse modeling iterations using the software provided with the systems and modeling software such as Golden Surfer ™ for creating final plots.

In addition to the regional surveys a final set of small scale surveys was conducted with collaborators at the USGS in February 2006 to compare geologic features found in seismic profiles and resistivity on a smaller, local scale. The
resistivity cable used had a custom AGI 100-m dipole-dipole array setup with 10-meter electrode spacing, marine water seal, Kevlar strength member and stainless steel anchors. There were 9 stainless steel potential electrodes and 2 graphite current electrodes. A sea anchor with sufficient tension for the survey speed (survey speeds varied from 4-6 kph) was also used. To obtain correct global positioning, a WAAS differential GPS was available throughout the survey area from a NMEA 0183 2.0 stream of the Lowrance 480M GPS/sonar. The transducer was set to 200 kHz and had a depth of resolution of ± 5 cm (system has maximum resolution up to 50 m with this setting). The entire set of small-scale surveys was conducted over a period of approximately 9 hours. Also the use of graphite current electrodes allowed for less aggregation on the electrodes which produced less noisy data and a greater depth of penetration in this survey compared to the previous surveys.

**Seismic Profiling**

The seismic data used in this study were collected by Locker et al., (2001) during a July 23-26, 1996 survey conducted from Tampa bay to Venice, Fl. For data collection over the course of the survey they used a high-resolution single channel Huntec “Boomer” seismic acquisition system. Seismic data were acquired using low power levels ranging from 100-200 J to maximize vertical resolution of the thin Holocene section that is found in northern Sarasota Bay. Along with the Boomer setup, a 10 Element Innovative transducer, streamer, and Elics Delph2 Digital seismic acquisition and processing software were also used.
In cases where digital data were not available paper records were taken using an ORE Geopulse boomer system.

Two seismic lines were used for comparison with the resistivity data collected in February 2006, line 2 in the north and line 24 in the south (Figures 7-10). Because of its length, line 24 was broken up into multiple lines but for our purposes the lines that were closest to our resistivity surveys, lines 24f and 24i, were used (Figures 9-10).
Figure 7. Location of resistivity lines A and B.
Figure 8. Location of resistivity lines D and E.
Figure 9. Location of resistivity lines I, J and K.
Figure 10. Location of resistivity lines F, G and H.
The acquisition parameters for all lines were set with a shot interval = 400 ms, sampling frequency = 8000 Hz and high/low filters set to 960 Hz/3200 Hz, respectively. Lines 2 and 24f both had recording lengths = 140 ms and line 24i had a record length = 240 ms. For comparison with resistivity surveys, selected sections just a few hundred meters long are examined. To estimate depths from seismic travel times we assumed the velocity of the seismic wave to be equal to 1700 m/s in the sediments on all lines.
Radon and Continuous Radon Sampling

Methods developed by collaborators at FSU (Burnett, et al., 2003) were used as the approach for quantifying SGD. This method used geochemical tracers and a mass balance model to identify areas of potentially high groundwater seepage in Sarasota Bay. Water and sediment samples collected from July 2002-July 2004 were analyzed for radon-222 using the radon emanation method. Surface water radon concentrations were converted to inventories and adjusted for diffusive flux to model advective flow. The Advection Calculation program used to calculate the flow rates was based on a radon mass balance and assumed steady-state conditions. Radon loss to the atmosphere was incorporated into the program, however, loss of radon via mixing and/or flushing was not accounted for. The following parameters were used in calculating advection rates within the model (M. Murray, pers. comm.):

- Rn concentration in surface water (dpm/L or pCi/L)
- Total water depth (m)
- Wind speed (m/s)
- Rn concentration in air (dpm/L or pCi/L)
- Water temperature
- Rn concentration in groundwater
- Porosity
- Area of measurement (m²)
Estimating Pore Water Resistivity from Terrain Resistivity

During this study of SGD, it was important to differentiate between the pore water \( (\rho_W) \) and subsurface/terrain resistivities \( (\rho_T) \). The relationship between these two parameters can be described using a formation factor \( (F) \), where \( F = \rho_T / \rho_W \). The formation factors are important because once this value is known for a given lithology; it can then be used to extrapolate the pore water resistivities extending over various lithographic units.

