

Prepared in cooperation with Miami-Dade County

Using State-of-the-Art Technology to Evaluate Saltwater Intrusion in the Biscayne Aquifer of Miami-Dade County, Florida

The fresh groundwater supplies of many communities have been adversely affected or limited by saltwater intrusion. An insufficient understanding of the origin of intruded saltwater may lead to inefficient or ineffective water-resource management. A 2008–2012 cooperative U.S. Geological Survey (USGS) and Miami-Dade County study of saltwater intrusion describes state-of-the-art technology used to evaluate the origin and distribution of this saltwater.

Background

During the first half of the twentieth century, saltwater began to intrude the Biscayne aquifer of Miami-Dade County, Florida, and resulted in the contamination of several municipal well fields. This saltwater intruded through a variety of means, including (1) encroachment of saltwater from the ocean along the base of the aquifer; (2) infiltration of saltwater from coastal saltwater mangrove marshes; and (3) the flow of saltwater inland through canals where it leaked into the aquifer (fig. 1). Most of this intrusion occurred prior to the installation of salinity control structures on canals during the 1940s and was exacerbated by reduced water levels during droughts. The influxes of saltwater prior to structure installation (termed historic) and recent influxes have combined or overlapped to create the current distribution of saltwater in the Biscayne aquifer of Miami-Dade County (fig. 2).

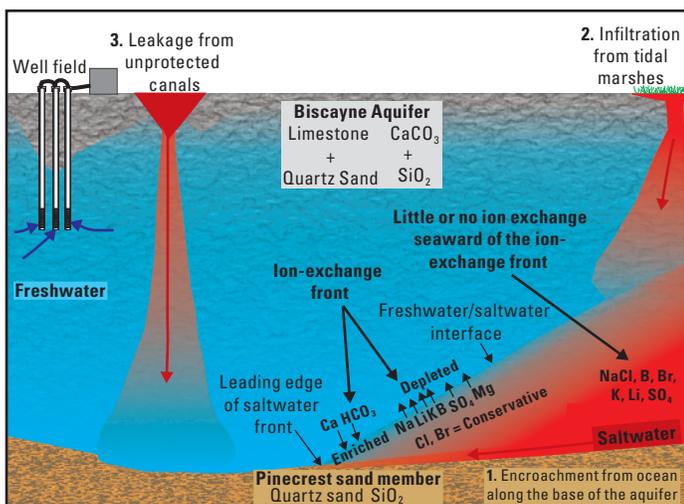


Figure 1. Origins of saltwater intrusion in the Biscayne aquifer, and resulting changes in water chemistry. [B, boron; Br, bromide; Ca, calcium; Cl, chloride; CaCO_3 , calcium carbonate; HCO_3 , bicarbonate; K, potassium; Li, lithium; Mg, magnesium; Na, sodium; SiO_2 , silica; SO_4 , sulfate]

Improved Monitoring

Conventional saltwater intrusion monitoring typically consists of collecting water samples from wells to evaluate the chloride concentration, specific conductance, or salinity of the water. These monitoring wells are expensive to install, and their spatial distribution is relatively sparse. In urban Miami-Dade County, these wells generally are spaced about 0.5 to 5 kilometers (km) apart.

Time-domain electromagnetic (TEM) soundings (figs. 3 and 4) were collected to augment the spatial coverage of the monitoring well network and to aid in the calibration and processing of a helicopter electromagnetic (HEM) survey (figs. 2 and 5) that had been flown in October 2001 (Fitterman and Prinos, 2011; Fitterman and others, 2012). State-of-the-art time-series electromagnetic induction log (TSEMIL) datasets (fig. 6) were used to monitor salinity in the aquifer, rather than the older, disputed approach of collecting conductivity profiles of borehole water. An improved understanding of the origin of saltwater intrusion has been provided by combining this geophysical information with the results of geochemical analyses of stable isotopes, major and trace ion chemical composition, and tritium-helium age dating (fig. 7).

