A New Focus on Groundwater–Seawater Interactions
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Multi-channel resistivity investigations of the freshwater–saltwater interface: a new tool to study an old problem

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Abstract It has been well established that fresh or brackish groundwater can exist both near and far from shore in many coastal and marine environments. The often permeable nature of marine sediments and the underlying bedrock provides abundant pathways for submarine groundwater discharge. While submarine groundwater discharge as a coastal hydrogeological phenomenon has been widely recognized, only recent advances in both geochemical tracers and geophysical tools have enabled a realistic, systematic quantification of the scales and rates of this coastal groundwater discharge. Here we present multi-channel electrical resistivity results using both a time series, stationary cable that has 56 electrodes spaced 2 m apart, as well as a 120 m streaming resistivity cable that has two current-producing electrodes and eight potential electrodes spaced 10 m apart. As the cable position remains fixed in stationary mode, we can examine in high resolution tidal forcing on the freshwater–saltwater interface. Using a boat to conduct streaming resistivity surveys, relatively large spatial transects can be rapidly (travel speed ~2–3 knots) acquired in shallow (~1–20 m) waters. Sediment formation factors, used to convert resistivity values to salinity, were calculated from porewater and sediment samples collected during the installation of an offshore well in Tampa Bay, Florida, USA. Here we examine the seabed resistivity from sites within Tampa Bay using both stationary and streaming configurations and discuss their overall effectiveness as a new tool to examine the dynamic nature of the freshwater–saltwater interface.

Key words electrical resistivity; coastal hydrogeology; formation factor; submarine groundwater discharge

INTRODUCTION

Submarine groundwater discharge (SGD) may provide an important additional pathway for material and constituent transport to the sea (Moore, 1996; Burnett *et al.*, 2003, 2006). This SGD may consist of both recycled seawater as well as land-derived fresh groundwater, yet the former component most often dominates a SGD signal (Michael *et al.*, 2005; Swarzenski, 2007). This recycled component may also recharge a coastal aquifer with ambient seawater and water column-derived constituents, including Cl^- and select nutrients. Near-shore dynamic mixing processes, driven in part by tidal forcing and density differences, create a zone of enhanced biogeochemical reactivity (Fig. 1) that has been called a "subterranean estuary" (Moore, 1999; Charette

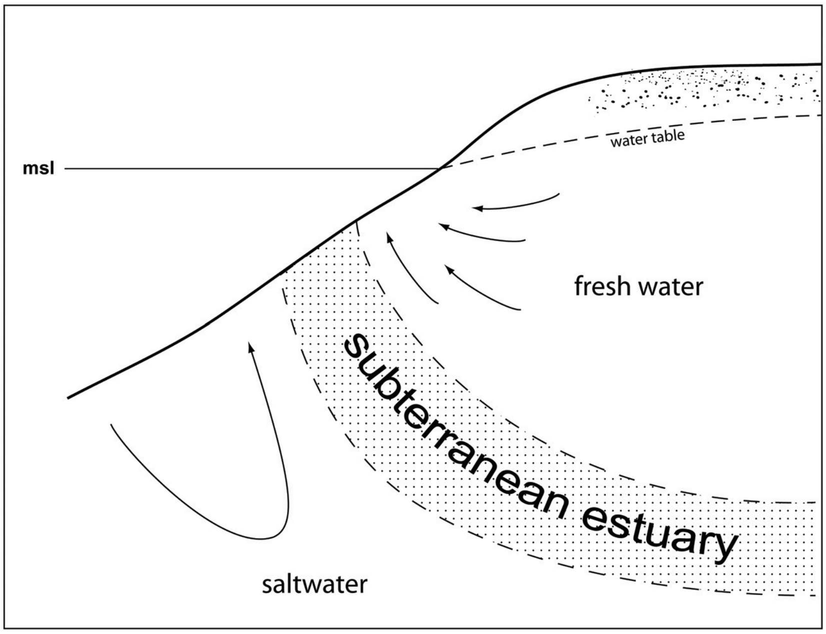

Fig. 1 Idealized hydrogeological cross-section at a land/sea interface, depicting the subterranean estuarine zone.

& Sholkovitz, 2006). While much is known about biogeochemical transport phenomena in surface water estuaries (Boyle *et al*., 1977; Sholkovitz, 1976, 1977; Swarzenski *et al.*, 2006a), still relatively little is known of such processes and reactions in subterranean estuaries. A useful tool for imaging the spatial scales and mixing dynamics of the freshwater–saltwater interface of a coastal aquifer is surface electrical resistivity.

