Saltwater intrusion monitoring in Florida

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Abstract Florida’s communities are largely dependent on freshwater from groundwater aquifers. Existing saltwater in the aquifers, or seawater that intrudes parts of the aquifers that were fresh, can make the water unusable without additional processing. The quality of Florida’s saltwater intrusion monitoring networks varies. In Miami-Dade and Broward Counties, for example, there is a well-designed network with recently constructed short open-interval monitoring wells that bracket the saltwater interface in the Biscayne aquifer. Geochemical analyses of water samples from the network help scientists evaluate pathways of saltwater intrusion and movement of the saltwater interface. Geophysical measurements, collected in these counties, aid the mapping of the saltwater interface and the design of monitoring networks. In comparison, deficiencies in the Collier County monitoring network include the positioning of monitoring wells, reliance on wells with long open intervals that when sampled might provide questionable results, and the inability of existing analyses to differentiate between multiple pathways of saltwater intrusion. A state-wide saltwater intrusion monitoring network is being planned; the planned network could improve saltwater intrusion monitoring by adopting the applicable strategies of the networks of Miami-Dade and Broward Counties, and by addressing deficiencies such as those described for the Collier County network.

Keywords Aquifer, saltwater intrusion, seawater encroachment, monitoring

Introduction

Florida’s freshwater resources are vitally important to its population and commerce, but if saltwater intrudes Florida’s aquifers, the groundwater from these areas might become undrinkable without additional processing. The U.S. Environmental Protection Agency (EPA) 2015 secondary standard for chloride in drinking water is 250 milligrams per liter (mg/L) (U.S. Environmental Protection Agency 2015). Seawater typically has a chloride concentration of about 19,000 mg/L (Stumm and Morgan 1981); therefore, even a relatively small fraction of seawater can render the water non-potable. South Florida (Figure 1) is surrounded by seawater on three sides, and saltwater is found in deep rock layers that underlie the freshwater aquifers. Some bodies of residual saltwater might have entered aquifers when sea levels were high during interglacial periods or during deposition when seawater was trapped in the sediments. This residual saltwater has not been completely removed by the flow of freshwater through the aquifers since the interglacial periods (e.g., Reese and Wacker 2009).
In Florida, saltwater has intruded through a number of pathways (Figure 2) including: (1) encroachment of seawater into aquifers in response to decreased fresh groundwater levels relative to sea level, (2) the flow of saltwater inland through canals, rivers, boat basins, and coastal marshes and subsequent leakage of this saltwater into aquifers, (3) movement of connate or relict saltwater in an aquifer, and (4) leakage of saltwater between aquifers (Prinos 2013). The reductions in fresh groundwater levels could be caused by public and private water supply withdrawals from aquifers, excessive drainage, reductions in precipitation, or increases in sea level. Saltwater in some aquifers might have emanated from multiple pathways. For example, saltwater leaking from canals might merge with saltwater from the sea that is encroaching inland along the base of the aquifer.

As water managers work to prevent and reverse saltwater intrusion in Florida, they use information from local, State, and Federal saltwater intrusion monitoring.
monitoring networks; however, there is considerable variability in the quality of monitoring conducted in the counties of Florida. In some areas, such as Broward and Miami-Dade Counties (Figure 1), state-of-the-art monitoring has been implemented, but in many areas of Florida, monitoring is not ideally located or designed to detect saltwater intrusion before it can reach and potentially contaminate well fields (see the Case Studies section of this article).

**Saltwater Intrusion Monitoring**

Saltwater intrusion monitoring networks are designed to determine the inland extent of saltwater intruding from the ocean, and the distribution of saltwater that entered an aquifer by other means. Monitoring networks ideally have wells located near the freshwater-saltwater interface that can be used to detect movement of this interface. The best networks are designed to monitor saltwater intrusion in three dimensions because saltwater can advance unequally through the layers of rock in an aquifer. Monitoring that can distinguish between the different pathways of saltwater intrusion is beneficial because remediation of saltwater intrusion requires an understanding of the contributing pathways. Advances in geochemistry and geophysics allow improved understanding of the extent, distribution, and pathways of saltwater intrusion as well as temporal changes in these factors (see the Differentiating between sources of saltwater intrusion section of this article).

**Monitoring well design and sampling.** Each year, thousands of wells in Florida are sampled to evaluate water quality. The sampling results constitute the primary source of information for evaluating saltwater intrusion. The
quality of these results depends on sampling technique and the design, location, and condition of the monitoring wells. The types of wells used to monitor saltwater intrusion in Florida vary from uncased boreholes drilled in solid rock, to short-screened interval, cased monitoring wells with seals and filter packs. Prinos (2013) describes how vertical flow in the open bore of long-screened wells, under ambient conditions or during pumping, can potentially bias the results of water samples or water-conductivity profiles. Prinos and Valderrama (2015) indicate that vertical flow within a long-screened well near Lake Okeechobee, Florida, likely prevented the detection of the saltwater interface that was evident in the data from proximal short-screened wells. Because of problems like these with the sampling of long-screened wells, Lapham et al. (1997) recommend using wells with screened intervals of 5 feet or less for studies of the fate and transport of groundwater constituents. For these reasons, short-screened monitoring wells that tightly bracket the saltwater interface in the aquifer provide the most useful information concerning movement of the freshwater-saltwater interface.