Time-Domain Electromagnetic Soundings

TEM soundings are surface geophysical measurements that are made by passing a transient current through a large, square transmitter loop to induce a circulating current system in the ground. The flow of the current through the ground generates a magnetic field that is measured as a decaying voltage by the receiver coil at the center of the transmitter loop. The rate of decay is controlled by the resistivity of the ground. Measured voltages are converted to apparent resistivity, from which a layered model of resistivity as a function of depth can be determined (fig. 3). Prinos and others (2014) developed the empirical relation that, in the Biscayne aquifer, resistivities between 10 and 15 ohm-meters are indicative of the mixing zone at the leading edge of the saltwater front. TEM soundings were used to aid in mapping the saltwater front and to provide information to calibrate the HEM survey (figs. 2 and 5; Fitterman and Prinos, 2011). Although TEM soundings do not provide the same vertical resolution or detail as a borehole electromagnetic induction log, a TEM sounding typically can be collected in a few hours and does not require the monitoring wells needed for induction logging. The resistivities determined through modeling of TEM sounding data generally corresponded closely to the results of electromagnetic induction logs collected in nearby wells (fig. 4). Prinos and others (2014) used TEM soundings to estimate the depth of the Biscayne aquifer where possible and compared these depths with previous estimates (fig. 4).

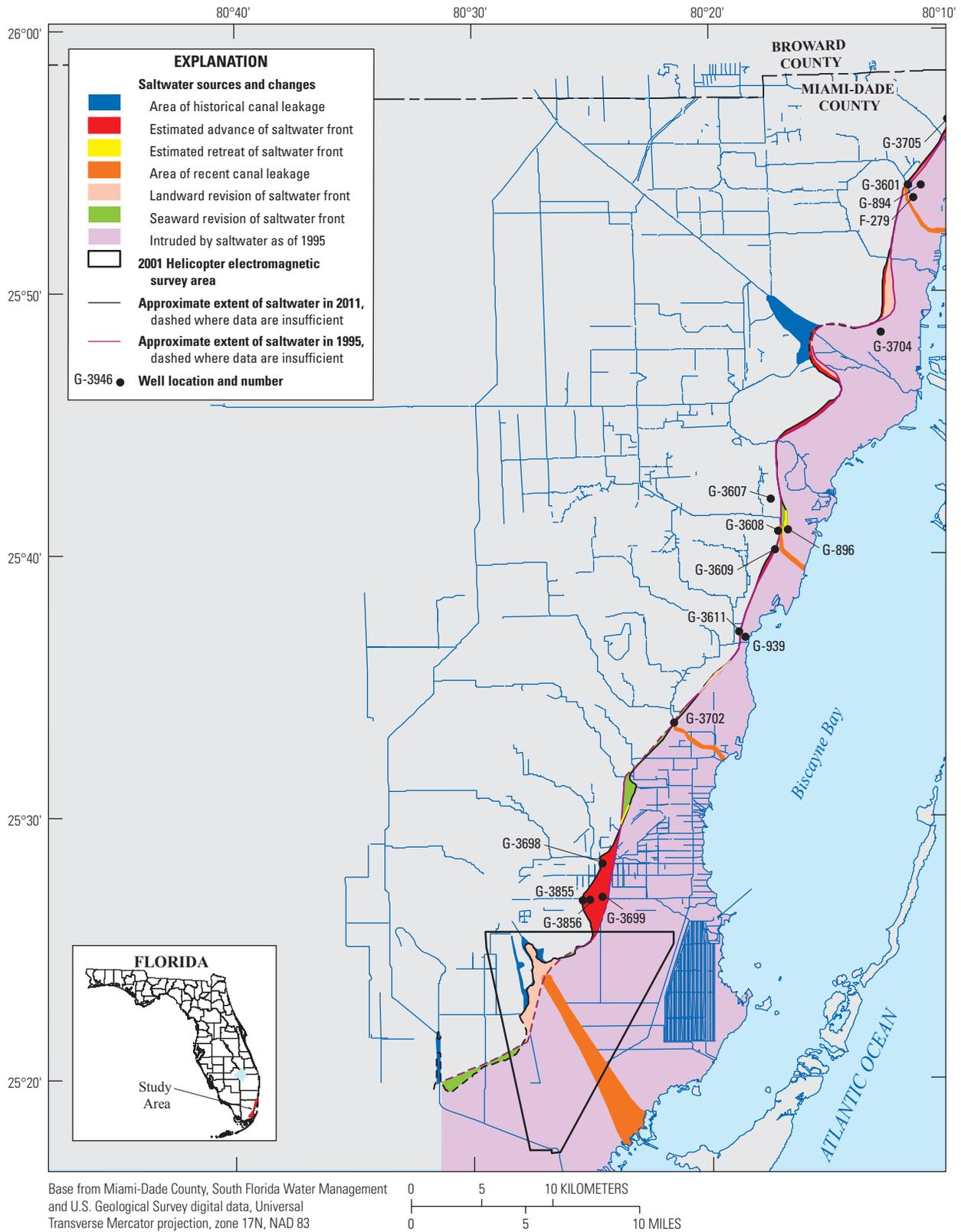


Figure 2. Origin and delineation of saltwater intrusion in the Biscayne aquifer, Miami-Dade County, Florida, basis for modifications to the mapped extent of the aquifer, and locations of well samples depicted in figure 7. Modified from Prinos and others (2014).