The direct current (DC) electrical resistivity approach measures potential differences that are produced by directing current flow into sediment. The resistivity (conductivity = $(\text{resistivity})^{-1}$) of a formation is a function of both the geological material and its textural character, including porosity, as well as the resistivity of porewaters contained in the geological matrix. The resistivity contrast between freshwater and saline water is strong compared to the resistivity differences between many common nearshore geological materials (sands, limestone). As a result the freshwater–saltwater interface is typically a dominant feature in the resistivity structure of nearshore sediments, and resistivity methods have been used for decades to map this interface. Resistivity techniques have advanced considerably with the development of high-resolution streaming and stationary marine cable configurations and multi-channel systems (Manheim *et al.*, 2004). These newer systems permit much more rapid multi-pole data acquisition and more user-friendly and accurate data reduction software packages. The advantage of the streaming multi-channel systems (towed behind a boat) is that relatively long transects across a shore face can be studied rapidly. While several groups are currently using such systems in streaming mode to study nearshore hydrogeological processes, we have implemented a new, stationary resistivity cable that consists of 56 electrodes spaced 2 m apart to study in high resolution, the freshwater–saltwater interface. Instead of rapid coverage of long transects, this system permits very detailed examination of the freshwater–saltwater interface over a 100-m lateral scale, and to ~20 m depth, with better signal-to-noise than the streaming systems. The high resolution offers detailed examination of coastal hydrology and the response of the freshwater–saltwater interface to tidal forcing (Swarzenski *et al*., 2006b).

METHODS

We surveyed the resistivity of Tampa Bay sediments (Fig. 2) using an Advanced Geosciences Inc. (AGI) Marine SuperSting R8 multi-channel system connected either to: (a) a streaming cable that consisted of two current producing electrodes and eight potential electrodes that acquire data with dipole-dipole geometries, or (b) an external switching box that controlled the flow of current along a 56 electrode, stationary cable. In stationary mode, current potentials are measured in a distributed array, with array geometry set by the user. For every resistivity measurement (~1 per sec), the SuperSting R8 injects an optimized current, reverses the polarity and then re-injects the current again to cancel spontaneous voltages that may occur down-cable. This process is typically repeated, and if the error is less than a pre-determined threshold value (i.e. 7%), then the next reading advances. Replicate measurements provide a means to assess wave-induced artefacts. Resistivity measurements were processed using an inverse modelling routine (AGI EarthImager) that can accommodate water-column salinity and depth observations. The resolution was optimized by using a starting model with the apparent resistivity pseudo-section and a best-fitting layered model was then developed using an iterative least squares smooth model inversion method.

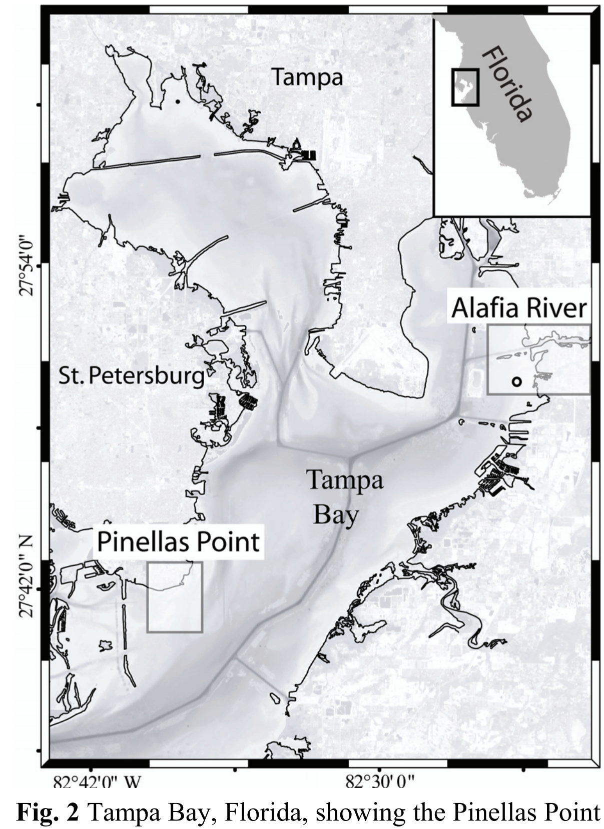

Fig. 2 Tampa Bay, Florida, showing the Pinellas Point and Alafia River study sites. ○ denotes the offshore well site at Bull Frog Creek used in the formation factor calculations.