**Differentiating between sources of saltwater intrusion.** Analyses of the chemical and isotopic composition of the water in an aquifer can be used to evaluate the pathways of saltwater intrusion. Prinos et al. (2014) provide an overview of these types of geochemical evaluations and summarize the applicable references. The composition of major and trace ions in water can be used to determine if saltwater has intruded into a part of the aquifer that was previously fresh, or was already brackish or saline. Gases that are dissolved in the water can provide information about the temperature of the water when it first entered the aquifer, and thereby provide information about the season during which the influx occurred. Isotopes of strontium can be used to determine the ages of carbonate strata with which groundwater has equilibrated. The isotopic signature that the saline groundwater acquires through chemical equilibrium with host rocks can be used to determine the strata from which the water likely emanated. Oxygen and hydrogen stable isotopes can be used to help evaluate the sources of the water in an aquifer. Tritium/helium-3 age dating can be used as a tracer of groundwater flow associated with saltwater intrusion.

**Water conductivity measurements.** Measurements of electrical conductivity in water can be used to evaluate saltwater intrusion in Florida because conductivity is proportional to the concentration of dissolved solids in water. These measurements can improve understanding of pathways by which saltwater is intruding. Conductivity measurements have been collected as (1) conductivity-depth profiles in long open-interval wells, (2) point measurements in streams and canals, (3) water sample analyses, and (4) time-series measurements in surface-water bodies and in wells. Conductivity-depth profiles in long open-interval wells can be adversely affected, however, by vertical flow within the well bore (Prinos 2013).
Geophysical logs, soundings, and surveys. Airborne, surface, and borehole geophysical logs, soundings, and surveys can be used to detect saltwater in aquifers (see for example Prinos et al. (2014) and Prinos and Valderrama (2015)). Methods include: (1) electromagnetic induction (EMI) logging, (2) time-series electromagnetic induction log (TSEMIL) dataset compilation, (3) time domain electromagnetic soundings, (4) continuous resistivity profiling, (5) capacitively coupled resistivity (CCR) surveys, (6) airborne electromagnetic surveys, and (7) direct current resistivity surveys. The information collected can be used to (1) map saltwater intrusion, (2) monitor temporal changes in salinity, (3) determine the best locations for monitoring wells, and (4) determine the best depths for monitoring well intakes. A primary advantage of surface geophysical mapping is that information can be obtained without the difficulties that might be associated with installing numerous monitoring wells. Airborne electromagnetic surveys can provide detailed three-dimensional information over relatively large areas in a fraction of the time it would take to provide similar information using ground-based surveys. These surveys are particularly useful in remote areas that do not have many features, such as railroad tracks, power lines, underground pipes and buildings, which can interfere with the surveys.

Case Studies

Biscayne aquifer, Miami-Dade and southern Broward Counties. Prinos et al. (2014) describe saltwater intrusion in the Biscayne aquifer of Miami-Dade and southern Broward Counties (Figure 1). Saltwater intrusion in this aquifer began early in the 20th century when canals were installed to drain the Everglades, and provide land for development. Following installation of these canals, water levels in the Everglades declined an estimated 9.5 feet near Miami, and saltwater intruded until it eventually contaminated local well fields (Prinos et al. 2014). The U.S. Geological Survey (USGS), in cooperation with Broward and Miami-Dade Counties, the South Florida Water Management District, and the Florida Power and Light Company, developed a monitoring network to evaluate saltwater intrusion in the Biscayne aquifer and provide the information necessary to prevent, mitigate, or remediate it. This network currently (2015) consists of 103 saltwater intrusion-monitoring sites. Most of these sites bracket the saltwater interface in the aquifer so that changes in position can be monitored.

Each year the USGS and its partners install additional monitoring wells where needed to improve evaluations of the causes and extent of the saltwater intrusion. In addition to this monitoring, Prinos et al. (2014) used a combination of geochemical sampling and airborne, surface, and borehole geophysical measurements to map the distribution of saltwater intrusion in Miami-Dade and southern Broward Counties. The TSEMIL datasets, consisting of a time series of electromagnetic induction logs collected in a monitoring well over a period of months or years, were used to evaluate
changes in the electrical conductivity of aquifer materials resulting from changes in water salinity. These datasets can be collected in short-screened interval polyvinyl-chloride-cased wells, and can be used to detect changes in aquifer salinity throughout its full thickness (Figure 3) without the problems that can occur in long open-interval wells. Using TSEMIL datasets and specific conductivity measurements, Prinos et al. (2014) identified influxes of saltwater in the aquifer that likely emanated from the leakage of brackish water from canals.