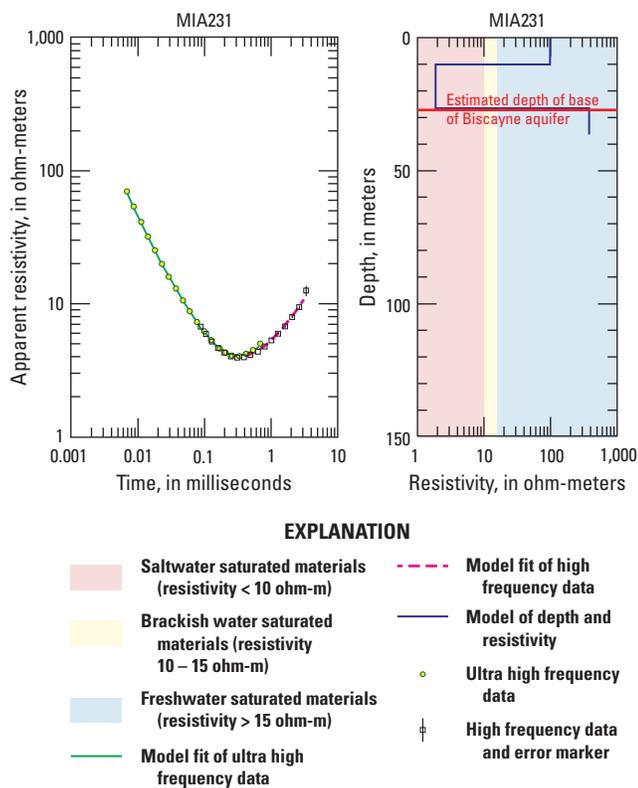


Figure 3. Time-domain electromagnetic sounding at site MIA231 collected March 3, 2009. Location of site is shown in figure 5. Modified from Fitterman and Prinos (2011).

Helicopter Electromagnetic Survey

The 2001 HEM survey consisted of densely spaced frequency-domain electromagnetic (FEM) measurements collected from an instrument pod (“bird”) suspended on a 30-meter (m) cable below a helicopter (Fitterman and others, 2012). Data were collected along 38 east-west flight lines, spaced 400 m apart, and one north-south flight line within a 123 square kilometer (km²) area (figs. 2 and 5). Measurements were made by passing a sinusoidally varying current through multiturn transmitter coils. Receiver and transmitter coils were spaced 7.9 m apart. Five coil pairs were operated at frequencies of 0.4, 1.5, 6.4, 25, and 100 kilohertz. Lower frequencies provide greater depth penetration. The conversion of the measured electromagnetic data to apparent resistivity is described in Fitterman and others (2012). Analysis of the data provided resistivity-depth functions, which were used to create resistivity depth-slice maps ranging in depth from 5 to 100 m. East-west and north-south cross sections of resistivity that coincided with the flight lines also were created. Cross sections show variations in the slope of the saltwater interface, and the maps show tongues of saltwater that correspond with the Card Sound Road Canal and the drainage ditches along U.S. Highway 1 (fig. 5). The density of resistivity information collected provides previously unparalleled, 3-dimensional understanding of saltwater intrusion in the area of the survey.