Formation factors could not be directly determined along the marine resistivity surveys, as boat-based coring was beyond the scope of this project. To estimate formation factors in sediments, however, pore water samples were collected with drive-point samplers at onshore and offshore sites within tens of meters of the coast. Pore water samples were extracted with a peristaltic pump and resistivities were measured in the field. At these same sites terrain resistivities were measured with various combinations of the EM-31, EM-34 and the small Schlumberger marine resistivity array, as access permitted.
3. Results and Discussion

Regional Comparison of Resistivity and Radon

The feasibility of identifying zones of SGD in a shallow estuary environment using a marine resistivity system was tested using a continuous resistivity profiling setup in three surveys collected in June 2002, May 2003 and February 2004 by the FGS and USGS, respectively. The survey lengths were approximately 14, 30 and 17 km long, respectively with a depth of penetration around 25 m.

The USGS surveys were conducted close to the same time as the radon surveys (Figure 11) which is why the FGS data are excluded from the comparisons that follow below.
Figure 11. Location map showing radon sampling sites. Radon advection rates were converted to estimated SGD rates for comparison with regional resistivity data.
The southern bay was characterized using the 2003 survey which covered mostly the middle and southern portions of the bay and consisted of resistivity data ranging from 0.1-3 Ω-m and the northern bay with the 2004 data that concentrated on the northern portion of the bay with values of approximately 0.1-30 Ω-m.

In some places the results of the resistivity inversions are clearly unreasonable. For example, at some sites inverted terrain resistivities between 1 and 3 m depth gave unreasonably high resistivity values. At these depths, values should reflect the highly conductive (very low resistivity) surface waters input into the bay by the Gulf of Mexico. An example is shown at 10 km along the May 2003 survey line on Figure 12. Such locations clearly represent inversion artifacts associated with noisy or sparse data; therefore, these values were disregarded during the interpretation process (see Appendix B for original data sets).

In order to visualize and interpret the data at various levels it was parsed by depth below sea level ranging from 5-15 m and plotted using ArcGIS software on the following maps (Figures 13-15).
Figure 12. Location map showing extents of resistivity surveys.
Figure 13. Radon versus resistivity at 5 m.
Figure 14. Radon versus resistivity at 10 m.
Figure 15. Radon versus resistivity at 15 m.
In the southern part of the bay, resistivities generally increase with depth from 5-15 m below the water surface (from approximately 0.3-1 Ω-m at 5 and 10 m to 1-3 Ω-m at 15 m). Data collected at the 10 m depth are being influenced by a conductive clay layer (clay = 1 to 100 Ω-m (Beck, 1981)) which produce resistivity values similar to those found in the shallow depths (< 5 m below sea level). At 15 m, the lithology is dominated by limestone a naturally more resistive (wet limestone = $10^2$ to $10^3$ Ω-m, (Beck, 1981)) material than clay that produces consistently higher resistivity values.

In comparison to the southern bay, the northern bay at a depth of 5 m has resistivity values that are uniformly high, ranging between 3 and 30 Ω-m, which may be explained by the proximity of the limestone to the sediment/surface water interface. At 10 m depth resistivity values are between 0.3 and 30 Ω-m and decrease even more to approximately 0.1 and 30 Ω-m at 15 m below sea level.

Thus on a regional scale, the northern bay differs from the southern bay because resistivities decrease with increasing depth- a result that is counterintuitive to what would be expected to occur in a region where a freshwater lens is expected to extend offshore. Even though resistivities decrease with depth they are still significantly higher than those found in the southern bay. So what would cause the sediments/pore waters to become more saline with depth? There are two possible explanations for the lower resistivity rates found at 15 m compared to resistivities at 10 or 5 m depth. The area between 3035000N and 342000E in Manatee County (Figure 15) is a relatively unpopulated region, which is used primarily for agricultural purposes. One
explanation is that the area is no longer just a discharge area (from the Intermediate aquifer) but also a recharge area and because of this two way head gradient, now saline surface waters may penetrate to greater depths through conduits found in the limestone and move into the underlying aquifers. The other possible explanation is that over pumping from the underlying Floridan aquifer for irrigation and other purposes has altered the extent and thickness of the freshwater lens and thereby reduced the amount of readily available freshwater.