Prinos et al. (2014) used tritium/helium-3 age dating methods to determine a close correspondence between droughts and timing of saltwater intrusion. The major ion composition of saltwater was used to identify locations where saltwater was intruding parts of the aquifer that were previously fresh, and where saltwater was intruding previously intruded areas. Surface and airborne geophysical methods were used to fill gaps in the network, and to provide a detailed understanding of the distribution of saltwater in the aquifer (Fitterman and Prinos 2011, Fitterman et al. 2012). A helicopter electromag-
A genetic survey collected in southeastern Miami-Dade County provided detailed information in an area that had previously been sparsely monitored (Figure 1; Fitterman et al. 2012). Using estimates of recharge temperatures determined from the dissolved-gas composition in water samples, Prinos et al. (2014) indicated that saltwater likely entered the aquifer in April or early May when water levels were typically at their lowest level during the year.

Collier County. Prinos (2013) describes the salinity-monitoring network in Collier County, Florida, and parts of Monroe and Lee Counties. In this area, the water table and the lower Tamiami aquifers (Figure 4) are important sources of water for public supply. Drainage efforts that began in the 1920s led to reduced water levels, saltwater encroachment along the bases of the aquifers, and the inland flow of saltwater in rivers, canals, and boat basins. In 1945 the City of Naples well field became saline as a result of saltwater intrusion and had to be abandoned and replaced. Saltwater intrusion near the replacement well fields remains a concern.

Schmerge (2001) determined that saltwater from deep aquifers was seeping upward into shallow aquifers by analyzing the ratio of strontium-87 to strontium-86 of water samples from 40 wells in the water table, lower Tamiami, sandstone, mid-Hawthorn, and Upper Floridan aquifers (Figure 4). By using field data and variable-density groundwater flow simulations, Shoemaker and Edwards (2003) determined that of the various pathways of saltwater intrusion affecting the northeastern part of Collier County, and extending northward.
into Lee County, upward leakage from deep saline water-bearing zones is probably the primary concern. Furthermore, they stated that lateral encroachment of seawater inland along the base of the aquifer is an important, but secondary concern in the lower Tamiami aquifer.

Prinos (2013) describes a variety of deficiencies in the existing network in Collier County that hamper a clear understanding of the current extent of saltwater intrusion, including: (1) locations and depths of monitoring wells are not optimized to detect changes in the position of the saltwater interface, (2) monitoring relies on a large percentage of (vertically-integrating) long open-interval wells that were neither designed nor intended to be used specifically for monitoring saltwater intrusion, and (3) existing monitoring does not differentiate between saltwater intruding through multiple pathways. Prinos (2013) indicated that the use of existing Florida Department of Environmental Protection (FDEP) standard operating procedures (SOPs) for groundwater sampling could, in many instances, result in samples that are not representative of maximum salinity in the aquifer because these SOPs were designed for general water-quality monitoring rather than saltwater intrusion monitoring.

Development of a Saltwater Intrusion-Monitoring Network for Florida

The State of Florida is in the process of developing a statewide saltwater intrusion-monitoring network consisting of wells from existing saltwater intrusion monitoring networks (Florida Salinity Network Workgroup 2015). Information provided in the case studies described herein indicates the following:

- A network of wells tightly bracketing the leading edges of the masses of intruding saltwater could improve understanding of ongoing saltwater intrusion.
- Geochemical sampling can be used to help differentiate between the sources of saltwater in an aquifer.
- Salinity samples from long-screened or long-open-interval wells can yield ambiguous results, whereas short-screened-interval wells can yield less ambiguous information.
- Ongoing replacement of old, poorly positioned wells with new wells that fill gaps in coverage is an important part of network maintenance.
- Geophysical studies can provide information concerning changes in salinity within the full thickness of the aquifer.
- The TSEMIL datasets can be used to detect influxes of conductive water at depths that might have been missed by multi-well clusters, and without the ambiguity that can result from sampling of long-open-interval wells.
- Salinity monitoring can be improved through the development of Florida Department of Environmental Protection SOPs specifically designed for sampling salinity in long-open-interval wells.

Ongoing improvements to monitoring networks are necessary to provide the quality of information needed by water managers, because saltwater
interfaces in many of Florida’s aquifers are moving, or the pathways of intrusion are shifting. For example, replacing older monitoring wells on an ongoing basis with new, optimally designed, and effectively positioned monitoring wells can help in this effort. Applying advancements in monitoring techniques to existing and future salinity monitoring networks will improve our understanding of the multiple pathways of saltwater intrusion into freshwater aquifers.

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**References**


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