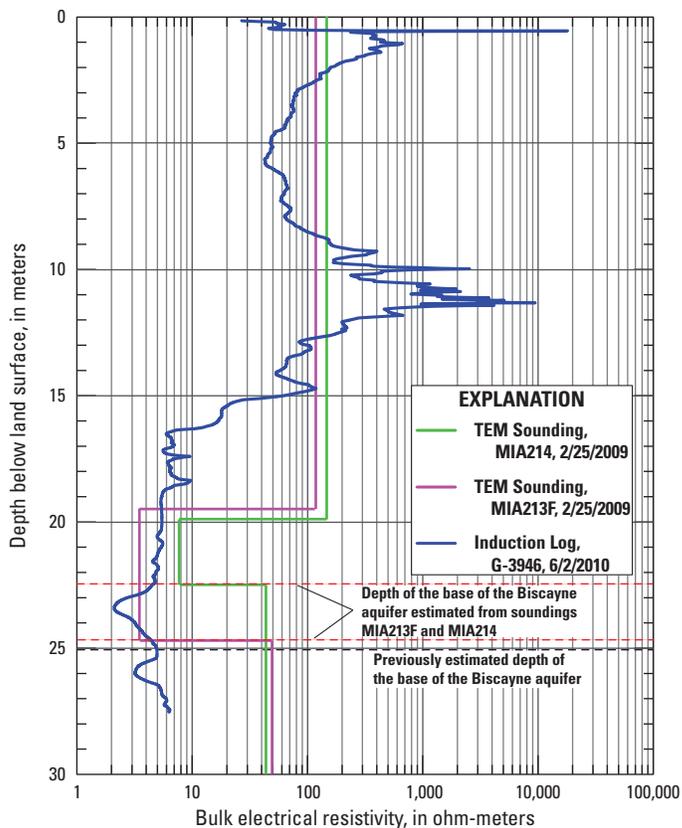


Figure 4. Comparison of modeled time-domain electromagnetic soundings MIA213F and MIA214 with an induction log from well G-3946. Locations of sites are shown in figure 5. Modified from Fitterman and Prinos (2011).

Time-Series Electromagnetic Induction Log Datasets

Although salinity profiles collected in wells with long open-intervals were used historically to describe changes in salinity throughout the full thickness of the Biscayne aquifer, vertical flow within the well bores under ambient and (or) pumped conditions adversely affected measurements or samples (Prinos and others, 2014). Electromagnetic induction logs collected in PVC-cased wells can detect changes in the bulk conductivity of the aquifer associated with saltwater intrusion within a radius of 20 to 100 centimeters (cm) from the center of the well without the adverse effects resulting from vertical flow within the well bores. TSEMIL datasets are created by removing minor calibration errors from induction logs. Each individual log in a time-series of logs is adjusted to the average or median bulk resistivity of the log set at selected depths where salinity in the aquifer is not changing (Prinos and others, 2014). The resulting TSEMIL dataset can be used to evaluate even relatively minor changes in bulk conductivity associated with saltwater intrusion throughout the thickness of the aquifer (fig. 6). An example TSEMIL dataset from well G-3699 shows that (1) between 2000 and 2011 the bulk conductivity of the aquifer increased in the depth interval 19.8 to 25.7 m below land surface (bls), (2) the depth to the saltwater interface decreased from about 25.5 to 21.5 m bls, and (3) bulk conductivity decreased in the depth intervals 10.5 to 13 m and 14.2 to 16 m bls (fig. 6). When saltwater monitoring wells are