There appears to be an inverse relationship regionally between advection rates and resistivity values in the northern and southern portions of the bay. The northern portion of the bay is dominated by lower flow rates ranging between 0.71 and 5.9 cm/day and higher resistivity values between 3.1 and 30.0 Ω-m. The south displays generally higher flow rates ranging from 5.9 to 24.0 cm/day with lower resistivity values between 0.31 and 3.1 Ω-m. This inverse relationship is the opposite of what would be expected if SGD were the dominant cause of resistivity variability throughout the bay.

Since SGD does not appear to be the only factor affecting resistivity signals then what else could also account for these changes? Both surveys were collected using the same equipment and processing software therefore acquisition and processing parameters are consistent for both the 2003 and 2004 surveys.

One factor that was variable between the 2003 and 2004 surveys were the time of data collection. Both data sets were collected during the dry season (December thru May) but they differ by the year and how far into the dry season
they were when collected. The May survey occurs at the very end of the dry season so aquifer levels would be at their lowest and the region would have gone for the longest periods with little to no rainfall, which would produce less available freshwater and therefore lower resistivity values.

In comparison, the February survey would have been collected earlier in the season when aquifer levels would have be higher than those found in May—when more ground water is needed for irrigation and public supply during the hotter, summer period. When compared with historical readings, February 2004 was characterized in a hydrologic conditions study conducted by the Southwest Water Management District as “wetter than normal” (SWFWMD, 2004) while May 2003 was characterized as “normal” (SWFWMD, 2003). This same pattern can also be seen in Figure 16, which shows data taken from three different rainfall gauges located in Sarasota Bay. The additional freshwater input during this time period may be another explanation for the higher overall resistivities found in the northern bay during the 2004 survey.
Figure 16. Rainfall data plots.
As previously stated, the flow rates which were calculated with an advection model did not take into account flushing and/or mixing which may explain the lower flow rates found in the north as opposed to the south. The north is privy to more flushing and mixing with gulf waters carried in daily with the tides by the various inlets that are found here.

Results from the final resistivity survey conducted in February 2006 also show consistently higher resistivity values in the north compared to the south. This survey was conducted over the course of a day which means there is an absence of seasonal variability in this survey. Thus at least some of the difference between the northern 2004 and southern 2003 surveys appear due to differences in lithology and seasonally-independent porewater variation. The consistency between overall resistivity patterns and lithology (more resistive limestone near the seafloor in the north and the conductive clay layer at ~10 m depth in the south) suggests that lithologic variations are perhaps the dominant contribution to the regional resistivity signatures in Sarasota Bay.

**Correlating Pore Water Resistivity and Terrain Resistivity Using Formation Factors**

Formation factors that were calculated from resistivity surveys taken along with pore water samples can be found in the following table. Table 1 below shows the results from three sites taken throughout the entire bay. These sites are found at New College in the north, 10th Street Park around the middle of the bay and finally Stickney Bridge in the south (Figure 3). As would be expected,
the formation factor decreases toward the south because of the presence of the highly conductive clays associated with the Peace River formation, which is found only in the southern part of the bay.

<table>
<thead>
<tr>
<th>Site</th>
<th>Terrain Resistivity (m/µS)</th>
<th>Pore Water Resistivity (m/µS)</th>
<th>Formation Factor ($\frac{\rho_T}{\rho_W}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New College</td>
<td>0.0018</td>
<td>0.00030</td>
<td>5.4</td>
</tr>
<tr>
<td>10th St. Park</td>
<td>0.0022</td>
<td>0.00050</td>
<td>4.5</td>
</tr>
<tr>
<td>Stickney Bridge</td>
<td>0.0013</td>
<td>0.00030</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Table 1. Formation factor results from the three regional sites sampled in Sarasota bay.
Local Scale Comparison of Resistivity and Seismic Data

Examining the bay to see if resistivity variations were found on both the regional and local scale was an essential part of this thesis. To conduct the local scale surveys, four site specific locations (chosen because of their proximity to geologic features found in the seismic record) were visited in February 2006 (Figures 7-10). Multiple resistivity survey lines (between 2 and 3 lines per site) ranging in length from ~300 m to 1100 m were all collected throughout the bay over the period of a few hours (approximately 9-10 hours).