RESULTS AND DISCUSSION

Formation resistivity (R_f) values of saturated sediments are derived from both the resistivity of the sediment grains (R_s) and the porewater resistivity (R_p), and are complexly controlled by sediment lithology, porewater salinity, porosity, and temperature. To interpret a resistivity profile obtained through the methods described above, it is useful to better understand the local relationships between the formation resistivity, lithology, and porewater resistivity. The porewater resistivity (ohm m) is easily measured where the porewater can be sampled directly, using a water conductivity meter. The porewater salinity–resistivity relationship can be expressed as $S = 7.042 \times R_p^{-1.0233}$ (at 25°C) where S = salinity; Manheim *et al.*, 2004). The formation resistivity in representative lithologies can be manually measured by extracting a sample of the matrix and using a Wenner-type probe. In saturated sediments the relationship between, R_f and R_p is often summarized in a simplified form of Archie's Law, in which a formation factor, F, is defined as $F = R_f R_p^{-1}$. From the measurements described above one can derive a local formation factor F for the types of sediments present. Assuming locally homogenous and saturated sediments, the formation factor, F, can then be used to interpret formation salinities from the time-series resistivity observations.

From auger cuttings collected during the installation of an offshore well in Tampa Bay (Fig. 2, latitude 27°50.308N; longitude 82°24.127W), we measured R_f, and R_p values from discrete sediment intervals to depths >11 m. In general, porewater salinities decreased in the surface sediments from a value of 20.5 (1 cm) to 17.9 at 90 cm, and then peaked at values in excess of 23 at 603 cm (Fig. 3(a)). Lowest porewater salinities (to 4.8) were observed at depths around 800 to 850 cm. Mean R_f values of 1.80 ± 0.18 ohm m (n = 17) at depth <1 m increased to values above 8 at a depth of 845 cm. Such R_f and R_p values yield formation factors, F, that ranged from 3 to above 6 (mean = 4.7 ± 1.1; n = 13) (Fig. 3(b)) and that predictably increase as sediments become coarser-grained.

Figure 4 shows two examples of modelled streaming and stationary resistivity profiles from the Tampa Bay region. A streaming resistivity profile (Fig. 4(a)) of the bed sediments from the lower Alafia River was acquired by boat travelling ~14 km upriver from Tampa Bay to evaluate surface water/groundwater (hyporheic) exchange processes prevalent in Florida's coastal rivers. For this line, a 100 m cable consisting of two current producing electrodes and eight potential electrodes spaced 10 m apart was used, and the 8-channel dipole-dipole resistivity data was subsequently merged with streaming GPS, depth and water column salinity. Periodic porewater and sediment resistivity values collected along this transect were used to derive a mean formation factor, F = 3, which was used to convert resistivity (ohm m) to salinity values. At the beginning (0 km) of this line, uniform saltwater intrusion can be seen to the cable exploration depth (i.e. ~20 m). Moving upstream, this saline water is gradually replaced by fresher groundwater, and by ~10 km, the resistivity results imply that the underlying groundwater is mostly fresh. The bathymetry of the river bed beyond 10 km also shows marked change in that the river bed transitions from being relatively smooth in the lower reaches of the river to exhibiting karst-type terrain features beyond 10 km.

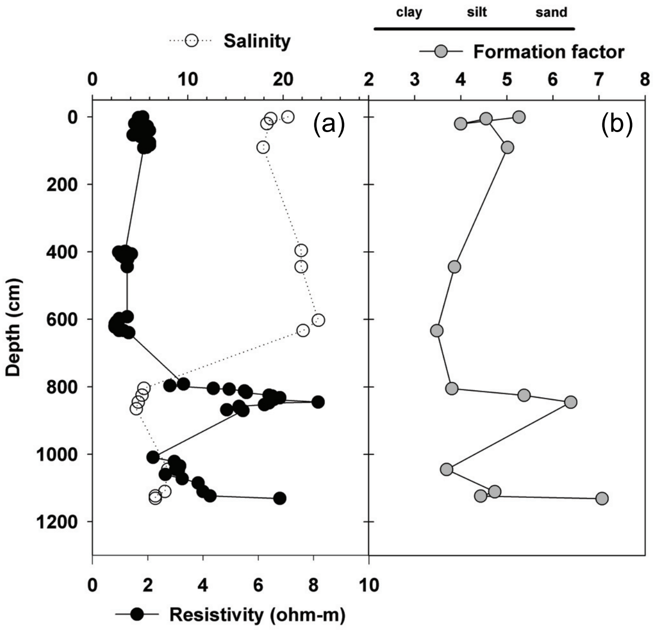

Fig. 3 (a) Seabed resistivity, porewater salinity, and (b) calculated formation factor, *F*, values derived from auger well cuttings collected during installation of an offshore well at Bull Frog Creek, Tampa Bay.