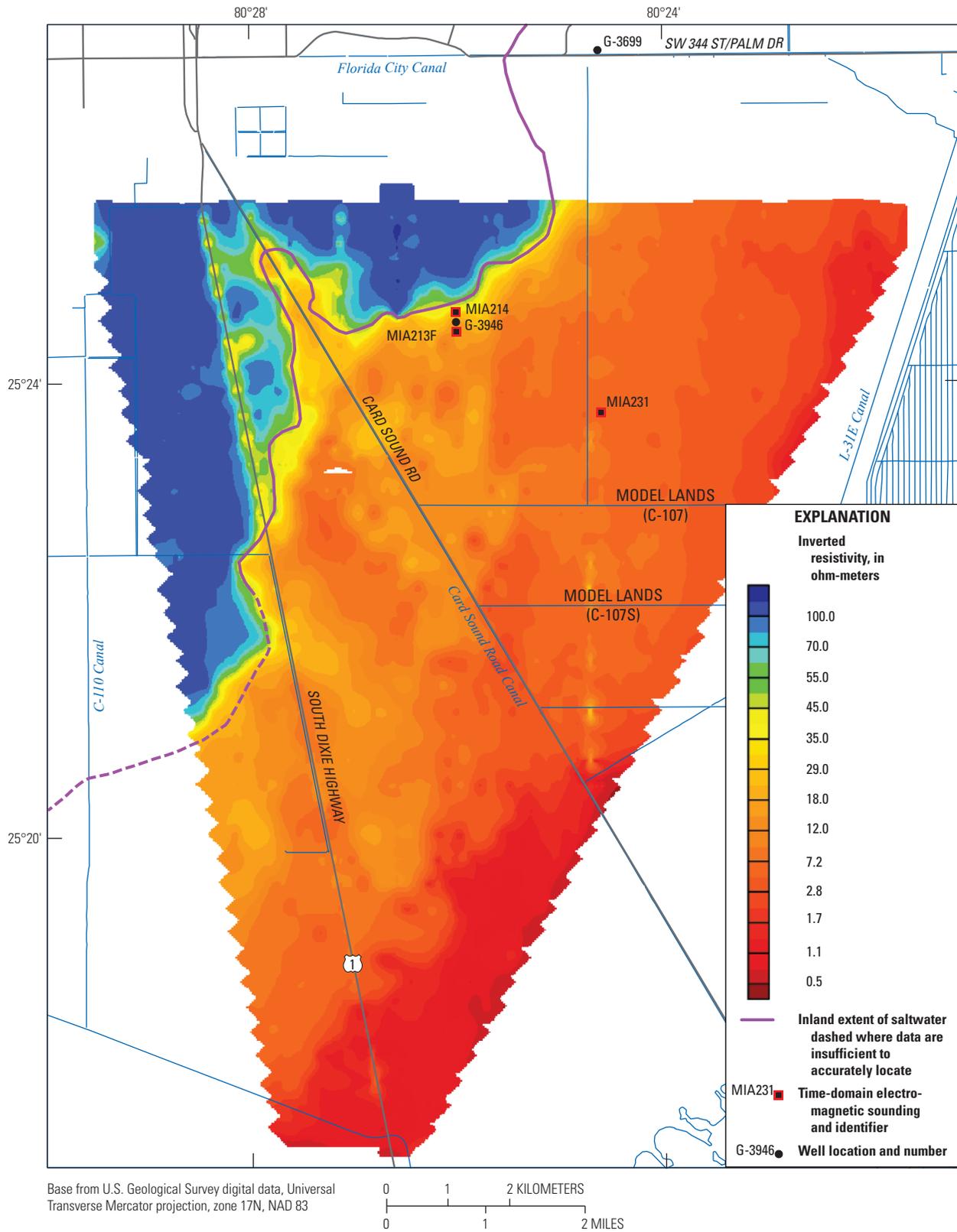


Figure 5. A 30-meter depth-inverted resistivity depth-slice map, from a helicopter electromagnetic survey collected in October 2001, in the Model Land, Miami-Dade County, Florida, and locations of sites shown in figures 3, 4, and 6. Modified from Fitterman and others (2012).