Overall results from these local scale surveys support the conclusions hypothesized in preceding sections related to the regional differences between the north and south, which assumed that a high conductivity (possibly semi-confining) clay layer is present in the south but not in northern Sarasota Bay.

The southern bay resembles the northern bay because both have a lower resistivity zone found at depth; however, the south differs from the north due to the presence of a highly conductive zone found below the sediment/surface water interface approximately 9 m below sea level (Figures 17 and 18).
Figure 17. Resistivity and seismic lines near Phillipi Creek. Location shown in Figure 9. Interpretations show a thickening of Holocene deposits compared to the northern bay. The clay-rich PRF is approximately 9 m thick. Higher resistivity limestone associated with the Arcadia is found at ~15 m depth. A stratigraphic section schematic of ROMP 6-1, located on Siesta Key (location shown in Figure 3) is shown to the right of the seismic profile.
Figure 18. Resistivity and seismic lines from Little Sarasota Bay. Location shown in Figure 10. Here Holocene deposits are thickest, up to 3 meters. Clays associated with the PRF are seen here and may act as a semi-confining unit between the over and underlying aquifers. Notice the high resistivity zones located above and below the conductive zone in the resistivity profiles.
This conductive layer is part of the clays associated with the PRF that have been mentioned previously in the regional geology section. Line K does not show the presence of a highly conductive layer (~0.25 Ω-m for surface waters) above the sediment/surface water interface that can be seen in both I and J. This may be due to additional noise that was present during data collection of line K (i.e. boat traffic in channel and/or proximity to the channel). The high resistivity areas in I and J are found approximately 15 m below sea level, which is deeper than the high resistivity zone found in the north (≤10 m). Lines F-H all easily indicate the position of a conductive layer of clays found below the sediment/surface water interface. These clays are resting on top of a high resistive zone located approximately 15-20 m below sea level (see figure 18).

Smaller lateral changes in resistivity (factors of less than 4 or 5) are not consistent between surveys collected less than a half hour apart. A possible explanation for this is that this horizontal inhomogeneity could be artifacts of inversion of noisy data. (Note repeat surveys do not perfectly duplicate positions, but are closer than the lateral dimensions of the features observed.) For example, lines A and B (See Figure 19 for locations) show no obvious similarity between runs except in the underlying fresh/high resistivity features located approximately 10 m below sea level. Small lateral variations are not depicted consistently in either line, i.e. between 360 and 460 m line B shows a high resistivity area that is not present in line A.
Figure 19. Resistivity and seismic lines near New College. Location shown in Figure 7. This interpretation shows the top of the limestone at shallow depths and in some areas outcropping at the seafloor. There appears to be two distinct layers (A and A2) in the Arcadia limestone. Holocene deposits are very thin or non-existent throughout the survey line.
Figure 20. Resistivity and seismic lines near Bowles Creek. Location shown in Figure 8. Interpretations show the presence of the limestone here is within 5 meters of the seafloor. Sags in the Arcadia are filled with Holocene or possibly PRF sediments. ROMP well 7-1, near Bowles Creek (location shown in Figure 3), has no significant clays layers. Note that no clays (PRF) are observed above the limestone (A) in the stratigraphic section schematic.
Consistent with results found in lines A and B, lines D and E (Figure 20) show a conductive layer above the sediment/surface water interface with a gradual freshening with depth. Similar to lines A and B, lines D and E show that lateral variability between surveys is not routinely reproduced in both of the runs, however, a high resistivity zone is present in the subsurface approximately 10 m below sea level that coincides with the one found in lines A and B.

In lines I-K resistivity patterns are similar to those the north with small scale horizontal changes not being reciprocated over all three lines and the fractured appearance to the underlying limestone.

Although changes in the lateral direction are not reliable, changes found in the vertical section are consistently reproduced during all surveys, therefore changes by a factor of 4 or 5 (or greater) that are not reliable in the horizontal direction can be believed in the vertical direction. As previously stated, there is a high resistivity zone found at depth in all survey lines with the only variation found in the south where a highly conductive area is located (this vertical feature is present in all southern survey lines except where noted in previous section) above the higher resistivity zone.