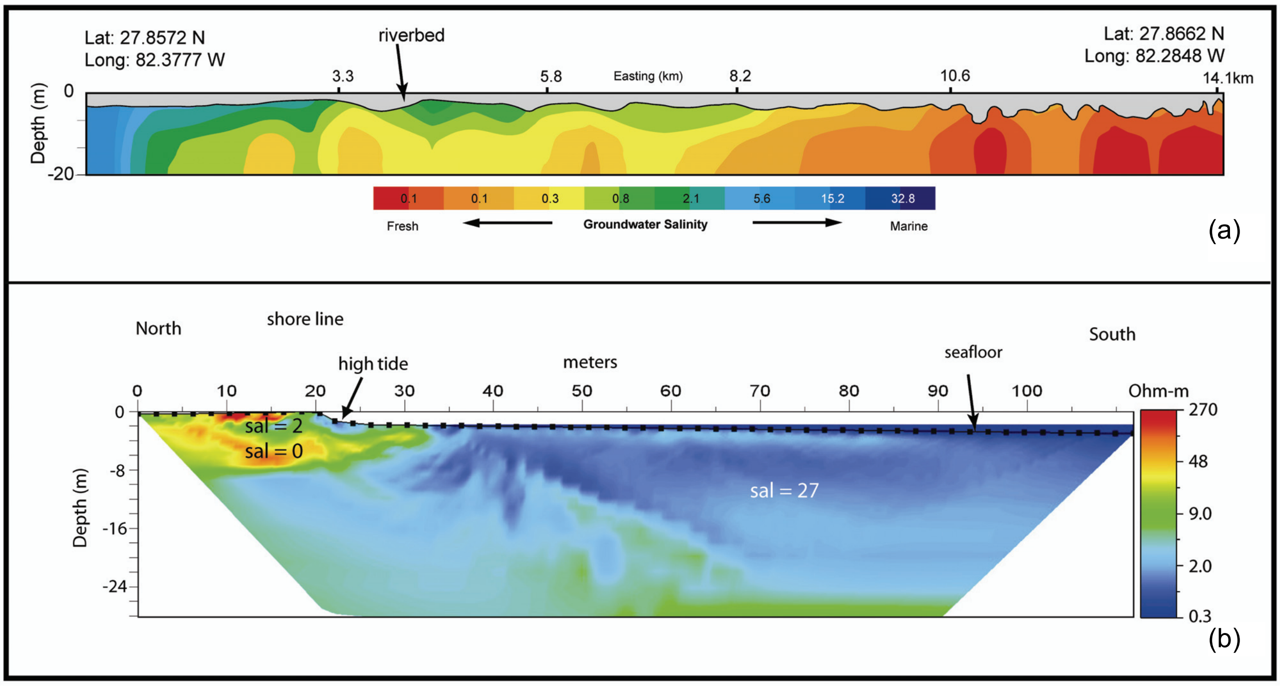

Fig. 4 (a) A 14.1 km long streaming resistivity profile of the lowest reach of the Alafia River, depicting the subsurface freshwater–saltwater interface to a depth of 20 m below the river bed. A formation factor, *F*, of 3 was used to convert resistivity units to representative groundwater salinity values (adapted from Swarzenski *et al.*, 2007). (b) A 116 m stationary resistivity profile across a beach face at Pinellas Point, showing the nearshore mixing dynamics of the surficial aquifer to 25 m depth as it discharged into bay surface waters. Annotated salinity values were measured using piezometer porewater samples (adapted from Swarzenski, 2007).

A stationary resistivity profile (Fig. 4(b)) was collected across a ~120 m long shore-perpendicular transect at Pinellas Point in southern Tampa Bay to examine submarine groundwater discharge processes. In contrast to the streaming resistivity method, the stationary cable lies fixed on the sea floor and contact of the 56 electrodes with sediment is facilitated using either sand bags or metal spikes. To ground truth the stationary resistivity measurements, we collected porewater samples by drive-point piezometer at discrete horizons for salinity values. At Pinellas Point, stationary resistivity measurements revealed a distinct tongue of freshened water that was being discharged about 30 m down cable. The expression of this water lens ("freshwater tunnelling") is characteristic of density-driven recirculation combined with tidal fluctuations and wave setup (Robinson *et al.*, 2006). By examining the detailed change in resistivity over a tidal cycle one can estimate a first-order SGD rate (Swarzenski *et al.*, 2006b).

CONCLUSION

Multi-channel electrical resistivity is a powerful tool to examine diverse coastal water mass mixing processes, including submarine groundwater discharge and hyporheic exchange within a coastal river. In streaming mode, large coastal areas may be examined rapidly by boat, yet we still have much to learn about the multi-channel system's performance in terms of reproducibility and resolution. In stationary mode, artefacts due to data acquisition or lithology are typically much lower than in streaming mode, and so this approach can provide high resolution information of the freshwater–saltwater interface and the response of this interface to tidal and other forcing factors.

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