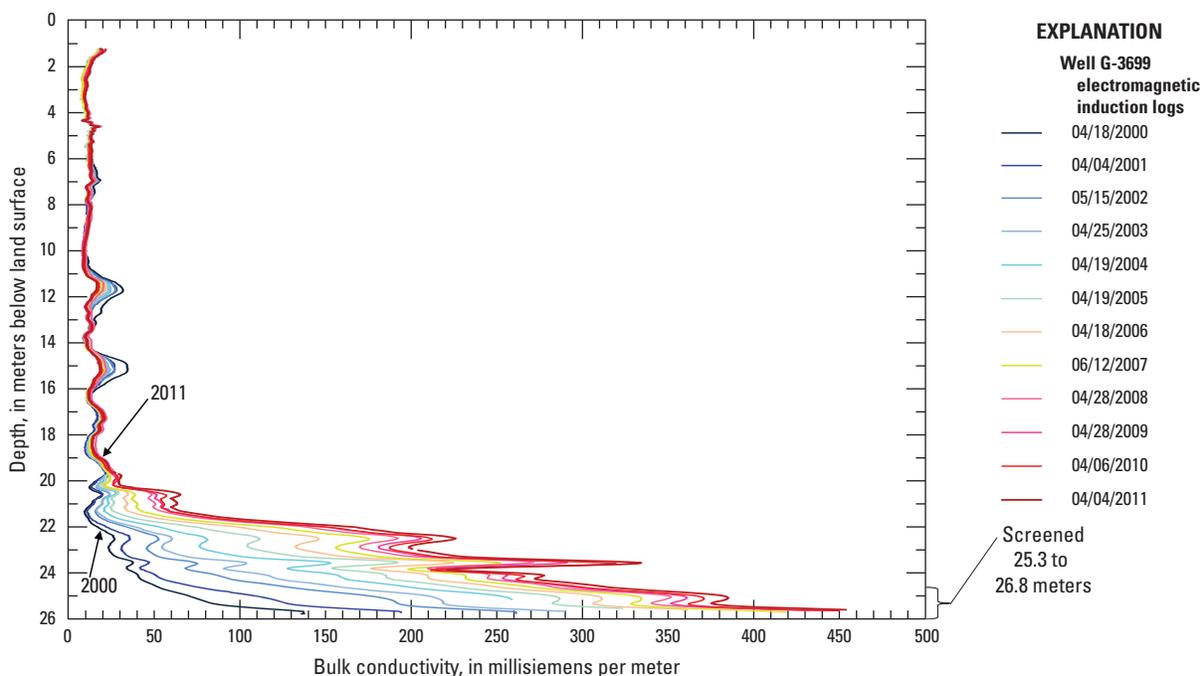


Figure 6. Time-series (04/18/2000–04/04/2011) electromagnetic induction log dataset collected in well G-3699. Location shown in figure 5.

drilled, some of the saltwater may enter shallow permeable strata in the aquifer. Decreases in bulk conductivity through time, in shallow strata above the saltwater interface, like those in the G-3699 TSEMIL dataset, have been observed in many other TSEMIL datasets, and are likely the result of saltwater that slowly dissipated after initially being trapped in these strata during well drilling and installation.

Geochemical Sampling

To evaluate the potential for saltwater intrusion at coastal well fields, water managers need to understand the origin of intruded saltwater (fig. 2), the current location of the saltwater, and any temporal changes in the location. Saltwater that intruded early in the 20th century and is gradually dissipating may pose less of a concern, for example, than saltwater that is actively intruding near a well field where it can contaminate water-supply wells. If the origin of saltwater is misconstrued, the corrective measures implemented to prevent further saltwater intrusion could fail to address the root cause. Geochemical sampling can improve the understanding of how and when saltwater intruded the aquifer.

Stable Isotopes

The isotopes of hydrogen, oxygen, and strontium can be used to evaluate the origin of saltwater. The concentrations of stable isotopes of hydrogen and oxygen in water are affected by fractionation occurring during evaporation and precipitation. The extent of fractionation that has occurred in water samples can be used to determine the likely sources of saltwater. The oxygen- and hydrogen-stable isotope composition of precipitation is known to follow a well-defined linear trend known as the global meteoric water line (GMWL). Local evaporation

causes systematic enrichment of the heavier oxygen- and hydrogen-stable isotopes that results in a divergence of the stable isotopic composition of local surface water from the GMWL. Differences in the extent of fractionation between seawater, rainfall, surface water, and water from tidal marshes can be used to evaluate the origin of groundwater. Prinos and others (2014) used oxygen- and hydrogen-stable isotopes and TSEMIL datasets to help determine where saltwater likely leaked from canals rather than having encroached along the base of the Biscayne aquifer.

Strontium isotope age dating of groundwater uses a known relation between age and the strontium-87 to strontium-86 ($^{87}\text{Sr}/^{86}\text{Sr}$) ratio of carbonate rocks. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in groundwater gradually equilibrates with the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the carbonate rocks through which it flows. Schmerge (2001) used this method in southwest Florida to identify areas where water from deeper aquifers had leaked upward into shallower aquifers. Prinos and others (2014) found that the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the groundwater samples that they collected did not indicate upward leakage of water from deeper aquifers, but rather, that the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of these samples generally correspond to the ages of the geologic strata of Biscayne aquifer.

Major and Trace Ion Chemical Composition

As saltwater intrudes a part of an aquifer that previously contained freshwater, the concentrations of certain ions in the mixed water can be affected by (1) dissolution of aquifer materials, (2) precipitation, (3) reduction of chemical species, and (4) adsorption onto or release from clay minerals, organic matter, oxyhydroxides, or fine-grained rock materials. These complex chemical changes occur in a part of the saltwater front called the ion-exchange front (fig. 1) and may include exchange of sodium in seawater with adsorbed calcium; adsorption of

potassium, boron, and lithium in seawater onto clay minerals; and enrichment in calcium and bicarbonate caused by dissolution of calcite and aragonite in carbonate aquifers. Prinos and others (2014) examined the amount of enrichment or depletion of these ions relative to the chemical compositions produced by mechanical mixing to help determine where saltwater has recently intruded and where intrusion is ongoing.