In both the north and south, smaller-scale seismic features (such as the bowl-shaped sag feature located at Bowlees Creek approximately 9 m below sea level or the “v” shaped sag feature found ~12 m below sea level at Phillipi Creek) do not have coincident resistivity signatures. So again, smaller scale features are probably the result of noise, and do not reflect geologic heterogeneities. This lack of a signal could have occurred because the CRP’s resolution is incapable
of detecting small scale (few meters) features so it instead depicts an overall picture of larger scale geometries.

Discussion

It appears that some of the high resistivity areas found in the north are right at the sediment/surface water interface and this may be explained by the close proximity of the limestone to the surface in this area where often the amount of sediment cover (sand) is very thin or non-existent. It should also be noted that breaks in the resistivity highs (these may represent conduits/fractures in the limestone) appear to be drawing down the more conductive surface waters to lower depths. A possible explanation for this is that the northern bay is acting not as an area of discharge but as one of discharge and recharge, which most likely has been created by a reversal in the head gradients due to over-pumping of the underlying aquifers for agricultural purposes (namely in Manatee county) for the past few years (See Hydrogeology section).

The south appears to have less variability (more contiguous) in the underlying limestone unlike the north, which had a discontinuous almost broken appearance to its limestone.

Unlike lines A-E in the north, lines F-H show a small zone of higher resistivity between the sediment/surface water interface and the top of the clay layer that is found about 10 m below sea level. This high resistivity area is probably a zone of fresh water associated with the Surficial Aquifer system. If this high resistivity area were due to channel effects (from the nearby Intercoastal
Waterway) then there would have been a gradational increase in resistivity values with depth similar to that of the north, not a zone of higher resistivity (freshwater saturated sediments) then a high conductivity zone (clay layer) and finally freshening with depth (freshwater saturated limestone).

Because a zone of higher resistivity is found below 15 m, it is my belief that the clay layer is acting as a semi-confining unit that is restricting any seepage from underlying and/or overlying aquifers (this area hasn't had any head gradient reversals so the regional gradient makes this an area of discharge).
4. Conclusions

Continuous resistivity profiling in karstic environments such as Sarasota Bay, appears to be a viable method for rapid, large scale surveys that yield information on the overall underlying geology and potential areas of interest. For smaller, more detailed investigations of SGD it would appear that radon sampling is the most appropriate and proven method for detecting and quantifying these changes.

Small scale (tens to hundreds of meters) surveys do not show consistent correlations with geological features imaged in seismic lines, and further show that horizontal variations in resistivity of a factor of < 4-5 are likely to be the product of inversion artifacts created during processing of the data, not changes in resistivity created by buried features. Sag features had no distinct corresponding resistivity signal. Vertical variability in survey lines appears consistent and is hence probably indicative of real features and/or facies changes occurring below the sediment/surface water interface (i.e. changes from saltwater saturated sands to limestone saturated with freshwater).
References


Horn, D.P., 2002, Beach groundwater dynamics, Geomorphology 48, 121-146 p.


Valiela, I., and D'Elia, C., 1990, Groundwater inputs to coastal waters, Biogeochemistry 10, no. 3: 175.
Appendices
Appendix A: Florida Geological Survey Data

In June 2002 a resistivity survey was collected by the Florida Geological Survey (FGS) in Sarasota Bay using the Zonge Streaming Resistivity/IP system of Zonge Engineering and Research Organization, Inc. This system continually recorded data from a GPS receiver and used a 10 m dipole-dipole array. Current was injected through a line of streaming electrodes, in tow behind the research vessel, at a preset interval and apparent resistivity values representing various depths were read for each injection. After data collection is complete, the data were inverted by Zonge, Inc. using 2-D inversion software.

The survey line extends 14 km beginning in Philippi Creek and ending at Stephen’s Point (see figure A for location). To facilitate ease during the inversion process the single survey line was broken up into multiple segments referred to as sections A through N, which are provided and labeled accordingly below. Because the survey line was divided after data collection was complete, only beginning and ending line navigation points were provided therefore only one line could be produced for the location map.
Appendix A: (Continued)

Inversion Model Resistivity (ohm-m)

Calculated Apparent Resistivity (ohm-m)

Observed Apparent Resistivity (ohm-m)

Survey Parameters:
- 10 m Dipole-Dipole data
- 4.0 hertz repetition rate
- Inversion control parameters:
  - ResSmth=1, dpW=0.5, dxW=1, dzW=1