Tritium-Helium Age Dating

Tritium-helium age dating can be used to date water younger than about 40 years. Generally tritium (^3H) and helium-3 (^3He) are nonreactive and unaffected by groundwater chemistry or by anthropogenic contamination. Tritium-helium age dating uses the known half-life of tritium and the $^3\text{H}/^3\text{He}$ ratio measured in water samples to estimate the age of the water. A commonly applied age-dating interpretation is that of piston flow, which assumes that the constituent concentration was not altered by transport processes (such as mixing or dispersion) from the point of entry to the measurement point in the aquifer. Prinos and others (2014) found that the interpreted piston-flow ages of water samples that had a chloride concentration of about 1,000 milligrams per liter (mg/L) or greater were generally older than those samples with a chloride concentration of less than about 1,000 mg/L, and the ages of water samples that had a chloride concentration of about 1,000 mg/L or greater correspond to a period during which droughts were frequent (fig. 7). This finding is reasonable because saltwater intrusion is more likely to occur during drought periods, when fresh groundwater heads are low and saltwater may encroach more readily along the base of the aquifer or flow inland in canals, rivers, or tidal marshes.

References

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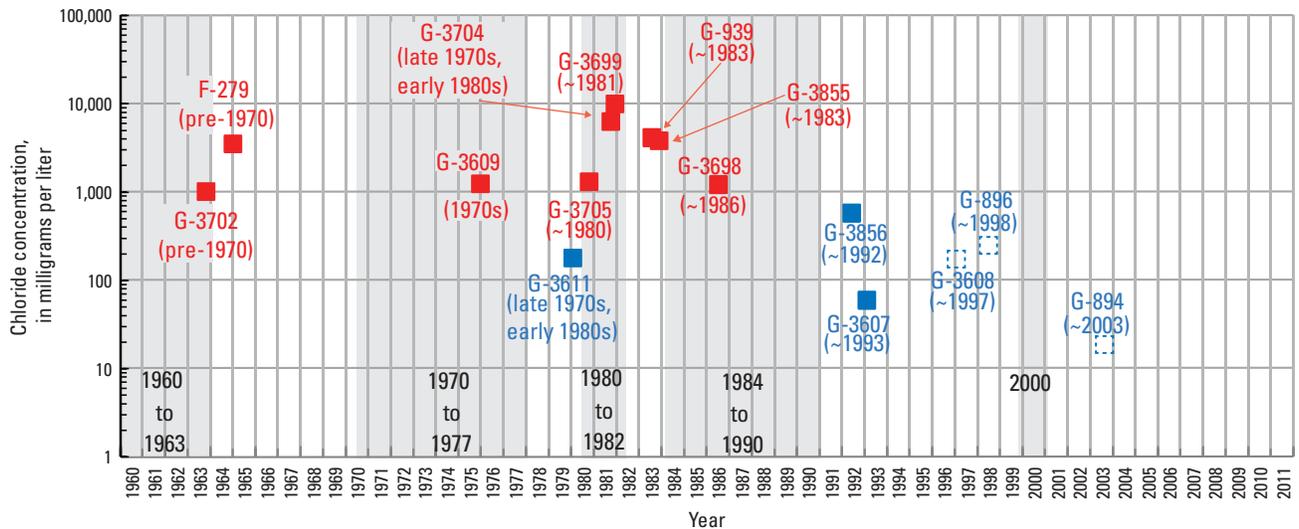


Figure 7. Hydrogen-3/Helium-3 interpreted piston flow ages of groundwater samples collected during 2009–2010 in Miami-Dade County, Florida, and dates of documented droughts in south Florida. [mg/L, milligrams per liter; ~, approximately; <, less than; ≥, greater than or equal to] Modified from Prinos and others, 2014. Locations of wells are shown in figure 2.

EXPLANATION

- 1985 Drought period and year(s)
- Analytical age of water sample and well identifier. Chloride concentration ≥ about 1,000 mg/L. Interpreted piston-flow age is in parentheses
- Analytical age of water sample and well identifier. Chloride concentration < about 1,000 mg/L. Interpreted piston-flow age is in parentheses. Dashed where gas fractionation may have affected sample