Florida State University
Marine Resistivity Survey
Line 220Jun07 A
2D Smooth-Model Inversion
Dipole-Dipole Resistivity Data
Appendix A: (Continued)

Survey Parameters:
- 10 m Dipole-Dipole data
- 4.0 hertz repetition rate
Inversion control parameters:
- ResSmth=1, dpW=0.5, dxW=1, dzW=1

Inversion Model Resistivity (ohm-m)

Calculated Apparent Resistivity (ohm-m)

Observed Apparent Resistivity (ohm-m)
Appendix A: (Continued)

Survey Parameters:
- 10 m Dipole-Dipole data
- 4.0 hertz repetition rate

Inversion control parameters:
- ResSmth=1, dpW=0.5, dxW=1, dzW=1

Florida State University
Marine Resistivity Survey
Line 220Jun07 A
2D Smooth-Model Inversion
Dipole-Dipole Resistivity Data

Author: Zonge
Drawn: Zonge
Date: 01/07/07
Scale: 1:4500
Report: Job 200220
Appendix A: (Continued)

Inversion Model Resistivity (ohm-m)

Calculated Apparent Resistivity (ohm-m)

Observed Apparent Resistivity (ohm-m)

Survey Parameters:
10 m Dipole-Dipole data
4.0 hertz repetition rate

Inversion control parameters:
ResSmth=1, dpW=0.5, dxW=1, dzW=1

Florida State University
Marine Resistivity Survey
Line 220Jun07 A
2D Smooth-Model Inversion
Dipole-Dipole Resistivity Data
Appendix A: (Continued)

Florida State University
Marine Resistivity Survey
Line 220Jun07 A
2D Smooth-Model Inversion
DipoleDipole Resistivity Data

Survey Parameters:
- 10 m DipoleDipole data
- 4.0 hertz repetition rate

Inversion control parameters:
- ResSmth=1, dpW=0.5, dxW=1, dzW=1

Inversion Model Resistivity (ohm-m)

Calculated Apparent Resistivity (ohm-m)

Observed Apparent Resistivity (ohm-m)
Appendix A: (Continued)

Florida State University
Marine Resistivity Survey
Line 220Jun07 A
2D Smooth-Model Inversion
Dipole-Dipole Resistivity Data

Survey Parameters:
10 m Dipole-Dipole data
4.0 hertz repetition rate

Inversion control parameters:
ResSmth=1, dpW=0.5, dxW=1, dzW=1

Inversion Model Resistivity (ohm-m)

Calculated Apparent Resistivity (ohm-m)

Observed Apparent Resistivity (ohm-m)
Appendix A: (Continued)

Survey Parameters:
- 10 m DipoleDipole data
- 4.0 hertz repetition rate

Inversion control parameters:
- ResSmth=1, dpW=0.5, dxW=1, dzW=1

Inversion Model Resistivity (ohm-m)

Calculated Apparent Resistivity (ohm-m)

Observed Apparent Resistivity (ohm-m)
Appendix A: (Continued)

Survey Parameters:
- 10 m Dipole-Dipole data
- 4.0 hertz repetition rate

Inversion control parameters:
- ResSmth=1, dpW=0.5, dxW=1, dzW=1

Florida State University
Marine Resistivity Survey
Line 220Jun07 A
2D Smooth-Model Inversion
Dipole-Dipole Resistivity Data

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Survey Parameters:
- 10 m Dipole-Dipole data
- 4.0 hertz repetition rate

Inversion control parameters:
- ResSmth=1, dpW=0.5, dxW=1, dzW=1

[Graphs showing observed and calculated resistivity data with elevation and apparent resistivity values]
Appendix A: (Continued)

Survey Parameters:
- Dipole-Dipole data
- 4.0 hertz repetition rate

Inversion control parameters:
- ResSmth=1, dpW=0.5, dxW=1, dzW=1

Florida State University
Marine Resistivity Survey
Line 220Jun07 A
2D Smooth-Model Inversion
Dipole-Dipole Resistivity Data

Inversion Model Resistivity (ohm-m)
Calculated Apparent Resistivity (ohm-m)
Observed Apparent Resistivity (ohm-m)
220Jun07 A, Section K

Survey Parameters:
- 10 m Dipole-Dipole data
- 4.0 hertz repetition rate

Inversion control parameters:
- ResSmth=1, dpW=0.5, dxW=1, dzW=1

Florida State University
Marine Resistivity Survey
Line 220Jun07 A
2D Smooth-Model Inversion
Dipole-Dipole Resistivity Data

Inversion Model Resistivity (ohm-m)
Calculated Apparent Resistivity (ohm-m)
Observed Apparent Resistivity (ohm-m)
Appendix A: (Continued)

Survey Parameters:
- 10 m Dipole-Dipole data
- 4.0 hertz repetition rate

Inversion control parameters:
- ResSmth=1, dpW=0.5, dxW=1, dzW=1

Florida State University
Marine Resistivity Survey
Line 220Jun07 A
2D Smooth-Model Inversion
Dipole-Dipole Resistivity Data

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Survey Parameters:
10 m Dipole-Dipole data
4.0 hertz repetition rate

Inversion control parameters:
ResSmth=1, dpW=0.5, dxW=1, dzW=1
Florida State University
Marine Resistivity Survey
Line 220Jun07 A
2D Smooth-Model Inversion
Dipole-Dipole Resistivity Data

Survey Parameters:
10 m Dipole-Dipole data
4.0 hertz repetition rate

Inversion control parameters:
ResSmth=1, dpW=0.5, dxW=1, dzW=1

Inversion Model Resistivity (ohm-m)

Calculated Apparent Resistivity (ohm-m)

Observed Apparent Resistivity (ohm-m)
Appendix A: (Continued)

Florida State University
Marine Resistivity Survey
Line 220Jun07 A
2D Smooth-Model Inversion
Dipole-Dipole Resistivity Data

Survey Parameters:
10 m Dipole-Dipole data
4.0 hertz repetition rate

Inversion control parameters:
ResSmth=1, dpW=0.5, dxW=1, dzW=1

Inversion Model Resistivity (ohm-m)

Calculated Apparent Resistivity (ohm-m)

Observed Apparent Resistivity (ohm-m)

Elevation (m)

0m 60m 120m 180m 240m

Florida State University
Marine Resistivity Survey
Line 220Jun07 A
2D Smooth-Model Inversion
Dipole-Dipole Resistivity Data

220Jun07 A, Section N

67
Appendix B: U.S. Geological Survey Data

First, we will examine the USGS 2003 cruise that extends 30 km and began just south of Whitaker Bayou and ends in Little Sarasota Bay just north of Casey Key. For ease during the inversion process the survey line was broken up into 3 segments which shall be referred to as line 1, line 2 and line 3 (Figure B).

Line 1 extends from Whitaker Bayou north to about the Manatee/Sarasota County line and covers the distances ranging from 0 to 5090 m along the survey line. The resistivities in this line range from a minimum of approximately 0.92 to a maximum of approximately 8.8 Ohm-meters (Ω-m). Coloring irregularities found above the sediment/surface water interfaces in all three lines may be due to discrepancies within the inversion software and for this reason some of the lower resistivity values observed in these areas were omitted from the given resistivity ranges for each line segment.

Line 2 begins at the Manatee/Sarasota border then goes west until it terminates approximately 0.5 km from Longboat Key. The distances covered are ~5179 to 6718 m along the survey line. Resistivity ranges here are between 0.53 and 2.8 Ω-m.

Line 3 begins due south of the end of line 2 (approximately 0.5 m from the landward side of Longboat key) and extends down through Little Sarasota Bay just north of Osprey, Fl. The distances covered are ~6746 to 29745 m along the survey line. Resistivity ranges here are between 2.8 and 8.4 Ω-m.
Appendix B: (Continued)

The USGS 2004 survey extends out for approximately 17 km beginning at New College and continues north-northwest before ending approximately 1.5 km east from the top of Longboat Key. The similarity between the 2003 and 2004 cruises is the seepage pattern illustrated, which mocks that of line 1 with its point-like distribution that appears to approach the surface/sediment water interface.

The obvious distinction between the two surveys is observed in the resistivity values collected from the 2004 survey, which shows values higher than those in 2003. Resistivity ranges here are between approximately 60 and 0.95 \( \Omega \cdot m \) with a maximum of 808 \( \Omega \cdot m \), which is probably again due to inversion software issues that were previously mentioned.
Appendix B: (Continued)

Figure A. Location map for all three resistivity surveys collected throughout Sarasota Bay. The single FGS survey was collected in June 2002 (red line) from Philipi Creek to Stephen’s Point. The two USGS surveys were collected in May 2003 (blue) and February 2004 (purple) and covered Sarasota and Little Sarasota Bays.
Appendix B: (Continued)

Figure B. Location map from 2003 USGS survey showing locations of lines 1-3.
Figure C. Original plot of resistivity profile line 1 showing inverted section from May 2003 USGS survey conducted in Sarasota Bay near New College. Location of this line segment is shown in Figure B. Inversion artifacts created during the various iterations are seen above the sediment/surface water interface as resistivity highs (orange/red) ranging between 2.9 and 8.8 Ohm-m.
Appendix B: (Continued)

Figure D. Original plot of resistivity profile line 2 showing inverted section from May 2003 USGS survey conducted in Sarasota Bay near the Manatee/Sarasota county line. Location of this line segment is shown in Figure B. Inversion artifacts created during the iteration process are seen above the sediment/surface water interface as resistivity highs ranging between 1.2 and 2.8 Ohm-m.
Appendix B: (Continued)

Figure E. Original plot of resistivity profile line 3 showing inverted section from May 2003 USGS survey conducted in Sarasota Bay. The survey line ran from Longboat Key in the north/mid bay down to Casey Key in the south. Location of this line segment is shown in Figure B. Inversion artifacts created during the multiple inversions are seen above the sediment/surface water interface as resistivity highs ranging between 2.8 and 8.4 Ohm-m.
Appendix B: (Continued)

Figure F. Original plot of resistivity profile showing inverted section from February 2004 USGS survey conducted in northern Sarasota Bay. Location of this line segment is shown in Figure A. Modifications to the inversion software used to create this profile have eliminated many of the inversion artifacts seen in previous survey lines collected in the 2003 survey. Unreasonably high values between 85 and 808 Ohm-m can still be attributed to noisy data and/or inversion discrepancies.
Appendix C: Electromagnetic Survey Data

Electromagnetic (EM) data were also collected for this thesis, however, because of the proximity of power lines and other electrical sources the data were too noisy to be used effectively.

Similar to resistivity, EM methods work by using electricity to induce current; however, the difference is found in the current source, which is an alternating current provided by an internal, self-contained transmitter coil. This transmitter coil generates an EM field that penetrates the subsurface before being picked up by a receiver coil. The magnitude of the resulting field is directly proportional to the terrain conductivity. The system used here was the Geonics EM-31 which operates at a frequency of 9800 kHz with an inter-coil spacing of 3.67 m.

Readings are collected in quadrature phase vertical dipole mode (VMD) and inverted for seabed conductivity assuming a simple 2-layered earth model (algorithm by S. Sandberg, pers. comm.). Surface water conductivity ($\sigma_1$) and depth ($d_1$) are measured directly, so the only unknown is seabed conductivity ($\sigma_2$).

This method is sensitive only to the conductivity of the uppermost few meters of sediment/rock, and only works in saline water when surface water depths are less than ~1-1.5 meters (Greenwood et al., 2006).
Appendix C: (Continued)

Greenwood et al. (2004) used electromagnetic methods to map pore water salinity over land and shallow marine waters in a coastal wetland located in Tampa Bay, Florida. Using the EM-31 and EM-34 of Geonics, Ltd., it was shown that information on seabed conductivity can be obtained in saline waters with depths equal to < 1.5 m. The EM method offers access to very shallow water and difficult coastal wetlands; however, field trials and models show that the towed EM technique is probably not suitable for imaging subtle conductivity anomalies beneath Tampa Bay (Greenwood et al., 2006).

Figure G. Schematic showing setup geometry for EM-31 in canoe. Surface water conductivity ($\sigma_1$), depth ($d_1$) and seabed conductivity ($\sigma_2$) are variables needed by the inversion algorithm to infer seabed conductivity.
Appendix C: (Continued)

Figure H. Location map showing electromagnetic data collected with the Geonics EM-31 in August 2004 from Robert's and Little Sarasota Bay. The proximity of power lines and other electrical interference to the instrument at the time of data collection created noisy data that could not be effectively used.